2/20

COMMENTARY ON STUDIES OF ^{36}Cl IN THE EXPLORATORY STUDIES FACILITY AT YUCCA MOUNTAIN

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-93-005

Prepared by

William M. Murphy

Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas

February 1997

3/20

ABSTRACT

$^{36}Cl/Cl$ ratios reported for leachates from rocks collected in the Exploratory Studies Facility (ESF) at Yucca Mountain, Nevada, have been interpreted to represent $^{36}Cl/Cl$ ratios of groundwater contained in the rocks (Fabryka-Martin et al., 1996a,b,c). Most values are comparable to those believed to have existed in natural deposition at the ground surface (approximately 400×10^{-15} to $1,200 \times 10^{-15}$). These data are generally consistent with travel times for groundwater from the ground surface to the ESF and the proposed repository horizon that are short relative to the half life of ^{36}Cl, which is 301,000 y. Reported modeling of groundwater flow indicates that infiltration rates in excess of 1 mm/y are required to account for these data. In eight areas along 4.6 km of the ESF from the north portal, elevated $^{36}Cl/Cl$ ratios (e.g., greater than $1,500 \times 10^{-15}$) have been interpreted to reflect unequivocal bomb pulse contamination and groundwater travel times of less than 50 y. Most unambiguously contaminated samples are associated with the surface manifestation of faults. Groundwater flow models that permit fracture flow to the ESF can account for the bomb pulse data. However, most contaminated samples were collected from rocks that show no sign of fault offset. In the reported modeling faulting primarily permits localized fracture flow through the nonwelded Paintbrush Tuff, which overlies the Topopah Spring Tuff and the repository horizon. In preliminary independent analyses reported in this commentary reasonable and relatively conservative interpretation with regard to groundwater travel time is that $^{36}Cl/Cl$ ratios in excess of 900×10^{-15} to $1,000 \times 10^{-15}$ indicate a bomb pulse component. This interpretation is supported by preliminary analyses indicating the population of $^{36}Cl/Cl$ ratios less than approximately 900×10^{-15} represents a normal distribution, which rapidly deviates from normality as larger values are included in the population. A population of published measurements of the relative intensity of the Earth's magnetic field over the post 280,000 y exhibits a normal distribution, supporting the idea that relatively undecayed $^{36}Cl/Cl$ ratios should be normally distributed. If samples containing $^{36}Cl/Cl > 900 \times 10^{-15}$ (in contrast to $1,500 \times 10^{-15}$) are assumed to be contaminated by a bomb pulse component, then the ^{36}Cl data from the ESF can be interpreted to indicate fairly widespread fast groundwater pathways. However, the flux associated with the fast pathways can not be estimated from the existing data.

4/20

CONTENTS

5/20

FIGURES

6/20

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-93-005. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards (NMSS), Division of Waste Management (DWM). The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

Technical discussions with Los Alamos National Laboratory staff (J.T. Fabryka-Martin and S. Levy) enhanced the effectiveness of this report. A.L. Unruh assisted with data manipulation. R.L. Mason and C.B. Connor provided consultations in statistics. G.W. Wittmeyer and S.A. Stothoff provided consultations in hydrology. J. Stamatakos provided consultations on geomagnetism. D.A. Pickett provided consultations on radioisotope geochemistry and analytical techniques and provided a constructive technical review. B. Sagar provided many constructive comments and questions.

7/20

1 INTRODUCTION

Draft reports on ^{36}Cl studies at Yucca Mountain (YM), Nevada, were released recently by Los Alamos National Laboratory (LANL) (Fabryka-Martin et al., 1996a,b). The former report is an update of a previously published LANL report (Fabryka-Martin et al., 1996c). The object of this commentary is to provide an overview of data and interpretations presented in these reports and a technical commentary on the significance of the data. An emphasis is placed on ^{36}Cl data from samples collected in the Exploratory Studies Facility (ESF) at YM. These data permit an important new understanding of the velocity and pathways for water flow in the unsaturated zone at YM.

Personal communication from J.T. Fabryka-Martin[1] indicates that many reported values of $^{36}Cl/Cl$ in the reports require revision, although differences between data in the draft reports and the unpublished corrected data are generally small and do not affect general interpretations of the data. Therefore, results of independent quantitative analyses using the incorrect draft data set are discussed in general terms in this commentary, but presentation of detailed data is deferred until analyses can be conducted using published corrected values.

[1]Fabryka-Martin, J.T. 1997. Los Alamos National Laboratory, personal communication.

8/20

2 BACKGROUND

^{36}Cl is a radioactive isotope with a half life of 301,000 y. It is generated naturally primarily by cosmic radiation effects on stable Cl and Ar in the atmosphere and occurs in nature at trace concentrations. Except for its radioactivity, ^{36}Cl behaves in geochemical systems as does stable Cl, so a conventional concentration scale for ^{36}Cl is the ratio of ^{36}Cl to total Cl. In the vicinity of YM, the natural $^{36}Cl/Cl$ ratio is estimated to have varied in the range of approximately 400×10^{-15} to $1{,}200 \times 10^{-15}$ over the last several hundred thousand years (Fabryka-Martin et al., 1996a, and personal communication[1]). The natural $^{36}Cl/Cl$ ratio of material deposited by precipitation and dry fall at the ground surface is variable because variations in the Earth's magnetic field affect cosmic radiation and the ^{36}Cl production rate and because the rate of stable Cl deposition varies with climatic conditions and geographic setting. Also, systems that have been isolated from the atmosphere for time periods that are comparable or long relative to the ^{36}Cl half life have diminished ^{36}Cl concentrations because of radioactive decay. ^{36}Cl was also produced at relatively high concentrations by testing of nuclear devices, particularly in the Pacific Proving Grounds during the 1950s. The possible contribution to ^{36}Cl at YM from Nevada Test Site activities was investigated and concluded generally to be small relative to natural sources and/or indistinguishable from bomb pulse sources (Fabryka-Martin et al., 1996a,b).

^{36}Cl is a useful tracer for evaluations of the behavior of groundwater. Chloride is soluble in groundwater, and dissolved chloride is relatively unaffected by gas-water-rock interactions in most groundwater systems. The age of a closed quantity of groundwater can be bounded using ^{36}Cl data on time scales comparable to the ^{36}Cl half life. Groundwater containing concentrations of ^{36}Cl that are elevated above natural levels due to contamination from nuclear testing contains at least some fraction of water that is less than 50 y old.

[1]Fabryka-Martin, J.T. 1997. Los Alamos National Laboratory, personal communication.

9/20

3 METHODOLOGY

In the LANL study $^{36}Cl/Cl$ ratios were analyzed and reported for groundwater from approximately 100 samples taken from the ESF (Fabryka-Martin et al., 1996a,c). Rock samples were collected from the north portal to approximately 5,693 m distance along the ESF at "systematic" 200 m intervals and at "features" including faults, fractures, lithophysal cavities, and lithologic contacts. $^{36}Cl/Cl$ measurements are available for samples taken over the first 4,579 m. One to five kg rock samples were coarsely broken to fragments of 1–4 cm (if they were intact) and the samples were leached with deionized water. AgCl was precipitated from the water and analyzed by mass spectrometry for $^{36}Cl/Cl$. The analytical data are interpreted to represent the chemistry of water in the rocks. Mostly small corrections were made for contamination with construction water used to bore the ESF based on the Br/Cl and $^{36}Cl/Cl$ ratios of the construction water. Effects of contamination by Cl leached from the rock (as opposed to Cl from pore water) were determined to be small or negligible for the ESF samples. However, for samples collected from borehole drill cuttings, rock Cl significantly affected $^{36}Cl/Cl$ ratios and corrections are required. Despite reported errors in the draft data set, the sampling and analytical work appear to be carefully performed and documented. Presentation of the data is accompanied by descriptions of quality assurance procedures, replicate analyses, screening of data of uncertain quality, detailed attention to analytical procedures, and circumspect regard for potential errors or misinterpretations.

10/20

4 DATA

All "systematic" samples from the ESF and a majority of "feature" samples have $^{36}Cl/Cl$ ratios between approximately 300×10^{-15} and approximately $1{,}500 \times 10^{-15}$. These results are consistent with previous results from ream cuttings from boreholes at YM when the latter are corrected for addition of rock Cl. The preferred interpretation in the LANL reports is that all samples contain natural ^{36}Cl derived from the atmosphere, although alternate interpretations are acknowledged including the possibility of bomb pulse contamination.

In eight areas in the ESF, samples have $^{36}Cl/Cl$ ratios above $1{,}500 \times 10^{-15}$ and up to approximately $4{,}000 \times 10^{-15}$. These samples are interpreted to contain an unambiguous component of bomb-pulse ^{36}Cl. Detection of Tc^{99} leachates from the Bow Ridge Fault gouge samples from the ESF confirms a bomb pulse component of the groundwater. These eight areas where $^{36}Cl/Cl$ was detected at values in excess of $1{,}500 \times 10^{-15}$ are presented in the following list in order of distance along the ESF in meters from the north portal (Fubryka-Martin et al., 1996a).

(i) The Bow Ridge Fault (4 samples of fault gouge) at a distance of 198 m in the ESF and at a depth of about 45 m from the ground surface

(ii) Topopah Spring Tuff that is broken by cooling joints (1 composite sample) at a distance of 1,244 m and a depth of about 163 m below and slightly west of the surface expression of the Imbricate Fault Zone

(iii) A shear zone sample at a distance of 1,400 m and at approximately 184 m below the ground surface

(iv) Broken lithophysal Topopah Spring Tuff (4 samples taken over lateral distance of 46 m from 1,896 to 1,942 m) about 177 m below the surface expression of Drill Hole Wash Fault Zone

(v) Fault gouge and calcite (1 sample) from a fault zone 2,440 m distant from the north portal and about 231 m below the ground surface at approximately the level of the main drift

(vi) Broken lithophysal Topopah Spring Tuff from a 1 m wide zone of cooling fractures 2,679 m into the ESF and approximately 306 m below the ground surface

(vii) Fractures and cooling joints (7 samples collected along 165 m of lateral distance from 3,428 m to 3,593 m) in the main drift at a depth of about 252 m below the surface exposure of the Sundance Fault

(viii) Two sets of cooling joints at 4,363 m and 4,420 m distance from the north portal of the ESF and about 245 m below the ground surface

Figure 4-1 illustrates the locations of these sites.

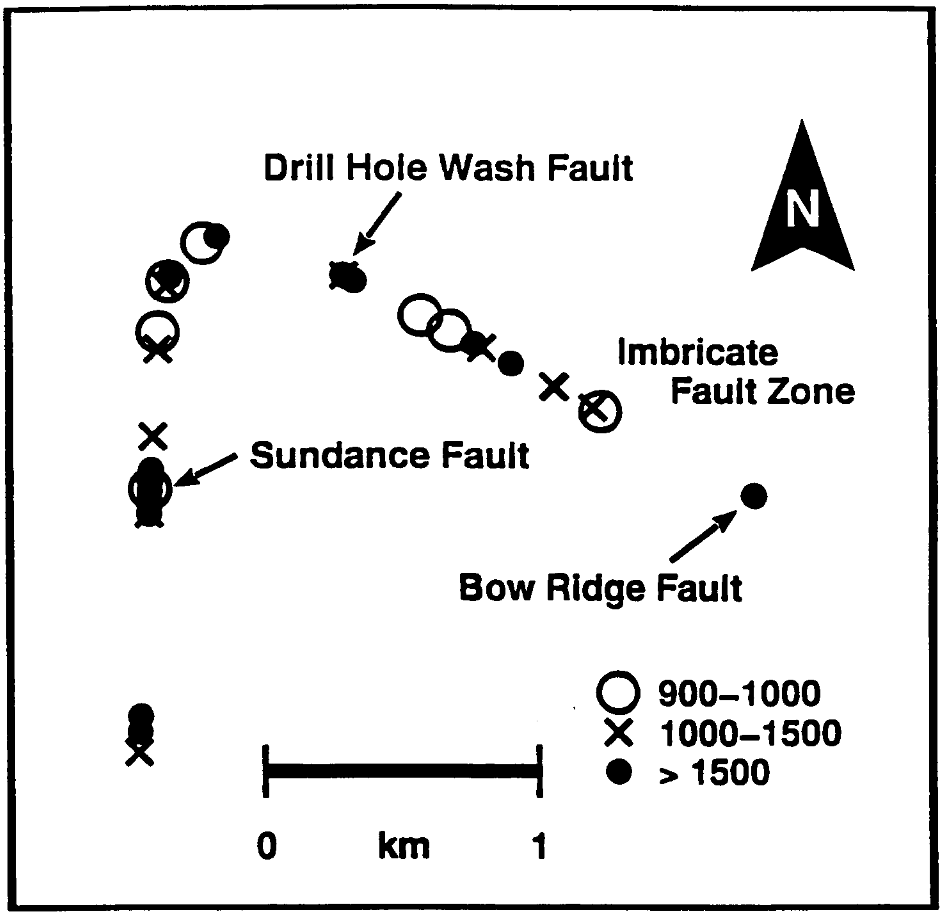

Figure 4-1. Map view of locations in the ESF where relatively elevated $^{36}Cl/Cl$ ratios have been detected and identification of $^{36}Cl/Cl$ anomalies associated with surface manifestations of faults. The course of the ESF extends along the series of sample locations from the north portal of the ESF located about 200 m southeast of the anomaly associated with the Bow Ridge Fault. The most distant sample for which $^{36}Cl/Cl$ data are published is about 79 m south of the southern most datum plotted on the map. Solid circles represent $^{36}Cl/Cl$ values reported to be greater than $1{,}500 \times 10^{-15}$, Xs represent locations where reported $^{36}Cl/Cl$ values are $1{,}000 \times 10^{-15}$ to $1{,}500 \times 10^{-15}$, and open circles are locations where reported $^{36}Cl/Cl$ values are 900×10^{-15} to $1{,}000 \times 10^{-15}$. The majority of samples from the ESF have $^{36}Cl/Cl < 900 \times 10^{-15}$, and are not plotted in the figure. Data are taken from Fabryka-Martin et al. (1996a). These data were reported in preliminary form and are subject to some revision (Fabryka-Martin, personal communication[1]).

---

[1] Fabryka-Martin, J.T. 1997. Los Alamos National Laboratory, personal communication

12/20

5 INTERPRETATIONS

$^{36}Cl/Cl$ ratios provide maximum limits on the groundwater age and hence travel time from the surface. Where there is a bomb pulse component of groundwater, at least some fraction of the water has traveled from the surface in less than 50 y. Almost all $^{36}Cl/Cl$ data from the ESF are comparable to or greater than present or reconstructed geohistorical values and are therefore consistent with groundwater travel times that are short relative to the 301,000 y half life of ^{36}Cl, for example, tens of thousands of years. Data from a few samples with the lowest $^{36}Cl/Cl$ ratios are possibly consistent with travel times of less than several hundreds of thousands of years. The minimum $^{36}Cl/Cl$ ratios measured in samples from the ESF are more than half as large as the present ratio in Cl deposition at the surface of YM. By comparison to the ^{36}Cl half life, no groundwater samples have been closed to atmospheric Cl input for a geologically long time, for example, millions of years.

Most samples from the ESF have $^{36}Cl/Cl$ in excess of the present background deposition ratio, which corresponds closely to the present value in saturated zone groundwater extracted from the J-13 well (Fabryka-Martin et al., 1996a). $^{36}Cl/Cl$ ratios in excess of the modern background may be consistent with the absence of a bomb pulse component because background $^{36}Cl/Cl$ deposition ratios at YM reconstructed for the geologic past by Fabryka-Martin et al. (1996a,b,c) are higher than present deposition ratios. The reconstructed ratio prior to 10 ka averages about 900×10^{-15} and rarely reaches maxima near $1{,}200 \times 10^{-15}$ over the past 1.8 million years. Based on the reconstructed history of input $^{36}Cl/Cl$ ratios, samples with values significantly greater than present day values indicate waters that are older than 10 ka if they are uncontaminated with bomb pulse ^{36}Cl. In the LANL reports $^{36}Cl/Cl$ ratios in excess of $1{,}500 \times 10^{-15}$ are concluded unambiguously to indicate bomb pulse contamination by water less than 50 y old.

Constraints on water fluxes by $^{36}Cl/Cl$ data require inferences about flow mechanisms and hydrologic conditions. Also, Cl mass balance relations can be useful to address fluxes (Fabryka-Martin et al., 1996b). Except for bomb pulse contaminated samples, $^{36}Cl/Cl$ ratios in all samples are comparable to values estimated for deposition in the source area over the last tens of thousands of years. Therefore, the average travel time for all the water at the level of the ESF is most likely to be short relative to the half life of ^{36}Cl. If all water at 300 m depth is younger than 30 ka, then its average velocity has been greater than 1 cm/y. For a water content of 10 percent, this velocity corresponds to a minimum flux of 1 mm/y. Fluxes associated with the fast pathways that delivered bomb pulse ^{36}Cl to the ESF can not be estimated from the existing data.

Fabryka-Martin et al. (1996a) offer four possible scenarios for the ages (travel times) of waters from the ESF with $^{36}Cl/Cl$ ratios less than $1{,}500 \times 10^{-15}$. Scenario 1 is that the groundwaters have travel times greater that 50 y and less than about 50,000 y. Variations in $^{36}Cl/Cl$ ratios reflect variations in the input value through this time period and little radioactive decay. Scenario 2 is that the groundwaters are older than 50 ka, which requires input of water in the past with a $^{36}Cl/Cl$ ratio significantly in excess of the present day value. Assuming input of water with initial $^{36}Cl/Cl$ ratio of $1{,}500 \times 10^{-15}$, maximum possible ages according to this scenario are calculated to average 350,000 y and range up to 700,000 y. Scenario 3 interprets the water to be modern with an initial $^{36}Cl/Cl$ ratio of 500×10^{-15}. In this scenario most water samples show evidence of bomb pulse contamination. In the fourth scenario, $^{36}Cl/Cl$ ratios are strongly affected by generation of ^{36}Cl by spallation of Ca nuclei in calcite in the rock, so ^{36}Cl values cannot be used to determine groundwater ages. Fabryka-Martin et al. (1996a) conclude that the latter two scenarios are highly unlikely because independent evidence such as ^{14}C and tritium data do not

13/20

corroborate widespread bomb pulse contamination and because mass balance relations indicate that ^{36}Cl generation in calcite is minor relative to atmospheric input. The authors also emphasize that the second scenario of maximum ages represents an extreme limit.

The first scenario depicting groundwaters with ages between 50 and 50,000 y accounts most reasonably for the data that do not have a bomb pulse component. However, the ^{36}Cl/Cl demarcation between bomb pulse contaminated and uncontaminated waters is difficult to define. Furthermore, this limit is likely to differ because of the separate histories of individual water samples; for example, some contaminated samples may have ^{36}Cl/Cl ratios that are less than some uncontaminated samples.

Several lines of evidence outlined in the following paragraphs suggest that samples with ^{36}Cl/Cl ratios greater than $1{,}100 \times 10^{-15}$ are affected by bomb pulse contamination, and it is reasonable to assume conservatively that values in excess of approximately 900×10^{-15} to $1{,}000 \times 10^{-15}$ are contaminated. The maximum value for the reconstructed ^{36}Cl/Cl ratio over the last 500 ka is $1{,}100 \times 10^{-15}$ according to Fabryka-Martin et al. (1996a), and this value was reached only for one brief period. In order to rationalize ^{36}Cl/Cl ratios in excess of $1{,}000 \times 10^{-15}$ observed in fossilized urine from packrat middens in the Paranagut Range, Fabryka-Martin et al. (1996a,b) invoked a higher present day ^{36}Cl/Cl ratio at that site coupled with reconstructed ratios for the past. According to their own reconstructions of past ^{36}Cl/Cl ratios (Fabryka-Martin et al., 1997a,b,c) it is unlikely that any particular groundwater sample that is unaffected by bomb pulse contamination would have ^{36}Cl/Cl ratios in excess of approximately $1{,}100 \times 10^{-15}$.

Preliminary independent (this report) statistical analyses of the data reported in Fabryka-Martin et al. (1996c) show that the ^{36}Cl/Cl data set exhibits a normal distribution of the population of values less than approximately 900×10^{-15}. As larger values are included, the normality of the distribution of values rapidly diminishes as indicated by deviation from linearity on a normal distribution quantile plot (probability plot) and by the rapid deterioration of the Shapiro-Wilks test p value for normality. The maximum p value approaching 0.9 for the data set of ^{36}Cl/Cl values less than about 900×10^{-15} is a strong indication of a normally distributed population. Reports of the details of these quantitative analyses are deferred until corrected data are published. Deviation from a normal distribution of populations including ^{36}Cl/Cl ratios in excess of 900×10^{-15} or $1{,}000 \times 10^{-15}$ may indicate bomb pulse contamination. However, it may be questioned whether or not the natural background distribution of ^{36}Cl/Cl should be normally distributed; deviation from normality may occur naturally and may not necessarily represent contamination by a bomb pulse component.

A primary control on the natural variation of ^{36}Cl/Cl is variation in the geomagnetic field. Recently a data base has been published for the relative intensity of the geomagnetic field over the last 280,000 y (Lehman et al., 1996) (figure 5-1). Plotting these data on a normal distribution quantile diagram (figure 5-2) demonstrates that the population conforms remarkably well to a normal distribution. This result is strong supporting evidence that values of the (relatively undecayed) ^{36}Cl/Cl ratio in natural systems are normally distributed.

Relative geomagnetic intensity data for the period from 6 to 45 ka represented in figure 5-1 reflect a bimodal tendency rather than the unimodal normal distribution exhibited by the whole data set. Alternate estimates of the geomagnetic intensity record for the past 50,000 y (Stoner et al., 1995; Guyodo and Valet, 1996) do not show this bimodal tendency. Variations in the geologic record of magnetic intensity on a scale of less than 10,000 y probably reflect local secular variations of the non-dipole component of the Earth's magnetic field and are not indicative of the global dipole field (Stamatakos, personal

14/20

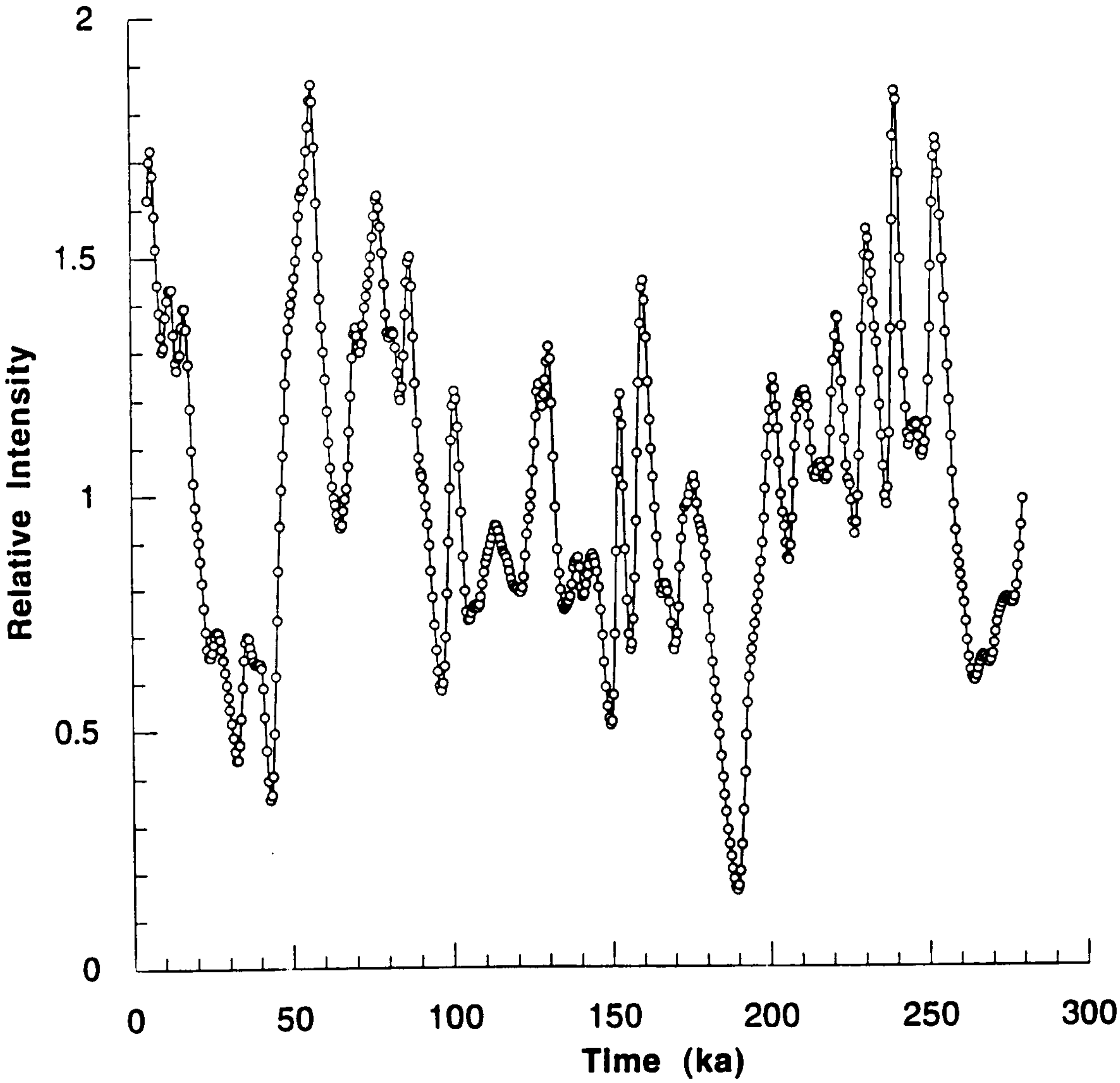

Figure 5-1. Intensity of the Earth's geomagnetic field relative to its present intensity as a function of the age of rocks from which it was determined (data from Lehman et al., 1996)

communication[1]). Given inherent uncertainties, it is reasonable to assume that the statistical distribution of values of the entire data set represented in figure 5-1 is the best representation of natural variation in the global dipole field. Also, variations in the ^{36}Cl/Cl ratio in natural deposition does not depend uniquely on the geomagnetic field intensity. Fabryka-Martin et al. (1996a,b) postulated that stable Cl deposition has been elevated during the past 10,000 y at YM, lowering ^{36}Cl/Cl. Normality of the distribution of geomagnetic field intensities represented in figure 5-1 does not prove that the distribution of natural ^{36}Cl/Cl deposition values is normal, but it is strong supporting evidence.

These arguments suggest that a conservative interpretation of the ^{36}Cl/Cl data, in the context of the distribution of the occurrence of young, fast flowing water in the ESF, is that samples with values greater than 900×10^{-15} to $1{,}000 \times 10^{-15}$ are likely to contain a bomb pulse component. Samples with values

[1]Stamatakos, J.A. 1997. Center for Nuclear Waste Regulatory Analyses, personal communication.

15/20

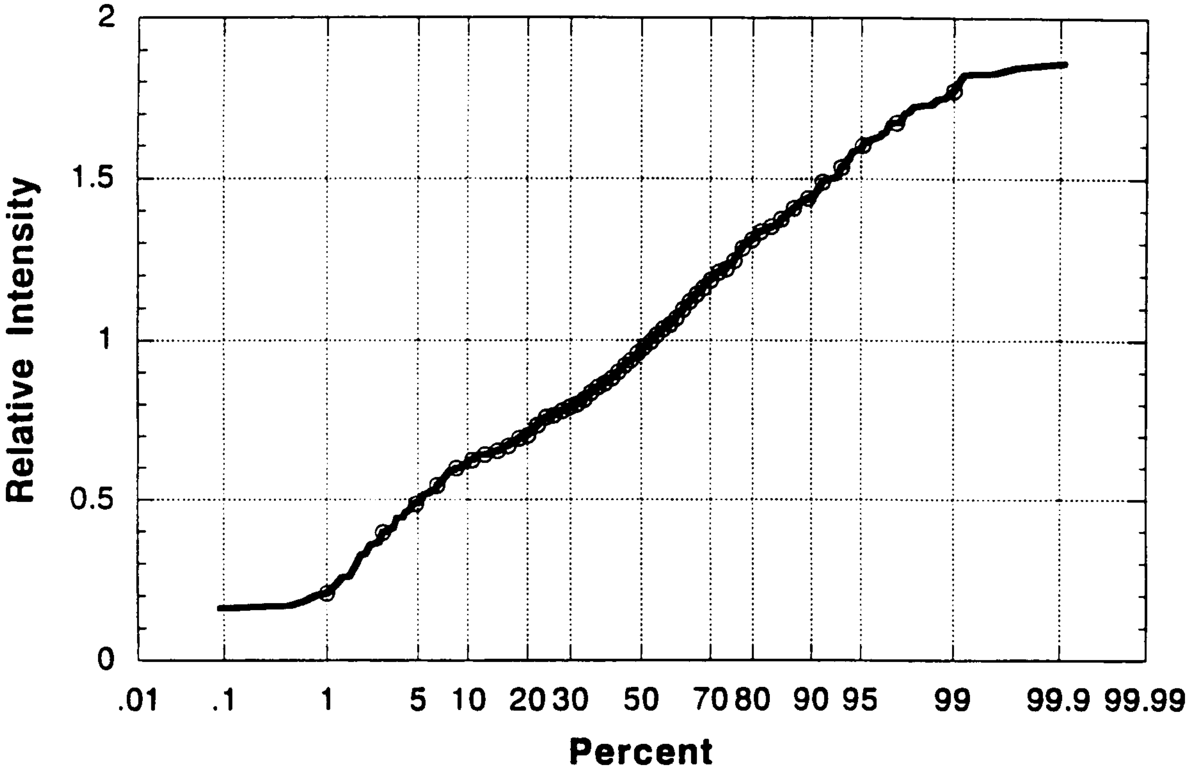

Figure 5-2. Values for the intensity of the Earth's geomagnetic field relative to its present intensity plotted on a normal distribution quantile plot (probability plot). A straight line in this coordinate system indicates that the data set conforms to a normal distribution.

in excess of $1,500 \times 10^{-15}$ constitute 21 of 110 samples reported in Fabryka-Martin et al. (1996a) and occur in eight fairly localized areas (figure 4-1). Samples with values of $^{36}Cl/Cl$ greater than $1,000 \times 10^{-15}$ number 34 in this data set, or nearly a third of all samples. Although these additional samples are from somewhat more widely distributed locations along the ESF than unambiguously contaminated samples with $^{36}Cl/Cl$ greater than $1,500 \times 10^{-15}$, many samples with $^{36}Cl/Cl$ between $1,000 \times 10^{-15}$ and $1,500 \times 10^{-15}$ are located in the eight zones of unambiguous contamination noted above. One additional clustered group of samples with reported $^{36}Cl/Cl$ values at $1,100 \times 10^{-15}$ to $1,200 \times 10^{-15}$ occurs in intact bedrock from a subunit contact at 1,056–1,062.5 m from the north portal and about 150 m below the surface expression of the western part of the Imbricate Fault Zone (figure 4-1). The general pattern observed of bomb pulse contamination in groundwater from rocks associated with fault zones at the ground surface is largely preserved by inclusion of the $1,000 \times 10^{-15}$ to $1,500 \times 10^{-15}$ $^{36}Cl/Cl$ ratio population. If samples containing $^{36}Cl/Cl$ greater than 900×10^{-15} are assumed to represent bomb pulse contamination, the general interpretation of ^{36}Cl data from the ESF begins to change from several isolated zones of fast groundwater flow and bomb pulse contamination to fairly widespread bomb pulse contamination and isolated zones of uncontaminated groundwater (figure 4-1).

Conversely, if $^{36}Cl/Cl$ ratios in excess of $1{,}000 \times 10^{-15}$ up to $1{,}500 \times 10^{-15}$ represent natural background, then it is unlikely that the uncontaminated water could not be old relative to the half life of ^{36}Cl because natural source values are estimated only to approach these values at their maxima.

6 STRUCTURAL CONTROL ON FAST GROUNDWATER FLOW

Most occurrences of bomb pulse contamination in the ESF and all of the most contaminated samples are associated with geologic features such as fracturing, joints, lithophysal cavities, faults, breccias, or lithologic boundaries. Many occurrences are also located below ground surface manifestations of faults. However, most contaminated samples were collected from rocks that show no sign of fault displacement in the ESF, and many geologic features were sampled that show no definitive evidence of bomb pulse contamination (Fabryka-Martin et al., 1996a). Fast groundwater pathways capable of delivering bomb pulse ^{36}Cl to depth must be associated with fractures. However, fast groundwater pathways indicated by bomb pulse ^{36}Cl/Cl ratios are not necessarily in structures in the ESF that transect all lithologic units (i.e., faults); they also occur in features characteristic of individual cooling units (e.g., joints). Based on the hydrological characteristics of the strata above the ESF it has been concluded that isolated zones where fast groundwater flow is apparent are associated with structural deformation permitting fracture flow through the nonwelded Paintbrush Tuff unit, which overlies the Topopah Spring Tuff (Fabryka-Martin et al., 1996a). Once through the relatively unfractured Paintbrush Tuff, water can flow in any accessible fractures in the welded Topopah Spring Tuff.

18/20

7 MODEL RESULTS

LANL groundwater flow modeling with particle tracking was performed using the FEHM code in an effort to rationalize the $^{36}Cl/Cl$ data (Fabryka-Martin et al., 1996a). Using hydraulic properties characteristic of YM, the models indicate generally that infiltration rates in excess of 1 mm/y are required to account for the data. By setting hydraulic parameters (e.g., increasing fracture aperture or decreasing van Genuchten α relative to "base case" values) to permit fracture flow through the nonwelded Paintbrush Tuff, the simulations show that a small fraction of bomb-pulse water can arrive at the level of the ESF in less than 50 y.

19/20

8 CONCLUDING COMMENTARY

The results of these studies of ^{36}Cl at YM appear to offer numerous new insights of fundamental importance for understanding flow rates and mechanisms at YM. Travel times associated with most water samples with no apparent bomb pulse component are reasonably interpreted to be in the range of tens of thousands of years. Minimum fluxes associated with these data are reasonably 1 mm/y or greater. However, definitive fast paths of radionuclide transport from the ground surface to greater than 300 m depth at the proposed repository horizon have been identified. Groundwater travel times along these paths are less than 50 y. Surface manifestations of faults and/or fracture pathways associated with faults in the nonwelded Paintbrush Tuff appear to have a strong control on several pathways for fast water flow. Fast water flow paths are a common feature throughout the portion of the ESF for which data have been reported. Adopting a somewhat conservative but reasonable assumption that samples containing $^{36}Cl/Cl$ ratios greater than 900×10^{-15} contain some bomb pulse ^{36}Cl, fast pathways for water flow from the surface to the ESF are fairly widespread. Despite these important conclusions, the LANL reports emphasize that the results are consistent with prior thinking and models on unsaturated flow at YM.

20/20

9 REFERENCES

Fabryka-Martin, J.T., A.V. Wolfsberg, P.R. Dixon, S. Levy, J. Musgrave, and H.J. Turin. 1996a. *Summary Report of Chlorine-36 Studies: Sampling, Analysis and Simulation of Chlorine-36 in the Exploratory Studies Facility*. Level 3 Milestone Report 3783M. LA-CST-TIP-96-002: Draft August 29, 1996. Los Alamos, NM: Los Alamos National Laboratory.

Fabryka-Martin, J.T., H.J. Turin, A.V. Wolfsberg, D. Brenner, P.R. Dixon, and J. Musgrave. 1996b. *Summary Report of Chlorine-36 Studies*. Level 3 Milestone Report 3782M. LA-CST-TIP-96-003. Draft August 30, 1996. Los Alamos, NM: Los Alamos National Laboratory.

Fabryka-Martin, J.T., P.R. Dixon, S. Levy, B. Liu, H.J. Turin, and A.V. Wolfsberg. 1996c. *Summary Report of Chlorine-36 Studies: Systematic for Chlorine-36 in the Exploratory Studies Facility*. LA-UR-96-1384. Los Alamos, NM: Los Alamos National Laboratory.

Guyodo, Y., and J.-P. Valet. 1995. Relative variations in geomagnetic intensity from sedimentary records: The past 200,000 years. *Earth and Planetary Science Letters* 143: 23–36.

Lehman, B., C. Laj, C. Kissel, A. Mazaud, M Paterne, and L. Labeyrie. 1996. Relative changes of the geomagnetic field intensity during the last 280,000 years obtained from piston cores in the Acores area. *Physics of the Earth Planetary Interiors* 93: 269–284.

Stoner, J.S., J.E.T. Channell, and C. Hillaire-Marcel. 1996. Late Pleistocene relative geomagnetic paleointensity from the deep Labrador Sea: Regional and global correlations. *Earth and Planetary Science Letters* 134: 237–252.