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Laboratory Column Experiments for Radionuclide Adsorption Studies of the Culebra Dolomite Member of the Rustler Formation

Daniel A. Lucero, Glenn O. Brown, Charles E. Heath

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Waste Isolation Pilot Plant

Laboratory Column Experiments for Radionuclide Adsorption Studies of the Culebra Dolomite Member of the Rustler Formation

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ABSTRACT

Radionuclide transport experiments were carried out using intact cores obtained from the Culebra member of the Rustler Formation inside the Waste Isolation Pilot Plant, Air Intake Shaft. Twenty-seven separate tests are reported here and include experiments with ^3H , ^{22}Na , ^{241}Am , ^{239}Np , ^{228}Th , ^{232}U and ^{241}Pu , and two brine types, AIS and ERDA 6. The ^3H was bound as water and provides a measure of advection, dispersion, and water self-diffusion. The other tracers were injected as dissolved ions at concentrations below solubility limits, except for americium.

^{22}Na was transported similarly to ^3H , which shows it is a conservative tracer in the Culebra samples and can be used as a replacement for ^3H to eliminate interference with ^{241}Pu analysis.

Two tracers eluted but were moderately retarded, ^{239}Np and ^{232}U . Three tracers, ^{241}Am , ^{228}Th and ^{241}Pu , were not detected in column effluent.

Breakthrough curves for eluting species were fitted to single and dual porosity models. The single porosity model assumed a homogeneous porous medium and advection-dispersion transport. The dual porosity model is similar to the Performance Assessment transport model, SECO-TP. A macro or advective pore space transports solute by advection and dispersion, while a micro or matrix pore space is only accessible by diffusion. Diffusion geometry is one-dimensional. Fitting ^3H and ^{22}Na data provided core porosity and solute dispersion coefficients. Fitted parameters for conservative solute showed little difference between single and dual porosity models indicating limited effective distinction between the two. In three cores, single porosity fits provided porosity only 1/2 to 1/6 of an independent estimate of the total porosity. In all cores the hydrodynamic dispersion coefficient was an order of magnitude greater than packed columns. This indicates significant preferential flow occurred in the columns and is consistent with dispersion in heterogeneous media.

No clear trend is apparent with regard to flow rate dependencies. Likewise, the Salado brine, ERDA 6 did not produce a significant change in retardation relative to AIS.

Fitted retardation factors, R for ^{239}Np ranged from 30 to 78 and from 2 to 18 for ^{232}U , with the single porosity model. In general, good fits could be obtained with the dual porosity model only if the advective porosity was allowed to retard the solute. The dual porosity fit for ^{232}U and ^{239}Np yielded matrix retardation's one to two orders of magnitude greater than the single porosity model. Those higher values may be the best estimates of the dolomite retardation potential. However, since the overall fitting to the elution curve is not clearly better than the single porosity model, the higher retardation is considered unproven by these experiments.

Theoretical analysis using the minimum detection limits for ^{241}Am , ^{228}Th and ^{241}Pu and the single porosity model provided minimum retardation estimates for the non-eluting species. Minimum R values were 520 to 18,000 for ^{241}Am , 9.1 to 47 for ^{228}Th , and 800 to 38,000 for ^{241}Pu . The range of these minimum R values is a function of the individual test conditions and does not indicate data uncertainty.

ACKNOWLEDGMENTS

Many persons contributed to this project and several deserve special note. Fred Gelbard was the original Principal Investigator and provided the initial vision for its scope and objectives. Hans Papenguth and later Larry Brush were overall Principal Investigators for the retardation of dissolved actinide program. They have integrated the results of this work into the larger program. George Newton of ITRI provided sample spikes, Kent Budge wrote the data fitting program used, and Yugal Behl of SCIRES Corporation assisted in test planning. Robert Holt of New Mexico Technical University provided core logging of the Air Intake Shaft cores, and J. A. Romero assisted in the initial test plan and equipment setup. Finally, Fred Salis was instrumental in the collection of much of this data and George Perkins provided a detailed review.

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LIST OF ACRONYMS

AIS	Air intake shaft
ASTM	American Society for Testing and Materials
BTC	Breakthrough curve
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ITRI	Inhalation Toxicology Research Institute
LSC	Liquid scintillation counter
MDA	Minimum detection activity
NIST	National Institute of Standards and Technology
PA	Performance Assessment
PI	Principal Investigator
QA	Quality Assurance
RMS	Root mean squared error
SOP	Standard operating procedure
SNL	Sandia National Laboratories
SVD	Singular value decomposition
WIPP	Waste Isolation Pilot Plant
γ Spec	Gamma ray spectrometry

INTRODUCTION

Under the authorization of Public Law 96-164 (1979), the U.S. Department of Energy (DOE) has been developing a nuclear waste disposal facility, the Waste Isolation Pilot Plant (WIPP), located approximately 42 km east of Carlsbad, New Mexico. The WIPP is designed to demonstrate the safe disposal of transuranic wastes produced by the defense nuclear-weapons program. Transuranic waste is defined as waste contaminated with radionuclides having an atomic number greater than 92, a half-life greater than 20 years and a concentration greater than 100 nCi/g (U.S. EPA, 1993). This radioactive waste is regulated by U.S. Environmental Protection Agency regulations 40 CFR Part 191 (U.S. EPA, 1993). These regulations place limits on cumulative radioactive release to the accessible environment over 10,000 years and require that Performance Assessment (PA) analyses be performed to demonstrate the WIPP facility compliance with the regulations.

PA analyses of the WIPP repository are being performed by Sandia National Laboratories (SNL) to determine if the repository would meet regulatory requirements. Preliminary WIPP PA calculations have been iterative in nature and have been performed using the best data and models available at the time. Initial PA calculations and sensitivity analyses (Helton et al., 1991 and 1992; Bertram-Howery et al., 1990) have identified the radionuclide retardation factor (relative transport rate of radionuclides with respect to the ambient fluid flow velocity) in the Culebra Dolomite as a key parameter.

Chemical retardation is caused by various chemical reactions that may occur between the chemical species in the solution and at the mineral/water interface. The chemical retardation phenomenon has been observed both in laboratory and field tests associated with groundwater contaminant transport studies involving inorganic contaminants (Weber et al., 1991, and references therein) and organic contaminants (Mackay et al., 1986).

Chemical retardation can be quantified by the distribution coefficient, k_d , (Fetter, 1993; p. 117-118)

$$k_d = \frac{S}{C} \quad (1)$$

where k_d is the distribution coef., S is the mass of solute sorbed per mass of sorbate and C is the aqueous solute mass concentration. Use of k_d assumes local adsorption equilibrium and a linear relationship between S and C over the range of interest. Non-linear isotherm forms are available (Fetter, 1993), but WIPP-specific materials and solutions are not adequate to derive those isotherm's parameters (Dosch, 1980, 1981; Dosch and Lynch, 1978; Lynch and Dosch, 1980; Nowak, 1980; Novak, 1992; and Trauth et al., 1992). Previously conducted batch experiments also do not differentiate between mechanisms contained in the sorption term (absorption and ion exchange) or other potential mechanisms, such as precipitation of actinide-bearing solids. Partly for those reasons, the SNL PA group has relied on expert judgment to develop the probability distributions for k_d (Trauth et al., 1992). However, the final PA calculations in support of the application to the EPA for opening the WIPP repository, required that these probability distributions be based on experimental data. The Working Agreement of the Consultation and

Cooperation Agreement between the Department of Energy and the State of New Mexico on the Waste Isolation Pilot Plant (as modified, U.S. DOE and State of New Mexico, 1988, p. 8-9) stipulates:

"DOE will select, after consultation with the State, a range of values to be conservative, but reasonable, based on the lowest reasonable values experimentally obtained. In the absence of experimentally justifiable values, k_d will equal zero, i.e., no credit for retardation will be taken in the performance assessment calculations."

Intact rock column experiments have been designed as one part of the Culebra retardation studies program to demonstrate retardation in the Culebra Dolomite. Semi-empirical batch sorption experiments have provided most of the sorption values submitted for performance assessment calculations. The strategy for batch experiments was to empirically identify combinations of geochemical parameters (brine composition, organic/inorganic ligands, rock composition, actinide concentration and oxidation state) that affect the value of k_d . Once those parameters were identified, a matrix of experiments was conducted to produce statistically valid k_d distributions. Results of the static sorption experiments were compared with results from the column flow experiments to provide the final k_d distributions submitted to PA (Brush, 1996b).

Column flow experiments with large diameter intact core provide information on the effects of advective fluid flow on sorption behavior in the Culebra Dolomite. A major value of the column experiments is that they simulate the subsurface environment, (albeit at an intermediate scale smaller than the field) and provide a means to quantify some effects of coupled transport processes under simulated flow conditions. However, recent multi-rate modeling of conservative tracer tests at the WIPP site (Meigs et al., 1997), combined with consideration of the effects of scale (Holt, 1997), indicate that the intact rock-column flow experiments may provide low values for retardation factors. It should be noted, therefore that inclusion of k_d values from the intact rock column experiments into the PA parameter set (Brush, 1996b) is conservative.

Additional column testing has been carried out by Lucero et al. (1995) with colloidal materials. Colloid experiments used the same procedures, materials and cores as reported here, with the exception of the introduction of humic compounds and bacteria. No increase in actinide transport over soluble rates were observed.

OBJECTIVE

The objective of the intact rock column flow experiments is to demonstrate and quantify transport retardation coefficients, (R) for the actinides Pu, Am, U, Th and Np, in intact core samples of the Culebra Dolomite. The measured R values are used to estimate partition coefficients, (k_d) for the solute species. Those k_d values may be compared to values obtained from empirical and mechanistic adsorption batch experiments, to provide predictions of actinide retardation in the Culebra.

Three parameters that may influence actinide R values were varied in the experiments; core, brine and flow rate. Testing five separate core samples from four different core borings provided an indication of sample variability. While most testing was performed with Culebra brine, limited tests were carried out with a Salado brine to evaluate the effect of intrusion of those lower waters. Varying flow rate provided an indication of rate dependent solute interactions such as sorption kinetics.

MATERIALS AND PROCEDURES

Detailed information on test materials, equipment and procedures are presented in Lucero et al. (1995), and WIPP Lab Notebooks (Lucero, 1995-1996). The following section summarizes the general procedures used and parameters specific to these tests.

Cores

CORE COLLECTION

Representative samples were needed from the Culebra Dolomite for the laboratory tests. The Culebra is a laterally extensive rock unit ranging in thickness from approximately 13 to 38 ft (Holt, 1997). Initially, vertical cores archived at the Westinghouse Core Library at the WIPP Site were examined to determine if any of them could be used for the retardation experiments. Most of the archived cores were 2 inches in diameter, and inadequate to capture the heterogeneity in the Culebra. No suitable larger diameter cores were available. Moreover, none of the cores had been preserved to prevent drying. Since drying may change mineral surface properties, experiments with these cores could be subject to criticism. Finally, and most importantly, the Culebra is confined above and below by relatively impermeable rock units, which restricts flow to a horizontal path. The best measure of Culebra transport would be achieved using horizontal core oriented parallel to the bedding. Therefore, it was decided to obtain new core at the WIPP site.

There are four shafts on the WIPP site where Culebra samples may be obtained: the exhaust shaft, the waste-handling shaft, the salt-handling shaft, and the air-intake shaft. Three shafts were rejected for horizontal coring for several reasons. The exhaust and waste shafts had been pressure-grouted and surrounding rock may be contaminated, while the waste-handling shaft does not have a suspended platform needed for drilling. Furthermore, the stratigraphy of the first three shafts has not been precisely mapped, so the location of the Culebra is not known accurately. Thus, the air intake shaft (AIS) was chosen for core drilling.

At the AIS the Culebra Dolomite is approximately 24 ft thick and has been mapped as three major units, with the lower Unit 3 having three subunits a, b and c. Selection of specific locations within the Culebra for drilling was based on the variability of flow within those units. Holt and Powers (1990) state Unit 3a is the most transmissive unit based on fluid production during the AIS geologic mapping. This suggests that the present day brine flow in the Culebra at the AIS is predominantly through that unit.

A 6-inch diameter core barrel was used for drilling which produced 5.7 inch diameter core. The scale of heterogeneity within the Culebra is on the order of one inch, and was a consideration in choosing the rock sample diameter. A 5.7 inch-diameter core is more likely to be removed intact and provides a representative sample with respect to heterogeneity. Smaller diameter cores would be less likely to capture the heterogeneity adequately. Larger samples (e.g., the next core barrel size available is 8 inch) would not provide any significant advantage at the expense of being much larger and therefore harder to manage.

Since the geologic properties of the Culebra Dolomite are not uniform, it was decided to collect samples from four different boreholes rather than extract all samples from one. Figure 1 shows the borehole positions in the AIS. Each borehole was drilled in a north-south direction, since that is the probable direction of flow in the Culebra at the site (Ramsey et al., 1996). "VPX" accompanied by a number follows the standard sample requisition numbering system established by SNL.

After removal from the core barrel, samples were sealed in PVC tubing, before being moved to surface and inspected for about 20 minutes. The cores were observed to have an abundance of horizontal and subhorizontal fractures, some along the bedding planes, and high-angle fractures. The orientation of some of the samples was marked on them, while for the remainder it can be determined by the analysis of geopetal features. A photograph album of the core is a part of the WIPP QA records. Practical constraints of transporting and storing cores limited the total length of cores to about 65 feet.

After inspection, cores were wrapped in heavy-duty plastic wrap and stored in capped PVC tubing to prevent drying. The cores were divided into two groups for safety, and stowed in secure areas. Storage temperature has been kept near 20° C and monitored continuously. Core temperature data are archived about every two months and provided to the WIPP QA Department. A copy of the data is also maintained in a Core Log Book kept in the laboratory.

Figure 1. Borehole locations.

Liquid production rates were measured during the drilling and are also listed in Table 1. VPX 27 would most likely to be representative of rocks found along rapid flow paths, as demonstrated by its borehole flow, an order of magnitude greater than the others. Other measurements performed on site were the temperature and the pH of the brine samples collected at the coring locations.

Table 1. Borehole properties.

Borehole	VPX 25	VPX 26	VPX 27	VPX 28
Depth (m)	218.2	218.2	219.8	219.9
Side of AIS	North	South	North	South
Borehole flow (L/min)	0.34	0.16	3.0	0.16
pH	7.65	7.69	8.10	8.09
Temperature (°C)	21.0	20.9	21.1	20.1

TEST SAMPLES

Tests used samples from all four boreholes to provide a range of core properties. Series A, B, C, D and E used cores VPX 28, 26, 28, 25 and 27 respectively, and are shown in Figures 2 through 6. Note that Figure 1 also shows the approximate position of the tested core sections. Core sections selected were relatively solid and intact, but demonstrated the fractures, gypsum infilling and vugs typical of WIPP Rustler cores. Core C had a fracture going almost entirely through the sample between 270° and 100°. That fracture is visible on both ends, but did not split the sample. It is not believed to be a drilling artifact, but may be a natural unloading fracture that is partly cemented. Table 2 lists dimensions, weights and density of the sample used in each Test.

Holt (1997) estimated core composition by visual inspection of Cores C, D and E photographs. He quantified solid dolomite, silty dolomite, gypsum, fractures and vugs. Core C showed the least evidence of macropores, (fractures, silty dolomite and vugs), Core E showed the most, while Core D was intermediate with respect to the other two. Hsieh et al. (1997) used gamma ray tomography to measure core density inside a separate sample of VPX 26. He quantified compositional changes throughout the sample and found that while dolomite content was relatively constant, macropores, (Hsieh's mixed voxels) increased by a factor of three in a distance of 6 cm along the length. Together, these studies indicate AIS Culebra cores are highly variable and should show measurable differences in transport properties.

ESTIMATED POROSITY

The total core porosity is an important parameter for interpretation of these results. Unfortunately, a direct measurement of the core porosity was not possible because of concerns that drying the samples would affect their chemical properties, and thus impact the latter retardation experiments. Measurements were made by Terra Tek (1996) and Brown (1995-1996, page 87) of separate end cuts from core VPX 26. Terra Tek reported an average porosity of 17.6% from three 1.5" diameter by 2" long sub-cores with only trace gypsum. Brown estimated a porosity of 15.5% from a slightly irregular 1.3" long by 5.7" diameter slice with

Figure 2. Photographs of Core VPX 28-6B, Test Series A.

Figure 3. Photographs of Core VPX 26-11A, Test Series B.

Figure 4. Photographs of Core VPX 28-6C, Test Series C.

Figure 5. Photographs of Core VPX 25-8A, Test Series D.

Figure 6. Photographs of Core VPX 27-7A, Test Series E.

Table 2. Test sample cores.

Series	A	B	C	D	E
Core: VPX	28-6B	26-11A	28-6C	25-8A	27-7A
Cut core measures					
Length (cm)	40.6	50.9	10.2	10.8	10.2
Diameter (cm)	14.5	14.5	14.5	14.5	14.5
Volume (cm ³)	6703	8404	1666	1773	1666
Wet weight (gm)	16582	20900	4146	4401	4102
Estimated Properties					
Dry bulk density (gm/cm ³)	2.38	2.40	2.40	2.40	2.38
Porosity	0.15	0.14	0.14	0.14	0.15

gypsum content. Both of those measurements are consistent with other WIPP cores studied by Kelley and Saulnier (1990).

As an alternative, estimates of total core porosity can be made by applying basic principles to the core volume and wet weight. First the dry sample weight, wt_d is given by,

$$wt_d = \frac{wt_w}{(1 + \theta_w)} \quad (2)$$

where wt_w is the wet sample weight and θ_w is the sample water content by weight. Dry bulk density, ρ_b is given by,

$$\rho_b = \frac{wt_d}{V_s} = \frac{wt_w}{(1 + \theta_w)V_s} \quad (3)$$

where V_s is the sample volume. With the bulk density defined, total porosity can then be calculated by,

$$\phi = 1 - \frac{\rho_b}{\rho_p} \quad (4)$$

where ρ_p is the bulk average mineral or particle density. Particle density will vary in these cores according to the gypsum content, which is again unknown without destructive sampling. Thus the particle density must be estimated with,

$$\rho_p = \frac{(1-x)\rho_d}{(1-x) + x\rho_d / \rho_g} + \frac{x\rho_g}{(1-x)\rho_g / \rho_d + x} \quad (5)$$

where ρ_d is dolomite's density, ρ_g is gypsum's density and x is the mass fraction of gypsum in the total solid minerals. Equation 5 follows from volume averaging the mineral densities. Substituting Eqs. 3 and 5 into Eq. 4 yields a direct expression for porosity,

$$\phi = 1 - \frac{wt_w}{(1 + \theta_w)V_s \left[\frac{(1-x)\rho_d}{(1-x) + x\rho_d / \rho_g} + \frac{x\rho_g}{(1-x)\rho_g / \rho_d + x} \right]} \quad (6)$$

In Eq. 6 wt_w and V_s are measured, ρ_d and ρ_g are approximated at 2.83 and 2.32 gm/cm³ respectively (Hsieh et al., 1997), and θ_w and x must be estimated from other measurements on AIS core samples. The cores were saturated when drilled and allowed to drain freely, but not dried, before storage. Thus, it can be assumed the dolomite intrinsic porosity is water filled, but the large pores are empty. With one exception, since the dolomite intrinsic porosity is relatively constant throughout the site, it is reasonable to assume that all the cores will have the same weight based water content regardless of their macroporosity. The exception results from the variable gypsum content in the cores. Gypsum will impact water contents and porosity estimates in two ways. Since it has no intrinsic porosity, increasing gypsum will reduce porosity and water content. However, because gypsum has a lower mineral density it reduces the net particle density, and will increase the porosity computed from bulk volumes (note Eq. 3). These two opposing factors tend to reduce the sensitivity of core porosity to estimated gypsum content.

Sewards et al. (1991) found gypsum ranging from 0 to 25% in the Culebra. Visual inspections of these cores indicate a similar range. A value of 10% is used here. Water content was measured on an end cut of VPX 26 at 3.6% by weight (Brown, 1995-1996, page 87), and will be assumed for these samples. Table 2 lists the estimated core porosity computed with those values. Surprisingly, the cores had equivalent porosity even though they appeared dissimilar.

CORE PREPARATION AND PRECONDITIONING

Cores were carefully removed from their storage tubes and cut to the desired length on a 10" dry diamond saw. A urethane rubber sleeve was poured around the core to form a liner using a custom form. Liner properties are listed in Table 3. After pouring, the liner was allowed to cure at room temperature a minimum of two days before mounting in a core holder. At no time during the core preparation was the sample heated above room temperature or allowed to dry.

Table 3. Liner properties.*

Brand	Devcon, Flexane 80 15800
Type	Two-part urethane rubber
Mix Ratio	3:1
Specific Volume	26.5 in ³ /lb
Operating Temperature	120° F, maximum wet
Cured Hardness	87, Shore A
Tensile Strength	2100 psi, ASTM D412
Tear resistance	250 pli, ASTM D624
Additives used	None

* ITW Devcon, 30 Endicott Street, Danvers, Massachusetts, 01923.

After mounting in their holders, the cores were preconditioned by leaching with their matching air intake shaft (AIS) brine. Preconditioning insures that the core is in chemical equilibrium with the leachate solution before the sample spikes are injected. Conditioning was generally carried out at standard flow conditions of 0.1 ml/min over a period of two weeks. Depending on the core, that provided two to eight pore volumes of flow.

Brines

Synthetic solutions matching the measured composition of water taken from the bore holes were used in most of the test series. In two tests, a brine matching the composition of the deeper Salado Formation brine, ERDA 6, was used to determine if transport is influenced by intrusion of deeper waters. Table 4 lists the composition of each brine used. These compositions are the average ion values of all samples neglecting ions occurring at concentrations less than 10 mg/l (Geotech, 1992; Brush, 1990).

Table 4. Brine composition.

Brine	VPX 25	VPX 26	VPX 27	VPX 28	ERDA 6
Ions (gm/L)					
Boron	0.0258	0.0263	0.0266	0.0274	0.68
Bromine	0.054	0.0226	0.0243	0.0217	0.88
Calcium	0.8750	0.832	0.8580	0.8350	0.49
Carbon, inorganic	0.0113	0.0121	0.017	0.0120	0.19
Chloride	18.9	19.3	19.2	19.4	170
Magnesium	0.4540	0.4190	0.4500	0.4230	1.04
Potassium	0.3220	0.3330	0.3220	0.3170	3.79
Sodium	13.1	13.8	13.3	14.2	112
Sulfate	6.65	7.25	6.94	7.41	16.3
Borehole pH	7.65	7.69	8.10	8.09	6.17

Craft and Siegel (1997) found that under atmospheric conditions the recipes used to mix the brines could produce solutions supersaturated with calcite. However, after mixing all solutions were passed through a 0.45 μ m filter to remove particulates. Thus, it may be assumed the solutions were saturated with respect to calcite.

Yeh (1993a and 1993b) measured the density and viscosity of a synthetic VPX 26 brine (Yeh's brine 2) and three Salado brines, QPBO2D, SB-139-B and L4P51. Table 5 lists measured density and dynamic viscosity values at 22° C, for VPX 26 and the Salado brine (QPBO2D) nearest in density to ERDA 6.

Table 5. Brine fluid properties.

Brine	Temperature (°C)	Density (Mg/m ³)	Temperature (°C)	Viscosity (N's/m ²)
VPX 26	22.1	1.0292	22.02	1.055 x 10 ⁻³
QPBO2D	22.5	1.1993	22.05	2.355 x 10 ⁻³
ERDA 6	22	1.191		

Column Apparatus

A schematic of the test apparatus is shown in Figure 7, and the more important components are listed in Table 6. Its major components were a column core holder, a syringe pump, a brine injection reservoir and an effluent collector. The column tracer test equipment was selected and assembled from generally off-the-shelf components to meet four requirements. First, materials which come in contact with the samples or brine must be nonreactive. Thus, all exposed surfaces were Teflon or Teflon coated. Second, the equipment testing conditions had to replicate as closely as possible the natural conditions in the Culebra, which required the maintenance of reservoir overburden pressure on the sample. Third, since tests continued for months at a time, most equipment had to be automatic and require minimum maintenance during operation. Therefore, automated syringe pumps and effluent collectors were used. Finally, due to the actinides used, the column apparatus had to fit into and be operated inside a glove box. This last requirement restricted some options and required keeping the operation as simple as possible.

Figure 7. Schematic of test apparatus.

Table 6. Core column test equipment.

Equipment	Make	Model
High Pressure Core Holder	TEMCO	HCB-5.7
Brine Accumulator	TEMCO	CC200 150
Syringe Pumps	ISCO	500 D
Syringe Pump Controller	ISCO	621240026-91266
Fraction Collector	Spectra/Chrom	CF-1
Leachate pressure transducer	Taber	2412, (8-50 psi)
Overburden pressure transducer	Taber	2404, (0-1000 psi)
Thermocouple	TTEC	Type K

Aluminum was used to construct the column barrel and the end fittings were made of brass. Each core is held in a flexible sleeve between two distributor plates. Overburden loads are simulated by applying pressure in the annulus between the column and the sleeve. That pressure is also applied to the top distributor plate which is free to slide up and down, while the bottom plate is fixed. Thus, the core is subjected to the reservoir pressure in all three directions while allowing the effluent to exit at atmospheric pressure. The distributor plates are Teflon coated on all surfaces that come in contact with the core or leachate. A triaxial confining pressure of 725 psi was applied during all tests. This overburden pressure was computed using the rock density profile above the borehole. Since the density profile immediately above the cores is not known, one available from well H17 was used to compute the overburden pressure (Mercer and Snyder, 1990).

Brine was pumped from an accumulator into the core. The accumulator is a simple cylinder and piston sealed at both ends. Double, high pressure, liquid chromatography syringe pumps drive water into one end of the accumulator, which forces brine out the other. The accumulator prevents contamination and fouling of the pumps, while the double pump configuration allows automatic filling of the syringe pumps and insures continuous operation. Effluent was collected with a fraction collector operating in time mode set to provide approximately 5 ml per sample. Once a day the tubes were capped, swiped for contamination and removed from the glove box.

Differential leachate pressure, overburden pressure and column temperature were continuously monitored and recorded using pressure transducers, thermocouples and a personal computer based data acquisition system as indications of overall test conditions. The differential pressure can be used to compute core conductivity, but the precision of that measurement is limited and was not used. This is due to the design of the core holder and the operational limitations of running a continuous test inside a glove box. The differential pressure was measured across the entire column and includes losses at the inlet and exit. In addition, air bubbles had a tendency to form in the transducer lines, producing an unbalanced hydrostatic pressure equal to several inches of water.

Isotopes

SELECTION CRITERIA

Column tests require an isotope with a half-life greater than one day and less than 1,000 years. The one day minimum is necessary to achieve adequate transport time during the experiment. Obviously, measurable amounts of a tracer must remain at the end of a test to have any hope of measuring it in the column effluent. The 1,000 year maximum is dictated by the need to have measurable activity at molar concentrations below solubility limits. Radioassay methods, gamma spectrometry (γ Spec) and liquid scintillation counting (LSC), were used to measure effluent molar concentration. Those techniques measure isotope decays, not molar mass as chemical methods do. At a constant molar concentration, a short lived isotope undergoes more decays and is thus easier to detect than a longer life isotope of the same element. Since the actinide solubilities are generally low, measurable activities cannot be achieved with solutions of isotopes with half-lives greater than approximately 1,000 years. Using short half-life isotopes adds considerable experimental difficulty. Extra effort and planning are needed to ensure that sample spikes are delivered at the desired time since long storage is not possible. Such short lived isotopes were only considered if they have strong gamma emissions that make radioassays easier or tomography possible.

Since radioassays were used to quantify the effluent concentrations, the isotope's decay emission is important. Of the two radio assay methods used, γ Spec is preferable, since it does not require sample preparation and can easily distinguish different isotopes. Sample tubes can be directly loaded into the instrument and all gamma emitting isotopes measured simultaneously. LSC requires the sample to be mixed with a scintillation cocktail. It has poor energy resolution, but can differentiate alpha and beta emissions. Therefore, LSC may require knowledge of what isotopes are present in the sample. LSC does have the advantage over γ Spec in that its detection limit is generally an order of magnitude lower.

The total mix of isotope and emissions had to be considered to minimize interference in radioassays of the various tracers. These considerations also had to take into account any short-lived daughter products. Since daughters in-grow with their own half-lives, a short-lived daughter will soon equal the activity of the parent in any solution.

In addition to the feasibility criteria listed above, the isotope had to be available at economical prices. This implies that the isotope could either be obtained from commercial suppliers, or in the case of short-lived isotopes, separated from a stock of a long-life parent. Isotopes obtainable from dedicated reactor operations were investigated but found to be too costly and operationally impractical.

AMERICIUM

Americium has two isotopes that meet the feasibility criteria, 240 and 241. The first is not economically available, but ^{241}Am is an acceptable tracer candidate. It has a 59.5 keV gamma emission with a 35.7% yield and two alphas with energies at 5.44 and 5.49 MeV with 12.8% and 85.2% yields. Its long half-life of 432.2 years requires relatively high molar concentrations for γ

Spec analysis, but LSC can go two orders of magnitude lower. Certified stocks were obtained from Isotope Products Laboratories, Burbank California in HCl solutions.

NEPTUNIUM

Four Neptunium isotopes meet the selection criteria, 234, 235, 238 and 239. With a 1.1 year half-life 235, is the longest lived of the four, but only has an alpha emission. The other three isotopes have similar half-lives of two to four days and multiple gamma emissions. ^{239}Np has two high yield, high energy γ ray emissions and was chosen. It was obtained from a stock of its parent ^{243}Am purchased from Oak Ridge National Lab and its separation followed Newton et al. (1995a).

PLUTONIUM

Plutonium has five feasible isotopes, 236, 237, 238, 241 and 246. The only good gamma emitter, 246, is not available except by dedicated reactor operations. Three isotopes, 236, 237 and 238 are alpha emitters, and 241 is a beta emitter. ^{241}Pu with a 14.4 year half-life was chosen since its beta emission would have minimum interference from the other isotopes present in the effluent. Certified stocks were obtained from Isotope Products Laboratories, Burbank California in HCl solutions.

SODIUM

^{22}Na with a 2.6 year half-life was used as a conservative tracer in most tests. As will be shown in a latter section, sodium is a conservative solute in the calcium rich Culebra Dolomite. ^{22}Na is readily available and its positron emission produces 511 keV gamma's with a 180% yield. Certified samples were obtained from Isotope Products as a dilute chloride salt solution in water.

TRITIUM

Tritium (^3H), when bound as water provides the ultimate conservative tracer for transport studies. By definition, it moves with the ground water flow unhindered by adsorption. With a 12.28 year half-life and strong beta emission, it is easily detected by LSC. Its only drawback is that its emission interferes with the analysis of ^{241}Pu . Certified stocks were obtained from Amersham Corporation, Arlington Heights, Illinois.

THORIUM

Thorium has only three isotopes that meet the selection criteria, 227, 228 and 234. Both 227 and 234 have short half-lives, 18.7 and 24.1 days respectively, compared to 228's 1.9 years. None of the three thorium isotopes have a strong gamma emission, thus ^{228}Th was chosen for its longer half-life. ^{228}Th also had an advantage since it is readily available in large quantities. It is the daughter of ^{232}U and spikes were obtained from a large supply of its parent maintained by Inhalation Toxicology Research (ITRI). Depending on the specific test requirements, the ^{232}U and ^{228}Th were either separated or left combined.

URANIUM

Four uranium isotopes, 230, 231, 232 and 237, are feasible tracers, but only ^{232}U is economically available. It has one gamma at 57.8 keV with a 0.2% yield and two alphas at 5.26 and 5.32 MeV with 31% and 68.6% yields respectively. It was obtained from a large stock maintained by ITRI. Spikes were prepared and assayed by ITRI before use.

SPIKE PREPARATION

Injection spikes were prepared and assayed by ITRI (Newton et al., 1995b). They dispensed the desired isotope activity into Teflon bottles and then added brine supplied by SNL to bring the total spike volume between 10 and 20 ml. These procedures produce a spike of known isotope activity with an ionic strength slightly less than the brine itself. Actinide stocks were maintained at low pH until they were diluted with the appropriate brine to the desired spike activity. Only at the last step was the spike pH brought to the natural brine pH listed in Table 4.

Spike Injection

During the planning phase for these experiments, several reviewers expressed concern that actinide spikes would plate out in the injection apparatus and never reach the core. Thus, a procedure was developed to insure the tracer materials reached the core at the desired activity and in soluble form. Before each core was mounted, a small reservoir, approximately 5 cm in diameter and 1 cm deep was milled into its inlet end (Heath, 1995). The reservoir provides an approximately 20 ml volume, enough to hold a typical tracer spike. When a spike was ready for injection, the pumps were turned off and the upper inlet tubing removed. A 12" long Teflon tube, attached to a plastic syringe, was inserted into the core holder and used to empty the inlet reservoir. The syringe was then removed, reservoir brine discarded, and the tracer spike drawn into the syringe. Next, a sample of the spike, typically 1 to 5 ml, was dispensed from the syringe into a fraction collection tube labeled "START". The syringe tube was then reinserted into the core and the spike injected directly into the reservoir. The spike solutions remaining in the syringe and tubing were then placed in a tube labeled "END". Finally, the inlet tubing was reconnected, and the pumps started. This operation typically took 15 minutes. The START and END tubes were weighed, topped off to the standard 5 ml volume with deionized water and assayed. Since the tubes were filled from the same syringe and at the same time as the spike, they provide proof that the actinides reached the core. While the temporary flow interruption and inlet reservoir are undesirable, their effects are small compared to the total test time and core size.

Some experiments with Cores A and B used 500 or 2000 ml slugs of tracer to provide a constant concentration boundary condition. For those tests a dedicated "hot" accumulator was placed inside the glove box. Tracer was loaded into it along with the appropriate brine volume. The hot accumulator then replaced the normal accumulator by connecting it directly to the pump output and core inlet. After the slug was injected, the hot accumulator was disconnected and normal operation resumed.

Test Conditions

Test objectives, spike activity, spike volume, flow rate and brine used for each experiment are listed in Table 7. Twenty-six individual tests have been run on the five cores, most of which had multiple isotopes in the injection spike. In total, there have been five ^3H spikes, three spikes with ^{241}Pu and ^{241}Am , four ^{228}Th spikes, ten spikes of ^{239}Np and ^{232}U , and twenty-two spikes of ^{22}Na . ^{22}Na was used repeatedly to quantify and monitor the core hydraulics. Two tests, C5 and C7, were carried out with ERDA 6 brine to quantify the impact of brine type on transport. Tests B5 to B8 and D6 were performed at different flow rates to measure flow rate dependencies. Most tests were carried out at a total flow rate of 0.1 ml/min. That flow corresponds to a volume flux (or Darcy flux) of 9.8×10^{-6} cm/s (3.2 m/yr). Division of the volume flux by the fitted porosity for each test will yield the effective seepage velocities in the advective porosity. This flow is at the upper end of the estimated natural conditions (Ramsey et al., 1996).

An important feature of these tests is the multiple spike injection in the same core. This strategy has three specific benefits. First, the multiple spikes allow direct comparison in the same core of different isotopes while minimizing interference in the radioassays. Second, multiple spikes provide a direct measure of core behavior with time, allowing changes in the core to be detected by the behavior of ^{22}Na . Finally, and most important, the multiple spikes with continuous analysis make very long tests practical. Once an isotope has been injected in a core, it is analyzed for in all later effluent, which is important in the quantification of noneluting actinides. As an example, while Test C3 was nominally carried out for two liters, all column effluent after that time, (over 62 liters) has been assayed for both ^{241}Am and ^{241}Pu . Thus minimum R analysis on those two isotopes can confidently be based on an eluted volume of approximately 250 pore volumes.

Spike Concentration

Actinide concentrations are reported here as isotope activities per volume or activities per mass. To assist readers, Appendix A contains conversions curies to molar or gram mass units.

Table 8 lists the actinide spike activity and concentration for each test sorted by isotope. Concentrations presented in the table are the largest values occurring during the experiments. On injection, the spike is diluted by brine in the column headspace, and then undergoes hydrodynamic dispersion. Even a conservative solute spike will normally be diluted by an order of magnitude by the time it reaches the outlet. Aqueous concentration of retarded solutes will be quickly reduced due to adsorption on to the mineral surface as defined in Eq. 1.

Spike concentration are compared to measured and computed solubility in Table 9. Solubility of Am, Th, and Np were computed by Craft and Siegel (1997). Values corresponding to solutions both supersaturated with calcite and in equilibrium with dolomite are listed. The range in Pu solubility was obtained from measurements made by Nitsche et al. (1992 and 1994) in AIS brine. Uranium solubility during the tests is clearly demonstrated by its elution from the cores with moderate retardation, as shown in the results. Pu, Np and Th spike activities were well below solubility. Americium had spike concentrations between 3.4 to 8.0×10^{-7} M necessitated by its the relatively low activity. Unfortunately, this was greater than the solubility

Table 7. Test conditions.

Test	Start Date	Brine	Tracer	Spike (ml)	Flow (ml/m)	Vol. (L)	Time (days)	Test Objective
A-1	4/5/95	AIS	0.641 $\mu\text{Ci } ^3\text{H}$	20	0.5	2	0.7	Porosity
A-2	4/28/95	AIS	500 $\mu\text{Ci } ^{22}\text{Na}$	500	0.02	0.5	11	Tomography
A-3	6/9/95	AIS	0.22 $\mu\text{Ci } ^3\text{H}$	20	0.1	2	13	Flow effects
A-4	7/25/95	AIS	23 $\mu\text{Ci } ^{22}\text{Na}$ 156 $\mu\text{Ci } ^{239}\text{Np}$	20	0.1	2	13	Tomography and Np Retardation
B-1	9/6/95	AIS	0.246 $\mu\text{Ci } ^3\text{H}$	13	0.1	0.5		Porosity
B-2	9/22/95	AIS	8.69 $\mu\text{Ci } ^{22}\text{Na}$ 375 $\mu\text{Ci } ^{239}\text{Np}$	18	0.1	2	13	Tomography and Np Retardation
B-3	10/4/95	AIS	8.23 $\mu\text{Ci } ^{22}\text{Na}$ 70.7 $\mu\text{Ci } ^{232}\text{U}$ 70.7 $\mu\text{Ci } ^{228}\text{Th}$	13.7	0.1	2	13	Tomography, U and Th Retardation
B-4	11/6/95	AIS	300 $\mu\text{Ci } ^{22}\text{Na}$	2000	0.1	4	30	Tomography
B-5	12/7/95	AIS	274 $\mu\text{Ci } ^{22}\text{Na}$	2000	0.05	2	60	Tomography
B-6	1/30/96	AIS	4.22 $\mu\text{Ci } ^{22}\text{Na}$ 5.94 $\mu\text{Ci } ^{232}\text{U}$	17	0.05	2	60	U Retardation
B-7	4/16/96	AIS	9.0 $\mu\text{Ci } ^{22}\text{Na}$ 4.28 $\mu\text{Ci } ^{232}\text{U}$	18	0.5	4		U Retardation
B-8	4/23/96	AIS	220 $\mu\text{Ci } ^{22}\text{Na}$	2000	0.5	4		Tomography
C-1	5/1/95	AIS	1 $\mu\text{Ci } ^{22}\text{Na}$ 10 $\mu\text{Ci } ^3\text{H}$	20	0.1	2	13.3	Porosity
C-2	6/19/95	AIS	3.7 $\mu\text{Ci } ^{22}\text{Na}$ 10 $\mu\text{Ci } ^{232}\text{U}$ 10 $\mu\text{Ci } ^{228}\text{Th}$	20	0.1	2	21	U and Th Retardation
C-3	7/10/95	AIS	3.3 $\mu\text{Ci } ^{22}\text{Na}$ 20 $\mu\text{Ci } ^{241}\text{Pu}$ 5.6 $\mu\text{Ci } ^{241}\text{Am}$	20	0.1	2	16	Pu and Am Retardation
C-4	7/26/95	AIS	11.5 $\mu\text{Ci } ^{22}\text{Na}$ 78.3 $\mu\text{Ci } ^{239}\text{Np}$	10	0.1	2	49	Np Retardation
C-5	9/13/95	ERDA	3.4 $\mu\text{Ci } ^{22}\text{Na}$ 26.8 $\mu\text{Ci } ^{239}\text{Np}$ 4.8 $\mu\text{Ci } ^{232}\text{U}$ 4.8 $\mu\text{Ci } ^{228}\text{Th}$	10	0.1	2	13	Brine Effects on Np, U and Th Retardation
C-6	10/18/95	AIS	5.3 $\mu\text{Ci } ^{22}\text{Na}$ 175 $\mu\text{Ci } ^{239}\text{Np}$	8.5	0.1	2	13	Duplicate Np Retardation
C-7	11/17/95	ERDA	6.83 $\mu\text{Ci } ^{22}\text{Na}$ 327 $\mu\text{Ci } ^{239}\text{Np}$ 50 $\mu\text{Ci } ^{232}\text{U}$	10	0.1	2	13	Duplicate Brine Effects

Table 7. Test conditions (continued).

Test	Start Date	Brine	Tracer	Spike (ml)	Flow (ml/m)	Vol. (L)	Time (days)	Test Objective
D-1	8/29/95	AIS	0.35 μ Ci 3 H	18	0.1	0.5	4.0	Porosity
D-2	9/13/95	AIS	3.4 μ Ci 22 Na 4.8 μ Ci 232 U 4.8 μ Ci 228 Th 26.8 μ Ci 239 Np	10	0.1	2	12	U, Th and Np Retardation
D-3	9/28/95	AIS	3.1 μ Ci 22 Na 16.1 μ Ci 241 Pu 4 μ Ci- 241 Am	10	0.1	2	13	Am and Pu Retardation
D-4	10/18/95	AIS	5.3 μ Ci 22 Na 175 μ Ci 239 Np	8.5	0.1	2	13	Duplicate Np Retardation
D-5	11/13/95	AIS	3.97 μ Ci 22 Na 43.2 μ Ci 232 U	10	0.1	2	13	U Retardation
D-6	1/30/96	AIS	3.4 μ Ci 22 Na 53 μ Ci 232 U	20	0.05	2	60	Flow Effects on U Retardation
E-1	12/20/95	AIS	3.17 μ Ci 22 Na 40 μ Ci 232 U 156 μ Ci 239 Np	20	0.1	2	12	Porosity, U and Np Retardation
E-2	1/16/96	AIS	3.07 μ Ci 22 Na 20 μ Ci 241 Pu 20 μ Ci 241 Am	18.5	0.1	2	13	Am and Pu Retardation

determined at a later date. Therefore, to be conservative, it will be assumed that the injected americium concentration was equal to the solubility without dolomite equilibrium (6.46×10^{-9} molar).

Effluent Analysis

Effluent was collected in Fisher, 13 $\times$ 100 mm screw cap tubes (Catalog No. 14-956-4A). With the large number of tubes used, it was impractical to tare weigh each one, thus an average tare weight of 4.70 gm was used. Spot checks of tubes indicate their weights varied on average less than 0.01 gm, with a 0.1 gm maximum variance. Filled tubes were weighed to one milligram precision on a Mettler PM12000 balance.

Effluent tube activity was measured with a Canberra automatic gamma spectrometer (γ Spec), equipped with a large area germanium detector (Canberra Model GL2020R) and multichannel analyzer. This detector was calibrated with a multiple energy source standard with the same geometry as the sample tubes. All calibration sources were traceable to the National Institute of Standards and Technology (NIST).

Table 8. Injection spike concentrations.

Test	Tracer	Brine	Activity (uCi)	Spike (ml)	Activity (mCi/L)	mole/L (10 ⁻⁹)	Mass (ug/L)
C3	²⁴¹ Am	AIS	5.6	20.0	0.28	338	81.6
D3	²⁴¹ Am	AIS	4.0	10.0	0.40	484	117
E2	²⁴¹ Am	AIS	12.2	18.5	0.66	797	192
A4	²³⁹ Np	AIS	156.0	20.0	7.80	0.14	0.03
B2	²³⁹ Np	AIS	375.0	18.0	20.8	0.38	0.09
C4	²³⁹ Np	AIS	78.3	10.0	7.83	0.14	0.03
C5	²³⁹ Np	ERDA 6	26.8	10.0	2.68	0.05	0.01
C6	²³⁹ Np	AIS	175.0	8.5	20.6	0.37	0.09
C7	²³⁹ Np	ERDA 6	327.0	10.0	32.7	0.59	0.14
D2	²³⁹ Np	AIS	26.8	10.0	2.68	0.05	0.01
D4	²³⁹ Np	AIS	175.0	8.5	20.6	0.37	0.09
E1	²³⁹ Np	AIS	464.0	20.0	23.2	0.42	0.10
C3	²⁴¹ Pu	AIS	20.0	20.0	1.00	40.3	9.71
D3	²⁴¹ Pu	AIS	16.1	10.0	1.61	64.8	15.6
E2	²⁴¹ Pu	AIS	11.3	18.5	0.61	24.6	5.93
B3	²²⁸ Th	AIS	70.7	13.7	5.16	27.6	6.19
C2	²²⁸ Th	AIS	10.0	20.0	0.50	2.68	0.60
C5	²²⁸ Th	ERDA 6	4.8	10.0	0.48	2.57	0.58
D2	²²⁸ Th	AIS	4.8	10.0	0.48	2.57	0.58
B3	²³² U	AIS	70.7	13.7	5.16	1040	241
B6	²³² U	AIS	101.0	17.0	5.94	1196	278
B7	²³² U	AIS	77.0	18.0	4.28	862	200
C2	²³² U	AIS	10.0	20.0	0.50	101	23.4
C5	²³² U	ERDA 6	4.8	10.0	0.48	96.7	22.4
C7	²³² U	ERDA 6	50.0	10.0	5.00	1007	234
D2	²³² U	AIS	4.8	10.0	0.48	96.7	22.4
D5	²³² U	AIS	43.2	10.0	4.32	870	202
D6	²³² U	AIS	53.0	20.0	2.65	534	124
E1	²³² U	AIS	31.0	20.0	1.55	312	72.4

Some isotopes do not emit adequate gamma radiation and were quantified by their alpha or beta emissions. Approximately every fifth sample was analyzed by liquid scintillation counting (LSC) on a Canberra model 2550 TR/AB. The LSC is calibrated with an unquenched ¹⁴C calibration standard traceable to NIST. Activity concentrations were computed as the ratio of the measured activity to the sample weight.

Table 9. Solubility of actinides in column brines.

Actinide	Brine	Solubility (Molar)	
		<i>Without dolomite equilibrium</i>	<i>With dolomite equilibrium</i>
<i>Computed Data</i>			
Am	VPX 28	6.46×10^{-9}	9.63×10^{-9}
Np	VPX 28	7.84×10^{-6}	1.10×10^{-5}
Np	ERDA 6	4.17×10^{-7}	9.51×10^{-7}
Th	VPX 28	1.90×10^{-7}	1.57×10^{-7}
Th	ERDA 6	3.98×10^{-7}	1.21×10^{-2}
<i>Measured Data</i>		<i>Low</i>	<i>High</i>
Pu	AIS	3.0×10^{-8}	7.6×10^{-7}

Minimum detection activities, MDA, for each isotope used and two important daughters of ^{228}Th (^{224}Ra and ^{212}Pb) are listed in Table 10 for both γ Spec and LSC. The MDA will vary for each isotope as a function of the analytical technique and interference from other isotopes in the sample. MDA levels are limited by machine sensitivity with no interference. The only major interference for the isotopes in these experiments occurs with the LSC analysis of ^3H and ^{241}Pu . The LSC cannot distinguish between those isotopes, thus ^3H use is limited to the initial hydraulic test of each core. ^{228}Th daughters produce some interference in both the γ Spec and LSC analysis. When they are present, the analysis is repeated for 30 to 45 days until they decay below interference levels.

^{232}U , is analyzed by both γ Spec and LSC since it has a weak, but measurable gamma ray (57 keV with 0.02% yield) and a strong alpha (5.32 MeV with 68.6% yield). The sensitivity by LSC is much better for this isotope and LSC results were used for all parameter fitting. The γ Spec does provide a quantitative comparison and documentation that the LSC is measuring ^{232}U . ^{241}Am was detected by both γ Spec or LSC. LSC has a much lower MDA but interference from ^{232}U obscures its analysis when uranium is present in the effluent. The strong ^{241}Am γ ray emission stills provides a reasonable detection limit in those cases.

A decay correction was automatically applied by the γ Spec software to identified isotopes. Following first order decay,

$$A = \frac{A_m}{e^{-\lambda(t_m - t_s)}} \quad (7)$$

with

$$\lambda = \ln(2)/t_{1/2} \quad (8)$$

Table 10. MDA for isotopes of interest.

Isotope	γ Spec(nCi/ml) ¹	LSC (pCi/ml) ²
³ H		1.5
²⁴¹ Am	0.06	0.1
²³⁹ Np	0.62	
²¹² Pb	0.02	
²⁴¹ Pu		1.5
²²⁴ Ra	0.27	
²²⁸ Th	3.8	
²³² U	1.2	0.1

1. γ Spec MDA analysis, 15 min. counts, performed 10-31-95. "WIPP Lab Notebook, WBS 1.1.5.1.5, Calibration and Equipment Records." Albuquerque, NM: Sandia National Laboratories. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM as WPO#40975.)
2. LSC MDA analysis, 15 min. counts, performed 3-9-95. WIPP Lab Notebook, WBS 1.1.5.1.5, Calibration and Equipment Records." Albuquerque, NM: Sandia National Laboratories. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM as WPO#40975.)

where A is the reported activity, A_m is the measured activity, λ is the first order decay constant, t_m is the time sample activity was measured, t_s is an initial sample time, and $t_{1/2}$ is the isotope half-life. Since a large number of samples were being analyzed, the initial sample time was always set to the time of spike injection, and not the time of sample elution. Generally, the difference between spike injection and sample analysis time was one to seven days. For isotopes with half-lives greater than a year, the timing is trivial and the activity difference is smaller than measurement precision. The only isotope where the timing correction is significant is ²³⁹Np with a 2.355 day half-life.

Parameter fitting of the solute breakthrough requires sample elution time and activity in $\mu\text{Ci/ml}$ at elution. Sample elution time was computed by,

$$t_j = \frac{\left[\left(\sum_{i=1}^{j-1} m_i + \frac{1}{2} m_j \right) / \rho \right] - DV}{Q} \quad (9)$$

where t_j is the midpoint time of sample j , m is the measure mass of sample i , ρ is the solution density given in Table 5, Q is the volume flow rate, and DV in the column exit dead volume. The column dead volume was calculated based on the geometry of the collection plate, (6.1 ml) and the length of the effluent tube, (0.021 ml/cm). For the short cores, C, D, and E this totaled 6.7 ml, while the long cores A and B, had more tubing and totaled 8.2 ml.

Sample activity per effluent mass was measured in $\mu\text{Ci/gm}$ and converted to volume activities by multiplication of the solution density given in Table 5. Activities at elution, Af_j were computed for ^{239}Np by,

$$Af_j = A_j e^{-\lambda(t, -t_j)} \quad (10)$$

Parameter Fitting for Eluted Species

Effluent curves were analyzed using COLUMN (Budge, 1996). That code provides parameter fits to the data for two different models. The first is the standard homogeneous porous media, advection dispersion model, based on the analytical solution of Parker and van Genuchten (1984). The second is a dual porosity, fractured-matrix numerical model similar to the Performance Assessment transport model, SECO-TP (WIPP Performance Assessment, 1992-1993).

COLUMN performs automatic least-squares fits of effluent data to theoretical effluent curves calculated using either the single-porosity or dual-porosity models. The fits are calculated using Marquardt minimization in which the curvature matrix is inverted using singular value decomposition (SVD). The advantage of SVD over other matrix decompositions is that a meaningful answer is returned even if there are dependencies in the model parameters being fit. COLUMN reports fitted parameter values, uncertainties, and the nature of any parameter dependencies to the analyst. The code requires the effluent activities, the collection times and the location along the column at which the effluent is collected (generally equal to the column length). In addition, the analyst must specify the spike volume and concentration and initial estimates of all model parameters. The analyst must convert the effluent volumes to collection times using the known flow rate.

Each column experiment includes at least one nonsorbing tracer, such as ^3H or ^{22}Na . This tracer is used to determine the hydrological parameters for each model, which are then used in subsequent fits of the sorbing tracers to determine the chemical retardation.

SINGLE POROSITY MODEL

The single porosity model assumes that, at least on the macroscopic scale, the rock is homogeneous. The mean pore velocity is determined by the porosity, ϕ , and the distribution of pore velocities is characterized by the dispersion, D . Chemical sorption is characterized by the retardation coefficient, R . Flux weighted concentrations were used, as recommended by Parker and van Genuchten (1984). The single porosity model is a simple model for which effluent curves can be computed analytically and whose parameters are easy to interpret. COLUMN is able to find optimal fits to the single porosity model in a few seconds of computer time.

DUAL POROSITY MODEL

The dual porosity model assumes that the rock column is heterogeneous, and divides it into two portions: a macropore space, in which transport is dominated by advection, and a surrounding rock matrix in which advection is negligible, but into which molecular diffusion can

take place. The hydrological parameters that describe the column include the advective porosity and matrix porosity, ϕ_f and ϕ_m ; the advective and matrix dispersions, D_f and D_m ; and the matrix block size, B . Chemical sorption is characterized by the advective and matrix retardation coefficients, R_f and R_m . The dual porosity model is similar to that used in SECO/TP. It is a complex model, and COLUMN can take up to a day to fit experimental data to dual porosity curves.

Another difficulty is the lumped parameter nature of the dual porosity model. The functional form of the transport equations makes the individual parameter definitions ambiguous. In other words, for the data available from the column experiments, it is difficult to distinguish fits using very different parameter values. For example, a decrease in D_m can be almost exactly offset by a decrease in B . We have chosen fixed values for matrix tortuosity, ϕ_m and matrix diffusion, D_m for the analyses described here. This leaves the matrix block size, B , as the single parameter describing the effects of dual porosity. Parameters fixed in the dual-porosity analysis are listed in Table 11. For U and Np matrix dispersion is set to the free-solution diffusion coefficients for the respective ions. The value used is the average of the probable oxidation states for both actinides reported by Brush (1996a). Diffusion into the matrix is computed assuming a one-dimensional plate geometry. This is analogous to a fracture or layered system.

Table 11. Fixed parameters used in all dual porosity analyses.

Parameter	Value
Matrix dispersion, D_m	
Na	$1.5 \times 10^{-5} \text{ cm}^2/\text{sec}$
U	$3 \times 10^{-6} \text{ cm}^2/\text{sec}$
Np	$2.2 \times 10^{-6} \text{ cm}^2/\text{sec}$
Matrix porosity, ϕ_m	0.11
Advective tortuosity	1
Matrix tortuosity	0.067
Advection computational cell length	1 cm
Matrix computational cell length	0.001 cm

Parameter Fitting for Noneluted Species

Determination of actinide retardation in the column experiments is problematic for isotopes that do not appear in the effluent. In such cases, actual retardation coefficients cannot be computed, since lack of detection means only that the test may not have been run long enough, or that the solute eluted from the column at a concentration lower than the analysis detection limits. Nevertheless, minimum values can be calculated based on the known hydraulics of flow and instrument MDA.

Two cases that limit estimates of retardation coefficients are shown in Figure 8. The figure presents possible breakthrough curves, only one of which will apply in a given test. The first curve, labeled A, is for a solute that eluted during the sampling, but whose maximum activity concentration at the outlet was below the MDA of the analysis instrument. In that case, the

Figure 8. Possible breakthrough curves for non-eluting solutes.

minimum R will be that value that produces a peak equal to the MDA. The second curve, labeled **B**, is for a solute that would elute at activities higher than the MDA if the test was run longer. Solute may be in the effluent, but at activities below the MDA. In that case, minimum R is defined by the smallest retardation value that does not produce an activity greater than the MDA before the last sample. The limiting case, **A** or **B** is a function of the spike activity, dispersion, radioactive decay, total sampling volume and the MDA.

Minimum R was determined by trial and error runs of the single porosity model using the last sample volume, and assuming constant values of flow rate, dispersion, porosity and MDA. The MDA was set at the value listed in Table 10. Flow rate, porosity and dispersion were equated to the fitted values from the ^{22}Na breakthrough for the same test. Finally, R was varied over an appropriate range to determine the limiting case, **A** or **B**, and the minimum R .

Partition Coefficients and Dispersivity

The solute partition coefficient, k_d was computed from fitted R values by (Fetter, 1993, p. 119),

$$k_d = \frac{(R-1)\phi}{\rho_b} \quad (11)$$

With this definition, k_d will have the inverse units of the bulk density, ρ_b (cm^3/gm , or ml/gm). Since the bulk density is not known exactly in these samples a value of 2.4 gm/cm^3 from Table 2 was used. Considering the accuracy of the parameter fit for R and ϕ , that

assumption is adequate. In single porosity fits, the fitted value was used for ϕ , while for dual porosity fits the value of ϕ_m assumed as 0.11 (Table 11) was employed. The use of fitted porosity is a conservative practice, since the fitted values are less than or equal to the estimated total porosity, and k_d is linear with ϕ .

The effect of flow rate on dispersion can be reduced by calculation of the dispersivity, α ,

$$\alpha = \frac{D - Dm}{\nu} \quad (12)$$

where D is the hydrodynamic dispersion, Dm is the molecular diffusion coefficient, and v is the seepage velocity (Fetter, 1993, p. 51). Molecular diffusion was assumed as 3×10^{-5} and 1.5×10^{-5} cm²/s for ³H and ²²Na respectively, which are representative values for those ions. The seepage velocity is given by,

$$v = \frac{Q}{A_{cs}\phi} \quad (13)$$

where A_{cs} is the column cross sectional area.

Daughter Product Analysis

At one time it was hoped that the minimum R of thorium could be lowered by observing the decay of its daughter products. ^{228}Th follows the decay chain:

All daughters are shorted lived with ^{224}Ra having the longest half-life of 3.62 days. The daughters have multiple gamma, alpha and beta emissions which provide low MDA's for some. Since the ^{224}Ra is mobile, with a retardation of about two, all columns receiving ^{228}Th have ^{224}Ra and its daughters in the effluent. Repeated measurement for ^{224}Ra in the effluent shows its reduction with time, indicating that any ^{228}Th if present, must be at an activity less than the measured ^{224}Ra . The eventual reduction of ^{224}Ra below its MDA would indicate ^{228}Th was also below the ^{224}Ra MDA.

Unfortunately, the daughter product decay analysis is inconclusive due to the use of ^{232}U in the experiments. ^{232}U is the parent of ^{228}Th , and has been used in all cores. With repeated use of ^{232}U it has eluted at measurable activities over much of the effluent curve. All effluent samples with ^{232}U experience growth of ^{228}Th and its daughters. This situation makes any analysis based on the absence of the daughters problematic and generally inconclusive.

RESULTS

Effluent Curves

Measured breakthrough curves for eluting species are shown in Appendix B and listed in Appendix C. In general, the curves have the shape expected for advection-dispersion transport. ^3H , ^{22}Na , ^{232}U and ^{239}Np eluted in that general order. There was little difference between ^3H and ^{22}Na , indicating sodium is a conservative species in this salt rich system. Figure 9 shows their similarity in Test C1 once the activities are scaled to the maximum.

Due to equipment problems, Test A2 did not yield useful results. Two test spikes, C4- ^{239}Np and C5- ^{232}U , were unusable due to low initial spike activity. Both isotopes eluted, but at activities too low to provide useful data for parameter fitting. As a result of these tests, later spike activities were increased.

^{232}U eluted after a mild retardation in all experiments. Figure 10 shows Test E1 results, a typical ^{232}U breakthrough curve for both γ Spec and LSC results. ^{22}Na elutes at one pore volume followed by ^{232}U . Both analysis methods provide similar results, but the LSC has less noise and obtains useful measurements after ^{232}U has fallen below the γ Spec MDA.

Figure 9. Comparison of ^3H and ^{22}Na effluent breakthrough in Test C1.

Figure 10. Comparison of γ Spec versus LSC in Test E1.

As mentioned previously, the short lived daughters of ^{228}Th require the holding of samples before LSC analysis. Figure 11 demonstrates the decay of the first and longest half-life daughter, ^{224}Ra , for test C2. The figure presents ^{224}Ra analysis of the samples at 5 different times, ^{22}Na activity, and the final analysis of ^{232}U by LSC. The first results, 6/21/95, show that the ^{224}Ra initially in equilibrium with the ^{228}Th breaks through with a retardation of about two. After breakthrough, the ^{224}Ra does not drop to zero, but instead declines until it reaches a level that represents the steady state balance between growth from the ^{228}Th in the column and transport out. Analysis of the same samples at later dates shows ^{224}Ra decreasing consistent with radioactive decay, until by 7/20/95 it is only slightly above the MDA. Finally, the ^{232}U LSC analysis carried out on 8/1/95 shows no interference. Since a daughter grows in a solution of its parent with its own half-life, the decay of ^{224}Ra is also proof that any ^{228}Th activity is below the MDA of the ^{224}Ra .

Eluted Species Parameter Fitting

The results of the analysis are summarized in Tables 12, 13 and 14 for the eluted species. The tables contain fitted porosity, dispersion and retardation values, and calculated values of partition coefficient, k_d and dispersivity, α . Also listed are values of the root mean squared error (RMS), between the measured and fitted effluent concentrations. RMS provides a method to compare the goodness-of-fit of the two models to a single breakthrough curve. The smaller the RMS, the better the fit. However, since RMS is a function of the absolute effluent activity, it should not be used to compare the fit between tests.

Most parameter fits were straightforward and require little explanation. The following paragraphs list a qualitative assessment of the data fits, and discusses the tests that experienced problems in their analysis. Plots of the curve fits are contained in Appendix B and listed in Appendix C.

Figure 11. Thorium 228 daughters in Test C2.

TEST A1

Test A1 measured core porosity with ^3H . The measured ^3H effluent concentrations were well matched by both single and dual porosity models, with the dual model fitting the data slightly better.

TEST A2

Test A2 was intended to image ^{22}Na by tomography. The equipment was unable to maintain a steady 0.02 ml/min flow rate and after much difficulty the test was terminated. No useful results were obtained.

TEST A3

Test A3 was similar to Test A1 except it was carried out at one-fifth the flow rate, 0.1 ml/min. Both single and dual porosity models fit the data well, but provided lower porosity when compared to Test A1. The single porosity yielded 1.9% for Test A3 contrasted to 4.4% for Test A1 while the dual porosity yielded 1.5% for Test A3 versus 3.2% for Test A1. The lower porosity estimated by Test A3 compared to Test A1 may indicate that the pore structure changed, resulting in fewer pores transporting the solute. This may have resulted from fines relocating and blocking pores, or the degassing of the pore water and subsequent formation of air bubbles within the core.

Table 12. Parameter fitting for conservative solutes.

Test	Isotope	Single Porosity				Dual Porosity				
		ϕ %	D cm ² /s	α cm	RMS nCi/ml	ϕ_f %	¹ D _f cm ² /s	α cm	B cm	RMS nCi/ml
A1	³ H	4.4	0.00372	0.3	0.20	3.2	0.00147	0.93	0.89	0.04
A2	²² Na			<i>Test</i>		<i>Failed</i>				
A3	³ H	1.9	0.00489	9.2	0.07	1.5	0.00465	7.06	6.00	0.06
A4	²² Na	2.1	0.00288	6.0	6.58	2.2	0.0025	5.45	13.5	11.4
B1	³ H	19.9	0.00134	26.4	0.03	7.9	0.00092	7.20	1.27	0.02
B2	²² Na	9.2	0.00118	10.7	1.01	6.0	0.00081	4.81	1.74	0.39
B3	²² Na	9.2	0.00142	12.9	0.69	4.9	0.00010	0.49	1.50	0.38
B4	²² Na	7.9	0.00207	16.2	6.90	8.0	0.002	15.8	12.0	8.34
B5	²² Na	7.9	0.00103	16.1	6.54	8.0	0.002	31.7	12.0	8.55
B6			<i>BTC</i>	<i>not</i>	<i>useable</i>	<i>due to</i>	<i>tailing</i>	<i>from</i>	<i>B5</i>	
B7	²² Na	13.0	0.00870	22.4	0.45	5.6	0.00656	7.25	0.58	0.12
B8	²² Na	8.3	0.00675	11.1	2.94	<i>Unable</i>	<i>to</i>	<i>fit</i>		

¹ Value of matrix retardation fixed at 1 for nonsorbing tracers.

Table 12. Parameter fitting for conservative solutes (continued).

Test	Isotope	Single Porosity				Dual Porosity				
		ϕ %	D cm ² /s	α cm	RMS nCi/ml	ϕ_f %	² D _f cm ² /s	α cm	B cm	RMS nCi/ml
C1	³ H	3.2	0.00057	1.8	7.42	2.2	0.00030	0.65	1.21	6.08
C1	²² Na	2.5	0.00038	0.9	0.02	2.6	0.00038	0.98	8.33	0.03
C2	²² Na	8.5	0.00266	22.4	2.37	3.7	0.00439	16.1	2.70	1.45
C3	²² Na	3.3	0.00204	6.7	2.44	<i>Unable to Fit</i>				
C4	²² Na	4.8	0.00133	6.3	4.65	1.3	0.00033	0.42	0.57	1.89
C5	²² Na	4.3	0.00250	10.7	1.19	1.6	0.00206	3.32	1.14	0.92
C6	²² Na	5.9	0.00170	9.9	2.63	1.5	0.00096	1.40	0.79	1.33
C7	²² Na	2.0	0.00155	3.0	2.63	1.9	0.00151	2.86	8.50	2.62
D1	³ H ³	14.3	0.00055	7.8	0.07	7.3	0.00047	3.40	0.78	0.04
D2	²² Na	8.0	0.00058	4.6	0.43	5.2	0.00046	2.37	1.05	0.21
D3	²² Na	8.9	0.00053	4.7	0.44	5.4	0.00042	2.25	0.88	0.42
D4	²² Na	9.7	0.00054	5.2	1.60	3.5	0.00035	1.21	0.67	0.81
D5	²² Na	9.7	0.00054	5.2	0.35	5.6	0.00034	1.89	0.76	0.31
D6	²² Na	9.6	0.00045	8.6	0.59	5.4	0.00020	2.14	0.73	0.60
E1	²² Na	18.3	0.00024	4.3	0.23	15.5	0.00022	3.38	1.46	0.15
E2	²² Na	23.8	0.00029	6.8	0.36	15.0	0.00025	3.71	0.88	0.37

² Value of matrix retardation fixed at 1 for nonsorbing tracers.³ Fit is for Co = 0.011 uCi/ml

Table 13. Parameter Fitting for U retardation.

Test	Single Porosity			Dual Porosity						
				Without Advective Retardation			With Advective Retardation			
	R	k_d cm ³ /gm	RMS nCi/ml	R_m	k_d cm ³ /gm	RMS nCi/ml	R_f	R_m	k_d cm ³ /gm	RMS nCi/ml
B3	4.50	0.13	1.36	68.8	3.1	4.99	1.14	65.4	3.0	4.95
B6	6.40	0.18	1.24	<i>Unable to fit</i>			<i>Unable to fit</i>			
B7	3.70	0.15	0.30	63.6	2.9	2.19	4.35	1.00	0	0.48
C2	13.9	0.46	1.69	4577	210	3.52	16.2	4287	200	3.09
C5		<i>BTC</i>	<i>not</i>	<i>useable</i>	<i>due to</i>	<i>low</i>	<i>spike</i>	<i>activity</i>		
C7	3.23	0.02	2.28	2975	140	5.32	2.64	486	22	2.11
D5	18.1	0.69	0.78	1500	69	2.22	12.6	675	30	0.54
D6	10.1	0.36	1.42	332	15	7.22	9.77	71.5	3.2	2.08
E1	1.80	0.06	1.30	236	11	3.27	1.84	29.3	1.3	1.14

Table 14. Parameter fitting for Np retardation.

Test	Single Porosity			Dual Porosity						
				Without Advective Retardation			With Advective Retardation			
	R	k_d cm ³ /gm	RMS nCi/ml	R_m	k_d cm ³ /gm	RMS nCi/ml	R_f	R_m	k_d cm ³ /gm	RMS nCi/ml
A4				<i>BTC</i>	<i>Not</i>	<i>Usable</i>				
B2				<i>BTC</i>	<i>Not</i>	<i>Usable</i>				
C4				<i>BTC</i>	<i>Not</i>	<i>Usable</i>				
C5*	22.2	0.38	1.75	2648	120	2.42	20.6	587	27	0.94
C6	77.5	1.88	0.37	5667	260	2.01	56.2	700	32	0.26
C7	75.1	0.62	2.28	<i>Unable</i>	<i>to</i>	<i>fit</i>	8.90	17421	800	1.71
D2	29.7	0.96	0.04	<i>Unable</i>	<i>to</i>	<i>fit</i>	18.3	10395	480	0.04
D4	37.0	1.46	0.25	5921	271	0.58	25.6	1095	50	0.07

*Test C5 results not considered reliable. See text for details.

TEST A4

A ^{22}Na and ^{239}Np spike was used in Test A4 to measure the latter's retardation. Sodium eluted and was well fit by both models. Porosity values were close to A3 fits. ^{239}Np was retarded enough that it did not elute at significant activities before its decay.

TEST B1

Fitting the ^3H spike for Test B1 yielded a good fit by the dual porosity model and a poor fit with the single porosity model. The single porosity fit yielded a porosity of 20%, which is considerably larger than the estimated total porosity of 15%.

TEST B2

Similar to A4, B2 spiked ^{22}Na and ^{239}Np to measure the latter's retardation. Sodium elution was fitted by both models with the dual porosity yielding a clearly better fit. Porosity values were lower than B1 fits, with the single porosity calculated as 9.2% and dual porosity as 6.0. ^{239}Np was retarded enough that it did not elute at useable activities before it decayed.

TEST B3

Test B3's objective was to measure uranium and thorium retardation. Thorium did not elute. As in the previous B tests, ^{22}Na tracer was fit better by the dual porosity model with values slightly lower than the B2 fits. The uranium eluted and was well fitted by the single porosity model with $R = 4.5$. In the dual models, measured activities were poorly fit if no advective retardation was assumed and adequately fitted if it was allowed.

TEST B4

A step injection of ^{22}Na was used in Test B4 for tomography imaging. Effluent fitting calculated good fits by both models with a single porosity value of 7.9% and a dual estimate of 8.0%.

TEST B5

Test B5 was similar to B4 with the exception that the flow rate was reduced to 0.05 ml/min. Both the single porosity fit of 7.9% and the dual porosity fit of 8.1% were consistent with B4.

TEST B6

Uranium retardation was measured at the low flow rate of 0.05 ml/min in Test B6. A high ^{22}Na tail activity from Test B5 was superimposed on the B6 effluent, which prevented a good fit by either pore model. Therefore, uranium retardation was fit using B5 parameters. The uranium R factor was 6.4 for the single porosity model. The dual porosity model was unable to fit the breakthrough curve.

TEST B7

Flow was increased in Test B7 to 0.5 ml/min, and a ^{22}Na and ^{232}U spike injected. The sodium effluent was fit well by both models, with the dual porosity estimate somewhat better. The estimated porosities were substantially different at 13.4% and 0.6% for the single and dual porosity models respectively. Uranium retardation at $R = 3.7$ was slightly less than previous tests.

TEST B8

Continuing at 0.5 ml/min, Test B8 was a step injection of ^{22}Na . A porosity of 8.3% was calculated by the single porosity fit, which is similar to B4 and B5 values. Surprisingly, the dual porosity model could not fit the measured effluent at the high flow rate.

TEST C1

Test C1 was a combined ^3H and ^{22}Na spike intended to test the suitability of using sodium as a conservative tracer in the Culebra cores. The two solutes eluted very similarly and provided similar fits by both pore models. With the single porosity model, ^3H provided a porosity of 3.2% while ^{22}Na yielded a value of 2.5%. That variation is within the fitting error. The dual porosity fitting computed fracture porosity of 2.2% and 2.6% for ^3H and ^{22}Na respectively.

TEST C2

Thorium and uranium retardation were measured in Test C2. Thorium did not elute above the MDA. ^{22}Na was fit well by both models. ^{232}U was well fitted by the single porosity model and the dual porosity model with fracture retardation. The no fracture retardation model provided a poor fit.

TEST C3

The objective of Test C3 was to measure ^{241}Pu and ^{241}Am retardation. Neither solute eluted. As for the ^{22}Na tracer, the dual porosity fit could not be completed because the fracture spacing, B , became so large that computer memory was exhausted. The magnitude of B determines the size of the matrix calculation grid.

TEST C4

^{239}Np and ^{22}Na were injected in Test C4. While measurable activities of ^{239}Np were detected in the effluent, the data were inadequate due to the rapid decay of the isotope. The ^{22}Na data provided porosity fits of 4.8% for the single and 1.3% for the fractures, with the fracture fit being noticeably better.

TEST C5

ERDA 6 brine was used in Test C5 to determine the impact on neptunium, uranium and thorium retardation resulting from the intrusion of a Salado brine into the Culebra. ^{228}Th did not elute above the MDA. ^{232}U eluted at activities too low to provide useful fitting data due to the low spike activity. The eluted ^{22}Na was fit somewhat better by the dual than the single porosity model. ^{239}Np eluted and was well fitted by the dual porosity model with advective retardation, but poorly fit by the other methods. Unfortunately, Test C5 results for ^{239}Np must be disregarded. As detailed by Brown (1995-1996, page 79), the ^{239}Np sample spike for the test experienced difficulties in preparation at ITRI. There is convincing evidence that the measured effluent ^{239}Np was not in solution, but instead was a nonrepresentative silicate colloid. It formed during the separation of the ^{239}Np from its parent, ^{243}Am , due to the use of concentrated HF acid in glass containers. The problem occurred only in Test C5 and did not affect the other ^{239}Np tests reported here.

TEST C6

Test C6 replicated C4 with the exception of using a higher ^{239}Np activity. Both ^{22}Na and ^{239}Np fittings were similar to Test C5 with the exception that neptunium had a larger single porosity retardation of 78.

TEST C7

Salado brine was again used in Test C7 to replicate C5. ^{22}Na elution yielded similar parameters as C5. Thorium did not elute. Neptunium exhibited retardation of 75 for the single porosity model, very close to the C6 retardation.

TEST D1

Test D1 measured the core porosity by ^3H . A single porosity fit gave could only be obtained if the concentration is left as a free parameter. This may be due to an incorrect input spike concentration. A very good fit is obtained for a porosity of 14.3% and an input spike concentration roughly half of that specified. That fitting is reported here and used in the dual porosity fit.

TEST D2

Uranium, thorium and neptunium retardation were measured in Test D2. ^{22}Na was well fit by both models with a single porosity fit of 8% and a fracture porosity of 5.2%. Neptunium was fit adequately by the dual porosity models, but not the single.

TEST D3

Test D3 injected ^{22}Na , ^{241}Am and ^{241}Pu . As in Test D2, ^{22}Na was well fit by both models with about the same porosity. The actinides did not elute above the MDA.

TEST D4

A replicate of Test D2 was carried out in D4. ^{22}Na fits were similar, while ^{239}Np retardation was somewhat lower.

TEST D5

Uranium retardation was measured in Test D5. Porosity values for ^{22}Na fits similar to previous tests with 9.7% and 5.6% for the single and dual porosity models respectively. ^{232}U retardation was fit at the relatively high values of 18 with single-porosity and 1500 with dual porosity without fracture retardation.

TEST D6

The flow rate was decreased to 0.05 ml/min in Test D6, and ^{232}U injected. Estimated porosity was similar to D5, but ^{232}U retardation was only about 60% the value fitted for Test D5.

TEST E1

Test E1's objective was porosity estimates, and ^{232}U and ^{239}Np retardation. Porosity fits were relatively high, 18.3% as fitted by the single porosity model. Uranium retardation was fit well by all three models, with the lowest R value estimates of any test.

TEST E2

Test E2 provided similar porosity estimates as E1. The injected ^{241}Am and ^{241}Pu did not elute above the MDA.

Single vs. Dual Porosity Models

It is possible to compare the applicability of the two porosity models by two steps. First, comparison of the fitted parameter values of ϕ and ϕ_f for the conservative solutes show that the dual porosity model provides ϕ_f values only slightly less than the single porosity model. This indicates that the "advective porosity" of the dual porosity model is largely the same void space as the porosity of the single model.

Second, a statistical test of the single and dual porosity models' ability to fit the effluent curves can be carried out using the Root Mean Squared error (RMS) between the measured and fitted effluent breakthrough curves for the conservative tracers. Two Student t , paired two sample for means tests were performed to determine if there is significant difference between the RMS of the single and dual porosity models. The two data sets tested where,

$$D_R = RMS_{single} - RMS_{dual} \quad (14)$$

and

$$D_N = (RMS_{single} - RMS_{dual}) / \text{Injected Activity} \quad (15)$$

Where D_R is the raw difference between the fits and D_N is the difference normalized by the injection activity. The hypotheses tested were:

$$H_0: D_R = 0 \quad (16)$$

$$H_a: D_R > 0 \quad (17)$$

and

$$H_0: D_N = 0 \quad (18)$$

$$H_a: D_N > 0 \quad (19)$$

The analysis was performed with Microsoft Excel. Both tests failed to reject H_0 . Therefore, it can be concluded there is no significant difference between the two fittings. It is apparent the dual porosity model is providing essentially a single porosity fit to the data.

Test Comparisons

Figure 12 presents are fitted single porosity values from the column experiments. Each fit is labeled by tracer and any special condition of brine, injection mode or flow rate. Tests not labeled were carried out at the standard flow rate with AIS brine. Also shown is the estimated total porosity for each core. Figures 13 and 14 show fitted uranium and neptunium retardation respectively.

The variability of conditions between the tests was relatively large, which makes their direct comparison difficult. Likewise some of the duplicate tests do not provide comparison due to testing or fitting problems on one of the replicates. Thus, any difference between flow rates or brine type is subject to considerable ambiguity. Therefore, the following two paragraphs are only observations and not substantiated results.

FLOW RATE DEPENDENCIES

No clear trend can be seen in relation to flow rate. Porosity estimates in B core are similar in B4, B5 and B8 which span an order of magnitude in flow rate. Similarly, D6 and D5 have equivalent porosity fittings. In regards to uranium retardation, in B core, the high flow Test B7 had the lowest R value, while in D core the lower flow rate Test D6 had the lower R . If flow rate dependencies are present they are within the parameter fitting errors.

BRINE EFFECTS

As would be expected, brine type had no impact on core porosity estimates. Test C5 and C7 had similar porosity fittings as the other Core C tests. Comparing Tests C2 and C7 indicates that uranium retardation was reduced by a factor of four. However, comparing Tests C6 and C7 shows neptunium retardation is near constant. Considering that all the R values are near the range display by other tests, no conclusion is possible.

Figure 12. Porosity computed by conservative solute fittings.

Figure 13. Fitted uranium retardation.

Figure 14. Fitted neptunium retardation.

Noneluted Species Minimum Retardation

Table 15 lists the limiting case, minimum R and minimum k_d for the noneluted species. All values were computed using the single porosity model and the procedures detailed earlier in the section Parameter Fitting for Noneluted Species. Effluent volumes were estimated based on Lucero (1997). For C Core, effluent volumes were projected to its September 4, 1997 termination date. Minimum R values were 520 to 18,000 for ^{241}Am based on the LSC MDA and an injection concentration equal to the solubility. Minimum R values were 9.1 to 47 for ^{228}Th , and 800 to 38,000 for ^{239}Pu . The range of these minimum R values is a function of the individual test conditions and does not indicate data uncertainty. The lower values are provided by the shorter duration tests, and nothing in the results of the eluting actinides would indicate that those tests will behave any differently for the noneluting species. Thus, it is recommended that the upper range value be used if a single R value is needed.

Table 15. Lower Bounds on Retardation for Noneluting Species.

Test	Element	Effluent Volume (L)	Limiting Case	Lower Limit of R	Lower Limit of k_d
C3	Am	71.4	B	18,000	254
D3	Am	48.2	B	2,800	35
E2	Am	15.0	B	520	53
C3	Pu	71.4	B	38,000	540
D3	Pu	48.2	B	3,700	140
E2	Pu	15.0	B	800	79
B3	Th	18	A	23	0.84
C2	Th	71.1	A	47	1.6
C5	Th	68.1	A	27	0.46
D2	Th	46	A	9.1	0.27

Relation of Transport Parameters to Other Estimates

The cores were estimated to have similar porosity, but fitted values differed greatly. Core E had fitted porosity values (0.18 and 0.24) greater than the estimated 0.15. On the other hand, all tests of A, B, C, and D Cores provided porosity values less than expected. The average of seven ^{22}Na fits on C core was 0.042 and the six D Core fits averaged 0.092. These results indicate that C and D Cores experienced significant preferential flow. The large fracture in Core C is possibly the cause of its preferential flow. The cause of the preferential flow in Core D is not believed to be a large fracture. Instead, visual examination suggests that any high permeability paths occur in the chalky material along bedding planes and possibly at connected vugs. Such paths are probably not continuous over the cores, but instead provide a loose network where flow converges and diverges in and out of the paths. The lack of continuous paths explains why the effluent curves are still well fitted by the single porosity model.

Fitted hydrodynamic dispersion coefficients were an order of magnitude greater than for uniform packed columns. This is shown using the classical Peclet diagram (Fetter, 1993, p. 54-56). The single porosity fit yielded dispersion coefficients, D for ^{22}Na of 0.0002 to 0.001 cm^2/s

with an average of $0.0006 \text{ cm}^2/\text{s}$. The aqueous molecular diffusion coefficient, D_m for NaCl is approximately $1.5 \times 10^{-5} \text{ cm}^2/\text{s}$ (Weast, 1985, Diffusion Coefficients of Strong Electrolytes). Taking the ratio of the average,

$$\frac{D}{D_m} = \frac{0.0006}{0.000015} = 40 \quad (20)$$

For packed columns that ratio would predict a Peclet number of 20, and falls in a region where advective dispersion dominates transport. The Peclet number is defined as the ratio of advective transport to diffusion,

$$P = \frac{vd}{D_m} \quad (21)$$

where d is a characteristic length normally defined as the mean grain diameter. The seepage velocity, v is given by Equation 13.

Solving Eqs. 21 and 13 for d yields,

$$d = \frac{PD_m A \phi}{Q} \quad (22)$$

Letting $P = 20$, $D_m = 0.000015 \text{ cm}^2/\text{s}$, $A = 165 \text{ cm}^2$, $Q = 0.0017 \text{ cm}^3/\text{s}$ and assuming $\phi = 0.15$, Eq. 22 yields $d = 4 \text{ cm}$. That value is clearly larger than any pore or particle in these cores.

Field scale dispersion is normally defined by the dispersivity, α , given in Equation 12. Table 12 lists the computed dispersivity values for each test that ranges from 0.3 to 26 cm. Gelhar (1986) has shown that field dispersivity can be estimated at 0.1 the transport distance. These experiments with 10 cm and 50 cm long cores had dispersivity of 0.09 to 0.8 the transport distance clearly indicating non-uniform advection. That is, flow in the cores is dominated by the spatially heterogeneous conductivity. Since only a portion of the pore space was accessed by the solute during the experiment, R and k_d values measured here are probably smaller than the core's full potential.

CONCLUSIONS

Two actinides eluted from the columns, U and Np. Retardation is lower for uranium, with R values of 2 to 18. Neptunium shows greater retardation and has R values of 30 to 78. The quoted retardation factors are for the single porosity model.

There is little evidence of dual porosity effects in the effluent curves, but porosity estimates and fitted dispersivity values indicate that significant preferential flow occurred in all cores. The time and space dimensions of these experiments place them at the lower end of the spectrum of Damkohler numbers (Holt, 1997). Thus, the evidence of preferential flow is to be expected. Since only a portion of the pore space was accessed by the solute during the experiment, R and k_d values measured here are probably smaller than the core's full potential.

Three actinides did not elute from the columns, Pu, Am and Th. Theoretical analysis shows that retardation is very high for plutonium and americium. Thorium is not yet well constrained, due to a high MDA. Minimum R values were 520 to 18,000 for Am, 9.1 to 47 for Th, and 800 to 38,000 for Pu. The range of these minimum R values is a function of the individual test conditions and does not indicate data uncertainty or measurement error.

No clear trend is apparent with regard to flow rate dependencies. Use of the Salado brine, ERDA 6, did not produced a significant change in actinide retardation compared to AIS.

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APPENDIX A

Activity to Concentration Conversions

Activity to Concentration Conversions

The rate of radioactive disintegration of an isotope is proportional to the time rate of change of its concentration and is described by first order decay (Knoll, 1989, p. 2-3). Expressed in traditional units, the activity of a sample is,

$$A = \frac{\lambda A_v M}{C} \quad (1)$$

where A is the radioactive activity (Ci), λ is the first order decay constant (s^{-1}), A_v is Avogadro's number (6.023×10^{23} atoms/mole), M is the number of moles of the isotope and C is a conversion from disintegration rate to activity ($3.7 \times 10^{10} \text{ Ci}^{-1} \text{ s}^{-1}$). The rate constant is related to the radioactive half-life, $t_{1/2}$ by,

$$\lambda = \frac{\ln(2)}{t_{1/2}} \quad (2)$$

Solving Equations 1 and 2 for the number of moles of the isotope yields the desired result,

$$M = \frac{ACt_{1/2}}{\ln(2)A_v} \quad (3)$$

The mass of isotope can be found by multiplying Equation 3 by the isotope gram-atomic weight w ,

$$m = wM \quad (4)$$

where m is the mass in grams. Values of w can be found in Weast (1985, Table of the Isotopes) and $t_{1/2}$ in Kocher (1981). Other sources may give slightly different values. Table A1 presents the results of applying Equations 3 and 4 to the isotopes used in the WIPP column retardation experiments. The half-lives given must be converted to units of seconds before application of Equation 3.

Table A1. Equivalent moles and gram mass to 1 curie of activity.

Isotope	Atomic Weight (gm)	Half Life	Moles per Curie	Grams per Curie
³ H	3.02	12.28 y	3.43×10^{-5}	1.03×10^{-4}
²² Na	21.99	2.602 y	7.28×10^{-6}	1.60×10^{-4}
²³² U	232.04	72 y	2.0×10^{-4}	4.7×10^{-2}
²²⁸ Th	228.04	1.913 y	5.35×10^{-6}	1.20×10^{-3}
²²⁴ Ra	224.02	3.62 d	2.77×10^{-8}	6.15×10^{-6}
²⁴¹ Am	241.06	432.2 y	1.21×10^{-3}	2.92×10^{-1}
²⁴¹ Pu	241.06	14.4 y	4.03×10^{-5}	9.71×10^{-3}
²³⁹ Np	239.05	2.355 d	1.80×10^{-8}	4.31×10^{-6}

Appendix A References

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APPENDIX B

Measured and Fitted Break Through Curves

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Figure B7. Test B4 measured and fitted ^{22}Na effluent concentrations.

Figure B8. Test B5 measured and fitted ^{22}Na effluent concentrations.

Figure B9. Test B6 measured and fitted ²²Na and ²³²U effluent concentrations. See text for explanation for ²²Na curve.

Figure B10. Test B7 measured and fitted ²²Na and ²³²U effluent concentrations.

Figure B11. Test B8 measured and fitted ^{22}Na effluent concentrations.

Figure B12. Test C1 measured and fitted ³H and ²²Na effluent concentrations.

Figure B13. Test C2 measured and fitted ²²Na and ²³²U effluent concentrations.

Figure B14. Test C3 measured and fitted ^{22}Na effluent concentrations. Figure B15. Test C4 measured and fitted ^{22}Na effluent concentrations.

Figure B16. Test C5 measured and fitted ²²Na and ²³⁹Np effluent concentrations. See text for explanation for ²³⁹Np.

Figure B17. Test C6 measured and fitted ²²Na and ²³⁹Np effluent concentrations.

Figure B18. Test C7 measured and fitted ^{22}Na , ^{239}Np and ^{232}U effluent concentrations.

Figure B19. Test D1 measured and fitted ^3H effluent concentrations.

Figure B20. Test D2 measured and fitted ²²Na and ²³⁹Np effluent concentrations.

Figure B21. Test D3 measured and fitted ^{22}Na effluent concentrations.

Figure B22. Test D4 measured and fitted ²²Na and ²³⁹Np effluent concentrations.

Figure B23. Test D5 measured and fitted ²²Na and ²³²U effluent concentrations.

Figure B24. Test D6 measured and fitted ²²Na and ²³²U effluent concentrations.

Figure B25. Test E1 measured and fitted ^{22}Na and ^{232}U effluent concentrations.

Figure B26. Test E2 measured and fitted ^{22}Na effluent concentrations.

APPENDIX C

MEASURED EFFLUENT CONCENTRATIONS FOR ^3H , ^{22}Na , ^{232}U and ^{239}Np .

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Table C1. Test A1, ^3H .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
5	0.000001	290	0.002120	570	0.000247
10	0.000001	295	0.002010	575	0.000233
15	0.000000	305	0.001900	580	0.000228
20	-0.000001	315	0.001820	585	0.000224
30	-0.000001	320	0.001740	590	0.000207
35	-0.000001	325	0.001650	595	0.000200
40	-0.000001	330	0.001600	600	0.000200
45	0.000001	335	0.001450	605	0.000192
50	-0.000001	340	0.001420	610	0.000189
55	-0.000002	345	0.001320	615	0.000184
65	0.000001	350	0.001280	620	0.000184
70	0.000002	355	0.001200	625	0.000177
75	0.000000	360	0.001180	630	0.000172
80	0.000001	365	0.001120	635	0.000168
85	0.000000	370	0.001060	640	0.000160
90	0.000002	375	0.001010	645	0.000165
95	0.000002	380	0.000998	655	0.000159
100	0.000000	385	0.000920	660	0.000151
110	0.000001	390	0.000889	665	0.000151
115	0.000002	395	0.000840	670	0.000142
120	0.000002	400	0.000786	675	0.000142
135	0.000001	405	0.000754	680	0.000142
140	0.000003	410	0.000724	685	0.000134
145	0.000003	415	0.000685	690	0.000131
150	0.000012	420	0.000669	695	0.000123
155	0.000032	425	0.000633	700	0.000123
160	0.000074	430	0.000606	705	0.000127
165	0.000150	435	0.000590	710	0.000113
170	0.000276	440	0.000536	715	0.000115
180	0.000487	445	0.000542	720	0.000113
185	0.000655	450	0.000506	725	0.000106
190	0.000943	455	0.000494	730	0.000112
195	0.001180	460	0.000452	735	0.000110
205	0.001540	465	0.000429	740	0.000085
210	0.001710	470	0.000420	750	0.000085
215	0.002230	475	0.000414	760	0.000086
225	0.002340	485	0.000380	765	0.000085
230	0.002520	495	0.000361	770	0.000083
235	0.002610	505	0.000365	775	0.000078
240	0.002690	515	0.000340	780	0.000079
245	0.002680	520	0.000326	785	0.000074
250	0.002660	530	0.000315	790	0.000076
255	0.002640	535	0.000299	795	0.000077
260	0.002550	540	0.000297	800	0.000083
265	0.002510	545	0.000285	805	0.000077
270	0.002470	550	0.000279	810	0.000073
275	0.002360	555	0.000277	815	0.000044
280	0.002300	560	0.000265	820	0.000071
285	0.002180	565	0.000247	835	0.000069

APPENDIX C

Effluent gm	Activity $\mu\text{Ci} / \text{gm}$	Effluent gm	Activity $\mu\text{Ci} / \text{gm}$	Effluent gm	Activity $\mu\text{Ci} / \text{gm}$
840	0.000070	1110	0.000047	1375	0.000028
845	0.000069	1115	0.000047	1380	0.000029
850	0.000068	1120	0.000048	1385	0.000031
855	0.000069	1125	0.000046	1390	0.000030
860	0.000067	1130	0.000044	1395	0.000028
865	0.000069	1135	0.000044	1410	0.000028
870	0.000066	1140	0.000042	1415	0.000030
875	0.000060	1145	0.000043	1420	0.000027
880	0.000061	1150	0.000045	1425	0.000032
885	0.000064	1155	0.000046	1435	0.000027
890	0.000067	1165	0.000043	1440	0.000026
895	0.000062	1170	0.000039	1445	0.000030
900	0.000064	1175	0.000043	1450	0.000028
905	0.000064	1185	0.000043	1455	0.000026
910	0.000061	1190	0.000039	1460	0.000029
915	0.000060	1195	0.000040	1465	0.000029
920	0.000062	1200	0.000038	1470	0.000024
930	0.000056	1205	0.000040	1475	0.000027
940	0.000054	1210	0.000039	1480	0.000027
945	0.000057	1215	0.000044	1485	0.000024
950	0.000055	1220	0.000039	1490	0.000029
955	0.000059	1225	0.000041	1495	0.000026
960	0.000054	1230	0.000039	1500	0.000024
965	0.000054	1235	0.000040	1505	0.000028
970	0.000057	1240	0.000038	1510	0.000024
975	0.000049	1250	0.000038	1515	0.000026
980	0.000052	1255	0.000039	1520	0.000026
985	0.000051	1260	0.000039	1525	0.000027
990	0.000051	1265	0.000036	1530	0.000022
995	0.000050	1270	0.000037	1535	0.000027
1000	0.000055	1275	0.000034	1540	0.000026
1005	0.000055	1280	0.000035	1550	0.000024
1010	0.000051	1285	0.000034	1555	0.000026
1015	0.000048	1290	0.000039	1560	0.000023
1020	0.000047	1295	0.000034	1565	0.000026
1025	0.000050	1300	0.000033	1570	0.000025
1030	0.000052	1305	0.000032	1575	0.000026
1035	0.000052	1310	0.000035	1580	0.000027
1040	0.000054	1315	0.000034	1585	0.000022
1045	0.000049	1320	0.000034	1590	0.000014
1050	0.000047	1325	0.000032	1595	0.000015
1060	0.000046	1330	0.000033	1600	0.000017
1065	0.000049	1335	0.000030	1610	0.000016
1070	0.000050	1340	0.000030	1615	0.000016
1075	0.000047	1345	0.000033	1620	0.000016
1080	0.000054	1350	0.000032	1625	0.000015
1085	0.000043	1355	0.000030	1630	0.000014
1095	0.000045	1360	0.000030	1635	0.000016
1100	0.000051	1365	0.000034	1640	0.000017
1105	0.000043	1370	0.000033	1645	0.000014

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1650	0.000015	1930	0.000021
1660	0.000014	1935	0.000022
1665	0.000015	1940	0.000025
1670	0.000013	1945	0.000020
1680	0.000015	1950	0.000015
1685	0.000015	1955	0.000016
1690	0.000013	1960	0.000015
1695	0.000014	1965	0.000016
1700	0.000014	1970	0.000016
1705	0.000016	1975	0.000015
1710	0.000015	1980	0.000016
1715	0.000014	1985	0.000019
1720	0.000016	1990	0.000018
1725	0.000014	1995	0.000017
1730	0.000013	2000	0.000015
1735	0.000012	2005	0.000016
1740	0.000012	2010	0.000015
1745	0.000014	2015	0.000021
1750	0.000013	2020	0.000016
1755	0.000021	2025	0.000016
1760	0.000027	2030	0.000015
1765	0.000021	2040	0.000021
1770	0.000031	2045	0.000015
1775	0.000018	2055	0.000017
1785	0.000021	2060	0.000017
1790	0.000021	2065	0.000016
1795	0.000024	2070	0.000016
1800	0.000024	2075	0.000019
1805	0.000014	2080	0.000019
1810	0.000015	2085	0.000015
1815	0.000018	2090	0.000015
1820	0.000022	2095	0.000018
1825	0.000019	2100	0.000020
1830	0.000024	2105	0.000021
1835	0.000019	2110	0.000020
1840	0.000022	2115	0.000013
1845	0.000028	2120	0.000013
1850	0.000017	2125	0.000013
1855	0.000013	2130	0.000014
1860	0.000018	2145	0.000013
1870	0.000025	2150	0.000016
1880	0.000032	2155	0.000021
1885	0.000012	2165	0.000024
1895	0.000020	2170	0.000019
1900	0.000020	2175	0.000017
1905	0.000017	2180	0.000023
1910	0.000024	2185	0.000022
1915	0.000022	2190	0.000000
1920	0.000014		
1925	0.000020		

Table C2. Test A3, ^3H .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1.10	0.000000	220.89	0.000799	436.25	0.000145
3.92	0.000028	225.27	0.000775	440.33	0.000132
7.55	0.000040	228.91	0.000753	445.21	0.000143
12.11	0.000047	233.36	0.000713	451.24	0.000155
16.53	0.000033	237.78	0.000699	453.33	0.000118
20.92	0.000032	242.18	0.000655	455.98	0.000133
25.27	0.000034	246.38	0.000642	460.58	0.000123
29.63	0.000049	250.54	0.000626	464.32	0.000115
33.94	0.000084	254.66	0.000594	468.22	0.000122
38.24	0.000164	258.98	0.000541	472.39	0.000121
42.51	0.000344	263.00	0.000533	476.61	0.000122
46.72	0.000594	267.29	0.000523	480.78	0.000113
51.05	0.000943	272.14	0.000505	484.17	0.000106
55.35	0.001305	276.48	0.000478	487.78	0.000111
59.63	0.001744	281.11	0.000431	491.59	0.000099
64.02	0.002038	285.47	0.000425	495.65	0.000108
68.37	0.002426	289.81	0.000398	499.70	0.000104
72.65	0.002714	294.04	0.000398	503.95	0.000092
77.00	0.002920	298.21	0.000389	508.27	0.000095
84.78	0.003202	302.39	0.000384	512.42	0.000086
89.01	0.003173	305.70	0.000360	518.69	0.000103
93.20	0.003265	313.89	0.000351	519.96	0.000038
97.42	0.003252	318.21	0.000342	523.80	0.000069
101.68	0.003209	322.30	0.000334	527.92	0.000081
105.88	0.003090	326.38	0.000333	532.16	0.000072
110.04	0.002989	330.68	0.000305	536.46	0.000075
114.22	0.002854	335.07	0.000312	540.79	0.000066
118.45	0.002724	339.49	0.000283	545.12	0.000067
122.60	0.002611	343.81	0.000273	549.28	0.000066
126.94	0.002467	348.06	0.000254	553.44	0.000058
131.19	0.002416	352.29	0.000251	557.67	0.000061
135.51	0.002282	356.47	0.000249	561.63	0.000059
139.78	0.002135	360.80	0.000249	565.87	0.000053
149.09	0.001851	365.23	0.000235	571.35	0.000063
153.70	0.001738	369.84	0.000239	574.75	0.000057
157.90	0.001697	374.05	0.000218	577.85	0.000044
162.20	0.001584	378.32	0.000198	582.11	0.000036
166.60	0.001510	382.58	0.000199	585.56	0.000028
171.02	0.001446	386.97	0.000202	589.76	0.000037
175.72	0.001319	391.06	0.000187	593.88	0.000038
180.32	0.001253	395.22	0.000189	598.08	0.000044
184.73	0.001167	399.42	0.000185	602.13	0.000040
189.17	0.001090	403.58	0.000174	606.40	0.000031
193.47	0.001084	407.73	0.000180	610.20	0.000035
197.77	0.001049	412.15	0.000175	614.70	0.000038
202.65	0.000988	416.08	0.000166	618.45	0.000025
207.15	0.000940	420.03	0.000162	622.64	0.000020
211.98	0.000875	424.15	0.000156	626.80	0.000028
216.48	0.000843	428.23	0.000154	630.96	0.000023
		432.18	0.000149	635.09	0.000024

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
639.24	0.000028	838.90	0.000021
643.35	0.000026	840.39	-0.000022
647.47	0.000026		
650.35	0.000021		
654.13	0.000024		
658.15	0.000025		
662.36	0.000020		
668.64	0.000044		
670.49	0.000019		
674.65	0.000025		
678.71	0.000024		
682.84	0.000021		
687.14	0.000017		
691.22	0.000017		
695.35	0.000018		
699.59	0.000024		
705.35	0.000033		
707.15	0.000000		
710.68	0.000009		
714.64	0.000011		
718.71	0.000014		
722.69	0.000004		
726.79	0.000004		
731.07	0.000017		
734.94	0.000014		
738.52	0.000004		
742.57	0.000012		
746.69	0.000016		
750.82	0.000016		
755.04	0.000013		
759.05	0.000008		
763.10	0.000008		
766.83	0.000003		
770.63	0.000000		
774.49	-0.000005		
778.29	-0.000008		
782.24	0.000005		
785.87	0.000004		
789.68	0.000004		
793.75	0.000000		
797.64	0.000001		
802.34	0.000009		
805.31	0.000002		
809.01	0.000001		
812.96	0.000003		
816.80	-0.000004		
820.77	0.000003		
824.85	0.000000		
828.60	-0.000005		
832.55	-0.000004		

Table C3. Test A4, ²²Na.

Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm
1.82	0.000803	341.38	0.017900	593.86	0.004440
8.49	0.000681	348.05	0.015100	599.55	0.003650
17.21	0.000505	352.00	0.020400	603.25	0.005250
22.16	0.000530	355.94	0.019300	608.25	0.003990
27.42	0.000454	361.24	0.015100	614.59	0.003480
33.01	0.000405	365.92	0.016200	619.27	0.004210
38.58	0.000389	372.17	0.012400		
48.36	0.000562	381.40	0.015600		
53.96	0.002860	384.93	0.017000		
59.37	0.012100	389.20	0.014200		
64.70	0.029900	395.08	0.011000		
70.16	0.051500	398.96	0.014200		
75.43	0.081400	404.07	0.011200		
80.78	0.103000	407.85	0.013300		
86.11	0.121000	414.77	0.011000		
91.32	0.141000	425.54	0.011100		
96.41	0.155000	430.06	0.009930		
107.59	0.156000	433.74	0.011000		
124.43	0.163000	439.96	0.007670		
129.46	0.165000	442.99	0.012200		
140.57	0.147000	446.88	0.009990		
145.99	0.146000	451.60	0.008050		
151.62	0.133000	456.30	0.008310		
157.22	0.128000	468.07	0.006730		
167.54	0.111000	472.04	0.008650		
177.27	0.104000	475.18	0.010100		
183.17	0.091500	479.65	0.008030		
188.40	0.093800	485.45	0.006070		
194.20	0.078800	490.14	0.006940		
200.01	0.071400	496.05	0.005970		
205.72	0.067400	499.76	0.008020		
216.53	0.062600	504.58	0.006260		
227.16	0.058800	509.36	0.006290		
232.29	0.056100	513.07	0.007410		
244.92	0.047100	519.52	0.004870		
254.40	0.047200	523.17	0.007270		
258.94	0.044400	527.47	0.006240		
269.34	0.035700	534.40	0.004280		
273.33	0.041400	537.53	0.007170		
277.87	0.035100	542.16	0.005190		
283.07	0.030600	548.81	0.004280		
298.45	0.031600	553.57	0.005280		
303.18	0.026300	556.78	0.006620		
312.57	0.026900	560.94	0.005180		
317.02	0.025500	565.60	0.005470		
322.18	0.021100	570.40	0.004850		
326.59	0.023900	576.95	0.003940		
331.19	0.020300	581.58	0.004780		
336.26	0.018700	585.94	0.004790		
		589.41	0.005610		

Table C4. Test B1, ^3H .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
4.42	0.000002	242.80	0.000015	479.99	0.000191
6.99	0.000002	247.54	0.000019	484.86	0.000186
10.35	0.000002	252.34	0.000024	489.76	0.000184
14.24	0.000003	257.13	0.000026	494.60	0.000189
18.48	0.000002	261.90	0.000028	499.46	0.000190
22.99	0.000002	266.57	0.000032	504.33	0.000193
27.62	0.000004	271.29	0.000038	509.17	0.000203
32.36	0.000003	275.87	0.000039	513.98	0.000196
37.25	0.000002	280.44	0.000040	518.83	0.000188
42.13	0.000000	285.05	0.000052	523.57	0.000200
47.09	0.000003	289.61	0.000054	528.38	0.000205
52.09	0.000001	292.54	0.000050	533.13	0.000202
57.15	0.000001	297.17	0.000055	537.83	0.000185
62.17	0.000001	302.49	0.000064	542.65	0.000193
67.11	0.000001	307.54	0.000068	547.36	0.000194
71.98	0.000003	312.49	0.000075	552.14	0.000185
76.74	0.000001	317.44	0.000076	556.91	0.000201
86.10	0.000002	322.34	0.000094	561.78	0.000184
90.83	0.000003	327.28	0.000086	566.52	0.000193
95.59	0.000002	332.24	0.000090	571.23	0.000193
100.28	0.000001	337.21	0.000107	576.10	0.000181
105.05	0.000000	342.27	0.000100	580.87	0.000196
114.57	0.000003	347.20	0.000106	585.66	0.000194
119.42	0.000002	352.21	0.000109	590.58	0.000178
124.25	0.000003	357.09	0.000111	595.48	0.000187
129.02	0.000002	361.96	0.000127	599.72	0.000188
133.89	0.000002	366.81	0.000123	604.51	0.000179
138.57	0.000001	371.66	0.000136	609.45	0.000179
140.60	0.000001	376.46	0.000132	614.29	0.000191
145.91	0.000003	381.20	0.000144	619.19	0.000178
150.65	0.000001	385.93	0.000147	624.19	0.000173
155.38	0.000000	390.55	0.000151	629.11	0.000173
160.11	0.000002	395.19	0.000146	634.02	0.000173
164.99	0.000001	399.82	0.000154	638.96	0.000178
169.84	0.000002	404.45	0.000148	643.87	0.000173
174.70	0.000005	409.18	0.000156	648.85	0.000172
179.56	0.000000	413.82	0.000160	653.75	0.000161
184.42	0.000005	418.50	0.000163	658.66	0.000176
189.29	0.000000	423.17	0.000163	663.56	0.000171
194.23	0.000002	427.83	0.000164	668.44	0.000163
199.19	0.000003	432.48	0.000179	673.33	0.000172
204.16	0.000002	437.12	0.000184	678.15	0.000170
209.09	0.000005	441.76	0.000177	682.48	0.000171
213.94	0.000009	446.48	0.000182	687.40	0.000160
218.83	0.000008	451.22	0.000178	692.22	0.000167
223.57	0.000009	455.95	0.000190	697.08	0.000160
228.52	0.000012	460.71	0.000186	701.94	0.000152
233.26	0.000013	465.47	0.000186	706.79	0.000159
237.92	0.000015	470.29	0.000188	711.63	0.000153
		475.10	0.000196	716.47	0.000158

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
721.27	0.000158	963.79	0.000106	1201.47	0.000069
726.04	0.000158	968.31	0.000094	1206.46	0.000058
730.76	0.000156	972.84	0.000089	1211.55	0.000062
735.74	0.000155	977.33	0.000091	1216.70	0.000058
740.62	0.000149	981.84	0.000097	1221.77	0.000058
745.58	0.000143	986.44	0.000099	1226.76	0.000065
750.76	0.000141	990.96	0.000091	1231.80	0.000066
755.90	0.000145	995.55	0.000085	1236.72	0.000059
760.95	0.000145	1000.12	0.000089	1241.82	0.000059
765.88	0.000138	1004.75	0.000096	1246.47	0.000061
770.72	0.000136	1009.39	0.000090	1251.31	0.000058
775.49	0.000145	1014.12	0.000097	1256.10	0.000056
780.27	0.000143	1018.75	0.000080	1260.92	0.000057
785.05	0.000145	1022.24	0.000098	1265.83	0.000060
789.84	0.000135	1027.06	0.000087	1270.66	0.000059
794.77	0.000135	1031.78	0.000085	1275.50	0.000061
799.64	0.000136	1036.47	0.000084	1280.38	0.000053
804.53	0.000126	1041.24	0.000086	1285.26	0.000059
809.33	0.000134	1046.02	0.000079	1290.10	0.000056
814.07	0.000137	1050.91	0.000085	1294.94	0.000055
818.77	0.000121	1055.76	0.000084	1299.74	0.000053
823.51	0.000123	1060.61	0.000081	1304.54	0.000053
828.17	0.000123	1065.52	0.000079	1309.06	0.000056
832.83	0.000123	1070.50	0.000075	1313.67	0.000053
837.47	0.000121	1075.48	0.000077	1318.30	0.000054
842.18	0.000115	1080.48	0.000078	1322.84	0.000054
846.90	0.000124	1085.39	0.000073	1327.31	0.000054
851.55	0.000121	1090.29	0.000075	1331.81	0.000052
856.27	0.000123	1095.19	0.000078	1336.33	0.000056
861.01	0.000124	1100.03	0.000071	1340.94	0.000053
865.82	0.000110	1104.79	0.000069	1345.56	0.000053
870.64	0.000111	1109.55	0.000074	1350.23	0.000059
875.27	0.000123	1114.41	0.000066	1354.91	0.000057
879.96	0.000112	1119.18	0.000078	1359.51	0.000055
884.71	0.000115	1123.89	0.000077	1364.14	0.000053
889.41	0.000116	1128.67	0.000074	1368.79	0.000049
894.31	0.000109	1133.41	0.000070	1373.37	0.000050
899.21	0.000114	1138.20	0.000073	1378.00	0.000049
904.29	0.000104	1143.08	0.000065	1382.58	0.000051
909.51	0.000114	1147.88	0.000074	1387.15	0.000051
915.07	0.000107	1152.68	0.000073	1391.74	0.000049
921.02	0.000105	1157.57	0.000063	1396.34	0.000053
925.58	0.000106	1162.30	0.000069	1400.92	0.000048
930.38	0.000113	1167.03	0.000062	1405.60	0.000050
935.19	0.000107	1171.93	0.000065	1410.31	0.000047
940.03	0.000108	1176.67	0.000065	1414.97	0.000048
944.86	0.000100	1181.52	0.000063	1419.67	0.000049
949.69	0.000104	1186.49	0.000065	1424.28	0.000048
954.43	0.000099	1191.37	0.000066	1428.89	0.000046
959.15	0.000098	1196.47	0.000063	1433.50	0.000046

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1438.07	0.000047	1676.37	0.000034	1914.17	0.000025
1442.78	0.000046	1681.18	0.000032	1918.97	0.000025
1447.34	0.000050	1685.92	0.000031	1923.82	0.000025
1451.90	0.000044	1690.58	0.000035	1928.70	0.000022
1456.54	0.000046	1695.27	0.000031		
1461.22	0.000046	1699.87	0.000033		
1465.84	0.000046	1704.47	0.000031		
1470.51	0.000042	1709.17	0.000029		
1475.33	0.000044	1713.78	0.000032		
1480.03	0.000045	1718.43	0.000032		
1484.79	0.000046	1723.20	0.000031		
1489.58	0.000044	1727.87	0.000034		
1494.42	0.000041	1732.60	0.000030		
1499.16	0.000042	1737.28	0.000030		
1503.99	0.000041	1742.03	0.000032		
1508.80	0.000044	1746.68	0.000030		
1513.54	0.000044	1751.33	0.000031		
1518.35	0.000040	1756.02	0.000030		
1523.25	0.000042	1760.67	0.000029		
1528.13	0.000042	1765.45	0.000030		
1533.04	0.000044	1770.18	0.000029		
1537.87	0.000039	1774.92	0.000030		
1542.74	0.000039	1779.62	0.000029		
1547.53	0.000036	1784.43	0.000029		
1552.29	0.000040	1789.35	0.000030		
1556.94	0.000037	1794.23	0.000028		
1561.60	0.000040	1799.13	0.000028		
1566.34	0.000038	1804.07	0.000028		
1570.97	0.000038	1808.90	0.000029		
1575.67	0.000039	1813.67	0.000029		
1580.40	0.000038	1818.45	0.000030		
1585.13	0.000037	1823.23	0.000028		
1589.88	0.000038	1828.03	0.000029		
1594.60	0.000038	1832.72	0.000029		
1599.32	0.000038	1837.40	0.000027		
1604.11	0.000038	1842.15	0.000026		
1608.88	0.000035	1846.83	0.000027		
1613.54	0.000036	1851.55	0.000026		
1618.36	0.000034	1856.32	0.000027		
1623.11	0.000035	1861.07	0.000024		
1627.94	0.000031	1865.85	0.000027		
1632.68	0.000036	1870.72	0.000025		
1637.49	0.000036	1875.53	0.000026		
1642.38	0.000033	1880.38	0.000025		
1647.24	0.000035	1885.43	0.000026		
1652.08	0.000034	1890.20	0.000026		
1656.93	0.000035	1895.08	0.000025		
1661.86	0.000033	1899.90	0.000025		
1666.70	0.000032	1904.67	0.000024		
1671.58	0.000034	1909.42	0.000024		

Table C5. Test B2, ²²Na.

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
2.99	0.000050	230.66	0.002240	502.19	0.011000
6.67	0.000115	235.51	0.002390	507.01	0.010800
10.58	0.000023	240.36	0.002800	511.83	0.010800
14.94	0.000057	245.28	0.003000	516.69	0.010500
19.13	0.000026	250.07	0.003530	521.57	0.010500
23.53	0.000022	254.75	0.003820	526.37	0.010500
27.90	0.000065	268.91	0.004900	531.27	0.010400
32.47	0.000030	273.86	0.005100	536.26	0.010100
36.88	0.000027	278.86	0.005420	541.18	0.010300
41.31	0.000024	283.91	0.005680	546.15	0.010100
45.80	0.000027	288.93	0.006290	551.16	0.009800
50.21	0.000029	293.96	0.006480	556.18	0.010100
54.71	0.000027	299.05	0.006960	561.31	0.009380
59.28	0.000029	303.99	0.007150	566.45	0.009460
63.76	0.000027	308.99	0.007320	571.51	0.009150
68.32	0.000027	313.95	0.008020	576.54	0.009060
72.82	0.000025	318.82	0.008130	581.43	0.009420
77.31	0.000028	323.69	0.008490	586.24	0.009140
81.71	0.000024	328.59	0.008850	591.01	0.009440
86.32	0.000029	333.51	0.009230	595.73	0.009070
90.84	0.000020	338.49	0.009310	600.39	0.009180
95.42	0.000029	343.34	0.009590	605.07	0.009070
99.99	0.000022	348.16	0.009890	609.82	0.008940
104.70	0.000026	352.95	0.010100	614.55	0.008920
109.68	0.000027	357.69	0.010600	632.95	0.008550
114.68	0.000019	367.21	0.010700	637.65	0.008480
119.70	0.000028	372.02	0.010700	642.34	0.008240
124.63	0.000031	376.79	0.011000	647.17	0.008030
129.52	0.000053	381.60	0.011100	651.86	0.008140
134.40	0.000034	400.68	0.011400	656.62	0.007970
139.33	0.000028	405.71	0.010900	661.35	0.008130
144.26	0.000060	410.51	0.011500	666.15	0.007630
149.10	0.000183	415.35	0.011400	670.98	0.007430
153.92	0.000056	420.21	0.011800	675.77	0.007360
158.77	0.000078	425.13	0.011200	680.70	0.007270
163.59	0.000078	430.04	0.011300	685.70	0.007280
168.41	0.000100	435.08	0.011300	690.82	0.006960
173.18	0.000143	439.90	0.011300	695.86	0.007140
177.98	0.000207	444.65	0.011800	701.01	0.006720
182.85	0.000243	449.45	0.011900	706.19	0.006800
187.59	0.000356	454.21	0.011600	711.40	0.006440
192.38	0.000481	459.00	0.011800	716.62	0.006630
197.21	0.000560	463.81	0.011500	721.80	0.006090
202.01	0.000785	468.61	0.011300	727.00	0.006480
206.75	0.000953	473.45	0.011200	732.14	0.006350
211.58	0.001050	478.25	0.011300	737.27	0.006150
216.35	0.001360	483.02	0.011300	742.29	0.006450
221.14	0.001610	487.79	0.011000	747.29	0.006080
225.93	0.001860	492.66	0.010700	752.24	0.006230
		497.38	0.011100	757.15	0.006130

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
762.12	0.005740	1029.37	0.003580	1290.39	0.002080
766.97	0.006190	1033.97	0.003570	1309.86	0.001910
771.85	0.005990	1038.60	0.003440	1329.14	0.001900
776.77	0.005730	1043.30	0.003260	1348.04	0.001910
781.76	0.005680	1047.96	0.003300	1367.39	0.001950
786.66	0.005640	1052.61	0.003240	1386.49	0.001760
791.62	0.005540	1057.28	0.003230	1405.95	0.001660
807.11	0.005150	1061.92	0.003310	1425.54	0.001630
811.94	0.005570	1066.62	0.003120	1445.58	0.001440
821.05	0.005400	1071.31	0.003170	1465.53	0.001450
825.84	0.005220	1075.96	0.003110	1484.73	0.001460
830.60	0.005260	1080.58	0.003180	1504.20	0.001470
835.37	0.005210	1085.19	0.003130	1523.08	0.001420
840.21	0.005060	1089.87	0.002890	1542.28	0.001320
845.15	0.004860	1094.52	0.003080	1562.24	0.001270
850.04	0.004990	1099.28	0.003030	1582.06	0.001260
854.87	0.004810	1104.01	0.002990	1602.29	0.001230
859.97	0.004720	1108.87	0.002890	1621.40	0.001230
864.71	0.004990	1113.80	0.002790	1641.13	0.001160
869.60	0.004580	1118.56	0.002840	1660.41	0.001050
874.27	0.004870	1123.33	0.002780	1679.58	0.001120
879.07	0.004610	1128.15	0.002850		
883.88	0.004650	1133.04	0.002660		
888.62	0.004580	1137.80	0.002800		
893.31	0.004530	1142.54	0.002730		
897.98	0.004560	1147.29	0.002670		
902.77	0.004460	1152.02	0.002660		
907.64	0.004290	1156.82	0.002540		
912.47	0.004320	1161.65	0.002650		
917.32	0.004400	1169.90	0.002440		
922.10	0.004300	1174.71	0.002490		
936.03	0.004260	1179.57	0.002440		
940.63	0.004320	1184.41	0.002450		
945.27	0.004200	1189.30	0.002370		
949.98	0.003970	1194.10	0.002530		
954.51	0.004320	1198.98	0.002430		
959.33	0.004070	1203.72	0.002400		
968.29	0.004000	1208.55	0.002430		
972.86	0.003950	1213.24	0.002350		
977.55	0.003830	1218.06	0.002360		
982.25	0.003780	1222.78	0.002350		
986.95	0.003930	1227.73	0.002080		
991.64	0.003910	1232.91	0.002240		
996.40	0.003660	1237.86	0.002120		
1001.15	0.003630	1242.24	0.002280		
1005.92	0.003600	1247.02	0.002240		
1010.70	0.003590	1251.85	0.002140		
1015.46	0.003550	1256.77	0.002080		
1020.08	0.003590	1261.71	0.002060		
1024.70	0.003640	1271.21	0.002150		

Table C6. Test B3, ^{22}Na .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
6.30	0.000841	234.19	0.004381	468.26	0.008981
9.91	0.000951	238.96	0.004841	472.99	0.009191
14.23	0.000801	243.76	0.005091	477.72	0.009391
18.06	0.001071	248.65	0.005091	482.52	0.008631
22.49	0.000791	253.17	0.006191	487.30	0.009131
27.01	0.000821	257.76	0.006341	492.10	0.008651
31.35	0.000811	262.34	0.006581	496.91	0.008731
35.97	0.000741	267.04	0.006701	501.77	0.008541
40.61	0.000741	271.64	0.007121	515.78	0.008561
45.24	0.000691	276.20	0.007881	530.07	0.008001
49.95	0.000691	280.85	0.007631	544.12	0.007731
54.59	0.000731	285.48	0.007891	558.19	0.007671
59.29	0.000661	290.12	0.007991	572.62	0.007291
63.92	0.000671	294.87	0.008261	587.59	0.006931
68.61	0.000641	299.61	0.008571	601.86	0.006871
73.33	0.000637	304.28	0.008591	616.39	0.006491
78.12	0.000731	309.06	0.008761	630.86	0.006511
82.82	0.000631	313.81	0.009121	645.24	0.006251
87.57	0.000721	318.62	0.009551	659.75	0.006001
92.24	0.000649	323.39	0.009411	674.15	0.005801
97.06	0.000711	328.13	0.009581	688.58	0.005561
101.81	0.000592	332.79	0.010061	703.25	0.005271
106.49	0.000627	337.66	0.009601	717.74	0.005041
111.16	0.000671	342.18	0.010361	732.50	0.004931
115.48	0.000681	346.82	0.009861	747.25	0.004831
120.00	0.000651	351.48	0.009861	761.57	0.004541
124.56	0.000614	356.08	0.010361	775.70	0.004871
129.11	0.000681	360.67	0.010061	790.00	0.004511
133.75	0.000658	365.39	0.010061	804.46	0.004171
138.36	0.000597	369.97	0.010061	818.70	0.004051
142.99	0.000691	374.34	0.010761	833.20	0.003821
147.64	0.000731	378.75	0.010661	847.66	0.003651
152.39	0.000660	383.29	0.010761	862.54	0.003531
157.07	0.000741	387.70	0.010861	877.54	0.003791
161.79	0.000801	392.28	0.010261	892.30	0.003421
166.62	0.000851	396.99	0.010161	906.94	0.003301
171.48	0.000951	401.82	0.009861	921.39	0.003571
176.34	0.001131	406.06	0.010261	935.83	0.003091
181.14	0.001301	410.64	0.010161	949.96	0.003141
185.98	0.001511	415.43	0.009861	964.24	0.002911
190.88	0.001541	420.17	0.009661	978.52	0.002721
195.73	0.001921	424.99	0.009511	993.01	0.002641
200.91	0.002021	429.71	0.009761	1007.51	0.002501
205.46	0.002511	434.49	0.009531	1022.18	0.002551
210.27	0.002541	439.34	0.009311	1037.39	0.002391
215.05	0.002981	444.14	0.009511	1051.70	0.002391
219.83	0.003351	449.01	0.009151	1066.00	0.002381
224.66	0.003681	453.94	0.009521	1080.44	0.002291
229.60	0.003851	458.62	0.009481	1094.94	0.002111
		463.53	0.009271	1109.54	0.002161

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1124.05	0.002091	1939.67	0.000340	2893.68	0.000072
1138.16	0.002011	1958.67	0.000381	2914.32	0.000152
1152.25	0.002021	1977.53	0.000397	2933.73	0.000094
1166.94	0.001851	1997.02	0.000310	2952.52	0.000057
1181.91	0.001831	2016.60	0.000393	2971.52	0.000079
1196.59	0.001801	2036.37	0.000334	2990.35	0.000102
1210.93	0.001721	2055.63	0.000390	3009.53	0.000109
1225.29	0.001691	2074.55	0.000295	3029.63	0.000081
1239.64	0.001771	2093.58	0.000424	3049.73	0.000039
1253.84	0.001581	2107.78	0.000320	3069.23	0.000030
1268.09	0.001541	2130.07	0.000329	3088.25	0.000065
1282.33	0.001481	2149.58	0.000266	3106.93	0.000112
1296.26	0.001681	2169.47	0.000329	3125.50	0.000061
1310.41	0.001531	2189.17	0.000367	3144.42	0.000066
1324.63	0.001571	2208.37	0.000277	3164.43	0.000046
1338.61	0.001501	2227.60	0.000238	3184.28	0.000044
1352.46	0.001451	2246.48	0.000269	3202.87	0.000012
1366.26	0.001331	2264.90	0.000281	3221.17	0.000014
1380.05	0.001391	2283.78	0.000261	3240.43	0.000013
1393.73	0.001431	2302.93	0.000223	3259.02	0.000008
1407.51	0.001301	2321.83	0.000329	3277.87	0.000027
1421.54	0.001231	2340.48	0.000322	3296.17	0.000072
1435.67	0.001191	2359.37	0.000230	3315.28	0.000013
1450.13	0.001191	2378.17	0.000248	3334.08	0.000047
1464.61	0.001231	2396.65	0.000251	3352.53	0.000104
1478.90	0.001091	2415.23	0.000193	3370.42	0.000035
1493.38	0.001101	2434.33	0.000213	3388.52	0.000036
1507.35	0.001231	2453.42	0.000267	3406.62	0.000034
1521.54	0.001081	2472.57	0.000145	3425.07	0.000051
1535.42	0.001071	2492.17	0.000170	3444.38	0.000006
1554.39	0.001021	2510.20	0.000206	3463.53	-0.000014
1573.54	0.000911	2529.08	0.000282	3483.85	-0.000016
1593.35	0.000821	2548.23	0.000102	3500.80	0.000026
1612.30	0.000931	2567.42	0.000141	3519.93	-0.000018
1631.81	0.000851	2586.53	0.000143	3538.47	0.000054
1650.87	0.000881	2605.82	0.000107	3557.38	0.000005
1670.17	0.000731	2623.10	0.000147	3577.78	-0.000019
1689.32	0.000821	2642.12	0.000060	3596.68	-0.000002
1708.78	0.000721	2660.98	0.000123	3615.98	0.000009
1728.42	0.000681	2679.83	0.000075	3635.07	0.000016
1748.30	0.000671	2698.77	0.000118	3654.22	0.000007
1768.10	0.000655	2718.17	0.000085	3673.33	-0.000001
1787.23	0.000701	2738.43	0.000049	3696.92	0.000009
1806.47	0.000656	2758.63	0.000111	3711.12	0.000022
1825.58	0.000721	2778.25	0.000218	3759.82	0.000062
1851.17	0.000602	2797.45	0.000086	3783.13	-0.000031
1869.72	0.000615	2817.33	0.000104	3801.97	0.000034
1883.17	0.000446	2835.08	0.000080	3821.03	-0.000024
1902.03	0.000475	2853.47	0.000238	3840.03	0.000081
1920.78	0.000400	2872.85	0.000063	3859.02	0.000032

Effluent gm	Activity $\mu\text{Ci} / \text{gm}$	Effluent gm	Activity $\mu\text{Ci} / \text{gm}$
3882.42	0.000136	4596.55	-0.000046
3896.50	-0.000029	4611.15	-0.000014
3910.80	0.000006	4625.67	-0.000044
3929.65	0.000006	4640.08	-0.000067
3943.98	0.000007	4654.53	-0.000052
3958.18	-0.000004	4669.13	-0.000067
3972.57	0.000023		
3987.47	-0.000014		
4002.82	0.000002		
4017.97	0.000020		
4032.88	0.000135		
4047.65	0.000033		
4062.12	0.000069		
4076.53	0.000040		
4090.67	0.000068		
4104.95	0.000066		
4119.37	0.000153		
4133.80	0.000007		
4148.53	0.000051		
4163.32	0.000009		
4177.77	0.000174		
4192.17	-0.000017		
4206.57	0.000009		
4220.92	-0.000047		
4235.22	-0.000035		
4248.43	0.000030		
4261.77	0.000011		
4275.42	0.000004		
4289.58	-0.000027		
4303.62	0.000018		
4317.63	-0.000025		
4331.37	-0.000033		
4345.22	-0.000020		
4358.83	-0.000023		
4372.62	-0.000057		
4386.22	-0.000014		
4399.98	0.000000		
4414.17	-0.000017		
4429.07	-0.000059		
4438.78	-0.000034		
4453.28	-0.000027		
4467.68	-0.000014		
4481.82	-0.000024		
4495.87	-0.000041		
4505.07	0.000026		
4514.32	0.000021		
4527.97	-0.000006		
4541.93	-0.000061		
4556.83	-0.000041		
4571.85	-0.000053		

Table C7. Test B3, ²³²U.

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
6.30	0.000118	463.53	0.006130	1892.62	0.020000
14.23	0.000108	487.30	0.007180	1939.67	0.018700
22.49	0.000117	511.13	0.008310	1987.17	0.019200
31.35	0.000107	534.73	0.008950	2036.37	0.018500
40.61	0.000108	558.19	0.009700	2084.10	0.018600
49.95	0.000110	582.55	0.010800	2130.07	0.018000
59.29	0.000108	606.65	0.011800	2179.38	0.017500
68.61	0.000105	630.86	0.012900	2227.60	0.016900
78.12	0.000103	654.91	0.014000	2274.22	0.018000
87.57	0.000103	678.96	0.014300	2321.83	0.016900
97.06	0.000100	703.25	0.015200	2369.17	0.016800
106.49	0.000102	727.56	0.016000	2415.23	0.016500
115.48	0.000102	752.06	0.016100	2463.02	0.016500
124.56	0.000100	775.70	0.016400	2510.20	0.016000
133.75	0.000102	799.62	0.017200	2557.85	0.015400
142.99	0.000111	823.48	0.018000	2605.82	0.014700
152.39	0.000116	847.66	0.017900	2651.48	0.015400
161.79	0.000110	872.71	0.018500	2698.77	0.015100
171.48	0.000148	897.12	0.018800	2748.62	0.014200
181.14	0.000174	921.39	0.017500	2797.45	0.014000
190.88	0.000220	945.47	0.020000	2843.18	0.013900
200.91	0.000259	968.94	0.019000	2893.68	0.013400
210.27	0.000322	993.01	0.020200	2943.02	0.012900
219.83	0.000400	1017.28	0.020400	2990.35	0.012400
229.60	0.000466	1042.25	0.020400	3039.68	0.012700
238.96	0.000526	1066.00	0.020700	3088.25	0.011800
248.65	0.000607	1090.08	0.021300	3111.52	0.012000
257.76	0.000699	1114.33	0.020200	3134.93	0.012200
267.04	0.000753	1138.16	0.020200	3159.42	0.011700
276.20	0.000886	1162.07	0.020200	3184.28	0.011700
285.48	0.000946	1186.83	0.020200	3207.12	0.011500
294.87	0.001050	1210.93	0.020100	3230.63	0.011500
304.28	0.001160	1234.84	0.021000	3254.32	0.011600
313.81	0.001350	1258.64	0.020100	3278.02	0.011600
323.39	0.001510	1282.33	0.021100	3300.87	0.011800
332.79	0.001670	1305.70	0.021600	3324.78	0.011800
342.18	0.001880	1329.45	0.022200	3348.18	0.011400
351.48	0.001930	1352.46	0.021600	3370.53	0.011400
360.67	0.002420	1375.44	0.022500	3393.23	0.011400
369.97	0.002600	1398.42	0.021500	3415.87	0.011300
378.75	0.002950	1421.54	0.022400	3439.42	0.010800
387.70	0.003240	1469.39	0.022000	3463.43	0.010900
396.99	0.003400	1516.93	0.020900	3488.57	0.010500
406.06	0.003730	1563.92	0.021800	3510.38	0.010700
415.43	0.004010	1612.30	0.020900	3533.80	0.010300
424.99	0.004630	1660.47	0.020500	3557.23	0.010500
434.49	0.004940	1708.78	0.020300	3582.48	0.009880
444.14	0.005380	1758.18	0.020000	3606.33	0.010100
453.94	0.005940	1806.47	0.019800	3630.28	0.009790
		1851.17	0.019200	3654.08	0.009690

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
3678.05	0.009690
3701.63	0.009960
3727.83	0.010100
3759.98	0.009730
3787.83	0.009870
3806.68	0.009490
3830.48	0.009390
3854.22	0.009420
3887.13	0.009720
3901.22	0.009490
3948.73	0.009450
3997.72	0.009330
4047.65	0.009130
4095.43	0.008720
4143.62	0.008730
4192.17	0.008400
4240.72	0.008910
4284.80	0.009190
4331.37	0.008790
4377.13	0.008740
4424.13	0.008440
4467.68	0.008450
4509.60	0.008590
4551.77	0.008530
4596.55	0.008310
4644.97	0.008320
4669.13	0.008400

Table C8. Test B4, ^{22}Na .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
2.09	0.000599	212.23	0.001170	844.44	0.108000
3.72	0.000554	216.83	0.001420	872.74	0.119000
5.84	0.000463	221.41	0.001830	886.61	0.119000
8.93	0.000416	230.36	0.002530	900.39	0.121000
10.54	0.000549	241.44	0.003570	914.41	0.122000
13.26	0.000389	250.41	0.004540	928.14	0.123000
14.75	0.000571	259.76	0.005660	942.06	0.122000
18.09	0.000452	265.01	0.006460	956.19	0.121000
21.75	0.000340	274.72	0.007930	970.57	0.115000
25.52	0.000329	284.62	0.009770	984.51	0.119000
29.55	0.000361	294.58	0.011400	999.03	0.120000
33.68	0.000526	304.33	0.013400	1013.45	0.121000
38.42	0.000241	314.17	0.014600	1027.93	0.125000
43.14	0.000314	323.95	0.017600	1041.99	0.118000
46.50	0.000405	328.85	0.020000	1098.00	0.120000
50.99	0.000314	338.66	0.022400	1112.82	0.123000
55.50	0.000311	347.87	0.028400	1127.51	0.126000
60.08	0.000287	352.49	0.025900	1141.67	0.131000
64.70	0.000316	366.40	0.030300	1155.71	0.127000
69.28	0.000300	380.65	0.032800	1169.79	0.131000
73.91	0.000267	394.89	0.036800	1183.92	0.128000
78.54	0.000283	409.66	0.038800	1211.65	0.134000
83.18	0.000266	424.37	0.046400	1226.17	0.127000
87.83	0.000295	434.01	0.048400	1240.54	0.134000
92.51	0.000301	448.24	0.052900	1255.55	0.125000
97.24	0.000293	462.30	0.056500	1270.57	0.125000
101.93	0.000289	476.44	0.059200	1284.97	0.133000
106.60	0.000286	490.42	0.060100	1299.68	0.131000
111.33	0.000297	504.50	0.064300	1314.21	0.137000
116.14	0.000229	518.22	0.072400	1328.69	0.132000
120.92	0.000311	532.00	0.073800	1343.21	0.129000
125.79	0.000280	546.17	0.074400	1357.89	0.131000
130.59	0.000262	560.53	0.077700	1372.41	0.143000
135.52	0.000283	574.79	0.079200	1400.12	0.141000
140.35	0.000274	588.96	0.083600	1414.69	0.137000
145.32	0.000344	602.97	0.088500	1443.38	0.141000
150.16	0.000309	616.84	0.084200	1457.37	0.144000
155.07	0.000405	630.43	0.092300	1471.26	0.144000
160.01	0.000290	644.30	0.092800	1485.04	0.145000
164.86	0.000327	658.39	0.091600	1498.86	0.139000
169.73	0.000309	672.66	0.092900	1512.74	0.144000
174.56	0.000298	687.08	0.096300	1527.11	0.141000
179.33	0.000355	715.53	0.096400	1541.81	0.138000
184.13	0.000472	729.61	0.102000	1556.80	0.136000
188.84	0.000509	743.86	0.103000	1571.73	0.139000
193.61	0.000608	772.12	0.103000	1586.42	0.143000
198.27	0.000730	786.30	0.106000	1600.96	0.142000
202.98	0.000936	800.55	0.105000	1615.40	0.139000
207.60	0.001070	815.15	0.109000	1629.47	0.146000
		829.77	0.107000	1643.74	0.145000

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1671.57	0.147000
1686.00	0.143000
1700.67	0.138000
1729.32	0.146000
1743.68	0.146000
1813.80	0.147000
1828.38	0.145000
1843.33	0.139000
1848.22	0.143000
1858.22	0.143000
1873.33	0.142000
1883.25	0.144000
1936.62	0.151000
1946.38	0.140000
1956.33	0.141000
1966.18	0.143000
1975.83	0.142000
1985.38	0.146000
1994.83	0.148000
2004.33	0.148000
2013.73	0.145000
2050.58	0.150000
2060.17	0.146000
2079.78	0.143000
2089.73	0.139000
2099.57	0.145000
2109.23	0.144000

Table C9. Test B5, ²²Na.

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
31.44	0.009730	369.75	0.032900	1495.88	0.131000
36.03	0.009220	389.12	0.035400	1523.79	0.137000
40.50	0.009830	399.01	0.038600	1537.85	0.135000
44.96	0.009510	414.02	0.042200	1551.97	0.132000
49.51	0.009640	429.71	0.041600	1580.75	0.131000
54.21	0.009600	445.12	0.047600	1595.03	0.138000
58.90	0.009030	459.61	0.051600	1623.31	0.126000
63.73	0.009370	473.79	0.054000	1638.69	0.134000
68.63	0.009300	488.77	0.054500	1652.53	0.135000
73.34	0.009240	503.87	0.056400	1681.14	0.130000
78.11	0.009010	532.72	0.062700	1710.89	0.124000
82.86	0.008480	560.02	0.066500	1739.81	0.124000
87.65	0.009320	575.27	0.069100	1754.25	0.124000
92.22	0.009100	605.24	0.073100	1784.49	0.126000
96.75	0.008900	619.55	0.072700	1799.22	0.125000
101.36	0.008560	634.88	0.081300	1814.72	0.127000
105.93	0.008840	649.47	0.079700	1830.57	0.130000
110.61	0.008820	665.35	0.080500	1845.23	0.133000
115.32	0.008490	678.23	0.083100	1860.21	0.129000
120.19	0.008420	692.60	0.082000	1904.11	0.130000
124.93	0.008690	721.99	0.085200	1919.08	0.133000
129.79	0.008280	736.61	0.086800	1938.85	0.133000
134.76	0.008630	751.02	0.092200	1945.73	0.135000
139.76	0.008350	765.61	0.090900	1997.85	0.139000
144.93	0.007980	780.78	0.088100	2012.08	0.136000
149.89	0.008550	795.33	0.091600	2026.74	0.138000
154.50	0.009080	809.99	0.095200	2040.27	0.138000
159.57	0.008500	838.17	0.100000	2054.02	0.135000
164.37	0.008650	852.67	0.095200	2068.19	0.133000
169.17	0.008580	867.42	0.094000	2082.99	0.131000
174.20	0.008550	882.22	0.095900	2097.18	0.134000
179.05	0.008740	896.45	0.102000	2111.49	0.131000
183.75	0.008550	910.85	0.104000	2125.70	0.134000
188.44	0.008800	940.40	0.107000	2140.00	0.125000
193.65	0.008360	954.57	0.103000	2155.10	0.123000
198.71	0.008870	968.82	0.104000	2169.93	0.126000
203.93	0.008960	1027.15	0.114000	2184.59	0.124000
208.99	0.009320	1055.00	0.113000	2213.30	0.119000
214.16	0.009220	1069.73	0.114000	2243.74	0.116000
224.22	0.010500	1112.89	0.115000	2257.84	0.114000
239.10	0.011400	1127.43	0.121000	2272.66	0.107000
253.17	0.014100	1155.79	0.116000	2286.36	0.107000
267.47	0.015400	1169.54	0.124000	2301.64	0.105000
282.67	0.017000	1183.50	0.123000	2315.71	0.099500
297.28	0.019900	1227.32	0.119000	2343.92	0.097300
311.65	0.023200	1241.84	0.127000	2358.33	0.093800
325.61	0.025200	1330.52	0.127000	2388.92	0.093900
335.08	0.029400	1344.75	0.128000	2402.36	0.089500
354.85	0.030500	1374.29	0.131000	2416.54	0.090200
		1481.51	0.132000	2461.31	0.078900

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
2475.49	0.080500	3651.40	0.014200
2489.25	0.080400	3679.63	0.015700
2518.54	0.069900	3693.86	0.015100
2533.50	0.072100	3707.13	0.015300
2560.81	0.063800	3722.14	0.015000
2619.43	0.059500	3749.36	0.014500
2632.75	0.056700		
2662.95	0.052600		
2677.87	0.051400		
2735.46	0.046800		
2749.88	0.047500		
2764.27	0.046000		
2778.41	0.044000		
2793.71	0.043400		
2823.23	0.041800		
2837.49	0.041400		
2861.52	0.040900		
2875.96	0.040100		
2918.95	0.034700		
2933.87	0.035000		
3016.41	0.032100		
3030.48	0.031800		
3073.55	0.027000		
3088.87	0.026500		
3102.30	0.027700		
3146.58	0.025100		
3161.53	0.024800		
3205.81	0.025100		
3220.28	0.022700		
3234.47	0.023600		
3249.53	0.022900		
3263.38	0.023500		
3278.19	0.022200		
3307.23	0.022400		
3321.94	0.021400		
3348.75	0.020600		
3363.56	0.020100		
3390.72	0.019700		
3404.70	0.020100		
3434.51	0.019400		
3462.88	0.018900		
3520.32	0.017900		
3535.78	0.017700		
3548.97	0.018800		
3563.51	0.017600		
3578.53	0.017600		
3592.97	0.017200		
3606.69	0.016600		
3621.29	0.015500		
3635.86	0.016700		

Table C10. Test B6, ²²Na.

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
95.61	0.011100	606.75	0.010900	1562.39	0.005820
104.65	0.011200	622.27	0.010400	1604.34	0.005520
113.68	0.011200	639.01	0.010400	1619.05	0.005670
123.27	0.011200	652.38	0.009810	1634.48	0.005730
133.22	0.011700	666.13	0.010300	1648.38	0.005100
143.05	0.011600	680.67	0.010200	1661.60	0.005420
153.12	0.011200	695.72	0.010100	1675.42	0.005320
162.86	0.011500	710.66	0.009680	1704.36	0.005710
172.70	0.011100	723.58	0.009980	1718.61	0.005390
181.74	0.011200	736.69	0.009560	1732.04	0.005580
186.49	0.011700	750.52	0.009520	1746.73	0.005340
195.72	0.012200	765.58	0.008910	1761.78	0.005480
205.04	0.011800	781.44	0.008860	1776.96	0.005360
214.54	0.012300	795.32	0.008870	1804.68	0.005370
224.03	0.012300	808.53	0.008830	1819.15	0.005220
233.50	0.012700	822.60	0.008290	1904.38	0.005540
242.58	0.013100	837.88	0.008670	1917.81	0.005350
251.61	0.013400	852.91	0.008150	1932.12	0.005410
261.28	0.012900	866.85	0.007670	1946.80	0.004680
271.10	0.013300	881.34	0.008100	1961.72	0.004340
280.97	0.013600	896.13	0.008090	1976.05	0.004680
290.96	0.013600	928.38	0.007630	1990.07	0.004470
300.55	0.013400	970.76	0.008180	2003.89	0.004590
310.08	0.013100	986.78	0.007720	2018.33	0.004420
319.59	0.013400	1002.20	0.007730	2048.18	0.004430
329.19	0.013600	1029.20	0.007260	2089.76	0.004140
339.55	0.013600	1044.34	0.007400	2104.53	0.004310
349.45	0.013800	1075.75	0.007060	2120.16	0.004290
359.05	0.013200	1089.94	0.007060	2145.80	0.004210
368.42	0.013500	1115.55	0.007060	2174.78	0.004380
378.09	0.013000	1131.28	0.007090	2189.24	0.004240
387.65	0.013400	1172.83	0.006380	2204.47	0.004230
396.51	0.014000	1186.33	0.006860	2217.66	0.004100
405.72	0.013100	1201.81	0.007010	2231.91	0.004260
415.59	0.013100	1241.94	0.006660	2247.60	0.004160
426.37	0.013100	1257.04	0.006570	2262.27	0.003910
436.54	0.012800	1267.54	0.006470	2276.35	0.003960
446.98	0.013200	1282.81	0.006300	2289.60	0.003950
460.61	0.012600	1296.94	0.006030	2305.44	0.004240
465.73	0.012600	1324.98	0.006170	2319.85	0.003850
475.46	0.012700	1340.42	0.006040	2362.38	0.003810
489.92	0.012500	1369.19	0.005760	2377.58	0.003870
506.15	0.012000	1382.51	0.005910	2392.51	0.003670
520.52	0.011900	1396.66	0.005980	2433.47	0.003680
534.43	0.011800	1413.07	0.005880	2448.22	0.003650
548.62	0.011800	1429.22	0.005760	2464.09	0.003820
564.66	0.011800	1457.09	0.005780	2521.02	0.003760
578.77	0.011100	1472.71	0.005830	2534.86	0.003490
592.01	0.010900	1488.55	0.005590	2549.02	0.003520
		1531.26	0.005720	2576.30	0.003720

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Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
2591.17	0.003580	3654.33	0.002700	4664.61	0.001820
2606.46	0.003760	3668.74	0.002630	4679.04	0.001450
2621.19	0.003410	3682.33	0.002680	4694.40	0.001790
2648.93	0.003800	3709.28	0.002630	4708.89	0.001420
2663.97	0.003780	3723.95	0.002350	4723.35	0.001730
2678.48	0.003550	3738.91	0.002540	4737.15	0.001670
2719.11	0.003790	3765.51	0.002520	4752.20	0.001690
2734.50	0.003590	3779.11	0.002410	4767.18	0.001320
2750.01	0.003570	3794.44	0.002460	4781.24	0.001640
2764.15	0.003440	3809.96	0.002350	4796.28	0.001420
2792.00	0.003570	3823.50	0.002370	4810.56	0.001870
2807.83	0.003400	3881.01	0.002570	4825.95	0.001480
2823.98	0.003420	3895.10	0.002440	4841.85	0.001370
2838.07	0.003660	3908.98	0.002390	4884.46	0.001450
2865.64	0.003550	3923.58	0.002350	4899.35	0.001530
2881.28	0.003620	3952.59	0.002230	4914.19	0.001390
2897.08	0.003680	3966.77	0.002200	4929.25	0.001290
2937.66	0.003670	4010.71	0.002200	4957.05	0.001680
2952.39	0.003670	4025.87	0.002350	4971.93	0.001460
2967.44	0.003670	4039.74	0.002320	4986.07	0.001590
2982.31	0.003490	4054.46	0.002150	5000.91	0.001630
3009.76	0.003520	4068.34	0.001980	5015.46	0.001400
3025.24	0.003400	4081.89	0.002460	5025.37	0.001650
3040.58	0.003200	4096.08	0.002230	5040.71	0.001340
3096.64	0.003020	4110.02	0.002430	5054.44	0.001540
3151.32	0.002980	4178.98	0.002080	5068.78	0.001560
3166.07	0.002740	4193.52	0.002390	5078.11	0.001580
3180.26	0.002930	4208.74	0.001920	5092.03	0.001400
3219.31	0.002990	4222.87	0.002250	5119.85	0.001580
3234.52	0.002750	4236.88	0.002310	5133.56	0.001240
3249.41	0.002820	4250.92	0.002120	5174.58	0.001550
3323.37	0.002980	4265.86	0.002160	5189.05	0.001460
3351.80	0.002740	4324.14	0.001980	5202.55	0.001850
3366.81	0.002930	4338.68	0.002170	5217.09	0.001540
3383.46	0.002990	4352.83	0.001740	5231.32	0.001530
3399.32	0.002750	4366.19	0.002170	5245.81	0.001560
3424.73	0.002820	4380.36	0.002320	5260.42	0.001670
3440.57	0.002760	4395.15	0.002140	5275.12	0.001580
3456.29	0.002720	4448.55	0.001750	5288.96	0.001620
3471.18	0.002680	4461.80	0.001990	5303.23	0.001560
3498.64	0.002840	4476.26	0.002100	5318.37	0.002160
3513.68	0.002700	4491.21	0.001760	5348.19	0.001310
3527.87	0.002760	4504.89	0.002110		
3540.87	0.002950	4519.61	0.001400		
3554.35	0.002650	4548.44	0.001870		
3567.79	0.002830	4563.61	0.001430		
3582.45	0.002960	4592.70	0.002000		
3596.74	0.002750	4607.76	0.001710		
3611.11	0.002630	4622.41	0.001840		
3639.14	0.002710	4636.42	0.001560		

Table C11. Test B6, ^{232}U .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
95.61	0.000804	606.75	0.001873	1562.39	0.013281
104.65	0.000655	622.27	0.002129	1604.34	0.013604
113.68	0.000246	639.01	0.002557	1619.05	0.013854
123.27	0.001052	652.38	0.001441	1634.48	0.014199
133.22	0.001381	666.13	0.002253	1648.38	0.013631
143.05	0.001106	680.67	0.002564	1661.60	0.013333
153.12	0.001201	695.72	0.002822	1675.42	0.014530
162.86	0.001057	710.66	0.003017	1704.36	0.014978
172.70	0.000959	723.58	0.002558	1718.61	0.014609
181.74	0.000077	736.69	0.002887	1732.04	0.015195
186.49	0.001032	750.52	0.003317	1746.73	0.014635
195.72	0.001034	765.58	0.004831	1761.78	0.015819
205.04	0.001002	781.44	0.004728	1776.96	0.015927
214.54	0.001111	795.32	0.004505	1804.68	0.015397
224.03	0.001025	808.53	0.004462	1819.15	0.015945
233.50	0.000942	822.60	0.005505	1904.38	0.016164
242.58	0.000879	837.88	0.005500	1917.81	0.016034
251.61	0.001151	852.91	0.005549	1932.12	0.015895
261.28	0.001107	866.85	0.005969	1946.80	0.014200
271.10	0.001212	881.34	0.006923	1961.72	0.013823
280.97	0.001064	896.13	0.007549	1976.05	0.013501
290.96	0.001255	928.38	0.006928	1990.07	0.013588
300.55	0.000747	970.76	0.009399	2003.89	0.014252
310.08	0.001049	986.78	0.009009	2018.33	0.014355
319.59	0.001055	1002.20	0.008499	2048.18	0.013628
329.19	0.001045	1029.20	0.009571	2089.76	0.013159
339.55	0.001388	1044.34	0.010133	2104.53	0.014206
349.45	0.001316	1075.75	0.009100	2120.16	0.013920
359.05	0.000786	1089.94	0.010221	2145.80	0.014701
368.42	0.000662	1115.55	0.011337	2174.78	0.015030
378.09	0.000802	1131.28	0.010581	2189.24	0.013700
387.65	0.000943	1172.83	0.010614	2204.47	0.014044
396.51	0.000872	1186.33	0.012200	2217.66	0.014496
405.72	0.000456	1201.81	0.011895	2231.91	0.013807
415.59	0.001235	1241.94	0.012511	2247.60	0.014442
426.37	0.001372	1257.04	0.012874	2262.27	0.013988
436.54	0.001074	1267.54	0.013353	2276.35	0.012988
446.98	0.001371	1282.81	0.011870	2289.60	0.013080
460.61	0.000903	1296.94	0.011423	2305.44	0.013953
465.73	0.001094	1324.98	0.013142	2319.85	0.014364
475.46	0.001202	1340.42	0.012596	2362.38	0.012246
489.92	0.001298	1369.19	0.012940	2377.58	0.013034
506.15	0.001431	1382.51	0.013625	2392.51	0.013363
520.52	0.000752	1396.66	0.013674	2433.47	0.012723
534.43	0.000699	1413.07	0.013371	2448.22	0.012051
548.62	0.001185	1429.22	0.012344	2464.09	0.012828
564.66	0.001407	1457.09	0.013422	2521.02	0.012676
578.77	0.001273	1472.71	0.013089	2534.86	0.011722
592.01	0.000422	1488.55	0.012441	2549.02	0.011729
		1531.26	0.013348	2576.30	0.012359

APPENDIX C

Effluent gm	Activity $\mu\text{Ci} / \text{gm}$	Effluent gm	Activity $\mu\text{Ci} / \text{gm}$	Effluent gm	Activity $\mu\text{Ci} / \text{gm}$
2591.17	0.012245	3654.33	0.009800	4664.61	0.008500
2606.46	0.012163	3668.74	0.010300	4679.04	0.006060
2621.19	0.011457	3682.33	0.009600	4694.40	0.008100
2648.93	0.012961	3709.28	0.009100	4708.89	0.005960
2663.97	0.012860	3723.95	0.008800	4723.35	0.007510
2678.48	0.012773	3738.91	0.009000	4737.15	0.007190
2719.11	0.012526	3765.51	0.008900	4752.20	0.007400
2734.50	0.012136	3779.11	0.008900	4767.18	0.005100
2750.01	0.012054	3794.44	0.009400	4781.24	0.007340
2764.15	0.011438	3809.96	0.008500	4796.28	0.006570
2792.00	0.012155	3823.50	0.009000	4810.56	0.007740
2807.83	0.012540	3881.01	0.009900	4825.95	0.005890
2823.98	0.010842	3895.10	0.009100	4841.85	0.004820
2838.07	0.011382	3908.98	0.009100	4884.46	0.006550
2865.64	0.012262	3923.58	0.008800	4899.35	0.006470
2881.28	0.011970	3952.59	0.008600	4914.19	0.006190
2897.08	0.011475	3966.77	0.008900	4929.25	0.005160
2937.66	0.011373	4010.71	0.008700	4957.05	0.007360
2952.39	0.011900	4025.87	0.008600	4971.93	0.005720
2967.44	0.011633	4039.74	0.008600	4986.07	0.006310
2982.31	0.011135	4054.46	0.008100	5000.91	0.007470
3009.76	0.011100	4068.34	0.007580	5015.46	0.006150
3025.24	0.010900	4081.89	0.008900	5025.37	0.006890
3040.58	0.011700	4096.08	0.008700	5040.71	0.005880
3096.64	0.010200	4110.02	0.008600	5054.44	0.006190
3151.32	0.011100	4178.98	0.008200	5068.78	0.006450
3166.07	0.010300	4193.52	0.009000	5078.11	0.006950
3180.26	0.009300	4208.74	0.006920	5092.03	0.005430
3219.31	0.010500	4222.87	0.008100	5119.85	0.006600
3234.52	0.009800	4236.88	0.008600	5133.56	0.004960
3249.41	0.010800	4250.92	0.008100	5174.58	0.006480
3323.37	0.011100	4265.86	0.007350	5189.05	0.006240
3351.80	0.010900	4324.14	0.007540	5202.55	0.007580
3366.81	0.011700	4338.68	0.008500	5217.09	0.006840
3383.46	0.010500	4352.83	0.006760	5231.32	0.006450
3399.32	0.010200	4366.19	0.008600	5245.81	0.006470
3424.73	0.010600	4380.36	0.008300	5260.42	0.007050
3440.57	0.011100	4395.15	0.007730	5275.12	0.006340
3456.29	0.010300	4448.55	0.008300	5288.96	0.006910
3471.18	0.009300	4461.80	0.008900	5303.23	0.006470
3498.64	0.010500	4476.26	0.008400	5318.37	0.007900
3513.68	0.009800	4491.21	0.007730	5348.19	0.004690
3527.87	0.010800	4504.89	0.008800		
3540.87	0.010900	4519.61	0.006390		
3554.35	0.009800	4548.44	0.007900		
3567.79	0.010900	4563.61	0.005520		
3582.45	0.010900	4592.70	0.008300		
3596.74	0.010800	4607.76	0.007210		
3611.11	0.010400	4622.41	0.007790		
3639.14	0.010100	4636.42	0.006410		

Table C12. Test B7, ²²Na.

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
65.54	0.000220	673.98	0.005960	1430.58	0.001910
74.51	0.000180	688.36	0.005930	1444.73	0.001870
83.62	0.000150	703.09	0.005740	1458.91	0.001880
101.60	0.000170	717.11	0.005560	1473.20	0.001840
110.92	0.000160	731.48	0.005440	1500.94	0.001820
120.21	0.000360	746.21	0.005230	1515.56	0.001690
129.60	0.000420	760.39	0.005200	1529.95	0.001710
139.06	0.000590	774.99	0.004960	1544.48	0.001660
148.51	0.000790	789.39	0.004780	1558.93	0.001680
157.79	0.001160	803.95	0.004690	1573.45	0.001660
167.21	0.001590	818.41	0.004640	1588.07	0.001620
176.57	0.001960	846.50	0.004210	1601.99	0.001540
186.15	0.002580	860.88	0.004270	1616.77	0.001540
195.61	0.003150	874.86	0.004160	1630.95	0.001480
205.15	0.003640	889.58	0.004050	1645.46	0.001510
214.73	0.004010	904.10	0.003810	1660.02	0.001460
224.66	0.004700	918.33	0.003820	1674.50	0.001430
233.67	0.005130	932.86	0.003720	1703.26	0.001390
243.29	0.005510	947.45	0.003550	1732.09	0.001390
252.89	0.005950	961.69	0.003470	1746.25	0.001350
262.37	0.006390	976.12	0.003350	1760.68	0.001310
272.03	0.006650	990.84	0.003400	1789.00	0.001310
281.46	0.007370	1004.83	0.003340	1803.54	0.001310
291.19	0.007270	1019.39	0.003180	1818.13	0.001310
300.48	0.007910	1033.60	0.003110	1832.52	0.001250
310.22	0.007940	1047.49	0.003120	1847.04	0.001280
319.70	0.008310	1062.17	0.002910	1861.28	0.001220
329.13	0.008310	1076.24	0.002820	1875.89	0.001220
343.50	0.008120	1090.92	0.002890	1890.51	0.001200
372.16	0.008710	1105.36	0.002770	1904.98	0.001140
386.72	0.008910	1119.86	0.002830	1919.39	0.001150
401.02	0.009110	1134.32	0.002740	1934.17	0.001160
415.36	0.009110	1149.13	0.002600	1948.22	0.001120
429.34	0.009110	1163.39	0.002570	1962.80	0.001120
443.68	0.008910	1176.99	0.002570	1975.51	0.001150
457.60	0.008910	1191.57	0.002440	2007.67	0.001160
472.07	0.008810	1232.27	0.002300	2023.31	0.001060
486.42	0.008710	1246.67	0.002370	2107.63	0.001060
500.64	0.008510	1261.33	0.002170	2175.48	0.000990
514.99	0.008270	1276.02	0.002200	2226.53	0.001030
529.34	0.008080	1290.37	0.002240	2243.08	0.000980
543.97	0.007720	1304.23	0.002130	2310.89	0.001010
572.64	0.007500	1318.98	0.002130	2327.74	0.001000
587.27	0.007290	1333.04	0.002030	2344.59	0.001060
601.74	0.006860	1348.20	0.002060	2361.40	0.001010
616.15	0.006780	1362.81	0.001960	2428.00	0.001030
630.75	0.006680	1377.46	0.001910	2444.64	0.000960
645.26	0.006560	1391.91	0.001940	2461.31	0.001040
659.35	0.006210	1406.37	0.001940	2511.59	0.000930
		1416.14	0.001890	2648.04	0.000820

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
2768.01	0.000740	3734.61	0.000230	4435.48	0.000000
2785.02	0.000760	3748.72	0.000230	4450.20	0.000050
2807.05	0.000690	3777.43	0.000250	4450.20	0.000030
2839.28	0.000680	3791.80	0.000260	4464.74	0.000060
2855.38	0.000670	3806.15	0.000220	4464.74	0.000020
2871.68	0.000610	3820.36	0.000180	4479.09	0.000010
2888.01	0.000630	3834.91	0.000180	4479.09	0.000070
2904.00	0.000630	3849.36	0.000250	4507.87	0.000080
2920.01	0.000620	3863.67	0.000250	4507.87	0.000030
2936.20	0.000590	3877.76	0.000270	4518.92	0.000060
2966.83	0.000610	3891.96	0.000270	4518.92	0.000100
2982.80	0.000600	3906.41	0.000290	4533.31	0.000090
3015.02	0.000540	3920.98	0.000320	4533.31	0.000020
3031.31	0.000580	3935.07	0.000230	4547.48	0.000050
3046.71	0.000580	3963.02	0.000300	4547.48	0.000030
3062.43	0.000540	3977.35	0.000330	4561.93	0.000040
3078.42	0.000570	4006.15	0.000250	4576.56	0.000040
3110.04	0.000540	4020.69	0.000210	4591.07	0.000000
3126.16	0.000540	4035.17	0.000260	4605.29	0.000050
3142.24	0.000530	4049.73	0.000310	4619.63	0.000030
3158.12	0.000530	4064.14	0.000270	4634.06	0.000060
3174.04	0.000500	4078.53	0.000240		
3190.19	0.000490	4092.95	0.000190		
3206.13	0.000490	4107.38	0.000160		
3222.16	0.000490	4121.82	0.000220		
3270.42	0.000500	4136.13	0.000190		
3286.64	0.000460	4150.42	0.000160		
3302.81	0.000450	4164.90	0.000200		
3319.12	0.000460	4179.81	0.000380		
3335.39	0.000440	4193.61	0.000170		
3351.80	0.000450	4208.03	0.000120		
3368.08	0.000430	4222.29	0.000140		
3384.62	0.000410	4236.99	0.000270		
3400.77	0.000440	4251.08	0.000140		
3433.34	0.000440	4262.30	0.000160		
3449.87	0.000370	4276.72	0.000080		
3466.35	0.000350	4291.20	0.000080		
3482.91	0.000390	4305.69	0.000140		
3499.30	0.000360	4320.36	0.000080		
3515.89	0.000360	4334.63	0.000080		
3532.04	0.000350	4348.84	0.000050		
3548.65	0.000360	4363.56	0.000110		
3564.83	0.000310	4378.00	0.000020		
3581.56	0.000320	4392.49	0.000100		
3598.24	0.000360	4392.49	0.000090		
3650.44	0.000280	4406.97	0.000020		
3664.46	0.000280	4406.97	0.000050		
3678.62	0.000270	4420.86	0.000030		
3692.63	0.000200	4420.86	0.000040		
3706.77	0.000270	4435.48	0.000040		

Table C13. Test B7, ^{232}U .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
65.54	0.000270	673.98	0.001780	1430.58	0.005910
74.51	0.000350	688.36	0.002020	1444.73	0.006210
83.62	0.000400	703.09	0.002230	1458.91	0.006310
101.60	-0.000040	717.11	0.002120	1473.20	0.006310
110.92	0.000190	731.48	0.002510	1500.94	0.006010
120.21	0.000200	746.21	0.002610	1515.56	0.006210
129.60	0.000010	760.39	0.002810	1529.95	0.006210
139.06	0.000160	774.99	0.002810	1544.48	0.006110
148.51	0.000020	789.39	0.002910	1558.93	0.006210
157.79	0.000140	803.95	0.003110	1573.45	0.006410
167.21	0.000250	818.41	0.003210	1588.07	0.006310
176.57	0.000130	846.50	0.003110	1601.99	0.005610
186.15	0.000190	860.88	0.003410	1616.77	0.006210
195.61	0.000300	874.86	0.003810	1630.95	0.005610
205.15	0.000430	889.58	0.004010	1645.46	0.005910
214.73	0.000350	904.10	0.003610	1660.02	0.006010
224.66	0.000430	918.33	0.003810	1674.50	0.005810
233.67	0.000400	932.86	0.004110	1703.26	0.005510
243.29	0.000390	947.45	0.004310	1732.09	0.005810
252.89	0.000620	961.69	0.004110	1746.25	0.005510
262.37	0.000560	976.12	0.004410	1760.68	0.005710
272.03	0.000530	990.84	0.004910	1789.00	0.005510
281.46	0.000530	1004.83	0.004910	1803.54	0.005610
291.19	0.000570	1019.39	0.004810	1818.13	0.005410
300.48	0.000790	1033.60	0.004610	1832.52	0.005310
310.22	0.000550	1047.49	0.004810	1847.04	0.005410
319.70	0.000720	1062.17	0.004710	1861.28	0.005110
329.13	0.000700	1076.24	0.004910	1875.89	0.005410
343.50	0.000540	1090.92	0.005410	1890.51	0.005310
372.16	0.000610	1105.36	0.005110	1904.98	0.005110
386.72	0.000650	1119.86	0.005310	1919.39	0.005210
401.02	0.000630	1134.32	0.005510	1934.17	0.005410
415.36	0.000760	1149.13	0.005310	1948.22	0.004910
429.34	0.000770	1163.39	0.005310	1962.80	0.005110
443.68	0.000820	1176.99	0.005610	1975.51	0.005010
457.60	0.000900	1191.57	0.005510	2007.67	0.005310
472.07	0.000880	1232.27	0.005610	2023.31	0.005010
486.42	0.000950	1246.67	0.005910	2107.63	0.004910
500.64	0.000880	1261.33	0.005610	2175.48	0.004810
514.99	0.000880	1276.02	0.005810	2226.53	0.004910
529.34	0.000950	1290.37	0.005810	2243.08	0.004510
543.97	0.000880	1304.23	0.005910	2310.89	0.004410
572.64	0.001130	1318.98	0.006110	2327.74	0.004510
587.27	0.001160	1333.04	0.005710	2344.59	0.004610
601.74	0.001090	1348.20	0.006110	2361.40	0.004510
616.15	0.001220	1362.81	0.005710	2428.00	0.004510
630.75	0.001530	1377.46	0.005910	2444.64	0.004210
645.26	0.001590	1391.91	0.006010	2461.31	0.004310
659.35	0.001520	1406.37	0.006410	2511.59	0.004010
		1416.14	0.006310	2648.04	0.003910

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Effluent gm	Activity $\mu\text{Ci} / \text{gm}$	Effluent gm	Activity $\mu\text{Ci} / \text{gm}$	Effluent gm	Activity $\mu\text{Ci} / \text{gm}$
2768.01	0.003710	3734.61	0.002070	4435.48	0.000610
2785.02	0.003710	3748.72	0.001970	4450.20	0.000830
2807.05	0.003610	3777.43	0.001930	4450.20	0.000830
2839.28	0.003410	3791.80	0.002000	4464.74	0.000870
2855.38	0.003610	3806.15	0.001910	4464.74	0.000620
2871.68	0.003210	3820.36	0.001840	4479.09	0.000620
2888.01	0.003310	3834.91	0.001650	4479.09	0.000770
2904.00	0.003410	3849.36	0.001760	4507.87	0.000880
2920.01	0.003410	3863.67	0.001890	4507.87	0.000690
2936.20	0.003210	3877.76	0.001970	4518.92	0.000710
2966.83	0.003010	3891.96	0.001840	4518.92	0.000930
2982.80	0.003210	3906.41	0.001730	4533.31	0.000940
3015.02	0.002910	3920.98	0.001710	4533.31	0.000740
3031.31	0.003210	3935.07	0.001590	4547.48	0.000840
3046.71	0.003110	3963.02	0.001630	4547.48	0.000730
3062.43	0.003010	3977.35	0.001690	4561.93	0.000780
3078.42	0.003210	4006.15	0.001440	4576.56	0.000780
3110.04	0.002910	4020.69	0.001280	4591.07	0.000610
3126.16	0.002910	4035.17	0.001400	4605.29	0.000830
3142.24	0.002910	4049.73	0.001560	4619.63	0.000830
3158.12	0.003010	4064.14	0.001400	4634.06	0.000870
3174.04	0.002910	4078.53	0.001390		
3190.19	0.002810	4092.95	0.001160		
3206.13	0.002810	4107.38	0.001090		
3222.16	0.002710	4121.82	0.001310		
3270.42	0.002510	4136.13	0.001370		
3286.64	0.002710	4150.42	0.001200		
3302.81	0.002710	4164.90	0.001250		
3319.12	0.002610	4179.81	0.001210		
3335.39	0.002510	4193.61	0.001110		
3351.80	0.002610	4208.03	0.000990		
3368.08	0.002610	4222.29	0.001070		
3384.62	0.002610	4236.99	0.001130		
3400.77	0.002510	4251.08	0.001080		
3433.34	0.002250	4262.30	0.001110		
3449.87	0.002170	4276.72	0.000880		
3466.35	0.002180	4291.20	0.000810		
3482.91	0.002410	4305.69	0.000960		
3499.30	0.002410	4320.36	0.000870		
3515.89	0.002240	4334.63	0.001120		
3532.04	0.002090	4348.84	0.000830		
3548.65	0.002220	4363.56	0.000930		
3564.83	0.002050	4378.00	0.000620		
3581.56	0.001970	4392.49	0.000930		
3598.24	0.002040	4392.49	0.000940		
3650.44	0.002220	4406.97	0.000740		
3664.46	0.002200	4406.97	0.000840		
3678.62	0.002180	4420.86	0.000730		
3692.63	0.002160	4420.86	0.000780		
3706.77	0.002100	4435.48	0.000780		

Table C14. Test B8, ²²Na.

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
4.58	0.000530	261.24	0.004110	868.73	0.079900
9.65	0.000547	266.05	0.004580	883.38	0.079500
25.36	0.000528	270.91	0.004810	897.99	0.079200
29.77	0.000585	275.80	0.005380	912.72	0.080200
34.46	0.000542	280.70	0.005650	927.29	0.082500
39.25	0.000489	285.52	0.006390	941.99	0.083500
44.05	0.000533	290.25	0.007060	956.84	0.078100
48.84	0.000510	295.08	0.007230	971.12	0.083700
53.64	0.000531	299.92	0.008050	985.65	0.084600
58.44	0.000483	304.70	0.008690	1000.17	0.086300
63.32	0.000477	309.56	0.008780	1014.69	0.087900
68.23	0.000506	314.44	0.009350	1029.16	0.086400
72.99	0.000507	319.17	0.010300	1043.67	0.087600
77.62	0.000529	323.94	0.011100	1058.35	0.087200
82.46	0.000514	328.79	0.011900	1072.80	0.088700
87.31	0.000503	333.63	0.012400	1087.28	0.090100
97.41	0.000483	338.45	0.012500	1101.74	0.089100
106.36	0.000559	343.24	0.013800	1116.31	0.090400
111.24	0.000496	357.70	0.016100	1130.85	0.091000
116.04	0.000485	386.52	0.020700	1159.99	0.092300
120.91	0.000509	401.05	0.022800	1174.58	0.090900
125.80	0.000403	415.47	0.026500	1189.22	0.091700
130.80	0.000516	430.07	0.029300	1204.06	0.089400
135.58	0.000537	444.56	0.030300	1218.07	0.094600
140.54	0.000529	458.97	0.032500	1232.65	0.092200
145.30	0.000531	473.58	0.035100	1247.18	0.094900
150.15	0.000530	487.91	0.039100	1261.83	0.093800
155.01	0.000589	502.42	0.041100	1276.50	0.094900
159.79	0.000579	517.15	0.042200	1290.92	0.097700
164.62	0.000589	545.94	0.047700	1303.55	0.095200
169.58	0.000597	577.09	0.051300	1318.11	0.096600
174.36	0.000664	591.77	0.053200	1332.57	0.096100
179.28	0.000688	606.54	0.053500	1347.20	0.099600
184.32	0.000727	620.56	0.057400	1361.70	0.097100
188.84	0.000842	635.02	0.059900	1376.22	0.097700
193.80	0.000846	649.76	0.060100	1390.84	0.097000
198.55	0.000966	664.18	0.063600	1405.31	0.097600
203.37	0.001000	678.75	0.063300	1419.97	0.099800
208.32	0.001170	693.41	0.063300	1434.42	0.099900
213.06	0.001370	707.80	0.068400	1449.33	0.096600
217.97	0.001520	722.43	0.067300	1463.57	0.101000
222.81	0.001670	736.78	0.069900	1478.17	0.098800
227.68	0.001870	751.45	0.069500	1492.92	0.097500
232.52	0.002190	766.07	0.072500	1507.86	0.095700
237.30	0.002430	780.57	0.071800	1521.72	0.098700
242.08	0.002760	795.16	0.072800	1536.28	0.101000
246.88	0.002990	809.52	0.075200	1550.92	0.100000
251.70	0.003410	824.25	0.074000	1565.41	0.100000
256.58	0.003620	839.88	0.079000	1579.96	0.101000
		854.32	0.078800	1594.63	0.100000

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Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1609.13	0.103000	2434.94	0.080300	3161.58	0.022300
1623.78	0.102000	2449.48	0.078500	3176.01	0.021900
1638.35	0.105000	2463.74	0.076700	3190.12	0.021800
1652.86	0.104000	2478.28	0.074400	3204.45	0.022000
1667.44	0.102000	2492.80	0.072700	3218.92	0.021100
1682.01	0.103000	2507.34	0.067800	3233.50	0.020500
1696.64	0.102000	2521.76	0.068400	3248.00	0.020500
1711.08	0.104000	2536.28	0.066200	3262.44	0.020100
1726.08	0.099700	2550.86	0.063500	3276.81	0.019500
1739.97	0.102000	2565.35	0.061800	3291.28	0.019600
1754.63	0.104000	2580.01	0.059000	3305.96	0.019200
1768.69	0.105000	2594.52	0.057500	3320.42	0.018300
1783.33	0.102000	2608.90	0.055700	3334.79	0.018500
1797.94	0.105000	2623.39	0.054100	3349.25	0.018000
1812.63	0.103000	2638.09	0.052000	3363.83	0.017600
1827.06	0.107000	2652.64	0.051400	3378.41	0.017300
1841.75	0.103000	2667.11	0.049900	3393.03	0.017300
1856.42	0.102000	2681.62	0.047900	3407.71	0.016400
1871.06	0.103000	2696.25	0.047200	3422.24	0.016000
1885.80	0.106000	2710.81	0.046500	3436.71	0.016200
1900.24	0.105000	2725.40	0.044500	3451.46	0.015700
1914.82	0.104000	2739.92	0.044100	3466.14	0.015500
1929.31	0.107000	2754.75	0.041000		
1943.84	0.105000	2769.53	0.041100		
1958.44	0.108000	2784.01	0.040100		
1982.64	0.107000	2798.31	0.039900		
2028.65	0.108000	2812.75	0.038900		
2042.87	0.105000	2827.54	0.035700		
2057.15	0.109000	2841.78	0.036500		
2071.47	0.107000	2856.29	0.036500		
2085.97	0.105000	2870.70	0.033600		
2100.54	0.104000	2885.16	0.034400		
2115.12	0.107000	2899.62	0.034500		
2129.68	0.106000	2914.42	0.031900		
2144.30	0.106000	2928.84	0.031900		
2159.04	0.106000	2943.55	0.031000		
2173.67	0.107000	2958.18	0.029300		
2217.03	0.104000	2972.91	0.029300		
2231.76	0.105000	2987.46	0.029300		
2246.24	0.103000	3002.43	0.028000		
2260.86	0.104000	3016.24	0.027700		
2289.98	0.102000	3030.75	0.027100		
2304.77	0.098400	3045.44	0.026000		
2318.87	0.102000	3059.93	0.026200		
2333.39	0.096700	3074.44	0.025800		
2347.92	0.095100	3088.95	0.025300		
2362.25	0.092600	3103.55	0.024600		
2377.01	0.088200	3118.12	0.024100		
2391.67	0.086900	3132.74	0.023400		
2405.99	0.085000	3147.49	0.022300		

Table C15. Test C1, ^3H .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
3.65	0.000007	245.63	0.005260	492.01	0.001770
9.43	0.000005	250.27	0.005190	497.09	0.001760
14.83	0.000010	255.10	0.004930	502.14	0.001710
20.23	0.000014	259.90	0.004920	507.16	0.001640
25.35	0.000508	265.10	0.004810	512.22	0.001650
30.11	0.009010	270.32	0.004630	517.08	0.001600
34.94	0.038900	275.48	0.004440	522.58	0.001540
40.11	0.079700	280.57	0.004260	528.18	0.001490
45.33	0.128000	285.67	0.003920	533.82	0.001450
50.60	0.155000	290.82	0.003800	539.58	0.001420
55.73	0.168000	295.78	0.003690	545.25	0.001410
60.12	0.186000	300.61	0.003540	550.94	0.001360
65.26	0.151000	305.73	0.003260	555.89	0.001340
70.46	0.122000	310.33	0.003110	560.84	0.001320
75.81	0.092900	315.13	0.003100	565.86	0.001280
81.07	0.074800	320.29	0.002950	570.88	0.001300
85.93	0.062300	325.29	0.002920	576.03	0.001190
90.61	0.053600	330.36	0.002820	581.21	0.001140
95.47	0.045300	334.96	0.002830	586.27	0.001020
100.66	0.038700	339.86	0.002760	591.27	0.001030
105.86	0.032700	344.91	0.002710	596.91	0.001140
110.52	0.025100	349.71	0.002650	602.37	0.001350
115.22	0.021700	354.71	0.002440	607.80	0.001330
119.94	0.019100	359.38	0.002510	613.28	0.001240
124.74	0.017500	364.38	0.002500	618.72	0.001090
129.62	0.016000	369.50	0.002520	624.16	0.001050
134.75	0.014900	374.55	0.002500	629.72	0.001050
139.94	0.013600	379.32	0.002410	635.22	0.001040
145.15	0.012400	384.52	0.002250	640.82	0.001050
148.21	0.011500	389.55	0.002250	646.34	0.001020
153.30	0.011000	394.67	0.002170	651.96	0.000995
158.45	0.010600	399.30	0.002130	657.50	0.000964
163.37	0.010100	404.08	0.002010	663.04	0.000978
168.57	0.009540	409.06	0.002010	668.69	0.000952
173.77	0.009290	414.18	0.001930	673.76	0.000949
178.89	0.008790	418.78	0.002350	678.76	0.000920
183.66	0.008440	423.46	0.002290	683.73	0.000922
188.41	0.008160	428.29	0.002220	688.81	0.000850
190.78	0.007560	433.21	0.002070	693.91	0.000824
195.87	0.007660	437.84	0.001920	698.91	0.000838
201.11	0.007250	442.50	0.001780	703.91	0.000846
206.25	0.006900	447.72	0.001690	709.01	0.000833
210.88	0.006610	452.49	0.001810	714.01	0.000856
215.95	0.006410	457.52	0.001900	719.04	0.000823
221.15	0.006070	462.53	0.001880	724.04	0.000820
226.40	0.005810	467.57	0.001860	729.07	0.000783
231.42	0.005700	472.47	0.001820	734.12	0.000798
236.12	0.005530	477.57	0.001790	739.16	0.000804
240.84	0.005510	482.64	0.001760	744.22	0.000800
		487.36	0.001780	749.28	0.000775

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
754.34	0.000781
759.42	0.000752
764.50	0.000738
769.56	0.000733
774.66	0.000712
779.86	0.000717
784.97	0.000706
790.05	0.000728
795.14	0.000682
800.34	0.000679
805.56	0.000665
810.69	0.000680
815.78	0.000682
820.88	0.000665
825.99	0.000656
831.03	0.000679
836.16	0.000647
841.26	0.000625

Table C16. Test C1, ²²Na.

Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm
3.65	0.000007	245.63	0.000016	492.01	0.000009
9.43	0.000004	250.27	0.000016	497.09	0.000010
14.83	0.000005	255.10	0.000015	502.14	0.000008
20.23	0.000005	259.90	0.000015	507.16	0.000009
25.35	0.000008	265.10	0.000015	512.22	0.000008
30.11	0.000036	270.32	0.000014	517.08	0.000009
34.94	0.000312	275.48	0.000014	522.58	0.000007
40.11	0.000578	280.57	0.000012	528.18	0.000008
45.33	0.000922	285.67	0.000013	533.82	0.000007
50.60	0.001060	290.82	0.000013	539.58	0.000007
55.73	0.001090	295.78	0.000014	545.25	0.000008
60.12	0.001220	300.61	0.000014	550.94	0.000007
65.26	0.000923	305.73	0.000011	555.89	0.000008
70.46	0.000695	310.33	0.000011	560.84	0.000008
75.81	0.000532	315.13	0.000011	565.86	0.000008
81.07	0.000431	320.29	0.000010	570.88	0.000007
85.93	0.000366	325.29	0.000010	576.03	0.000008
90.61	0.000309	330.36	0.000010	581.21	0.000008
95.47	0.000266	334.96	0.000012	586.27	0.000007
100.66	0.000229	339.86	0.000012	591.27	0.000006
105.86	0.000185	344.91	0.000010	596.91	0.000007
110.52	0.000056	349.71	0.000011	602.37	0.000008
115.22	0.000048	354.71	0.000010	607.80	0.000008
119.94	0.000044	359.38	0.000010	613.28	0.000006
124.74	0.000041	364.38	0.000010	618.72	0.000007
129.62	0.000039	369.50	0.000009	624.16	0.000008
134.75	0.000034	374.55	0.000011	629.72	0.000011
139.94	0.000031	379.32	0.000009	635.22	0.000011
145.15	0.000029	384.52	0.000008	640.82	0.000008
148.21	0.000034	389.55	0.000010	646.34	0.000007
153.30	0.000027	394.67	0.000010	651.96	0.000007
158.45	0.000026	399.30	0.000009	657.50	0.000007
163.37	0.000025	404.08	0.000010	663.04	0.000006
168.57	0.000025	409.06	0.000009	668.69	0.000007
173.77	0.000024	414.18	0.000008	673.76	0.000007
178.89	0.000023	418.78	0.000011	678.76	0.000006
183.66	0.000024	423.46	0.000014	683.73	0.000007
188.41	0.000023	428.29	0.000014	688.81	0.000008
190.78	0.000029	433.21	0.000010	693.91	0.000008
195.87	0.000021	437.84	0.000014	698.91	0.000008
201.11	0.000018	442.50	0.000012	703.91	0.000007
206.25	0.000019	447.72	0.000007	709.01	0.000007
210.88	0.000019	452.49	0.000010	714.01	0.000006
215.95	0.000017	457.52	0.000009	719.04	0.000007
221.15	0.000017	462.53	0.000010	724.04	0.000007
226.40	0.000017	467.57	0.000008	729.07	0.000006
231.42	0.000017	472.47	0.000009	734.12	0.000007
236.12	0.000018	477.57	0.000009	739.16	0.000007
240.84	0.000018	482.64	0.000009	744.22	0.000007
		487.36	0.000010	749.28	0.000007

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
754.34	0.000007
759.42	0.000006
764.50	0.000006
769.56	0.000007
774.66	0.000006
779.86	0.000007
784.97	0.000008
790.05	0.000007
795.14	0.000007
800.34	0.000008
805.56	0.000007
810.69	0.000007
815.78	0.000008
820.88	0.000006
825.99	0.000006
831.03	0.000006
836.16	0.000008
841.26	0.000007

Table C17. Test C2, ^{22}Na .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
2.41	0.001700	234.56	0.002750	477.86	0.000939
5.33	0.001760	239.33	0.002570	503.61	0.000662
8.65	0.004190	244.25	0.002510	508.80	0.000688
12.95	0.011200	249.06	0.002610	513.98	0.000648
17.81	0.026200	253.90	0.002050	519.13	0.000692
22.81	0.034100	258.65	0.002250	524.29	0.000668
27.64	0.040300	263.48	0.002070	529.31	0.000658
32.37	0.043300	268.33	0.002130	534.32	0.000661
37.25	0.041600	273.11	0.002000	539.19	0.000646
41.96	0.039600	277.89	0.001780	544.12	0.000568
46.65	0.039400	282.79	0.001700	549.09	0.000618
51.31	0.037800	287.58	0.001760	553.87	0.000579
55.99	0.034700	292.30	0.001700	558.82	0.000617
60.61	0.031000	297.10	0.001640	563.82	0.000553
65.22	0.028500	301.92	0.001650	568.62	0.000617
69.90	0.024800	306.72	0.001620	573.44	0.000557
74.56	0.022300	311.58	0.001560	578.22	0.000546
79.13	0.020300	316.44	0.001500	583.00	0.000546
83.72	0.018600	321.21	0.001460	587.86	0.000565
88.54	0.015800	326.01	0.001450	592.74	0.000590
93.24	0.014100	330.94	0.001410	597.53	0.000601
97.87	0.012300	335.92	0.001230	602.37	0.000581
102.49	0.012200	340.90	0.001290	607.19	0.000541
107.02	0.011100	345.84	0.001280	612.09	0.000576
111.62	0.010100	350.94	0.001180	616.97	0.000562
116.15	0.008590	356.15	0.001240	621.86	0.000620
120.77	0.007940	361.28	0.001080	626.61	0.000598
125.35	0.007560	366.37	0.001210	631.44	0.000702
130.29	0.006880	371.60	0.001090	636.32	0.000578
135.31	0.006170	376.76	0.001080	640.92	0.000626
140.31	0.005660	381.85	0.001210	645.73	0.000562
145.39	0.005300	386.85	0.001070	650.59	0.000583
150.48	0.005070	391.71	0.000974	655.35	0.000596
155.63	0.004770	396.60	0.001100	660.14	0.000576
160.68	0.004660	401.43	0.001050	664.99	0.000546
165.70	0.004350	406.14	0.001110	669.84	0.000496
170.63	0.004080	410.79	0.000952	674.66	0.000496
175.58	0.003880	415.64	0.001430	679.58	0.000525
180.53	0.003940	420.42	0.000984	684.58	0.000504
185.47	0.003690	425.38	0.000953	689.46	0.000502
190.32	0.003940	430.19	0.000934	694.36	0.000458
195.27	0.003400	438.43	0.000992	699.34	0.000454
200.23	0.003460	443.24	0.000907	704.39	0.000484
205.20	0.003000	448.01	0.001010	709.23	0.000491
210.11	0.003230	452.89	0.000890	714.28	0.000493
215.10	0.002940	457.81	0.000956	719.18	0.000425
220.00	0.003020	457.81	0.000956	724.01	0.000433
224.91	0.002510	462.71	0.000890	728.76	0.000447
229.76	0.002730	467.74	0.000960	733.71	0.000437
		472.85	0.000850	738.63	0.000499

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
743.49	0.000389
748.42	0.000416
753.40	0.000417
758.43	0.000402
763.33	0.000415
768.22	0.000397
773.17	0.000414
778.09	0.000424
782.98	0.000349
787.89	0.000556
792.75	0.000348

Table C18. Test C2, ^{232}U .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
0.00	0.002860	964.48	0.004720	2046.57	0.001920
12.95	0.005450	984.34	0.004390	2085.02	0.001830
32.37	0.006270	1004.33	0.004430	2104.43	0.001830
51.31	0.006900	1024.13	0.004110	2122.63	0.001800
69.90	0.007930	1043.79	0.004210	2139.25	0.001800
88.54	0.009540	1063.37	0.003800	2156.67	0.001690
107.02	0.009800	1083.46	0.003840	2192.17	0.001650
125.35	0.011000	1103.45	0.003510	2209.93	0.001640
145.39	0.011400	1123.36	0.003310	2227.35	0.001590
165.70	0.011700	1143.36	0.003040	2244.93	0.001610
185.47	0.011500	1164.12	0.003520	2262.25	0.001560
205.20	0.011600	1184.21	0.003290	2279.53	0.001550
224.91	0.011400	1204.73	0.003100	2296.70	0.001500
244.25	0.011900	1224.95	0.002990	2313.77	0.001710
263.48	0.011400	1283.16	0.002890	2331.07	0.001660
282.79	0.012100	1303.18	0.002990	2348.53	0.001680
301.92	0.012100	1323.71	0.002900	2361.77	0.001670
321.21	0.012000	1343.69	0.002880	2379.62	0.001670
340.90	0.011800	1363.30	0.002860	2396.93	0.001730
361.28	0.011300	1382.33	0.002780	2415.55	0.001640
381.85	0.011300	1402.20	0.002730	2430.62	0.001630
401.43	0.011300	1421.74	0.002870	2447.63	0.001580
420.42	0.011100	1441.56	0.002680	2464.63	0.001550
438.43	0.010900	1461.31	0.002650	2481.85	0.001520
457.81	0.010600	1481.30	0.002530	2499.63	0.001500
477.86	0.010100	1500.78	0.002580	2517.52	0.001470
498.49	0.009440	1520.65	0.002360	2535.52	0.001500
519.13	0.009220	1539.96	0.002380	2553.50	0.001460
539.19	0.008750	1559.54	0.002280	2571.12	0.001400
558.82	0.008160	1579.23	0.002200	2589.02	0.001410
578.22	0.008020	1598.99	0.002180	2606.75	0.001390
597.53	0.007440	1619.00	0.002140	2624.53	0.001410
616.97	0.007560	1644.47	0.001800	2642.68	0.001410
636.32	0.007290	1663.70	0.002320	2662.17	0.001420
655.35	0.007030	1676.27	0.002130	2681.47	0.001380
674.66	0.006520	1679.77	0.002490	2700.22	0.001360
694.36	0.005860	1732.32	0.002330	2719.10	0.001310
714.28	0.005800	1751.23	0.002160	2738.07	0.001290
733.71	0.005280	1770.03	0.002190	2757.08	0.001240
753.40	0.005130	1788.85	0.002090	2775.98	0.001260
773.17	0.004900	1807.72	0.002040	2794.60	0.001220
792.75	0.004690	1826.42	0.002030	2808.48	0.001220
812.62	0.004580	1845.13	0.002010	2825.68	0.001220
832.66	0.004250	1863.77	0.001970	2844.12	0.001190
852.62	0.004310	1882.30	0.001980	2862.20	0.001170
869.38	0.004970	1901.17	0.001920	2879.98	0.001150
907.10	0.004490	1920.35	0.001830	2897.63	0.001110
926.61	0.004970	1939.48	0.002010	2915.72	0.001110
945.41	0.005080	1992.15	0.001970	2932.48	0.001130
		2011.22	0.001980	2951.17	0.001130

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
2969.98	0.001150
2988.22	0.001180
3006.38	0.001180
3024.95	0.001150
3043.12	0.001210
3061.98	0.001180
3080.88	0.001180
3099.88	0.001170
3118.98	0.001160
3137.50	0.001140
3156.47	0.001120
3172.58	0.000000

Table C19. Test C3, ^{22}Na .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
0.00	0.000473	299.13	0.002170	847.65	0.000419
10.27	0.002190	303.90	0.002210	866.77	0.000398
16.21	0.010700	308.63	0.002040	884.95	0.000394
21.41	0.024900	313.32	0.001980	901.53	0.000419
25.87	0.041400	318.02	0.001990	920.43	0.000392
45.40	0.048200	322.68	0.002010	939.51	0.000436
50.17	0.045600	327.51	0.001750	958.59	0.000465
54.89	0.043000	332.47	0.001730	977.44	0.000461
59.59	0.038300	337.28	0.001670	996.80	0.000605
64.35	0.034200	342.11	0.001680	1036.33	0.000768
68.97	0.030900	346.97	0.001660	1056.44	0.000468
73.42	0.027900	357.22	0.001460	1075.70	0.000568
77.88	0.025000	362.15	0.001540	1095.57	0.000553
82.26	0.022000	367.24	0.001490	1115.18	0.000545
86.71	0.020200	372.40	0.001410	1134.86	0.000497
96.52	0.017900	377.35	0.001470	1153.76	0.000449
101.02	0.015200	382.43	0.001270	1172.78	0.000401
110.72	0.013800	387.53	0.001100	1191.97	0.000379
115.32	0.011900	392.57	0.001250	1210.81	0.000375
119.89	0.010300	397.58	0.001160	1230.34	0.000357
124.49	0.009490	402.50	0.001190	1249.64	0.000348
134.22	0.008710	407.44	0.001140	1269.15	0.000368
138.88	0.007890	412.18	0.001140	1288.54	0.000439
148.75	0.007690	416.79	0.001130	1307.59	0.000463
153.38	0.006710	421.51	0.001070	1327.67	0.000525
162.98	0.005870	426.22	0.001170	1365.78	0.000452
167.75	0.005780	430.99	0.001040	1384.58	0.000510
172.63	0.005480	435.77	0.001170	1403.70	0.000430
177.51	0.005470	440.54	0.001430	1423.21	0.000412
182.33	0.005360	444.33	0.001180	1442.23	0.000409
187.30	0.004760	448.48	0.001080	1461.62	0.000407
192.24	0.004700	453.14	0.001020	1481.52	0.000402
197.10	0.004700	457.79	0.000905	1491.95	0.000420
201.87	0.004440	462.54	0.001030	1511.19	0.000438
206.78	0.004210	467.23	0.001020	1531.39	0.000431
211.74	0.004180	481.78	0.000868	1549.74	0.000452
216.90	0.003840	501.08	0.000818	1569.02	0.000464
227.02	0.003550	520.54	0.000794	1588.16	0.000426
232.02	0.003620	560.28	0.000688	1607.12	0.000419
242.23	0.003370	578.70	0.000656	1627.66	0.000457
247.06	0.003320	597.47	0.000605	1647.02	0.000497
251.83	0.003110	616.50	0.000579	1666.27	0.000513
256.33	0.003280	656.43	0.000562	1684.37	0.000527
265.54	0.003080	676.03	0.000548	1702.57	0.000517
270.27	0.002820	714.74	0.000520	1720.57	0.000519
274.95	0.002810	733.59	0.000513	1739.12	0.000498
279.76	0.002540	752.20	0.000485	1757.53	0.000506
284.43	0.002480	790.74	0.000447	1776.33	0.000501
294.33	0.002400	809.56	0.000437	1795.37	0.000544
		828.26	0.000424		

Table C20. Test C4, ²²Na.

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
3.34	0.000360	268.63	0.009660	520.44	0.002560
11.49	0.000329	273.26	0.008880	524.93	0.002360
21.15	0.000628	283.00	0.008660	529.58	0.002230
25.88	0.009140	287.63	0.008490	534.25	0.002260
30.84	0.060200	297.34	0.008040	539.06	0.002150
35.76	0.111000	301.96	0.007620	543.77	0.002220
40.72	0.143000	306.56	0.007270	548.40	0.002120
45.72	0.155000	311.32	0.007130	553.05	0.001940
50.87	0.127000	315.89	0.006990	557.64	0.001950
55.96	0.107000	320.49	0.006560	562.32	0.001890
61.05	0.090600	325.10	0.006340	566.89	0.002060
66.25	0.078400	329.88	0.005940	571.54	0.001900
71.27	0.072000	334.49	0.005750	576.17	0.001840
76.34	0.065700	339.19	0.005860	580.83	0.001770
81.22	0.060800	343.89	0.005380	585.53	0.001860
86.06	0.052600	348.60	0.005310	590.18	0.001650
90.88	0.046200	353.47	0.005330	594.81	0.001750
95.53	0.042500	363.35	0.004920	599.53	0.001660
100.02	0.038300	368.21	0.004680	604.06	0.001640
104.56	0.034000	373.08	0.004570	608.56	0.001680
109.15	0.030900	378.04	0.004320	613.27	0.001630
113.79	0.028000	382.96	0.004270	617.93	0.001560
118.39	0.026300	387.85	0.004040	622.51	0.001470
123.03	0.024900	392.77	0.003810	627.21	0.001600
127.65	0.023500	397.72	0.003790	631.99	0.001550
132.36	0.022300	402.64	0.003620	636.74	0.001530
137.09	0.020700	407.44	0.003680	641.61	0.001300
141.77	0.021300	412.25	0.003530	646.37	0.001400
146.46	0.020200	416.97	0.003620	650.94	0.001450
151.09	0.019200	421.70	0.003200	655.77	0.001310
155.90	0.018500	426.46	0.003130	660.48	0.001460
160.91	0.017500	431.19	0.003240	665.48	0.001290
166.04	0.016900	435.50	0.003200	670.26	0.001350
171.10	0.015800	438.98	0.003990	674.73	0.001280
176.26	0.015500	443.24	0.003340	679.72	0.001290
181.44	0.014900	453.09	0.003160	684.37	0.001290
186.29	0.015800	457.68	0.003080	688.94	0.001270
191.23	0.014600	462.39	0.002860	693.86	0.001250
201.25	0.013900	467.11	0.002700	698.52	0.001310
211.23	0.013700	471.78	0.002730	703.02	0.001340
216.07	0.013500	476.41	0.002580	707.57	0.001260
220.93	0.012600	481.14	0.002540	712.12	0.001230
225.72	0.012200	485.90	0.002480	716.61	0.001440
230.54	0.011700	490.68	0.002340	721.22	0.001200
240.22	0.011600	495.56	0.002240	724.86	0.002050
244.93	0.011300	500.51	0.002170	729.65	0.001150
254.82	0.010900	505.39	0.002290	734.14	0.001250
259.45	0.010400	509.99	0.002260	738.83	0.001110
264.04	0.009380	514.02	0.002580	743.35	0.001080
		516.12	0.004060	748.04	0.001080

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
752.71	0.001120	1133.50	0.000602	2145.72	0.000332
757.39	0.001160	1152.41	0.000572	2164.27	0.000287
762.10	0.001080	1170.60	0.000747	2197.32	0.000312
766.87	0.001100	1189.02	0.000530	2216.47	0.000282
771.53	0.001060	1208.11	0.000576	2235.62	0.000271
775.78	0.001130	1226.65	0.000554	2251.58	0.000331
780.56	0.001080	1245.80	0.000520	2271.27	0.000310
785.63	0.001010	1265.09	0.000496	2290.55	0.000288
790.68	0.001020	1279.38	0.000501	2309.32	0.000296
795.69	0.000992	1299.40	0.000444	2328.13	0.000291
800.72	0.000966	1318.00	0.000464	2345.02	0.000485
805.81	0.000976	1336.52	0.000843	2364.03	0.000353
810.77	0.000896	1355.21	0.000454	2391.33	0.000339
815.68	0.000856	1374.65	0.000449	2410.90	0.000277
820.54	0.000949	1393.57	0.000416	2429.67	0.000308
824.94	0.001050	1412.81	0.000465	2448.28	0.000270
830.00	0.000961	1437.00	0.000460	2466.68	0.000262
834.83	0.000918	1456.84	0.000431	2485.13	0.000272
839.43	0.000912	1481.21	0.000480	2503.85	0.000251
844.00	0.001010	1499.25	0.000488	2522.98	0.000247
848.76	0.001020	1514.82	0.000630	2541.92	0.000277
853.44	0.000893	1542.00	0.000446	2560.48	0.000263
858.21	0.000826	1560.33	0.000429	2578.38	0.000257
863.03	0.000897	1583.99	0.000429	2596.38	0.000249
867.79	0.000937	1608.42	0.000413	2614.48	0.000235
882.81	0.000930	1627.65	0.000392	2633.02	0.000272
887.52	0.000875	1651.78	0.000383	2651.43	0.000269
897.48	0.000819	1669.97	0.000423	2670.20	0.000272
902.34	0.000983	1688.40	0.000379	2688.87	0.000229
907.01	0.000829	1706.97	0.000383	2707.48	0.000237
910.20	0.001090	1725.58	0.000362	2723.70	0.000227
914.93	0.000899	1744.83	0.000347	2742.05	0.000361
919.59	0.000909	1764.18	0.000325	2760.75	0.000240
929.28	0.000883	1783.63	0.000301	2779.47	0.000208
933.88	0.000985	1803.10	0.000326	2798.03	0.000245
938.68	0.000830	1821.82	0.000346	2817.17	0.000225
943.36	0.000857	1859.40	0.000351	2836.73	0.000233
948.10	0.000783	1878.27	0.000386	2855.12	0.000322
952.85	0.000834	1902.93	0.000293	2874.00	0.000216
957.66	0.000875	1922.23	0.000315	2892.75	0.000203
962.39	0.000793	1939.97	0.000487	2911.65	0.000231
972.23	0.000766	1958.87	0.000320	2930.18	0.000374
992.83	0.000773	1983.22	0.000333	2947.72	0.000192
1007.22	0.000748	2002.43	0.000310	2965.62	0.000245
1025.38	0.000725	2021.23	0.000302	2984.60	0.000267
1043.93	0.000665	2050.95	0.000315	3003.33	0.000235
1062.27	0.000643	2069.97	0.000315	3022.22	0.000220
1080.25	0.000861	2088.92	0.000322	3041.02	0.000227
1095.26	0.000675	2108.02	0.000325	3059.98	0.000182
1114.04	0.000649	2126.50	0.000281	3079.15	0.000157

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
3098.33	0.000276	4035.57	0.000162
3117.82	0.000159	4051.87	0.000157
3136.87	0.000171	4070.87	0.000135
3155.07	0.000160	4090.03	0.000258
3173.88	0.000199	4109.02	0.000140
3192.97	0.000174	4127.87	0.000175
3211.70	0.000170	4146.38	0.000167
3230.38	0.000157	4165.30	0.000133
3249.78	0.000155	4184.12	0.000153
3269.28	0.000167	4202.93	0.000154
3285.82	0.000269	4222.38	0.000161
3304.53	0.000250	4241.92	0.000150
3323.52	0.000189	4260.73	0.000438
3342.25	0.000161	4279.62	0.000160
3361.15	0.000166	4298.08	0.000158
3380.43	0.000167	4316.78	0.000146
3399.47	0.000170	4335.73	0.000178
3418.90	0.000155	4354.38	0.000096
3437.73	0.000151	4369.68	0.000170
3456.83	0.000171	4387.92	0.000141
3475.83	0.000165	4406.18	0.000106
3494.67	0.000145	4424.18	0.000101
3513.75	0.000178	4441.82	0.000101
3532.25	0.000185	4459.73	0.000113
3550.78	0.000185	4477.88	0.000109
3569.22	0.000184	4495.92	0.000112
3587.62	0.000166	4510.18	0.000130
3606.02	0.000168	4528.30	0.000108
3624.38	0.000217	4546.17	0.000118
3642.82	0.000184	4564.53	0.000096
3661.57	0.000183	4582.47	0.000108
3676.38	0.000198	4600.72	0.000113
3695.28	0.000162	4619.12	0.000117
3713.88	0.000205	4637.60	0.000102
3732.63	0.000168	4656.18	0.000098
3751.30	0.000138	4674.82	0.000099
3770.08	0.000172	4693.45	0.000115
3788.98	0.000178	4711.87	0.000134
3807.77	0.000172	4730.13	0.000118
3826.78	0.000173	4748.68	0.000103
3845.72	0.000162	4767.38	0.000120
3864.53	0.000159	4786.03	0.000096
3883.62	0.000155	4805.02	0.000092
3902.55	0.000136	4824.07	0.000102
3921.43	0.000143	4842.73	0.000132
3940.60	0.000147	4861.50	0.000098
3959.47	0.000155	4875.67	0.000091
3978.88	0.000153		
3997.53	0.000347		
4016.48	0.000151		

Table C21. Test C5, ²²Na.

Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm
6.24	0.008200	543.27	0.000675	873.86	0.000346
15.69	0.018600	554.27	0.000592	879.46	0.000383
25.42	0.037800	565.48	0.000653	884.85	0.000366
34.87	0.055200	576.51	0.000637	890.27	0.000429
44.39	0.046900	587.40	0.000611	895.83	0.000377
54.04	0.033500	598.45	0.000593	901.31	0.000354
63.96	0.022900	609.56	0.000557	906.79	0.000385
74.23	0.015200	620.60	0.000599	912.30	0.000371
84.54	0.010900	631.86	0.000436	917.86	0.000411
95.15	0.008230	643.36	0.000516	923.40	0.000370
106.30	0.006150	649.11	0.000485	928.87	0.000347
117.66	0.005000	654.79	0.000465	934.40	0.000354
129.22	0.004420	660.45	0.000502	939.95	0.000426
140.84	0.004100	666.10	0.000449	945.55	0.000340
152.36	0.003610	671.67	0.000457	951.18	0.000356
163.74	0.003080	677.43	0.000504	956.74	0.000359
174.81	0.003110	682.98	0.000482	961.06	0.000436
185.86	0.002570	688.66	0.000469	969.68	0.000470
196.82	0.002340	694.42	0.000493	974.71	0.000393
207.61	0.002250	699.94	0.000553	980.16	0.000451
218.42	0.001980	705.37	0.000454	985.61	0.000431
229.44	0.001970	710.68	0.000443	991.10	0.000394
240.35	0.001690	716.15	0.000529	996.63	0.000497
251.22	0.001580	721.64	0.000463	1002.13	0.000494
262.28	0.001320	727.25	0.000423	1007.56	0.000401
272.82	0.001420	732.78	0.000471	1013.06	0.000410
283.61	0.001370	738.24	0.000424	1018.59	0.000421
294.35	0.001270	743.70	0.000475	1024.10	0.000440
305.20	0.001180	749.25	0.000398	1029.51	0.000476
315.96	0.001230	754.60	0.000460	1035.03	0.000443
326.86	0.001230	760.05	0.000412	1040.53	0.000382
337.54	0.000990	765.46	0.000449	1046.02	0.000405
348.43	0.000870	770.95	0.000406	1051.56	0.000393
366.70	0.000833	776.49	0.000442	1057.24	0.000366
377.42	0.000868	781.97	0.000403	1062.71	0.000436
388.17	0.000883	787.60	0.000473	1068.20	0.000368
399.08	0.000816	793.24	0.000391	1073.80	0.000421
410.08	0.000777	798.26	0.000459	1079.30	0.000362
420.91	0.000747	802.61	0.000452	1084.77	0.000317
431.73	0.000675	807.62	0.000398	1090.29	0.000357
442.63	0.000732	818.52	0.000422	1095.83	0.000424
453.88	0.000703	824.15	0.000767	1101.36	0.000338
465.18	0.000704	829.79	0.000411	1106.97	0.000360
476.54	0.000631	835.26	0.000414	1112.74	0.000396
487.87	0.000584	840.83	0.000358	1118.34	0.000395
499.04	0.000707	846.33	0.000492	1123.84	0.000361
510.24	0.000648	851.93	0.000889	1129.36	0.000389
521.29	0.000569	857.37	0.000395	1135.29	0.000332
532.26	0.000602	862.93	0.000376	1140.72	0.000344
		868.37	0.000415	1146.22	0.000374

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1151.77	0.000369	1423.51	0.000329	1708.57	0.000261
1157.18	0.000365	1429.03	0.000332	1714.33	0.000194
1162.90	0.000378	1434.61	0.000340	1719.77	0.000257
1168.43	0.000359	1440.24	0.000370	1725.38	0.000235
1173.91	0.000373	1446.01	0.000354	1730.82	0.000230
1179.45	0.000365	1451.42	0.000401	1736.22	0.000250
1185.21	0.000355	1457.21	0.000335	1741.72	0.000254
1190.53	0.000363	1463.00	0.000346	1747.17	0.000249
1195.96	0.000333	1468.68	0.000301	1752.68	0.000249
1201.43	0.000311	1474.25	0.000365	1758.15	0.000247
1206.97	0.000334	1479.82	0.000383	1763.53	0.000250
1212.37	0.000353	1485.49	0.000350	1768.63	0.000254
1217.89	0.000364	1490.82	0.000364	1774.30	0.000258
1223.33	0.000314	1496.19	0.000364	1779.83	0.000308
1228.76	0.000376	1501.60	0.000337	1785.28	0.000297
1234.20	0.000381	1506.99	0.000349	1790.82	0.000259
1239.52	0.000369	1512.26	0.000359	1796.62	0.000268
1245.19	0.000307	1517.51	0.000367	1802.52	0.000253
1250.74	0.000319	1522.85	0.000297	1808.32	0.000279
1256.43	0.000342	1528.21	0.000343	1814.12	0.000256
1262.16	0.000321	1533.45	0.000390	1819.68	0.000257
1267.91	0.000341	1538.86	0.000342	1825.37	0.000302
1273.74	0.000445	1544.00	0.000351	1831.07	0.000238
1279.52	0.000325	1549.34	0.000326	1836.57	0.000265
1285.29	0.000370	1554.66	0.000372	1842.17	0.000200
1291.17	0.000348	1560.02	0.000316	1847.73	0.000252
1296.91	0.000483	1565.44	0.000385	1849.15	0.000595
1302.70	0.000391	1570.68	0.000363	1854.08	0.000290
1308.45	0.000361	1575.98	0.000321	1859.55	0.000251
1314.57	0.000330	1581.43	0.000295	1864.97	0.000000
1319.90	0.000369	1586.79	0.000333	1870.52	0.000257
1325.59	0.000333	1592.29	0.000319	1876.00	0.000278
1331.17	0.000338	1597.78	0.000306	1882.03	0.000239
1336.58	0.000360	1603.27	0.000390	1887.40	0.000254
1341.77	0.000432	1614.69	0.000271	1893.05	0.000234
1347.17	0.000313	1626.08	0.000258	1898.62	0.000240
1352.49	0.000334	1631.67	0.000357	1904.07	0.000303
1357.76	0.000450	1637.25	0.000349	1909.57	0.000279
1363.21	0.000340	1642.70	0.000325	1915.08	0.000240
1368.58	0.000379	1648.19	0.000358	1920.57	0.000321
1373.94	0.000344	1653.69	0.000326	1926.12	0.000264
1379.23	0.000285	1658.69	0.000337	1931.50	0.000322
1384.61	0.000337	1664.26	0.000315	1937.02	0.000240
1389.96	0.000325	1669.75	0.000460	1943.43	0.000156
1395.34	0.000331	1675.33	0.000290	1948.15	0.000292
1400.74	0.000328	1680.85	0.000335	1954.07	0.000211
1404.84	0.000364	1686.47	0.000307	1959.53	0.000231
1408.05	0.000480	1691.92	0.000248	1968.07	0.000209
1412.75	0.000383	1697.52	0.000294	1973.72	0.000239
1417.91	0.000375	1702.98	0.000255	1979.30	0.000242

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Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1985.27	0.000194	2260.33	0.000305	2512.50	0.000000
1990.33	0.000225	2266.08	0.000209	2517.42	0.000245
1995.80	0.000233	2271.82	0.000210	2522.25	0.000474
2001.18	0.000271	2277.17	0.000242	2527.10	0.000238
2006.85	0.000244	2282.58	0.000229	2531.93	0.000260
2012.47	0.000284	2288.43	0.000265	2536.93	0.000202
2018.13	0.000231	2294.02	0.000277	2541.78	0.000216
2023.63	0.000229	2298.77	0.000356	2546.58	0.000243
2029.17	0.000226	2303.42	0.000232	2551.40	0.000240
2034.77	0.000231	2307.68	0.000293	2556.32	0.000232
2040.32	0.000229	2312.57	0.000238	2561.12	0.000211
2045.78	0.000198	2317.25	0.000251	2565.85	0.000230
2051.27	0.000256	2321.92	0.000304	2570.77	0.000226
2056.82	0.000277	2327.88	0.000231	2575.40	0.000364
2062.43	0.000243	2333.95	0.000250	2580.20	0.000267
2067.97	0.000241	2339.98	0.000220	2584.80	0.000234
2073.47	0.000232	2345.87	0.000253	2589.65	0.000254
2078.92	0.000000	2351.65	0.000274	2594.27	0.000298
2084.57	0.000181	2357.13	0.000235	2599.07	0.000209
2090.08	0.000222	2362.52	0.000216	2603.88	0.000261
2095.63	0.000216	2367.78	0.000221	2608.48	0.000264
2101.22	0.000237	2372.92	0.000251	2613.43	0.000219
2106.58	0.000203	2378.10	0.000222	2618.05	0.000262
2112.43	0.000236	2383.17	0.000263	2622.47	0.000234
2118.32	0.000215	2388.33	0.000244	2627.27	0.000227
2123.37	0.000254	2393.42	0.000247	2631.92	0.000235
2129.63	0.000192	2398.43	0.000231	2636.62	0.000262
2135.27	0.000226	2403.57	0.000279	2641.27	0.000256
2140.72	0.000251	2408.53	0.000239	2645.92	0.000232
2146.53	0.000251	2413.73	0.000241	2650.78	0.000275
2151.30	0.000306	2418.68	0.000226	2655.28	0.000232
2157.12	0.000208	2423.78	0.000253	2660.05	0.000213
2162.43	0.000218	2428.77	0.000219	2664.77	0.000270
2167.85	0.000241	2433.65	0.000232	2669.40	0.000231
2173.20	0.000210	2438.67	0.000235	2674.08	0.000222
2178.55	0.000220	2443.72	0.000286	2678.57	0.000245
2183.78	0.000262	2448.72	0.000241	2683.08	0.000261
2189.23	0.000246	2453.77	0.000262	2687.88	0.000337
2194.67	0.000223	2458.70	0.000359	2690.13	0.000411
2200.08	0.000231	2463.68	0.000239	2692.35	0.000401
2205.42	0.000239	2468.53	0.000264	2696.72	0.000299
2210.98	0.000202	2473.43	0.000221	2701.23	0.000242
2216.50	0.000220	2478.28	0.000209	2705.82	0.000267
2221.65	0.000234	2483.15	0.000395	2710.38	0.000260
2227.25	0.000215	2488.02	0.000207	2715.05	0.000275
2232.68	0.000202	2492.88	0.000274	2724.63	0.000289
2238.13	0.000224	2497.67	0.000273	2729.42	0.000303
2243.72	0.000218	2502.63	0.000223	2734.33	0.000369
2249.15	0.000284	2507.53	0.000246	2739.12	0.000286
2254.73	0.000243	2512.50	0.000235	2744.00	0.000284

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
2748.72	0.000258
2753.48	0.000267
2758.18	0.000256
2762.92	0.000243
2767.57	0.000278
2772.30	0.000248
2777.03	0.000274
2781.63	0.000274
2786.57	0.000231
2800.33	0.000176
2819.43	0.000179
2838.42	0.000141
2857.28	0.000163
2876.47	0.000152
2895.98	0.000179
2915.27	0.000166
2934.32	0.000165
2953.37	0.000183
2972.48	0.000178
2991.43	0.000162
3010.78	0.000137
3030.07	0.000165
3049.32	0.000174
3068.48	0.000172
3084.88	0.000192
3103.98	0.000183

Table C22. Test C5, ²³⁹Np.

Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm
6.24	0.000000	543.27	0.012200	873.86	0.007550
15.69	0.000487	554.27	0.012300	879.46	0.007140
25.42	0.000774	565.48	0.011600	884.85	0.007740
34.87	0.001310	576.51	0.011700	890.27	0.007090
44.39	0.002880	587.40	0.011800	895.83	0.006890
54.04	0.004910	598.45	0.011300	901.31	0.007390
63.96	0.006000	609.56	0.010500	906.79	0.007120
74.23	0.006550	620.60	0.010500	912.30	0.006900
84.54	0.007490	631.86	0.010500	917.86	0.006540
95.15	0.007300	643.36	0.010800	923.40	0.006980
106.30	0.007040	649.11	0.010200	928.57	0.006360
117.66	0.006940	654.79	0.010500	934.40	0.006590
129.22	0.007990	660.45	0.010700	939.95	0.006270
140.84	0.009610	666.10	0.009940	945.55	0.006580
152.36	0.009740	671.67	0.010800	951.18	0.006270
163.74	0.010400	677.43	0.010400	956.74	0.006280
174.81	0.011100	682.98	0.010300	961.06	0.007510
185.86	0.012100	688.66	0.010300	969.68	0.006640
196.82	0.012900	694.42	0.009600	974.71	0.006600
207.61	0.014700	699.94	0.009780	980.16	0.006390
218.42	0.015300	705.37	0.010400	985.61	0.006500
229.44	0.014800	710.68	0.010300	991.10	0.006270
240.35	0.015000	716.15	0.009290	996.63	0.006280
251.22	0.017100	721.64	0.009600		
262.28	0.016300	727.25	0.009420		
272.82	0.017300	732.78	0.009790		
283.61	0.016500	738.24	0.009610		
294.35	0.017300	743.70	0.010100		
305.20	0.017800	749.25	0.008730		
315.96	0.016800	754.60	0.010200		
326.86	0.017200	760.05	0.009150		
337.54	0.017200	765.46	0.009120		
348.43	0.016200	770.95	0.009160		
366.70	0.017000	776.49	0.009040		
377.42	0.014900	781.97	0.009060		
388.17	0.016100	787.60	0.008330		
399.08	0.015400	793.24	0.008680		
410.08	0.015500	798.26	0.009610		
420.91	0.015200	802.61	0.010200		
431.73	0.015100	807.62	0.009520		
442.63	0.015000	818.52	0.008520		
453.88	0.014000	824.15	0.008130		
465.18	0.013800	829.79	0.008200		
476.54	0.012800	835.26	0.008080		
487.87	0.013700	840.83	0.008280		
499.04	0.013100	846.33	0.007660		
510.24	0.013200	851.93	0.007770		
521.29	0.012800	857.37	0.007920		
532.26	0.012600	862.93	0.007620		
		868.37	0.007570		

Table C23. Test C6 ²²Na.

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
0.01	0.000206	238.19	0.001990	476.26	0.000749
4.60	0.000374	243.00	0.002040	481.35	0.000717
9.25	0.001640	247.79	0.001910	486.38	0.000825
14.12	0.019500	252.54	0.001900	490.86	0.000779
19.06	0.040000	257.37	0.001740	495.91	0.000786
24.23	0.063800	262.26	0.001750	500.84	0.000671
29.23	0.075000	266.90	0.001810	505.70	0.000758
34.29	0.078000	271.47	0.001710	510.56	0.000811
39.25	0.071600	276.06	0.001660	515.26	0.000851
44.26	0.058400	280.73	0.001670	519.55	0.000801
49.28	0.048600	285.32	0.001550	524.38	0.000732
54.13	0.038200	290.08	0.001530	529.22	0.000681
58.99	0.029500	294.84	0.001480	534.11	0.000745
63.87	0.024600	299.65	0.001460	539.00	0.000692
68.65	0.019300	304.47	0.001460	543.86	0.000800
73.45	0.016600	309.37	0.001370	548.29	0.000648
78.16	0.013800	314.20	0.001330	562.54	0.000805
82.94	0.012000	319.12	0.001270	577.06	0.000659
87.65	0.010400	324.03	0.001140	591.06	0.000748
92.37	0.009480	329.06	0.001270	604.95	0.000828
97.18	0.008060	333.66	0.001270	618.98	0.000629
102.07	0.007680	338.29	0.001220	633.65	0.001120
106.80	0.006990	343.06	0.001240	647.41	0.000496
111.61	0.006460	347.78	0.001330	662.51	0.000541
116.52	0.006330	352.50	0.001210	676.06	0.000595
121.41	0.006010	357.29	0.001170	690.63	0.000472
126.26	0.005730	361.97	0.001130	704.90	0.000592
131.01	0.005260	366.76	0.001050	718.85	0.000539
135.97	0.005040	371.56	0.001210	733.28	0.000465
140.77	0.004510	376.34	0.001100	747.46	0.000484
145.81	0.004540	381.15	0.001140	762.24	0.000573
150.60	0.004430	385.92	0.001180	776.46	0.000501
155.47	0.004180	390.16	0.001220	788.97	0.000485
160.44	0.003890	394.21	0.001070	803.61	0.000508
165.40	0.003530	398.61	0.001140	818.18	0.000453
170.43	0.003500	403.22	0.001080	832.53	0.000605
175.39	0.003260	407.91	0.001110	846.71	0.000400
180.47	0.003320	412.68	0.001010	860.79	0.000404
185.33	0.003060	417.37	0.000924	874.54	0.000497
190.32	0.002830	422.26	0.001020	888.73	0.000441
195.33	0.002830	426.98	0.001470	903.64	0.000597
200.05	0.002620	431.72	0.001040	917.45	0.000414
204.87	0.002810	436.58	0.000916	933.47	0.000457
209.66	0.002590	441.40	0.000936	947.74	0.000369
214.43	0.002590	446.34	0.000902	962.52	0.000457
219.14	0.002410	451.25	0.000882	976.93	0.000391
223.97	0.002320	456.20	0.000840	991.26	0.000454
228.78	0.002170	461.24	0.000923	1005.45	0.000385
233.52	0.002140	466.35	0.000805	1019.65	0.000402
		471.22	0.000924	1033.87	0.000387

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1048.76	0.000348	1852.28	0.000473
1063.40	0.000410	1866.70	0.000291
1078.65	0.000327	1881.08	0.000328
1093.67	0.000344	1895.57	0.000363
1108.29	0.000315	1910.32	0.000383
1122.63	0.000284	1924.48	0.000500
1136.97	0.000246	1938.82	0.000480
1151.26	0.000407	1953.15	0.000253
1155.85	0.000412	1967.47	0.000255
1181.83	0.000391	1981.87	0.000442
1196.15	0.000414		
1210.33	0.000371		
1224.82	0.000343		
1238.95	0.000336		
1252.90	0.000467		
1266.16	0.000434		
1279.81	0.000303		
1294.13	0.000288		
1307.88	0.000346		
1321.95	0.000313		
1336.34	0.000303		
1351.32	0.000386		
1366.23	0.000408		
1394.67	0.000298		
1409.03	0.000312		
1436.26	0.000299		
1449.87	0.000315		
1464.28	0.000312		
1477.44	0.000310		
1491.87	0.000299		
1506.60	0.000296		
1520.95	0.000262		
1535.32	0.000284		
1561.03	0.000318		
1575.10	0.000387		
1588.78	0.000295		
1603.09	0.000352		
1617.66	0.000315		
1646.48	0.000523		
1661.19	0.000262		
1675.67	0.000313		
1690.15	0.000244		
1704.63	0.000218		
1718.95	0.000317		
1758.27	0.000284		
1784.58	0.000277		
1794.18	0.000284		
1808.68	0.000402		
1823.18	0.000272		
1837.83	0.000306		

Table C24. Test C6, ²³⁹Np.

Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm
0.01	0.000000	238.19	0.000387	476.26	0.009570
4.60	0.000000	243.00	0.000483	481.35	0.009780
9.25	0.000000	247.79	0.000513	486.38	0.010800
14.12	0.000000	252.54	0.000497	490.86	0.010500
19.06	0.000261	257.37	0.000567	495.91	0.011000
24.23	0.000000	262.26	0.000688	500.84	0.010700
29.23	0.000000	266.90	0.000822	505.70	0.011000
34.29	0.000000	271.47	0.000948	510.56	0.011500
39.25	0.000373	276.06	0.001000	515.26	0.013300
44.26	0.000000	280.73	0.001030	519.55	0.012300
49.28	0.000275	285.32	0.001030	524.38	0.012500
54.13	0.000331	290.08	0.001120	529.22	0.013000
58.99	0.000000	294.84	0.001260	534.11	0.013400
63.87	0.000000	299.65	0.001400	539.00	0.013800
68.65	0.000313	304.47	0.001520	543.86	0.014400
73.45	0.000248	309.37	0.001630	548.29	0.014300
78.16	0.000345	314.20	0.001520	562.54	0.014100
82.94	0.000231	319.12	0.001940	577.06	0.015600
87.65	0.000196	324.03	0.001860	591.06	0.016600
92.37	0.000299	329.06	0.002180	604.95	0.021500
97.18	0.000220	333.66	0.002190	618.98	0.018600
102.07	0.000266	338.29	0.002430	633.65	0.019300
106.80	0.000215	343.06	0.002800	647.41	0.017700
111.61	0.000200	347.78	0.002680	662.51	0.019900
116.52	0.000292	352.50	0.002970	676.06	0.020100
121.41	0.000247	357.29	0.003090	690.63	0.021300
126.26	0.000251	361.97	0.003410	704.90	0.025500
131.01	0.000000	366.76	0.003760	718.85	0.022500
135.97	0.000220	371.56	0.003770	733.28	0.023700
140.77	0.000255	376.34	0.004140	747.46	0.024100
145.81	0.000203	381.15	0.004090	762.24	0.029300
150.60	0.000205	385.92	0.005000	776.46	0.026100
155.47	0.000221	390.16	0.004770	788.97	0.028700
160.44	0.000212	394.21	0.004860	803.61	0.028700
165.40	0.000192	398.61	0.005310	818.18	0.031200
170.43	0.000189	403.22	0.005660	832.53	0.030400
175.39	0.000240	407.91	0.005720	846.71	0.029900
180.47	0.000181	412.68	0.005940	860.79	0.029700
185.33	0.000225	417.37	0.005830	874.54	0.033100
190.32	0.000230	422.26	0.006730	888.73	0.029100
195.33	0.000237	426.98	0.006610	903.64	0.031400
200.05	0.000197	431.72	0.006850	917.45	0.032200
204.87	0.000273	436.58	0.007490	933.47	0.037600
209.66	0.000272	441.40	0.007360	947.74	0.038200
214.43	0.000279	446.34	0.008090	962.52	0.037700
219.14	0.000304	451.25	0.008190	976.93	0.037700
223.97	0.000288	456.20	0.008680	991.26	0.039500
228.78	0.000372	461.24	0.008810	1005.45	0.037700
233.52	0.000348	466.35	0.009310	1019.65	0.040000
		471.22	0.009270	1033.87	0.038600

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1048.76	0.039300	1852.28	0.023600
1063.40	0.039300	1866.70	0.021900
1078.65	0.040300	1881.08	0.023900
1093.67	0.041000	1895.57	0.023600
1108.29	0.040000	1910.32	0.022600
1122.63	0.041900	1924.48	0.020100
1136.97	0.039600	1938.82	0.023100
1151.26	0.037600	1953.15	0.021600
1155.85	0.035200	1967.47	0.023100
1181.83	0.032500	1981.87	0.020500
1196.15	0.034100		
1210.33	0.035600		
1224.82	0.033300		
1238.95	0.036100		
1252.90	0.034400		
1266.16	0.037300		
1279.81	0.031800		
1294.13	0.031300		
1307.88	0.034900		
1321.95	0.032600		
1336.34	0.033000		
1351.32	0.033200		
1366.23	0.034900		
1394.67	0.031500		
1409.03	0.031400		
1436.26	0.031200		
1449.87	0.028300		
1464.28	0.029200		
1477.44	0.031300		
1491.87	0.028900		
1506.60	0.031100		
1520.95	0.027200		
1535.32	0.028500		
1561.03	0.028900		
1575.10	0.027100		
1588.78	0.026800		
1603.09	0.029100		
1617.66	0.029900		
1646.48	0.025100		
1661.19	0.028300		
1675.67	0.026900		
1690.15	0.023700		
1704.63	0.024400		
1718.95	0.024300		
1758.27	0.025000		
1784.58	0.022100		
1794.18	0.023000		
1808.68	0.023300		
1823.18	0.021600		
1837.83	0.022900		

Table C25. Test C7, ²²Na.

Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm
6.99	0.000330	272.28	0.002890	793.64	0.000694
11.70	0.000552	277.31	0.002880	804.36	0.000714
16.74	0.011200	282.28	0.002850	815.70	0.000650
21.84	0.040700	287.42	0.002610	827.08	0.000594
26.87	0.073800	292.07	0.002650	838.43	0.000608
32.14	0.101000	307.57	0.002290	850.51	0.000622
37.41	0.109000	318.69	0.002000	861.91	0.000621
42.59	0.104000	329.76	0.001990	871.97	0.000554
47.56	0.091800	341.21	0.001810	881.58	0.000633
52.63	0.075100	352.75	0.001670	892.23	0.000599
57.64	0.060900	363.95	0.001800	902.37	0.000653
62.61	0.051900	375.64	0.001450	913.08	0.000559
67.59	0.044000	387.10	0.001600	923.68	0.000640
72.40	0.037000	397.13	0.001590	934.41	0.000652
77.29	0.032100	408.20	0.001440	939.78	0.000600
82.31	0.027600	419.00	0.001330	950.41	0.000581
87.27	0.023900	428.42	0.001540	961.26	0.000581
92.18	0.020800	437.72	0.001260	977.46	0.000466
97.17	0.017600	447.71	0.001160	993.91	0.000458
102.39	0.015600	457.77	0.001250	1010.86	0.000483
117.22	0.012500	468.23	0.001010		
122.02	0.011700	479.19	0.001030		
126.98	0.010600	490.87	0.001020		
131.97	0.010100	502.59	0.000964		
136.90	0.009240	513.59	0.001070		
142.21	0.007950	524.89	0.001010		
147.66	0.006960	536.47	0.000980		
153.17	0.006930	547.46	0.001030		
158.59	0.006520	558.61	0.000962		
164.25	0.005790	569.42	0.000937		
170.09	0.005220	580.01	0.000868		
175.56	0.005420	590.51	0.001010		
181.14	0.005080	600.83	0.000903		
187.01	0.004700	610.98	0.000858		
192.68	0.004690	621.27	0.000821		
198.50	0.004410	626.41	0.000916		
204.39	0.004030	636.56	0.000916		
210.00	0.004030	647.22	0.000866		
215.45	0.004170	658.48	0.000841		
220.73	0.004180	670.19	0.000741		
226.32	0.003680	681.29	0.000814		
231.60	0.003750	687.02	0.000765		
236.63	0.003870	697.46	0.000821		
241.60	0.003560	708.23	0.000789		
246.75	0.003660	719.22	0.000762		
252.00	0.003280	729.92	0.000733		
257.10	0.003250	740.44	0.000759		
262.11	0.003050	751.30	0.000726		
267.14	0.003100	761.76	0.000723		
		783.06	0.000695		

Table C26. Test C7, ²³⁹Np.

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
6.99	0.000000	272.28	0.001060	793.64	0.008500
11.70	0.000000	277.31	0.001120	804.36	0.008510
16.74	0.000000	282.28	0.001190	815.70	0.008530
21.84	0.000000	287.42	0.001250	827.08	0.008470
26.87	0.000000	292.07	0.001300	838.43	0.010500
32.14	0.000000	307.57	0.000919	850.51	0.010200
37.41	0.000000	318.69	0.003270	861.91	0.008570
42.59	0.000000	329.76	0.004210	871.97	0.008930
47.56	0.000000	341.21	0.003060	881.58	0.009060
52.63	0.000000	352.75	0.003230	892.23	0.009280
57.64	0.000000	363.95	0.004400	902.37	0.011000
62.61	0.000000	375.64	0.004370	913.08	0.010300
67.59	0.000290	387.10	0.003550	923.68	0.010300
72.40	0.000247	397.13	0.003170	934.41	0.009040
77.29	0.000297	408.20	0.002990	939.78	0.009860
82.31	0.000277	419.00	0.003160	950.41	0.009580
87.27	0.000331	428.42	0.004190	961.26	0.010200
92.18	0.001130	437.72	0.004000	977.46	0.008710
97.17	0.002470	447.71	0.004340	993.91	0.009260
102.39	0.003910	457.77	0.004000	1010.86	0.009450
117.22	0.010300	468.23	0.004130	1027.87	0.008790
122.02	0.009810	479.19	0.004610	1043.67	0.010700
126.98	0.006390	490.87	0.004590	1060.25	0.009480
131.97	0.005310	502.59	0.004880	1075.76	0.010800
136.90	0.004910	513.59	0.005870	1091.79	0.011600
142.21	0.005880	524.89	0.005530	1107.61	0.011300
147.66	0.009010	536.47	0.008030	1123.99	0.009220
153.17	0.010200	547.46	0.006670	1134.60	0.011500
158.59	0.010800	558.61	0.006080	1151.16	0.010500
164.25	0.011800	569.42	0.006580	1168.07	0.010000
170.09	0.013200	580.01	0.006820	1233.72	0.011700
175.56	0.013500	590.51	0.006780	1249.53	0.010300
181.14	0.004840	600.83	0.006880	1282.11	0.010600
187.01	0.003870	610.98	0.007130	1327.12	0.011800
192.68	0.003470	621.27	0.007080	1343.59	0.010700
198.50	0.003400	626.41	0.007140	1360.15	0.011100
204.39	0.003680	636.56	0.007070	1392.95	0.009430
210.00	0.004070	647.22	0.007780	1408.08	0.010200
215.45	0.002190	658.48	0.007530	1423.75	0.011000
220.73	0.001490	670.19	0.009480	1439.91	0.009600
226.32	0.001500	681.29	0.008410	1456.39	0.009400
231.60	0.001390	687.02	0.007640	1472.28	0.010100
236.63	0.001220	697.46	0.008830	1494.83	0.009260
241.60	0.001110	708.23	0.007860	1514.24	0.008560
246.75	0.001090	719.22	0.008030	1530.45	0.007840
252.00	0.000969	729.92	0.007880	1547.39	0.008740
257.10	0.001010	740.44	0.008040	1564.67	0.009000
262.11	0.001060	751.30	0.009580	1581.67	0.009610
267.14	0.000986	761.76	0.008210	1598.65	0.009770
		783.06	0.008060	1615.34	0.008850

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1632.04	0.010000	2433.23	0.021400	3227.28	0.049300
1646.98	0.010500	2448.78	0.023900	3243.80	0.052300
1661.58	0.007250	2464.82	0.021300	3260.40	0.055100
1677.78	0.010900	2480.35	0.021600	3276.73	0.060600
1694.57	0.010900	2496.05	0.026500	3293.13	0.048900
1710.58	0.009210	2511.83	0.024800	3309.88	0.056600
1723.90	0.011400	2528.83	0.028400	3326.57	0.059200
1740.73	0.012200	2545.85	0.024600	3337.88	0.049800
1757.30	0.011100	2562.88	0.029900	3354.13	0.070300
1774.37	0.009010	2579.68	0.030200	3370.82	0.064500
1789.97	0.011000	2595.23	0.029200	3415.83	0.074300
1806.53	0.010500	2611.22	0.023800	3462.53	0.075800
1822.90	0.012000	2633.87	0.025400	3478.47	0.065800
1839.35	0.011400	2649.17	0.024100	3491.10	0.058900
1855.93	0.012100	2665.22	0.025700	3506.48	0.081000
1872.55	0.008890	2681.82	0.028300	3522.87	0.091900
1889.38	0.010700	2693.12	0.030700	3539.18	0.108000
1906.07	0.011900	2704.38	0.023800	3555.55	0.059200
1922.82	0.012400	2721.72	0.027000	3570.90	0.067400
1939.05	0.010800	2739.27	0.030600	3586.73	0.120000
1954.07	0.014700	2755.37	0.029900	3603.40	0.084500
1970.40	0.014700	2771.77	0.033500	3619.42	0.097100
1986.73	0.013300	2787.27	0.029600	3635.03	0.098800
2003.30	0.012500	2802.57	0.033500	3651.17	0.108000
2019.58	0.011700	2817.52	0.038800	3667.73	0.102000
2035.87	0.011100	2833.33	0.030200	3683.68	0.130000
2052.43	0.018800	2849.65	0.028900	3699.33	0.121000
2069.67	0.013800	2866.17	0.032000		
2086.30	0.014600	2882.48	0.034900		
2102.58	0.015600	2899.13	0.030300		
2118.93	0.016500	2915.67	0.029600		
2134.77	0.015900	2931.63	0.037300		
2151.10	0.018800	2947.43	0.029500		
2167.12	0.017900	2962.97	0.028100		
2182.85	0.014500	2978.92	0.031800		
2198.13	0.022800	2995.17	0.034000		
2214.87	0.018500	3008.62	0.036100		
2232.63	0.020000	3022.22	0.037900		
2243.93	0.017000	3039.02	0.029000		
2259.18	0.019100	3054.18	0.053100		
2273.72	0.021000	3069.67	0.030300		
2288.18	0.022100	3086.03	0.045200		
2304.37	0.020200	3101.97	0.039900		
2319.33	0.018600	3117.52	0.046700		
2334.78	0.017600	3132.82	0.048100		
2350.48	0.019800	3148.28	0.038400		
2367.17	0.018700	3163.33	0.040200		
2383.87	0.031900	3176.87	0.054600		
2401.38	0.025400	3193.98	0.041100		
2417.72	0.024800	3211.22	0.044000		

Table C27. Test C7, ^{232}U .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
6.99	0.000097	272.28	0.002364
11.70	0.000375	277.31	0.002392
16.74	0.002565	282.28	0.002252
21.84	0.004497	287.42	0.002305
26.87	0.011348	292.07	0.002201
32.14	0.028743	307.57	0.002078
37.41	0.041366	318.69	0.001922
42.59	0.047035	329.76	0.001696
47.56	0.044758	341.21	0.001691
52.63	0.038277	352.75	0.001697
57.64	0.029630	363.95	0.002117
62.61	0.025202	375.64	0.001762
67.59	0.021704	387.10	0.001773
72.40	0.018117	397.13	0.001789
77.29	0.014483	408.20	0.001745
82.31	0.012173	419.00	0.001761
87.27	0.011006	428.42	0.001659
92.18	0.009259	437.72	0.001608
97.17	0.008075	447.71	0.001665
102.39	0.008014	457.77	0.001471
117.22	0.008652		
122.02	0.008095		
126.98	0.007833		
131.97	0.007907		
136.90	0.007089		
142.21	0.006465		
147.66	0.005798		
153.17	0.005629		
158.59	0.005539		
164.25	0.004964		
170.09	0.004716		
175.56	0.004544		
181.14	0.004278		
187.01	0.004502		
192.68	0.004170		
198.50	0.003701		
204.39	0.003270		
210.00	0.002907		
215.45	0.002963		
220.73	0.003002		
226.32	0.003055		
231.60	0.002993		
236.63	0.003095		
241.60	0.003199		
246.75	0.003113		
252.00	0.003053		
257.10	0.002752		
262.11	0.002409		
267.14	0.002755		

Table C28. Test D1, ^3H .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1.41	0.000012
5.92	0.000014
14.14	0.000017
19.19	0.000024
24.19	0.000055
29.03	0.000120
33.82	0.000209
38.56	0.000336
43.27	0.000468
48.03	0.000590
52.76	0.000702
56.82	0.000691
61.44	0.000834
66.08	0.000918
70.82	0.000956
75.56	0.000931
101.78	0.000889
116.87	0.000854
138.80	0.000763
158.81	0.000621
176.75	0.000538
196.06	0.000455
215.42	0.000382
228.49	0.000349
247.91	0.000306
262.36	0.000283
297.96	0.000231
317.98	0.000188
333.04	0.000185
348.68	0.000163
401.05	0.000127
420.72	0.000110
435.25	0.000111
440.21	0.000097
469.83	0.000089
481.50	0.000085

Table C29. Test D2, ²²Na.

Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm
3.17	0.000000	544.95	0.000503	826.24	0.000246
10.30	0.000043	554.92	0.000432	831.31	0.000202
19.15	0.000697	565.07	0.000433	836.39	0.000158
28.80	0.003950	570.04	0.000454	841.41	0.000216
38.44	0.010300	575.01	0.000446	846.35	0.000176
48.06	0.016900	579.84	0.000419	851.24	0.000189
57.93	0.021500	584.70	0.000395	856.25	0.000180
67.64	0.024000	589.44	0.000417	861.15	0.000183
77.42	0.024900	594.26	0.000425	865.97	0.000176
87.24	0.023000	599.14	0.000383	870.97	0.000172
97.37	0.019600	607.94	0.000386	875.98	0.000158
107.73	0.016500	612.91	0.000372	880.88	0.000185
117.77	0.014700	617.68	0.000343	885.83	0.000235
128.05	0.012400	622.49	0.000369	890.77	0.000186
138.21	0.010500	627.31	0.000392	895.65	0.000146
148.12	0.009490	632.34	0.000339	900.54	0.000154
158.36	0.008920	636.74	0.000497	905.40	0.000195
168.52	0.007830	641.22	0.000364	910.30	0.000142
178.39	0.007390	645.81	0.000342	915.03	0.000504
188.13	0.006460	650.41	0.000348	919.93	0.000159
198.08	0.005490	654.98	0.000306	924.72	0.000171
207.27	0.005210	659.79	0.000315	929.54	0.000175
217.01	0.004640	664.56	0.000324	934.43	0.000141
227.13	0.004110	669.26	0.000280	939.30	0.000159
235.87	0.003910	673.97	0.000345	944.05	0.000204
245.39	0.003560	678.88	0.000276	948.88	0.000184
255.24	0.003160	683.68	0.000298	953.94	0.000152
285.15	0.002550	688.68	0.000284	959.04	0.000161
294.63	0.002420	693.64	0.000278	964.09	0.000133
304.13	0.002160	698.72	0.000294	969.08	0.000144
313.55	0.002070	703.76	0.000301	973.93	0.000592
323.03	0.001730	708.65	0.000290	978.76	0.000152
332.53	0.001690	717.15	0.000279	983.64	0.000157
351.30	0.001560	721.98	0.000279	988.61	0.000197
360.95	0.001450	726.97	0.000276	993.56	0.000124
369.89	0.001200	731.76	0.000247	998.50	0.000147
379.66	0.001170	736.54	0.000305	1007.34	0.000160
389.32	0.001150	740.38	0.000410		
398.97	0.001070	745.27	0.000285		
408.59	0.001000	750.14	0.000235		
418.53	0.000906	754.96	0.000242		
428.37	0.000773	759.88	0.000215		
438.29	0.000850	764.93	0.000249		
447.97	0.000801	769.37	0.000238		
457.60	0.000753	774.08	0.000217		
467.25	0.000723	778.89	0.000221		
476.68	0.000724	783.85	0.000234		
486.29	0.000649	788.65	0.000253		
496.02	0.000591	793.52	0.000216		
506.04	0.000570	801.94	0.000234		
515.78	0.000537	806.97	0.000204		
525.41	0.000581	811.85	0.000223		
535.03	0.000514	816.88	0.000204		
		821.87	0.000199		

Table C30. Test D2, ²³⁹Np.

Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm
3.17	0.000000	506.04	0.000468	783.85	0.000771
10.30	0.000000	515.78	0.000443	788.65	0.000843
19.15	0.000000	525.41	0.000437	793.52	0.000707
28.80	0.000000	535.03	0.000558	801.94	0.000731
38.44	0.000000	544.95	0.000487	806.97	0.000717
48.06	0.000000	554.92	0.000546	811.85	0.000709
57.93	0.000000	565.07	0.000624	816.88	0.000788
67.64	0.000000	570.04	0.000534	821.87	0.000755
77.42	0.000000	575.01	0.000600	826.24	0.000818
87.24	0.000000	579.84	0.000550	831.31	0.000686
97.37	0.000000	584.70	0.000576	836.39	0.000717
107.73	0.000000	589.44	0.000636	841.41	0.000759
117.77	0.000000	594.26	0.000580	846.35	0.000905
128.05	0.000000	599.14	0.000617	851.24	0.000822
138.21	0.000000	607.94	0.000590	856.25	0.000905
148.12	0.000000	612.91	0.000528	861.15	0.000823
158.36	0.000000	617.68	0.000696	865.97	0.000905
168.52	0.000000	622.49	0.000609	870.97	0.000740
178.39	0.000000	627.31	0.000621	875.98	0.000878
188.13	0.000000	632.34	0.000594	880.88	0.000793
198.08	0.000000	636.74	0.000760	885.83	0.000834
207.27	0.000000	641.22	0.000662	890.77	0.000817
217.01	0.000000	645.81	0.000676	895.65	0.000854
227.13	0.000000	650.41	0.000618	900.54	0.000848
235.87	0.000000	654.98	0.000624	905.40	0.000719
245.39	0.000000	659.79	0.000644	910.30	0.000915
255.24	0.000000	664.56	0.000774	915.03	0.000934
285.15	0.000000	669.26	0.000590	919.93	0.000884
294.63	0.000000	673.97	0.000783	924.72	0.000781
304.13	0.000000	678.88	0.000691	929.54	0.000710
313.55	0.000000	683.68	0.000695	934.43	0.000778
323.03	0.000000	688.68	0.000624	939.30	0.000891
332.53	0.000000	693.64	0.000757	944.05	0.000917
351.30	0.000000	698.72	0.000619	948.88	0.000779
360.95	0.000000	703.76	0.000749	953.94	0.000734
369.89	0.000000	708.65	0.000830	959.04	0.000772
379.66	0.000000	717.15	0.000676	964.09	0.000818
389.32	0.000000	721.98	0.000814	969.08	0.000967
398.97	0.000000	726.97	0.000692	973.93	0.000901
408.59	0.000000	731.76	0.000771	978.76	0.000870
418.53	0.000292	736.54	0.000763	983.64	0.000967
428.37	0.000287	740.38	0.000832	988.61	0.000709
438.29	0.000347	745.27	0.000788	993.56	0.000801
447.97	0.000373	750.14	0.000827	998.50	0.000910
457.60	0.000412	754.96	0.000749	1007.34	0.000869
467.25	0.000390	759.88	0.000821	1012.23	0.000797
476.68	0.000300	764.93	0.000816	1016.72	0.000797
486.29	0.000401	769.37	0.000820	1020.96	0.000938
496.02	0.000400	774.08	0.000782	1025.45	0.000976
		778.89	0.000741	1030.06	0.000838

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1034.74	0.000863	1321.39	0.001180	0.00	0.000000
1039.52	0.000852	1325.77	0.000885	0.00	0.000000
1044.18	0.000790	1330.54	0.000885	0.00	0.000000
1048.90	0.000956	1335.33	0.001010	0.00	0.000000
1053.71	0.000945	1340.18	0.000879	0.00	0.000000
1058.52	0.000926	1345.08	0.000871	0.00	0.000000
1063.31	0.000771	1349.73	0.001080	0.00	0.000000
1068.19	0.000940	1354.52	0.001010	0.00	0.000000
1073.08	0.000861	1359.26	0.001010	0.00	0.000000
1077.93	0.000811	1364.13	0.000867	0.00	0.000000
1082.08	0.000907	1369.88	0.001070	0.00	0.000000
1087.04	0.000897	1374.30	0.001110	0.00	0.000000
1091.60	0.000877	1378.65	0.001120	0.00	0.000000
1106.69	0.000867	1383.14	0.000865	0.00	0.000000
1111.37	0.000978	0.00	0.000000	0.00	0.000000
1116.05	0.000776	0.00	0.000000	0.00	0.000000
1120.61	0.001100	0.00	0.000000	0.00	0.000000
1125.25	0.001100	0.00	0.000000	0.00	0.000000
1130.02	0.000989	0.00	0.000000	0.00	0.000000
1135.04	0.001050	0.00	0.000000	0.00	0.000000
1140.27	0.000900	0.00	0.000000	0.00	0.000000
1145.38	0.001030	0.00	0.000000	0.00	0.000000
1150.51	0.000851	0.00	0.000000	0.00	0.000000
1155.44	0.000819	0.00	0.000000	0.00	0.000000
1160.35	0.000943	0.00	0.000000	0.00	0.000000
1165.29	0.000971	0.00	0.000000	0.00	0.000000
1170.27	0.001030	0.00	0.000000	0.00	0.000000
1175.01	0.001010	0.00	0.000000	0.00	0.000000
1179.71	0.000839	0.00	0.000000	0.00	0.000000
1184.07	0.001060	0.00	0.000000	0.00	0.000000
1188.14	0.000982	0.00	0.000000	0.00	0.000000
1192.39	0.000968	0.00	0.000000	0.00	0.000000
1195.84	0.001150	0.00	0.000000	0.00	0.000000
1200.59	0.001110	0.00	0.000000	0.00	0.000000
1205.31	0.000980	0.00	0.000000	0.00	0.000000
1210.08	0.000959	0.00	0.000000	0.00	0.000000
1214.84	0.000853	0.00	0.000000	0.00	0.000000
1219.56	0.000835	0.00	0.000000	0.00	0.000000
1224.34	0.000999	0.00	0.000000	0.00	0.000000
1229.33	0.000892	0.00	0.000000	0.00	0.000000
1234.45	0.000911	0.00	0.000000	0.00	0.000000
1239.54	0.001070	0.00	0.000000	0.00	0.000000
1249.27	0.001000	0.00	0.000000	0.00	0.000000
1253.86	0.001050	0.00	0.000000	0.00	0.000000
1258.50	0.000815	0.00	0.000000	0.00	0.000000
1268.50	0.000991	0.00	0.000000	0.00	0.000000
1278.76	0.001180	0.00	0.000000	0.00	0.000000
1283.79	0.001020	0.00	0.000000	0.00	0.000000
1293.58	0.001110	0.00	0.000000	0.00	0.000000
1312.63	0.001200	0.00	0.000000	0.00	0.000000

APPENDIX C

[illegible]

Table C31. Test D3, ^{22}Na .

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1.71	0.000125	248.03	0.004040	536.46	0.000733
4.64	0.000081	252.69	0.003540	541.33	0.000756
8.02	0.000065	257.30	0.003740	546.22	0.000689
11.61	0.000066	285.67	0.002790	556.25	0.000681
15.54	0.000077	290.48	0.002690	561.23	0.000670
19.63	0.000159	299.82	0.002520	566.13	0.000653
23.81	0.000115	304.72	0.002470	571.03	0.000667
28.12	0.000533	309.63	0.002380	575.85	0.000634
32.52	0.002060	314.46	0.002230	580.65	0.000651
36.88	0.004660	319.19	0.002360	585.65	0.000610
41.29	0.009000	324.01	0.002320	590.67	0.000588
45.86	0.012800	328.73	0.002140	595.64	0.000611
53.35	0.017000	343.38	0.001960	600.63	0.000644
57.70	0.019000	348.16	0.001860	605.66	0.000651
62.12	0.020200	352.33	0.002020	610.61	0.000600
66.58	0.020600	357.41	0.001780	615.56	0.000561
71.02	0.020400	362.08	0.001880	620.65	0.000591
78.16	0.019700	366.19	0.001900	625.63	0.000571
87.84	0.018200	370.46	0.001830	630.55	0.000538
92.63	0.017600	375.03	0.001630	635.30	0.000549
97.33	0.016800	379.59	0.001660	640.17	0.000525
102.23	0.016200	384.27	0.001420	644.89	0.000588
107.13	0.014900	388.90	0.001660	649.68	0.000531
112.06	0.014400	393.66	0.001530	654.67	0.000540
116.90	0.014100	398.46	0.001450	659.54	0.000485
121.59	0.013500	402.94	0.001350	664.25	0.000478
126.37	0.012700	407.84	0.001320	669.15	0.000514
134.73	0.011300	412.70	0.001340	678.93	0.000472
139.56	0.010700	417.61	0.001290	698.90	0.000457
144.45	0.009810	422.55	0.001400	718.28	0.000470
149.44	0.009190	427.50	0.001210	737.84	0.000402
158.37	0.008700	432.67	0.001170	756.51	0.000357
163.21	0.008550	437.60	0.001250	774.68	0.000369
168.04	0.008150	442.27	0.001160	793.89	0.000368
172.96	0.007210	447.12	0.001100	813.47	0.000352
177.76	0.007330	451.96	0.001100	830.98	0.000322
182.53	0.006700	456.96	0.001040	848.37	0.000318
187.19	0.006600	461.91	0.001050	865.64	0.000469
191.78	0.006670	475.27	0.000878	873.22	0.000431
196.40	0.006420	480.33	0.000923	889.16	0.000334
201.10	0.005860	485.32	0.000856	907.61	0.000316
205.83	0.005510	490.16	0.000882	926.44	0.000308
210.61	0.005120	495.26	0.000842	944.64	0.000307
215.25	0.005110	500.16	0.000874	964.18	0.000278
220.02	0.004910	505.09	0.000799	983.29	0.000253
224.81	0.004730	509.82	0.000851	1002.39	0.000231
229.72	0.004320	514.50	0.000925	1022.01	0.000365
234.55	0.004430	519.30	0.000765	1041.20	0.000235
239.31	0.004110	524.07	0.000774	1060.37	0.000228
		531.64	0.000758	1079.84	0.000215

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1098.66	0.000230
1117.22	0.000392
1136.02	0.000238
1155.47	0.000197
1174.44	0.000197
1193.14	0.000210
1212.25	0.000225
1231.16	0.000191
1248.77	0.000171
1267.45	0.000151
1285.96	0.000174
1305.10	0.000160
1324.24	0.000221
1343.66	0.000255
1362.65	0.000144
1381.52	0.000143
1420.78	0.000124
1439.94	0.000174
1459.58	0.000159
1479.20	0.000109
1497.38	0.000296
1516.00	0.000124
1535.37	0.000116
1555.14	0.000118
1571.08	0.000185
1591.06	0.000108
1609.48	0.000154
1626.73	0.000180
1645.51	0.000101
1664.91	0.000114
1683.42	0.000103
1703.37	0.000092
1723.57	0.000092
1742.98	0.000291
1761.88	0.000101
1780.23	0.000094
1799.78	0.000197
1819.08	0.000090
1835.82	0.000101
1854.43	0.000093
1874.55	0.000094
1893.53	0.000100
1912.92	0.000104
1932.32	0.000085
1951.42	0.000098
1970.67	0.000082
1990.62	0.000076
2010.65	0.000089
2029.88	0.000088
2049.25	0.000101

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
2068.75	0.000079
2087.83	0.000093
2107.27	0.000104
2126.02	0.000095
2145.17	0.000083
2163.98	0.000087
2182.78	0.000086
2200.53	0.000104
2217.93	0.000082
2236.22	0.000130
2254.58	0.000088
2273.18	0.000078
2292.32	0.000094
2311.03	0.000080
2330.43	0.000079
2348.98	0.000092
2367.88	0.000086
2386.65	0.000087
2405.42	0.000092
2424.87	0.000147
2444.83	0.000081
2463.98	0.000083
2482.90	0.000062
2502.17	0.000093
2521.32	0.000070
2539.02	0.000375
2558.63	0.000081
2575.27	0.000090
2592.85	0.000089
2611.52	0.000084
2630.45	0.000080
2649.62	0.000095
2668.73	0.000102
2683.47	0.000082
2700.25	0.000089
2719.88	0.000077
2739.07	0.000068
2758.23	0.000069
2777.00	0.000069
2796.48	0.000072

Table C32. Test D4, ²²Na.

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$	Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
4.81	0.000178	245.07	0.004210	488.68	0.000769
8.25	0.000022	250.05	0.004390	493.50	0.000823
12.21	0.000013	254.87	0.004220	498.32	0.000780
16.46	0.000013	259.93	0.003670	503.27	0.000777
20.96	0.000040	264.64	0.003830	508.14	0.000734
25.63	0.000295	269.43	0.003760	512.98	0.000747
30.58	0.001310	274.05	0.003660	518.02	0.000701
35.54	0.004120	278.69	0.003450	522.82	0.000694
40.14	0.009230	283.33	0.003490	527.88	0.000674
45.29	0.014000	288.05	0.003160	532.60	0.000652
50.12	0.020200	292.80	0.003150	537.47	0.000619
54.91	0.029700	297.60	0.002910	542.22	0.000659
59.87	0.030700	302.51	0.002720	546.96	0.000627
64.78	0.030700	307.43	0.002400	561.46	0.000516
69.71	0.033400	312.11	0.002590	576.11	0.000620
74.56	0.031900	317.03	0.002540	590.65	0.000491
79.21	0.031800	321.97	0.002260	604.94	0.000537
83.71	0.032600	326.88	0.002230	619.31	0.000423
88.57	0.029700	331.67	0.002200	633.97	0.000457
93.44	0.028600	336.54	0.002020	648.36	0.000354
98.36	0.026100	341.16	0.002060	663.08	0.000337
103.16	0.025500	345.87	0.001930	677.33	0.000555
108.20	0.022100	350.61	0.001980	691.89	0.000323
113.12	0.021700	355.21	0.001870	706.66	0.000330
117.98	0.020600	360.07	0.001750	721.27	0.000423
122.88	0.018600	364.92	0.001700	735.59	0.000293
127.77	0.017600	369.72	0.001730	768.92	0.000333
132.84	0.016300	374.39	0.001720	783.32	0.000271
137.76	0.015700	378.18	0.001840	797.41	0.000321
142.66	0.014200	382.46	0.001670	811.13	0.000242
147.41	0.014400	386.98	0.001490	825.26	0.000216
152.07	0.013200	391.63	0.001490	839.59	0.000215
157.00	0.011900	396.43	0.001420	854.01	0.000245
161.98	0.010500	401.12	0.001300	869.11	0.000176
166.85	0.010400	405.76	0.001360	884.63	0.000156
171.93	0.009250	410.27	0.001320	900.31	0.000184
176.91	0.009040	415.09	0.001680	915.83	0.000538
186.81	0.008380	419.82	0.001280	930.89	0.000140
191.84	0.008070	429.56	0.001160	945.47	0.000159
196.81	0.007440	434.40	0.001150	959.89	0.000158
201.69	0.007210	439.31	0.001110	974.22	0.000137
206.44	0.006740	444.35	0.001050	988.38	0.000154
211.11	0.006480	449.26	0.001120	1002.78	0.000134
215.61	0.006350	454.32	0.000944	1014.63	0.000113
220.52	0.005720	459.40	0.000894	1030.07	0.000195
225.31	0.005640	464.43	0.001230	1045.44	0.000105
230.34	0.005240	469.34	0.000862	1060.60	0.000107
235.15	0.004770	474.19	0.000878	1075.50	0.000112
240.13	0.004520	478.98	0.000887	1090.02	0.000087
		483.72	0.000801	1103.06	0.000100

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1117.51	0.000091
1122.22	0.000153
1135.39	0.000102
1148.75	0.000084
1163.56	0.000080
1189.77	0.000088
1204.11	0.000075
1218.13	0.000104
1232.27	0.000072
1246.63	0.000081
1260.38	0.000083
1274.58	0.000062
1288.03	0.000074
1302.86	0.000055
1317.91	0.000059
1332.79	0.000039
1347.46	0.000067
1361.81	0.000050
1376.41	0.000056
1391.01	0.000064
1406.24	0.000031
1420.26	0.000055
1432.21	0.000054
1446.79	0.000032
1461.25	0.000046
1475.87	0.000039
1490.12	0.000040
1504.10	0.000057
1530.76	0.000037
1544.95	0.000186
1573.77	0.000074
1588.60	0.000077
1603.16	0.000026
1617.86	0.000459
1632.61	0.000029
1647.15	0.000024
1661.75	0.000023
1676.18	0.000165
1690.83	0.000063
1730.23	0.000052
1743.88	0.000065
1758.52	0.000051
1773.08	0.000056
1787.58	0.000072
1802.40	0.000054
1816.95	0.000067
1831.38	0.000062
1846.42	0.000058
1876.07	0.000054
1888.38	0.000093

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1902.13	0.000053
1916.48	0.000069
1931.02	0.000046
1945.22	0.000045
1959.47	0.000036
1973.88	0.000048

Table C33. Test D4, ²²Na.

Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm
4.81	0.000178	245.07	0.004210	488.68	0.000769
8.25	0.000022	250.05	0.004390	493.50	0.000823
12.21	0.000013	254.87	0.004220	498.32	0.000780
16.46	0.000013	259.93	0.003670	503.27	0.000777
20.96	0.000040	264.64	0.003830	508.14	0.000734
25.63	0.000295	269.43	0.003760	512.98	0.000747
30.58	0.001310	274.05	0.003660	518.02	0.000701
35.54	0.004120	278.69	0.003450	522.82	0.000694
40.14	0.009230	283.33	0.003490	527.88	0.000674
45.29	0.014000	288.05	0.003160	532.60	0.000652
50.12	0.020200	292.80	0.003150	537.47	0.000619
54.91	0.029700	297.60	0.002910	542.22	0.000659
59.87	0.030700	302.51	0.002720	546.96	0.000627
64.78	0.030700	307.43	0.002400	561.46	0.000516
69.71	0.033400	312.11	0.002590	576.11	0.000620
74.56	0.031900	317.03	0.002540	590.65	0.000491
79.21	0.031800	321.97	0.002260	604.94	0.000537
83.71	0.032600	326.88	0.002230	619.31	0.000423
88.57	0.029700	331.67	0.002200	633.97	0.000457
93.44	0.028600	336.54	0.002020	648.36	0.000354
98.36	0.026100	341.16	0.002060	663.08	0.000337
103.16	0.025500	345.87	0.001930	677.33	0.000555
108.20	0.022100	350.61	0.001980	691.89	0.000323
113.12	0.021700	355.21	0.001870	706.66	0.000330
117.98	0.020600	360.07	0.001750	721.27	0.000423
122.88	0.018600	364.92	0.001700	735.59	0.000293
127.77	0.017600	369.72	0.001730	768.92	0.000333
132.84	0.016300	374.39	0.001720	783.32	0.000271
137.76	0.015700	378.18	0.001840	797.41	0.000321
142.66	0.014200	382.46	0.001670	811.13	0.000242
147.41	0.014400	386.98	0.001490	825.26	0.000216
152.07	0.013200	391.63	0.001490	839.59	0.000215
157.00	0.011900	396.43	0.001420	854.01	0.000245
161.98	0.010500	401.12	0.001300	869.11	0.000176
166.85	0.010400	405.76	0.001360	884.63	0.000156
171.93	0.009250	410.27	0.001320	900.31	0.000184
176.91	0.009040	415.09	0.001680	915.83	0.000538
186.81	0.008380	419.82	0.001280	930.89	0.000140
191.84	0.008070	429.56	0.001160	945.47	0.000159
196.81	0.007440	434.40	0.001150	959.89	0.000158
201.69	0.007210	439.31	0.001110	974.22	0.000137
206.44	0.006740	444.35	0.001050	988.38	0.000154
211.11	0.006480	449.26	0.001120	1002.78	0.000134
215.61	0.006350	454.32	0.000944	1014.63	0.000113
220.52	0.005720	459.40	0.000894	1030.07	0.000195
225.31	0.005640	464.43	0.001230	1045.44	0.000105
230.34	0.005240	469.34	0.000862	1060.60	0.000107
235.15	0.004770	474.19	0.000878	1075.50	0.000112
240.13	0.004520	478.98	0.000887	1090.02	0.000087
		483.72	0.000801	1103.06	0.000100

APPENDIX C

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1117.51	0.000091
1122.22	0.000153
1135.39	0.000102
1148.75	0.000084
1163.56	0.000080
1189.77	0.000088
1204.11	0.000075
1218.13	0.000104
1232.27	0.000072
1246.63	0.000081
1260.38	0.000083
1274.58	0.000062
1288.03	0.000074
1302.86	0.000055
1317.91	0.000059
1332.79	0.000039
1347.46	0.000067
1361.81	0.000050
1376.41	0.000056
1391.01	0.000064
1406.24	0.000031
1420.26	0.000055
1432.21	0.000054
1446.79	0.000032
1461.25	0.000046
1475.87	0.000039
1490.12	0.000040
1504.10	0.000057
1530.76	0.000037
1544.95	0.000186
1573.77	0.000074
1588.60	0.000077
1603.16	0.000026
1617.86	0.000459
1632.61	0.000029
1647.15	0.000024
1661.75	0.000023
1676.18	0.000165
1690.83	0.000063
1730.23	0.000052
1743.88	0.000065
1758.52	0.000051
1773.08	0.000056
1787.58	0.000072
1802.40	0.000054
1816.95	0.000067
1831.38	0.000062
1846.42	0.000058
1876.07	0.000054
1888.38	0.000093

Effluent <i>gm</i>	Activity $\mu\text{Ci} / \text{gm}$
1902.13	0.000053
1916.48	0.000069
1931.02	0.000046
1945.22	0.000045
1959.47	0.000036
1973.88	0.000048

Table C34. Test D5, ²²Na.

Effluent gm	Activity μCi / gm	Effluent gm	Activity μCi / gm
26.97	0.000091	666.76	0.000687
36.58	0.001780	679.96	0.000669
46.62	0.006940	693.74	0.000649
56.78	0.014700	707.83	0.000633
66.66	0.018000	722.03	0.000620
76.22	0.018900	736.81	0.000614
85.72	0.017700	751.73	0.000574
95.40	0.017700	765.15	0.000566
104.89	0.015600	779.68	0.000537
114.34	0.014600	793.10	0.000519
122.81	0.013200	807.28	0.000525
133.04	0.012200	821.33	0.000518
143.20	0.011500	835.26	0.000517
153.37	0.010000	849.53	0.000497
163.58	0.008890	862.91	0.000491
178.35	0.007850	878.38	0.000469
192.86	0.006760	893.22	0.000457
206.72	0.006120	909.02	0.000436
220.92	0.005440	923.46	0.000427
235.09	0.004850	937.60	0.000406
250.01	0.004360	952.19	0.000433
264.85	0.003800	966.84	0.000412
279.69	0.003350	978.57	0.000400
295.27	0.003210	996.29	0.000403
310.22	0.002920	1010.37	0.000420
325.38	0.002420		
340.08	0.002280		
354.82	0.002100		
369.78	0.001860		
383.32	0.001840		
397.17	0.001660		
410.76	0.001530		
425.63	0.001450		
439.68	0.001400		
454.86	0.001250		
468.68	0.001210		
482.22	0.001140		
497.25	0.001050		
511.93	0.001010		
526.57	0.001000		
540.98	0.000928		
554.77	0.000911		
568.67	0.000930		
579.89	0.000867		
595.18	0.000820		
610.01	0.000800		
624.25	0.000748		
638.77	0.000742		
652.99	0.000696		

APPENDIX D
Reprinted Memorandums

Appendix D Errata

The following modifications should be made to Appendix D.

Page	Comment
D-4 - D-6	Brush (1987) should read Brush (1988)
D-5	Brush, L.H.; Add closing parentheses after D_{soil} s. WPO# is 37400.
D-6	The following references should be added: Higgo, J.J.W, T.G. Cole, L.V.C. Rees, and D.S. Cronan. 1987. Diffusion of Radionuclides through Deep-Sea Sediments. DOE/RW/87.053. London, UK: Department of the Environment. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM as WPO#49299.) Li, Y., and S. Gregory. 1974. "Diffusion of Ions in Sea Water and in Deep-Sea Sediments," <i>Geochimica et Cosmochimica Acta</i> . Vol. 38, no. 5, 703-714.
D-24	Sewards et al., 1992: "Brearly" should read "Brearley."
D-24	Sewards et al., 1991: S.J. Lambert and C.L. Stein were also authors.
D-24	Siegel et al., 1991: Correct page numbers are 2-1 through 2-164. This is chapter 2 of SAND88-0196.
D-93	Callout for "Novak (1996)" should read "Novak and Moore (1996)."
D-94	Drez, 1996. Title word "Estimate" is singular. WPO # is 35552.
D-95	"Weiner, R." should read "Weiner, R.F."
D-109	Callout for "Siegel, 1996a" should read "Siegel, 1996."
D-111	Callout for "Novak and Babb, 1995" should read "Babb and Novak, 1995."
D-113	Reference for "Lucero et al., 1995": "Geldbard" should read "Gelbard."
D-113	Reference for "Novak, C.F. and Babb, S.C." Should read "Babb, S.C., and Novak, C.F." WPO # is 28119.
D-113	Reference for "Siegel, M.D.": Date should read "July 17, 1996." WPO # is 38231.

List of Reprinted Memorandums

- Brush, L.H. 1996a. "Revised Free-Solution Tracer Diffusion Coefficients (D_{sois}) for Dissolved Pu, Am, U, Th, Np, Cm, and Ra in Boreholes and the Culebra for Use in PA Calculations to Support the WIPP CCA." Memorandum to M.S. Tierney, dated May 11, 1996. Albuquerque, NM: Sandia National Laboratories. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM as WPO#38510.)
- Brush, L.H. 1996b. "Ranges and Probability Distributions of Kds for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA." Memorandum to M.S. Tierney, dated June 10, 1996. Albuquerque, NM: Sandia National Laboratories. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM as WPO#38801.)
- Craft, C.C., and M.D. Siegel. 1997. "Additional Calculations of Solubility-Limited Concentrations of Actinides for Injection Spikes Used in WIPP Core Column Experiments at Sandia National Laboratories." Memorandum to D. Lucero, dated June 9, 1997. Albuquerque, NM: Sandia National Laboratories. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM in WPO#40975; Reprinted in Appendix D.)
- Lucero, D.A. 1997. "Memo of Record for Column Effluent Times." Memorandum to G. Perkins, dated February 3, 1997. Albuquerque, NM: Sandia National Laboratories. . (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM in records package WPO#40975.)
- Terra Tek. 1996. "Results of Porosity and Permeability Measurements of VPX 26-11 Core Sample." Letter report to Y. Behl. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM in records package WPO#40975.)
- Yeh, S. 1993a. "Revised Viscosity Measurements of Culebra Brines." Memorandum to F. Gelbard, dated August 13, 1993. Albuquerque, NM: Sandia National Laboratories. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM in records package WPO#8760.)
- Yeh, S. 1993b. "Viscosity Measurements of Salado Brines." Memorandum to F. Gelbard, dated August 13, 1993. Albuquerque, NM: Sandia National Laboratories. (Copy on file in the Sandia WIPP Central Files, Sandia National Laboratories, Albuquerque, NM in records package WPO#8761.)

WPO 38510

Sandia National Laboratories

Albuquerque, New Mexico 87185-1341

date: May 11, 1996

to: M. S. Tierney, MS-1328 (Org. 6741)

L. H. Brush

from: L. H. Brush, MS-1341 (Org. 6748)

INFORMATION ONLY

subject: Revised Free-Solution Tracer Diffusion Coefficients (D_{sol} s) for Dissolved Pu, Am, U, Th, Np, Cm, and Ra in Boreholes and the Culebra for Use in the PA Calculations to Support the WIPP CCA

This memorandum revises the free-solution tracer diffusion coefficients (D_{sol} s) recommended by Brush (1996) for use in the long-term performance-assessment (PA) calculations to support the Waste Isolation Pilot Plant (WIPP) Compliance Certification Application (CCA). After submission of this memorandum, C. T. Stockman suggested a better way of using the D_{sol} s for Pu, U, and Np in the PA calculations (see below).

Brush (1996) modified the D_{sol} s for Pu, U, and Np from Brush (1987) (see Table 1) slightly to be consistent with the oxidation states of Pu, U, and Np predicted for WIPP disposal rooms and assumed for boreholes and the Culebra. Actinide Source Term Program and the Dissolved Actinide Retardation Research Program personnel have predicted that Pu will speciate as Pu(III) or Pu(IV), but not as Pu(V) nor Pu(VI), U will speciate as U(IV) or U(VI), and Np will speciate as Np(IV) or Np(V), but not as Np(VI), in WIPP disposal rooms, boreholes, and the Culebra. Because Brush (1996) believed that PA personnel required fixed values of D_{sol} for Pu, U, and Np for the calculations to support the WIPP CCA, he recommend that PA use the mean of the D_{sol} s for Am(III) and Th(IV) compiled by Brush (1987) for Pu, the mean of the D_{sol} s for Th(IV) and U(VI) from Brush (1987) for U, and the mean of the D_{sol} s for Th(IV) and Np(V) from Brush (1987) for Np.

However, Stockman suggested that PA personnel sample D_{sol} s for Pu, U, and Np the same way they will sample the oxidation states for these elements in WIPP disposal rooms and the Culebra for predictions of solubilities and K_d s, respectively. PA will sample solubilities and K_d s for either Pu(III), U(IV), and Np(IV), or Pu(IV), U(VI), and Np(V) in any given vector. PA will specify the oxidation states of these elements by sampling "oxstat," a parameter with a uniform distribution of 0 to 1. If the sampled value of oxstat is 0.5 or less, PA will use the solubilities predicted for Pu(III), U(IV), and Np(IV). If oxstat is greater than 0.5, PA will use solubilities for Pu(IV), U(VI), and Np(V). Therefore, I recommend that, if oxstat is 0.5 or less, PA use the D_{sol} s for

Am(III), Th(IV), and Th(IV) compiled by Brush (1987) for Pu(III), U(IV), and Np(IV), respectively, for that vector (see Table 2). If oxstat is greater than 0.5, I recommend that PA use the D_{so1s} for Th(IV), U(VI), and Np(V) from Brush (1987) for Pu(IV), U(VI), and Np(V), respectively.

REFERENCES

- Brush, L.H. 1987. *Feasibility of Disposal of High-Level Radioactive Wastes into the Seabed: Review of Laboratory Investigations of Radionuclide Migration through Deep-Sea Sediments*. SAND87-2438. Albuquerque, NM: Sandia National Laboratories.
- Brush, L.H. "Free-Solution Tracer Diffusion Coefficients (D_{so1s}) for Dissolved Pu, Am, U, Th, Np, Cm, and Ra in Boreholes and the Culebra for Use in the PA Calculations to Support the WIPP CCA." Unpublished memorandum to M.S. Tierney, May 2, 1996. Albuquerque, NM: Sandia National Laboratories.

Table 1. Values of D_{sol} from Brush (1987). Table includes only the elements needed for the PA calculations to support the WIPP CCA. Table retyped by L. H. Brush on May 2, 1996. Table checked by L. J. Storz on May 2, 1996.

Element	Species for Which D_{sol} Was Determined	Temperature at Which D_{sol} Was Determined (C)	D_{sol} , cm^2/sec
Pu	Pu^{4+} , PuO_2^+	4	3×10^{-6}
Am	Am^{3+}	4	3×10^{-6}
U	UO_2^{2+}	25	4.26×10^{-6}
Th	Th^{4+}	18	1.53×10^{-6}
Np	NpO_2^+	4	3×10^{-6}
Cm	Cm^{3+}	4	3×10^{-6}
Ra	Ra^{2+}	0	4.02×10^{-6}

Values for Pu^{4+} and PuO_2^+ , Am^{3+} , and NpO_2^+ from Higgo et al. (1987); values for UO_2^{2+} , Th^{4+} , and Ra^{2+} from Li and Gregory (1974); value for Am^{3+} applied to Cm^{3+} by oxidation-state analogy.

Table 2. Revised Values of D_{sol} for Use in the PA Calculations to Support the WIPP CCA. Table compiled by L. H. Brush on May 11, 1996. Table checked by L. J. Storz on May 13, 1996.

Element	Oxidation State for Which D_{sol} Was Estimated	D_{sol} , cm^2/sec
Pu	Pu(III)	3×10^{-6}
	Pu(IV)	1.53×10^{-6}
Am	Am(III)	3×10^{-6}
U	U(IV)	1.53×10^{-6}
	U(VI)	4.26×10^{-6}
Th	Th(IV)	1.53×10^{-6}
Np	Np(IV)	1.53×10^{-6}
	Np(V)	3×10^{-6}
Cm	Cm(III)	3×10^{-6}
Ra	Ra(II)	4.02×10^{-6}

Distribution:

MS 1320 E. J. Nowak (Org. 6831)
MS 1320 R. V. Bynum (Org. 6831)
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MS 1343 R. F. Weiner (Org. 6751)
MS 1395 L. E. Shephard (Org. 6800)
MS 1395 M. G. Marietta (Org. 6821)
MS 1330 SWCF (Org. 6352), WBS 1.1.10.3.1 (2)

date: June 10, 1996

to: M. S. Tierney, MS-1328 (Org. 6741)

L. H. Brush

from: L. H. Brush, MS-1341 (Org. 6748)

INFORMATION ONLY

subject: Ranges and Probability Distributions of K_d s for Dissolved Pu, Am, U, Th, and Np in the Culebra for the PA Calculations to Support the WIPP CCA

INTRODUCTION

This memorandum contains ranges and probability distributions of matrix distribution coefficients (K_d s) for dissolved Pu, Am, U, Th, and Np under conditions expected during transport in the Culebra Dolomite member of the Rustler Formation. In this memo, a matrix K_d is the equilibrium ratio of the mass of Pu, Am, U, Th, or Np adsorbed on the solid phase(s) per unit mass of solid(s) divided by the concentration of that element in the aqueous phase (see, for example, Freeze and Cherry, 1979). Performance-assessment (PA) personnel require K_d s for Pu, Am, U, Th, and Np for their calculations to support the Waste Isolation Pilot Plant (WIPP) Compliance Certification Application (CCA) (Ramsey, 1996). (We will include this memorandum and all of the other memoranda cited herein in the parameter and analysis records packages for these K_d s.) Actually, PA requires K_d s for various isotopes of these elements; but Ramsey (1996) did not specify them. However, Garner (1996) stated that PA needs K_d s for ^{239}Pu , ^{241}Am , ^{234}U , and ^{230}Th . It is reasonable to assume that, in view of the small differences among the masses of different isotopes of these elements, one can apply a K_d determined for one isotope to any other isotope of the same element. We are submitting K_d s for Np in case PA requires them for sensitivity calculations to show that omitting this element does not affect the long-term performance of the repository significantly.

We, the Sandia-National-Laboratories (SNL), and SNL-subcontractor personnel working on or familiar with the dissolved-actinide Retardation Research Program (RRP) or related aspects of PA, have established these ranges and distributions from results obtained by the RRP through May 31, 1996 (see Table 1 below). These ranges and distributions pertain to dolomite-rich rock in the matrix (intact rock between the fractures) of the Culebra. (We use the terms

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SWCF-A:1.1.1D.3.1: PDD: QA: Culebra Dissolved Actinide Distribution
Coefficients (K_d s), WFO # 38231

"matrix" and "fractures" in a general sense, corresponding to transport pathways with relatively low and high transmissivities, respectively. Our use of these terms is consistent with the double-porosity conceptual model of the Culebra proposed by L. Meigs and her colleagues at SNL and its subcontractors.) The ranges and distributions in Table 1 *do not* include K_{ds} for the clay-rich rock associated with fracture surfaces and dispersed in the matrix of the Culebra. We believe that, based on Sowards (1991) and Sowards et al. (1991, 1992) and recent, yet-to-be published studies of Culebra mineralogy, clay minerals such as corrensite (an ordered mixture of chlorite and saponite) *are* present on fracture surfaces *and* in the matrix of the Culebra at concentrations high enough to increase the retardation of Pu, Am, U, Th, and Np relative to that observed in laboratory studies with dolomite-rich rock (see Description of Laboratory Studies Used to Determine Matrix K_{ds} below). However, we *have not* included K_{ds} for clay minerals in these ranges and distributions because we do not have sufficient laboratory data for clay-rich rock under expected Culebra conditions at this time. Furthermore, we *have not* taken any credit for sorption by clay minerals on fractures. We believe that omitting K_{ds} for clays is conservative.

FRACTURE-SURFACE K_{ds}

We recommend that PA personnel set the fracture-surface K_{ds} (actually, K_{ds}) for Pu, Am, U, Th, and Np in the Culebra to zero. A distribution coefficient expressed on a per-unit-surface-area basis, or K_s , is the equilibrium ratio of the mass of Pu, Am, U, Th, or Np adsorbed on the solid phase(s) per unit area of solid(s) divided by the concentration of that element in the aqueous phase (Freeze and Cherry, 1979). We also recommend that PA not include sorption by a discrete layer of material associated with fracture surfaces. Setting these K_{ds} to zero will not affect the predicted retardation of actinide elements by the Culebra because: (1) we *have not* taken credit for sorption by clay minerals on fracture surfaces; (2) the surface area of the dolomite-rich rock lining the fractures is very small relative to that of the dolomite-rich rock in the matrix. WIPP Performance Assessment Department (1992) discussed sorption on fractures in detail.

MATRIX K_{ds}

This section briefly describes the laboratory studies used to determine matrix K_{ds} for dissolved Pu, Am, U, Th, and Np, and the modeling study used to predict the oxidation-state distributions of these elements under conditions expected in the Culebra. It then discusses the methodologies used to establish ranges and probability distributions of these K_{ds} .

Description of Laboratory Studies Used to Determine Matrix K_d s

The RRP carried out several laboratory studies of the sorption of Pu, Am, U, Th, and Np by dolomite-rich rock from the Culebra. Papenguth and Behl (1996) described these studies in detail. These studies used different experimental methods and considered the effects of several factors on actinide sorption in the Culebra. The results used to establish ranges and probability distributions of matrix K_d s for Pu, Am, U, Th, and Np in the Culebra appear in Appendices B through F, respectively, of this memorandum. (These lengthy appendices are available on request to anyone who did not receive them with this memo.) Detailed descriptions of these laboratory studies and the complete results will appear as SNL and/or SNL subcontractor reports by the time of submission of the CCA.

I Triay and her group at Los Alamos National Laboratory (LANL) carried out an empirical study of the sorption of Pu(V), Am(III), U(VI), Th(IV), and Np(V) by samples of dolomite-rich rock from the Culebra. Triay used four synthetic fluids, Brine A, ERDA-6, AISinR, and H-17, for her experiments with dolomite-rich rock. Brine A, developed by Moeckle (1983) to simulate fluids equilibrated with K- and Mg-bearing minerals in overlying potash-rich zones in the Salado Formation prior to entering WIPP disposal rooms, is also similar to intergranular Salado brines at or near the stratigraphic horizon of the repository. These brines could accumulate in WIPP disposal rooms after filling and sealing, and flow from the repository into the Culebra in the event of human intrusion into the repository. ERDA-6 simulates brines that occur in isolated but occasionally large reservoirs in the underlying Castile Formation (Popielak et al., 1983). These brines could flow through the repository and into the Culebra in the event of human intrusion. AISinR simulates brine sampled from the Culebra in the WIPP Air Intake Shaft (AIS). H-17 simulates Culebra brine from the H-17 Hydropad. Triay also studied the effects of the partial pressure of CO_2 (and, hence, dissolved CO_2 concentration and, to some extent, pH) on sorption. She carried out experiments on the bench top (in contact with atmospheric CO_2 , which contains about 0.035% CO_2) and in glove boxes with atmospheres containing 0.24, 1.4, and 4.1% CO_2 . The CO_2 partial pressures in these runs were $10^{-3.5}$, $10^{-2.73}$, $10^{-1.98}$, and $10^{-1.50}$ atm, respectively, the range of P_{CO_2} calculated for Culebra ground waters by Siegel et al. (1991). Furthermore, Triay studied the effects of dissolved actinide concentration on sorption. These experiments yielded sorption isotherms, plots of the quantity of radionuclide sorbed by the solid phase or phases versus the final dissolved radionuclide concentration; or plots of K_d s versus the final dissolved radionuclide concentration. (We will include these isotherms in the parameter and analysis records packages for these K_d s.) These plots in turn provided information on the nature of the reaction(s) responsible for removal of radionuclides from solution. Finally, Triay studied the effects of equilibration time (3-days and 1-, 3-, 6-, or 8-weeks) and direction of reaction (sorption or desorption) on sorption. Triay crushed the samples, selected the 75-to-500- μm

size fraction (significantly larger than the mean dolomite grain diameter of about 2 μm), washed these subsamples with dilute HCl to remove crystallographically strained surfaces, fine particles of dolomite, and Fe- and Mn-oxyhydroxides, and pretreated them with the same type of brine to be used for the actual experiment for periods of time for the most part identical to those of the sorption and desorption runs. Triay carried out each of the pretreatments and the actual experiments with 20 ml of brine and 1 g of rock. During the runs that yielded the K_d s to be used by PA, she used one actinide element at a time. At the end of her runs, Triay separated the aqueous and solid phases by sequential filtration to 0.2 μm , analyzed the solutions by liquid scintillation counting (LSC), and determined K_d s from the differences between the initial and the final radionuclide concentrations in the solutions. She carried out most of her experiments, and all of the runs that yielded the K_d s to be used by PA, with samples of dolomite-rich rock taken from AIS core segments adjacent to those used for the column-transport study (see below). X-ray-diffraction analysis of this rock failed to detect clay minerals in most cases. Because the detection limit of this technique is about 1%, the rock that yielded the K_d s for PA contains a lower concentration of clay minerals than the Culebra as a whole (estimated, based on previously published and ongoing studies of Culebra mineralogy, to be about 1 to 5%). Triay also carried out a few experiments with dolomite from the H-19 Hydropad and clay-rich rock from the lower, unnamed member of the Rustler. (The clay minerals in the lower member are identical to those lining fracture surfaces and dispersed in the matrix of the Culebra.) This study yielded a large number of K_d s for actual samples of nearly pure Culebra dolomite and actinide-bearing synthetic fluids closely resembling those that could actually flow through the Culebra after human intrusion.

P. V. Brady and his colleagues at SNL and LANL carried out a mechanistic study of the sorption of Pu(V), Am(III), Nd(III) (a nonradioactive analog of Am(III) and Pu(III)), U(VI), Th(IV), and Np(V) from synthetic 0.05, 0.5, and 5 M NaCl solutions by samples of well characterized, pure dolomite from Norway. Brady used a limited-residence-time (1 min.) reaction vessel to minimize the extent of dolomite dissolution, actinide precipitation, and other reactions unrelated to sorption during his experiments. This allowed him to study the effects of pH (from about 3 or 4 to 9 or 10 in most cases), the CO_2 concentration of the headspace (atmospheric, 0.5, and 5%), and the concentrations of potentially significant cations and anions on sorption in the absence of complexities caused by other reactions. Brady crushed the samples, selected the <106- μm size fraction, washed them with dilute HCl, and pretreated them overnight in an NaCl solution with the same concentration to be used for the actual experiments, and a solution-to-solid ratio of 100 ml per g of dolomite. He carried out the actual experiments with several actinide elements at a time, and a solution-to-solid ratio of 200 ml/g. After his runs, Brady separated the aqueous and solid phases with a 0.22- μm filter, analyzed the solutions by inductively coupled plasma emission/mass spectrometry, and determined K_d s from the differences between the initial and the final radionuclide concentrations in the solutions. Although

this study did not yield K_d s for actual samples of Culebra rock nor for synthetic Culebra fluids, it did yield results that have proven highly useful for interpreting the results of the empirical sorption study at LANL, and for extending the empirical data to the basic conditions (pH values of about 9 to 10) expected to result from use of an MgO backfill in WIPP disposal rooms (see below).

D. A. Lucero and his colleagues at SNL have studied actinide transport through intact, 5.7-inch-diameter cores obtained from the Culebra in the WIPP AIS. Lucero obtained the cores used for this study from 16-to-18-ft-long horizontal boreholes aligned in the current direction of ground-water flow in the vicinity of the AIS (see Predictions of Actinide Oxidation States in the Culebra below) and stored them under conditions that minimized evaporation of pore water. Prior to his experiments, Lucero cut 4-to-20-inch sections from the original cores and potted them in Neoprene. He then placed the potted core sections in Al core holders, mounted them vertically in a glove box, and pressurized them to about 50 atm, the *in situ* pressure at the depths (716 and 721 ft.) from which these cores were obtained. Lucero carried out spike injections or, in a few experiments, continuous injections of Pu(V), Am(III), U(VI), Th(IV), and/or Np(V) by introducing synthetic AISinR or, in a few runs, synthetic ERDA-6 with low concentrations of the radionuclide(s) into a cavity cut in the top of each core. He then pumped additional brine through these cores at low flow rates (0.1 ml/min and, in a few runs, 0.05 ml/min) for periods of up to 237 days (equivalent to pumping up to 34.2 pore volumes of brine through these cores). These flow rates are at or close to the upper limit of the range of *in situ* fluid velocities. He collected the effluent continuously and analyzed it every 5 ml by γ spectrometry or LSC. He also used scanning γ emission tomography to image the cores. By injecting different radionuclides at different times and, in some cases, by using different brines, Lucero carried out multiple, sequential experiments with the same core. Because this study quantified actinide sorption from fluids flowing through intact samples of Culebra rock, it complements the static empirical and mechanistic sorption studies with crushed Culebra rock or pure dolomite. However, this study did not yield K_d s directly. For U and Np, which were moderately retarded by sorption, the observed delays between the elution peaks of nonsorbed radionuclides (such as ^3H or ^{22}Na) and those of U and Np yielded discrete values for the retardation factors R , which were then used, along with porosities determined with the nonsorbing tracers, to calculate K_d s. For Pu, Am, and Th, which were strongly retarded by sorption, Lucero did not observe breakthrough, even after pumping brine through these cores for 61, 118, and 211 days (Pu and Am) and 133, 146, and 237 days (Th) (equivalent to 8.83, 17.0, and 30.4 pore volumes for Pu and Am, and 19.1, 21.0, and 34.2 pore volumes for Th). Therefore, he was only able to calculate minimum values of R and K_d . These minimum values depend on factors such as the initial concentration of each radionuclide, the volume of brine pumped through the core, and the analytical detection limit for the radionuclide.

Because oxidation state significantly affects the chemical behavior, including sorption, of the actinide elements, predictions of the oxidation-state distributions of Pu, U, and Np in the Culebra are necessary to establish ranges and probability distributions of matrix K_d s for use in the PA calculations. For Pu, U, and Np, the following oxidation states are possible in low-temperature, geochemical systems: Pu(III), Pu(IV), Pu(V), and Pu(VI); U(IV) and U(VI); and Np(IV), Np(V), and Np(VI). For Am and Th, only one oxidation state, Am(III) or Th(IV), respectively, is possible.

We have used experimentally based predictions of the oxidation-state distributions of Pu, U, and Np in WIPP disposal rooms from the Actinide Source Term Program (ASTP) to specify the oxidation states of these elements in the Culebra. Based on a laboratory study carried out under expected WIPP conditions by D. Clark and his colleagues at LANL and previously published results obtained for applications other than the WIPP Project, ASTP personnel have predicted that Pu will speciate as Pu(III) or Pu(IV), but not as Pu(V) nor Pu(VI), that U will speciate as U(IV) and U(VI), and that Np will speciate as Np(IV) and Np(V), but not as Np(VI), in deep (Castile and Salado) brines in the repository. To evaluate the applicability of these predictions to the Culebra, H. W. Stockman of SNL carried out a modeling study of the oxidation states of Pu, U, and Np in the Culebra (see below). This study showed that Culebra fluids are poorly poised (have limited capacity to either oxidize or reduce actinide elements). Therefore, it is reasonable to use the oxidation-state distributions of Pu, U, and Np predicted for WIPP disposal rooms to specify the oxidation states of these elements in the Culebra. Using the ASTP predictions for the Culebra will ensure consistency between the oxidation-state distributions of these elements in WIPP disposal rooms and at the point of injection of deep (Castile or Salado) brines into the Culebra following human intrusion into the repository. This will in turn obviate the need to specify redox reactions in the Culebra, and the need to incorporate possible concomitant dissolution and/or precipitation reactions in SECO, the PA model for Culebra flow and transport.

ASTP and PA personnel will calculate solubilities for *either* Pu(III), U(IV), and Np(IV), *or* Pu(IV), U(VI), and Np(V) in any given vector. PA will specify the oxidation states of these elements by sampling "oxstat," a parameter with a uniform probability distribution of 0 to 1. If the sampled value of oxstat is 0.5 or less, PA will use the solubilities predicted for Pu(III), U(IV), and Np(IV). (These solubilities are also sampled parameters.) If oxstat is greater than 0.5, PA will use solubilities for Pu(IV), U(VI), and Np(V). We recommend that PA use the ranges and distributions of K_d s for the oxidation states of Pu, U, and Np sampled for each vector.

This approach is equivalent to assuming that the oxidation-state distributions of Pu, U, and Np predicted for WIPP disposal rooms will be maintained along the

entire off-site transport pathway in the Culebra. (Previous PA calculations have predicted that, in the absence of climatic change, fluid will flow from the point of injection into the Culebra to the south or the southeast, and that the distance from the point of injection to the boundary of the Land Withdrawal Area will be about 2.5 or 3 km.) This assumption is certainly reasonable at the point of injection of deep brines into the Culebra and for some, perhaps significant, distance along the flow path. Because, in general, redox equilibrium is not observed in low-temperature aqueous solutions (see, for example, Lindberg and Runnells, 1984), the oxidation states of Pu, U, and Np predicted for the repository *could* persist along the entire flow path in the Culebra. At some point, however, the oxidation-state distributions of these elements *might* equilibrate with ambient conditions in the Culebra.

To evaluate the applicability of ASTP predictions to the Culebra, Stockman used the EQ3/6 geochemical software package (Daveler and Wolery, 1992; Wolery, 1992a, 1992b; Wolery and Daveler, 1992) to predict the oxidation-state distributions of Pu, U, and Np after mixing deep (Castile and Salado) brines containing these elements with Culebra brines. Stockman made various assumptions as to: (1) which naturally occurring or waste-derived dissolved species will control redox conditions in the deep brines after injection into the Culebra; (2) which naturally occurring dissolved or solid species control redox conditions in Culebra brines; (3) whether to use the data base in EQ3/6, or to modify it based on recently published studies of actinide chemistry. By calculating oxidation-state distributions of Pu, U, and Np before and after mixing deep brines with Culebra brines *under all possible combinations of these assumptions*, Stockman showed that Culebra fluids are poorly poised (have limited capacity to either oxidize or reduce actinide elements). Therefore, it is reasonable to assume that the oxidation-state distributions of Pu, U, and Np predicted for WIPP disposal rooms will be maintained along the entire off-site transport pathway.

Predictions of Brine Mixing in the Culebra

Brine composition could also affect the sorptive behavior of actinide elements in the Culebra. Therefore, predictions of the extent to which deep (Castile and Salado) and Culebra brines mix in the Culebra are necessary to specify weighting factors to combine the ranges and probability distributions of matrix K_d s for dissolved Pu, Am, U, Th, and Np established for deep and Culebra brines and obtain an overall range and distribution for a given element or elemental oxidation state.

Opinions differ significantly on the extent to which deep and Culebra brines will mix in the Culebra. One extreme of a range of possibilities is that, because of the density difference between deep and Culebra brines and/or limited spreading due to heterogeneity, a "slug" of deep brine will flow along the entire off-site transport pathway without significant mixing. The other extreme is that, because

of relatively high heterogeneity, hydrodynamic dispersion will result in rapid mixing, and the composition of the injected fluid will resemble that of Culebra ground water on the order of hundreds of meters from the point of injection.

We are submitting these ranges and distributions to PA concurrently with the submission of Culebra hydrologic parameters by personnel from Geohydrology Department 6115. Therefore, we could not carry out brine-mixing calculations with the current hydrologic parameters prior to establishing these ranges and distributions. In the absence of mixing calculations, E. J. Nowak, Manager of Chemical & Disposal Room Processes Department 6831, instructed us to take the following, conservative approach: (1) establish *separate* ranges and distributions for deep and the Culebra brines for each actinide element or elemental oxidation state; (2) recommend that PA personnel use the range and distribution that results in less retardation for each element or elemental oxidation state.

Methods Used to Establish Ranges of Matrix K_d s

This subsection briefly describes the methods used to establish ranges of matrix K_d s for dissolved Pu, Am, U, Th, and Np under conditions expected in the Culebra. We carried out most of the work described in this subsection at a meeting held April 1 and 2, 1996, here at the BDM Building. Sixteen SNL and SNL-subcontractor personnel working on or familiar with the RRP or related aspects of PA participated in all or part of this meeting. Two US DOE Carlsbad-Area-Office and Carlsbad-Technical-and-Administrative-Contractor personnel observed all or part of it. Appendix A (see below) contains the invitation to, agenda for, and list of the participants and observers at this meeting. (This and the other six appendices are available on request to anyone who did not receive them with this memorandum.) Detailed descriptions, including all of the empirical-sorption, mechanistic-sorption, and column-transport data considered and included or excluded, appear in Appendices B through F, respectively. Appendix G contains the results of experiments on the effects of four organic ligands on these K_d s.

At this meeting, we decided to establish *experimentally obtained* ranges for Am(III), U(VI), Th(IV), and Np(V), and to use the experimentally obtained ranges for Am(III) and Th(IV), and the oxidation-state analogy to establish ranges for Pu(III), and Pu(IV), U(IV), and Np(IV). Based on the ASTP predictions of oxidation-state distributions for Pu, U, and Np in WIPP disposal rooms and Stockman's predictions for the Culebra *under most of the possible combinations of assumptions* (see Predictions of Actinide Oxidation States in the Culebra above), we *did not* plan to establish an experimentally obtained range for Pu(V), nor to use the experimentally obtained range for U(VI) and the oxidation-state analogy to establish ranges for Pu(VI) and Np(VI).

We established *separate* ranges for the deep (Castile and Salado) and the Culebra brines for each actinide element or elemental oxidation state (see

Predictions of Brine Mixing in the Culebra above). However, we *did not* establish separate ranges for the two deep brines studied by Triay and her group in the LANL empirical sorption study (Brine A and ERDA-6) because the PA calculations carried out with the multiphase flow code Brine and Gas Flow to support the WIPP CCA have predicted that, in some vectors, the brine in WIPP disposal rooms will comprise mainly Castile brine; in other vectors, it will comprise mainly Salado brine; and in the rest, it will comprise various proportions of these and Culebra brines that will seep into the repository from above. (The latter brines will resemble Castile brines after reacting with Salado minerals.) Therefore, we established one range for Brine A and ERDA-6 to simulate these compositional variations. Similarly, the Culebra off-site transport pathway predicted by previous PA calculations (see Predictions of Actinide Oxidation States in the Culebra) contains ground waters that resemble *both* Culebra fluids used by Triay (AISinR and H-17). Therefore, we established one range and distribution for these fluids to simulate possible compositional variations along the flow path.

For U(VI), Th(IV), and Np(V) (see Appendices , we used the following methods to establish separate, *experimentally obtained* ranges for the deep and the Culebra brines. First, we considered *all* of the 6-week sorption data from the empirical study by Triay, the only experiments in which she has extensively studied the effects of dissolved actinide concentration on sorption. Because these are the only experiments carried out using a range of dissolved radionuclide concentrations, they are the only runs for which sorption isotherms have provided information on the nature of the reaction(s) responsible for removal of radionuclides from solution. (We will include these isotherms in the parameter and analysis records packages for these K_d s.) At the time of this meeting, Triay had not completed the 6-week desorption experiments. We would not, however, have included the results of the 6-week desorption runs, and did not include any data from the 3-day, nor the 1- nor 3-week desorption runs because these data could be artificially higher than those obtained from the sorption runs. Possible reasons for this include: (1) removal of a weakly sorbed actinide species concentrated in the aqueous phase by discarding the solution at the conclusion of a sorption experiment, thereby concentrating a strongly sorbed species prior to the start of a desorption run; (2) saturation of a sorption site with a high K_d followed by removal of the dissolved actinide after a sorption experiment, thereby resulting in sorption of a higher proportion of the actinide on the sorption site with a high K_d during the desorption run.

To establish the *initial* ranges for the deep brines, we first considered *all* the data obtained from the 6-week sorption experiments carried out with Brine A and ERDA-6 on the bench top (in contact with ambient atmospheric CO_2). Atmospheric CO_2 has a partial pressure of about $10^{-3.5}$ atm, the lowest CO_2 partial pressure used in the LANL study. This partial pressure is equivalent to a CO_2 content of 0.033% in the LANL study. We did not use data from runs equilibrated with higher partial pressures of CO_2 for the initial ranges for the deep

brines because we anticipate that an MgO backfill will be emplaced in WIPP disposal rooms to remove CO₂. Next, we discarded the data from runs in which the difference between the activity of the radionuclide in a standard (the radionuclide-bearing brine with which runs were started) and that in a control (a run conducted identically to that of an actual run, but without any rock) exceeded 3 σ , where the standard deviation σ equals the square root of the total number of LSC counts. Discarding these data yielded the *initial* ranges for deep brines.

To establish the *initial* ranges for the Culebra brines (AISinR and H-17), we first considered *all* the data obtained from the 6-week sorption experiments carried out on the bench top (0.033% CO₂) and in glove boxes with atmospheres containing 0.24 and 1.4% CO₂. These three atmospheres had CO₂ partial pressures of 10^{-3.5}, 10^{-2.73}, and 10^{-1.98} atm, respectively. Siegel now considers this range more likely for groundwaters in the predicted off-site transport pathway than the previous range of 10^{-3.5} to 10^{-1.50} atm calculated for the Culebra as a whole by Siegel et al. (1991). We also discarded the data from runs in which the difference between the activity of the radionuclide in a standard and that in a control exceeded 3 σ to obtain the *initial* ranges for Culebra brines.

We then compared these initial ranges with the data from the mechanistic sorption study by Brady and his colleagues at SNL and LANL. For the most part, we used Brady's data to extend Triay's empirical sorption data for the deep brines to the basic conditions expected to result from the use of an MgO backfill in WIPP disposal rooms. We assumed that, if mixing is sufficient to produce fluids with compositions similar to those of Culebra brines, the pH of these mixtures will also be similar to those of Culebra brines. Therefore, we *did not* use Brady's data to extend Triay's data for the Culebra brines to basic conditions. So far, Brady has reported data obtained with 0.05 and 0.5 M NaCl solutions, but not with 5 M NaCl. Therefore, we used only his data for 0.5 M NaCl and atmospheric CO₂ (the lowest CO₂ partial pressure used in this study) to extend Triay's data for the deep brines to basic conditions. This comparison yielded our *revised* ranges for the deep brines.

Next, we compared the revised ranges with the data from the transport study with intact Culebra cores by Lucero and his colleagues at SNL. Lucero carried out his experiments under ambient atmospheric conditions; therefore, the CO₂ content of these experiments was probably similar to that in the LANL bench-top runs. Because Lucero *did not* observe breakthrough of Th(IV) (nor of Pu(V) nor Am(III)), it was only possible to determine minimum values of K_d for Th(IV) (and for Pu(V) and Am(III)). This minimum K_d (and those for Pu(V)) are consistent with the revised ranges based on the empirical and mechanistic sorption studies. Lucero *did* observe breakthrough of U(VI) and Np(V) in his experiments. Therefore, it was possible to determine actual K_ds for these elements. In most cases, the K_ds determined for U(VI) and Np(V) from the transport study are less than the lower limits of the ranges obtained for these elements from the sorption studies. Therefore, we extended the revised ranges where necessary to obtain

final ranges for U(VI) and Np(V) in the deep brines (Castile and Salado) and Culebra brines (see Table 1).

Finally, we used the experimentally obtained ranges for Th(IV) and the oxidation-state analogy to establish ranges for Pu(IV), U(IV), and Np(IV).

We attempted to use the same methods to establish experimentally obtained ranges for Am(III) (see Appendix C). Inspection of the sorption isotherms for the 6-week LANL sorption data, however, revealed that the K_d s are proportional to the final dissolved Am(III) concentration. (We did not observe significant trends such as this in the isotherms for U(VI), Th(IV), nor Np(V)). These trends suggest that sorption of Am by the container walls, precipitation of an Am-bearing solid phase, coprecipitation of Am by another phase, incomplete separation of the aqueous and the solid phases at the end of an experiment, or some combination of these processes occurred in the runs with Am(III). Triay carried out additional posttest analyses of the brines from some of her 6-week sorption experiments with Am(III) to determine, if possible, what caused these trends, and to redetermine these K_d s. However, she continued to obtain data that displayed trends similar to those described above, and thus cannot rule out the occurrence of processes other than sorption. Therefore, we recommend using the *experimentally obtained* ranges for Pu(V) (Appendix B) for Am(III) by assuming that the K_d s for Am(III) are greater than or equal to those for Pu(V). This assumption is reasonable in view of results such as those in Figure 5 of Canepa (1992). In this case, the Am(III) K_d obtained for the Yucca Mountain Project is about one order of magnitude higher than that obtained for Pu(V) under the same conditions. (We will cite additional examples of differences between the K_d s for Am(III) and Pu(V) in future reports and presentations.) We *have not* used the oxidation-state analogy to justify the use of Pu(V) data for Am(III); instead, this approach is based on *differences* in the behavior of these oxidation states. Furthermore, we recommend using the range for Am(III) for Pu(III) (Table 1); for this recommendation, we invoke the oxidation-state analogy.

Methods Used to Establish Probability Distributions of Matrix K_d s

M. S. Tierney, the PA Parameter Task Leader, provided guidance on establishing probability distributions of parameters for use in the PA calculations to support the CCA (see Tierney, 1996a; 1996b).

The RRP has studied the effects of several factors on sorption (see Description of Laboratory Studies Used to Determine Matrix K_d s, Predictions of Actinide Oxidation States in the Culebra, and Predictions of Brine Mixing in the Culebra above). Papenguth and Behl (1996) designed these studies to encompass the ranges of these factors expected in the Culebra. Therefore, the ranges of matrix K_d s established above correspond to the expected ranges of these factors in the Culebra. However, because of uncertainties about the extent to which deep (Castile and Salado) and Culebra brines will mix, there are uncertainties as to the

probability distributions of these factors (especially brine type, the partial pressure of CO_2 , and the resulting pH) in the Culebra. Therefore, we *do not* recommend that PA use a Student t distribution based on the data included in these ranges, despite the fact that we included more than three data points for every range shown in Table 1.

Tierney (1996a) states that use of the uniform or log-uniform [probability] distribution "is appropriate when all that is known about a parameter is its range." Because we cannot specify probability distributions for the factors that affect sorption, we recommend that PA personnel use a uniform or a log-uniform distribution. Tierney (1996a) specifies use of a log-uniform distribution "when the range ... spans many orders of magnitude." Inspection of the ranges for deep and Culebra brines in Table 1 reveals that these ranges span 1.40 and 2.60 orders of magnitude (deep and Culebra brines, respectively) for Pu(III) and Am(III); 1.35 orders of magnitude (deep brines only) for Pu(IV), U(IV), Th(IV), and Np(IV); 3.00 orders of magnitude (deep brines only) for U(VI); and 2.65 and 2.30 orders of magnitude (deep and Culebra brines, respectively) for Np(V). (Each of these values is the common logarithm of the maximum value of each range divided by its minimum value. We could not calculate this parameter for Th(IV) and Culebra brines because we were unable to establish this range; see Appendix E below. We could not calculate this parameter for the range for U(VI) and Culebra brines because its minimum value is 0.) Because these ranges all span three orders of magnitude or less, we recommend that PA use a uniform distribution instead of a log-uniform distribution for all of them.

Methods Used for Final Selection of the Range of Matrix K_d s for Use in PA Calculations

We recommend that PA personnel use the range and probability distribution of matrix K_d s for deep (Castile and Salado) or Culebra brines that results in less retardation for each element or elemental oxidation state (see Predictions of Brine Mixing in the Culebra above). Because we have recommended that PA use a uniform distribution for *all* the ranges (see Methods Used to Establish Probability Distributions of Matrix K_d s above), the *average* K_d that PA will sample for all of its vectors is the mean of the maximum and minimum values of each range. Therefore, we compared the means of the ranges for deep and Culebra brines to determine which range results in less retardation for each element or elemental oxidation state. Inspection of the ranges in Table 1 reveals that the means are 260 and 2005 ml/g (deep and Culebra brines, respectively) for Pu(III) and Am(III); 10,450 ml/g (deep brines only) for Pu(IV), U(IV), Th(IV), and Np(IV); 15.015 and 35 ml/g (deep and Culebra brines, respectively) for U(VI); and 451 and 100.5 ml/g (deep and Culebra brines, respectively) for Np(V). (Each of these values is the sum of the maximum and the minimum values of each range divided by two; to facilitate this comparison, we *did not* round each result to one significant figure. We could not calculate this parameter for Th(IV) and Culebra brines because we could not establish this range; see Appendix E below.)

Therefore, we recommend that PA use a range of 20 to 500 ml/g (the range for deep brines) for Pu(III) and Am(III); a range of 900 to 20,000 ml/g (deep brines) for Pu(IV), U(IV), Th(IV), and Np(IV); a range of 0.03 to 30 ml/g (deep brines) for U(VI); and a range of 1 to 200 ml/g (Culebra brines) for Np(V). In Table 1, these ranges appear in bold font.

Because the ASTP has decided to specify the oxidation states of Pu, U, and Np by sampling the "oxstat" parameter (see Predictions of Actinide Oxidation States in the Culebra), the range and distribution for each specified oxidation state will constitute the range and distribution for each of these elements during a given vector.

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Table 1. Ranges of Matrix K_{ds} (ml/g) for Pu, Am, U, Th, and Np, and Dolomite-Rich Culebra Rck. Ranges in bold font to be used by PA. Oxidation state of Pu, U, and Np to be specified by the value of "oxstat" parameter sampled to calculate dissolved actinide concentrations in WIPP disposal rooms. All probability distributions are uniform (see text). Table compiled by L. H. Brush on April 3, 1996, based on results of meeting held April 1 and 2, 1996. Table checked by Brush and Y. Behl on April 3, 1996. Table revised by Brush on April 6, 1996, based on memo by D. A. Lucero and G. O. Brown dated April 5, 1996. Table checked by Behl on April 8, 1996.

Oxidation State	Element				
	Pu	Am	U	Th	Np
VI	NA	NA	0.03 to 30 ^{A,C} 0 to 70 ^{B,C}	NA	NA
V	NA	NA	NA	NA	2 to 900; ^{A,C} 1 to 200 ^{B,C}
IV	900 to 20,000; ^{A,D}	NA	900 to 20,000; ^{A,E}	900 to 20,000; ^{A,C}	900 to 20,000; ^{A,G}
	NE		NE	NE	NE
III	20 to 500; ^{A,H} 10 to 4,000 ^{B,H}	20 to 500; ^{A,I} 10 to 4,000 ^{B,I}	NA	NA	NA

A: range for deep (Castile and Salado) brines only (see text).

B: range for Culebra brines only (see text).

C: experimentally obtained range (see text).

D: experimentally obtained range for Th(IV) applied to Pu(IV) by oxidation-state analogy.

E: experimentally obtained range for Th(IV) applied to U(IV) by oxidation-state analogy.

F: experimentally obtained range for Th(IV) and deep brines applied to Th(IV) and Culebra brines.

G: experimentally obtained range for Th(IV) applied to Np(IV) by oxidation-state analogy.

H: experimentally obtained range for Pu(V) applied to Pu(III) (see text).

I: experimentally obtained range for Pu(V) applied to Am(III) (see text).

NA: not applicable (element will not speciate in this oxidation state).

NE: not established for Culebra brines (see Appendix E).

APPENDIX A: MEETING TO ESTABLISH RANGES AND PROBABILITY
DISTRIBUTIONS OF ACTINIDE K_d s FOR THE WIPP PA
CALCULATIONS AND THE CCA

Invitation

March 25, 1996

Dear Colleague:

Attached is the agenda for the meeting to establish ranges and probability distributions of actinide K_d s for use in the long-term performance-assessment (PA) calculations to support the WIPP Compliance Certification Application (CCA). We will hold this meeting at the BDM Sandia Vista Building at 2301 Buena Vista SE in Albuquerque, NM, on Monday and Tuesday, April 1 and 2, 1996. Currently, we plan to meet in the Nuclear Waste Management Conference Room, the large conference room, all day Monday and Tuesday morning, and in Room 2105, a small conference room, on Tuesday afternoon. Because a key is required to enter the building in which the large conference room is located, I or someone else will meet you in the reception area of the Sandia Vista Building at 8:45 on Monday morning to take you to the large conference room if you do not have a key.

I view this as our main opportunity to reach consensus on the ranges and probability distributions of K_d s for Pu, Am, U, Th, and Np that we will submit to the US DOE's Carlsbad Area Office for their use in meeting the requirements of the Consultation and Cooperation (C & C) Agreement with the State of New Mexico, and then to PA personnel for their calculations to support the CCA.

Because most of you presented most of your results at the Retardation Research Program Review Meeting in Carlsbad last month, I have scheduled only one presentation for next week's meeting, Predictions of Actinide Oxidation States in the Culebra by Harlan Stockman of Sandia. However, please bring viewgraphs updated to include as many of your new data as possible for use in our discussions. Because you are very busy, please do not feel obligated to spend a lot of time making nice viewgraphs.

Thank you very much in advance for taking time out of your busy schedule to participate in this meeting. I am looking forward to your input next week.

Best regards,

Larry Brush
WIPP Chemical & Disposal Room
Processes Department 6748

Distribution:

R. J. Lark, DOE/CAO
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MS 1330 SWCF (Org. 6352), WBS 1.1.10.3.1 (2)

Agenda

Monday and Tuesday, April 1 and 2, 1996
BDM Sandia Vista Building
2301 Buena Vista SE
Albuquerque, NM

Monday, April 1

9:00 - 9:30	Introduction	L. H. Brush, SNL
9:30 - 10:30	Predictions of Actinide Oxidation States in the Culebra	H. W. Stockman, SNL
10:30 - 10:45	Break	
10:45 - 11:45	Proposed Use of Ranges and Distributions of K_d s by PA	M. S. Tierney, SNL
11:45 - 13:00	Lunch	BDM Cafeteria
13:00 - 15:00	Discussion of Range and Distribution of K_d s for Pu(V)	All participants
15:00 - 15:15	Break	
15:15 - 17:15	Discussion of Range and Distribution of K_d s for Am(III) and Pu(III)	All participants

Agenda (continued)

Tuesday, April 2

8:00 - 10:00	Discussion of Range and Distribution of K_d s for Th(IV), Pu(IV), and U(IV)	All participants
10:00 - 10:15	Break	
10:15 - 11:45	Discussion of Range and Distribution of K_d s for U(VI) and, if necessary, Pu(VI)	All participants
11:45 - 13:00	Lunch	BDM Cafeteria
13:00 - 13:30	Discussion of Range and Distribution of K_d s for U(VI) (continued)	All participants
13:30 - 13:45	Break	
13:45 - 15:45	Discussion of Range and Distribution of K_d s for Np(V)	All participants

Participants

Y. Behl, SciRes (SNL column transport study)
P. V. Brady, SNL (Principal Investigator for the SNL/LANL mechanistic sorption study)
L. H. Brush, SNL (Principal Investigator for the dissolved-actinide Retardation Research Program (RRP))
R. V. Bynum, SAIC (Actinide Source Term Program management)
C. Duffy, independent LANL contractor (LANL empirical sorption study)
K. M. Economy, Ecodynamics (PA Culebra transport calculations)
R. Holt, independent SNL contractor (characterization of clay minerals in the Culebra)
E. J. Nowak, SNL (Manager, WIPP Chemical & Disposal Room Processes Department 6748)
H. W. Papenguth, SNL (former Principal Investigator for the dissolved-actinide RRP)
W. G. Perkins, SNL (Retardation Research Program management)
M. D. Siegel, SNL (Principal Investigator for the Stanford mechanistic sorption study, brine mixing, and characterization of clay minerals in the Culebra)
H. W. Stockman, SNL (predictions of actinide oxidation states in the Culebra)
C. T. Stockman, SNL (predictions of actinide oxidation states in the Culebra)
M. S. Tierney, SNL (Task Leader for the PA database)
I. Triay, LANL (Group Leader, Chemical Science and Technology Group, and Principal Investigator for the LANL empirical sorption study)
R. F. Weiner, SNL (Actinide Source Term Program)

Observers

D. Hobart, Carlsbad Administrative and Technical Assistance Contractor (Actinide Source Term Program, Retardation Research Program)
R. J. Lark, US DOE Carlsbad Area Office

APPENDIX B: RANGES AND PROBABILITY DISTRIBUTIONS OF
MATRIX K_d s FOR Pu(V) AND DOLOMITE-RICH
CULEBRA ROCK

Based on a laboratory study carried out under expected WIPP conditions and previously published results obtained for applications other than the WIPP Project, ASTP personnel have predicted that Pu will speciate as Pu(III) or Pu(IV), but not as Pu(V) nor Pu(VI), in deep (Castile and Salado) brines in the repository. Furthermore, a modeling study of the effects of mixing deep and Culebra brines on the oxidation states of Pu, U, and Np in the Culebra showed that Culebra fluids are poorly poised (see Predictions of Actinide Oxidation States in the Culebra above). Therefore, Pu will not speciate as Pu(V) in the Culebra. However, we could not establish experimentally obtained ranges of matrix K_d s for Am(III) (see Methods Used to Establish Ranges of Matrix K_d s above and Appendix C below). Instead, we established experimentally obtained ranges for Pu(V) and used them for Am(III) and Pu(III) by assuming that the K_d s for Am(III) and Pu(III) are greater than or equal to those for Pu(V).

To establish the *initial* ranges for Pu(V) and the deep brines, we first considered *all* of the data from the 6-week empirical sorption experiments carried out with Brine A and ERDA-6 on the bench top (0.033% CO₂) by Triay and her group at LANL (see Methods Used to Establish Ranges of Matrix K_d s for the reasons for considering these data). These runs were: #6004, #6024, #6044, #6064, and #6084 (see Table B-1 below), and #6005, #6025, #6045, #6065, and #6085 (Table B-2). Next, we discarded the data from #6025, #6045, and #6065, the runs in which the difference between the activity of the ²³⁹Pu in a standard and that in a control exceeded 3 σ , where σ is the standard deviation (see Methods Used to Establish Ranges of Matrix K_d s.) Discarding the data from these three runs yielded an *initial* range of 22.7 ml/g (from #6004) to 459 ml/g (#6005) for Pu(V) and the deep brines.

To establish the *initial* ranges for Pu(V) and the Culebra brines, we first considered *all* of Triay's 6-week sorption data obtained with AISinR and H-17 on the bench top (0.033% CO₂) and in glove boxes with atmospheres containing 0.24 and 1.4% CO₂ (see Methods Used to Establish Ranges of Matrix K_d s). These were: #6006, #6026, #6046, #6066, #6086, #24006, #24026, #24046, #24066, #24086, #12006, #12026, #12046, #12066, and #12086 (Table B-3), and #6007, #6027, #6047, #6067, #6087, #24007, #24027, #24047, #24067, #24087, #12007, #12027, #12047, #12067, and #12087 (Table B-4). We then discarded the data from #6006, #24006, #24066, and #6007, the runs in which the difference between the activity of the ²³⁹Pu in a standard and that in a control exceeded 3 σ , to obtain the *initial* range of 9.61 ml/g (from #12007) to 3,620 ml/g (#12046) for Pu(V) and the Culebra brines.

Next, we compared these initial ranges with the data from the mechanistic sorption study by Brady and his colleagues at SNL and LANL. We used Brady's data to extend Triay's empirical sorption data for the deep brines to the basic conditions expected to result from the use of an MgO backfill in WIPP disposal rooms, *but not* to extend

Triay's data for the Culebra brines to basic conditions (see Methods Used to Establish Ranges of Matrix K_d s). Brady's data for 0.5 M NaCl, atmospheric CO_2 , and the highest pH values under these conditions are (to three significant figures) 350 and 411 ml/g at a pH of 9.87 and 9.88, respectively (Table B-5). Because these values are *within* the initial range for Pu(V) and the deep brines (see above), and because we did not use this comparison to extend the initial range for Pu(V) and the Culebra brines to basic conditions, our *revised* ranges for Pu(V) remain 22.7 to 459 ml/g and 9.61 to 3,620 ml/g for the deep and Culebra brines, respectively.

We then compared both of these revised ranges with the data from the transport study with intact Culebra cores by Lucero and his colleagues at SNL. Lucero carried out his experiments under ambient atmospheric conditions; therefore, the CO_2 content of these experiments was probably similar to that in Triay's bench-top (0.033% CO_2) runs. Because Lucero *did not* observe breakthrough of Pu(V), it was only possible to determine a minimum K_d for this element. Lucero and his colleagues submitted their results on March 28, 1996, (see Table B-6), then revised them on April 5 and 16, 1996 (Tables B-7 and B-8, respectively). The minimum K_d s reported for experiments C-3, D3, and E-2 (Table B-8) *are consistent with the K_d s reported by Triay for Pu(V) and AISinR in her experiments carried out on the bench top* (0.033% CO_2) (Table B-3). Because these values are consistent with the revised range for Pu(V) and the Culebra brines (see above), and because Lucero did not carry out any experiments with Pu(V) and the deep brines (Table B-8), our *final* ranges for Pu(V) remain 22.7 to 459 ml/g and 9.61 to 3,620 ml/g for the deep and Culebra brines, respectively. However, we rounded these ranges to 20 to 500 ml/g and 10 to 4,000 ml/g, respectively prior to inclusion in Table 1 above.

We recommend that PA personnel use a uniform probability distribution for both of these ranges (see Methods Used to Establish Probability Distributions of Matrix K_d s above).

Furthermore, we recommend that PA use the range of 20 to 500 ml/g (the range for deep brines) for Pu(V) because this range results in less retardation of this element than the range for Culebra brines (see Methods Used for Final Selection of the Range of Matrix K_d s for Use in PA Calculations above).

Finally, we recommend that PA use a range of 20 to 500 ml/g for Pu(III) and Am(III) (see Methods Used to Establish Ranges of Matrix K_d s and Appendix C).

Table B-1. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Pu(V), Dolomite-Rich Culebra Rock, and Brine A (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. No K_d s in this table excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{239}Pu Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
Brine A	1.98×10^{-7} to 2.39×10^{-7}	22.7, #6004	23.7, #24004	31.9, #12004	28.3 #18004
Brine A	1.11×10^{-8} to 5.28×10^{-8}	54.9, #6024	261, #24024	38.5, #12024	35.9 #18024
Brine A	2.38×10^{-8} to 3.16×10^{-8}	28.0, #6044	34.6, #24044	43.9 #12044	39.4 #18044
Brine A	3.78×10^{-9} to 7.03×10^{-9}	27.2, #6064	30.5, #24064	65.0 #12064	32.1 #18064
Brine A	3.08×10^{-9} to 3.37×10^{-9}	28.6, #6084	30.5, #24084	31.2 #12084	30.3 #18084

Table B-2. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Pu(V), Dolomite-Rich Culebra Rock, and ERDA-6 (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{239}Pu Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
ERDA-6	1.45×10^{-9} to 6.01×10^{-8}	459, #6005	6,890, #24005	7,070, #12005	151 #18005
ERDA-6	3.88×10^{-10} to 1.24×10^{-8}	3,920, #6025	6,500, #24025	6,960 #12025	205 #18025
ERDA-6	2.36×10^{-10} to 6.35×10^{-9}	2,980, #6045	3,040, #24045	7,540 #12045	253 #18045
ERDA-6	1.59×10^{-10} to 1.67×10^{-9}	677, #6065	1,140, #24065	1,970 #12065	170 #18065
ERDA-6	3.29×10^{-11} to 1.20×10^{-10}	147, #6085	1,180, #24085	1,460 #12085	4,550 #18085

Table B-3. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Pu(V), Dolomite-Rich Culebra Rock, and AISinR (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{239}Pu Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
AISinR	1.76×10^{-9} to 9.71×10^{-8}	348, #6006	62.5, #24006	1,890, #12006	4,100 #18006
AISinR	4.22×10^{-10} to 3.91×10^{-8}	1,990, #6026	37.2, #24026	1,050 #12026	5,050, #18026
AISinR	1.91×10^{-10} to 1.85×10^{-8}	221, #6046	39.8, #24046	3,620 #12046	6,260 #18046
AISinR	1.20×10^{-10} to 3.18×10^{-9}	435, #6066	50.3, #24066	848 #12066	1,910 #18066
AISinR	8.43×10^{-11} to 1.93×10^{-9}	499, #6086	42.9, #24086	1,070, #12086	1,360 #18086

Table B-4. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Pu(V), Dolomite-Rich Culebra Rock, and H-17 (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{239}Pu Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
H-17	5.94×10^{-8} to 3.01×10^{-7}	157, #6007	89.5, #24007	9.61, #12007	26.7 #18007
H-17	4.55×10^{-9} to 7.16×10^{-8}	191, #6027	155, #24027	13.3 #12027	33.5 #18027
H-17	3.80×10^{-9} to 3.18×10^{-8}	332, #6047	183, #24047	14.3 #12047	36.6 #18047
H-17	9.35×10^{-10} to 5.48×10^{-9}	256, #6067	182, #24067	25.2 #12067	43.7 #18067
H-17	2.01×10^{-10} to 2.00×10^{-9}	235, #6087	637, #24087	93.9 #12087	45.8 #18087

Table B-5. Effects of pH and P_{CO_2} on Matrix K_d s for Pu(V) and Pure Dolomite (SNL/LANL Mechanistic Sorption Study). Sorption runs with Norwegian dolomite and 0.5 M NaCl. Data current as of March 31, 1996. Table retyped by L. H. Brush on April 24, 1996. Table checked by Y. Behl on April 28, 1996.

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
9.88	410.9	NA	NA
9.87	349.56	NA	NA
8.42	0	NA	NA
6.7	-44.928	NA	NA
6.2	34.662	NA	NA
5.81	34.662	NA	NA
5.21	34.662	NA	NA
4.62	128.72	NA	NA
4.05	-113.15	NA	NA
3.51	-44.928	NA	NA
3.11	-310.23	NA	NA

NA: not applicable.

Table B-5. Effects of pH and P_{CO_2} on Matrix K_d s for Pu(V) and Pure Dolomite
(SNL/LANL Mechanistic Sorption Study) (continued).

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
6.9	NA	465.69	NA
8.49	NA	3711.1	NA
7.32	NA	1029.4	NA
7.19	NA	1162.5	NA
6.99	NA	968.83	NA
6.88	NA	418.41	NA
6.55	NA	319.12	NA
6.17	NA	570.38	NA
5.28	NA	199.2	NA
3.97	NA	99.265	NA
3.13	NA	99.265	NA

NA: not applicable.

Table B-5. Effects of pH and P_{CO_2} on Matrix K_d s for Pu(V) and Pure Dolomite
(SNL/LANL Mechanistic Sorption Study) (continued).

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
6.39	NA	NA	124.82
6.91	NA	NA	499.76
6.89	NA	NA	NR
6.8	NA	NA	499.76
6.75	NA	NA	520.02
6.84	NA	NA	371.73
6.49	NA	NA	423.82
6.07	NA	NA	222.63
5.76	NA	NA	147.77
4.91	NA	NA	22.561
3.62	NA	NA	124.82

NA: not applicable.

NR: not reported.

Table B-6. Minimum Values of R and K_d for Pu(V) in Intact Culebra Cores (SNL Column Transport Study). Data current as of March 26, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R_{min}	Porosity (%)	$K_{d, min}$ (ml/g)	Range ($\pm$ ml/g)
C-3	VPX-28-6C	AIS.	0.1	211	30.45	5,200	3.7 ^S	84	NA
D-3	VPX-25-8A	AIS.	0.1	118	17.02	1,140	9.1, ^S 5.3 ^D	46	NA
E-2	VPX-27-7A	AIS.	0.1	61	8.83	405	23, ^S 15.7 ^D	40	NA

AIS: AISinR.

D: dual porosity assumed.

NA: not available yet.

S: single porosity assumed.

Table B-7. Minimum Values of R and K_d for Pu(V) in Intact Culebra Cores (SNL Column Transport Study). Data current as of March 26, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996. Table revised by Brush on April 6, 1996, based on memo by Lucero and Brown dated April 5, 1996. Table checked by Y Behl on April 8, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R_{min}	Porosity (%)	$K_{d, min}$ (ml/g)	Range ($\pm$ ml/g)
C-3	VPX-28-6C	AIS.	0.1	211	30.45	5,200	3.7 ^S	84	NA
D-3	VPX-25-8A	AIS.	0.1	118	17.02	1,140	9.1 ^S	46	NA
E-2	VPX-27-7A	AIS.	0.1	61	8.83	405	23 ^S	40	NA

AIS: AISinR.

NA: not available yet.

S: single porosity assumed.

Table B-8. Minimum Values of R and K_d for Pu(V) in Intact Culebra Cores (SNL Column Transport Study). Data current as of March 26, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996. Table revised by Brush on April 6, 1996, based on memo by Lucero and Brown dated April 5, 1996. Table checked by Y Behl on April 8, 1996. Table revised by Brush on April 17, 1996, based on memo by Brown dated April 16, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R_{min}	Porosity (%)	$K_{d, min}$ (ml/g)	Range ($\pm$ ml/g)
C-3	VPX-28-6C	AIS.	0.1	211	30.45	5,200	3.7 ^S	84	NA
D-3	VPX-25-8A	AIS.	0.1	118	17.02	1,140	9.1 ^S	45	NA
E-2	VPX-27-7A	AIS.	0.1	61	8.83	405	23 ^S	40	NA

AIS: AISinR.

NA: not available yet.

S: single porosity assumed.

APPENDIX C: RANGES AND PROBABILITY DISTRIBUTIONS OF MATRIX K_d s FOR Am(III) AND DOLOMITE-RICH CULEBRA ROCK

For Am, only one oxidation state, Am(III), is possible in the Culebra (see Predictions of Actinide Oxidation States in the Culebra above). Therefore, we attempted to establish experimentally obtained ranges of matrix K_d s for Am(III), and use them and the oxidation-state analogy to establish ranges for Pu(III).

To establish the *initial* ranges for Am(III) and the deep brines, we first considered *all* of the data from the 6-week empirical sorption experiments carried out with Brine A and ERDA-6 on the bench top (0.033% CO₂) by Triay and her group at LANL (see Methods Used to Establish Ranges of Matrix K_d s above for the reasons for considering these data). These runs were: #6012, #6032, #6052, #6072, and #6092 (see Table C-1), and #6013, #6033, #6053, #6073, and #6093 (see Table C-2 below). We discarded the data from #6012, #6032, #6013, #6033, #6073, and #6093, the runs in which the difference between the activity of the ²⁴³Am in a standard and that in a control exceeded 3 σ , where σ is the standard deviation (see Methods Used to Establish Ranges of Matrix K_d s.) Even after discarding the results of these six runs, however, the defensibility of the remaining data is questionable because the K_d s retained for Brine A increase significantly as the final dissolved concentration of ²⁴³Am increases. (We will include these isotherms in the parameter and analysis records packages for these K_d s. However, this trend is also apparent in Table C-1.) Furthermore, the isotherm obtained by plotting the quantity of radionuclide sorbed by the solid phase or phases versus the final dissolved radionuclide concentration does not appear to pass through the origin. The K_d s are also proportional to the final dissolved ²⁴³Am concentration in the runs carried out in the glove box with an atmosphere containing 1.4% CO₂, and, based on the trends observed with *both* retained and discarded data, *appeared* to increase similarly in the runs conducted in the glove boxes with atmospheres containing 0.24 and 4.1% CO₂ (see Table C-1). Moreover, based on the trends observed with *both* retained and discarded data, these K_d s also *appear* proportional to the final dissolved ²⁴³Am concentration at all four CO₂ concentrations in the runs with ERDA-6 (Table C-2). These trends suggest that sorption of Am by the container walls, precipitation of an Am-bearing solid phase, coprecipitation of Am by another phase, incomplete separation of the aqueous and the solid phases at the end of an experiment, or some combination of these processes occurred in the runs with Am(III). We thought we had eliminated reactions other than sorption by the rock in these experiments because: (1) LANL personnel had filtered the brines sequentially, with a minimum filter size of 0.2 μ m, after these runs; (2) we had discarded results from the runs in which the difference between the activity of the radionuclide in the standard and that in the control exceeded 3 σ before examining these data; (3) the final Am(III) concentrations in these runs were less than the solubilities predicted by FMT for these brines. Triay carried out additional posttest analyses of the brines from her 6-week sorption experiments with Am(III) with 0.033% CO₂ to determine, if possible, what caused these trends, and to redetermine these K_d s. She did not attempt any additional posttest analyses of the brines from experiments conducted in the glove boxes because

she had removed them from these glove boxes after the original runs, thus exposing them to conditions different from those during the runs. Triay first recounted the brines to determine if mistaken sample identification or improper data entry had caused the trends described above. She then refiltered, centrifuged, and/or ultracentrifuged the brines to remove any suspended particles, and recounted them. Finally, she recalculated the K_d s using the controls instead of the standards to specify the initial dissolved ^{243}Am concentration. Despite these efforts, the data continued to display trends similar to those described above.

The 6-week LANL sorption experiments carried out with Am(III) and the Culebra brines (AISinR and H-17) yielded the same trends described above for the deep brines (compare Tables C-3 and C-4 with Tables C-1 and C-2). Therefore, we could not use them to establish a range for Am(III) .

We did not use the data from the mechanistic sorption study by Brady and his colleagues at SNL and LANL, nor the column transport study by Lucero and his colleagues at SNL to establish a range for Am(III) for several reasons. First, Brady had used pure Norwegian dolomite and pure NaCl solutions, not actual Culebra dolomite and synthetic Culebra fluids. (Although we used his data to *extend* the initial ranges established with Triay's empirical data to the basic conditions expected to result from the use of an MgO backfill in WIPP disposal rooms, we *did not* believe this would be defensible in the absence of *any* empirical data for actual Culebra dolomite and synthetic Culebra fluids.) Furthermore, Brady's data for Am(III) with atmospheric and 0.5% CO_2 (see Table C-6), the headspace concentrations corresponding to CO_2 partial pressures within the range that Siegel now considers likely for groundwaters in the Culebra off-site transport pathway (see Methods Used to Establish Ranges of Matrix K_d s), were all "high" above a pH of about 5 or 6. ("High" means that insufficient ^{243}Am remained in solution after these runs to determine a K_d). Moreover, although Brady *did* obtain data for Nd(III) with atmospheric and 0.5% CO_2 at neutral or nearly neutral values of pH (Table C-5), he also obtained them with pure Norwegian dolomite and pure NaCl solutions, not actual Culebra dolomite and synthetic Culebra fluids. Finally, because Lucero *did not* observe breakthrough of Am(III) , it is only possible to determine minimum K_d s for this element (Tables C-7 through C-9). These minimum values are significantly lower than actual Am(III) K_d s typically obtained for applications other than the WIPP Project (see below).

Therefore, we recommend using the *experimentally obtained* ranges for Pu(V) (see Table 1 and Appendix B above) for Am(III) by assuming that the K_d s for Am(III) are greater than or equal to those for Pu(V) . This assumption is reasonable in view of results such as those in Figure 5 of Canepa (1992). In this case, the Am(III) K_d obtained for the Yucca Mountain Project is about one order of magnitude higher than that obtained for Pu(V) under the same conditions. (We will cite additional examples of differences between the K_d s for Am(III) and Pu(V) in future reports and presentations.) We *have not* used the oxidation-state analogy to justify the use of Pu(V) data for Am(III) ; instead, this approach is based on *differences* in the behavior of these oxidation states. Furthermore, we recommend using the range for Am(III) for Pu(III) ; for this recommendation, we *have* used the oxidation-state analogy.

REFERENCE

- Canepa, J.A. 1992. *Proceedings of the DOE/Yucca Mountain Site Characterization Project Radionuclide Adsorption Workshop at Los Alamos National Laboratory, September 11-12, 1990*. LA-12325-C. Los Alamos, NM: Los Alamos National Laboratory.

Table C-1. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Am(III), Dolomite-Rich Culebra Rock, and Brine A (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{243}Am Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
Brine A	1.72×10^{-9} to 2.95×10^{-9}	965, #6012	1,040, #24012	1,320, #12012	1,260, #18012
Brine A	1.13×10^{-9} to 1.47×10^{-9}	927, #6032	1,120, #24032	1,140, #12032	1,070, #18032
Brine A	4.64×10^{-10} to 5.61×10^{-10}	509, #6052	521, #24052	553, #12052	597, #18052
Brine A	3.31×10^{-10} to 4.14×10^{-10}	330, #6072	356, #24072	392, #12072	346, #18072
Brine A	2.65×10^{-10} to 3.24×10^{-10}	67.9, #6092	76.6, #24092	86.8, #12092	77.8, #18092

Table C-2. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Am(III), Dolomite-Rich Culebra Rock, and ERDA-6 (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{243}Am Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
ERDA-6	2.18×10^{-10} to 4.66×10^{-10}	5,620, #6013	9,590, #24013	10,800, #12013	5,230, #18013
ERDA-6	1.57×10^{-10} to 7.10×10^{-10}	5,100, #6033	4,760, #24033	8,110, #12033	2,080, #18033
ERDA-6	1.06×10^{-10} to 2.02×10^{-10}	1,650, #6053	1,610, #24053	2,010, #12053	1,210, #18053
ERDA-6	1.22×10^{-10} to 1.51×10^{-10}	978, #6073	877, #24073	832, #12073	754, #18073
ERDA-6	9.23×10^{-11} to 1.16×10^{-10}	211, #6093	272, #24093	249, #12093	258, #18093

Table C-3. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Am(III), Dolomite-Rich Culebra Rock, and AISinR (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font! excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{243}Am Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
AISinR	1.14×10^{-9} to 4.02×10^{-9}	1,790, #6014	730, #24014	637, #12014	507, #18014
AISinR	6.95×10^{-10} to 2.29×10^{-9}	1,660, #6034	594, #24034	676, #12034	504, #18034
AISinR	1.92×10^{-10} to 4.47×10^{-10}	934, #6054	760, #24054	437, #12054	436, #18054
AISinR	1.27×10^{-10} to 2.89×10^{-10}	653, #6074	640, #24074	344, #12074	334, #18074
AISinR	1.26×10^{-10} to 1.64×10^{-10}	190, #6094	145, #24094	133, #12094	156, #18094

Table C-4. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Am(III), Dolomite-Rich Culebra Rock, and H-17 (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{243}Am Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
H-17	6.35×10^{-10} to 1.69×10^{-9}	1,590, #6015	1,310, #24015	688, #12015	547, #18015
H-17	4.42×10^{-10} to 1.77×10^{-9}	1,140, #6035	1,120, #24035	622, #12035	484, #18035
H-17	2.27×10^{-10} to 3.60×10^{-10}	870, #6055	836, #24055	499, #12055	633, #18055
H-17	1.57×10^{-10} to 3.16×10^{-10}	826, #6075	626, #24075	418, #12075	383, #18075
H-17	1.43×10^{-10} to 3.36×10^{-10}	76.1, #6095	187, #24095	189, #12095	155, #18095

Table C-5. Effects of pH and P_{CO_2} on Matrix K_d s for Nd(III) and Pure Dolomite (SNL/LANL Mechanistic Sorption Study). Sorption runs with Norwegian dolomite and 0.05 M NaCl. Data current as of March 31, 1996. Table retyped by L. H. Brush on April 24, 1996. Table checked by Y. Behl on April 28, 1996.

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
9.08	2864.3	NA	NA
8.41	1619.2	NA	NA
7.52	1225.2	NA	NA
6.72	1141.4	NA	NA
6.49	571.49	NA	NA
6.19	497.91	NA	NA
5.74	546.24	NA	NA
5.25	272.78	NA	NA
4.63	241.5	NA	NA
4.2	279.24	NA	NA
3.75	202.2	NA	NA
3.35	141.3	NA	NA

NA: not applicable.

Table C-5. Effects of pH and P_{CO_2} on Matrix K_d s for Nd(III) and Pure Dolomite
(SNL/LANL Mechanistic Sorption Study) (continued).

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
7.08	NA	538.93	NA
6.81	NA	403.05	NA
6.45	NA	261.86	NA
6.26	NA	386.81	NA
5.92	NA	149.45	NA
5.18	NA	84.721	NA
4.35	NA	55.485	NA
3.64	NA	51.358	NA

NA: not applicable.

Table C-5. Effects of pH and P_{CO_2} on Matrix K_d s for Nd(III) and Pure Dolomite
(SNL/LANL Mechanistic Sorption Study) (continued).

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
6.33	NA	NA	226.71
6.24	NA	NA	179.19
6.15	NA	NA	182.28
6.01	NA	NA	169.89
5.88	NA	NA	168.9
5.76	NA	NA	111.58
5.54	NA	NA	72.6
5.21	NA	NA	206.36
3.42	NA	NA	34.636

NA: not applicable.

Table C-6. Effects of pH and P_{CO_2} on Matrix K_d s for Am(III) and Pure Dolomite (SNL/LANL Mechanistic Sorption Study). Sorption runs with Norwegian dolomite and 0.5 M NaCl. Data current as of March 31, 1996. Table retyped by L. H. Brush on April 24, 1996. Table checked by Y. Behl on April 28, 1996.

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
9.88	High	NA	NA
9.87	High	NA	NA
8.42	High	NA	NA
6.7	High	NA	NA
6.2	High	NA	NA
5.81	High	NA	NA
5.21	High	NA	NA
4.62	791.15	NA	NA
4.05	630.75	NA	NA
3.51	285.41	NA	NA
3.11	92.603	NA	NA

NA: not applicable.

Table C-6. Effects of pH and P_{CO_2} on Matrix K_d s for Am(III) and Pure Dolomite
(SNL/LANL Mechanistic Sorption Study) (continued).

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
6.9	NA	High	NA
8.49	NA	High	NA
7.32	NA	High	NA
7.19	NA	High	NA
6.99	NA	High	NA
6.88	NA	High	NA
6.55	NA	High	NA
6.17	NA	High	NA
5.28	NA	1130.9	NA
3.97	NA	65.441	NA
3.13	NA	158.09	NA

NA: not applicable.

Table C-6. Effects of pH and P_{CO_2} on Matrix K_d s for Am(III) and Pure Dolomite
(SNL/LANL Mechanistic Sorption Study) (continued).

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
6.39	NA	NA	High
6.91	NA	NA	High
6.89	NA	NA	High
6.8	NA	NA	High
6.75	NA	NA	High
6.84	NA	NA	High
6.49	NA	NA	High
6.07	NA	NA	High
5.76	NA	NA	1934.3
4.91	NA	NA	333.78
3.62	NA	NA	-10.908

NA: not applicable.

Table C-7 Minimum Values of R and K_d for Am(III) in Intact Culebra Cores (SNL Column Transport Study). Data current as of March 26, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R_{min}	Porosity (%)	$K_{d, min}$ (ml/g)	Range ($\pm$ ml/g)
C-3	VPX-28-6C	AIS.	0.1	211	30.45	1,420	3.7 ^S	11	NA
D-3	VPX-25-8A	AIS.	0.1	118	17.02	350	9.1, ^S 5.3 ^D	14	NA
E-2	VPX-27-7A	AIS.	0.1	61	8.83	200	23, ^S 15.7 ^D	20	NA

AIS: AISinR.

D: dual porosity assumed.

NA: not available yet.

S: single porosity assumed.

Table C-8. Minimum Values of R and K_d for Am(III) in Intact Culebra Cores (SNL Column Transport Study). Data current as of March 26, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996. Table revised by Brush on April 6, 1996, based on memo by Lucero and Brown dated April 5, 1996. Table checked by Y. Behl on April 8, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R_{min}	Porosity (%)	$K_{d, min}$ (ml/g)	Range ($\pm$ ml/g)
C-3	VPX-28-6C	AIS.	0.1	211	30.45	1,420	3.7 ^S	11	NA
D-3	VPX-25-8A	AIS.	0.1	118	17.02	350	9.1 ^S	14	NA
E-2	VPX-27-7A	AIS.	0.1	61	8.83	200	23 ^S	20	NA

AIS: AISinR.

NA: not available yet.

S: single porosity assumed.

Table C-9. Minimum Values of R and K_d for Am(III) in Intact Culebra Cores (SNL Column Transport Study). Data current as of March 26, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996. Table revised by Brush on April 6, 1996, based on memo by Lucero and Brown dated April 5, 1996. Table checked by Y. Behl on April 8, 1996. Table revised by Brush on April 17, 1996, based on memo by Brown dated April 16, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R_{min}	Porosity (%)	$K_{d,min}$ (ml/g)	Range ($\pm$ ml/g)
C-3	VPX-28-6C	AIS.	0.1	211	30.45	1,420	3.7 ^S	23	NA
D-3	VPX-25-8A	AIS.	0.1	118	17.02	350	9.1 ^S	14	NA
E-2	VPX-27-7A	AIS.	0.1	61	8.83	200	23 ^S	20	NA

AIS: AISinR.

NA: not available yet.

S: single porosity assumed.

APPENDIX D: RANGES AND PROBABILITY DISTRIBUTIONS OF
MATRIX K_d s FOR U(VI) AND DOLOMITE-RICH
CULEBRA ROCK

Based on experimental results, ASTP personnel have predicted that U will speciate as U(IV) or U(VI) in deep (Castile and Salado) brines in WIPP disposal rooms. Furthermore, a modeling study of the effects of mixing deep and Culebra brines on the oxidation states of Pu, U, and Np in the Culebra showed that Culebra fluids are poorly poised (see Predictions of Actinide Oxidation States in the Culebra above). Therefore, we established experimentally obtained ranges of matrix K_d s for U(VI) and used the experimentally obtained ranges for Th(IV) (see Appendix E below) and the oxidation-state analogy to establish ranges for U(IV) (and Np(IV)).

To establish the *initial* ranges for U(VI) and the deep brines, we first considered *all* of the data from the 6-week empirical sorption experiments carried out with Brine A and ERDA-6 on the bench top (0.033% CO₂) by Triay and her group at LANL (see Methods Used to Establish Ranges of Matrix K_d s above for the reasons for considering these data). These runs were: #6008, #6028, #6048, #6068, and #6088 (see Table D-1 below), and #6009, #6029, #6049, #6069, and #6089 (Table D-2). Next, we discarded the data from #6008, #6028, #6048, #6068, and #6009, the runs in which the difference between the activity of the ²³³U in a standard and that in a control exceeded 3 σ , where σ is the standard deviation (see Methods Used to Establish Ranges of Matrix K_d s). Discarding the data from these five runs yielded an *initial* range of 3.76 ml/g (from #6029) to 21.8 ml/g (#6088) for U(VI) and the deep brines.

To establish the *initial* ranges for U(VI) and the Culebra brines, we first considered *all* of Triay's 6-week sorption data obtained with AISinR and H-17 on the bench top (0.033% CO₂) and in glove boxes with atmospheres containing 0.24 and 1.4% CO₂ (see Methods Used to Establish Ranges of Matrix K_d s). These were: #6010, #6030, #6050, #6070, #6090, #24010, #24030, #24050, #24070, #24090, #12010, #12030, #12050, #12070, and #12090 (Table D-3), and #6011, #6031, #6051, #6071, #6091, #24011, #24031, #24051, #24071, #24091, #12011, #12031, #12051, #12071, and #12091 (Table D-4). We then discarded the data from #6010, #6050, #6070, #24010, #24030, #12010, #6011, #6031, #6051, #6071, #12011, and #12051, the runs in which the difference between the activity of the ²³³U in a standard and that in a control exceeded 3 σ , to obtain the *initial* range of -1.66 ml/g (from #12091) to 68.7 ml/g (#24091) for U(VI) and the Culebra brines. However, we set the lower limit of this range equal to 0 ml/g because there is no reason why a K_d could have a value less than 0.

Next, we compared these initial ranges with the data from the mechanistic sorption study by Brady and his colleagues at SNL and LANL. We used Brady's data to extend Triay's empirical sorption data for the deep brines to the basic conditions expected to result from the use of an MgO backfill in WIPP disposal rooms, *but not* to extend Triay's data for the Culebra brines to basic conditions (see Methods Used to Establish Ranges of Matrix K_d s). Brady's data for 0.5 M NaCl, atmospheric CO₂, and the highest

pH values under these conditions are (to three significant figures) 10.6 and 34.7 ml/g at a pH of 9.87 and 9.88, respectively (Table D-5). Because these values are *greater than the upper limit* of the initial range for U(VI) and the deep brines (see above), we extended this range to obtain a *revised* range for U(VI) and deep brines of 3.76 ml/g to 34.7 ml/g. Because we did not use this comparison to extend the initial range for U(VI) and the Culebra brines to basic conditions, this *revised* range remains 0 to 68.7 ml/g.

We then compared both of these revised ranges with the data from the transport study with intact Culebra cores by Lucero and his colleagues at SNL. Lucero carried out his experiments under ambient atmospheric conditions; therefore, the CO₂ content of these experiments was probably similar to that in the LANL bench-top (0.033% CO₂) runs. Lucero *did* observe breakthrough of U(VI) in his experiments. Therefore, it was possible to determine actual K_{ds} for this element. Lucero and his colleagues submitted their results on March 28, 1996, (see Table D-6), then revised them on April 5 and 16, 1996 (Tables D-7 and D-8, respectively). The K_d reported for Experiment C-7 with the deep brine ERDA-6 (Table D-8) is *less than the lower limit of the revised range of K_{ds} for U(VI) and the deep brines obtained from the empirical and mechanistic sorption studies* (see above). Therefore, we extended this range to obtain a *final* range for U(VI) and deep brines of 0.029 ml/g to 34.7 ml/g, and rounded it to 0.03 to 30 ml/g prior to inclusion in Table 1 above. Because Lucero's K_{ds} for U(VI) and the Culebra brine AISinR (B-3, B-6, C-2, D-5, and D-6 in Table D-8) are *within* the revised range for U(VI) and the Culebra brines (see above), our *final* range remains 0 to 68.7 ml/g, rounded to 0 to 70 ml/g for inclusion in Table 1.

We recommend that PA personnel use a uniform probability distribution for both of these ranges (see Methods Used to Establish Probability Distributions of Matrix K_{ds} above).

Finally, we recommend that PA use the range of 0.03 to 30 ml/g (the range for deep brines) for U(VI) because this range results in less retardation of this element than the range for Culebra brines (see Methods Used for Final Selection of the Range of Matrix K_{ds} for Use in PA Calculations above).

Table D-1. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for U(VI), Dolomite-Rich Culebra Rock, and Brine A (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{233}U Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
Brine A	1.65×10^{-6} to 2.81×10^{-6}	12.5, #6008	4.77, #24008	1.16, #12008	0.709, #18008
Brine A	7.89×10^{-7} to 1.05×10^{-6}	16.8, #6028	2.86, #24028	1.21, #12028	2.67, #18028
Brine A	1.85×10^{-7} to 2.72×10^{-7}	19.9, #6048	5.23, #24048	1.47, #12048	2.46, #18048
Brine A	7.60×10^{-8} to 1.09×10^{-7}	16.6, #6068	6.81, #24068	0.933, #12068	2.30, #18068
Brine A	2.14×10^{-8} to 4.16×10^{-8}	21.8, #6088	4.70, #24088	-5.41, #12088	1.44, #18088

Table D-2. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for U(VI), Dolomite-Rich Culebra Rock, and ERDA-6 (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{233}U Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
ERDA-6	2.62×10^{-6} to 2.99×10^{-6}	0.542, #6009	1.29, #24009	4.13, #12009	3.75, #18009
ERDA-6	8.61×10^{-7} to 9.87×10^{-7}	3.76, #6029	1.52, #24029	5.92, #12029	3.17, #18029
ERDA-6	2.14×10^{-7} to 2.56×10^{-7}	3.86, #6049	2.38, #24049	7.25, #12049	3.22, #18049
ERDA-6	8.40×10^{-8} to 9.28×10^{-8}	3.88, #6069	4.35, #24069	6.24, #12069	4.76, #18069
ERDA-6	2.31×10^{-8} to 2.87×10^{-8}	6.55, #6089	2.11, #24089	7.04, #12089	1.04, #18089

Table D-3. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for U(VI), Dolomite-Rich Culebra Rock, and ASlinR (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{233}U Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
ASlinR	2.86×10^{-6} to 3.04×10^{-6}	2.56, #6010	0.351, #24010	0.550, #12010	1.67, #18010
ASlinR	9.57×10^{-7} to 1.06×10^{-6}	2.62, #6030	2.69, #24030	2.05, #12030	0.756, #18030
ASlinR	2.63×10^{-7} to 2.87×10^{-7}	3.74, #6050	0.389, #24050	1.65, #12050	3.73, #18050
ASlinR	8.22×10^{-8} to 9.50×10^{-8}	4.02, #6070	3.16, #24070	1.03, #12070	0.341, #18070
ASlinR	2.60×10^{-8} to 2.79×10^{-8}	7.51, #6090	0.117, #24090	1.73, #12090	1.88, #18090

Table D-4. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for U(VI), Dolomite-Rich Culebra Rock, and H-17 (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{233}U Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
H-17	2.76×10^{-6} to 2.97×10^{-6}	3.63, #6011	0.313, #24011	-0.745, #12011	-0.104, #18011
H-17	1.11×10^{-6} to 1.16×10^{-6}	5.55, #6031	1.30, #24031	0.157, #12031	0.530, #18031
H-17	2.72×10^{-7} to 2.92×10^{-7}	6.97, #6051	3.03, #24051	-1.83, #12051	2.26, #18051
H-17	8.73×10^{-8} to 9.86×10^{-8}	5.12, #6071	1.90, #24071	1.50, #12071	-1.22, #18071
H-17	6.89×10^{-9} to 2.83×10^{-8}	10.2, #6091	68.7, #24091	-1.66, #12091	2.96, #18091

Table D-5. Effects of pH and P_{CO_2} on Matrix K_d s for U(VI) and Pure Dolomite (SNL/LANL Mechanistic Sorption Study). Sorption runs with Norwegian dolomite and 0.5 M NaCl. Data current as of March 31, 1996. Table retyped by L. H. Brush on April 24, 1996. Table checked by Y. Behl on April 28, 1996.

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
9.88	34.662	NA	NA
9.87	10.6	NA	NA
8.42	7691.2	NA	NA
6.7	4794.1	NA	NA
6.2	3345.6	NA	NA
5.81	5685.5	NA	NA
5.21	2476.5	NA	NA
4.62	2476.5	NA	NA
4.05	2621.3	NA	NA
3.51	2342.8	NA	NA
3.11	1897.1	NA	NA

NA: not applicable.

Table D-5. Effects of pH and P_{CO_2} on Matrix K_d s for U(VI) and Pure Dolomite
(SNL/LANL Mechanistic Sorption Study) (continued).

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
6.9	NA	775.74	NA
8.49	NA	-112.13	NA
7.32	NA	44.55	NA
7.19	NA	123.88	NA
6.99	NA	286.76	NA
6.88	NA	849.72	NA
6.55	NA	1114	NA
6.17	NA	455.52	NA
5.28	NA	1774.6	NA
3.97	NA	1611.4	NA
3.13	NA	4222.7	NA

NA: not applicable.

Table D-5. Effects of pH and P_{CO_2} on Matrix K_d s for U(VI) and Pure Dolomite
(SNL/LANL Mechanistic Sorption Study) (continued).

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
6.39	NA	NA	475.59
6.91	NA	NA	69.799
6.89	NA	NA	0
6.8	NA	NA	0
6.75	NA	NA	69.799
6.84	NA	NA	69.799
6.49	NA	NA	296.73
6.07	NA	NA	1517.2
5.76	NA	NA	2056.6
4.91	NA	NA	3075.4
3.62	NA	NA	1674.5

NA: not applicable.

Table D-6. Measured Values of R and Calculated Values of K_d for U(VI) in Intact Culebra Cores (SNL Column Transport Study). Values in bold font to be excluded from ranges and distributions because fits to elution data were inferior to those assuming single porosity and dual porosity with fracture retardation. Data current as of March 30, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R	Poro-sity (%)	K_d (ml/g)	Range ($\pm$ ml/g)
B-3	VPX-26-11A	AIS.	0.1	NA	NA	3.4; ^S 1, 18.3; ^N 3.1, 5.2 ^{DF}	9.8 ^S 5.2 ^{DN} 5.2 ^{DF}	.084 ^S 0.68 ^{DN} .039 ^{DF}	.022 ^S .67 ^{DN} 0.03 ^{DF}
B-6	VPX-26-11A	AIS.	0.05	NA	NA	13.1; ^S 1, NA; ^{DN} NA, NA ^{DF}	4.8 ^S NA ^{DN} NA ^{DF}	0.25 ^S NA ^{DN} NA ^{DF}	0.07 ^S NA ^{DN} NA ^{DF}
C-2	VPX-28-6C	AIS.	0.1	21	2	10.4; ^S 1, 260; ^{DN} 12.0, 0.6 ^{DF}	5.7 ^S 3.5 ^{DN} 3.5 ^{DF}	0.23 ^S 3.9 ^{DN} 0.17 ^{DF}	0.08 ^S 7 ^{DN} 0.06 ^{DF}
C-7	VPX-28-6C	ER-6	0.1	13	2	2.7; ^S 1, 0.6; ^{DN} 2.7, 0.76 ^{DF}	3.9 ^S 2.1 ^{DN} 2.1 ^{DF}	.029 ^S .069 ^{DN} .016 ^{DF}	.022 ^S 0.13 ^{DN} .005 ^{DF}

Table D-6. Measured Values of R and Calculated Values of K_d for U(VI) in Intact Culebra Cores (SNL Column Transport Study) (continued)

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R	Porosity (%)	K_d (ml/g)	Range ($\pm$ ml/g)
D-5	VPX-25-8A	AIS.	0.1	13	2	21; ^S 1, 184; ^{DN} NA, NA ^{DF}	17.3 ^S 7.1 ^{DN} 7.1 ^{DF}	1.50 ^S 5.6 ^{DN} NA ^{DF}	0.38 ^S 5.5 ^{DN} NA ^{DF}
D-6	VPX-25-8A	AIS.	0.05	60	2	10.1; ^S 1, NA; ^{DN} 12.3, 71 ^{DF}	15.5 ^S 7.1 ^{DN} 7.1 ^{DF}	0.61 ^S NA ^{DN} 0.35 ^{DF}	0.15 NA ^{DN} 0.19 ^{DF}

AIS: AISinR.

DF: dual porosity and fracture retardation assumed.

DN: dual porosity and no fracture retardation assumed.

ER.-6: ERDA-6.

NA: not available yet.

S: single porosity assumed.

Table D-7. Measured Values of R and Calculated Values of K_d for U(VI) in Intact Culebra Cores (SNL Column Transport Study). Data current as of March 30, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996. Table revised by Brush on April 6, 1996, based on memo by Lucero and Brown dated April 5, 1996. Table checked by Y. Behl on April 8, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R	Poro-sity (%)	K_d (ml/g)	Range ($\pm$ ml/g)
B-3	VPX-26-11A	AIS.	0.1	NA	NA	3.4 ^S	9.8 ^S	0.084 ^S	NA ^S
B-6	VPX-26-11A	AIS.	0.05	NA	NA	13 ^S	4.8 ^S	0.25 ^S	NA ^S
C-2	VPX-28-6C	AIS.	0.1	21	2	10.4 ^S	5.7 ^S	0.23 ^S	NA ^S
C-7	VPX-28-6C	ER-6	0.1	13	2	2.7 ^S	3.9 ^S	0.029 ^S	NA ^S
D-5	VPX-25-8A	AIS.	0.1	13	2	21 ^S	17.3 ^S	1.5 ^S	NA ^S
D-6	VPX-25-8A	AIS.	0.05	60	2	10 ^S	15.5 ^S	0.61 ^S	NA ^S

AIS: AISinR.

ER-6: ERDA-6.

NA: not available yet.

S: single porosity assumed.

Table D-8. Measured Values of R and Calculated Values of K_d for U(VI) in Intact Culebra Cores (SNL Column Transport Study). Data current as of March 30, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996. Table revised by Brush on April 6, 1996 based on memo by Lucero and Brown dated April 5, 1996. Table checked by Y. Behl on April 8, 1996. Table revised by Brush on April 17, 1996, based on memo by Brown dated April 16, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R	Porosity (%)	K_d (ml/g)	Range ($\pm$ ml/g)
B-3	VPX-26-11A	AIS.	0.1	NA	NA	3.4 ^S	9.8 ^S	0.10 ^S	NA ^S
B-6	VPX-26-11A	AIS.	0.05	NA	NA	13 ^S	4.8 ^S	0.25 ^S	NA ^S
C-2	VPX-28-6C	AIS.	0.1	21	2	10.4 ^S	5.7 ^S	0.23 ^S	NA ^S
C-7	VPX-28-6C	ER-6	0.1	13	2	2.7 ^S	3.9 ^S	0.029 ^S	NA ^S
D-5	VPX-25-8A	AIS.	0.1	13	2	21 ^S	17.3 ^S	1.5 ^S	NA ^S
D-6	VPX-25-8A	AIS.	0.05	60	2	10 ^S	15.5 ^S	0.61 ^S	NA ^S

AIS: AISinR.

ER-6: ERDA-6.

NA: not available yet.

S: single porosity assumed.

APPENDIX E: RANGES AND PROBABILITY DISTRIBUTIONS OF MATRIX K_d s FOR Th(IV) AND DOLOMITE-RICH CULEBRA ROCK

For Th, only one oxidation state, Th(IV), is possible in the Culebra (see Predictions of Actinide Oxidation States in the Culebra above). Therefore, we established an experimentally obtained range of matrix K_d s for Th(IV), and used it and the oxidation-state analogy to establish ranges for Pu(IV), U(IV), and Np(IV).

To establish the *initial* ranges for Th(IV) and the deep brines, we first considered *all* of the data from the 6-week empirical sorption experiments carried out with Brine A and ERDA-6 on the bench top (0.033% CO₂) by Triay and her group at LANL (see Methods Used to Establish Ranges of Matrix K_d s above for the reasons for considering these data). These runs were: #7011A and #7011B (see Table E-1 below), and #7007A, #7007B, #7008A, #7008B, #7009A, #7009B, #7010A, and #7010B (Table E-2). Next, we discarded the data from #7011A and #7011B, the runs in which the difference between the activity of the ²³⁰Th in a standard and that in a control exceeded 3 σ , where σ is the standard deviation (see Methods Used to Establish Ranges of Matrix K_d s). Discarding the data from these two runs yielded an *initial* range of 864 ml/g (from #7010A) to 15,000 ml/g (#7008B) for Th(IV) and the deep brines.

For the *initial* ranges for Th(IV) and the Culebra brines, we first considered *all* of Triay's 6-week sorption data obtained with AISinR and H-17 on the bench top (0.033% CO₂) and in glove boxes with atmospheres containing 0.24 and 1.4% CO₂ (see Methods Used to Establish Ranges of Matrix K_d s). These were: #7012A, #7012B, #7054A, #7054B, #7026A, #7026B, #7040A, and #7040B (Table E-3), and #7013A, #7013B, #7055A, #7055B, #7027A, #7027B, #7041A, and #7041B (Table E-4). Unfortunately, we had to discard the data from *all* of these the runs because the difference between the activity of the ²³⁰Th in a standard and that in a control exceeded 3 σ . Therefore, we assumed that the *initial* range of 864 to 15,000 ml/g for Th(IV) and the deep brines does not differ significantly from that for Th(IV) and the Culebra brines.

Next, we attempted to compare these initial ranges with the data from the mechanistic sorption study by Brady and his colleagues at SNL and LANL. However, Brady *did not* obtain any usable results for Th because of one or more of the following reasons: (1) the walls of the containers used to prepare Th-bearing solutions sorbed essentially all of it prior to his experiments; (2) essentially all of the Th precipitated on the walls of these containers prior to his runs; (3) the walls of his apparatus sorbed essentially all of the Th during his runs; (4) essentially all of the Th precipitated on the dolomite and/or the apparatus during his runs. Therefore, our *revised* ranges for Th(IV) remained 864 to 15,000 ml/g for *both* the deep and Culebra brines.

We then compared the revised range with the data from the transport study with intact Culebra cores by Lucero and his colleagues at SNL. Lucero carried out his experiments under ambient atmospheric conditions; therefore, the CO₂ content of these

experiments was probably similar to that in the LANL bench-top (0.033% CO₂) runs. Because Lucero *did not* observe breakthrough of Th(IV), it was only possible to determine a minimum K_d for this element. Furthermore, the minimum K_ds calculated for Th are significantly lower than those calculated for Pu and Am, the other elements for which Lucero did not observe breakthrough (compare Tables B-8, C-9, and E-6), because: (1) the detection limit of γ-spectrometric analysis (one of the two methods used in this study) for ²²⁸Th in the effluent is much higher than those for ²⁴¹Pu and ²⁴¹Am because of the low yield of the ²²⁸Th γ emission; (2) although ²²⁸Th emits α particles detectable by LSC (the other analytical method used in this study), its daughter products have interfering α emissions; (3) lowering the detection limit for ²²⁸Th by observing the decay of its daughters, such as ²²⁴Ra, was not possible because of interference by identical daughters produced by the decay of ²³²U, which was used in all of the cores. Lucero and his colleagues submitted their results on March 28, 1996, (Table E-5), then revised them on April 5, 1996 (Table E-6). The minimum K_ds reported for experiments C-2, C-5, and D-2 (Table E-6) *are consistent with the revised range obtained from the empirical and mechanistic sorption studies* (see above). Therefore, our *final* range remains 864 to 15,000 ml/g, rounded to 900 to 20,000 ml/g prior to inclusion in Table 1 above.

We recommend that PA personnel use a uniform probability distribution for this range (see Methods Used to Establish Probability Distributions of Matrix K_ds above).

Finally, based on the oxidation-state analogy, we recommend that PA use a range of 900 to 20,000 ml/g for Pu(IV), U(IV), and Np(IV) (see Table 1).

Table E-1. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Th(IV), Dolomite-Rich Culebra Rock, and Brine A (LANL Empirical Sorption Study). Six -week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 30 and April 3, 1996, based on information provided by LANL on March 28 and April 1, 1996. Table checked by Brush and S. Boone on April 3, 1996.

Brine	Initial ^{230}Th Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
Brine A	ND	ND	ND	ND	ND
Brine A	ND	ND	ND	ND	ND
Brine A	ND	ND	ND	ND	ND
Brine A	ND	ND	ND	ND	ND
Brine A	ND	ND	ND	ND	ND
Brine A	ND	ND	ND	ND	ND
Brine A	NA	313, #7011A	205, #7053A	338, #7025A	694, #7039A
Brine A	NA	250, #7011B	227, #7053B	352, #7025B	706, #7039B
Brine A	ND	ND	ND	ND	ND
Brine A	ND	ND	ND	ND	ND

NA: not available yet.

ND: not determined.

Table E-2. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Th(IV), Dolomite-Rich Culebra Rock, and ERDA-6 (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 30 and April 3, 1996, based on information provided by LANL on March 28 and April 1, 1996. Table checked by Brush and S. Boone on April 3, 1996.

Brine	Initial ^{230}Th Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
ERDA-6	ND	ND	ND	ND	ND
ERDA-6	ND	ND	ND	ND	ND
ERDA-6	NA	5,340, #7007A	6,600, #7049A	12,900, #7021A	4,600, #7035A
ERDA-6	NA	5,270, #7007B	8,950, #7049B	15,900, #7021B	7,060, #7035B
ERDA-6	NA	6,650, #7008A	8,720, #7050A	8,670, #7022A	7,340, #7036A
ERDA-6	NA	15,000, #7008B	6,450, #7050B	7,780, #7022B	9,620, #7036B
ERDA-6	NA	2,180, #7009A	1,640, #7051A	14,100, #7023A	6,810, #7037A
ERDA-6	NA	2,820, #7009B	3,740, #7051B	7,270, #7023B	45,600, #7037B
ERDA-6	NA	864, #7010A	1,930, #7052A	High, #7024A	364, #7038A
ERDA-6	NA	1,300, #7010B	1,780, #7052B	1,130, #7024B	2,850, #7038B

NA: not available yet.

ND: not determined.

Table E-3. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Th(IV), Dolomite-Rich Culebra Rock, and AISinR (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 30 and April 3, 1996, based on information provided by LANL on March 28 and April 1, 1996. Table checked by Brush and S. Boone on April 3, 1996.

Brine	Initial ^{230}Th Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
AISinR	ND	ND	ND	ND	ND
AISinR	ND	ND	ND	ND	ND
AISinR	ND	ND	ND	ND	ND
AISinR	ND	ND	ND	ND	ND
AISinR	ND	ND	ND	ND	ND
AISinR	ND	ND	ND	ND	ND
AISinR	NA	High, #7012A	10,800, #7054A	4,580, #7026A	57,100, #7040A
AISinR	NA	High, #7012B	16,900, #7054B	7,080, #7026B	High, #7040B
AISinR	ND	ND	ND	ND	ND
AISinR	ND	ND	ND	ND	ND

NA: not available yet.

ND: not determined.

Table E-4. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Th(IV), Dolomite-Rich Culebra Rock, and H-17 (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 30 and April 3, 1996, based on information provided by LANL on March 28 and April 1, 1996. Table checked by Brush and S. Boone on April 3, 1996.

Brine	Initial ^{230}Th Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
H-17	ND	ND	ND	ND	ND
H-17	ND	ND	ND	ND	ND
H-17	ND	ND	ND	ND	ND
H-17	ND	ND	ND	ND	ND
H-17	ND	ND	ND	ND	ND
H-17	ND	ND	ND	ND	ND
H-17	NA	12,100, #7013A	7,580, #7055A	High, #7027A	14,500, #7041A
H-17	NA	High, #7013B	High, #7055B	23,700, #7027B	14,300, #7041B
H-17	ND	ND	ND	ND	ND
H-17	ND	ND	ND	ND	ND

NA: not available yet.

ND: not determined.

Table E-5. Minimum Values of R and K_d for Th(IV) in Intact Culebra Cores (SNL Column Transport Study). Data current as of March 26, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R_{min}	Porosity (%)	$K_{d, min}$ (ml/g)	Range ($\pm$ ml/g)
C-2	VPX-28-6C	AIS.	0.1	237	34.15	35	5.7, ^S 3.5 ^D	0.87	NA
C-5	VPX-28-6C	ER.-6	0.1	146	20.98	22	3.9, ^S 2.3 ^D	0.36	NA
D-2	VPX-25-8A	AIS.	0.1	133	19.12	8.5	8.2, ^S 5.5 ^D	0.25	NA

AIS: AISinR.

D: dual porosity assumed.

ER-6: ERDA-6.

NA: not available yet.

S: single porosity assumed.

Table E-6. Minimum Values of R and K_d for Th(IV) in Intact Culebra Cores (SNL Column Transport Study). Data current as of March 26, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996. Table revised by Brush on April 6, 1996, based on memo by Lucero and Brown dated April 5, 1996. Table checked by Y. Behl on April 8, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Effluent Vol. (L)	R_{min}	Porosity (%)	$K_{d, min}$ (ml/g)	Range ($\pm$ ml/g)
C-2	VPX-28-6C	AIS.	0.1	237	34.15	35	5.7 ^S	0.87	NA
C-5	VPX-28-6C	ER.-6	0.1	146	20.98	22	3.9 ^S	0.36	NA
D-2	VPX-25-8A	AIS.	0.1	133	19.12	8.5	8.2 ^S	0.25	NA

AIS: AISinR.

ER.-6: ERDA-6.

NA: not available yet.

S: single porosity assumed.

APPENDIX F: RANGES AND PROBABILITY DISTRIBUTIONS OF
MATRIX K_d s FOR Np(V) AND DOLOMITE-RICH
CULEBRA ROCK

Based on experimental results, ASTP personnel have predicted that Np will speciate as Np(IV) or Np(V), but not as Np(VI), in deep (Castile and Salado) brines in WIPP disposal rooms. Furthermore, a modeling study of the effects of mixing deep and Culebra brines on the oxidation states of Pu, U, and Np in the Culebra showed that Culebra fluids are poorly poised (see Predictions of Actinide Oxidation States in the Culebra above). Therefore, we established experimentally obtained ranges of matrix K_d s for Np(V) and used the experimentally obtained ranges for Th(IV) (see Appendix E above) and the oxidation-state analogy to establish ranges for Np(IV) (and U(IV)).

For the *initial* ranges for Np(V) and the deep brines, we first considered *all* of the data from the 6-week empirical sorption experiments carried out with Brine A and ERDA-6 on the bench top (0.033% CO_2) by Triay and her group at LANL (see Methods Used to Establish Ranges of Matrix K_d s above for the reasons for considering these data). These runs were: #6020, #6040, #6060, and #6080 (see Table F-1 below), and #6021, #6041, #6061, #6081 (Table F-2). Next, we discarded the data from #6040, #6021, and #6041, the runs in which the difference between the activity of the ^{237}Np in a standard and that in a control exceeded 3σ , where σ is the standard deviation (see Methods Used to Establish Ranges of Matrix K_d s). Discarding the data from these three runs yielded an *initial* range of 8.64 ml/g (from #6020) to 47.7 ml/g (#6061) for Np(V) and the deep brines.

For the *initial* ranges for Np(V) and the Culebra brines, we first considered *all* of Triay's 6-week sorption data obtained with AISinR and H-17 on the bench top (0.033% CO_2) and in glove boxes with atmospheres containing 0.24 and 1.4% CO_2 (see Methods Used to Establish Ranges of Matrix K_d s). These were: #6022, #6042, #6062, #6082, #24022, #24042, #24062, #24082, #12022, #12042, #12062, and #12082 (Table F-3), and #6023, #6043, #6063, #6083, #24023, #24043, #24063, #24083, #12023, #12043, #12063, and #12083 (Table F-4). We then discarded the data from #24042 and #24082, the runs in which the difference between the activity of the ^{237}Np in a standard and that in a control exceeded 3σ , to obtain the *initial* range of 2.09 ml/g (from #12022) to 163 ml/g (#6042) for Np(V) and the Culebra brines.

Next, we compared these initial ranges with the data from the mechanistic sorption study by Brady and his colleagues at SNL and LANL. We used Brady's data to extend Triay's empirical sorption data for the deep brines to the basic conditions expected to result from the use of an MgO backfill in WIPP disposal rooms, *but not* to extend Triay's data for the Culebra brines to basic conditions (see Methods Used to Establish Ranges of Matrix K_d s). Brady's data for 0.5 M NaCl, atmospheric CO_2 , and the highest pH values under these conditions are (to three significant figures) 892 and 938 ml/g at a pH of 9.87 and 9.88, respectively (Table F-5). Because these values are *greater than the upper limit* of the initial range for Np(V) and the deep brines (see above), we extended

this range to obtain a *revised* range for Np(V) and deep brines of 8.64 to 938 ml/g. Because we did not use this comparison to extend the initial range for Np(V) and the Culebra brines to basic conditions, this *revised* range remains 2.09 to 163 ml/g.

We then compared both of these revised ranges with the data from the transport study with intact Culebra cores by Lucero and his colleagues at SNL. Lucero carried out his experiments under ambient atmospheric conditions; therefore, the CO₂ content of these experiments was probably similar to that in the LANL bench-top (0.033% CO₂) runs. Lucero *did* observe breakthrough of Np(V) in his experiments. Therefore, it was possible to determine actual K_ds for this element. Lucero and his colleagues submitted their results on March 28, 1996, (see Table F-6), then revised them on April 5, 1996 (Table F-7). The K_d reported for Experiment C-7 with the deep brine ERDA-6 (Table F7) *is less than the lower limit of the revised range of K_ds for Np(V) and the deep brines obtained from the empirical and mechanistic sorption experiments* (see above). Therefore, we extended this range to obtain a *final* range for Np(V) and deep brines of 2.0 to 938 ml/g, and rounded it to 2 to 900 ml/g prior to inclusion in Table 1 above. Because Lucero's K_ds for Np(V) and the Culebra brine AISinR (C-6, D-2, and D4 in Table F-7), *are also less than the lower limit of the revised range for Np(V) and the Culebra brines obtained from the sorption studies* (see above), we extended this range to obtain a *final* range of 1.0 to 163 ml/g, rounded to 1 to 200 ml/g (Table 1).

We recommend that PA personnel use a uniform probability distribution for both of these ranges (see Methods Used to Establish Probability Distributions of Matrix K_ds above).

Furthermore, we recommend that PA use the range of 1 to 200 ml/g (the range for Culebra brines) for Np(V) because this range results in less retardation of this element than the range for deep brines (see Methods Used for Final Selection of the Range of Matrix K_ds for Use in PA Calculations above).

Table F-1. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Np(V), Dolomite-Rich Culebra Rock, and Brine A (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{237}Np Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
Brine A	ND	ND	ND	ND	ND
Brine A	6.80×10^{-7} to 9.26×10^{-6}	8.64, #6020	5.05, #24020	224, #12020	380, #18020
Brine A	3.86×10^{-6} to 4.52×10^{-6}	16.1, #6040	31.9, #24040	11.8, #12040	8.91, #18040
Brine A	6.09×10^{-7} to 6.56×10^{-7}	20.3, #6060	150, #24060	21.3, #12060	21.9, #18060
Brine A	2.16×10^{-7} to 2.58×10^{-7}	37.5, #6080	32.5, #24080	36.7, #12080	27.0, 18080

ND: not determined.

Table F-2. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Np(V), Dolomite-Rich Culebra Rock, and ERDA-6 (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{237}Np Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
ERDA-6	ND	ND	ND	ND	ND
ERDA-6	4.43×10^{-7} to 9.85×10^{-7}	218, #6021	241, #24021	562, #12021	508, #18021
ERDA-6	4.81×10^{-7} to 1.46×10^{-6}	55.2, #6041	181, #24041	153, #12041	117, #18041
ERDA-6	1.70×10^{-7} to 5.58×10^{-7}	47.7, #6061	280, #24061	163, #12061	29.9, #18061
ERDA-6	8.59×10^{-9} to 2.78×10^{-7}	31.7, #6081	14,000, #24081	High! #12081	High! #18081

ND: not determined.

Table F-3. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Np(V), Dolomite-Rich Culebra Rock, and AISinR (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{237}Np Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
AISinR	ND	ND	ND	ND	ND
AISinR	7.62×10^{-6} to 8.72×10^{-6}	5.12, #6022	3.70, #24022	2.09, #12022	2.19, #18022
AISinR	6.06×10^{-7} to 4.53×10^{-6}	163, #6042	11.9, #24042	2.35, #12042	2.23, #18042
AISinR	5.26×10^{-7} to 8.08×10^{-7}	20.4, #6062	9.64, #24062	4.06, #12062	4.83, #18062
AISinR	2.39×10^{-7} to 3.81×10^{-7}	32.9, #6082	46.7, #24082	9.89, #12082	10.4, #18082

ND: not determined.

Table F-4. Effects of Initial Radionuclide Concentration and P_{CO_2} on Matrix K_d s for Np(V), Dolomite-Rich Culebra Rock, and H-17 (LANL Empirical Sorption Study). Six-week sorption runs with VPX-25-8. No K_d s in this table excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of April 3, 1996. Table compiled by L. H. Brush on March 23 and 30, 1996, based on information provided by LANL on March 19 and 26, 1996. Table checked by Brush and S. Boone on April 3, 1996. Table revised by Brush on June 7, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Range of Initial ^{237}Np Conc. (M)	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 0.24% CO_2	K_d (ml/g), 1.4% CO_2	K_d (ml/g), 4.1% CO_2
H-17	ND	ND	ND	ND	ND
H-17	2.88×10^{-7} to 9.88×10^{-6}	52.4, #6023	19.0, #24023	2.96, #12023	1.40, #18023
H-17	3.30×10^{-6} to 4.93×10^{-6}	15.8, #6043	13.3, #24043	3.23, #12043	2.37, #18043
H-17	3.44×10^{-7} to 8.87×10^{-7}	40.1, #6063	25.8, #24063	47.1, #12063	4.61, #18063
H-17	2.16×10^{-7} to 8.19×10^{-6}	44.2, #6083	8.02, #24083	3.79, #12083	6.60, #18083

ND: not determined.

Table F-5. Effects of pH and P_{CO_2} on Matrix K_d s for Np(V) and Pure Dolomite (SNL/LANL Mechanistic Sorption Study). Sorption runs with Norwegian dolomite and 0.5 M NaCl. Data current as of March 31, 1996. Table retyped by L. H. Brush on April 24, 1996. Table checked by Y. Behl on April 28, 1996.

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
9.88	938.1	NA	NA
9.87	891.95	NA	NA
8.42	324.37	NA	NA
6.7	59.493	NA	NA
6.2	59.493	NA	NA
5.81	-6.7249	NA	NA
5.21	59.493	NA	NA
4.62	59.493	NA	NA
4.05	59.493	NA	NA
3.51	59.493	NA	NA
3.11	-6.7249	NA	NA

NA: not applicable.

Table F-5. Effects of pH and P_{CO_2} on Matrix K_d s for Np(V) and Pure Dolomite
(SNL/LANL Mechanistic Sorption Study) (continued).

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
6.9	NA	82.353	NA
8.49	NA	623.53	NA
7.32	NA	352.94	NA
7.19	NA	248.87	NA
6.99	NA	248.87	NA
6.88	NA	159.66	NA
6.55	NA	82.353	NA
6.17	NA	159.66	NA
5.28	NA	82.353	NA
3.97	NA	82.353	NA
3.13	NA	159.66	NA

NA: not applicable.

Table F-5. Effects of pH and P_{CO_2} on Matrix K_d s for Np(V) and Pure Dolomite (SNL/LANL Mechanistic Sorption Study) (continued).

pH (standard units)	K_d (ml/g), atmospheric CO_2	K_d (ml/g), 0.5% CO_2	K_d (ml/g), 5% CO_2
6.39	NA	NA	-56.83
6.91	NA	NA	100.36
6.89	NA	NA	0
6.8	NA	NA	100.36
6.75	NA	NA	100.36
6.84	NA	NA	100.36
6.49	NA	NA	100.36
6.07	NA	NA	15.721
5.76	NA	NA	15.721
4.91	NA	NA	100.36
3.62	NA	NA	15.721

NA: not applicable.

Table F-6. Measured Values of R and Calculated Values of K_d for Np(V) in Intact Culebra Cores (SNL Column Transport Study). Values in bold font to be excluded from ranges and distributions because fits to elution data were inferior to those assuming single porosity and dual porosity with fracture retardation. Data current as of March 30, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R	Porosity	K_d (ml/g)	Range ($\pm$ ml/g)
C-5	VPX-28-6C	ER.-6	0.1	13	2	30.8; ^S 1, 166; ^{DN} 7.0, 103 ^{DF}	3.9 ^S 2.3 ^{DN} 2.3 ^{DF}	0.51 ^S 1.65 ^{DN} 0.06 ^{DF}	0.29 ^S 1.0 ^{DN} 0.03 ^{DF}
C-6	VPX-28-6C	AIS.	0.1	13	2	58.5; ^S 1, 301; ^{DN} 22, 158 ^{DF}	4.5 ^S 1.85 ^{DN} 1.85 ^{DF}	1.12 ^S 2.4 ^{DN} .169 ^{DF}	0.26 ^S 1.4 ^{DN} .048 ^{DF}
C-7	VPX-28-6C	ER.-6	0.1	13	2	119; ^S 1, 910; ^{DN} 169, 0 ^{DF}	3.9 ^S 2.1 ^{DN} 2.1 ^{DF}	2.0 ^S 8.3 ^{DN} 1.53 ^{DF}	0.8 ^S 11.9 ^{DN} 38 ^{DF}
D-2	VPX-25-8A	AIS.	0.1	12	2	47; ^S 1, 1670; ^N 6.6, NA ^{DF}	8.2 ^S 5.5 ^{DN} 5.5 ^{DF}	1.64 ^S 40 ^{DN} NA ^{DF}	0.58 ^S 6 ^{DN} NA ^{DF}

Table F-6. Measured Values of R and Calculated Values of K_d for Np(V) in Intact Culebra Cores (SNL Column Transport Study) (continued).

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R	Porosity	K_d (ml/g)	Range ($\pm$ ml/g)
D-4	VPX-25-8A	AIS.	0.1	13	2	39; ^S 1, 340; ^{DN} 17.5, 154 ^{DF}	10.0 ^S 4.8 ^{DN} 4.8 ^{DF}	1.65 ^S 7.1 ^{DN} 0.34 ^{DF}	0.22 ^S 4.2 ^{DN} 0.07 ^{DF}

AIS: AISinR.

DF: dual porosity and fracture retardation assumed.

DN: dual porosity and no fracture retardation assumed.

ER-6: ERDA-6.

NA: not available yet.

S: single porosity assumed.

Table F-7. Measured Values of R and Calculated Values of K_d for Np(V) in Intact Culebra Cores (SNL Column Transport Study). Data current as of March 30, 1996. Table compiled by L. H. Brush on March 30, 1996, based on memo by D. A. Lucero, G. O. Brown, and K. G. Budge dated March 28, 1996. Table checked by Brush on March 31, 1996. Table revised by Brush on April 6, 1996, based on memo by Lucero and Brown dated April 5, 1996. Table checked by Y. Behl on April 8, 1996.

Run #	Solid (core)	Brine	Flow rate (ml/min)	Run Time (days)	Ef-fluent Vol. (L)	R	Poro-sity	K_d (ml/g)	Range ($\pm$ ml/g)
C-6	VPX-28-6C	AIS.	0.1	13	2	59 ^S	4.5 ^S	1.1 ^S	NA
C-7	VPX-28-6C	ER-6	0.1	13	2	120 ^S	3.9 ^S	2.0 ^S	NA
D-2	VPX-25-8A	AIS.	0.1	12	2	47 ^S	8.2 ^S	1.6 ^S	NA
D-4	VPX-25-8A	AIS.	0.1	13	2	39 ^S	10.0 ^S	1.6 ^S	NA

AIS: AISinR.

ER-6: ERDA-6.

NA: not available yet.

S: single porosity assumed.

APPENDIX G: EFFECTS OF ORGANIC LIGANDS ON RANGES AND
PROBABILITY DISTRIBUTIONS OF MATRIX K_d s
FOR Pu(V), Am(III), U(VI), Th(IV), Np(V), AND
DOLOMITE-RICH CULEBRA ROCK

Triay and her group at LANL carried out two sets of experiments on the effects of four organic ligands (acetate, citrate, ethylenediaminetetraacetic acid or EDTA, and lactate) on the K_d s for dissolved Pu(V), Am(III), U(VI), Th(IV), and Np(V) under conditions expected in the Culebra. Brush (1990) concluded that these and six other organic and two inorganic ligands could affect the solubilities of the actinide elements in TRU waste. Therefore, he estimated the concentrations of these 12 ligands in three quantities of brine that could resaturate WIPP disposal rooms after filling and sealing. Since 1990, the ASTP has reduced the number of organic ligands of concern from twelve to four (acetate, citrate, EDTA, and oxalate). Triay carried out experiments with acetate, citrate, EDTA, and lactate because the ASTP had not eliminated lactate from consideration yet, and because Triay concluded that oxalate would be extremely insoluble given the dissolved Ca concentrations expected in WIPP brines. Triay conducted the first set of runs with ERDA-6 and H17, and acetate, citrate, EDTA, and lactate all present at concentrations as close as possible to the "minimum" and "maximum" concentrations estimated by Brush (1990) (see Table G-1 below). Soon after Triay started their preliminary experiments, Weiner (1996) used the quantities of acetate, citrate, EDTA, and oxalate in TRU waste estimated by Drez (1996) to predict the concentrations of these organic ligands in brines in the repository (Table G-1).

Tables G-2, G-3, G-4, G-5, and G-6 give the results of the preliminary experiments with ERDA-6 and H-17, and Pu(V), Am(III), U(VI), Th(IV), and Np(V), respectively. At low concentrations, acetate, citrate, EDTA, and lactate have little or no effect on the K_d s for these elements (compare the results for "low-concentration organics" to those for "none," the runs without any organic ligands present.) In fact, for Pu(V) and ERDA-6 in contact with ambient atmospheric or (about 0.033%) CO_2 ; Am(III), ERDA-6, and 0.033% CO_2 ; and U(VI), ERDA-6, and 0.033% CO_2 , low concentrations of these organic ligands actually *increase* the K_d s relative to those obtained without any organic ligands. However, at high concentrations, these organic ligands significantly *decrease* the K_d s for all of these elements. Note that the low and the high concentrations of acetate, citrate, and EDTA used in these preliminary runs bracket the predicted concentrations of these organic ligands (Table G-1).

Triay used ERDA-6 and H-17, which contain 19 and 74.1 mM Mg, respectively, for this set of experiments. However, ASTP personnel have predicted the effects of acetate, citrate, EDTA, and oxalate on the solubilities of the actinide elements by assuming that all of these organic ligands will dissolve in intergranular Salado brine as it accumulates in WIPP disposal rooms. Novak (1996) used FMT to predict that the Mg concentration in SPC brine (Brine A modified by omitting minor and trace constituents, and used by the ASTP to simulate Salado brine in several experimental and modeling studies) will be 454 mM after equilibration with halite, anhydrite, the actinide elements and the organic ligands in TRU waste, and an MgO backfill. This Mg concentration is significantly higher than that of ERDA-6 before or after equilibration with this backfill (19 and 48 mM, respectively) and significantly higher than that of H-17 (74.1 mM). Because we hoped that competition among Mg and Pu, Am, U, Th, and Np for the binding sites on these organic ligands

would mitigate the effects of these organics on the K_d s for these elements. Triay carried out an additional set of experiments with acetate, citrate, EDTA, and lactate at low, intermediate, and high concentrations (see Table G-1) and with Brine A modified to simulate the composition of Salado brine after equilibration with an MgO backfill.

Table G-7 shows the results of these experiments. Low concentrations of organics significantly decreased the K_d s for Th relative to those obtained without any organics, but had much less effect on the K_d s for the other elements. Intermediate concentrations of organics significantly decreased the K_d s for all of the elements except U(VI). High concentrations significantly decreased the K_d s for all five of these elements.

However, we *have not* revised the ranges and probability distributions of K_d s for Pu, Am, U, Th, and Np shown in Table 1 (see above) because large quantities of other metals (see below) will be present to form complexes with these organic ligands, thus preventing them from forming complexes with the actinide elements and decreasing the K_d s for the actinides in the Culebra. (These other metals will also prevent these organic ligands from increasing the solubilities of the actinide elements in WIPP disposal rooms.) These other metals include Fe, large quantities which will be present in WIPP disposal rooms in steel waste containers (drums and boxes) and as steels, stainless steels, and other Fe-base materials in the waste; Mg, large quantities of which will be emplaced in the repository as an MgO backfill to remove microbially produced CO_2 (but will be present as MgCO_3 and/or $\text{Mg}(\text{OH})_2$, and magnesium oxychloride after reaction with CO_2 and/or brine); and Cr, Mn, Ni, Pb, and V, which will be present in lesser but still sufficient quantities in steel drums and boxes, and in steels, stainless steels, and other Fe-base alloys in the waste, and in other waste constituents. Preliminary modeling of the equilibria among dissolved and solid-phase Pu and Am, Fe, Mg, and Ni, and EDTA imply that, under the conditions expected in WIPP disposal rooms, Ni would form complexes with 99.8% of the EDTA expected to be present in the repository, thus preventing it from complexing significant quantities of Pu and Am. A detailed description of these calculations, and any additional modeling or laboratory studies of these competitive equilibria, will appear elsewhere.

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June 10, 1996

Weiner, R. 1996. "Dissolved Ligand Concentrations." Unpublished memorandum to C. F. Novak, March 27, 1996. Albuquerque, NM: Sandia National Laboratories.

Table G-1. Concentrations of Organic Ligands in Experiments with ERDA-6, H-17, and Modified Brine A, and Predicted Concentrations of Organic Ligands in Brines in WIPP Disposal Rooms. Table compiled by L. H. Brush on May 10, 1996, based on information provided by LANL on April 25, 1996. Table checked by L. J. Storz on May 17, 1996.

Organic Ligand	Low Conc. (ERDA-6 and H-17) (mM)	High Conc. (ERDA-6 and H-17) (mM)	Low Conc. (Modified Brine A) (mM)	Intermediate		Predicted Conc. in WIPP (mM)
				Conc. (Modified Brine A) (mM)	High Conc. (Modified Brine A) (mM)	
Acetate	0.195 (ERDA-6)	19.5172 (ERDA-6)	0.489	4.89	48.9	1.062
	0.195 (H-17)	19.5172 (H-17)				
Citrate	0.0340 (ERDA-6)	3.4002 (ERDA-6)	0.03417	0.3417	3.417	0.465
	0.0340 (H-17)	3.4002 (H-17)				
EDTA	0.000146 (ERDA-6)	0.0146 (ERDA-6)	0.00011	0.0011	0.011	0.00416
	0.000146 (H-17)	0.0146 (H-17)				
Lactate	0.00761 (ERDA-6)	0.7610 (ERDA-6)	0.02088	0.2088	2.088	Not predicted
	0.00796 (H-17)	0.7956 (H-17)				
Oxalate	NU	NU	NU	NU	NU	7.404

NU: Not used because LANL expected Ca-oxalate to precipitate from these brines at very low oxalate concentrations.

Table G-2. Effects of Brine, Organic Ligands, and P_{CO_2} on Matrix K_d s for Pu(V) and Dolomite-Rich Culebra Rock (LANL Empirical Sorption Study). One-week sorption runs with H-19, B-4, Box 7. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Still counting new controls for underlined samples. Data current as of May 30, 1996. Table compiled by L. H. Brush on May 16, 1996, based on information provided by LANL on May 15, 1996. Table checked by L. J. Storz on May 16 and 17, 1996. Table revised by Brush on May 31 and June 1, 1996, based on information provided by LANL on May 30 and 31, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Additive	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 4.1% CO_2
ERDA-6	None	157, #JRF O-131	<u>217</u> , #JRF O-181
ERDA-6	None	158, #JRF O-132	<u>223</u> , #JRF O-182
ERDA-6	Avg. without organics	158	<u>220</u>
ERDA-6	Low-conc. organics	787, #JRF O-139	171, #JRF O-189
ERDA-6	Low-conc. organics	142, #JRF O-140	184, #JRF O-190
ERDA-6	Avg. w. low-conc. org.	464	178
ERDA-6	High-conc. organics	6.44, #JRF O-137	10.3, #JRF O-187
ERDA-6	High-conc. organics	7.48, #JRF O-138	9.10, #JRF O-188
ERDA-6	Avg. w. high-conc. org.	6.96	9.70

Table G-2. Effects of Brine, Organic Ligands, and P_{CO_2} on Matrix K_d s for Pu(V) and Dolomite-Rich Culebra Rock (LANL Empirical Sorption Study) (continued).

Brine	Additive	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 4.1% CO_2
H-17	None	18.4, #JRF O-31	<u>8.51,</u> <u>#JRF O-81</u>
H-17	None	19.8, #JRF O-32	<u>9.19,</u> <u>#JRF O-82</u>
H-17	Avg. without organics	19.1	<u>8.85</u>
H-17	Low-conc. organics	9.50, #JRF O-39	4.45, #JRF O-89
H-17	Low-conc. organics	17.0, #JRF O-40	7.73, #JRF O-90
H-17	Avg. w. low-conc. org.	13.2	6.14
H-17	High-conc. organics	1.39, #JRF O-37	0.315, #JRF O-87
H-17	High-conc. organics	0.934, #JRF O-38	0.515, #JRF O-88
H-17	Avg. w. high-conc. org.	1.16	0.415

Table G-3. Effects of Brine, Organic Ligands, and P_{CO_2} on Matrix K_d s for Am(III) and Dolomite-Rich Culebra Rock (LANL Empirical Sorption Study). One-week sorption runs with H-19, B-4, Box 7. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Still counting new controls for underlined samples. Data current as of May 30, 1996. Table compiled by L. H. Brush on May 16, 1996, based on information provided by LANL on May 15, 1996. Table checked by L. J. Storz on May 16 and 17, 1996. Table revised by Brush on May 31 and June 1, 1996, based on information provided by LANL on May 30 and 31, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Additive	K_d , (ml/g), 0.033% CO_2	K_d , (ml/g), 4.1% CO_2
ERDA-6	None	199, #JRF O-141	<u>2,890</u> , #JRF O-191
ERDA-6	None	1,220, #JRF O-142	<u>2,160</u> , #JRF O-192
ERDA-6	Avg. without organics	710	<u>2,520</u>
ERDA-6	Low-conc. organics	1,390 #JRF O-161	1,680, #JRF O-199
ERDA-6	Low-conc. organics	1,470, #JRF O-171	1,880, #JRF O-200
ERDA-6	Avg. w. low-conc. org.	1,430	1,780
ERDA-6	High-conc. organics	10.6, #JRF O-147	7.40, #JRF O-197
ERDA-6	High-conc. organics	7.84, #JRF O-151	5.05, #JRF O-198
ERDA-6	Avg. w. high-conc. org.	9.22	6.22

Table G-3. Effects of Brine, Organic Ligands, and P_{CO_2} on Matrix K_d s for Am(III) and Dolomite-Rich Culebra Rock (LANL Empirical Sorption Study) (continued).

Brine	Additive	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 4.1% CO_2
H-17	None	533, #JRF O-41	<u>379</u> , #JRF O-91
H-17	None	549, #JRF O-42	<u>391</u> , #JRF O-92
H-17	Avg. without organics	541	<u>385</u>
H-17	Low-conc. organics	503, #JRF O-49	311, #JRF O-99
H-17	Low-conc. organics	497, #JRF O-50	299, #JRF O-100
H-17	Avg. w. low-conc. org.	500	305
H-17	High-conc. organics	7.79, #JRF O-47	3.58, #JRF O-97
H-17	High-conc. organics	7.37, #JRF O-48	3.75, #JRF O-98
H-17	Avg. w. high-conc. org.	7.58	3.66

Table G-4. Effects of Brine, Organic Ligands, and P_{CO_2} on Matrix K_d s for U(VI) and Dolomite-Rich Culebra Rock (LANL Empirical Sorption Study). One-week sorption runs with H19, B-4, Box 7. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Still counting new controls for underlined samples. Negative K_d s set to 0.00 before determining the mean. Data current as of May 30, 1996. Table compiled by L. H. Brush on May 16, 1996, based on information provided by LANL on May 15, 1996. Table checked by L. J. Storz on May 16 and 17, 1996. Table revised by Brush on May 31 and June 1, 1996, based on information provided by LANL on May 30 and 31, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Additive	K_d , (ml/g), 0.033% CO_2	K_d , (ml/g), 4.1% CO_2
ERDA-6	None	-0.148, #JRF O-111	<u>-0.296</u> , #JRF O-159
ERDA-6	None	0.220, #JRF O-112	<u>0.275</u> , #JRF O-160
ERDA-6	Avg. without organics	0.110	<u>0.138</u>
ERDA-6	Low-conc. organics	<u>1.83</u> , #JRF O-119	<u>-0.0367</u> , #JRF O-168
ERDA-6	Low-conc. organics	<u>-0.371</u> , #JRF O-120	<u>-0.933</u> , #JRF O-169
ERDA-6	Avg. w. low-conc. org.	<u>0.915</u>	<u>0.00</u>
ERDA-6	High-conc. organics	<u>-0.631</u> , #JRF O-117	<u>-0.475</u> , #JRF O-166
ERDA-6	High-conc. organics	<u>-0.638</u> , #JRF O-118	<u>-0.948</u> , #JRF O-167
ERDA-6	Avg. w. high-conc. org.	<u>0.000</u>	<u>0.00</u>

Table G-4. Effects of Brine, Organic Ligands, and P_{CO_2} on Matrix K_d s for U(VI) and Dolomite-Rich Culebra Rock (LANL Empirical Sorption Study) (continued).

Brine	Additive	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 4.1% CO_2
H-17	None	-2.11, #JRF O-11	<u>-1.69,</u> <u>#JRF O-61</u>
H-17	None	-1.79, #JRF O-12	<u>-0.323,</u> <u>#JRF O-62</u>
H-17	Avg. without organics	0.00	<u>0.00</u>
H-17	Low-conc. organics	-1.27, #JRF O-19	-0.601, #JRF O-69
H-17	Low-conc. organics	-1.67, #JRF O-20	-1.44, #JRF O-70
H-17	Avg. w. low-conc. org.	0.00	0.00
H-17	High-conc. organics	-1.77, #JRF O-17	-1.81, #JRF O-67
H-17	High-conc. organics	-1.51, #JRF O-18	-1.67, #JRF O-68
H-17	Avg. w. high-conc. org.	0.00	0.00

Table G-5. Effects of Brine, Organic Ligands, and P_{CO_2} on Matrix K_d s for Th(IV) and Dolomite-Rich Culebra Rock (LANL Empirical Sorption Study). One-week sorption runs with H-19, B-4, Box 7. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Still counting new controls for underlined samples. Data current as of May 30, 1996. Table compiled by L. H. Brush on May 16, 1996, based on information provided by LANL on May 16, 1996. Table checked by L. J. Storz on May 16 and 17, 1996. Table revised by Brush on May 31 and June 1, 1996, based on information provided by LANL on May 30 and 31, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Additive	K_d , (ml/g), 0.033% CO_2	K_d , (ml/g), 4.1% CO_2
ERDA-6	None	120, #JRF O-101	<u>153</u> , #JRF O-148
ERDA-6	None	98.6, #JRF O-102	<u>169</u> , #JRF O-149
ERDA-6	Avg. without organics	109	<u>161</u>
ERDA-6	Low-conc. organics	101, #JRF O-109	157, #JRF O-157
ERDA-6	Low-conc. organics	99.9, #JRF O-110	166, #JRF O-158
ERDA-6	Avg. w. low-conc. org.	100	162
ERDA-6	High-conc. organics	30.0, #JRF O-107	55.0, #JRF O-155
ERDA-6	High-conc. organics	32.8, #JRF O-108	63.2, #JRF O-156
ERDA-6	Avg. w. high-conc. org.	31.4	59.1

Table G-5. Effects of Brine, Organic Ligands, and P_{CO_2} on Matrix K_d s for Th(IV) and Dolomite-Rich Culebra Rock (LANL Empirical Sorption Study) (continued).

Brine	Additive	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 4.1% CO_2
H-17	None	15.0, #JRF O-1	<u>12.0</u> , #JRF O-51
H-17	None	16.6, #JRF O-2	<u>11.3</u> , #JRF O-52
H-17	Avg. without organics	15.8	<u>11.6</u>
H-17	Low-conc. organics	13.8, #JRF O-9	9.72, #JRF O-59
H-17	Low-conc. organics	14.4, #JRF O-10	9.20, #JRF O-60
H-17	Avg. w. low-conc. org.	14.1	9.46
H-17	High-conc. organics	5.72, #JRF O-7	0.874, #JRF O-57
H-17	High-conc. organics	8.04, #JRF O-8	1.06, #JRF O-58
H-17	Avg. w. high-conc. org.	6.88	0.967

Table G-6. Effects of Brine, Organic Ligands, and P_{CO_2} on Matrix K_d s for Np(V) and Dolomite-Rich Culebra Rock (LANL Empirical Sorption Study). One-week sorption runs with H-19, B-4, Box 7. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Still counting new controls for underlined samples. Data current as of May 30, 1996. Table compiled by L. H. Brush on May 16, 1996, based on information provided by LANL on May 15, 1996. Table checked by L. J. Storz on May 16 and 17, 1996. Table revised by Brush on May 31 and June 1, 1996, based on information provided by LANL on May 30 and 31, 1996. Table checked by L. J. Storz on June 10, 1996.

Brine	Additive	K_d , (ml/g), 0.033% CO_2	K_d , (ml/g), 4.1% CO_2
ERDA-6	None	96.5, #JRF O-121	<u>136.</u> #JRF O-170
ERDA-6	None	87.6, #JRF O-122	<u>148.</u> #JRF O-172
ERDA-6	Avg. without organics	92.0	<u>142</u>
ERDA-6	Low-conc. organics	<u>83.6.</u> #JRF O-129	<u>175.</u> #JRF O-179
ERDA-6	Low-conc. organics	<u>79.1.</u> #JRF O-130	<u>147.</u> #JRF O-180
ERDA-6	Avg. w. low-conc. org.	<u>81.4</u>	<u>161</u>
ERDA-6	High-conc. organics	<u>63.9.</u> #JRF O-127	<u>131.</u> #JRF O-177
ERDA-6	High-conc. organics	<u>63.3.</u> #JRF O-128	<u>113.</u> #JRF O-178
ERDA-6	Avg. w. high-conc. org.	<u>63.6</u>	<u>122</u>

Table G-6. Effects of Brine, Organic Ligands, and P_{CO_2} on Matrix K_d s for Np(V) and Dolomite-Culebra Rock (LANL Empirical Sorption Study) (continued).

Brine	Additive	K_d (ml/g), 0.033% CO_2	K_d (ml/g), 4.1% CO_2
H-17	None	5.17, #JRF O-21	<u>0.905,</u> <u>#JRF O-71</u>
H-17	None	4.37, #JRF O-22	<u>1.06,</u> <u>#JRF O-72</u>
H-17	Avg. without organics	4.77	<u>0.983</u>
H-17	Low-conc. organics	4.86, #JRF O-29	1.33, #JRF O-79
H-17	Low-conc. organics	4.44, #JRF O-30	0.694, #JRF O-80
H-17	Avg. w. low-conc. org.	4.65	1.01
H-17	High-conc. organics	1.45, #JRF O-27	-0.236, #JRF O-77
H-17	High-conc. organics	1.67, #JRF O-28	-0.433, #JRF O-78
H-17	Avg. w. high-conc. org.	1.56	0.00

Table G-7. Effects of Organic Ligands on Matrix K_d s (ml/g) for Pu(V), Am(III), U(VI), Th(IV), and Np(V), Dolomite-Rich Culebra Rock, and Modified Brine A (LANL Empirical Sorption Study). One-week sorption runs with H-19, B-4, Box 7. K_d s in bold font excluded from ranges and distributions because of unacceptable differences between standards and controls. Data current as of May 30, 1996. Table compiled by L. H. Brush on May 16, 1996, based on information provided by LANL on May 15, 1996. Table checked by L. J. Storz on May 16, 1996. Table revised by Brush on May 31, 1996, based on information provided by LANL on May 30, 1996. Table checked by L. J. Storz on June 10, 1996.

Element and Oxidation State					
Additive	Pu(V)	Am(III)	U(VI)	Th(IV)	Np(V)
None	8.73, #JRF-233	528, #JRF-243	19.3, #JRF-213	11,300, #JRF-203	22.7, #JRF-223
None	10.1, #JRF-234	501, #JRF-244	19.1, #JRF-214	10,700, #JRF-204	17.1, #JRF-224
Avg. without organics	9.42	514	19.2	11,000	19.9
Low-conc. organics	7.69, #JRF-239	355, #JRF-249	12.4, #JRF-219	1.70, #JRF-209	11.9, #JRF-229
Low-conc. organics	8.84, #JRF-240	325, #JRF-250	17.2, #JRF-220	6.47, #JRF-210	10.5, #JRF-230
Avg. w. low- conc. organics	8.26	340	14.8	4.08	11.2
Intermed.- conc. organics	5.03, #JRF-237	67.6, #JRF-247	16.6, #JRF-217	1.05, #JRF-207	6.25, #JRF-227
Intermed.- conc. organics	5.06, #JRF-238	36.7, #JRF-248	16.8, #JRF-218	6.29, #JRF-208	5.89, #JRF-228
Avg. w. inter.- conc. org.	5.04	52.2	16.7	3.67	6.07

Table G-7. Effects of Organic Ligands on Matrix K_{ds} (ml/g) for Pu(V), Am(III), U(VI), Th(IV), and Np(V), Dolomite-Rich Culebra Rock, and Modified Brine A (LANL Empirical Sorption Study) (continued).

Additive	Element and Oxidation State				
	Pu(V)	Am(III)	U(VI)	Th(IV)	Np(V)
High-conc. organics	2.55, #JRF-235	2.34, #JRF-245	10.1, #JRF-215	0.469, #JRF-205	1.93, #JRF-225
High-conc. organics	2.22, #JRF-236	2.05, #JRF-246	8.01, #JRF-216	0.467, #JRF-206	2.49, #JRF-226
Avg. w. high-conc. org.	2.38	2.20	9.06	0.468	2.21

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WBS: 1.1.10.3.4

date: 9 June, 1997

to: ED:Lucero MS-1320 (6832)

Malcolm Siegel for CC Craft

from: C. C. Craft, M. D. Siegel, MS-1320 (6832)

subject: Additional calculations of solubility-limited concentrations of actinides for injection spikes used in WIPP core column experiments at Sandia National Laboratories

INFORMATION ONLY

Summary

Calculations have been previously carried out to evaluate the possibility that precipitation of neptunium, americium, or thorium had occurred in either the VPX series or ERDA-6 WIPP core column experiments at Sandia National Laboratories (Siegel, 1996a). This memo summarizes a second round of solubility calculations using the most recent, QA-approved version of the FMT code (version 2.3, "FMT_PA97.EXE") on the VAX Alpha machines. The calculations corroborate the conclusions of the previous calculations: it is likely that the initial concentrations of Am in VPX-28 water exceeded the solubility of AmOHCO_3 solid. Initial concentrations of Np and Th in the columns in ERDA-6 and VPX-28 were below the solubility limits of their respective stable solids. The calculations also suggest that the compositions of the solutions used in the core column experiments were slightly different than those measured in the field. The calculations suggest that under atmospheric conditions, the recipes used to mix the brines correspond to solutions that would be supersaturated with respect to calcite. However, it is unlikely that these compositional differences will affect the solubilities of the actinides significantly.

Method of Calculation

The recipes corresponding to salts used in synthesis of the brine simulants are shown in Table 1a. The data tables supplied by you are attached as Appendix A. The recipes used for the VPX-28 and ERDA-6 brines may be supersaturated with respect to dolomite under atmospheric conditions; therefore, the solubilities both with and without dolomite equilibrium were calculated. In cases where

dolomite in the mass balance and mass action calculations was not included, magnesite was also omitted. In FMT calculations, constant CO_2 partial pressure is represented by a condition in which excess "solid" CO_2 with a specific dimensionless chemical potential is present. For atmospheric $p\text{CO}_2$ the appropriate value of -167.151 is input for the CO_2 solid in the thermodynamic database (CHEMDAT file) called by the code. Details of the method of calculations for each water are given below.

In these calculations, the most recent version of the FMT database file (FMT_970407.CHEMDAT) was used after modifications to include constant CO_2 fugacity and excess radionuclide solids as described below. (Note that the identification of "active" solids is found in the CHEMDAT files and may not always agree with the comments in the INGUESS files).

When the above assumptions concerning CO_2 fugacity and stable solids are used in FMT calculations, the calculated equilibrium composition differ slightly from the salt recipes used to initially define the solutions. These differences are due to calculated precipitation or dissolution that changes the amount of calcium and carbonate in solution. The compositions of the final "stable" solutions according to the FMT calculations are compared to the field "or targeted" compositions in Table 1b.

Castile Waters: ERDA-6

The calculations were carried out in 4 steps:

- 1) BATCH calculation of brine speciation with the "nMOLES, nEXACT" flag and a fixed total CO_2 in the absence of radionuclides. The assumed salt concentrations for ERDA-6 are listed in Appendix A and are converted to molar concentrations in the attached Excel file SOLDAT2.xls (sheet "recipe"). (The calculated molar concentrations also can be found in the *.inguess files for each system). This calculation produces a *.for88 file.
- 2) A series of calculations was carried out next to correct for the fact that although the initial input values were molar concentrations, FMT accepts them as if they were molal concentrations. To correct for this, the *.for88 file was renamed to *.inguess, and a series of BATCH calculations were carried out with the "MOLES, EXACT" flag. In these calculations, the H_2O value was adjusted downward in the *.inguess file until the molar concentration value for Cl in the FMT.OUT file was equivalent to that found in Table 1b.
- 3) Calculation of brine speciation at fixed partial pressure of CO_2 in the absence of radionuclides (this is accomplished by renaming the FMT *.for88 file to a *.inguess file and specifying 10 moles of solid CO_2 in the file; this produces a second *.for88 file from a BATCH run.
- 4) Calculation of brine speciation at fixed partial pressure of CO_2 with an excess amount of radioelement. This is accomplished by renaming the *.for88 file to a *.inguess file, and specifying the concentrations of the solids $\text{Am}(\text{OH})_3$, NpO_2OH and $\text{ThO}_2(\text{am})$ to be 1 molar in a BATCH run.

The sums of the molar concentrations of the aqueous radionuclide species are reported as the solubility-limited radioelement concentrations in Table 2. The stable solid and the calculated pH values in equilibrium with atmospheric CO_2 are also listed.

Culebra waters VPX-28

Calculations for VPX-28 were carried out in a different way:

1. A BATCH run for pure water was used to create a *.for88 file.
2. The *.for88 files were renamed *.inguess files and these files were edited by specifying the molar amounts of salts listed in Table 1a above.
3. Further BATCH runs were made using the "MOLES,EXACT" flag, in which the H_2O was again adjusted to convert molarity to molality, but this time, the molar Br^- concentration in Table 1a was used as a reference.
4. The next two steps were the same as steps 3 and 4 in the calculations for ERDA-6 brine:
 - Calculation of brine speciation at fixed partial pressure of CO_2 in the absence of radionuclides (this is accomplished by renaming the FMT *.for88 file to a *.inguess file and specifying 10 moles of solid CO_2 in the file; this produces a second *.for88 file from a BATCH run.
 - Calculation of brine speciation at fixed partial pressure of CO_2 with an excess amount of radioelement (accomplished by renaming the *.for88 file to a *.inguess file, specifying the concentrations of the solids $\text{Am}(\text{OH})_3$, NpO_2OH and $\text{ThO}_2(\text{am})$ to be 1 molar in a BATCH run.)

Results and Discussion

Solubility-limiting concentrations of radionuclides in VPX-28 and ERDA-6 brines

The results of the calculations are summarized in Table 2. Output (and input) files for the BATCH runs are included on a disk that was submitted with this document to the WIPP Central Files. The 10 subdirectory names found there reflect the brines (ERDA-6 or VPX-28), the actinides (Am, Th, or Np), and the chemical conditions (dolomite present or absent) considered. Each subdirectory contains: 1) a ccc.com file which names the VAX files used in the calculation for that system, 2) a ccc.in file which describes the initial system in terms of total element concentrations, 3) a ccc.ing (inguess file) file which describes the input for the final radionuclide speciation calculation; 4) a ccc.for file which contains the tabulated results in the *.for88 file format, and 5) a ccc.out file which contains the results in the *.out format. For more description of the output file format, please refer to the Users Guide for the FMT code (Novak and Babb, 1995). The file SOLDAT2.xls tabulates the detailed speciation for each of the 10 systems examined. These Excel workbook sheets were prepared by importing text from the ccc.out files from each subdirectory on the diskette.

The calculations corroborate the conclusions of previous calculations: it is likely that the initial concentrations of Am in VPX-28 water exceeded the solubility of AmOHCO_3 solid. Initial concentrations of Np and Th in the columns in ERDA-6 and VPX-28 were below the solubility limits of their respective stable solids.

Uncertainty in brine compositions

Several sources of error in our predictions of solubilities are related to the solution compositions assumed in the calculations. Foremost among these is the lack of reliable measurements of the in-situ pmH or f_{CO_2} in the core column experiments. The results of the calculations of the solubilities and the pmH presented in this memo are valid only for systems in which equilibrium is established between atmospheric CO_2 and CO_2 in the pore water. Secondly, as mentioned above, these calculations suggest that the compositions of the solutions used in the core column experiments were slightly different than those measured in the field. It is likely that under atmospheric conditions, the recipes used to mix the brines correspond to solutions that would not be in equilibrium with calcite. In the case of ERDA-6 water, the calculations predict that some CO_2 is lost from the solution during equilibration with the atmosphere. Finally, the "trial and error" procedure described above that was used to convert molarity to molality in these calculations may introduce some error into the results.

As noted above, the compositions of the final "stable" solutions according to the FMT calculations are compared to the field or "targeted" compositions in Table 1b. The differences in compositions are consistent with observations that the compositions of the brines as measured by ICP differed from those predicted from the salt recipe used to prepare the brines (J. Kelly, personal communication), suggesting that some precipitation from VPX-28 may have occurred in the laboratory. The differences are within the observed uncertainty in ICP measurements for brines and similar to the compositional differences among the VPX series brines sampled in the Air Intake Shaft (Table 3, Lucero et al., 1995). It is unlikely that these compositional differences will affect the solubilities of the actinides significantly. However, these calculations do indicate that the composition and stability of brines used in any future diffusion or column experiments should be examined after they have been pre-equilibrated with crushed dolomite.

This memo was reviewed by R. Moore.

References:

Lucero, D. A., F. Geldbard, Y. K. Behl and J. A. Romero, 1995. *Test Plan for Laboratory Column Experiments for Radionuclide Adsorption Studies of the Culebra Dolomite Member of the Rustler Formation at the WIPP Site, TP 95-03*, Sandia National Laboratories, Albuquerque, NM.

Novak, C. F. and Babb, S. C., 1995. *FMT Chemical Aqueous Solubility Calculations: User Guide and Reference Manual, Version 2.0*, Draft WIPP Document, December 27, 1995, Sandia National Laboratories, Albuquerque, NM.

Siegel, M. D., *Initial Calculations of Solubility-Limited Concentrations and Saturation States of Radioelement Solids for Injection Spikes Used in WIPP Core Column Experiments at Sandia National Laboratories*, memo to L. Brush, July 1, 1996

Enclosures

Table 1. Brine compositions assumed for solubility calculations

- a. Brine recipes in terms of salts
- b. Compositions of the final "stable" solutions according to the FMT calculations compared to the field or "targeted" compositions

Table 2. Solubility-limited concentrations (molarity) for column experiments

Appendix A. Copies of salt recipes supplied by Dan Lucero

Appendix B. List of files found on diskette included in records package.

Distribution w/enc and diskettes.

SWCF-A: WBS 1.1.10.3.4; TD:QA: Core Column Tests: Actinide Solubilities

Distribution w/enc and w/o diskettes.

MS-1320 G. W. Perkins 6831

Distribution w/o enc.

MS-1320 E. J. Nowak 6831

MS-1341 J. T. Holmes 6832

MS-1341 S. Miller 6811

Table 1a. Brine recipes in terms of salts

Compound	ERDA-6 (g/L)	VPX-28 (g/L)	Molecular Weight (g)
NaCl	261.64	29.34	58.44
Na ₂ SO ₄	23.70	7.910	142.04
Na ₂ B ₄ O ₇ •10H ₂ O	6.00	0	381.39
NaBr	1.13	0.02794	102.91
KCl	7.23	0	74.55
MgCl ₂ •6H ₂ O	3.86	0	203.3
CaCl ₂ •2H ₂ O	1.762	3.063	146.98
NaHCO ₃	1.34	0.08392	84.007
MgSO ₄	0	2.094	120.38
Na ₂ B ₄ O ₇	0	0.1275	201.22
K ₂ SO ₄	0	0.7063	174.27

Table 1b. Compositions of the "stable" solutions according to the FMT calculations compared to the field or "target" compositions (g/L)

Element	VPX-28 "FMT stable"	VPX-28 "target"	ERDA-6 "FMT stable"	ERDA-6 "target"
Na	14.176	14.161	114.3504	111.942
Cl	19.261	19.277	167.9309	164.360
SO ₄	7.654	7.410	16.37965	16.028
K	0.317	0.317	3.869851	3.792
Br	0.022	0.022	0.897122	0.877
C	0.007	0.012	0.018612	0.192
Mg	0.478	0.423	0.471137	0.462
Ca	0.786	0.835	0.049798	0.480
pH	7.87	8.09	8.17	6.17

*no dolomite or magnesite precipitation

Table 2. Solubility-limited concentrations (molarity) for column experiments; $\log p\text{CO}_2 = -3.5$

Brine	Element	total tracer concentration (Molar)	Without dolomite equilibrium		With dolomite equilibrium		Solid Phase
			calculated pml-H*	solubility	calculated pml-H*	solubility	
VPX-28	Am	3.38E-07	7.73	6.46E-09	7.64	9.63E-09	AmOHCO ₃
ERDA-6/10	Np	6.48E-10	8.71	4.17E-07	8.23	9.51E-07	KNpO ₂ CO ₃ (s)
VPX-28	Np	4.21E-10	7.72	7.84E-06	7.64	1.10E-05	KNpO ₂ CO ₃ (s)
ERDA-6/10	Th	2.82E-10	8.72	3.98E-07	8.23	1.21E-07	ThO ₂ (amorphous)
VPX-28	Th	2.67E-8	7.73	1.90E-07	7.64	1.57E-07	ThO ₂ (amorphous)

* rounded to 3 significant figures.

Appendix A. Copies of salt recipes supplied by Dan Lucero

Two Liter Batch Preparation

1. Addition of Components:

Lot. No.	Salt	Lot No. (500g)	Mass (g)/2L	(10L) Desired wt (g)	Actual wt (g)
751450	NaCl *	947724	523.28	2,616.4	2,616.4001
751628	Na ₂ SO ₄ *		47.40	237	237.0004
51183	Na ₂ B ₄ O ₇ ·10H ₂ O		12.00	60	60.0000
25252	NaHCO ₃		2.68	13.4	13.4001
53458	NaBr *		2.26	11.3	11.2999
130280	KCl *		14.46	72.3	72.3000
742062	MgCl ₂ ·6H ₂ O		7.72	38.6	38.6016
741925	CaCl ₂ (anhydrous)·2H ₂ O		2.66 3.5235	17.6175	17.6182

2. pH Adjustment: Adjust pH using 10% HCl to pH 6.17, measured with a combination glass electrode.

3. Filtration: Filter solution through a medium glass frit filter.

4. Notes:

Add about 500 mL of deionized water to a 2 L volumetric flask. Using a magnetic stirrer, allow each component to dissolve before adding next. Keep flask stoppered between additions. No heating is necessary.

Dilute to 2 L after pH adjustment.

* Chemical is dried in a 110°C oven overnight

Lori R. Montano 10/30/95 ^{10/31/95}

Two Liter Batch Preparation

1. Addition of Components:

Lot. No.	Salt	Lot No. (500g)	Mass (g)/2L	(10L) Desired wt (g)	Actual wt (g)
751450	NaCl *	947724	523.28	2,616.4	2,616.4001
751628	Na ₂ SO ₄ *		47.40	237	237.0004
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25252	NaHCO ₃		2.68	13.4	13.4001
53458	NaBr *		2.26	11.3	11.2999
30280	KCl *		14.46	72.3	72.3000
42062	MgCl ₂ ·6H ₂ O		7.72	38.6	38.6016
141925	CaCl ₂ (an)·2H ₂ O		2.66 3.5235	17.6175	17.6182

2. pH Adjustment: Adjust pH using 10% HCl to pH 6.17, measured with a combination glass electrode.

3. Filtration: Filter solution through a medium glass frit filter.

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Add about 500 mL of deionized water to a 2 L volumetric flask. Using a magnetic stirrer, allow each component to dissolve before adding next. Keep flask stoppered between additions. No heating is necessary.

Dilute to 2 L after pH adjustment.

* Chemical is dried in a 110°C oven overnight

Lari R. Montano 10/30^{um} 31/95

Appendix B. List of directories and files found on diskette included in records package.

This diskette contains input and out files for FMT calculations of solubility of Am, Np and Th solids in VPX-28 and ERDA6 brines. Each subdirectory at the lowest level contains input files: (cc.com, ccc.in, ccc.ing) and output files (ccc.f88 or .ccc.out files).

Directories:

e6Npdno
e6Npdol
e6Thdno
e6Thdol
Vpamdno
Vpamdol
VpNpdno
VpNpdol
VpThdno
VpThdol

Files:

soldat2.xls

Sandia National Laboratories

Albuquerque, New Mexico 87185

date: February 3, 1997

to: George Perkins, 6832, MS1320

from: Dan Lucero, 6832, MS1320

INFORMATION ONLY

subject: Memo of Record for Column Effluent Times

Test	Start/End	Cum Time	Time (sec)	Tracer	Flowrate
C-3	Start 7/10/95			Am, Pu	0.1 ml/min
*	End 4/9/96	269 days	2.3e07 s		0.1 ml/min
**	Restart 6/4/96				0.05 ml/min
In Process	2/4/97	241 days	2.1e07 s		0.05 ml/min
D-3	Start 9/28/95			Am, Pu	0.1 ml/min
	End 1/30/96	125 days	1.1e07 s		
D-6	Start 1/30/96				0.05 ml/min
	End 3/19/96	48 days	4.1e06 s		
	Start 3/19/96				0.1 ml/min
*	End 4/9/96	21 days	1.8e06 s		
**	Restart 6/4/96				0.05 ml/min
In Process	2/4/97	241 days	2.1e07 s		
E-2	Start 1/16/96			Am, Pu	0.1 ml/min
	End 4/9/96	83 days	7.2e06 s		
	Restart 6/4/96				0.05 ml/min
Post Test	End 7/15/96	41 days	3.5e06 s		

* Test suspended per memo from L. Brush

** Test restarted per verbal instructions from J. Nowak

cc: Glen Brown, OSU

John Holmes, 6832, MS1341

SWCF-A:1.1.10.3.4,1.1.5.1.5:Effluent memo of record;QA;

Sandia National Laboratories

Albuquerque, New Mexico 87185

date 13 August 1993

to Fred Gelbard, 6119

from *Stephen Yeh*
Stephen Yeh, 6119

INFORMATION ONLY

subject: Revised Viscosity Measurements of Culebra Brines

Enclosed is my revised report titled "Determination of the Viscosity of Synthetic Culebra Brines in the Temperature Range of 20°C to 30°C." The revision results in only a very small change to the viscosities.

Copy to:

6115 R. Beauheim

6115 S. Webb

6119 D. Lucero

6119 H. Papenguth

6119 K. Robinson

6119 J.A. Romero

6119 File 3.2

6303 SWCF/WBS 1.1.5.1.5 RUC/SOK ^{SJL} 9/1/93

DETERMINATION OF THE VISCOSITY OF SYNTHETIC CULEBRA BRINES
IN THE TEMPERATURE RANGE OF 20°C TO 30°C

Stephen Yeh
Department 6119
Sandia National Laboratories
Revised August 1993

ABSTRACT

Experimentally determined values for two synthetic Culebra brines (one based on the composition of VPX26E brine, one based on average compositions of VPX26A, -B, -C, -D, and -E brines -- see Appendix for Analytical Report on brine compositions) show that the viscosity of the brines are very close to predetermined values for a sodium chloride solution of comparable concentration (about 4% salinity). In a temperature range of 20°C to 30°C, the values vary from 1.079 cP $\pm$ 0.0027 cP to 0.8610 cP $\pm$.0037 cP for synthetic Culebra brine 1 and 1.106 cP $\pm$ 0.0035 cP to 0.8857 cP $\pm$ 0.0009 cP for synthetic Culebra brine 2.

INTRODUCTION

The viscosity of synthetic Culebra brine 1 (mixed 2/15/93) was determined experimentally at two degree (Celsius) increments on 6/14-16/93. The composition of "synthetic Culebra brine 1" -- see Table 5 -- used an old, incorrect recipe based on VPX26E brine composition; a new recipe based on the average compositions of VPX26A, -B, -C, -D, and -E was developed and tested as "synthetic Culebra brine 2". The viscosity of synthetic Culebra brine 2 (mixed 5/3/93) was also determined at two degree increments on 6/28-30/93. New calibrated Cannon-Fenske viscometers (No. U383/50 for brine 1 and No. U513/50 for brine 2) were used in conjunction with a Jupiter Viscosity Timer Model 821 and a PolyScience 730 Immersion Circulator constant temperature bath. Deionized Ultra Filtered water from Fisher Scientific Co. was used for checking the viscosity. The calibration certificates for applicable instruments and a list of equipment and manufacturers are given in the Appendices.

EXPERIMENT

The viscometer is initially rinsed with deionized water by filling the bulb with about 6.7 or 6.8 mL of liquid (depending on charge volume specified by manufacturer) and drawing it through and up into the capillary a few times. The water is then poured out and a fresh charge of deionized water is added. The viscometer is inserted vertically in the self-aligning holder in the constant temperature bath (initially set at 20°C) and left for about ten

minutes to allow the liquid inside to equilibrate. The temperature in the bath is monitored by a calibrated thermocouple. (See Appendix for calibration certificate).

To check the viscometer, the meniscus of the water is allowed to flow freely past two marked points. Light timers that are activated by the refraction change as the meniscus passes the sensor are mounted across the markings. The elapsed, or efflux, time is recorded. To convert the efflux time to viscosity in centipoise, it is multiplied by the viscometer constant (supplied and verified by the manufacturer -- constants are given for 40°C and 100°C and are extrapolated for the desired temperatures) and then multiplied by the density of the liquid being tested. In the case of the deionized water check, the densities at varying temperatures were taken from the Handbook of Chemistry and Physics (Weast, 1990, page F-4). About five runs are made and recorded.

If the determined viscosity values for the deionized water agree within a couple percent of the tabulated viscosities (from Weast, 1990, page F-40) then the brine can now be tested. The same rinsing procedure used with deionized water is used with brine (i.e. 6.7 or 6.8 mL drawn in, rinsed, poured out and refilled). Again the viscometer is allowed to reach testing temperature and then flow times are recorded. Ten runs are made at each temperature.

Following the brine test-runs, deionized water is used again (same procedure for rinsing, etc.) and values compared to previous values to check for large discrepancies or errors such as brine precipitation and blockage of the viscometer capillary. Again, about five time values are recorded. Once assured there are no significant discrepancies, the water bath is raised two degrees Centigrade, and the above procedure is repeated.

Brine densities are recorded at various temperatures (about 20°C to 30°C) using a Mettler Portable Density/Specific Gravity Meter model DA-110. The meter is checked with deionized water and densities verified to be accurate to three decimal places.

RESULTS

Table 1 shows a summary of the data for brine 1. Table 2 shows a summary of the data for brine 2. Given are averages of the individual times and temperatures (not reprinted here), one standard deviation, two standard deviations, densities, number of points or readings, and calculated viscosities and errors.

Errors refer only to the viscosity calculations and were calculated as follows: For the deionized water checks, percent error is relative to tabulated book values from the Handbook of Chemistry and Physics. For the standard deviations, errors reflect what percent of the average viscosity the deviation is (i.e. deviation divided by average viscosity multiplied by 100% = error). Temperature standard deviations indicate temperature fluctuations or error over time, not actual thermocouple calibration error.

Tables 3 and 4 briefly summarize the determined viscosities

and densities and their respective temperatures for brines 1 and 2.

Table 5 gives the composition of synthetic Culebra brine 1 followed by the composition of synthetic Culebra brine 2.

Five graphs follow. The first four graphs show how the viscosity (Figures 1 and 3) and density (Figures 2 and 4) of synthetic Culebra brine 1 and 2 vary with temperature. In Figures 1 and 3, error bars are included for temperature and viscosity and indicate two standard deviations (about 95% confidence). Again, temperature error bars indicate fluctuations over time, not thermocouple error. The thermocouple error (see Appendix A) is about $+0.1^{\circ}\text{C}$, which means the measured temperatures are about 0.1°C too high. This results in an error in the viscosity calculations of less than one-half of one percent (for example, viscosities read off of Figure 1 may be 0.004 cP too high). For the densities in Figures 2 and 4, since measurements were not repeated for a given temperature, (constant temperature is too hard to keep without fluctuation) there are no error bars, but estimated density error is about 0.001 g/mL or about 0.1%. (Note: This was not added into the error calculation for viscosity). The equation for the line fits were derived using the method of least squares (Fred Gelbard wrote a program in Fortran that was used for this purpose).

The fifth graph shows the viscosity trends of both of the Culebra brines on the same scale for comparison.

DISCUSSION

The graphs for the viscosity of Culebra brine show a general decreasing trend. The values also agree with published salinity viscosities (see Reference 1).

The errors calculated for the experimental viscosities of the brines were mostly less than 0.5% and show experimental consistency. Taking into account thermocouple (calibration) error and density error adds only about 0.5% at the most to the viscosity values. Viscosity errors were slightly lower for synthetic Culebra brine 2 than for brine 1. This may be because the temperature fluctuated less during testing of brine 2 (which may or may not be due to the meter that was hooked up to the thermocouple.) But water viscosity errors seemed slightly higher for synthetic Culebra brine 2 than brine 1 (which may have been due to the different viscometers used). The deionized water viscosities differed from published values by no more than 2.9% for all tests. Even if one takes into account that the times increase slightly for progressing runs at the same temperature (i.e. pre-check times versus post-check times), and therefore probably for the whole test, the error remains near or under 3%.

The density measurements were harder to take because the meter drifted during measurements. The drift was probably due to the brine changing temperature when introduced into the meter. Also, the meter's thermometer was too inaccurate (it usually did not change much, if at all), so the same thermocouple as for the water bath was used. Density values in Tables 1 and 2 for the brines

were extrapolated from the line fit equations. One should note that comparing published values for the viscosity of a 4% salinity solution (Reference 1) to the brine viscosities show evidence that saline solution viscosities may be applicable to brines.

Comparing the viscosities for synthetic Culebra brine 1 to synthetic culebra brine 2 show that the brine 2 values are consistently 0.02 cP or more higher than the brine 1 values; that is, the curves in Figures 1 and 3 are very nearly parallel. Comparing brine compositions shows that there are about three more grams of $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ in brine 2 as compared to brine 1. That extra amount of salt is approximately a 5.9% increase in the salinity of brine 2 over brine 1. It seems that even a seemingly minor change like that is noticeable in the experimental data (though not proportionally 5.9% higher; the data shows that brine 2 is 2.7% more viscous than brine 1 on average) and suggests that brine viscosities are sensitive to such small changes in concentration.

CONCLUSION

The experimental procedure for determining the viscosity of brine seems to be very consistent and relatively simple. The accuracy of the results is limited only by the accuracy of the thermocouple (small at about 0.1°C), time variations in the constant temperature water bath (which appeared minimal at about 0.1°C and could also include the thermocouple error), and possible clogging in the viscometer due to precipitation of brine or particulates. Though no visible problems were noted, sometimes the efflux times for the water checks dropped over time (i.e. after maybe five or more flow measurements). This may indicate that the viscometer is cleaning itself out slowly when it has water soaking in it; but, times do not change by more than about one second. Possible considerations regarding this may include more water checks.

The synthetic Culebra brine viscosities seem to follow closely the viscosities of a comparable percent by weight sodium chloride solution.

Possible future measurements include determining viscosities for actual Salado brine which is much more concentrated than Culebra brine. Synthetic Salado brines may also be tested. Those data can also be compared to saline viscosity data.

TABLE 1

C=calib. const.

Viscosity=pCt: p=density C=0.0042462 t=time
 (g/mL) to 0.0042493 (s)
 (cSt/s)

Approximate temperature:		Temp (C)	Time (s)	Visc. (cP)	%error:
20 degrees (C)	pre-check :Average:	20.17	239.9	1.018	1.6
	6pts :Std.Dev.:	0.26	0.59	0.0025	0.25
	p=.9982 :2 Std. Dev.:	0.52	1.18	0.005	0.5
	Brine test:Average:	20.26	248.5	1.079	
	10pts :Std.Dev.:	0.14	0.31	0.0013	0.13
	p=1.0220 :2 Std. Dev.:	0.28	0.62	0.0027	0.25
	post-check:Average:	20.03	240.2	1.019	1.7
	5pts :Std.Dev.:	0.03	0.19	0.0008	0.08
	p=.9982 :2 Std. Dev.:	0.06	0.38	0.0016	0.16
22 degrees (C)	pre-check :Average:				
	0pts :Std.Dev.:	no	data	taken	here
	p=.9978 :2 Std. Dev.:				
	Brine test:Average:	22.03	238.2	1.033	
	10pts :Std.Dev.:	0.05	0.15	0.0006	0.06
	p=1.0204 :2 Std. Dev.:	0.1	0.3	0.0013	0.13
	post-check:Average:	22.02	229.5	0.9729	1.9
	5pts :Std.Dev.:	0.03	0.08	0.0003	0.03
	p=.9978 :2 Std. Dev.:	0.06	0.16	0.0007	0.07
24 degrees (C)	pre-check :Average:	24.02	217.7	0.9223	1.2
	5pts :Std.Dev.:	0.03	0.09	0.0004	0.04
	p=.9973 :2 Std. Dev.:	0.06	0.18	0.0008	0.09
	Brine test:Average:	24.03	227.5	0.9844	
	10pts :Std.Dev.:	0.03	0.45	0.0019	0.19
	p=1.0186 :2 Std. Dev.:	0.06	0.9	0.0039	0.4
	post-check:Average:	24.1	218.7	0.9266	1.7
	3pts :Std.Dev.:	0	0	0	0
	p=.9973 :2 Std. Dev.:	0	0	0	0

TABLE 1
(cont'd)

Approximate temperature:		Temp (C)	Time (s)	Visc. (cP)	%error:
26 degrees (C)	pre-check :Average:	25.98	209.3	0.8861	1.8
	5pts :Std.Dev.:	0.03	0.26	0.0011	0.12
	p=.9968 :2 Std. Dev.:	0.06	0.52	0.0022	0.25
	Brine test:Average:	26	217.9	0.9411	
	10pts :Std.Dev.:	0	0.31	0.0013	0.14
	p=1.0169 :2 Std. Dev.:	0	0.62	0.0027	0.29
	post-check:Average:	26	210.4	0.8908	2.3
	5pts :Std.Dev.:	0	0.05	0.0002	0.02
	p=.9968 :2 Std. Dev.:	0	0.1	0.0004	0.04
28 degrees (C)	pre-check :Average:	27.95	201.3	0.8516	2.3
	5pts :Std.Dev.:	0	0.09	0.0004	0.05
	p=.9962 :2 Std. Dev.:	0	0.18	0.0008	0.09
	Brine test:Average:	28	208.6	0.8993	
	10pts :Std.Dev.:	0.06	0.27	0.0012	0.13
	p=1.0151 :2 Std. Dev.:	0.12	0.54	0.0023	0.26
	post-check:Average:	27.95	200	0.8461	1.6
	5pts :Std.Dev.:	0	0.52	0.0022	0.26
	p=.9962 :2 Std. Dev.:	0	1.04	0.0044	0.52
30 degrees (C)	pre-check :Average:	29.95	191.3	0.8187	1.4
	5pts :Std.Dev.:	0	0.04	0.0002	0.02
	p=.9956 :2 Std. Dev.:	0	0.08	0.0003	0.04
	Brine test:Average:	29.95	200.1	0.861	
	10pts :Std.Dev.:	0	0.43	0.0018	0.21
	p=1.0133 :2 Std. Dev.:	0	0.86	0.0037	0.43
	post-check:Average:	30	192	0.8117	1.8
	5pts :Std.Dev.:	0.04	0.08	0.0003	0.04
	p=.9956 :2 Std. Dev.:	0.08	0.16	0.0007	0.09

TABLE 2

C=calib. const.

Viscosity=pCt: p=density C=0.0039950 t=time
 (g/mL) to 0.0039980 (s)
 (cSt/s)

Approximate temperature:		Temp (C)	Time (s)	Visc. (cP)	%error:
20 degrees (C)	pre-check :Average:	20	254.5	1.016	1.4
	6pts :Std.Dev.:	0	0.12	0.0005	0.05
	p=.9982 :2 Std. Dev.:	0	0.24	0.001	0.09
	Brine test:Average:	20.01	268.2	1.106	
	10pts :Std.Dev.:	0.04	0.42	0.0017	0.15
	p=1.0315 :2 Std. Dev.:	0.08	0.84	0.0035	0.32
	post-check:Average:	20.05	255.5	1.02	1.8
	5pts :Std.Dev.:	0.05	0.25	0.001	0.1
	p=.9982 :2 Std. Dev.:	0.1	0.5	0.002	0.2
22 degrees (C)	pre-check :Average:	22.03	244.4	0.9748	2.1
	5pts :Std.Dev.:	0.04	0.19	0.0007	0.07
	p=.9978 :2 Std. Dev.:	0.09	0.38	0.0015	0.15
	Brine test:Average:	22.02	256.4	1.055	
	10pts :Std.Dev.:	0.03	0.18	0.0007	0.07
	p=1.0295 :2 Std. Dev.:	0.07	0.35	0.0014	0.13
	post-check:Average:	22.04	244.3	0.9744	2.1
	5pts :Std.Dev.:	0.04	0.27	0.0011	0.11
	p=.9978 :2 Std. Dev.:	0.08	0.54	0.0022	0.22
24 degrees (C)	pre-check :Average:	24	234.5	0.9341	2.6
	5pts :Std.Dev.:	0	0	0	0
	p=.9973 :2 Std. Dev.:	0	0	0	0
	Brine test:Average:	24	246	1.01	
	10pts :Std.Dev.:	0	0.07	0.0003	0.03
	p=1.0276 :2 Std. Dev.:	0	0.13	0.0006	0.06
	post-check:Average:	24	233.6	0.93	2.1
	3pts :Std.Dev.:	0	0.11	0.0004	0.05
	p=.9973 :2 Std. Dev.:	0	0.22	0.0009	0.09

TABLE 2
(cont'd)

Approximate temperature:		Temp (C)	Time (s)	Visc. (cP)	%error:
26 degrees (C)	pre-check :Average:	26	223.9	0.8919	2.5
	5pts :Std.Dev.:	0	0.07	0.0003	0.03
	p=.9968 :2 Std. Dev.:	0	0.14	0.0006	0.07
	Brine test:Average:	26	235.3	0.9644	
	9pts :Std.Dev.:	0.02	0.09	0.0004	0.04
	p=1.0256 :2 Std. Dev.:	0.05	0.18	0.0007	0.07
	post-check:Average:	25.99	223.5	0.8903	2.3
	5pts :Std.Dev.:	0.02	0	0	0
	p=.9968 :2 Std. Dev.:	0.04	0	0	0
28 degrees (C)	pre-check :Average:	28.01	214.2	0.8526	2.4
	5pts :Std.Dev.:	0.02	0.09	0.0004	0.05
	p=.9962 :2 Std. Dev.:	0.04	0.18	0.0007	0.08
	Brine test:Average:	28	227.3	0.9297	
	10pts :Std.Dev.:	0	0.05	0.0002	0.02
	p=1.0237 :2 Std. Dev.:	0	0.1	0.0004	0.04
	post-check:Average:	28	215.2	0.8566	2.9
	5pts :Std.Dev.:	0	0.08	0.0003	0.04
	p=.9962 :2 Std. Dev.:	0	0.17	0.0007	0.08
30 degrees (C)	pre-check :Average:	30	204.9	0.815	2.2
	5pts :Std.Dev.:	0	0.15	0.0006	0.07
	p=.9956 :2 Std. Dev.:	0	0.3	0.0012	0.15
	Brine test:Average:	30.02	217	0.8857	
	10pts :Std.Dev.:	0.05	0.11	0.0004	0.05
	p=1.0217 :2 Std. Dev.:	0.1	0.21	0.0009	0.1
	post-check:Average:	30.02	205.6	0.8178	2.5
	10pts :Std.Dev.:	0.05	0.31	0.0012	0.15
	p=.9956 :2 Std. Dev.:	0.11	0.62	0.0025	0.3

TABLE 3

DATA SUMMARY
 PROPERTIES OF SYNTHETIC CULEBRA BRINE 1

Computed (From Measured) Values:

<u>Temperature (°C)</u>	<u>Viscosity (cP)</u>
20.26	1.079
22.03	1.033
24.03	0.9844
26.00	0.9411
28.00	0.8993
29.95	0.8610

Measured Values:

	<u>Temperature (°C)</u>	<u>Density (g/mL)</u>
In order taken:	21.1	1.0207
	22.5	1.0196
	23.7	1.0187
	24.2	1.0181
	26.5	1.0160
	27.5	1.0153
	31.7	1.0115
	29.5	1.0140
	28.5	1.0148
	27.5	1.0159
	26.8	1.0164
	26.3	1.0172
	25.2	1.0183
	24.8	1.0184
	24.4	1.0190
	24.0	1.0192
	23.7	1.0194
	23.0	1.0198
	22.6	1.0202
	21.3	1.0210
	20.1	1.0220
	19.4	1.0228
	20.0	1.0220
	20.5	1.0210
	21.9	1.0206
	29.6	1.0130
	30.0	1.0130
	29.0	1.0138
	28.2	1.0142
	25.7	1.0168
	25.0	1.0175

TABLE 4

DATA SUMMARY
 PROPERTIES OF SYNTHETIC CULEBRA BRINE 2

<u>Computed (From Measured) Values:</u>	
<u>Temperature (°C)</u>	<u>Viscosity (cP)</u>
20.01	1.106
22.02	1.055
24.00	1.010
26.00	0.9644
28.00	0.9297
30.02	0.8857

<u>Measured Values:</u>		
	<u>Temperature (°C)</u>	<u>Density (g/mL)</u>
In order taken:	21.5	1.0298
	22.1	1.0292
	23.3	1.0281
	25.0	1.0265
	26.8	1.0250
	27.5	1.0240
	28.1	1.0237
	28.7	1.0230
	29.8	1.0223
	30.5	1.0212
	30.0	1.0220
	29.2	1.0233
	28.6	1.0233
	28.1	1.0235
	27.8	1.0239
	27.3	1.0244
	26.4	1.0256
	26.0	1.0258
	25.7	1.0261
	25.2	1.0269
	24.7	1.0275
	24.3	1.0277
	23.9	1.0280
	23.6	1.0285
	22.5	1.0296
	22.1	1.0299
	21.6	1.0300
	21.0	1.0303
	19.9	1.0312
	20.3	1.0310
	23.0	1.0282
	29.5	1.0212
	28.6	1.0222
	28.0	1.0228
	20.7	1.0308

TABLE 5

COMPOSITION OF SYNTHETIC CULEBRA BRINE 1

<u>Compound</u>	<u>Quantity (g/L)</u>
NaHCO ₃	0.0839
CaCl ₂ *2H ₂ O	0.01563
MgSO ₄	2.054
K ₂ SO ₄	0.742
Na ₂ SO ₄	7.615
NaCl	29.20
Na ₂ B ₄ O ₇	0.1256

pH = 8.11

COMPOSITION OF SYNTHETIC CULEBRA BRINE 2

<u>Compound</u>	<u>Quantity (g/L)</u>
NaHCO ₃	0.08492
CaCl ₂ *2H ₂ O	3.052
MgSO ₄	2.074
K ₂ SO ₄	0.742
Na ₂ SO ₄	7.615
NaCl	29.20
Na ₂ B ₄ O ₇	0.1223
NaBr	0.0291

pH = 7.67

Figure 1

VISCOSITY (cP) vs. TEMPERATURE (C)
Synthetic Culebra Brine 1

Figure 2

DENSITY (g/mL) vs. TEMPERATURE (C)
Synthetic Culebra Brine 1

Figure 3

VISCOSITY (cP) vs. TEMPERATURE (C)
Synthetic Culebra Brine 2

Figure 4

DENSITY (g/mL) vs. TEMPERATURE (C)
Synthetic Culebra Brine 2

Figure 5

VISCOSITY (cP) vs. TEMPERATURE (C)
VPX26E Synthetic and VPX26 Synthetic Culebra Brines

APPENDIX A
CERTIFICATES OF CALIBRATION

Certificate of Calibration

Viscometer No. 50 U513

CANNON-FENSKE ROUTINE TYPE FOR TRANSPARENT LIQUIDS

(Standard Test ASTM D 445, IP 71 and ISO 3104)

Constant at 40°C

0.003992 mm²/s², (cSt/s)

Constant at 100°C

0.003974 mm²/s², (cSt/s)

The viscometer constant at other temperatures can be obtained by interpolation or extrapolation. To obtain kinematic viscosity in mm²/s(cSt) multiply the efflux time in seconds by the viscometer constant. To obtain viscosity in mPa · s (cP) multiply the kinematic viscosity in mm²/s(cSt) by the density in grams per milliliter.

The above constants assume a value for the coefficient of thermal expansion typical to that for mineral oil, and that the viscometer was filled with test sample at room temperature. If the filling temperature T_F is substantially different than room temperature, the viscometer constant at test temperature T_T is $C_o (1 - B [T_T - T_F])$. The values of C_o and B shown below are based on a coefficient of thermal expansion typical to that for a mineral oil.

Kinematic viscosities of the standards used in calibrating were established in Master Viscometers as described in Ind. Eng. Chem. Anal. Ed. 16,708(1944), ASTM D 2162, and the Journal of Research of the National Bureau of Standards, Vol. 52, No. 3, March 1954, Research Paper 479.

Kinematic viscosities are based on the value for water adopted by the National Institute for Standards and Technology and The American Society for Testing Materials July 1, 1953. The kinematic viscosity basis is 1.0038 mm²/s(cSt) for water at 20°C (ITS-90). The gravitational constant, g , is 980.1 cm/sec² at the Cannon Instrument Company. The gravitational constant varies up to 0.1% in the United States. To make this small correction in the viscometer constant, multiply the above viscometer constant by the factor $[g(\text{at your laboratory}) / 980.1]$. The calibration data below are traceable to the National Institute for Standards and Technology. Temperature measurement traceable to NIST (Test No. 246089).

CALIBRATION DATA AT 40°C

Viscosity Standard	Kinematic Viscosity mm ² /s, (cSt)	Efflux Time Seconds	Constant mm ² /s ² , (cSt/s)
9203	1.0084	252.66	0.003991
9204	2.045	512.09	0.003993

Room Temp. (approx) 21 °C.

Average = 0.003992

Charge (approx) 6.8 ml.

$C_o = 0.003998$

Driving fluid head (approx) 9.4 cm.

$B = 76 \times 10^{-6}/^{\circ}\text{C}$

Working diameter of lower reservoir 3.0 cm.

Constant at 100° C. is 0.46 % lower than the constant at 40° C.

Calibrated by VSM 366008 on 29-Oct-92 under supervision of

Please note: This calibration remains valid for 10 years unless (1) the viscometer has been damaged or (2) materials which chemically attack borosilicate glass (e.g., hydrofluoric acid or highly alkaline solutions) have been used. Nonetheless, it is recommended that the calibration be verified with kinematic viscosity standards periodically; if a change in calibration is indicated, carefully examine all sources of error, including especially temperature measurement since most apparent changes in calibration of the viscometer are due to errors in temperature measurement.

R. E. Manning, Ph.D., P.E.

W. A. Lloyd, Ph.D., P.E.

M. R. Hoover, Ph.D.

M. K. Gerfin, C.Q.E.

Cannon Instrument Co.

State College, PA 16804, USA

Test No.: 366008 - 11

The S.I. unit of kinematic viscosity is 1 meter squared per second, and is equal to 10⁴ stokes. The S.I. unit of viscosity is 1 pascal second, and is equal to 10 poises. One centistokes is equal to one millimeter squared per second.

Certificate of Calibration

Viscometer No. 50
U383

CANNON-FENSKE ROUTINE TYPE FOR TRANSPARENT LIQUIDS

(Standard Test ASTM D 445, IP 71 and ISO 3104)

Constant at 40°C

0.004243 mm²/s², (cSt/s)

Constant at 100°C

0.004224 mm²/s², (cSt/s)

The viscometer constant at other temperatures can be obtained by interpolation or extrapolation. To obtain kinematic viscosity in mm²/s(cSt) multiply the efflux time in seconds by the viscometer constant. To obtain viscosity in mPa · s (cP) multiply the kinematic viscosity in mm²/s(cSt) by the density in grams per milliliter.

The above constants assume a value for the coefficient of thermal expansion typical to that for mineral oil, and that the viscometer was filled with test sample at room temperature. If the filling temperature T_F is substantially different than room temperature, the viscometer constant at test temperature T_T is $C_0 (1 - B [T_T - T_F])$. The values of C_0 and B shown below are based on a coefficient of thermal expansion typical to that for a mineral oil.

Kinematic viscosities of the standards used in calibrating were established in Master Viscometers as described in Ind. Eng. Chem. Anal. Ed. 16,708(1944), ASTM D 2162, and the Journal of Research of the National Bureau of Standards, Vol. 52, No. 3, March 1954, Research Paper 2479.

Kinematic viscosities are based on the value for water adopted by the National Institute for Standards and Technology and The American Society for Testing Materials July 1, 1953. The kinematic viscosity basis is 1.0038 mm²/s(cSt) for water at 20°C (ITS-90). The gravitational constant, g , is 980.1 cm/sec² at the Cannon Instrument Company. The gravitational constant varies up to 0.1% in the United States. To make this small correction in the viscometer constant, multiply the above viscometer constant by the factor $[g(\text{at your laboratory}) / 980.1]$. The calibration data below are traceable to the National Institute for Standards and Technology. Temperature measurement traceable to NIST (Test No. 246089).

CALIBRATION DATA AT 40°C

Viscosity Standard	Kinematic Viscosity mm ² /s, (cSt)	Efflux Time Seconds	Constant mm ² /s ² , (cSt/s)
9203	1.0086	237.72	0.004243
9204	2.045	481.89	0.004244

Room Temp. (approx.) 22 °C.

Average = 0.004243

Charge (approx.) 6.7 ml.

$C_0 = 0.004249$

Driving fluid head (approx.) 9.2 cm.

$B = 76 \times 10^{-6}/^{\circ}\text{C}$

Working diameter of lower reservoir 3.0 cm.

Constant at 100° C. is 0.46 % lower than the constant at 40° C.

Calibrated by MAG 371036 on 12-May-92 under supervision of

R E Manning
R. E. Manning, Ph.D., P.E.
W. A. Lloyd, Ph.D., P.E.
M. R. Hoover, Ph.D.
M. K. Gerfin, C.Q.E.
Cannon Instrument Co.
State College, PA 16804, USA

Please note: This calibration remains valid for 10 years unless (1) the viscometer has been damaged or (2) materials which chemically attack borosilicate glass (e.g., hydrofluoric acid or highly alkaline solutions) have been used. Nonetheless, it is recommended that the calibration be verified with kinematic viscosity standards periodically, if a change in calibration is indicated, carefully examine all sources of error, including especially temperature measurement since most apparent changes in calibration of the viscometer are due to errors in temperature measurement.

Test No.: 371036 - 2

The S.I. unit of kinematic viscosity is 1 meter squared per second, and is equal to 10⁴ stokes. The S.I. unit of viscosity is 1 pascal second, and is equal to 10 poises. One centistokes is equal to one millimeter squared per second.

Standards Laboratory Certificate

Sandia National Laboratories

Albuquerque, New Mexico 87185

File No. 4522

THERMOCOUPLE TYPE

OMEGA

Model No. 6" Probe

Serial No. 92321-1

Submitted by: 6119

Certified: November 16, 1992

Expires: November 16, 1993

Tests performed between the temperatures of -40 to 100 deg C show this thermocouple to be in agreement within ± 1 deg C of the values published in IPTS-68.

Under normal use conditions it is probable this thermocouple will remain within the above accuracies for the certification interval.

Metrologist: J. J. LaMarr, 2414

Certified by: J. M. Simons, 2414

TLC29:JJL

1/30/92

SERIAL #
STD 257

MV READING

TEMPERATURE

DELTA

Δ
°C

STD 257

0.0001	-0.019 C	0.000
NON	-1.5312	-40.109
NON	-1.5304	-40.084
NON	-1.5301	-40.076
NON	-1.5303	-40.081
NON	-1.5307	-40.092
NON	-1.5314	-40.111
NON	-1.5320	-40.128
NON	-1.5322	-40.133
NON	-1.5226	-39.871
NON	-1.5240	-39.910
NON	-1.5261	-39.967
NON	-1.5280	-39.937
NON	-1.5223	-39.863
NON	-1.5295	-40.059
NON	-1.5213	-39.854
NON	-1.5215	-39.867
NON	-1.5215	-40.059
NON	-1.5310	-40.100
NON	-1.5331	-40.158
3201	-1.5343	-40.209 C
3202	-1.5345	-40.214 C
3203	-1.5252	-39.961 C
3204	-1.5247	-39.947 C

-.229 ←
-.234
.019
.033

SERIAL #
STD 257

MV READING

TEMPERATURE

DELTA

Δ
°C

STD 257

0.0001	0.019 C	0.000
NON	0.9361	23.398
NON	0.9361	23.398
NON	0.9361	23.398
NON	0.9387	23.393
NON	1.0549	26.332
NON	0.9384	23.406
NON	0.9380	23.398
NON	0.9361	23.398
NON	0.9387	23.398
NON	0.9371	23.398
NON	0.9377	23.426
NON	0.9354	23.456
NON	0.9353	23.456
NON	0.9351	23.456
NON	0.9357	23.456
NON	0.9377	23.456
NON	0.9382	23.456
NON	0.9388	23.456
NON	0.9387	23.456
3201	0.9418	23.558 C
3202	0.9440	23.612 C
3203	0.9441	23.614 C
3204	0.9435	23.607 C

.038 ←
.092
.094
.087

 

TEMPERATURE

98.445

1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2033, 2034, 2035, 2036, 2037, 2038, 2039, 2040, 2041, 2042, 2043, 2044, 2045, 2046, 2047, 2048, 2049, 2050, 2051, 2052, 2053, 2054, 2055, 2056, 2057, 2058, 2059, 2060, 2061, 2062, 2063, 2064, 2065, 2066, 2067, 2068, 2069, 2070, 2071, 2072, 2073, 2074, 2075, 2076, 2077, 2078, 2079, 2080, 2081, 2082, 2083, 2084, 2085, 2086, 2087, 2088, 2089, 2090, 2091, 2092, 2093, 2094, 2095, 2096, 2097, 2098, 2099, 2100, 2101, 2102, 2103, 2104, 2105, 2106, 2107, 2108, 2109, 2110, 2111, 2112, 2113, 2114, 2115, 2116, 2117, 2118, 2119, 2120, 2121, 2122, 2123, 2124, 2125, 2126, 2127, 2128, 2129, 2130, 2131, 2132, 2133, 2134, 2135, 2136, 2137, 2138, 2139, 2140, 2141, 2142, 2143, 2144, 2145, 2146, 2147, 2148, 2149, 2150, 2151, 2152, 2153, 2154, 2155, 2156, 2157, 2158, 2159, 2160, 2161, 2162, 2163, 2164, 2165, 2166, 2167, 2168, 2169, 2170, 2171, 2172, 2173, 2174, 2175, 2176, 2177, 2178, 2179, 2180, 2181, 2182, 2183, 2184, 2185, 2186, 2187, 2188, 2189, 2190, 2191, 2192, 2193, 2194, 2195, 2196, 2197, 2198, 2199, 2200, 2201, 2202, 2203, 2204, 2205, 2206, 2207, 2208, 2209, 2210, 2211, 2212, 2213, 2214, 2215, 2216, 2217, 2218, 2219, 2220, 2221, 2222, 2223, 2224, 2225, 2226, 2227, 2228, 2229, 2230, 2231, 2232, 2233, 2234, 2235, 2236, 2237, 2238, 2239, 2240, 2241, 2242, 2243, 2244, 2245, 2246, 2247, 2248, 2249, 2250, 2251, 2252, 2253, 2254, 2255, 2256, 2257, 2258, 2259, 2260, 2261, 2262, 2263, 2264, 2265, 2266, 2267, 2268, 2269, 2270, 2271, 2272, 2273, 2274, 2275, 2276, 2277, 2278, 2279, 2280, 2281, 2282, 2283, 2284, 2285, 2286, 2287, 2288, 2289, 2290, 2291, 2292, 2293, 2294, 2295, 2296, 2297, 2298, 2299, 2300, 2301, 2302, 2303, 2304, 2305, 2306, 2307, 2308, 2309, 2310, 2311, 2312, 2313, 2314, 2315, 2316, 2317, 2318, 2319, 2320, 2321, 2322, 2323, 2324, 2325, 2326, 2327, 2328, 2329, 2330, 2331, 2332, 2333, 2334, 2335, 2336, 2337, 2338, 2339, 2340, 2341, 2342, 2343, 2344, 2345, 2346, 2347, 2348, 2349, 2350, 2351, 2352, 2353, 2354, 2355, 2356, 2357, 2358, 2359, 2360, 2361, 2362, 2363, 2364, 2365, 2366, 2367, 2368, 2369, 2370, 2371, 2372, 2373, 2374, 2375, 2376, 2377, 2378, 2379, 2380, 2381, 2382, 2383, 2384, 2385, 2386, 2387, 2388, 2389, 2390, 2391, 2392, 2393, 2394, 2395, 2396, 2397, 2398, 2399, 2400, 2401, 2402, 2403, 2404, 2405, 2406, 2407, 2408, 2409, 2410, 2411, 2412, 2413, 2414, 2415, 2416, 2417, 2418, 2419, 2420, 2421, 2422, 2423, 2424, 2425, 2426, 2427, 2428, 2429, 2430, 2431, 2432, 2433, 2434, 2435, 2436, 2437, 2438, 2439, 2440, 2441, 2442, 2443, 2444, 2445, 2446, 2447, 2448, 2449, 2450, 2451, 2452, 2453, 2454, 2455, 2456, 2457, 2458, 2459, 2460, 2461, 2462, 2463, 2464, 2465, 2466, 2467, 2468, 2469, 2470, 2471, 2472, 2473, 2474, 2475, 2476, 2477, 2478, 2479, 2480, 2481, 2482, 2483, 2484, 2485, 2486, 2487, 2488, 2489, 2490, 2491, 2492, 2493, 2494, 2495, 2496, 2497, 2498, 2499, 2500, 2501, 2502, 2503, 2504, 2505, 2506, 2507, 2508, 2509, 2510, 2511, 2512, 2513, 2514, 2515, 2516, 2517, 2518, 2519, 2520, 2521, 2522, 2523, 2524, 2525, 2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534, 2535, 2536, 2537, 2538, 2539, 2540, 2541, 2542, 2543, 2544, 2545, 2546, 2547, 2548, 2549, 2550, 2551, 2552, 2553, 2554, 2555, 2556, 2557, 2558, 2559, 2560, 2561, 2562, 2563, 2564, 2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574, 2575, 2576, 2577, 2578, 2579, 2580, 2581, 2582, 2583, 2584, 2585, 2586, 2587, 2588, 2589, 2590, 2591, 2592, 2593, 2594, 2595, 2596, 2597, 2598, 2599, 2600, 2601, 2602, 2603, 2604, 2605, 2606, 2607, 2608, 2609, 2610, 2611, 2612, 2613, 2614, 2615, 2616, 2617, 2618, 2619, 2620, 2621, 2622, 2623, 2624, 2625, 2626, 2627, 2628, 2629, 2630, 2631, 2632, 2633, 2634, 2635, 2636, 2637, 2638, 2639, 2640, 2641, 2642, 2643, 2644, 2645, 2646, 2647, 2648, 2649, 2650, 2651, 2652, 2653, 2654, 2655, 2656, 2657, 2658, 2659, 2660, 2661, 2662, 2663, 2664, 2665, 2666, 2667, 2668, 2669, 2670, 2671, 2672, 2673, 2674, 2675, 2676, 2677, 2678, 26

△
°C

.741
.772
.688
.688

Standards Laboratory Certificate

Sandia National Laboratories

Albuquerque, New Mexico 87185

THERMOCOUPLE TYPE

File No. 4522

OMEGA

Model No. 6" PROBE

Serial No. 92321-1

Submitted by: 6119

Certified: August 12, 1993

Expires: August 12, 1994

Tests performed between the temperatures of -40 to 100 deg C show this thermocouple to be in agreement within ± 1 deg C of the values published in IPTS-68.

Under normal use conditions it is probable this thermocouple will remain within the above accuracies for the certification interval.

Metrologist: J. J. LaMarr, 4344

J. M. Simons
Certified by: J. M. Simons, 4344

TLC29:JJL

7/8/93

6" Type K TC

92321-1
8/12/93

74522

SA-TESTING

Std

Test

R

°C

mV

°C

27.5885 19.981

.8008 20.07

27.7686 21.760

.8724 21.84

27.8643 22.705

.9094 22.36

28.3910 27.913

1.1230 28.03

29.0656 34.596

1.3964 34.74

29.1028 34.965

1.4117 35.12

CERTIFICATE

APPENDIX B
BRINE COMPOSITION ANALYSES

ANALYTICAL REPORT

TO: FRED GELBARD

PROJECT: 6S0007000

DATE: 15-APR-92

REQUISITION: 7070

VOLUME I OF IV

PREPARED BY:

CHEM-NUCLEAR GEOTECH ANALYTICAL LABORATORY
2597 B 3/4 ROAD
P.O. BOX 14000
GRAND JUNCTION, COLORADO 81502-5504
(303-248-6165) D-152

ANALYTICAL RESULTS

CUSTOMER ID: VPX 26 A
TICKET ID:

DATE: 16-APR-92
LAB ID: 195510

REQUESTOR: FRED GELBARD
SAMPLE MATRIX: BRINE
REQUISITION: 7070

PROJECT NUMBER: 6S0007000
DATE RECEIVED: 25-FEB-92
DATE COLLECTED: 12-DEC-91

ANALYSIS REQUESTED	RESULTS	RESULTS	RESULTS	UNITS	RPD	METHOD OF ANALYSIS
Silver	<0.1			MG/L		AS-5 R04
Aluminum	<0.05			MG/L		AS-2 R05
Boron	25.8	25.3		MG/L	2.	AS-5 R04
Bromide	22.2	22.9		MG/L	-3.	D-3 R08
Calcium	847	815		MG/L	4.	AS-5 R04
Cadmium	<0.05			MG/L		AS-6 R03
Chloride	19300	19300		MG/L	0.	D-3 R08
Chromium	<0.1			MG/L		AS-5 R04
Copper	<0.25			MG/L		AS-5 R04
Fluoride	1.5	1.6		MG/L	-6.	D-3 R08
Iron	<0.50			MG/L		AS-5 R04
Iodide	0.08	0.08		MG/L	0.	D-3 R08
Potassium	331	340		MG/L	-3.	AS-1 R04
Lithium	0.336	0.339		MG/L	-1.	AS-6 R03
Magnesium	424	410		MG/L	3.	AS-5 R04
Manganese	0.19	0.18	0.16	MG/L	9.	AS-5 R04
Molybdenum	<0.5			MG/L		AS-5 R04
Sodium	13900	13600		MG/L	2.	AS-5 R04
Ammonium	<0.10			MG/L		F-6 R05
Nitrate	<0.2	<0.2		MG/L		D-3 R08
Lead	<0.03			MG/L		AS-6 R03
pH	7.63	7.70			-1.	H-4 R03
Phosphate	0.1	0.1		MG/L	0.	F-4 R05
Antimony	<0.6			MG/L		AS-5 R04
Specific Gravity	1.03	1.03		G/CC	0.	K-4 R01
Silica	9.19	9.86		MG/L	-7.	AS-5 R04
Sulfate	7300	7190		MG/L	2.	D-3 R08
Strontium	9.58	10.0		MG/L	-4.	AS-5 R04
Total Dissolved Solids	44000	45000		MG/L	-2.	K-3 R04
Titanium	<1			MG/L		AS-5 R04
Total Inorganic Carbon	13.3	13.0		MG/L	2.	K-5 R03
Uranium	<0.05			MG/L		AS-6 R03
Vanadium	<0.5			MG/L		AS-5 R04
Zinc	<0.2			MG/L		AS-5 R04

(SECTION 1)

D-153

CUSTOMER ID: VPX 26 B
TICKET ID:

ANALYTICAL RESULTS

DATE: 16-APR-92
LAB ID: 195511

REQUESTOR: FRED GELBARD
SAMPLE MATRIX: BRINE
REQUISITION: 7070

PROJECT NUMBER: 6S0007000
DATE RECEIVED: 25-FEB-92
DATE COLLECTED: 15-DEC-91

ANALYSIS REQUESTED	RESULTS	RESULTS	RESULTS	UNITS	RPD	METHOD OF ANALYSIS
Silver	<0.1			MG/L		AS-5 R04
Aluminum	<0.05			MG/L		AS-2 R05
Boron	26.2	25.2		MG/L	4.	AS-5 R04
Bromide	22.2	22.8		MG/L	-3.	D-3 R08
Calcium	846	820		MG/L	3.	AS-5 R04
Cadmium	<0.05			MG/L		AS-6 R03
Chloride	19200	19400		MG/L	-1.	D-3 R08
Chromium	<0.1			MG/L		AS-5 R04
Copper	<0.25			MG/L		AS-5 R04
Fluoride	1.5	1.6		MG/L	76.	D-3 R08
Iron	<0.50			MG/L		AS-5 R04
Iodide	0.07	0.08		MG/L	-13.	D-3 R08
Potassium	341	333		MG/L	2.	AS-1 R04
Lithium	0.329	0.342		MG/L	-4.	AS-6 R03
Magnesium	430	411		MG/L	5.	AS-5 R04
Manganese	0.25	0.23		MG/L	8.	AS-5 R04
Molybdenum	<0.5			MG/L		AS-5 R04
Sodium	13900	13500		MG/L	3.	AS-5 R04
Ammonium	<0.10			MG/L		F-6 R05
Nitrate	<0.2	<0.2		MG/L		D-3 R08
Lead	<0.03			MG/L		AS-6 R03
pH	7.59	7.69			-1.	H-4 R03
Phosphate	<0.1			MG/L		F-4 R05
Antimony	<0.6			MG/L		AS-5 R04
Specific Gravity	1.03	1.03		G/CC	0.	K-4 R01
Silica	8.76	9.57		MG/L	-9.	AS-5 R04
Sulfate	7310	7210		MG/L	1.	D-3 R08
Strontium	9.66	10.0		MG/L	-3.	AS-5 R04
Total Dissolved Solids	44000	45000		MG/L	-2.	K-3 R04
Titanium	<1			MG/L		AS-5 R04
Total Inorganic Carbon	12.0	12.0		MG/L	0.	K-5 R03
Uranium	<0.05			MG/L		AS-6 R03
Vanadium	<0.5			MG/L		AS-5 R04
Zinc	<0.2			MG/L		AS-5 R04

(SECTION 1)

CUSTOMER ID: VPX 26 C
TICKET ID: .

REQUESTOR: FRED GELBARD
SAMPLE MATRIX: BRINE
REQUISITION: 7070

ANALYTICAL RESULTS

DATE: 16-APR-92
LAB ID: 195512

PROJECT NUMBER: 680007000
DATE RECEIVED: 25-FEB-92
DATE COLLECTED: 16-DEC-91

ANALYSIS REQUESTED	RESULTS	RESULTS	RESULTS	UNITS	RPD	METHOD OF ANALYSIS
Silver	<0.1			MG/L		AS-5 R04
Aluminum	<0.05			MG/L		AS-2 R05
Boron	25.6	27.5	26.2	MG/L	4.	AS-5 R04
Bromide	22.3	22.7		MG/L	-2.	D-3 R08
Calcium	845	818		MG/L	3.	AS-5 R04
Cadmium	<0.05			MG/L		AS-6 R03
Chloride	19300	19300		MG/L	0.	D-3 R08
Chromium	<0.1			MG/L		AS-5 R04
Copper	<0.25			MG/L		AS-5 R04
Fluoride	1.6	1.6		MG/L	0.	D-3 R08
Iron	<0.50			MG/L		AS-5 R04
Iodide	0.09	0.09		MG/L	0.	D-3 R08
Potassium	310	331	329	MG/L	4.	AS-1 R04
Lithium	0.325	0.348		MG/L	-7.	AS-6 R03
Magnesium	426	412		MG/L	3.	AS-5 R04
Manganese	<0.15			MG/L		AS-5 R04
Molybdenum	<0.5			MG/L		AS-5 R04
Sodium	14000	13600		MG/L	3.	AS-5 R04
Ammonium	<0.10			MG/L		F-6 R05
Nitrate	<0.2	<0.2		MG/L		D-3 R08
Lead	<0.03			MG/L		AS-6 R03
pH	7.56	7.63			-1.	H-4 R03
Phosphate	<0.1			MG/L		F-4 R05
Antimony	<0.6			MG/L		AS-5 R04
Specific Gravity	1.03	1.03		G/CC	0.	K-4 R01
Silica	9.59	10.1	10.4	MG/L	4.	AS-5 R04
Sulfate	7320	7210		MG/L	2.	D-3 R08
Strontium	9.61	9.81		MG/L	-2.	AS-5 R04
Total Dissolved Solids	44000	44000		MG/L	0.	K-3 R04
Titanium	<1			MG/L		AS-5 R04
Total Inorganic Carbon	11.8	11.5		MG/L	3.	K-5 R03
Uranium	<0.05			MG/L		AS-6 R03
Vanadium	<0.5			MG/L		AS-5 R04
Zinc	<0.2			MG/L		AS-5 R04

(SECTION 1)

CUSTOMER ID: VPX 26 D
TICKET ID:

ANALYTICAL RESULTS

DATE: 16-APR-92
LAB ID: 195513

REQUESTOR: FRED GELBARD
SAMPLE MATRIX: BRINE
REQUISITION: 7070

PROJECT NUMBER: 680007000
DATE RECEIVED: 25-FEB-92
DATE COLLECTED: 16-DEC-91

ANALYSIS REQUESTED	RESULTS	RESULTS	RESULTS	UNITS	RPD	METHOD OF ANALYSIS
Silver	<0.1	<0.1		MG/L		AS-5 R04
Aluminum	<0.05			MG/L		AS-2 R05
Boron	26.4	26.7		MG/L	-1.	AS-5 R04
Bromide	22.8	22.9		MG/L	0.	D-3 R08
Calcium	857	823		MG/L	4.	AS-5 R04
Cadmium	<0.05			MG/L		AS-6 R03
Chloride	19400	19500		MG/L	-1.	D-3 R08
Chromium	<0.1	<0.1		MG/L		AS-5 R04
Copper	<0.25			MG/L		AS-5 R04
Fluoride	1.5	1.6		MG/L	-6.	D-3 R08
Iron	<0.50			MG/L		AS-5 R04
Iodide	0.09	0.09		MG/L	0.	D-3 R08
Potassium	323	335	351	MG/L	4.	AS-1 R04
Lithium	0.327	0.35		MG/L	-7.	AS-6 R03
Magnesium	433	418		MG/L	4.	AS-5 R04
Manganese	<0.15			MG/L		AS-5 R04
Molybdenum	<0.5	<0.5		MG/L		AS-5 R04
Sodium	13900	13700		MG/L	1.	AS-5 R04
Ammonium	<0.10			MG/L		F-6 R05
Nitrate	<0.2	<0.2		MG/L		D-3 R08
Lead	<0.03			MG/L		AS-6 R03
pH	7.53	7.58			-1.	H-4 R03
Phosphate	<0.1			MG/L		F-4 R05
Antimony	<0.6			MG/L		AS-5 R04
Specific Gravity	1.03	1.03		G/CC	0.	K-4 R01
Silica	9.30	9.95	10.1	MG/L	4.	AS-5 R04
Sulfate	7330	7200		MG/L	2.	D-3 R08
Strontium	9.72	9.89		MG/L	-2.	AS-5 R04
Total Dissolved Solids	46000	44000		MG/L	4.	K-3 R04
Titanium	<1			MG/L		AS-5 R04
Total Inorganic Carbon	12.1	11.8		MG/L	3.	K-5 R03
Uranium	<0.05			MG/L		AS-6 R03
Vanadium	<0.5			MG/L		AS-5 R04
Zinc	<0.2			MG/L		AS-5 R04

(SECTION 1)

ANALYTICAL RESULTS

DATE: 16-APR-92

LAB ID: 195514

CUSTOMER ID: VPX 26 E
TICKET ID:REQUESTOR: FRED GELBARD
SAMPLE MATRIX: BRINE
REQUISITION: 7070PROJECT NUMBER: 680007000
DATE RECEIVED: 25-FEB-92
DATE COLLECTED: 16-DEC-91

ANALYSIS REQUESTED	RESULTS	RESULTS	RESULTS	UNITS	RPD	METHOD OF ANALYSIS
Silver	<0.1			MG/L		AS-5 R04
Aluminum	<0.05			MG/L		AS-2 R05
Boron	26.4	27.6		MG/L	-4.	AS-5 R04
Bromide	22.2	22.7		MG/L	-2.	D-3 R08
Calcium	838	815		MG/L	3.	AS-5 R04
Cadmium	<0.05			MG/L		AS-6 R03
Chloride	19000	19300		MG/L	-2.	D-3 R08
Chromium	<0.1			MG/L		AS-5 R04
Copper	<0.25			MG/L		AS-5 R04
Fluoride	1.6	1.6		MG/L	0.	D-3 R08
Iron	<0.50			MG/L		AS-5 R04
Iodide	0.08	0.08		MG/L	0.	D-3 R08
Potassium	327	344		MG/L	-5.	AS-1 R04
Lithium	0.326	0.341		MG/L	-4.	AS-6 R03
Magnesium	421	409		MG/L	3.	AS-5 R04
Manganese	<0.15			MG/L		AS-5 R04
Molybdenum	<0.5			MG/L		AS-5 R04
Sodium	14100	13500	14000	MG/L	2.	AS-5 R04
Ammonium	<0.10			MG/L		F-6 R05
Nitrate	<0.2	<0.2		MG/L		D-3 R08
Lead	<0.03			MG/L		AS-6 R03
pH	7.45	7.55			-1.	H-4 R03
Phosphate	<0.1			MG/L		F-4 R05
Antimony	<0.6			MG/L		AS-5 R04
Specific Gravity	1.03	1.03		G/CC	0.	K-4 R01
Silica	9.42	9.80	10.3	MG/L	4.	AS-5 R04
Sulfate	7290	7170		MG/L	2.	D-3 R08
Strontium	9.54	9.73		MG/L	-2.	AS-5 R04
Total Dissolved Solids	44000	44000		MG/L	0.	K-3 R04
Titanium	<1			MG/L		AS-5 R04
Total Inorganic Carbon	12.0	11.9		MG/L	1.	K-5 R03
Uranium	<0.05			MG/L		AS-6 R03
Vanadium	<0.5			MG/L		AS-5 R04
Zinc	<0.2			MG/L		AS-5 R04

(SECTION I)

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APPENDIX C

LIST OF EQUIPMENT AND MANUFACTURERS

PolyScience 730 Immersion Circulator
Serial # 926370
PolyScience
P.O. Box 48312
Niles, IL 60648
(708) 965-0611

Jupiter Viscosity Timer Model 821
Serial # J 2033-1
Jupiter Instrument Company
407 Commerce Way A15
Jupiter, FL 33458
(407) 743-8486

Mettler Portable Density/Specific Gravity Meter DA-110
Mfg. No. NJA31791
Mettler Instrument Corporation
Box 71
Hightstown, NJ 08520
(609) 488-3000

Cannon-Fenske Routine Viscometer
Viscometer No. U383 size 50
Viscometer No. U513 size 50
Cannon Instrument Company
P.O. Box 16
State College, PA 16804

Deionized Ultra Filtered Water
Lot No. 923068
Fisher Scientific Company
Fairlawn, NJ 07410
(201) 796-7100

REFERENCES

Earlougher, Robert C. Jr. 1977. Advances In Well Test Analysis. 2nd edition. Society of Petroleum Engineers of AIME, New York. Page 241.

Analytical Report. Volume I of IV. Chem-Nuclear Geotech Analytical Laboratory, Grand Junction, CO. 1992. Section 1.

Weast, Robert C. 1989. Handbook of Chemistry and Physics. 70th edition (1989-1990). Boca Raton, Florida: CRC Press, Inc.

WP08761

Sandia National Laboratories

Albuquerque, New Mexico 87185

date 13 August 1993

to Fred Gelbard, 6119

from: *Stephen Yeh*
Stephen Yeh, 6119

INFORMATION ONLY

subject: Viscosity Measurements of Salado Brines

Enclosed is my report on the viscosities of three Salado brines.

Copy to:

6115 R. Beauheim

6115 S. Webb

6119 D. Lucero

6119 H. Papenguth

6119 K. Robinson

6119 J.A. Romero

6119 File 3.2

6303 SWCF/WBS 1.1.5.1.5

*LUC/SOK sgc
9/1/93*

DETERMINATION OF THE VISCOSITY OF SALADO BRINES
IN THE TEMPERATURE RANGE OF 20°C TO 35°C

Stephen Yeh
Department 6119
Sandia National Laboratories
August 1993

ABSTRACT

Experimentally determined values for three Salado brines (field brines L4P51 and QPBO2D, and synthetic brine SB-139-B) were measured in a temperature range of 20°C to 35°C. The viscosity values decrease with temperature from $2.572 \text{ cP} \pm 0.0075 \text{ cP}$ to $1.619 \text{ cP} \pm .005 \text{ cP}$.

INTRODUCTION

The viscosity of QPBO2D Salado brine (bottled 8/16/90) was determined experimentally at two degree (Celsius) increments on 7/12-16/93. The viscosity of SB-139-B synthetic Salado brine (mixed 6/18/93) was determined on 7/19-22/93 for six temperatures: 20, 26, 27, 28, 29, and 35 degrees Celsius. The viscosity of L4P51 Salado brine (bottle date 7/22/93) was also determined for the above six temperatures on 7/26-29/93. New calibrated Cannon-Fenske viscometers (No. U736/50 for QPBO2D, No. U677/50 for SB-139-B, and No. U667/50 for L4P51) were used in conjunction with a Jupiter Viscosity Timer Model 821 and a PolyScience 730 Immersion Circulator constant temperature bath. Deionized Ultra Filtered water from Fisher Scientific Co. was used for checking the viscosity. The calibration certificates for applicable instruments and a list of equipment and manufacturers are given in the Appendices.

EXPERIMENT

The viscometer is initially rinsed with deionized water by filling the bulb with about 7.0 mL of liquid (depending on charge volume specified by manufacturer) and drawing it through and up into the capillary a few times. The water is then poured out and a fresh charge of deionized water is added. The viscometer is inserted vertically in the self-aligning holder in the constant temperature bath (initially set at 20°C) and left for about ten minutes to allow the liquid inside to equilibrate. The temperature in the bath is monitored by a calibrated thermocouple. (See Appendix for calibration certificate).

To check the viscometer, the meniscus of the water is allowed to flow freely past two marked points. Light timers that are activated by the refraction change as the meniscus passes the

sensor are mounted across the markings. The elapsed, or efflux, time is recorded. To convert the efflux time to viscosity in centipoise, it is multiplied by the viscometer constant (supplied and verified by the manufacturer -- viscometer constants are given for 40°C and 100°C and are extrapolated to the desired testing temperatures) and then multiplied by the density of the liquid being tested. In the case of the deionized water check, the densities at varying temperatures were taken from the Handbook of Chemistry and Physics (Weast, 1990, page F-4). About five runs are made and recorded at each temperature.

If the determined viscosity values for deionized water agree within a couple percent of the tabulated viscosities (from Weast, 1990, page F-40) then the brine can now be tested. The same rinsing procedure used with deionized water is used with brine (i.e. about 1-4 mL drawn in, rinsed, poured out and refilled). Again the viscometer is allowed to reach testing temperature and then flow times are recorded. Ten runs are made at each temperature.

Following the brine test-runs, deionized water is used again (same procedure for rinsing, etc.) and values compared to previous values to check for large discrepancies or errors such as brine precipitation and blockage of the viscometer capillary. Again, about five time values are recorded. Once assured there are no significant discrepancies, the water bath is raised to the next desirable temperature, and the above procedure is repeated.

Brine densities are recorded at various temperatures (about 20°C to 35°C) using a Mettler Portable Density/Specific Gravity Meter model DA-110. The meter is checked with deionized water and densities verified to be accurate to three decimal places.

RESULTS

Tables 1, 2, and 3 show summaries of the data for the QPBO2D, SB-139-B, and L4P51 brines respectively. Given are averages of the individual times and temperatures (not reprinted here), one standard deviation, two standard deviations, densities, number of points or readings, and calculated viscosities and errors.

Errors refer only to the viscosity calculations and were calculated as follows: For the deionized water checks, percent error is relative to tabulated book values from the Handbook of Chemistry and Physics. For the standard deviations, errors reflect what percent of the average viscosity the deviation is (i.e. deviation divided by average viscosity multiplied by 100% = error). Temperature standard deviations indicate temperature fluctuations or error over time, not actual thermocouple calibration error.

Tables 4, 5, and 6 briefly summarize the determined viscosities and densities and their respective temperatures for the three brines.

Table 7 gives the composition of the synthetic Salado brine.

Following are seven graphs. The graphs for the viscosity and density of Salado brines show a general decreasing trend with

increasing temperature. The first six graphs show how the density (Figures 1, 3, and 5) and viscosity (Figures 2, 4, and 6) of QPBO2D, SB-139-B, and L4P51 vary with temperature. In Figures 2, 4, and 6, error bars are included for temperature and viscosity and indicate two standard deviations (about 95% confidence). Again, temperature error bars indicate fluctuations over time, not thermocouple error. The thermocouple error (see Appendix A) is about $+0.1^{\circ}\text{C}$, which means the measured temperatures are about 0.1°C too high. This results in an error in the viscosity calculations of less than one-half of one percent (for example, viscosities read off of Figure 1 may be 0.004 cP too high). For the densities in Figures 1, 3, and 5, since measurements were not repeated for a given temperature, (constant temperature is too hard to keep without fluctuation) there are no error bars, but estimated density error is about 0.001 to 0.005 g/mL or about 0.1 to 0.5%. (Note: This was not added into the error calculation for viscosity). The equation for the line fits were derived using the method of least squares. The seventh graph shows the viscosity trends of all three Salado brines on the same scale for comparison.

DISCUSSION

The errors calculated for the experimental viscosities of the brines were mostly less than 0.5% and show experimental consistency. Taking into account thermocouple (calibration) error and density error adds only about 0.5% at most to the viscosity values. The deionized water viscosities differed from published values by no more than 2.4% for all tests. Even if one takes into account that the times increase slightly for progressing runs at the same temperature (i.e. pre-check times versus post-check times), and therefore probably for the whole test, the error remains near or under 3%.

The density measurements were harder to take because the meter drifted during measurements. The drift was probably due to the brine changing temperature when introduced into the meter. Also, the meter's thermometer was too inaccurate (it usually did not change much, if at all), so the same thermocouple as for the water bath was used. Density values in Tables 1, 2, and 3 for the brines were extrapolated from the line fit equations.

Comparing the viscosities for the different brines show that L4P51 values are consistently 0.05 cP to 0.10 cP higher than the QPBO2D values. The QPBO2D values in turn are consistently about 0.15 cP higher than the SB-139-B values. All this is to say the curves for the three Salado brines are very nearly parallel (as seen in Figure 7). This would suggest that the QPBO2D and L4P51 brines may be more concentrated in solutes than SB-139-B (which has lower viscosities). This could be because SB-139-B is a synthetic and therefore probably not as saturated as a natural brine. From previous viscosity experiments with Culebra brines, it seems that even a seemingly minor change in concentration is noticeable in the experimental data; the actual data show that a 5.9% increase in

salt or solute results in an average increase of 2.7% in the viscosity. This suggests that brine viscosities are sensitive to such small changes in concentration.

CONCLUSION

The experimental procedure for determining the viscosity of brine seems to be very consistent and relatively simple. The accuracy of the results is limited only by the accuracy of the thermocouple (small at about 0.1°C), time variations in the constant temperature water bath (which appeared minimal at about 0.1°C and could also include the thermocouple error), and possible clogging in the viscometer due to precipitation of brine or particulates. Though no visible problems were noted, sometimes the efflux times for the water checks dropped over time (i.e. after maybe five or more flow measurements). This may indicate that the viscometer is cleaning itself out slowly when it has water soaking in it; but, times do not change by more than about one or two seconds. Possible considerations regarding this may include more water checks.

The Salado brine viscosities seem like they would be similar to viscosities of a comparable percent by weight sodium chloride solution but there are no available saline solution data available for comparison.

TABLE 1

C=calib. const.

Viscosity=pCt: p=density C=0.0040328 t=time
 (g/mL) to 0.0040373 (s)
 (cSt/s)

Approximate temperature:		Temp(C)	Time(s)	Visc. (cP)	%error:
20 degrees (C)	pre-check :Average:	19.99	251.5	1.014	1.2
	6pts :Std.Dev.:	0.04	0.23	0.0009	0.09
	p=.9982 :2 Std. Dev.:	0.08	0.46	0.0019	0.19
	Brine test:Average:	20.07	508.5	2.473	
	10pts :Std.Dev.:	0.05	0.62	0.003	0.12
	p=1.2046 :2 Std. Dev.:	0.1	1.24	0.006	0.24
	post-check:Average:	20.02	252.2	1.016	1.4
	5pts :Std.Dev.:	0.04	0.19	0.0008	0.08
	p=.9982 :2 Std. Dev.:	0.09	0.39	0.0016	0.16
22 degrees (C)	pre-check :Average:	22.05	240	0.9666	1.2
	5pts :Std.Dev.:	0.04	0.23	0.0009	0.09
	p=.9978 :2 Std. Dev.:	0.07	0.46	0.0019	0.2
	Brine test:Average:	22.05	485.6	2.355	
	10pts :Std.Dev.:	0.02	0.67	0.0032	0.14
	p=1.2017 :2 Std. Dev.:	0.05	1.35	0.0065	0.28
	post-check:Average:	22.05	240.2	0.9674	1.3
	5pts :Std.Dev.:	0.04	0.09	0.0004	0.04
	p=.9978 :2 Std. Dev.:	0.07	0.18	0.0007	0.07
24 degrees (C)	pre-check :Average:	24.01	229.5	0.9237	1.4
	5pts :Std.Dev.:	0.04	0.04	0.0002	0.02
	p=.9973 :2 Std. Dev.:	0.08	0.09	0.0004	0.04
	Brine test:Average:	24.04	463.5	2.243	
	11pts :Std.Dev.:	0.02	0.45	0.0022	0.1
	p=1.1988 :2 Std. Dev.:	0.04	0.9	0.0044	0.2
	post-check:Average:	24.03	229.6	0.9241	1.4
	5pts :Std.Dev.:	0.03	0.4	0.0016	0.17
	p=.9973 :2 Std. Dev.:	0.05	0.8	0.0032	0.35

TABLE 1
(cont'd)

Approximate temperature:		Temp(C)	Time(s)	Visc. (cP)	%error:
26 degrees (C)	pre-check :Average:	26.04	217.9	0.8765	0.6
	5pts :Std.Dev.:	0.04	0.15	0.0006	0.07
	p=.9968 :2 Std. Dev.:	0.08	0.3	0.0012	0.14
	Brine test:Average:	26.02	439.4	2.12	
	10pts :Std.Dev.:	0.03	0.15	0.0007	0.03
	p=1.1959 :2 Std. Dev.:	0.05	0.3	0.0014	0.07
	post-check:Average:	25.97	219.6	0.8833	1.5
	5pts :Std.Dev.:	0.03	0.35	0.0014	0.16
	p=.9968 :2 Std. Dev.:	0.05	0.7	0.0028	0.32
28 degrees (C)	pre-check :Average:	27.97	210.3	0.8453	1.5
	5pts :Std.Dev.:	0.03	0.04	0.0002	0.02
	p=.9962 :2 Std. Dev.:	0.05	0.09	0.0004	0.05
	Brine test:Average:	28.01	422.4	2.033	
	10pts :Std.Dev.:	0.02	0.08	0.0004	0.02
	p=1.1930 :2 Std. Dev.:	0.04	0.16	0.0008	0.04
	post-check:Average:	28.01	210.9	0.8477	1.8
	5pts :Std.Dev.:	0.07	0.15	0.0006	0.07
	p=.9962 :2 Std. Dev.:	0.15	0.3	0.0012	0.14
30 degrees (C)	pre-check :Average:	29.94	202.3	0.8125	1.9
	6pts :Std.Dev.:	0.04	0.13	0.0005	0.06
	p=.9956 :2 Std. Dev.:	0.08	0.25	0.001	0.12
	Brine test:Average:	30.02	404.9	1.944	
	10pts :Std.Dev.:	0.06	0.5	0.0024	0.12
	p=1.1900 :2 Std. Dev.:	0.13	1	0.0048	0.25
	post-check:Average:	29.95	202.8	0.8145	2.1
	5pts :Std.Dev.:	0	0.08	0.0003	0.04
	p=.9956 :2 Std. Dev.:	0	0.17	0.0007	0.09

TABLE 1
(cont'd)

Approximate temperature:		Temp (C)	Time (s)	Visc. (cP)	%error:
32 degrees (C)	=====	=====	=====	=====	=====
pre-check	:Average:	32.01	: 194.3	: 0.7798	: 2 :
5pts	:Std.Dev.:	0.02	: 0.09	: 0.0004	: 0.05 :
p=.9950	:2 Std. Dev.:	0.04	: 0.18	: 0.0007	: 0.09 :
	-----	-----	-----	-----	-----
Brine test	:Average:	32.01	: 389.4	: 1.865	: :
12pts	:Std.Dev.:	0.05	: 3.28	: 0.0157	: 0.84 :
p=1.1871	:2 Std. Dev.:	0.09	: 6.56	: 0.0314	: 1.7 :
	-----	-----	-----	-----	-----
post-check	:Average:	32	: 194.7	: 0.7814	: 2.2 :
5pts	:Std.Dev.:	0.04	: 0.26	: 0.001	: 0.13 :
p=.9950	:2 Std. Dev.:	0.07	: 0.52	: 0.0021	: 0.27 :
	=====	=====	=====	=====	=====
34 degrees (C)	=====	=====	=====	=====	=====
pre-check	:Average:	33.99	: 186	: 0.7459	: 1.6 :
7pts	:Std.Dev.:	0.05	: 0.3	: 0.0012	: 0.16 :
p=.9944	:2 Std. Dev.:	0.1	: 0.6	: 0.0024	: 0.32 :
	-----	-----	-----	-----	-----
Brine test	:Average:	34.04	: 370.9	: 1.771	: :
10pts	:Std.Dev.:	0.02	: 0.3	: 0.0015	: 0.08 :
p=1.1841	:2 Std. Dev.:	0.04	: 0.6	: 0.0029	: 0.16 :
	-----	-----	-----	-----	-----
post-check	:Average:	33.97	: 187.1	: 0.7503	: 2.2 :
5pts	:Std.Dev.:	0.04	: 0.2	: 0.0008	: 0.11 :
p=.9944	:2 Std. Dev.:	0.09	: 0.4	: 0.0016	: 0.21 :
	=====	=====	=====	=====	=====
	=====	=====	=====	=====	=====

TABLE 2

C=calib. const.

Viscosity=pCt: p=density C=0.0041808 t=time
 (g/mL) to 0.0041860 (s)
 (cSt/s)

Approximate temperature:		Temp(C)	Time(s)	Visc. (cP)	%error:
20 degrees (C)	pre-check :Average:	20.04	243.8	1.019	1.7
	5pts :Std.Dev.:	0.02	0.09	0.0004	0.04
	p=.9982 :2 Std. Dev.:	0.04	0.18	0.0008	0.08
	Brine test:Average:	20.05	458.5	2.301	
	11pts :Std.Dev.:	0.04	0.51	0.0025	0.11
	p=1.1988 :2 Std. Dev.:	0.08	1.02	0.0051	0.22
	post-check:Average:	20.07	244.7	1.022	2
	5pts :Std.Dev.:	0.04	0.33	0.0014	0.14
	p=.9982 :2 Std. Dev.:	0.09	0.67	0.0028	0.27
26 degrees (C)	pre-check :Average:	26.03	211	0.88	1.1
	6pts :Std.Dev.:	0.03	0.15	0.0006	0.07
	p=.9968 :2 Std. Dev.:	0.05	0.29	0.0012	0.14
	Brine test:Average:	26.04	400	1.991	
	11pts :Std.Dev.:	0.04	0.38	0.0019	0.1
	p=1.1897 :2 Std. Dev.:	0.08	0.76	0.0038	0.19
	post-check:Average:	25.99	211.5	0.8821	1.3
	5pts :Std.Dev.:	0.02	0.11	0.0005	0.06
	p=.9968 :2 Std. Dev.:	0.04	0.22	0.0009	0.1
27 degrees (C)	pre-check :Average:	27	207.8	0.8664	1.8
	5pts :Std.Dev.:	0.04	0.23	0.001	0.12
	p=.9965 :2 Std. Dev.:	0.07	0.46	0.0019	0.22
	Brine test:Average:	27	392.7	1.952	
	10pts :Std.Dev.:	0.02	0.37	0.0018	0.09
	p=1.1883 :2 Std. Dev.:	0.05	0.75	0.0037	0.19
	post-check:Average:	26.96	208.9	0.871	2.3
	5pts :Std.Dev.:	0.02	0.14	0.0006	0.07
	p=.9965 :2 Std. Dev.:	0.04	0.28	0.0012	0.14

TABLE 2
(cont'd)

Approximate temperature:		Temp (C)	Time (s)	Visc. (cP)	%error:
28 degrees (C)	pre-check :Average:	27.95	204.6	0.8526	2.4
	5pts :Std.Dev.:	0	0.08	0.0003	0.04
	p=.9962 :2 Std. Dev.:	0	0.17	0.0007	0.08
	Brine test:Average:	27.96	382.4	1.899	
	10pts :Std.Dev.:	0.02	0.44	0.0022	0.12
	p=1.1868 :2 Std. Dev.:	0.04	0.88	0.0044	0.23
	post-check:Average:	27.95	203.3	0.8472	1.7
	5pts :Std.Dev.:	0	0.04	0.0002	0.02
	p=.9962 :2 Std. Dev.:	0	0.09	0.0004	0.05
29 degrees (C)	pre-check :Average:	28.98	198.8	0.8282	1.6
	5pts :Std.Dev.:	0.03	0.09	0.0004	0.05
	p=.9959 :2 Std. Dev.:	0.05	0.18	0.0007	0.08
	Brine test:Average:	29.04	373.4	1.851	
	10pts :Std.Dev.:	0.02	0.48	0.0023	0.12
	p=1.1852 :2 Std. Dev.:	0.05	0.95	0.0047	0.25
	post-check:Average:	29	198.5	0.8269	1.5
	5pts :Std.Dev.:	0	0.09	0.0004	0.05
	p=.9959 :2 Std. Dev.:	0	0.18	0.0007	0.08
35 degrees (C)	pre-check :Average:	34.99	175.9	0.731	1.6
	6pts :Std.Dev.:	0.02	0.09	0.0004	0.05
	p=.9940 :2 Std. Dev.:	0.04	0.18	0.0007	0.1
	Brine test:Average:	35.01	329.3	1.619	
	10pts :Std.Dev.:	0.03	0.09	0.0025	0.15
	p=1.1761 :2 Std. Dev.:	0.06	0.18	0.005	0.31
	post-check:Average:	34.99	176.8	0.7347	2.1
	5pts :Std.Dev.:	0.02	0.16	0.0007	0.1
	p=.9940 :2 Std. Dev.:	0.04	0.33	0.0014	0.19

TABLE 3

C=calib. const.

Viscosity=pCt: p=density C=0.0039857 t=time
 (g/mL) to 0.0039907 (s)
 (cSt/s)

Approximate temperature:		Temp (C)	Time (s)	Visc. (cP)	%error:
20 degrees (C)	pre-check :Average:	20.04	254.6	1.014	1.2
	5pts :Std.Dev.:	0.02	0.08	0.0003	0.03
	p=.9982 :2 Std. Dev.:	0.04	0.17	0.0006	0.06
	Brine test:Average:	20.01	527	2.572	
	10pts :Std.Dev.:	0.02	0.77	0.0038	0.15
	p=1.2230 :2 Std. Dev.:	0.04	1.54	0.0075	0.29
	post-check:Average:	20.03	255.4	1.017	1.5
	5pts :Std.Dev.:	0.03	0.09	0.0004	0.04
	p=.9982 :2 Std. Dev.:	0.05	0.18	0.0007	0.07
26 degrees (C)	pre-check :Average:	25.99	220.1	0.8751	0.53
	6pts :Std.Dev.:	0.02	0	0	0
	p=.9968 :2 Std. Dev.:	0.04	0	0	0
	Brine test:Average:	26.04	452.1	2.187	
	10pts :Std.Dev.:	0.02	0.26	0.0013	0.06
	p=1.2127 :2 Std. Dev.:	0.05	0.52	0.0025	0.11
	post-check:Average:	25.99	221.2	0.8795	1
	5pts :Std.Dev.:	0.04	0.26	0.001	0.11
	p=.9968 :2 Std. Dev.:	0.08	0.52	0.002	0.23
27 degrees (C)	pre-check :Average:	26.94	216.5	0.8604	1.1
	5pts :Std.Dev.:	0.02	0	0	0
	p=.9965 :2 Std. Dev.:	0.04	0	0	0
	Brine test:Average:	26.98	441.3	2.131	
	10pts :Std.Dev.:	0.03	0.69	0.0033	0.15
	p=1.2110 :2 Std. Dev.:	0.05	1.37	0.0066	0.31
	post-check:Average:	27	215.9	0.8581	0.8
	5pts :Std.Dev.:	0	0.23	0.0009	0.1
	p=.9965 :2 Std. Dev.:	0	0.47	0.0019	0.22

TABLE 3
(cont'd)

Approximate temperature:		Temp(C)	Time(s)	Visc.(cP)	%error:
28 degrees (C)	pre-check :Average:	27.94	211.1	0.8387	0.72
	5pts :Std.Dev.:	0.04	0.04	0.0002	0.02
	p=.9962 :2 Std. Dev.:	0.08	0.09	0.0003	0.04
	Brine test:Average:	28	430.7	2.077	
	10pts :Std.Dev.:	0.02	0.82	0.004	0.19
	p=1.2093 :2 Std. Dev.:	0.03	1.64	0.0079	0.38
	post-check:Average:	28.02	212.2	0.843	1.2
	5pts :Std.Dev.:	0.03	0.09	0.0004	0.05
	p=.9962 :2 Std. Dev.:	0.05	0.18	0.0007	0.08
29 degrees (C)	pre-check :Average:	28.97	207.8	0.8257	1.3
	5pts :Std.Dev.:	0.04	0.11	0.0004	0.05
	p=.9959 :2 Std. Dev.:	0.09	0.22	0.0009	0.11
	Brine test:Average:	28.99	421.9	2.033	
	10pts :Std.Dev.:	0.03	0.65	0.0032	0.16
	p=1.2075 :2 Std. Dev.:	0.07	1.3	0.0063	0.31
	post-check:Average:	29.01	207.9	0.8261	1.4
	5pts :Std.Dev.:	0.02	0.11	0.0004	0.05
	p=.9959 :2 Std. Dev.:	0.04	0.23	0.0009	0.11
35 degrees (C)	pre-check :Average:	34.95	183.9	0.7286	1.3
	5pts :Std.Dev.:	0	0.05	0.0002	0.03
	p=.9940 :2 Std. Dev.:	0	0.11	0.0004	0.05
	Brine test:Average:	34.95	371.9	1.775	
	10pts :Std.Dev.:	0	0.06	0.0003	0.02
	p=1.1973 :2 Std. Dev.:	0	0.13	0.0006	0.03
	post-check:Average:	34.95	184.7	0.7317	1.7
	5pts :Std.Dev.:	0	0.05	0.0002	0.03
	p=.9940 :2 Std. Dev.:	0	0.11	0.0004	0.05

TABLE 4

DATA SUMMARY
PROPERTIES OF QPBO2D SALADO BRINE

<u>Computed (From Measured) Values:</u>	
<u>Temperature (°C)</u>	<u>Viscosity (cP)</u>
20.07	2.473
22.05	2.355
24.04	2.243
26.02	2.120
28.01	2.033
30.02	1.944
32.01	1.865
34.04	1.770

<u>Measured Values:</u>		
	<u>Temperature (°C)</u>	<u>Density (g/mL)</u>
In order taken:	18.8	1.2090
	19.9	1.2060
	20.3	1.2040
	22.5	1.1993
	24.6	1.1957
	27.4	1.1930
	28.7	1.1910
	30.3	1.1890
	31.0	1.1880
	32.0	1.1869
	34.4	1.1850
	33.1	1.1857
	32.7	1.1864
	31.9	1.1875
	31.3	1.1885
	30.5	1.1901
	29.7	1.1917
	28.0	1.1930
	26.9	1.1932

TABLE 5

DATA SUMMARY
 PROPERTIES OF SB-139-B SYNTHETIC SALADO BRINE

<u>Computed (From Measured) Values:</u>	
<u>Temperature (°C)</u>	<u>Viscosity (cP)</u>
20.05	2.301
26.04	1.991
27.00	1.952
27.96	1.899
29.04	1.851
35.01	1.619

<u>Measured Values:</u>		
	<u>Temperature (°C)</u>	<u>Density (g/mL)</u>
In order taken:	18.6	1.2020
	19.5	1.1999
	20.2	1.1982
	20.5	1.1975
	21.2	1.1963
	21.8	1.1959
	22.9	1.1946
	23.5	1.1937
	24.4	1.1922
	26.0	1.1910
	26.8	1.1895
	29.6	1.1865
	27.0	1.1875
	28.7	1.1856
	27.7	1.1880
	29.4	1.1860
	30.0	1.1830
	31.7	1.1802
	33.4	1.1803
	35.0	1.1771
	34.2	1.1782
	31.0	1.1825
	29.0	1.1855
	28.0	1.1864
	27.3	1.1871
	24.7	1.1913
	23.8	1.1921
	25.5	1.1899
	22.8	1.1932
	21.4	1.1942
	30.5	1.1837
	28.6	1.1850
	32.5	1.1805

TABLE 6

DATA SUMMARY
PROPERTIES OF L4P51 SALADO BRINE

<u>Computed (From Measured) Values:</u>	
<u>Temperature (°C)</u>	<u>Viscosity (cP)</u>
20.01	2.572
26.02	2.187
26.98	2.131
28.00	2.077
28.99	2.033
34.95	1.775

<u>Measured Values:</u>	
<u>Temperature (°C)</u>	<u>Density (g/mL)</u>
In order taken: 22.2	1.2238
23.0	1.2165
23.8	1.2135
26.1	1.2110
28.2	1.2088
30.2	1.2064
31.5	1.2050
34.5	1.2022
34.5	1.2011
32.3	1.2022
30.8	1.2040
29.0	1.2065
26.9	1.2083
26.3	1.2099
25.4	1.2110
25.1	1.2109
24.6	1.2125
24.0	1.2132
23.5	1.2134
20.9	1.2250
17.9	1.2290
18.8	1.2285
21.2	1.2248

TABLE 7

COMPOSITION OF SB-139-B SYNTHETIC SALADO BRINE

<u>Compound</u>	<u>Quantity (g/L)</u>
NaHCO ₃	*
CaCl ₂ *2H ₂ O	1.2790
MgSO ₄	19.9259
MgCl ₂ *6H ₂ O	130.6083
KCl	32.3960
NaCl	203.1150
Na ₂ B ₄ O ₇	7.0018
NaBr	1.8745

* Did not have appropriate equipment to accurately measure out 0.00013 g of a salt.

pH = 6.15

Figure 1

DENSITY (g/mL) vs. TEMPERATURE (C)
QPBO2D Salado Brine

Figure 2

VISCOSITY (cP) vs. TEMPERATURE (C)
QPBO2D Salado Brine

Figure 3

DENSITY (g/mL) vs. TEMPERATURE (C)
SB-139-B Synthetic Salado Brine

Figure 4

VISCOSITY (cP) vs. TEMPERATURE (C)
SB-139-B Synthetic Salado Brine

Figure 5

DENSITY (g/mL) vs. TEMPERATURE (C)
L4P51 Salado Brine

Figure 6

VISCOSITY (cP) vs. TEMPERATURE (C)
L4P51 Salado Brine

Viscosity (cP)

Temperature (C)

Figure 7

VISCOSITY (cP) vs. TEMPERATURE (C)
QPBO2D, SB-139-B Synthetic, and L4P51 Salado Brines

APPENDIX A
CERTIFICATES OF CALIBRATION

Certificate of Calibration

Viscometer No. 50
U736

CANNON-FENSKE ROUTINE TYPE FOR TRANSPARENT LIQUIDS

(Standard Test ASTM D 445, IP 71 and ISO 3104)

Temp °C	Constant (cSt/s)
20	.0040379
22	.0040367
24	.0040358
26	.0040352
28	.0040346
30	.0040340
32	.0040334
34	.0040328

SLJ-7/24

Constant at 40°C

0.004031 mm²/s², (cSt/s)

Constant at 100°C

0.004012 mm²/s², (cSt/s)

The viscometer constant at other temperatures can be obtained by interpolation or extrapolation. To obtain kinematic viscosity in mm²/s(cSt) multiply the efflux time in seconds by the viscometer constant. To obtain viscosity in mPa·s (cP) multiply the kinematic viscosity in mm²/s(cSt) by the density in grams per milliliter.

The above constants assume a value for the coefficient of thermal expansion typical to that for mineral oil, and that the viscometer was filled with test sample at room temperature. If the filling temperature T_F is substantially different than room temperature, the viscometer constant at test temperature T_T is $C_0 (1 - B [T_T - T_F])$. The values of C_0 and B shown below are based on a coefficient of thermal expansion typical to that for a mineral oil.

Kinematic viscosities of the standards used in calibrating were established in Master Viscometers as described in Ind. Eng. Chem. Anal. Ed. 16,708(1944), ASTM D 2162, and the Journal of Research of the National Bureau of Standards, Vol. 52, No. 3, March 1954, Research Paper 2479.

Kinematic viscosities are based on the value for water adopted by the National Institute for Standards and Technology and The American Society for Testing Materials July 1, 1953. The kinematic viscosity basis is 1.0038 mm²/s(cSt) for water at 20°C (ITS-90). The gravitational constant, g , is 980.1 cm/sec² at the Cannon Instrument Company. The gravitational constant varies up to 0.1% in the United States. To make this small correction in the viscometer constant, multiply the above viscometer constant by the factor $[g(\text{at your laboratory}) / 980.1]$. The calibration data below are traceable to the National Institute for Standards and Technology. Temperature measurement traceable to NIST (Test No. 246089).

CALIBRATION DATA AT 40°C

Viscosity Standard	Kinematic Viscosity mm ² /s, (cSt)	Efflux Time Seconds	Constant mm ² /s ² , (cSt/s)
9303	1.0079	250.20	0.004028
9304	2.047	507.58	0.004033
Room Temp. (approx.) 19 °C			Average = 0.004031
Charge (approx.) 6.9 ml			$C_0 = 0.004037$
Driving fluid head (approx.) 9.2 cm			$B = 78 \times 10^{-6} / ^\circ\text{C}$
Working diameter of lower reservoir 3.0 cm			

Constant at 100° C. is 0.47 % lower than the constant at 40° C.

Calibrated by VSM 368048 on 08-Mar-93 under supervision of

Mr. E. Manning
R. E. Manning, Ph.D., P.E.
W. A. Lloyd, Ph.D., P.E.
M. R. Hoover, Ph.D.
M. K. Gerfin, C.Q.E.
Cannon Instrument Co.
State College, PA 16804, USA

Please note: This calibration remains valid for 10 years unless (1) the viscometer has been damaged or (2) materials which chemically attack borosilicate glass (e.g., hydrofluoric acid or highly alkaline solutions) have been used. Nonetheless, it is recommended that the calibration be verified with kinematic viscosity standards periodically; if a change in calibration is indicated, carefully examine all sources of error, including especially temperature measurement since most apparent changes in calibration of the viscometer are due to errors in temperature measurement.

Test No.: 368048 - 5

The S.I. unit of kinematic viscosity is 1 meter squared per second, and is equal to 10⁴ stokes. The S.I. unit of viscosity is 1 pascal second, and is equal to 10 poises. One centistokes is equal to one millimeter squared per second.

Certificate of Calibration

Viscometer No. 50
U667

CANNON-FENSKE ROUTINE TYPE FOR TRANSPARENT LIQUIDS

(Standard Test ASTM D 445, IP 71 and ISO 3104)

Temp °C	Constant
20	0.0039907
26	0.0039867
27	0.0039853
28	0.0039850
29	0.0039877
35	0.0039857

54.7/26

Constant at 40°C 0.003984 mm²/s², (cSt/s)

Constant at 100°C 0.003964 mm²/s², (cSt/s)

The viscometer constant at other temperatures can be obtained by interpolation or extrapolation. To obtain kinematic viscosity in mm²/s(cSt) multiply the efflux time in seconds by the viscometer constant. To obtain viscosity in mPa · s (cP) multiply the kinematic viscosity in mm²/s(cSt) by the density in grams per milliliter.

The above constants assume a value for the coefficient of thermal expansion typical to that for mineral oil, and that the viscometer was filled with test sample at room temperature. If the filling temperature T_F is substantially different than room temperature, the viscometer constant at test temperature T_T is $C_0 (1 - B [T_T - T_F])$. The values of C_0 and B shown below are based on a coefficient of thermal expansion typical to that for a mineral oil.

Kinematic viscosities of the standards used in calibrating were established in Master Viscometers as described in Ind. Eng. Chem. Anal. Ed. 16,708(1944), ASTM D 2162, and the Journal of Research of the National Bureau of Standards, Vol. 52, No. 3, March 1954, Research Paper 2479.

Kinematic viscosities are based on the value for water adopted by the National Institute for Standards and Technology and The American Society for Testing Materials July 1, 1953. The kinematic viscosity basis is 1.0038 mm²/s(cSt) for water at 20°C (ITS-90). The gravitational constant, g , is 980.1 cm/sec² at the Cannon Instrument Company. The gravitational constant varies up to 0.1% in the United States. To make this small correction in the viscometer constant, multiply the above viscometer constant by the factor $[g(\text{at your laboratory}) / 980.1]$. The calibration data below are traceable to the National Institute for Standards and Technology. Temperature measurement traceable to NIST (Test No. 246089).

CALIBRATION DATA AT 40°C

Viscosity Standard	Kinematic Viscosity mm ² /s, (cSt)	Efflux Time Seconds	Constant mm ² /s ² , (cSt/s)
9303	1.0079	253.08	0.003983
9304	2.047	513.62	0.003985

Room Temp. (approx.) 22 °C. Average = 0.003984

Charge (approx.) 7.0 ml. $C_0 = 0.003990$

Driving fluid head (approx.) 9.0 cm. $B = 81 \times 10^{-6} / ^\circ\text{C}$

Working diameter of lower reservoir 3.0 cm.

Constant at 100° C. is 0.49 % lower than the constant at 40° C.

Calibrated by VSM 368036 on 23-Feb-93 under supervision of

[Signature]
R. E. Manning, Ph.D., P.E.
W. A. Lloyd, Ph.D., P.E.
M. R. Hoover, Ph.D.
M. K. Gerfin, C.Q.E.
Cannon Instrument Co.
State College, PA 16804, USA

Please note: This calibration remains valid for 10 years unless (1) the viscometer has been damaged or (2) materials which chemically attack borosilicate glass (e.g., hydrofluoric acid or highly alkaline solutions) have been used. Nonetheless, it is recommended that the calibration be verified with kinematic viscosity standards periodically, if a change in calibration is indicated, carefully examine all sources of error, including especially temperature measurement since most apparent changes in calibration of the viscometer are due to errors in temperature measurement.

Test No.: 368036 - 9

The S.I. unit of kinematic viscosity is 1 meter squared per second, and is equal to 10⁴ stokes. The S.I. unit of viscosity is 1 pascal second, and is equal to 10 poises. One centistokes is equal to one millimeter squared per second.

Certificate of Calibration

Viscometer No. 50
U677

CANNON-FENSKE ROUTINE TYPE FOR TRANSPARENT LIQUIDS

(Standard Test ASTM D 445, IP 71 and ISO 3104)

Temp °C	Constant (cSt)
20	0.0041860
26	0.0041839
27	0.0041836
28	0.0041832
29	0.0041833
35	0.0041808

Sy. 7/22/93

Constant at 40°C

0.004179 mm²/s², (cSt/s)

Constant at 100°C

0.004158 mm²/s², (cSt/s)

The viscometer constant at other temperatures can be obtained by interpolation or extrapolation. To obtain kinematic viscosity in mm²/s(cSt) multiply the efflux time in seconds by the viscometer constant. To obtain viscosity in mPa·s (cP) multiply the kinematic viscosity in mm²/s(cSt) by the density in grams per milliliter.

The above constants assume a value for the coefficient of thermal expansion typical to that for mineral oil, and that the viscometer was filled with test sample at room temperature. If the filling temperature T_F is substantially different than room temperature, the viscometer constant at test temperature T_T is $C_0 (1 - B [T_T - T_F])$. The values of C_0 and B shown below are based on a coefficient of thermal expansion typical to that for a mineral oil.

Kinematic viscosities of the standards used in calibrating were established in Master Viscometers as described in Ind. Eng. Chem. Anal. Ed. 16,708(1944), ASTM D 2162, and the Journal of Research of the National Bureau of Standards, Vol. 52, No. 3, March 1954, Research Paper 2479.

Kinematic viscosities are based on the value for water adopted by the National Institute for Standards and Technology and The American Society for Testing Materials July 1, 1953. The kinematic viscosity basis is 1.0038 mm²/s(cSt) for water at 20°C (ITS-90). The gravitational constant, g , is 980.1 cm/sec² at the Cannon Instrument Company. The gravitational constant varies up to 0.1% in the United States. To make this small correction in the viscometer constant, multiply the above viscometer constant by the factor $[g(\text{at your laboratory}) / 980.1]$. The calibration data below are traceable to the National Institute for Standards and Technology. Temperature measurement traceable to NIST (Test No. 246089).

CALIBRATION DATA AT 40°C

Viscosity Standard	Kinematic Viscosity mm ² /s, (cSt)	Efflux Time Seconds	Constant mm ² /s ² , (cSt/s)
9303	1.0079	241.28	0.004177
9304	2.047	489.68	0.004180
Room Temp. (approx.) 22 °C.			Average = 0.004179
Charge (approx.) 7.2 ml.			$C_0 = 0.004185$
Driving fluid head (approx.) 9.0 cm.			$B = 83 \times 10^{-6}/^{\circ}\text{C}$
Working diameter of lower reservoir 3.0 cm.			

Constant at 100° C. is 0.50 % lower than the constant at 40° C.

Calibrated by VSM 368038 on 23-Feb-93 under supervision of

M. R. Hoover

R. E. Manning, Ph.D., P.E.
W. A. Lloyd, Ph.D., P.E.
M. R. Hoover, Ph.D.
M. K. Gerfin, C.Q.E.
Cannon Instrument Co.
State College, PA 16804, USA

Please note: This calibration remains valid for 10 years unless (1) the viscometer has been damaged or (2) materials which chemically attack borosilicate glass (e.g., hydrofluoric acid or highly alkaline solutions) have been used. Nonetheless, it is recommended that the calibration be verified with kinematic viscosity standards periodically; if a change in calibration is indicated, carefully examine all sources of error, including especially temperature measurement since most apparent changes in calibration of the viscometer are due to errors in temperature measurement.

Test No.: 368038 - 7

The S.I. unit of kinematic viscosity is 1 meter squared per second, and is equal to 10⁴ stokes. The S.I. unit of viscosity is 1 pascal second, and is equal to 10 poises. One centistokes is equal to one millimeter squared per second.

Standards Laboratory Certificate

Sandia National Laboratories

Albuquerque, New Mexico 87185

File No. 4522

THERMOCOUPLE TYPE

OMEGA

Model No. 6" Probe

Serial No. 92321-1

Submitted by: 6119

Certified: November 16, 1992

Expires: November 16, 1993

Tests performed between the temperatures of -40 to 100 deg C show this thermocouple to be in agreement within ± 1 deg C of the values published in IPTS-68.

Under normal use conditions it is probable this thermocouple will remain within the above accuracies for the certification interval.

Metrologist: J. J. LaMarr, 2414

Certified by: J. M. Simons, 2414

TLC29:JJL

1/30/92

SERIAL # MV READING

TEMPERATURE

DELTA

STD 257

-39.980 °C

Δ
°C

STD 400	-0.0001	-0.019 C	0.000
NON	-1.5313	-40.127 C	-40.109
NON	-1.5304	-40.103 C	-40.084
NON	-1.5301	-40.094 C	-40.076
NON	-1.5303	-40.100 C	-40.081
NON	-1.5307	-40.111 C	-40.092
NON	-1.5314	-40.130 C	-40.111
NON	-1.5320	-40.146 C	-40.129
NON	-1.5322	-40.152 C	-40.133
NON	-1.5226	-39.990 C	-39.871
NON	-1.5240	-39.929 C	-39.910
NON	-1.5261	-39.985 C	-39.967
NON	-1.5250	-39.955 C	-39.937
NON	-1.5223	-39.892 C	-39.863
NON	-1.5295	-40.078 C	-40.059
NON	-1.5213	-39.854 C	-39.836
NON	-1.5226	-39.897 C	-39.869
NON	-1.5215	-40.078 C	-40.059
NON	-1.5310	-40.119 C	-40.100
NON	-1.5331	-40.176 C	-40.158
3201	-1.5343	-40.209 C	-40.190
3202	-1.5345	-40.214 C	-40.196
3203	-1.5252	-39.961 C	-39.942
3204	-1.5247	-39.947 C	-39.929

-0.229 ←
-0.234
.019
.033

SERIAL # MV READING

TEMPERATURE

DELTA

STD 257

23.520 °C

Δ
°C

STD 400	0.0001	0.019 C	0.000
NON	0.9361	23.417 C	23.398
NON	0.9361	23.417 C	23.398
NON	0.9361	23.417 C	23.398
NON	0.9359	23.412 C	23.393
NON	1.0340	23.350 C	23.332
NON	0.9364	23.424 C	23.406
NON	0.9360	23.414 C	23.396
NON	0.9361	23.417 C	23.398
NON	0.9357	23.407 C	23.388
NON	0.9351	23.392 C	23.378
NON	0.9372	23.416 C	23.402
NON	0.9384	23.424 C	23.408
NON	0.9355	23.420 C	23.405
NON	0.9352	23.461 C	23.450
NON	0.9331	23.469 C	23.458
NON	0.9317	23.436 C	23.436
NON	0.9332	23.469 C	23.450
NON	0.9388	23.483 C	23.465
NON	0.9387	23.481 C	23.462
3201	0.9418	23.558 C	23.539
3202	0.9440	23.612 C	23.593
3203	0.9441	23.614 C	23.594
3204	0.9435	23.607 C	23.588

.038 ←
.092
.094
.087

SERIAL #

STD 257

STD 400

MV READING

TEMPERATURE

64.801 °C

DELTA

Δ
°C

NON	2.64001	64.019 C	0.000
NON	2.6406	64.945 C	64.927
NON	2.6398	64.926 C	64.907
NON	2.6399	64.928 C	64.910
NON	2.6397	64.924 C	64.905
NON	2.6399	64.928 C	64.910
NON	2.6416	64.969 C	64.951
NON	2.6398	64.926 C	64.907
NON	2.6408	64.950 C	64.932
NON	2.6342	64.791 C	64.772
NON	2.6363	64.842 C	64.823
NON	2.6408	64.950 C	64.932
NON	2.6405	64.943 C	64.924
NON	2.6394	64.916 C	64.899
NON	2.6416	64.969 C	64.951
NON	2.6413	64.962 C	64.944
NON	2.6406	64.945 C	64.927
NON	2.6413	64.962 C	64.944
NON	2.6432	65.008 C	64.989
NON	2.6441	65.030 C	65.011
3201	2.6508	65.191 C	65.173
3202	2.6520	65.220 C	65.202
3203	2.6500	65.172 C	65.155
3204	2.6494	65.157 C	65.139

.390 ←
.419
.371
.356

SERIAL #

STD 257

STD 400

MV READING

TEMPERATURE

-18.593 °C

DELTA

Δ
°C

NON	0.0005	0.093 C	0.000
NON	-0.7300	-18.762 C	-18.854
NON	-0.7290	-18.735 C	-18.829
NON	-0.7286	-18.725 C	-18.818
NON	-0.7292	-18.741 C	-18.838
NON	-0.7306	-18.762 C	-18.851
NON	-0.7311	-18.780 C	-18.886
NON	-0.7307	-18.767 C	-18.856
NON	-0.7303	-18.751 C	-18.840
NON	-0.7300	-18.735 C	-18.818
NON	-0.7297	-18.717 C	-18.801
NON	-0.7294	-18.707 C	-18.787
NON	-0.7291	-18.697 C	-18.773
NON	-0.7288	-18.687 C	-18.759
NON	-0.7285	-18.677 C	-18.745
NON	-0.7282	-18.667 C	-18.731
NON	-0.7279	-18.657 C	-18.717
NON	-0.7276	-18.647 C	-18.703
NON	-0.7273	-18.637 C	-18.689
NON	-0.7270	-18.627 C	-18.675
NON	-0.7267	-18.617 C	-18.661
NON	-0.7264	-18.607 C	-18.647
NON	-0.7261	-18.597 C	-18.633
NON	-0.7258	-18.587 C	-18.619
 	

6" Type K TC

92321-1
8/12/93

74522

CA 75.75 MM 75.75 MM

Std	°C	Test	°C
✓	°C	mV	°C

27.5885	19.781	.8008	20.07
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27.7686	21.760	.8724	21.84
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27.8647	22.705	.9094	22.76
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28.3910	27.913	1.1230	28.03
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29.0656	34.596	1.3964	34.74
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29.1028	34.965	1.4117	35.12
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CERTIFICATE

APPENDIX B

LIST OF EQUIPMENT AND MANUFACTURERS

PolyScience 730 Immersion Circulator
Serial # 926370
PolyScience
P.O. Box 48312
Niles, IL 60648
(708) 965-0611

Jupiter Viscosity Timer Model 821
Serial # J 2033-1
Jupiter Instrument Company
407 Commerce Way A15
Jupiter, FL 33458
(407) 743-8486

Mettler Portable Density/Specific Gravity Meter DA-110
Mfg. No. NJA31791
Mettler Instrument Corporation
Box 71
Hightstown, NJ 08520
(609) 488-3000

Cannon-Fenske Routine Viscometer
Viscometer No. U736 size 50
Viscometer No. U677 size 50
Viscometer No. U667 size 50
Cannon Instrument Company
P.O. Box 16
State College, PA 16804

Deionized Ultra Filtered Water
Lot No. 923068
Fisher Scientific Company
Fairlawn, NJ 07410
(201) 796-7100

REFERENCES

Earlougher, Robert C. Jr. 1977. Advances In Well Test Analysis. 2nd edition. Society of Petroleum Engineers of AIME, New York. Page 241.

Analytical Report. Volume I of IV. Chem-Nuclear Geotech Analytical Laboratory, Grand Junction, CO.. 1992. Section 1.

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UC Category (19)

UC-721, DOE/ER

19980622 086

DTIC QUALITY INSPECTED 1

DOE