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# Fluid inclusion studies of samples from the Exploratory Study Facility, Yucca Mountain, Nevada

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*Prepared for the Institute for Energy and Environmental Research*

*December, 1998*

# Foreword
## Arjun Makhijani

In July 1998 IEER commissioned Dr. Yuri Dublyansky of the Siberian Branch of the Russian Academy of Sciences to prepare and study mineral samples that he collected in the previous month from the Yucca Mountain tunnel in Nevada. This five-mile tunnel has been drilled to study the suitability of the site for disposal of spent fuel from US nuclear power plants and highly radioactive waste from military plutonium production. Dr. Dublyansky is a geologist who specializes in fluid inclusions in minerals.

Fluid inclusions are small amounts of liquid and/or gas trapped in tiny cavities in mineral deposits. Study of these inclusions can yield information about whether an underground area had been dry or saturated in the past. When analyzed using isotopic dating techniques, such inclusions can also be used to estimate the date(s) in the past when water may have entered a particular area. It should also be possible to distinguish whether the water entered into the repository zone as a result of percolation from above or an upwelling from below. Finally, estimates can also be made of the temperature of the water.

Water is expected to be the main pathway by which the radioactive materials in spent nuclear fuel and other highly radioactive waste would reach the human environment. Water is also a principal means by which the containment of the wastes may become compromised. Hence, the question of whether a repository location has been dry or saturated in the past is an important one. This is especially the case when metal canisters are to be used in an oxidizing environment, as the Department of Energy is proposing to do at Yucca Mountain.

IEER's purpose in commissioning this report was to enable an independent assessment of these crucial questions. This study will help concerned policy-makers and the public to examine independently collected evidence important in evaluating the official study of the Yucca Mountain site, known as the Viability Assessment, which is to be issued in December 1998.

There has long been a controversy as to the presence of groundwater at some time in the past in the region of the proposed repository. This controversy has not yet been resolved. It is of the utmost importance to resolve it, since the presence of warm or hot water in the repository would change considerably the assessment of its suitability. For instance, technical details of the Viability Assessment revealed so far show that the DOE will be relying heavily on the integrity of the canisters containing the wastes over tens of thousands of years to keep long-lived radioactive materials out of the groundwater. But under saturated, warm conditions these canisters could deteriorate very rapidly. Dr. Dublyansky's study does not resolve all the questions and should be regarded as preliminary. But its findings are very disturbing and call for careful and intensive further work, especially as regards the age of the formation of the minerals in which the fluid inclusions have been found.

The subject matter is as complex as it is important. Questions relating to the management of long-lived radioactive wastes are among the most difficult that we face. The science is difficult enough. If it is confounded with opportunistic politics, as it has been throughout the DOE repository program, it will be impossible to make the sound technical judgments that are necessary to protect future generations. IEER's previous work has discussed many reasons that DOE's repository program should be terminated, not least because of the severe institutional problems in its management. Further, the radiation doses estimated for Yucca Mountain, should the groundwater become contaminated, have been far higher than for other sites that have been studied. The fact that historical claims of Native Americans to the land are not an important part of the official evaluation of the site or of the broader debate about it continues to be very troubling. But we have not before this time issued a special report dedicated to the specific issue of the geologic suitability of the Yucca Mountain site.

We have had Dr. Dublyansky's report extensively reviewed by independent scientists unaffiliated with the Yucca Mountain program as well as by scientists who are one way or another involved in evaluating that effort. We sent a draft copy of Dr. Dublyansky's report to Dr. Lake Barrett, Acting Director of the Office of Civilian Radioactive Waste Management (OCRWM), so that scientists of his choosing could review it. Generally, the reviews found Dr. Dublyansky's work to be of exemplary quality. The one exception was the review arranged by the DOE and compiled by Joe Whelan.[1]

I have worked closely with Dr. Dublyansky to ensure that all comments, including those made by DOE-selected reviewers, have been carefully addressed on their merits. When warranted, Dr. Dublyansky has made changes to his draft report. In other cases he has provided clarifications and additional explanations. Of course, since he is the author of the study, he has had the normal prerogative of making the judgment of how each review comment should be addressed.

One of the most interesting things about the DOE-arranged review compiled by Joe Whelan is its misrepresentation of some of the reviewers own data regarding certain mineral deposits at Yucca Mountain. As one who has had occasion to review many studies, I also found the *ad hominem* tone of some of the remarks highly inappropriate. This was not a final report we sent for review. It was a draft, sent out for review in the full expectation and commitment that we would take reviewers comments seriously. The *ad hominem* comments were therefore completely uncalled for and are not in keeping with normal scientific discourse. Despite the personal innuendoes, gross misreading of evidence clearly presented in the report, and misrepresentation by the reviewers of their own data, IEER has worked to treat their comments fairly. To enable the public to see all the evidence, IEER is going to the extraordinary length of publishing some of the reviews, including the DOE-arranged review compiled by Joe Whelan. A reply by Dr.

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[1] Joe Whelan, James Paces, Brian Marshall, Zell Peterman, John Stuckless, Leonid Neymark (all of the US Geological Survey) and Edwin Roeder (Harvard University), "Review of 'Fluid Inclusion Studies of Samples from the Exploratory Studies Facility, Yucca Mountain, Nevada,'" forwarded to IEER with a cover memo by Joe Whelan to Dennis Williams, dated November 9, 1998 and a cover letter from J. Russell Dyer to Dr. Arjun Makhijani, dated November 13, 1998. Review "compiled by" Joe Whelan.

Dublyansky on a point-by-point basis to the DOE-arranged review is also published in an appendix to this report.

The DOE has an unfortunate history of rushing into large projects with huge budgets and jumping to conclusions about them before the scientific work is complete.[2] This Yucca Mountain project is no exception. The Department claims that it has completed work on assessing the viability of Yucca Mountain as a repository site. Yet, at the same time, it is preparing to conduct joint sampling and study of the critical issue of fluid inclusions (the subject of this report) with Dr. Dublyansky. The DOE-appointed reviewers of this report, while highly critical in their detailed remarks, agree that further work is warranted:

> "Although we question Dublyansky's science and biases, we cannot reject his fluid inclusion data out of hand. Despite the fact that calcite is a notoriously difficult mineral for fluid inclusion studies, those difficulties are surmountable with care, and Dublyansky claims to have taken all reasonable precautions in conducting his studies. The fluid inclusion data should therefore be verified...and the timing of their formation should be constrained by isotopic dating of the host minerals."[3]

Dr. Dublyansky's recommendations are very similar. He does not claim to know the date of the mineral deposits that have the fluid inclusions studied in this report. That remains to be established. Other crucial facts, such as the presence of high molecular weight hydrocarbons in a few samples, provide further indicative, though not definitive, evidence of water ingress into the Yucca Mountain repository location. Further work is also needed in this respect.

Dr. Dublyansky's work has impressed the independent reviewers immensely. These reviewers, who have never before done any work with IEER, concurred in their evaluation of the high quality of the report and the research on which it is based. One of them, Professor Larryn W. Diamond, of the Department of Mineralogy and Petrology, Institute of Earth Sciences in the University of Leoben in Austria, conducted an independent evaluation of some of the mineral samples. It is also noteworthy that the principal expert on fluid inclusions of the Congressionally-mandated Nuclear Waste Technical Review Broad, Dr. Robert Bodnar, reassessed some of his previous opinions of the subject after he worked with Dr. Dublyansky in June 1998 and had a chance to study some of the samples Dr. Dublyansky had taken in 1995. In a letter to the NWTRB, dated July 8, 1998, Dr. Bodnar agreed that elevated-temperature fluid inclusions were present in the samples and that they were not artifacts of the preparation of the samples. Further, he found evidence, though not conclusive, of the presence of aromatic hydrocarbons. Finally, he also recommended further sampling and study.[4]

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[2] IEER analyzed this tendency in DOE's Environmental Management program in a report by Marc Fioravanti and Arjun Makhijani, entitled *Containing the Cold War Mess*, published in October 1997.

[3] Joe Whelan to Dennis Williams, memorandum regarding review of Yuri Dublyansky's report, November 9, 1998.

[4] Robert Bodnar to Leon Reiter (Nuclear Waste Technical Review Board), letter dated July 8, 1998.

When Dr. Dublyansky visited Nevada earlier this year, he discussed the subject of a joint sampling program with DOE and the US Geological Survey. There was interest on the part of some scientists but the USGS refused to go ahead with it.

Dr. Dublyansky collected his own samples from the Yucca Mountain tunnel in June 1998. The locations have been marked and bar-coded by the Yucca Mountain Characterization Project. The present study is based on data derived from that sampling.

The DOE will be making a grave technical mistake if it declared Yucca Mountain to be a viable site, as it seems set to do later in December 1998, before this crucial issue is resolved. Such a finding, issued in the face of considerable agreement about the need for further examination of fluid inclusions would be at variance with sound scientific practice.

IEER believes that it is crucial that a joint sampling program be established, that careful joint studies be done, and that they be subjected to truly independent review. Draft findings should be presented to the public with the underlying data so that the broadest possible scrutiny is possible. This will likely take two years or more. The issuance of the Viability Assessment should be put off until that time.

Given the many problems with Yucca Mountain, and the possibility that these joint studies will yield further negative findings for the suitability of Yucca Mountain as a repository, it would be prudent for the DOE to begin making back-up plans for long-term management of spent fuel and military high-level waste. The DOE has typically failed to provide any insurance for many of its key programs, resulting in higher expenditures, greater delays, and larger environmental risks. IEER has put forward such a plan, but the DOE has ignored it.[5] We believe that it is high time for the DOE to address our specific recommendations.

Financial support for IEER's work on nuclear waste (including DOE's Yucca Mountain program) and other environmental and security issues related to nuclear weapons and nuclear power is provided by support from individual donors and the Beldon II Fund, the C.S. Fund, the DJB Foundation, the HKH Foundation, the John D. and Catherine T. MacArthur Foundation, the John Merck Fund, the New Land Foundation, the Ploughshares Fund, the Public Welfare Foundation, the Town Creek Foundation, the Turner Foundation, the Unitarian Universalist Veatch Program at Shelter Rock, and the W. Alton Jones Foundation. Their generous support makes our independent work and outreach possible. We hope and expect that Dr. Dublyansky's report will initiate a new and more scientifically thorough phase of work on one of the most vital environmental issues that we all face.

Arjun Makhijani, Ph.D.
President, IEER
Takoma Park
November 25, 1998

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[5] See *Science for Democratic Action*, vol. 6, no. 1, May 1997.

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# Main Findings and Recommendations

This report analyzes mineral samples of calcite collected from Yucca Mountain in June 1998 by the author. Calcite (calcium carbonate) is a mineral that often forms veins and incrustations in rock fractures. It is practically always formed by precipitation from water. Calcite can be formed in geologic media by percolation of water from the surface or by upwelling of water from below.

Examination of calcite samples from the Yucca Mountain subsurface discussed in this report leads to two principal conclusions:

- the studied calcite was formed by upwelling of water and not from percolation of surface water; and
- the water that entered the Yucca Mountain repository area in the past from below was at elevated temperatures.

The main evidence for these findings is as follows:

1. Water was found trapped in tiny cavities in the calcite samples. These trapped water bodies are called fluid inclusions. Many fluid inclusions had vapor bubbles formed in them, indicating that the water had shrunk after it became trapped. The shrinkage of water evidences that the water has cooled from its original temperature. This is evidence of the presence of water at elevated temperature in the repository zone in the geologic past that could not have come from surface sources.
2. A few samples showed the presence of hydrocarbons. These are all-gas inclusions in calcite, in which traces of aromatic hydrocarbons were found. Aromatic hydrocarbons are heavy molecules that could not have originated in surface sources. There is evidence of hydrocarbons in the geologic media beneath Yucca Mountain area. Hence, the trapped hydrocarbons provide supplementary, though at present, fragmentary additional evidence of upwelling of water into the repository horizon.
3. Veins and crusts at Yucca Mountain besides calcites contain other minerals such as opal, quartz, and minor fluorite. These minerals are typically precipitate from warm or hot water. In particular, it is extremely rare for quartz and fluorite to be formed from surface water percolation. Hence, the presence of these minerals is strong evidence of past presence of upwelling warm water in the Yucca Mountain area.
4. Minerals formed in unsaturated zone, that is, above the water table, are typically deposited in laminated formations consisting of millions of tiny crystals. For example, stalactites in caves are created in this way. By contrast, large individual perfectly shaped crystals require a saturated environment to form. The calcite at Yucca Mountain often forms perfectly shaped individual crystals, clearly indicating that the area was, at some time in the past, saturated.

The study also addresses the question of the age of the calcites. This is because the only way to estimate the future performance of any site as a geologic repository is to study its past. The timing of the formation of the calcites is important because it provides evidence of when the area was saturated and hence of the probability of its becoming saturated in the future during the period relevant to repository performance.

Peak radiation does from Yucca Mountain are expected to occur in the period between 100,000 years and one million years from now. Saturation in the recent geologic past would have serous negative repercussions for the suitability of Yucca Mountain as a repository. This is because saturation of the Yucca Mountain repository after burial of highly radioactive waste may cause the waste canisters to corrode far more rapidly than if the area remained dry. On the other hand, if water entered Yucca Mountain many millions of years ago, and not since then, this specific issue would be of far less consequence.

The findings of the research for the timing of past repository saturation are only tentative and indicative. There are indications that the calcite may have been formed in the recent geologic past (less than one million years). This is a very complex and difficult area of work and considerable further research is needed to clarify this crucial question.

### *Recommendations*

Much more data need to be acquired and analyzed in order to assess the implications of the new findings on the repository suitability. Specifically, three questions need to be addressed:

1. What is the age and what was the recurrence period of water upwelling?

2. What was the volume of fluids involved at different stages of this activity?

3. What was the spatial structure of ancient hydrothermal system?

This may be accomplished through concerted effort of researchers, involving:

a. Detailed fluid inclusion studies in calcite and other minerals from Yucca Mountain. Such study may provide important information on the spatial structure of the ancient hydrothremal system;

b. Careful dating of calcite samples hosting fluid inclusions indicating elevated entrapment temperatures. Such study would constrain timing of ancient hydrothermal system; and

c. Detailed isotopic study of mineral phases may provide important information on the origin of fluids and pattern of fluid migration.

# 1. Introduction

This report summarizes results of research on fluid inclusions from the calcite samples gathered in the Exploratory Study Facility (ESF), Yucca Mountain, Nevada in June, 1998.

The purpose of this research was to get insight into the paleo hydrology of Yucca Mountain and specifically address one important question: was the currently unsaturated zone[1] of the mountain unsaturated during the formation of these calcites, or did the deposition occur in a saturated environment?

According to the presently accepted concept by the Yucca Mountain Project, the unsaturated zone at Yucca Mountain was formed 9-10 million years ago and since that time the water table has never risen more than 85-100 m above its present level (e.g., Marshall et al., 1993), which is 300 m below the repository horizon. This would mean that the water table never reached zone where the high-level nuclear waste repository is planned to be constructed. The concept of the Yucca Mountain repository relies on the unsaturated environment as a major barrier that will prevent migration of radionuclides from repository into the accessible environment.

According to current regulations, performance of the repository must be ensured for at least 10,000 years in the future (10CFR60). Moreover, peak doses are expected to occur after 100,000 years or more. Therefore, the viability of the site critically depends on whether or not the hypothesis on the long-term stability of the unsaturated zone is correct.

Calcite-opal veinlets found in drill cores from unsaturated zone on the early stages of Yucca Mountain characterization indicated that water with chemistry "alien" to silicate bedrock tuff moved through the mountain in geological past. In 1995-1997, when a 7.8 km long tunnel (Exploratory Study Facility or ESF) was excavated into Yucca Mountain, many more occurrences of secondary minerals become available for study.

The origin of these secondary minerals, or, strictly speaking, the origin of the waters that deposited them, is of great importance, because it may provide information regarding the long-term stability of the unsaturated zone.

From the onset of the studies on Yucca Mountain calcite and opal, they were presumed to be formed in unsaturated zone from gravitation-driven water films that percolated down along open interconnected fractures (Szabo and Kyser, 1985; 1990; Whelan and Stuckless, 1992; Vaniman and Whelan, 1994, etc.). Calcite and opal were extensively studied in terms of their stable (carbon, oxygen) and radiogenic (strontium, uranium, thorium, lead) isotope compositions, and isotopic ages (U-series disequilibrium, $^{14}$C, and U/Pb methods).

The fluid inclusion method, probably the only method capable of unequivocal determination of mineral origin, has never been adequately applied in these studies. To date, the U.S. DOE has published only 7 temperatures measured by the fluid inclusion method (DOE, 1993). The DOE has published no data since the ESF was actually constructed.

These (elevated) temperatures were either attributed to calcite of old, 8-10 million years age, or simply dismissed (Roedder et al., 1994). Recent work by the DOE contractors on calcite samples removed from ESF have failed to discover fluid inclusions suitable for determination of paleo temperatures. The research concluded that calcite in the ESF was formed from low-temperature waters in un-

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[1] Unsaturated, or vadose, zone extends from water table upwards to land surface, as opposed to saturated, or phreatic, zone extending from water table downwards.

saturated environment (Roedder and Whelan, 1998).

In 1995 I had an opportunity to collect and study samples from the first 200 m of the ESF tunnel excavated by that time[2]. I was able to make 82 measurements of paleo temperatures from 6 samples. Obtained temperatures along with auxiliary data on calcite textures clearly indicated that calcite in question was formed in saturated environment from aqueous fluids with slightly elevated temperatures (Dublyansky and Reutsky, 1995; Dublyansky et al., 1996a,b; Dublyansky, 1998a).

My fluid inclusion data have been evaluated by the U.S. Nuclear Waste Technical Review Board (NWTRB). In the course of this evaluation, I spent one week at Virginia Technical Institute and State University, carrying out a verification study with the Board's consultant, Dr. Robert Bodnar.[3] I its follow-up letter to the Board, Dr. Bodnar wrote:

> *"The most important result of the work conducted in the Fluid Research Laboratory during the week of June 15-19, 1998, is that the high temperatures reported earlier by Dublyansky were confirmed to be real and not an artifact of sample preparation or data collection. There is little doubt that the calcite in sample SS#85-86 either formed at or was later exposed to aqueous fluids with temperatures of at least 72 °C. The important question, then, that must be answered is "What is the age of the calcite being studied?'*[4]

In June 1998 I collected more samples from the entire extent of the 8.7 km-long ESF tunnel, and in October 1998 I performed a study of the fluid inclusions in them. This report discusses the results of my study.

Altogether I obtained about 300 measurements of fluid inclusion temperatures. Along with other features of the studied samples, they represent compelling evidence indicating that during the deposition of calcite, a saturated environment existed within Yucca Mountain at the level of planned repository.

This issue has direct and significant bearing on the suitability of the site as a potential host for the high-level nuclear waste repository. The critical questions remaining to be resolved are:

- When did it happen?
- Did it happen as one-stage process, or water was upwelling and receding intermittently?
- If the upwelling occurred in pulses, what was the recurrence period of these pulses and what was the duration of each pulse?
- How much water was involved?
- What was the spatial distribution of this upwelling?
- What was the cause of the upwelling?

Only when all these questions have been satisfactorily answered can we address the ultimate question:

- Could it happen in the future, on time scales comparable to those during which radiation doses could be significant?

Without theses answers, any assessment of the site viability or suitability will necessarily be incomplete.

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[2] The study of the 12 samples collected in 1995 was carried out in the Institute of Mineralogy and Petrography in Novosibirsk, Russia. The results are briefly summarized in this report.

[3] Report on this study is attached as Appendix 1.

[4] Letter of July 8, 1998 from Robert J. Bodnar to Dr. Leon Reiter of the Nuclear Waste Technical Review Board. Available at the official NWTRB web site at http://www.nwtrb.gov.

## 2. Fluid inclusions and the information that may be obtained from them

Fluid inclusion method is an established research tool extensively used by economic and petroleum geologists for prospecting and exploration of ore deposits and oil fields. Principles of the method are described in the pioneering treatise by Edwin Roedder (1984). This book is an encyclopedia of fluid inclusion information from different geological settings – from magmatic and high-grade metamorphic to hydrothermal and sedimentary.

Sedimentary systems encompassing relatively low-temperature and low-pressure geological environments have become a subject of vigorous study in early 1980s, which was driven, at least in part, by urgent needs of oil companies exploring sedimentary terrains. An excellent book, summarizing methodologies and possible pitfalls of fluid inclusion studies in this area of relatively low-temperature inclusions was published by Goldstein and Reinolds (1994).

A short explanation of the basics of the fluid inclusion method is provided below.

Fluid inclusions are fluid-filled vacuoles sealed within minerals. When a crystal precipitates from a fluid (e.g., water) the surface of the crystal is never perfect. Such imperfections on the crystal surface become engulfed by the crystal as it grows. This process creates tiny, commonly tens of microns in size, vacuoles containing the fluid present at the moment of sealing. Such inclusions are called *primary* fluid inclusions.

After mineral precipitation is complete, the crystals may be deformed and micron-wide cracks may develop. These micro-cracks may be filled with fluid present during or after the deformation. Concurrent re-crystallization leads to so-called "healing" of fractures, during which process the liquid-filled fracture transforms into a group of fluid inclusions aligned along the fracture surface. Since these inclusions contain fluids present after mineral growth, they are called *secondary* inclusions.

A similar mechanism may be responsible for entrapment of inclusions before crystal growth is complete; they are termed *pseudo-secondary*.

Groups of secondary inclusions cut across growth zones of a crystal and terminate at the crystal surface; groups of pseudo-secondary inclusions terminate up against a growth zone boundary inside the crystal. Natural crystals may contain primary, pseudo-secondary and secondary inclusions.

If a vacuole has trapped a portion of an aqueous solution and was sealed at some elevated temperature it will experience significant change upon cooling to room temperature. Both the solid crystal containing the vacuole and liquid inside it will shrink upon cooling. The thermal expansion of liquids (e.g., water) is significantly larger than that of solids (e.g., calcite). Therefore, as crystals cool from the temperature of formation to ambient temperature, the pressure in the sealed inclusion decreases. At a certain point homogeneous one-phase inclusion splits onto two phases: a low-density vapor bubble appears in the liquid filling the vacuole – a process called *heterogenization*. (An inclusion trapped at the temperature close to ambient will not heterogenize. The inclusion must be sealed at temperatures of at least 35-40 °C to nucleate a bubble upon cooling.)

As long as the vacuole remains sealed (i.e., its volume does not change), this process may be reversed. Upon heating, the liquid in such two-phase inclusion will expand and the vapor bubble will disappear at a temperature which called *homogenization temperature* ($T_h$). This temperature provides the estimate of the entrapment (sealing) temperature for given inclusion.

The interpretation of the homogenization temperature depends on the type of inclusion for which it was measured. $T_h$'s obtained for primary and pseudo-secondary inclusions reflect temperatures of fluids from which the crystal was precipitated. In case of secondary inclusions, information may be obtained on the temperatures of fluids present after the crystal growth ceased.

Important information which might be derived from fluid inclusions is the *salinity of ancient waters*. Pure water freezes and melts precisely at 0 °C; the addition of salts is known to depress the freezing temperature. Therefore, by cooling inclusions to low temperatures and then measuring the temperature of the disappearance of ice upon thawing (called *final melting temperature*, $T_{fm}$), it is possible to estimate the concentration of dissolved salts. This parameter is conventionally expressed in weight percent of sodium chloride (wt % NaCl) equivalent. NaCl is the most common salt found in fluid inclusions.

In some instances, the aqueous liquids from which a crystal grows may be not homogeneous, but contain separate gaseous phases, immiscible with the liquid. For example, boiling or effervescent fluids are examples of such heterogeneous mixtures that may be present during the time of entrapment.

Inclusions may trap such gases and form all-gas or gas-rich inclusions. Such inclusions may also provide quite valuable information. By crushing them and releasing gas into a non-reactive liquid (e.g., glycerol) it is possible to estimate the *pressure during the inclusion entrapment*. Gas bubbles may expand, maintain the same size, or contract upon crushing. This will indicate pressure higher than, equal to, and lower than ambient atmospheric pressure, respectively.

The composition of gases trapped in inclusions may be studied by means of Raman spectrometry. An inclusion is irradiated with a laser beam whose energy changes in response to its interaction with the polyatomic molecules of the fluids inside inclusion – an effect called Raman scattering. This method allows the identification of some components of fluid inclusions ($CO_2$, $CH_4$, $N_2$, $NH_3$, CO, $H_2S$, $C_2H_6$, etc.). These are called Raman-active components. Details on the Raman microspectrometry may be found in the paper by Burke (1994).

**Summary.** Fluid inclusions may provide information on: (a) the temperature of fluids during and after the crystallization of minerals; (b) the chemistry of fluids; and (c) the pressure of fluids from which minerals grow. This information is necessary to determine the origin of minerals and the environment in which they were formed.

# 3. Technical details on sampling, sample preparation, equipment and techniques used

## *3.1. Sampling*

Samples for this study were collected on June 8 and 9, 1998 from the Experimental Study Facility (ESF), which is a horseshoe-shaped 7.8 km-long tunnel excavated in the tuffs (Fig. 1). In compliance with the Integrated Sampling program adopted by the Yucca Mountain Characterization Project, the locations of each sample were marked on the tunnel walls by plastic plates, and each sample was assigned an individual number and bar code. Besides the 1995 sample set, I will also discuss the data from our first set of samples (set-1995) that was collected in March 1995 when only the first 200 m of the tunnel had been excavated. This first set of samples was collected from stratigraphically higher welded tuff Tiva Canyon, located above the design repository level and separated from the potential repository horizon – welded tuff Topopah Spring – by a layer of a highly-porous non-welded bedded unit (see Appendix 2). One sample from the 1998 set (number 2206) is also from Tiva Canyon tuff. The remainder of the 1998 set was gathered from the Topopah Spring tuff at the potential repository level.

## *3.2. Sample preparation*

Fluid inclusions are typically quite small (tens of microns), therefore all studies and observations need to be done under the microscope. In order to study fluid inclusions, the doubly polished wafers 0.2-0.4 mm thick need to be prepared from a mineral.

Calcite is soft and cleavable mineral (which means its crystals tend to break along some directions much easier than along others). This property of calcite creates a potential hazard of stretching or damaging inclusions due to stress or vibration (e.g., when cutting sample on a diamond saw) or heating (e.g., during polishing or mounting the sample with some epoxies). Stretched or leaked inclusions yield homogenization temperatures which do not reflect natural processes and are therefore meaningless.

In preparing samples from Yucca Mountain, all possible precautions have been taken to avoid any mechanical or thermal damage to the inclusions during sample preparation. Working with the first set of samples we used cleavage chips instead of polished plates. The samples from the second set have been cut using a low-speed *Buehler Isomet* saw set at ~120 rpm with cold water as a coolant. The freshly cut surfaces were manually ground and polished using grinding powder (600 grit and 5 micron) and *Buehler Metadi* water-based diamond fluid (1 micron). The polished surfaces were mounted on glass slides using cyanoacrylic glue. The operations were repeated to produce doubly polished sections.

The procedures adopted ensured that during sample preparation the samples were never heated to a temperature in excess of 35 °C. This may be shown through the following observation. Relatively low-temperature inclusions ($T_h$ of 35 to ~50 °C) being homogenized and then cooled back to room temperature virtually never heterogenize again – i.e., they do not re-nucleate the bubble after the cooling. Instead, they remain as a one-phase liquid. The reason for this behavior will be discussed later (Section 6.6). The fact that in my studies I observed two-phase inclusions with homogenization temperatures as low as 35 °C indicates that the samples were not heated above this temperature during preparation.

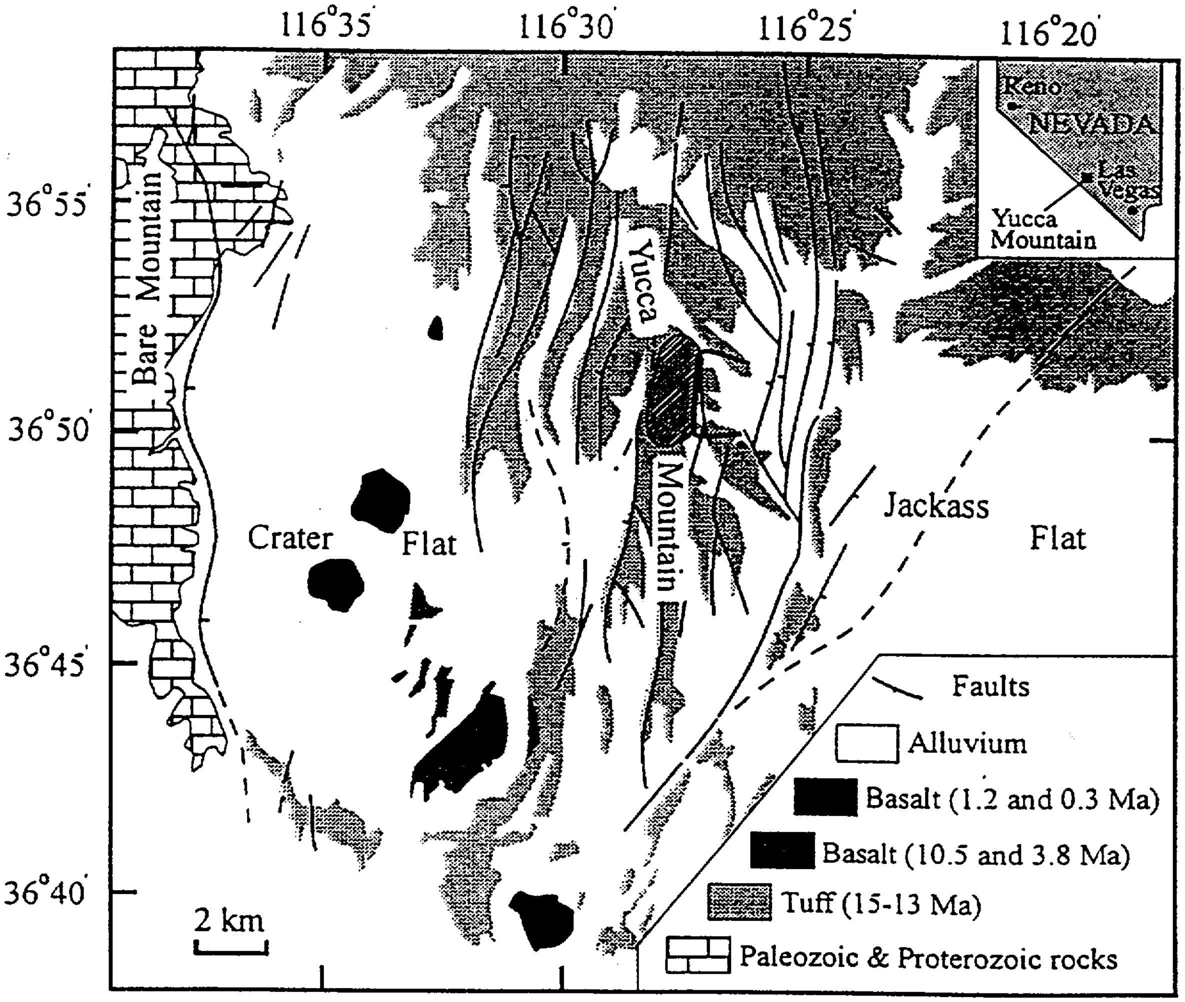


Fig. 1. Schematic geologic map of Yucca Mountain area. Patterned ellipsoid shows the exploratory block. Bold C-shaped line represents projection of the Experimental Study Facility tunnel

## 3.3. Analytical procedures and equipment used

The prepared doubly polished sections were examined under an *Olympus BX-60* microscope at different magnifications. The inclusions were documented with a *Polaroid* digital camera; sometimes, a *Sony* video printer was used for the purpose of rapid mapping.

After preliminary observations, sections were taken off glass slides (the cyanoacrylic glue having been dissolved in acetone). Typically, after the ungluing, the doubly polished sections broke onto numerous fragments, each 1 to 10 square mm in size. These fragments were examined under the microscope one by one to find groups of inclusions. Generally, I examined 20-50 such fragments from each sample. Typically only two to five fragments among these were found to contain two-phase inclusions which are needed for carrying out thermometric study.

Thermometric studies were conducted on a *Linkam THMSG* stage. Part of the homogenization temperature measurements on the 1995 sample set was made on a stage manufactured at the Institute of Mineralogy and Petrography in Novosibirsk, Russia.

***Homogenization.*** As discussed above, researchers working with soft cleavable minerals should always keep in mind the possibility that inclusions may have been stretched by some natural process or during sample preparation. Such "disturbed" inclusions may produce temperatures which are meaningless in terms of genetic interpretations. Problems associated with sample preparation can be minimized by careful sample handling; the possibility of inclusion stretching by some natural process (e.g., mechanical stress, or thermal impact) needs to be evaluated. The safest way to avoid this problem is to measure homogenization temperatures not on single inclusions, but on *fluid inclusion assemblages* (FIA's) – finely discriminated and pertographically associated groups of inclusions (Goldstein and Reinolds, 1994). Variability of data within an FIA will alert the researcher of the possible stretching, re-equilibration, necking or immiscibility – factors which make the interpretation of measured temperatures much more complicated and sometimes problematic. By contrast, consistency of data obtained from many inclusions in an FIA will indicate that the measured temperatures reflect the true temperatures during inclusion entrapment.

The question: What is a "consistent" result? has no straightforward answer. Goldstein and Reinolds (1994) recommend that FIAs with 90 % of inclusions homogenizing within a 10-15 °C interval should be considered as showing a consistent result (p. 151).

Taking into account this guideline, I measured homogenization temperatures on petrographically defined groups of fluid inclusions, FIAs. Some of my samples contained groups of the vapor-liquid inclusions with similar vapor-to-liquid ratios. In association with a few such groups I observed inclusions with elevated contents of gas in them. This may reflect hetrogeneous entrapment and/or necking-down. Since measurements on such inclusions may yield erroneous temperature estimates, such groups were not used for thermometric studies.

A cycling technique was applied to measure homogenization temperatures. Temperature in the stage was increased in increments of 1 °C. The sample was held at each temperature for 1 or 2 minutes for thermal equilibration. Each inclusion in the analyzed group was examined for the presence of a bubble, after which the next heating step was performed. If the presence or absence of a bubble in an inclusion at a certain temperature was not apparent (typically, for small inclusions less than 5 micron in size) the sample was cooled down to 20 °C (homogenized inclusions would not heterogenize after such cooling). This procedure made it possible to obtain measurements on assemblages of up to 20-25 inclusions, with an accuracy of 1 °C.

*Freezing.* The inclusions in Yucca Mountain calcites have proved to be difficult subjects for freezing studies due to their small sizes and the low salinity of entrapped fluids. The results of freezing experiments can only be interpreted if all three phases, solid, liquid and vapor, are present in an inclusion during the final melting. In comparatively low-temperature minerals such as the Yucca Mountain calcite, inclusions that are homogenized by heating virtually never heterogenize upon cooling to room temperature. Therefore, to carry out freezing experiments I had to artificially stretch the inclusions. This was done by heating them to 250 °C (the pressure in an inclusion increases very rapidly with increasing temperature) and/or cooling to the temperature of liquid nitrogen (inclusion may be stretched by expanding ice when water freezes).

An interesting outcome of the "overheating" experiments was the finding that most of inclusions did not stretch upon heating to 200-250 °C, i.e., they did not nucleate bubbles. Rather, they remained as one-phase liquids. (I held some of my samples for 10-25 minutes at these temperatures.) This applied equally to inclusions that initially were two-phase ($T_h$=35-70 °C) and those that originally were all-liquid. This result seems to be in conflict with the $H_2O$ phase diagram, which indicates that the pressure in such inclusions should increase very rapidly and be very high (~4.5 kbars) at 250 °C. It is also in conflict with common perception of the fluid inclusions in calcite as being susceptible to stretching upon slightest overheating.

A possible explanation of this behavior is that calcite may accommodate very high internal pressures in inclusions through elastic deformations. Therefore, the time of overheating may be more important than the temperature. At the present stage, this effect cannot be quantified.

Many inclusions that I studied revealed the final melting temperatures of >0 °C which indicates possible metastable behavior in the system (pure water ice should melt at 0 °C and ice of saline water melts at <0 °C). To ensure that this was not related to a too-fast heating, I routinely held such inclusions at 0 (+0.1/-0.1) °C for 5-10 min., which typically did not led to melting.

*Other methods.* Gas chromatographic analyses (discussed in Appendix 1) were carried out at the Institute of Mineralogy and Petrography, Russian Academy of Sciences, Novosibirsk, Russia on the chromatograph *LHM-8* with two different types of gas detectors (flame-ionisation detector and catharometer). Gas was extracted from samples by heating them to 250-500 °C. Raman spectrometric analyses were performed at Virginia Tech, Blacksburg, VA using a *Dilor XY* Raman microprobe with *Princeton Instruments* CCD detector and *Lexial* Argon ion 5 watt laser. Analyses of carbon and oxygen isotopes in calcite were carried out at McMaster University, Hamilton, Ontario, Canada, using a *VG SIRA* mass spectrometer with an *Autocarb* analyser and U-series disequilibrium analyses were performed using VG354 mass spectrometer.

# 4. Occurrences of calcite in the ESF

Calcite in the ESF occurs as various epigenetic formations. In places it forms "common" veinlets (i.e., veinlets in which the opening of a fissure is entirely filled with calcite). An example of such veinlet is given in Fig. 2.

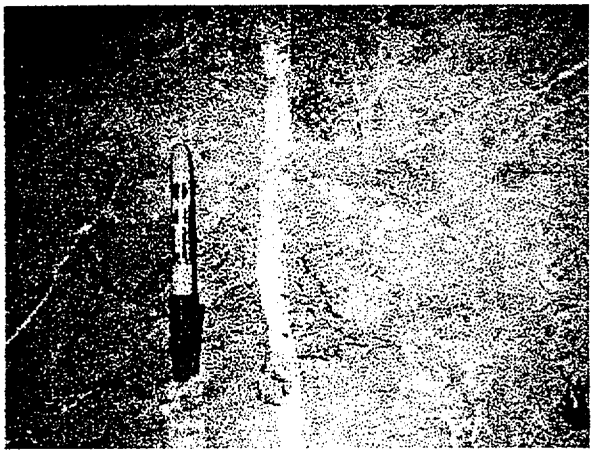


Fig. 2. Station 67+81.0. Dune Wash fault zone. Sample 2210. Calcite veinlets in Topopah Spring welded tuff.

Such veinlets, however, are rare.

Another rare, but fascinating occurrence is calcite coating floors of small tectonic cavities, like one shown in Fig. 3. Thin and apparently stress-related fissures propagate in various directions from such cavities; some of such fissures are filled with milky-white calcite.

Fig. 3. Station 28+27, Alcove 5. Tectonic cavity in Topopah Spring tuff with crystalline calcite deposited on its floor.

Fig. 4. Station 37+37.0. Alcove 6, station 0+55.1. Northern Ghost Dance Fault zone. Sample 2222. Low-angle veinlet and micro-breccia.

Calcite also occurs along low- to steep-angle fractures forming complex bodies, which consist of "common" veinlets build up of massive milky-white calcite, calcite-cemented breccias, and crusts featuring free-growth crystals in fissure's opening. The shape of such bodies is often irregular, as it is shown in Fig. 4.

Calcite forms crusts, 1 to 3 cm thick on the floors of lithophisal cavities (Fig. 5). I did not observe calcite in thin fractures, intersecting these cavities.

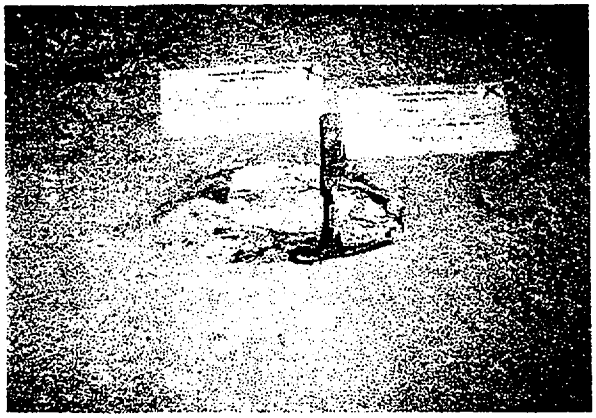
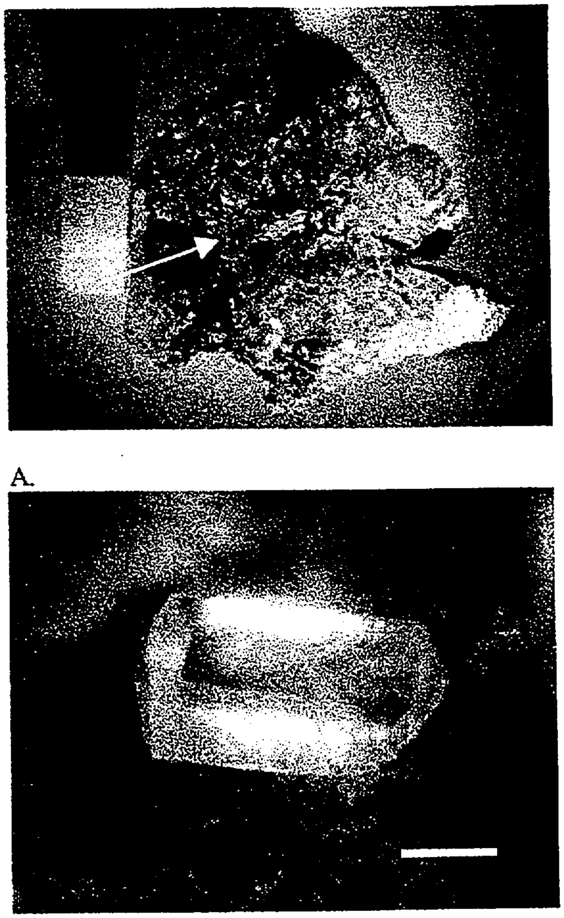


Fig. 5. Station 38.37. Sample 2220. Lithophisa in Topopah Spring tuff featuring calcite lining on the floor.

Calcite also coats fracture walls or, in fractured zones, surfaces of broken fragments of bedrock tuffs (Fig. 6-A). On some occasions, it forms small individual euhedral crystals (Fig. 6-B).



B.

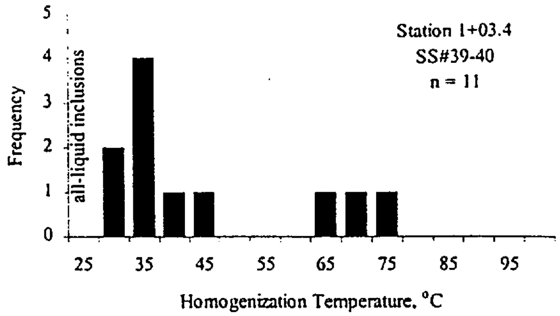
Fig. 6. Station 52.13. Sample 2215. A – Translucent blocky calcite, coating broken fragments of tuff (scale bar is 2 cm); B – Close up: individual euhedral calcite crystal crystallized on tuff surface (arrow on A; scale bar is 5 mm).

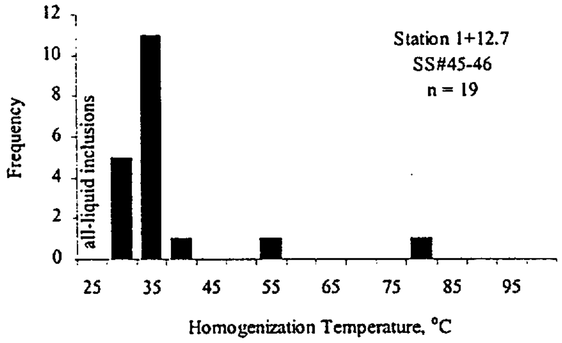
# 5. Fluid inclusion results

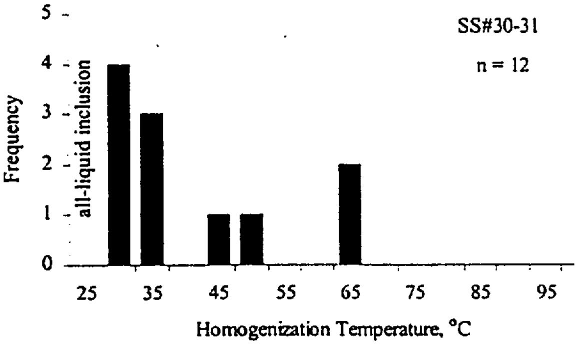
## 5.1. Samples from the first 200 m of the ESF (set-1995, results of previous studies)

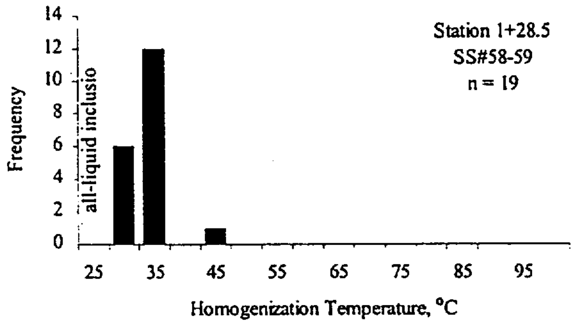
The samples, collected on March 1, 1995 and studied in Novosibirsk in 1995 and partly in Blacksburg, VA in June 1998 (see Appendix 1) are labeled according to the numbers of the steel sets between which they were taken. All samples are from Tiva Canyon tuff (Tpc unit).

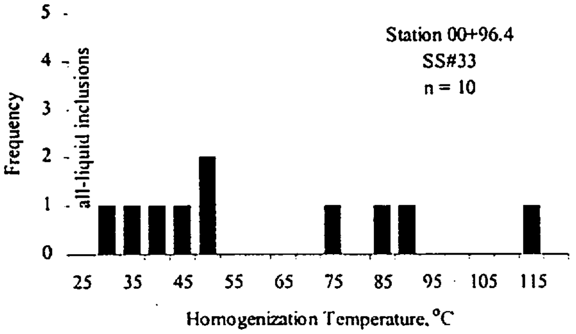
Thermometric data are given below:

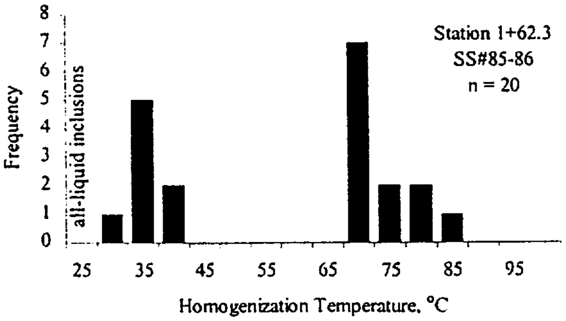












## 5.2. Samples from the ESF (set-1998)

Samples collected in the ESF in 1998 were assigned numbers from SPC00532201 through SPC00532232. Below we use the last four digits to identify the samples. The numbers of the stations reflect their distance from the north portal in meters, except for the alcoves, where the distance is indicated from the main tunnel.

Quantitative fluid inclusion results were obtained on seven samples. In three more samples, two-phase gas-liquid inclusions suitable for thermometry have not been found.

A brief summary on the fluid inclusion distribution in studied samples is given in table below. The table also indicates the presence or absence of fluorite in the samples.

| *Sample* | *Inclusions* | | | *Fluorite* |
|---|---|---|---|---|
| | *All-gas* | *Gas-liquid(*)* | All-liquid | |
| 2206 | + | + | + | + |
| 2215 | - | - | + | + |
| 2217 | + | + | + | - |
| 2218 | + | - | + | - |
| 2220 | + | + | + | - |
| 2221 | - | + | + | - |
| 2222 | + | + | + | - |
| 2224 | + | + | + | + |
| 2225 | - | - | + | - |
| 2226 | + | + | + | - |

* Only gas-liquid inclusions suitable for thermometry are indicated

Detailed results obtained on individual samples are given below.

## Sample 2206

***Station:*** 76+00.6

***Field description.*** Calcite crust on the foot wall of the opening, up to 2 cm thick. Bedrock tuff appears to be altered (calcitized). In one location, the crust has pink color (possible presence of disseminated fluorite).

***Bedrock***: Tiva Canyon Tuff (Tpc unit).

***Depth from land surface:*** ~70 m.

***Minerals and textures.*** On a visual basis, there occur at least two generations of *calcite*. (1) ~1 mm-thick layer of slightly brownish calcite on the contact with the bedrock tuff. White empty globules 0.1-0.2 mm in size (opal?) often occur on its surface. (2) ~1 cm-thick layer of translucent large-crystalline calcite with free-growth crystals at its top. Under the microscope, up to four generations of calcite, separated by hiatuses (caused by dissolution) or layers of opal can be distinguished. The outer layer contains crystals of free growth with well-developed pinacoidal face and intergrowth.

Colorless and violet globules of *fluorite* are associated with the latest stages of calcite growth. They are often overgrown by calcite and make the latter look violet. Part of the globular aggregates reside on the calcite surface. Sometimes fluorite forms individual crystals on the calcite surface up to ~0.2 mm in size. Crystals are irregularly colored from light- to dark-violet. Crystals are isometric (simple forms100, 111, 110) but often distorted.

Fig. 7. Sample 2206. Quartz and calcite. Scale bar is 1 mm.

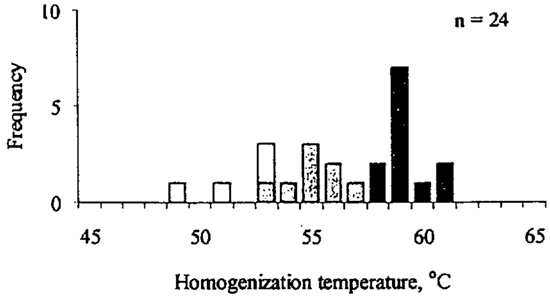


Fig. 8. Sample. 2206. Black – group of inclusions along growth zone; gray – inclusions along low-angle plane; white – inclusions forming a 3-D group.

*Opal* has a botrioidal appearance. *Quartz* occurs as globules 1-2 mm in diameter, composed of radially aligned micro crystals. The tips of crystals in globules are <0.1 mm in size. Some individual quartz crystals have size of up to 2 mm (Fig. 7). They have a perfect shape and a diamond luster; they are translucent. Some of them are overgrown by a thin layer of opal. Crystals of fluorite were also observed on the surface of quartz.

Fragments of tuff 2 to 15 mm in size occur in the middle of the crust. They are cemented by opal and calcite. Translucent euhedral crystals (*zeolite*?) occur on the surface of these fragments.

***Fluid inclusions.*** Calcite contain numerous all-gas inclusions. All-liquid aqueous inclusions are abundant. Two-phase gas-liquid inclusions are rare. They occur as 3-D groups, groups along low-angle planes and along growth zones.

The results of thermometric studies are shown in Fig. 8. Homogenization temperatures for each group of inclusions cluster within narrow, 4-5 °C interval. The result, therefore is quite consistent and measured temperatures may be considered true temperatures of paleo fluids.

## Sample 2215

***Station***: 52+13

***Bedrock***: Middle Nonlythophisal crystal poor Topopah Spring Tuff (Tptpmn unit)

***Depth from land surface***: ~ 260 m.

***Field description.*** Steep-angle fracture lined with thin, ~0.5 mm, crust of dark powdery to violet micro crystalline fluorite (subsample 2215A). In places this layer of fluorite is covered by a crust of translucent blocky calcite crystals (subsample 2215B).

***Minerals and textures***, subsample 2215B. *Calcite* is water-clear, blocky. It forms 0.5 to 3 mm thick crust on the fracture wall, as well as coats broken fragments of tuffs (Fig. 9-A). Sometimes it forms individual crystals (Fig. 8-B). Tuff on the contact with calcite and fluorite appears to be unaltered. Calcite contains globules of slightly brownish *fluorite* up to 1 mm in diameter, as well as numerous angular solid inclusions (they have not been identified).

***Fluid inclusions.*** Calcite contains all-liquid inclusions. Two-phase gas-liquid inclusions suitable for thermometry have not been found.

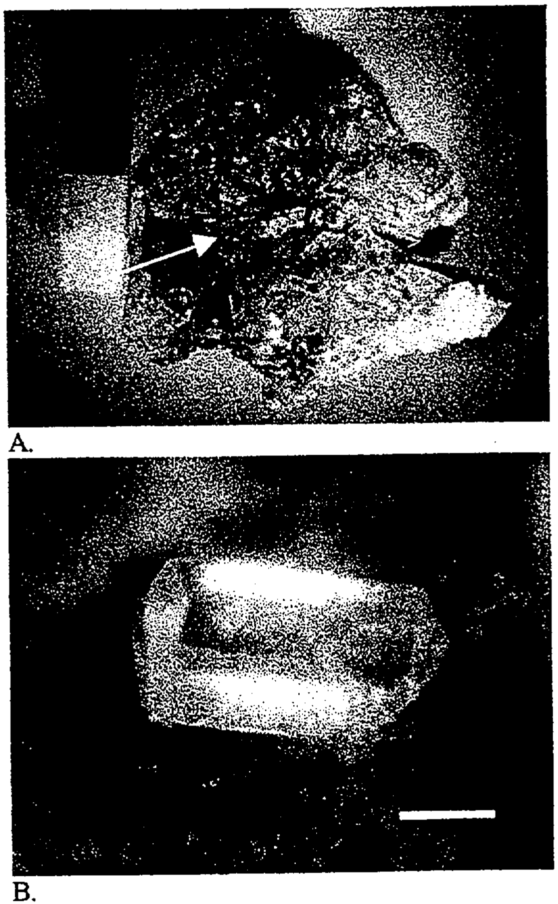


Fig. 9. A - calcite coating fragments of tuff (scale bar is 2 cm); B – close up: individual calcite crystal on the surface of tuff fragment (arrow in A). Scale bar is 0.5 mm.

## Sample 2217

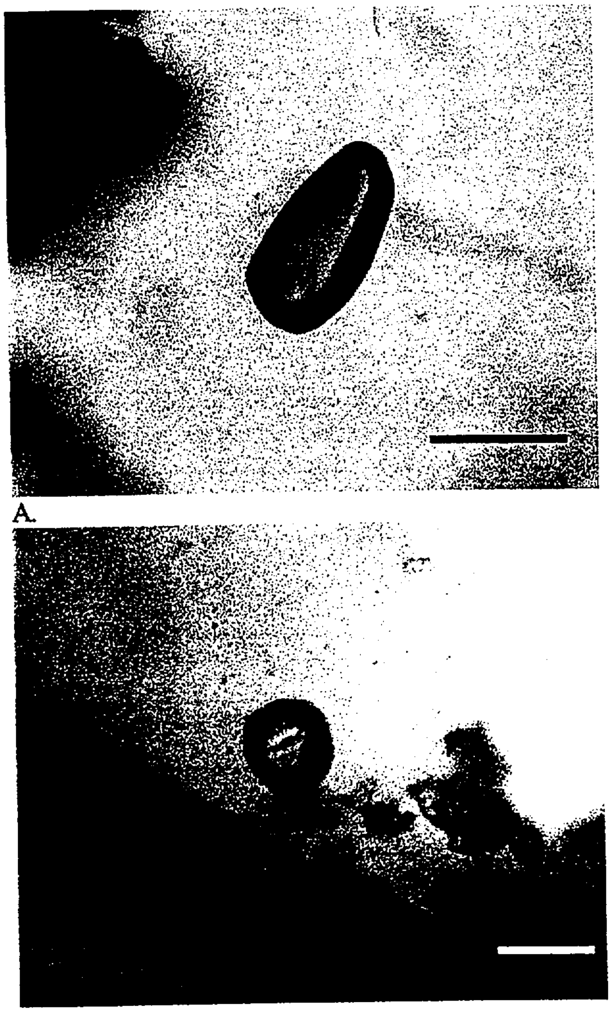
***Station***: 38+64.0

***Bedrock***: Middle Nonlithophysal crystal-poor Topopah Spring Tuff (Tptpmn unit).

***Depth from land surface***: ~260 m.

***Field description.*** Local opening in a vertical fracture (otherwise closed) 5-10 cm wide. Calcite encrusts one wall of the opening but does not occur in the fracture.

***Textures.*** Water-clear calcite forms crystals 1-4 mm in size. The shape of crystals is distorted: their dimensions perpendicular to the bedrock are significantly smaller than in other directions. Calcite is crystallized on the agglomerations of the sand-sized particles and entrap these agglomerations. Outer layers of calcite are typically translucent, and this mustard-colored material is readily visible through them. In some instances, sandy material forms elongated layers 0.1-0.3 mm thick. Calcite sometimes grows on both sides of these layers.


A.

B.

Fig. 10. All-gas inclusions. A – scale bar 100 μ; B – scale bar 25 μ.

***Fluid inclusions.*** Calcite contains all-gas (Fig. 10), all-liquid, and gas-liquid inclusions.

All-gas inclusions occur randomly and typically are restricted to the portions of calcite closest to the substratum. On one occasion, however, I observed gas inclusions clearly restricted to calcite growth zones (Fig. 11). This indicates the primary character of these inclusions.

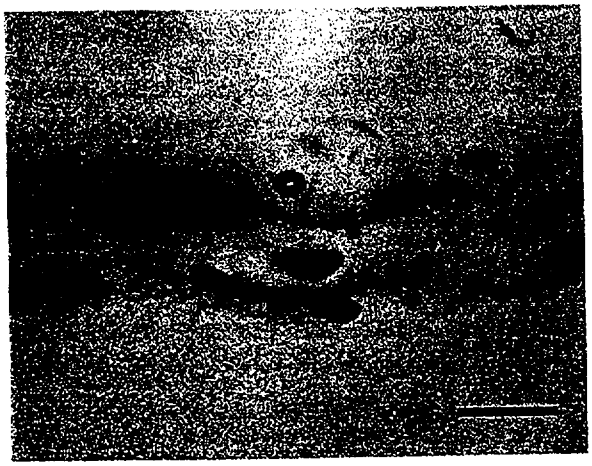


Fig. 11. All-gas inclusions aligned along the growth zones (two of them are not in focus). Such alignment indicate the primary character of inclusions. Scale bar is 100 μ.

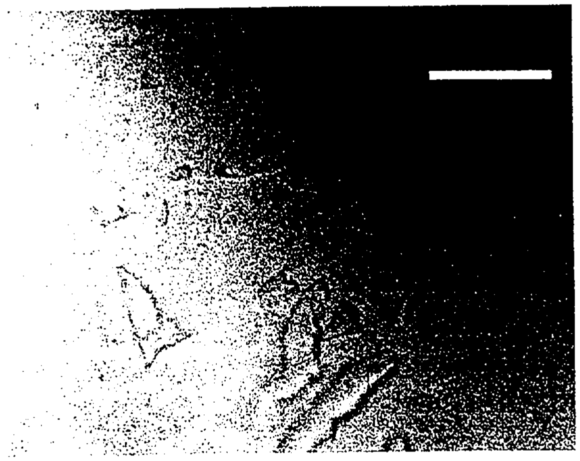


Fig. 12. Group of vapor-liquid inclusions. Scale bar is 20 μ.

The two-phase gas-liquid inclusions are rare. They are restricted to zones of calcite closest to the tuffaceous substratum. Blocky sparry calcite of outer parts of the crust is devoid of the two-phase inclusions and contains only all-liquid inclusions. Two-phase inclusions form groups along the low-angle planes (Fig. 12) or along steep-angle curvilinear surfaces (probably, healed fractures). The results of thermometric studies are given in Fig. 13. As is apparent from the figure, homogenization temperatures exhibit significant scatter, which indicates possible "disturbed" character of inclusions in this sample (stretching or leakage). The highest temperatures (>50 °C) should probably be disregarded.

### *Freezing experiments.*

Freezing experiments were carried out on four inclusions from two groups. Two inclusions from the group shown in Fig. 12 yielded final melting temperature, $T_{fm}$'s of –0.9 and –0.95 °C, which correspond to the salinity of 1.57 and 1.65 wt. %, NaCl-equiv. Two inclusions from another group yielded $T_{fm}$ of –0.3 and –0.4 °C (0.53 and 0.71 wt. %, NaCl-equiv.).

I attempted to perform a freezing experiment on one all-gas inclusion (shown in Fig. 14). Some tiny light-colored phases appeared upon rapid cooling to a temperature of ~-100 °C. On heating, these phases re-grouped to form one rounded phase. The phase disappeared in this inclusion at temperatures from –30 to –10 °C. The behavior of this phase did not show any dependence on the temperature regime: in a number of experiments it disappeared when the temperature in the stage was increasing and when it was decreasing.

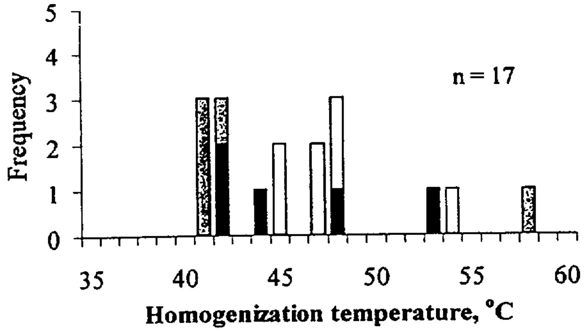


Fig. 13. Sample 2217. Black and gray – inclusions along low-angle plane (see Fig. 12); white – inclusions along steep-angle bent zone (healed fracture). Measurements show significant scatter, indicating possible "disturbed" character of fluid inclusions in this sample. The highest temperatures (>50 °C) should probably be neglected.

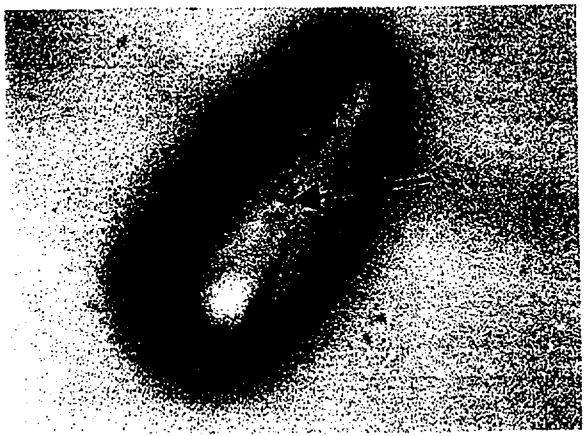


Fig. 14. Sample 2217. All-gas inclusion (see Fig. 10-A) containing unidentified phase (arrow) at –35 °C.

## Sample 2218

***Station***: 45+26

***Bedrock***: Middle Nonlythophisal crystal poor Topopah Spring Tuff (Tptpmn unit)

***Depth from land surface***: ~ 230 m.

***Field description.*** Lithophisa ~60 cm wide and 40 cm high. No other cavities around. The bottom of the cavity is lined with calcite. The walls of the cavity are covered by a ~1 mm thick layer of white α-quartz and tridimite crystals (identified by XRD).

***Minerals and textures.*** Tuff on the contact appears to be altered to a depth of 3-8 mm. Two individual crystals of ***garnet*** (~3 mm in size; identified by XRD) were found in this altered zone and one in calcite. Calcite often appears to be crystallized as porous mass, composed of isometric crystals ~ 1mm in size. In other places calcite is massive. Fragments of tuff (3 to 10 mm in size) incorporated in the calcite look altered, almost decomposed.

Fig. 15. All-gas inclusion in the middle of an individual grain of calcite. Scale bar is 50 μ.

***Fluid inclusions.*** Calcite contains all-liquid inclusions, as well as all-gas inclusions (Fig. 15). Two-phase gas liquid inclusions suitable for thermometric studies were not found.

## Sample 2220

***Station***: 38+37.0

***Bedrock***: Middle Nonlithophysal crystal-poor Topopah Spring Tuff (Tptpmn unit).

***Depth from land surface***: ~260 m.

***Field description.*** Cavity in the bedrock tuff, 60 cm wide and 35 cm high. Thick, up to 2 cm crust of calcite coats cavity floor, as well as the lower part of hanging walls. There are individual euhedral crystals of calcite up to 1.0-1.5 cm large. No apparent feeder-fissure.

***Minerals and textures.*** A 1 mm-thick layer of white *quartz* (alteration?) occurs on the contact with the bedrock tuff. After that a 1.5 cm layer of milky-white *calcite* is deposited. It reveals traces of competitive growth, induction surfaces. In places, this zone is strongly corroded; a new-formed water-clear and well shaped crystals of calcite < 1mm in size are present in the corrosion cavities. This calcite also occurs as thin, ~1 mm, veinlets in bedrock tuff. The described "Calcite-1" is cut by nearly horizontal and rough surface of dissolution, on which "Calcite-2" is deposited. It is also milky-white, but somewhat more translucent. Both calcites form flattened crystals of free growth; crystals of the "Calcite-1" are "blade-shaped", whereas crystals of the "Calcite-2" are blocky. The orientation of crystals is also different.

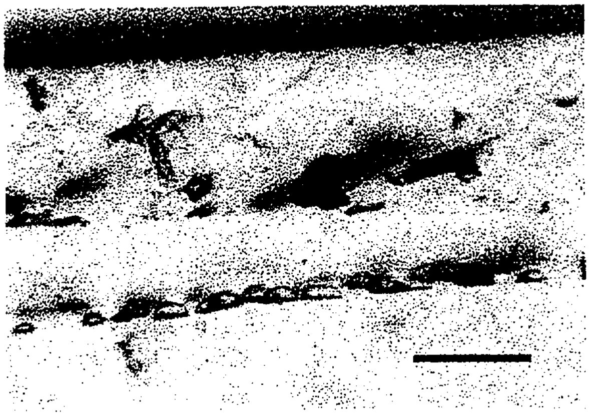


Fig. 16. Primary inclusions of opal in calcite near the crystal surface (top of the picture). Scale bar is 100 μ.

*Opal* is often present as primary solid inclusions, which have a half-spherical shape with the flat side aligned along the growth zones. Such inclusions often occur at the latest stages of calcite growth, close to the surface of blocky sparry crystals (Fig. 16).

***Fluid inclusions.*** *All-gas inclusions* are abundant in this sample. In contrast to most other samples studied from the ESF, where all-gas inclusions are mostly restricted to the earliest generations of calcite, in this sample such inclusions occur throughout the calcite crust.

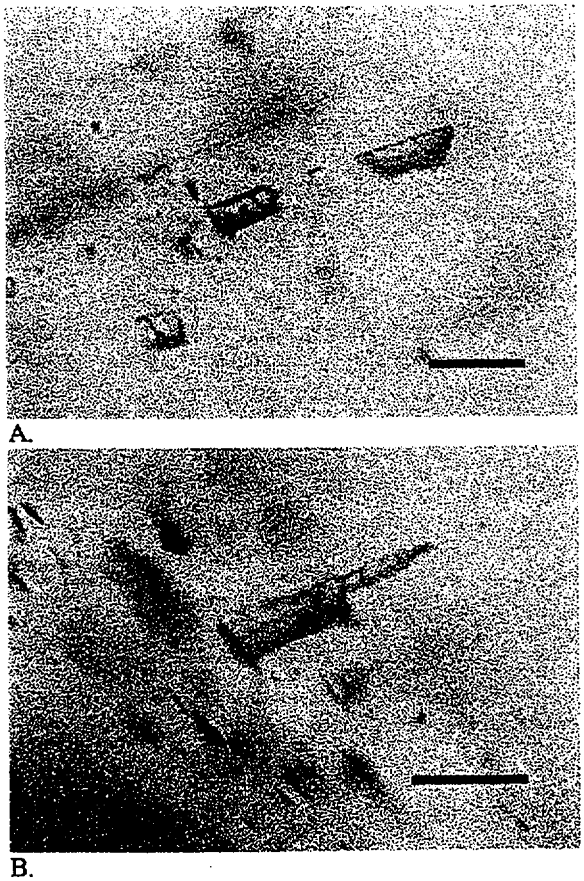


Fig. 17. Two-phase inclusions from a group along growth zone. Homogenization temperatures are 37 (A) and 38 °C (B). Scale bars correspond to 10 μ in both images.

All-liquid inclusions are also abundant. Gas-liquid inclusions suitable for thermometry are rare. They occur along growth zones (Fig. 17), low-angle planes and form 3-D groups.

The results of thermometric studies are shown in Fig. 18. Inclusions in individual groups homogenize within narrow temperature intervals (3 to 8 °C). This indicates that obtained temperatures reflect true temperatures of paleo fluids.

Freezing experiments performed on several inclusions with $T_h$ = 36-40 °C yielded no numeric results. Two inclusions from a growth zone showed $T_{fm}$ = +0.3 and +0.4 °C. Ice in two inclusions from another group melted at exactly 0 °C (ice crystals grew and diminished very fast as the temperature in the stage oscillated between –0.1 to +0.1 °C). The data suggest that aqueous fluid in inclusions is very diluted (essentially, it is fresh water).

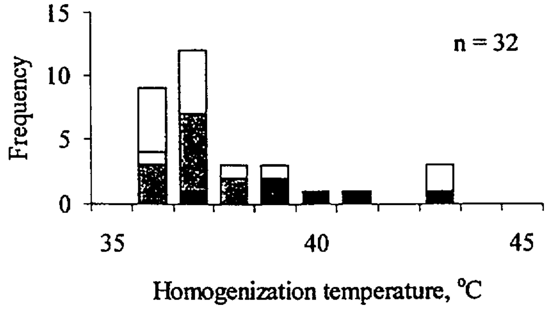


Fig. 18. Sample 2220. Black – group of inclusions along growth zone; dark gray – inclusions along low-angle plane; light-gray – inclusions forming a 3-D group; white – individual inclusions.

## Sample 2221

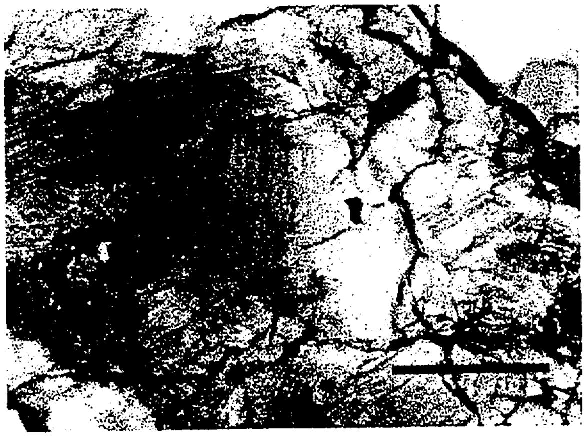
***Station***: 37+37.0 Alcove 6 - Northern Ghost Dance Fault Alcove, S.D.4

***Station within alcove:*** 0+12.6

***Bedrock***: Middle Nonlithophysal crystal-poor Topopah Spring Tuff (Tptpmn unit).

***Depth from land surface:*** ~230 m.

***Field description.*** Vertical opening associated with calcite-cemented breccia-vein. Calcite encrusts both walls of the opening. Sometimes it forms near horizontal plates with crystals on both sides. These may be fragments of wall linings fallen on the cavity floor and overgrown by later-stage calcite.



A.

B.

Fig. 19. "Stressed" calcite in the basement of a crust. Outer parts of the sample are not damaged. Scale bars correspond to 5 mm in both images.

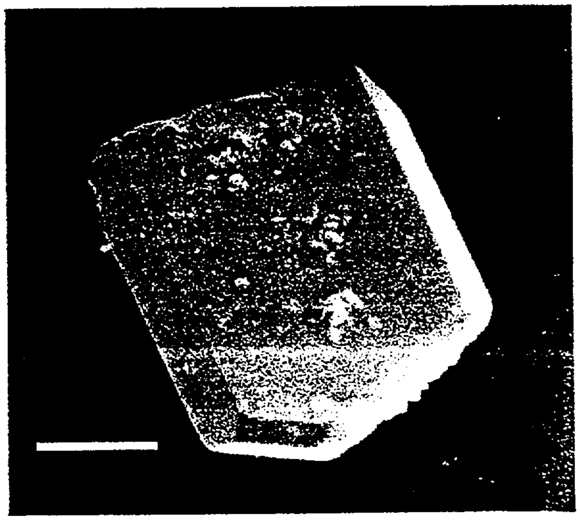


Fig. 20. Scanning Electron Microscope (SEM) microphotograph of a mineral (hematite?) from tuff alteration zone, overgrown by calcite. Scale bar is 50 μ.

***Textures.*** *Calcite* occurring as breccia cement is milky-white semi-translucent. It cements small angular fragments of the tuff. The latter appears to be altered. Calcite in crusts is water-clear translucent. It forms nearly isometric blocky crystals growing on tuff or clay substratum.

A white powdery layer occurs on the contact between one crust and the bedrock tuff. This layer consists of *tridimite* (supposedly, early vapor-phase alteration of tuff). The layer also contain tabular crystals with metallic luster (*hematite*?) (Fig. 20). Similar crystals analyzed from another sample (2226) appeared to be a mixture of oxides of Fe, Mn and Ti.

Calcite in the basement of the crust often appears to be mechanically stressed and exhibits twinning (Fig. 19). The latest euhedral crystals do not bear indications of mechanical damage.

Calcite contains solid inclusions of an unidentified translucent cubic mineral (possibly *fluorite*).

***Fluid inclusions.*** All-gas inclusions have not been found in this sample. All-liquid inclusions are abundant. Gas-liquid inclusions are rare. They occur as groups along healed fractures. Inclusions in such groups are typically small (1-5 μ in size).

Results of thermometric studies are shown in Fig. 21. The scatter in the data is significant. It should be noted, that inclusions associated with healed fractures yield larger scatter (up to 13 °C within a group), than isometric, possibly primary inclusions forming a 3 D group (8 °C). At this stage, the high-temperature part of the data (>40 °C) should probably be disregarded.

Freezing experiments were carried out on several large inclusions, bubbles in which were generated by stretching. They yielded $T_{fm}$ of +0.2 to +0.3 °C. This indicates metastable ice melting and low-salinity fluids.

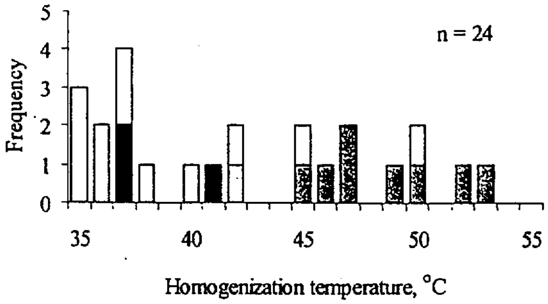


Fig. 21. Sample 2221. Black and gray – inclusions along healed fractures; white – inclusions in 3-D group (possibly primary).

## Sample 2222

***Station:*** 37+37.0 Alcove 6 - Northern Ghost Dance Fault Alcove.

***Station within alcove***: 0+55.1

***Bedrock***: Middle Nonlithophysal crystal-poor Topopah Spring Tuff (Tptpmn unit).

***Depth from land surface***: ~ 230 m.

***Field description.*** Low-angle veinlet partly made up of crystalline calcite, partly cementing breccia fragments of tuff (Fig. 22). At both ends, when it enters shattered tuffs, veinlet splits into several discontinuous fragments.

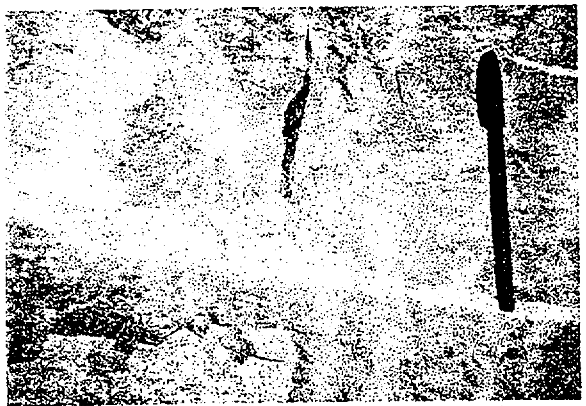
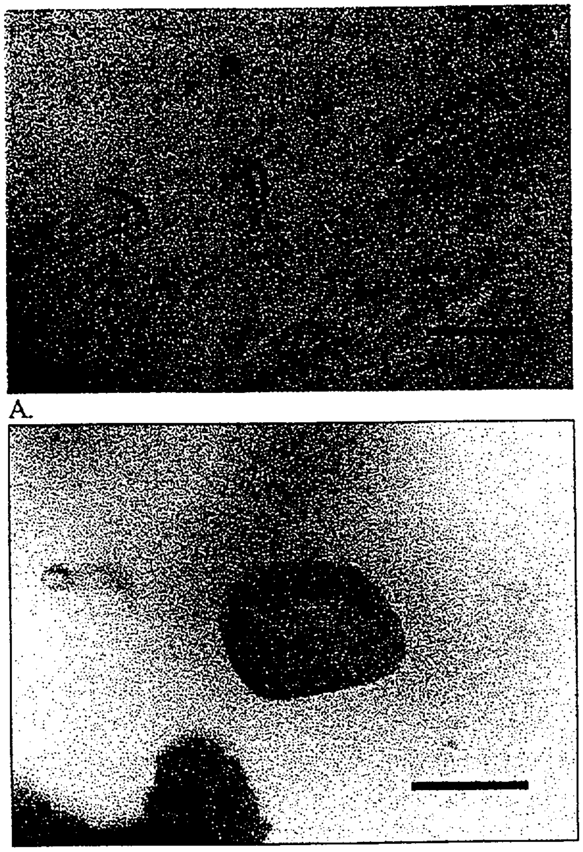


Fig. 22. Low-angle veinlet and breccia (sample 2222)

***Textures.*** Calcite is milky-white, massive. It completely fills the fracture opening. In places this massive calcite contains cavities (dissolution?) with their inner surfaces composed of the euhedral heads of tabular calcite crystals. Near the contact (2-4 mm), calcite is small-crystalline, granular.

***Fluid inclusions.*** In the vicinity of the tuff fragments, calcite contains numerous and large (visible under binocular microscope) all-gas inclusions. All-liquid inclusions are also abundant.



A.

B.

Fig. 23. Gas-liquid inclusions: A - group of fluid inclusions along a low-angle plane ($T_h$ = 36-37 °C); B – individual inclusion ($T_h$ = 35 °C). Scale bars correspond to 10 μ in both images.

Gas-liquid inclusions are rare. They occur in groups (also containing all-liquid inclusions; Fig. 23) aligned along low- to steep-angle planes.

***Thermometic study.*** The results of thermometric study are shown in Fig. 24. All studied inclusions (35) homogenized within a very narrow interval of 5 °C. The results are quite consistent. The measured temperatures may be considered true temperatures of ancient fluids.

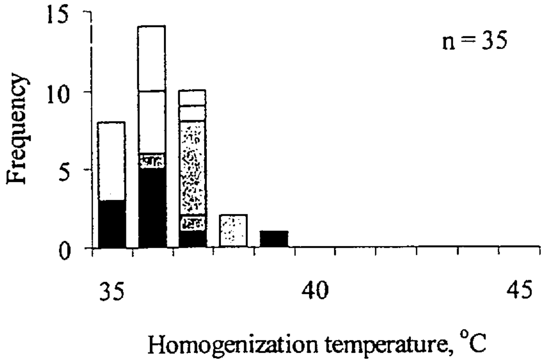
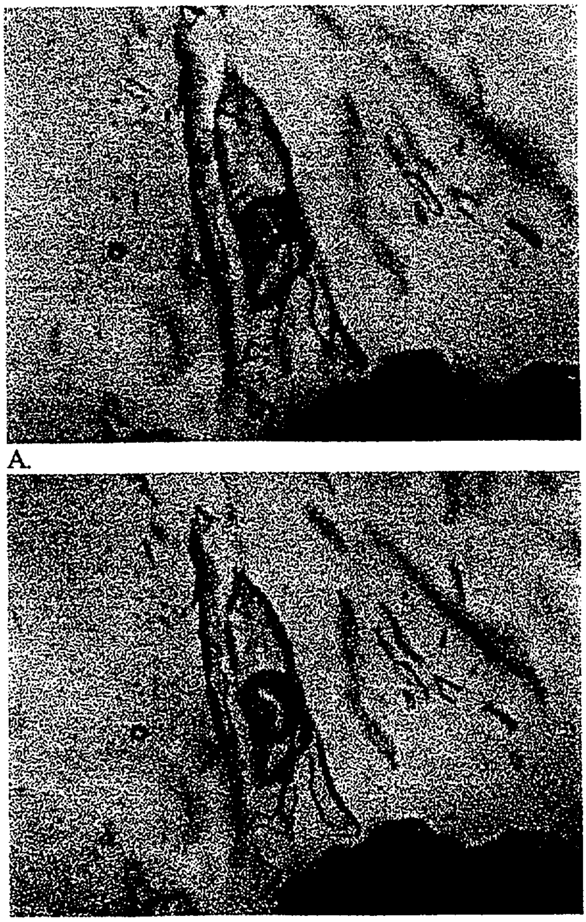


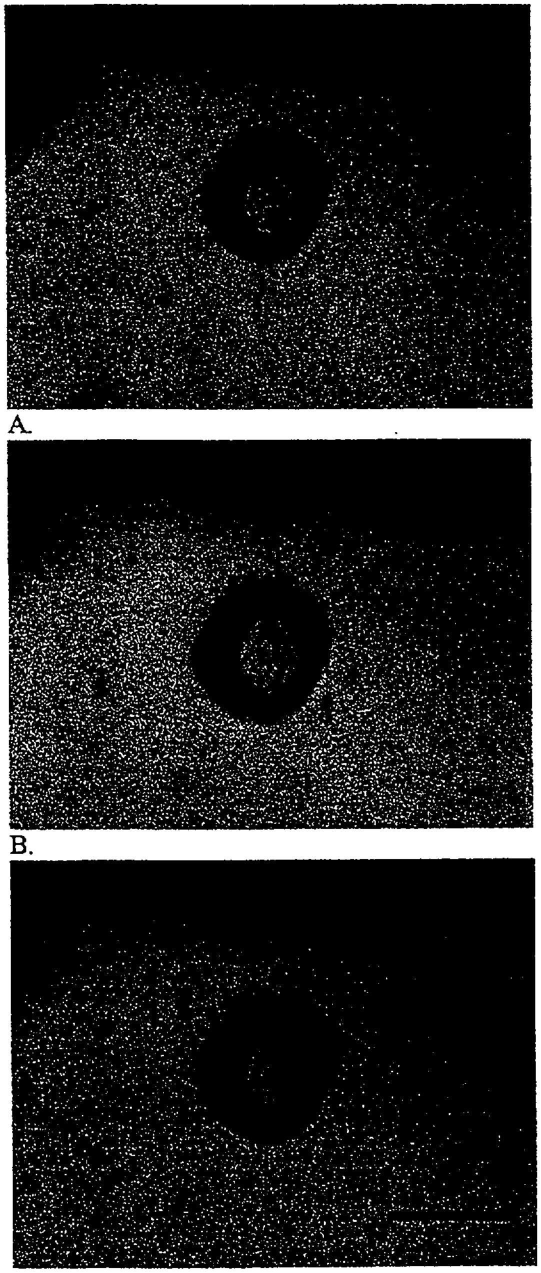
Fig. 24. Sample 2222. Five groups of inclusions (2 to 10 inclusions each).

***Freezing experiments.*** One large artificially stretched inclusion was subjected to freezing (Fig. 25). The ice in inclusion melted at +0.35 °C suggesting low salinity of trapped fluids.


A.

B.

Fig. 25. Freezing experiment on artificially stretched inclusion. A – T = -20 °C, inclusion is frozen; B – T>+0.35 °C.


A.

B.

C.

Fig. 26. Freezing experiment on the all-gas inclusion: A – three phases at T < -30 to -50 °C; B – one condensed phase; C – homogeneous inclusion (at T >-30 to -5 °C). Scale bar is 20 μ

In one all-gas inclusion, several segregations of a condensed phase appeared upon fast (50 not change on cooling or heating. Upon heating, the phase disappeared at random temperatures varying from –30 to –5 °C. The phase does not luminesce under UV excitation (vide-band UV-filter, 330-385 nm). The behavior is similar to one observed in the sample 2217.

## Sample 2224

***Station***: 37+37.0 Alcove 6 - Northern Ghost Dance Fault Alcove

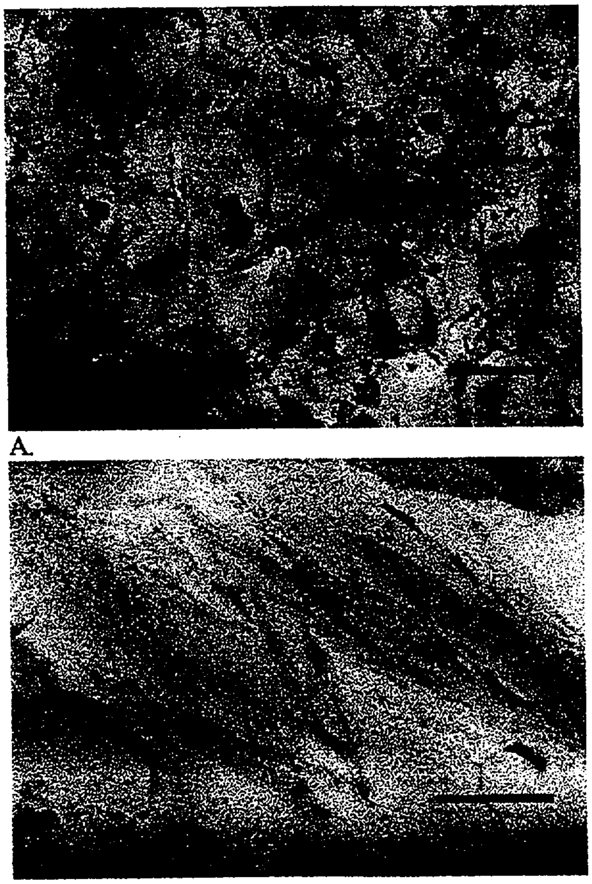
***Station within alcove***: 0+40.5

***Bedrock:*** Middle Nonlithophisal crystal-poor Topopah Spring Tuff (Tptpmn unit).

***Depth from land surface:*** ~220 m.

***Field description.*** Calcite crust lining the wall of a steep-angle open fracture.

***Minerals and textures.*** *Calcite* forms crystals on both sides of the crust. From one side, closest to the tuff contact, crystals have an appearance of a confined growth: their shape is distorted. Textural relationships reveal presence of the two generations of calcite, which grew in opposite directions from central "seam".


A.

B.

Fig. 27. Granular character of Calcite-1 (A) and sharp "phantom" crystals in Calcite-2 (B). Scale bars correspond to 0.5 mm in both images.

Calcite-1 probably grew within some porous medium. Crystals are <1 mm in size, semi-translucent. Calcite-1 often has a granular appearance (Fig. 27-A) and associates with delicate "nets" composed of filamentous silica, as well as with micro druses of *quartz* and micro inclusions of *fluorite*. Calcite-2 does not contain silicate phases, but traps abundant all-gas inclusions. Its translucent crystals, 2-5 mm in size, are equant, blocky. They often exhibit zoning that reveals shape of crystals during the formation of the crust (Fig. 27-B).

*Quartz* forms micro-druses composed of perfectly shaped water-clear crystals up to 2 mm in size.

*Fluorite* occurs as cubic violet micro crystals (0.1-0.2 mm in size), aggregates of several crystals (Fig. 28), as well as slightly brownish spherules inside calcite and quartz. The relationships with host minerals indicate its syngenetic character.

***Fluid inclusions.*** Calcite-2 contain abundant all-gas inclusions (Fig.29). All-liquid inclusions are present in both generations of calcite. Two-phase gas-liquid inclusions occur along curvilinear low-angle planes (healed

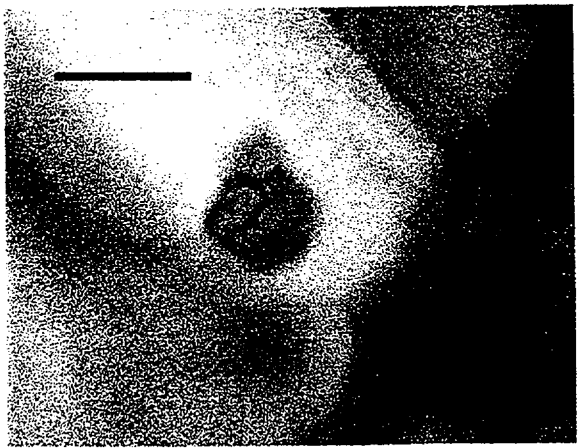


Fig. 28. Fluorite near the surface of the calcite crystal. Scale bar is 30 μ

Fig. 29. All-gas inclusion in calcite and quartz crystals. Scale bar is 20 μ

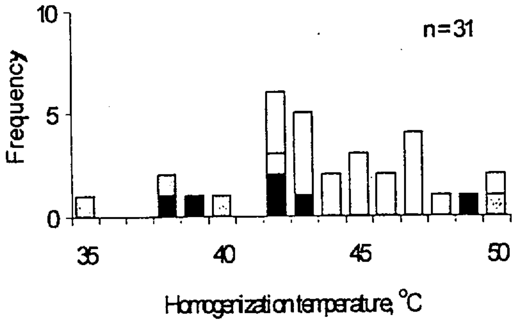


Fig. 30. Sample 2224. Black and dark-gray – groups of inclusions along healed fractures; light-gray and white – groups of large inclusions along low-angle planes (growth zones?)

fractures; inclusions are small, 4-10 μ); large inclusions with slightly flattened shape were found in low-angle planes.

***Thermometric study.*** The results of the thermometric study are shown in Fig. 30. The data display substantial scatter. Larger scatter is characteristic for inclusions associated with healed fractures. Thermometric data on large inclusions associated with low-angle planes (possible growth zones) are somewhat more consistent.

## Sample 2225

***Station***: 29+76

***Bedrock***: Middle Nonlythophisal crystal poor Topopah Spring Tuff (Tptpmn unit)

***Depth from land surface***: ~ 290 m.

***Field description.*** Lithophisa 60 cm wide and 30 cm high. Calcite coats the floor of the cavity forming crust up to 1.5 cm thick. Bedrock of the inner surface of the lithophisa is covered by a ~1 mm thick layer of quartz crystals (vapor-phase alteration?).

***Minerals and textures.*** *Calcite* is milky-white, semi-translucent. Tabular crystals are present, which in places are cut by corrosion and covered by layers of opal. This sequence again is cut by corrosion, after which another "portion" of calcite and opal was deposited.

*Opal* also occurs as primary inclusions, group of which follow the growth zones. The surface of calcite crystals is often covered by small, several micron in size "droplets" of ideally translucent opal.

***Fluid inclusions.*** Calcite contain abundant all-liquid inclusions. Two-phase gas-liquid inclusions suitable for thermometry have not been found.

## Sample 2226

***Station:*** 0+28.5 - Alcove 5.

***Field description.*** Low-angle veinlet. There is a gradual transition from a hair-wide fissure with alteration zone of ~ 1 cm on both sides (bleached tuff), to calcite-cemented micro breccia (cement is not abundant), to large calcite crystals on the floor of the fissure's widening, to massive crystalline calcite filling (partly or entirely) a 1.0-1.5 mm wide fissure.

***Minerals and textures.*** There is a ~1 mm-thick layer of *α-quartz* (identified by XRD) on the contact between tuff and calcite. Similar rims are typical of samples from lithophisae, where they are often composed of *tridimite*. Also, stringers and tabular crystals of a mineral containing Fe, Mn, and Ti (*hematite*?)*. It occurs in altered tuff, as well as in calcite-opal crust where it sometimes serve as a "seed" for crystallization of opal and calcite (Fig. 31).

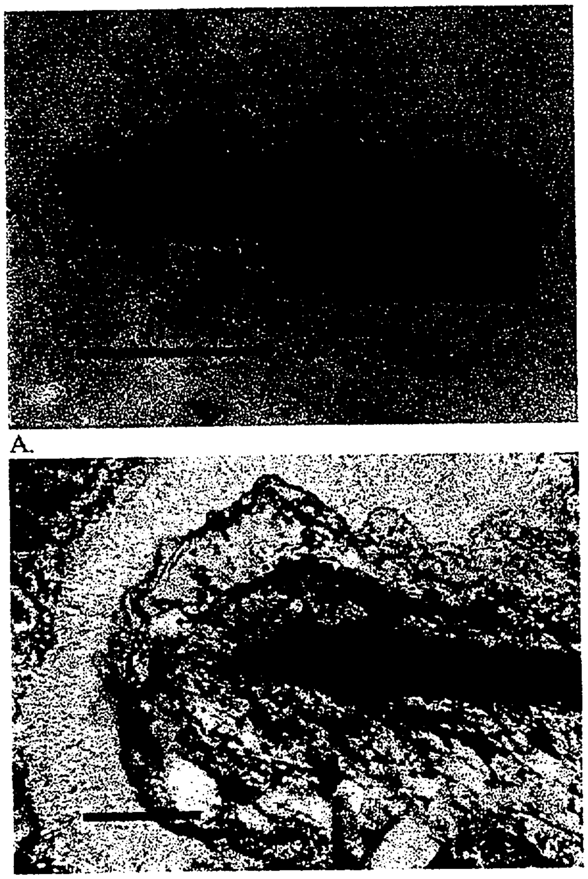


Fig. 31. Hematite (?). A – embedded in calcite; B – overgrown by layers of opal and calcite. Scale bars correspond to 1 mm in both images

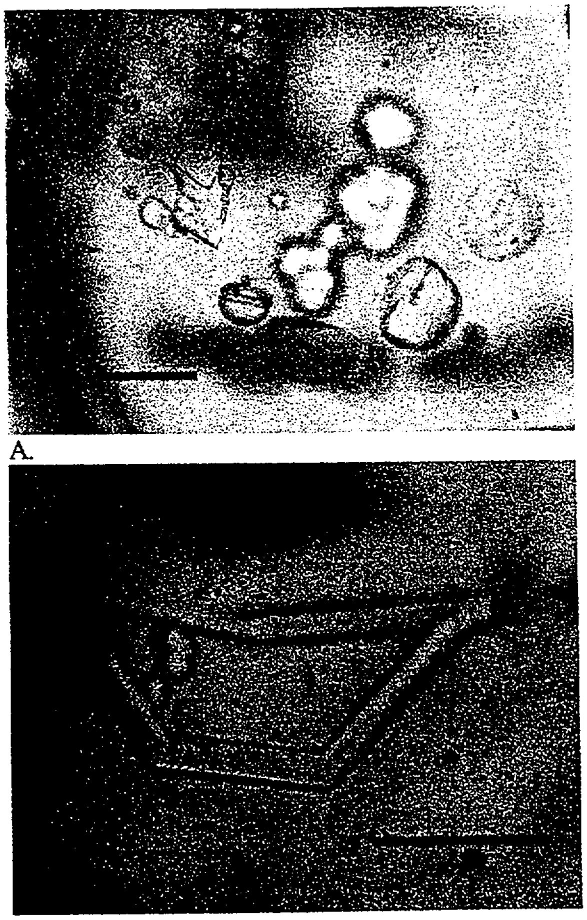


Fig. 32. Solid inclusions of opal in calcite + one two-phase aqueous inclusion ($T_h$ = 37 °C). Scale bar corresponds to 25μ in both images.

Thin, ~0.5 mm fractures in tuff are often filled with *calcite*.

Botrioidal *opal* forms a layer within calcite crust. It also occurs as water-clear blobs and thin films on the surface and at the tips of calcite crystals. Besides, opal is present as

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* Analysis on microprobe Cameca yielded concentrations: $TiO_2$ (2.16), MgO (0.38), MnO (6.22), FeO (81.12)

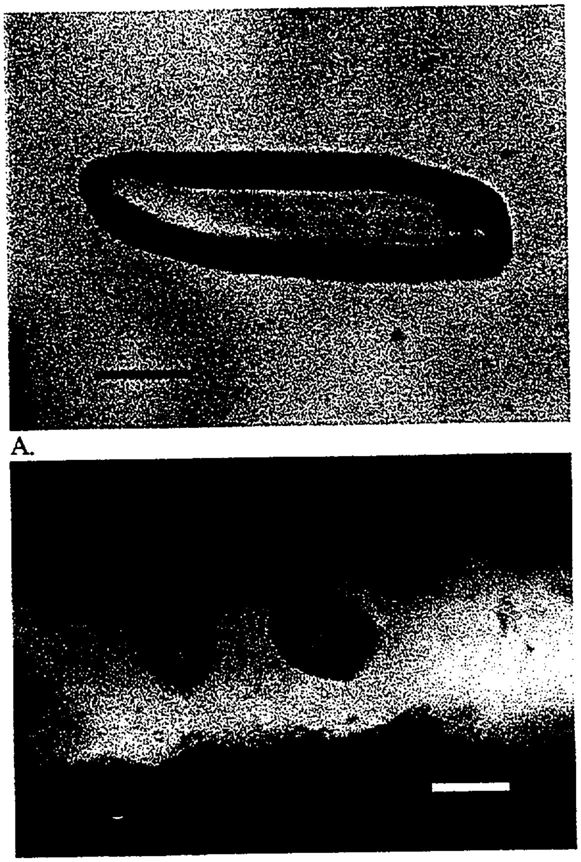

Fig. 33. All-gas inclusion in calcite crust (A, scale bar is 25 μ) and in calcite veinlet in tuff (B, scale bar is 100 μ).

solid inclusions in calcite (Fig. 31). The shape of these inclusions and their association with growth zones indicate that deposition of these two minerals occurred simultaneously.

***Fluid inclusions.*** All-gas inclusions often occur near the contact between calcite and tuff, calcite and opal, as well as in thin, ~0.5 mm wide, veinlets penetrating the bedrock tuff (Fig. 33).

Gas-liquid inclusions are rare. They occur as groups along growth zones (Fig. 34) and low-angle planes.

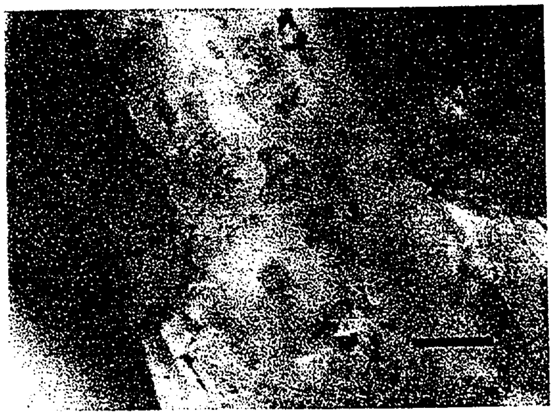

Fig.34. Group of gas-liquid inclusions in calcite near the contact with opal (upper right corner). $T_h$ = 39-40 °C. Scale bar is 20 μ

***Thermometric study.*** The results of the thermometric study are given in Fig. 35. All inclusions (42 from 3 groups) homogenized within a narrow interval of 7 °C.

The results are quite consistent; the measured temperatures may be considered true temperatures of paleo fluids.

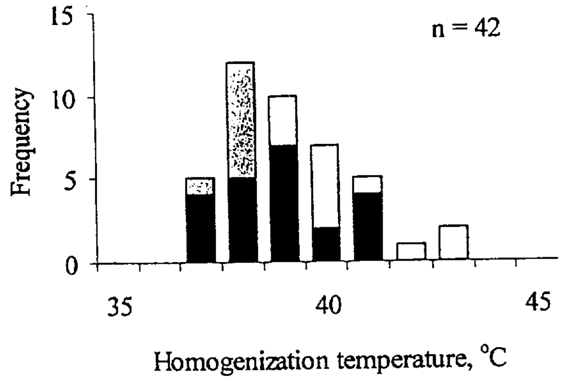

Fig. 35. Sample 2226. Black – inclusions along growth zone; Gray – inclusions in low-angle zones.

## 5.3. U-series dating

The age of the hydrothermal activity at Yucca Mountain is of critical importance from the standpoint of the suitability of the site as a potential host of a high-level nuclear waste disposal facility. With this in mind we made an attempt to measure absolute ages of calcites, for which hydrothermal origin was proven through fluid inclusion studies.

Four samples from the first sample set-1995 were subjected to TIMS U-series dating at McMaster University, Hamilton, Ontario, Canada (laboratory of Prof. D.Ford).

Three analyses (SS#30-31, SS#39-40, and SS#58-59) failed. One sample, SS#45-46, yielded the following results:

- Sample weight = 4.5945 gm;
- Spike = 0.484 gm;
- Concentration of U = 0.1396 ppm;
- Activity ratio $^{234}U/^{238}U = 1.4734 \pm 0.44$ ($2\sigma$);
- Calculated initial value $^{234}U/^{238}U = 1.7648 \pm 0.008$ ($2\sigma$);
- $^{230}Th/^{234}U = 0.8416 \pm 3.37$ ($2\sigma$);
- $^{230}Th/^{232}Th = 14 \pm 3.41$ ($2\sigma$);
- Age (in thousands of years, uncorrected for detrital thorium) = 169 (+13/-12) years; and
- Age (in thousands of years, corrected for detrital thorium) = 160 (+13/-12) years (two standard deviation errors).

The data above were treated by program for data reduction (Code and Algorithm by S.E.Lauritzen and J.Lundberg, 1997, Dept. of Geology, University of Bergen, Norway).

The sample that was dated was relatively large in size. Calcite crust ~10 mm thick was build up of two layers of slightly different color. Opal was not identified in the calcite. A layer of drusy quartz occurred at the bottom of sample.

The concentration of uranium in the sample is approximately equal to the average value of the samples from ESF analyzed by the USGS researchers (average U concentration from 20 samples is 0.139 ppm; Paces et al., 1996)

The analysis is internally consistent. The age, 160,000 years, reflects an average age of the crust; ages of inner layers may be older and outer layer – younger than this age. It is unlikely, however, that the ages of the early parts of the crusts are older than 1 million years. If it were so, the average measured age would have been much older than 160,000 years.

Although the average includes deposits over a significant time span, it represents the first direct datum on a sample with a known saturated-zone origin. Since it appears to be in conflict with findings of the DOE researchers on the old ages of early calcites at Yucca Mountain, the analysis needs to be reproduced and verified in the course of the subsequent studies.

# 6. Discussion

## 6.1. The issue: Saturated vs. Unsaturated paleo hydrology at Yucca Mountain

The origin of the epigenetic calcite and associated minerals (opal, quartz, zeolites, fluorite) found at Yucca Mountain is a subject of ongoing debate. The concept presently accepted by the U.S. Department of Energy and endorsed by a 1992 National Research Council report is that they were formed from rain waters percolating along interconnected fractures in the unsaturated (vadose) zone and carrying dissolved carbonate from overlying soils (NAS/NRC, 1992; Roedder et al., 1994; Stuckless et al., 1998; and many others).

A competing hypothesis envisages deposition of these minerals from deep-seated, elevated-temperature waters that welled up through the mountain and discharged on the surface (Szymanki, 1989; Hill et al., 1995; Dublyansky at al., 1998).

The issue is of great importance from the standpoint of the suitability of the Yucca Mountain site to host the high-level nuclear waste repository. Recent works by the U.S. Geological Survey group have demonstrated that calcite and opal at Yucca Mountain were deposited over an extensive period of time from 7-9 million years ago to as recently as ~20,000 years ago (Whelan and Moscati, 1998; Paces et al., 1998; Neymark at al., 1998). These age data are being used to estimate the percolation flux through the Yucca Mountain unsaturated zone. This concept is used as the basis for the Total System Performance Assessment by the U.S. DOE (see, e.g., the U.S. Nuclear Waste Technical Review Board's Report to the U.S. Congress and the U.S. Secretary of Energy; NWTRB, 1998). The plausibility of this approach is critically dependent on the interpretation of the origin of secondary minerals at Yucca Mountain as being formed by rainwater in the unsaturated zone. However, if this interpretation is proven to be in error, the whole concept of the performance of the Yucca Mountain repository will need to be re-evaluated.

## 6.2. A few words on the terminology

There is some ambiguity in applying the term "hydrothermal" to fluids with temperatures of 35-75 °C, like those from which calcite at Yucca Mountain was deposited. The term has been used by researcher in the past including the present author. The terms "hydrothermal" fluid or "thermal" water do not have strict definitions, and the perception of these terms strongly depends on the specific field of expertise of a geologist who uses it. For instance, an ore geologist would not consider fluids with the temperature of less than 50-100 °C as hydrothermal. There is also perception, that "true" hydrothermal fluids should reveal some links with the source of heat, like cooling magmatic bodies, etc.

In hydrology, however the threshold for thermal water is much lower. For instance, a definition accepted by most European hydrologists calls the water thermal if its temperature *at the orifice* is 4-6 °C higher than the mean annual temperature of the area. (Schoeller, 1962). In this context the temperatures in subsurface environments above those to be expected from normal thermal gradients are also considered hydrothermal (Dublyansky, 1997).

In order to remove any ambiguity regarding the use of terms I am specifying that the terms thermal and hydrothermal are used in this study to refer to waters if they reveal temperatures higher than may be expected at a given depth within the unsaturated zone.

## 6.3. Methodology: the study of epigenetic calcite for paleo hydrologic reconstruction

Long-term stability of the regional hydrogeologic system is of significant concern for all sites intended for geological isolation of nuclear or other hazardous wastes. Fracture-filling calcites in crystalline and other rocks represent "footprints" of paleo hydrologic systems. Integrated studies of stable and radiogenic isotopes and fluid inclusions in calcite veinlets, accompanied by U-series and/or U/Pb dating are used in a number of national programs to constrain the past thermal and fluid history of the prospective waste disposal sites. Pertinent examples are: Chalk River Site in Canada (Bukata et al., 1998), Olkiluoto Site in Finland (Blith et al., 1998), and Äspö Hard Rock Laboratory in Sweden (Wallin and Peterman, 1995).

At Yucca Mountain, the "descending meteoric water" interpretation was based on extensive isotopic studies; one crucial method, fluid inclusion studies, was either not applied, or its results were inadequate (Dublyansky, 1994).

## 6.4. Discussion: Why isotopic methods are not sufficient for paleo hydrologic reconstructions?

Paleo-hydrologic reconstructions based solely on isotopic methods contain an inherent uncertainty. The isotopic composition of calcite ($\delta^{18}O$ and $\delta^{13}C$) deposited from an aqueous fluid depends on the two parameters: initial composition of these isotopes in the mineral-forming fluid, and the fractionation coefficients, governing partitioning of isotopes between the fluid and the depositing calcite. The fractionation coefficients are temperature-dependent. Therefore, we have two equations with three unknowns (the isotopic composition of carbon, that of oxygen in mineral-forming fluid, and the temperature).

Evidently, such a system of equations can only be solved by assigning one of the unknowns with some arbitrary value (that was done, for example, by Szabo and Kyser (1990) who managed to "prove" the rainwater origin for the Yucca Mountain calcite this way).

Fluid inclusion studies provide independent information on the temperature of calcite deposition. This eliminates one of the unknowns and makes it possible to calculate initial values of the mineral-forming fluids.

My opinion is that the absence of adequate fluid inclusion research is one of the major and most regrettable deficiencies in the Yucca Mountain characterization activities.

## 6.5. Origin of secondary minerals in the ESF

The results of my studies show that hydrothermal origin for 13 calcite samples removed from the ESF is fairly certain. Below, I summarize results that imply deposition of these calcite in the saturated environment.

### Mineralogy

The presence of crystalline quartz and fluorite within calcite crusts is not compatible with the postulated by the DOE rain water origin of the mineral-forming fluids. Quartz and fluorite were reported by the USGS researchers (Paces et al., 1996):

> *"Nearly all low-temperature secondary mineral occurrences consist of calcite and various silica phases including quartz, chalcedony and opal." (p. 8)*

and

> *"Other phases are present (fluorite, clay minerals, zeolites, Mn-oxides, organic phases) but are volumetrically inconsequential." (p. 9)*

No explanation have been offered for their presence, although the fluorite and quartz are typical minerals of the low-temperature hydrothermal assemblages:

> *"Fluorite occurs as a typical hydrothermal vein mineral with quartz, barite, calcite, sphalerite, and galena" (McGraw-Hill..., 1988, p. 195).*

## Coarse crystals

The coarse-crystalline character of the calcite, predominance of euhedral sparry crystals in the Yucca Mountain crusts are not compatible with the meteoric water-film model of deposition. The "per-descensum" (meteoric) concept essentially ascribes the calcites at Yucca Mountain to a speleothemic, or flowstone, origin. Flowstones (i.e., layered formations deposited from gravitational water films), are well studied in natural caves (e.g., Hill and Forti, 1997).

Although the chemistry of the bedrock in carbonate caves and at Yucca Mountain is quite different, the analogy with speleothems is, in my opinion, justifiable. Caves represent not only the closest, but probably the only known natural analog for the postulated "descending film water" origin of the Yucca Mountain calcites. Such peculiar depositional setting imposes constraints on the textures of depositing minerals. These constraints have to do with physics, rather than with geology. In other words, if postulated "descending film water" origin of calcite at Yucca Mountain is correct, this calcite should not necessarily "*mimic*" speleothems, but it should comply with the physical laws (gravitation, surface tension, etc.) governing speleothemic growth. In this context, parameters such as rates of deposition, chemistry of host rocks, liquid and gas flux rates play a secondary role.

Due to their deposition from thin films of water, flowstones are always built up of tiny palisade calcite crystals and do not form large euhedral crystals:

> *"... distinctive fabrics of palisade calcite are formed because precipitation usually occurs from thin water films that flow over the growing speleothem surfaces. Large crystal terminations do not form on the speleothem surface because they form projections that disturb the water flow away from the projections which, as a consequence, are gradually eliminated." (Kendall and Broughton, 1978, p. 519)*

The size of the free-growth crystals forming on the outside layer of flowstone is controlled by the thickness of the water film from which the flowstone grows (typically, < 1 mm). By contrast, at Yucca Mountain calcite often forms well shaped free-growth crystals up to 1.5 cm in size. Such textures are not compatible with the postulated film-water origin for the Yucca calcite crusts; instead, they clearly indicate a phreatic (saturated) environment during their formation. To my knowledge, nowhere in the world (except for the publications of the USGS scientists on Yucca Mountain) large free-growth calcite crystals were reported to form from film waters.

## Growth layers

Another generic feature of the flowstones is fine rhythmic lamination. This lamination appears due to the fact that the waters depositing calcite seep through from the soil. Biological activity of the latter varies with the seasons of the year, as well as in concert with the longer-period climatic changes. Percolating soil waters carry varying amounts of humic substances (humic and fulvic acids) and layers of calcite deposited from these waters acquire different coloration as a consequence. Even in apparently colorless specimens typical of speleothems from cold climatic settings this banding is readily revealed through luminescence under the UV or other excitation. This feature makes flowstone an excellent source of information on past environments (Shopov, 1997).

In contrast, the calcites from the ESF do not reveal rhythmic lamination, either on a visual basis or under UV luminescence. I examined all my samples under microscope using a wide-band UV filter (330-385 nm). None of samples revealed growth banding or luminescence. I also used more energetic impulse UV excitation, provided by powerful photographic flash to study 12 samples from the 1995 set. After such excitation, the Yucca Mountain samples typically yielded 1-8 s-long bluish-white luminescence (Dublyansky and Reutsky, 1995) that is characteristic of the low-temperature hydrothermal calcite from elsewhere (Dublyansky, 1997).

One calcite sample studied by means of Raman spectrometry did not show luminescence under Ar-laser excitation (see Appendix 1, Fig. 5).

### Character of fluid inclusions

The issue, critical from the standpoint of the suitability of Yucca Mountain as a potential high-level nuclear waste site is whether the calcite found in its interior was deposited in saturated (phreatic) or in unsaturated (vadose) zone. Fluid inclusions trapped in calcite which was deposited in the unsaturated, vadose zone should reflect this setting. The vadose zone is (by definition) located above the water table and contains both water and air at atmospheric pressure. Goldstein and Reinolds (1994) note that

> *"Cementation and crack healing may trap fluid inclusions representing the vadose zone's fluid heterogeneity. Fluid inclusions from the vadose zone are characterized by all-liquid fluid inclusions ... and two-phase (liquid + vapor) fluid inclusions characterized by highly variable L:V ratios. ... Two-phase inclusions result from heterogeneous entrapment of the two fluid phases in the vadose zone. ... Inclusions in which the bubble dominates the cavity volume are to be expected. Bubbles in two-phase inclusions are at about one-atmosphere internal pressure. ... There should be no confusion between an FIA from the vadose zone and those from other environments." (p. 81).*

By contrast, most of inclusions in the Yucca Mountain calcites are all-liquid. Two-phase gas-vapor inclusions are rare and typically occur as groups with consistent liquid-to-vapor ratios. Such inclusions strongly suggest entrapment from homogeneous liquid.

All-gas fluid inclusions and, in some samples, all-gas + gas-rich inclusions reflect, most probably, heterogeneous entrapment (i.e., system where gas bubble existed as a separate phase in liquid during entrapment. Two observations, however, made such inclusions non-attributable to vadose zone setting: (1) less-than-atmospheric internal pressures; and (b) presence of aromatic hydrocarbons in some of them.

In many instances, all-gas inclusions were found to occur as individual inclusions, with no apparent relation to aqueous inclusions.

In summary, the types of inclusions found in calcite samples from ESF are not characteristic of the vadose zone setting. Instead, they reflect saturated, phreatic environment during the formation of the minerals.

### Elevated formation temperatures

The geological history of Yucca Mountain precludes any thermal event such as burial or intrusions of magmatic bodies that could have led to thermal re-equilibration of the inclusions studied in the calcites. Therefore, the measured temperatures, 35-75 °C, may be considered to reflect the formation temperatures for these calcite samples. Such elevated temperatures are not compatible with the postulated vadose zone setting.

According to normal practice of the fluid inclusion studies, inclusions, for which primary, pseudo secondary of secondary origin cannot be determined with certainty, are treated as secondary. Some of our inclusions fall in this category. In the case of Yucca Mountain, however, secondary inclusions are of no lesser (and, perhaps, of even greater) importance than primary ones. Trapped at elevated temperatures, they indicate saturated environments within Yucca Mountain after the crystal growth ceased. Therefore, secondary inclusions characterize fluids younger than secondary minerals.

### Presence of gases at less-than-atmospheric pressure

Several crushing experiments were performed on the all-gas inclusions (see Appendix 1). In all experiments the matching fluid entered the inclusion vacuole upon rupture, and the bubble shrank. To eliminate the possibility that bubbles contracted due to the absorption of a gas in the matching fluid, two different types of the latter were used. One was standard immersion oil (A) the second was glycerol which is known to be non-reactive with regard to most gas chemistries encountered in fluid inclusions. The degree of bubble contraction remained the same in both fluids.

A pair of equations may be written:

$$P_{NOW}V = nRT_{NOW},$$

$$P_{ENT}V = nRT_{ENT},$$

where $P$ is the pressure, $V$ is the volume of an inclusion (or a bubble), $n$ is the number of moles of a gas in the inclusion, $R$ is the gas constant, and indices $NOW$ and $ENT$ denote parameters in the unbroken inclusion now, at room pressure and temperature, and parameters during the inclusion entrapment. Since we are discussing unbroken inclusions, the volume $V$ should be held constant. Assigning $nR/V = a =$ cons., equations may be re-written as:

$$P_{NOW} = aT_{NOW},$$

$$P_{ENT} = aT_{ENT}.$$

The temperature at the moment of entrapment may be determined as:

$$T_{ENT} = (P_{ENT}T_{NOW})/P_{NOW}.$$

The pressure of entrapment, $P_{ENT}$, of less than 1 bar is highly unlikely. It should be approximately equal to 1 bar in vadose setting and be >1 bar in saturated, phreatic, setting. On another hand, from crushing experiments we know that $P_{NOW} < 1$ bar. Therefore:

$$P_{ENT}/P_{NOW} > 1, \text{ and } T_{ENT} > T_{NOW}.$$

In other words, the entrapment temperature for all-gas inclusions should have been higher than the present-day ambient temperature.

Presence of inclusions filled with gases with pressures less than 1 atmosphere argues against the vadose zone setting. If these inclusions were trapped "*air-water wapor-$CO_2$*" phase, representative of the unsaturated zone atmosphere, as was suggested earlier (Roedder et al., 1994), these gases in inclusions should have retained pressures of about 1 atmosphere. This criterion is successfully used to tell apart the vadose unsaturated and phreatic saturated environment (Goldstein and Reinolds, 1994).

Roedder et al. (1994) suggested that less-than-atmospheric pressures revealed by crushing may be explained by condensation of water vapor in a trapped air bubble. This mechanism, although physically plausible, needs to be supported by numerical calculations. How much water needs to be condensed to decrease the pressure in inclusion to the extent that it will contract upon crushing (volumetric change of ~20 %)? How much water may be condensed in the inclusion from water vapor due to cooling from, 40 to 25 °C? Also important is that this hypothetical mechanism requires temperatures of entrapment higher than ambient (condensation of water vapor requires decrease of the temperature). Finally, this model does not account for the presence of hydrocarbons in inclusions.

Another question which was raised during the review of this report was: How can inclusions with internal pressure <1 atmosphere be formed in the saturated zone, where the pressure changes with depth according to the hydrostatic law (which is, approximately 1 atmosphere per 10 m depth)?

A possible explanation is that the gas bubbles were trapped at shallow depth, close to contemporaneous water table. The saturated zone extends from the water table downward. Therefore, hydrostatic pressure in this zone is ~ 1 atmosphere near the water table and increases with depth. The actual pressure in the entrapment zone will depend on the depth from water table.

### Presence of gaseous aromatic hydrocarbons in all-gas inclusions

Aromatic hydrocarbons cannot be attributed to soil- and other unsaturated-zone environment. The presence of aromatic and probably other hydrocarbons suggests the relation of studied calcite with the presence of natural gas potential of the Paleozoic sedimentary rocks underlying Yucca Mountain. Existence of such potential was suggested by Mattson et al. (1992) on the basis of the Conodont color alteration index (CAI) analysis[5]. This matter will be discussed in more detail in Section 6.7.

### Stable isotopic properties of calcite

Stable isotopic studies of speleothems represent an established method of paleo climatic reconstruction. Changes in delta $^{18}$O values from one growth layer to another provide a proxy of the paleo temperature record, whereas the changes of the delta $^{13}$C may be used to constrain the evolution of vegetation on the land surface (Ford, 1997). Stable isotopic data provide another insight into the origin of the Yucca Mountain calcites.

Typically, vadose-zone speleothems formed from water films (e.g., stalactites) display stronger response to the climate change as compared to phreatic, subaqueous speleothems. Variations of delta $^{18}$O are greater in a meteoric water flowstone (e.g., 8 ‰ for Jewel Cave, South Dakota) and smaller in a subaqueous speleothem (2.5 ‰ for Devil's Hole, Nevada; Ford, 1997). At Yucca Mountain, calcites display variations of delta $^{18}$O much smaller than would be expected for vadose speleothems deposited over long time intervals during the late Tertiary and Quaternary. In some samples they are less than 0.5 ‰ (Fig. 36). Such "dead-flat" behavior of oxygen is not compatible with the vadose-zone speleothemic (or film water) origin. At the same time, such behavior is quite typical of the low-temperature hydrothermal calcite from elsewhere (Dublyansky and Ford, 1997).

### Isotopic parameters of parent fluids

Calcite studied from the ESF has isotopic values: $\delta^{18}$O from -10.6 to -12.14 and $\delta^{13}$C from -2.6 to -6.0 ‰ PDB. According to the fluid inclusion results, it was deposited from waters with the temperature of up to 50 °C. By applying well-established temperature-dependent fractionation coefficients (Friedman and O'Neil, 1997; Faure, 1986) it may be calculated that the parent waters that deposited cal-

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[5] Conodonts are microfossils that occur in marine rocks of Late Cambrian to Triassic age. Conodonts change color in response to heating due to carbonization of organic matter sealed in them. Color of conodonts indicates the highest temperature reached by rocks containing them. This method is used to assess thermal history and evaluate the degree of thermal maturation of rocks with respect to oil and gas generation.

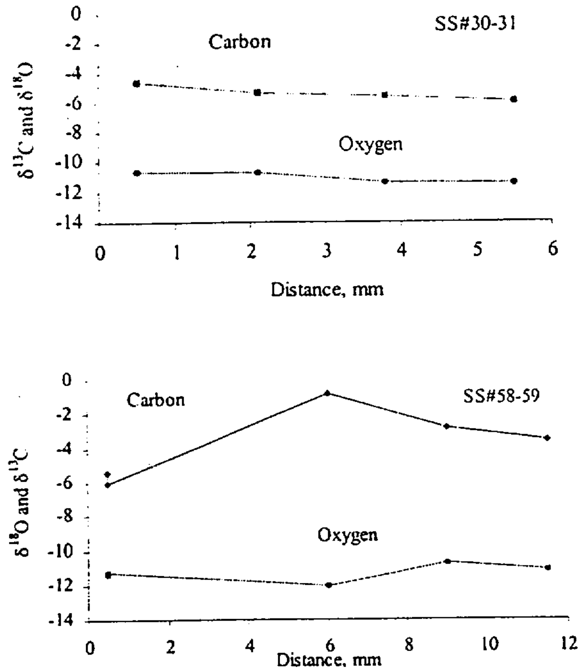

Fig. 36. Stable isotopic properties of hydrothermal calcite from the ESF across crusts.

cite crusts had $\delta^{18}O$ of -4.6 to -6.2 ‰ SMOW and $\delta^{13}C$ varying from +0.2 to -3.2 ‰ PDB (calculated for 50 °C)[6]. These values deviate significantly from the modern values of waters in the Yucca Mountain Tertiary aquifer ($\delta^{18}O$ -14.0 to -12.8 ‰ SMOW and $\delta^{13}C$ -12.7 to -4.9 ‰ PDB; NAS/NRC, 1992, p. 157).

**Salinity of fluids**

Most of fluid inclusions studied so far did not yield numeric results regarding the salinity of trapped waters. This indicates low concentrations, probably close to fresh waters.

Some inclusions, however, yielded apparent concentrations of dissolved salts (expressed in conventional NaCl-equivalent) as high as 0.7 to 1.7 wt %. As in the case of fluid inclusion temperatures (see Section 6.2), these concentrations will be considered as "very diluted" or "fresh" waters by geologists, dealing with ore deposits. A hydrologist, however, would call such waters "brackish" or even "saline". Such salt concentrations are not expected for meteoric waters in volcanic rocks. They are compatible, however, with the salinity of the semi-confined Paleozoic carbonate aquifer (1.5 wt % of NaCl; Peterman et al., 1994).

## 6.6. Origin and significance of all-liquid inclusions

All studied samples from ESF contained, besides rare two-phase vapor-liquid and mono-phase all-gas inclusions, abundant all-liquid inclusions.

The appearance of a shrinkage bubble in an inclusion strongly depends on the two parameters: (a) difference between the temperature of entrapment and ambient temperature, and (b) size of inclusion. In order to appear, a bubble must cross a "thermodynamic threshold": some excess of energy needs to be spent on the creation of its surface. The surface tension relates to the curvature of the surface (i.e., to the size of a bubble) as $1/r^3$, where $r$ is radius of the bubble. In other words, the lower the entrapment temperature (and, respectively the difference $T_{entrapment}$-$T_{ambient}$) and the smaller the size of the inclusions – the lower are chances that a bubble will appear in inclusion upon its cooling from $T_{entrapment}$ to $T_{ambient}$. Relatively small inclusions (ca. 10-20 micron) trapped at relatively low temperatures (ca. 30-70 °C) have small chances to heterogenize (which is, nucleate a shrinkage bubble) upon cooling to room temperature. Fluid in such inclusions may exist in "stretched" state for millions of years. Roedder (1984) noted that

> *"...inclusions as large as 20 μm in some minerals formed at 100 °C seldom show bubbles. Aqueous inclusions formed 70 °C may be as large*

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[6] $\delta^{18}O_{caclite}$ - $\delta^{18}O_{water}$ = $2.78(10^6T^{-2})-2.89$ (where T is absolute temperature) and

$\delta^{13}C_{water} \cong \delta^{13}C_{calcite} + 2.8$ (at 50 °C)

> *as 100 μm and still not nucleate vapor bubble...* " (p. 292).

The appearance of bubbles in such inclusions is a stochastic process, so it is expected that populations trapped at low temperatures will typically be represented by mostly all-liquid inclusions and only small proportion of the two-phase vapor-liquid inclusions.

## 6.7. Relation of epigenetic minerals to the hydrocarbons in the Paleozoic rocks

A gas inclusion composition with aromatic hydrocarbons (see Appendix 1) is not compatible with the aerated vadose, unsaturated setting. Perhaps the only reasonable source of such hydrocarbons is organic matter in the Paleozoic carbonates, which underlay the Tertiary volcanic rocks of Yucca Mountain. These Paleozoic carbonates are known to have limited natural gas potential (Mattson et al., 1992; Grow et al., 1994; Fig. 37). Grow with co-authors (1994) pointed out that:

> *"While much of the Cambrian through Triassic rocks have thermal potential for gas, extensive Late Tertiary faulting at Yucca Mountain suggest that seals might be inadequate for retaining gas." (p. 1298).*

In the context of this study, however, we are interested not in *economic* hydrocarbon potential, but in possible explanations for the appearance of hydrocarbons in calcite.

Restricted data available to-date indicate that thermal history of Paleozoic carbonaceous rocks under Yucca Mountain was such as to allow organic matter trapped in these sedimentary rocks to be transformed into oil and gas. The only drill hole which penetrated Silurian dolomite under Yucca Mountain (UE25p#1) produced Conodonts having color alteration index, CAI, of 3 (Grow et al., 1994). Such a value is typical of rocks that have reached temperatures of ~180 °C and is in the range where:

> *"... oil is no longer generated, but in the range where gas is generated and previously generated oil is being converted to gas" (Grow et al., 1994. p. 1301).*

Although the amount of these hydrocarbons in Paleozoic rocks may presently be quite small, they represent a plausible source of tiny amounts of gases trapped in fluid inclusions. Moreover, it should be noted that the fluid inclusions were formed in the geologic past, so that the oil-to-gas ratio yielded by current exploration would not necessarily be relevant to the time of calcite formation.

## 6.8. A hint on the spatial structure of the system

In terms of the spatial distribution of measured homogenization temperatures, the following observation may be important. Two samples that yielded temperatures higher than other samples (SS#85-86 and 2206) are both from Tiva Canyon tuff. Also, both these samples are from the eastern part of the exploratory block (see Appendix 2), closest to the Paintbrush (~2 km to the east of the repository block). Fault zone which might have served as major avenue for upwelling fluids.

The reason for this suggestion is that there is a present-day thermal anomaly associated with this fault (locally elevated groundwater temperatures as indicated by borehole temperature measurements, reported by Sass et al., 1987). This anomaly may represent an "echo" of ancient activity (Fig. 38).

Although it is premature to make strong conclusions on the basis of only two samples, this hypothesis needs to be addressed in the future, when the spatial structure of the ancient upwelling system is studied.

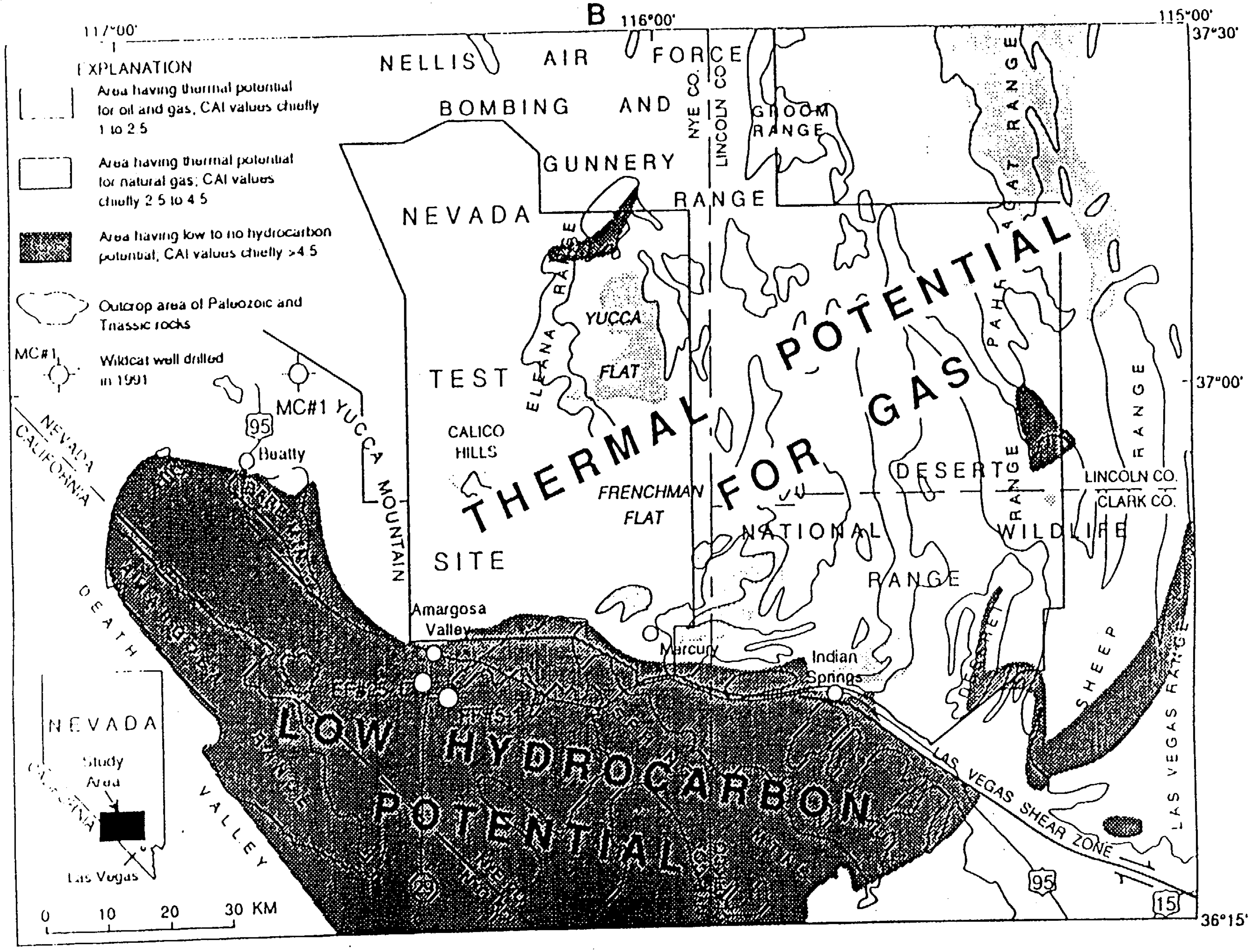

Fig. 38. Thermal potential for gas in Southern Nevada based on Conodont color alteration indexes (CAI). From Grow et al., 1994.

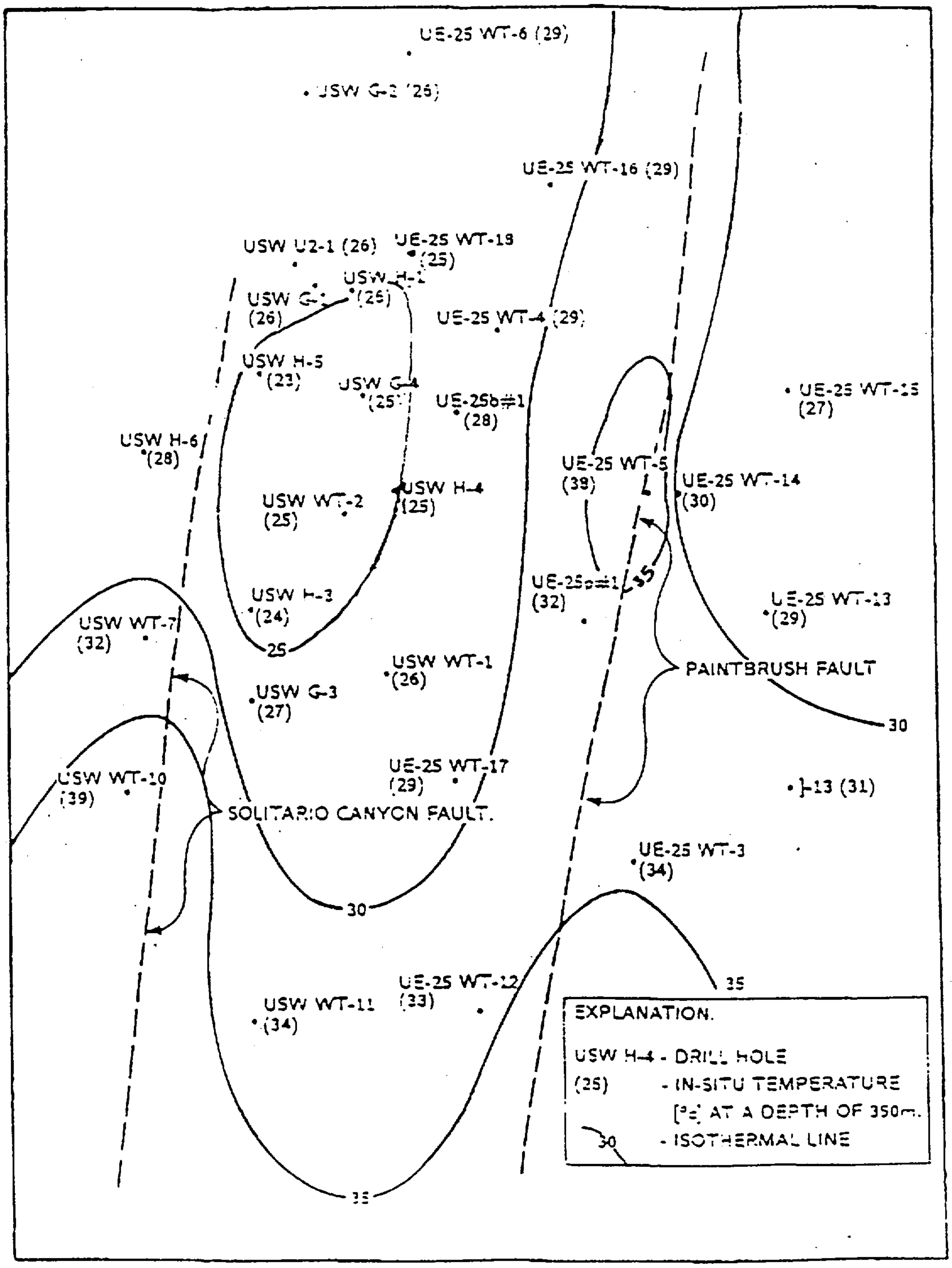

Fig. 38. Borehole temperatures at depth 350 m and isothermal lines suggested by them. Data from Sass et al., 1987; modified from Szymanski, 1987.

## *6.9. Discussion: Use of the Yucca Mountain calcites for paleo climatic reconstructions*

It has been suggested (Whelan et al., 1994) that the stable isotopic record of calcites from Yucca Mountain may be used as a paleoclimatic proxy. They wrote:

> *"Fluids infiltrating into the UZ* [unsaturated zone] *should contain dissolved carbonate species derived from interactions within the thin soils atop Yucca Mountain, with $\delta^{13}C$ largely controlled by the plant assemblage ... and $\delta^{18}O$ reflecting that of meteoric waters." (p. 2741).*

They also suggested that:

> *"Past climate changes in southern Nevada, such as during the most recent glacial stage, were accompanied by profound changes in mean annual air temperature and regional air mass circulation patterns – and, presumably, significant changes in the $\delta^{18}O$ of precipitation at Yucca Mountain." (p. 2743).*

In the most recent work, Paces et al. (1998) and Marshall et al. (1998) develop this approach further, claiming that:

(a) opal-calcite coatings were formed over a time period ranging from 7-9 Ma to as little as 16 Ka BP with the "remarkably constant" growth rate of between 1 and 5 mm per million years (Neymark et al., 1998);

(b) this time span included major, but gradual shift in climate from one favoring grasses in the Miocene to one favoring abundant shrubs and trees in the Quaternary; and

(c) the depositional environment involved water moving down through connected fractures as sheets or films.

However, as is apparent from the data discussed above, a significant part of calcite crusts studied by me from the ESF was formed from ascending heated aqueous fluids. Therefore, their stable isotopic properties may have little to do with past climates. Also, no isotopic changes, which could represent a "response" of calcite to climatic change have been detected in my samples (see Fig. 36).

Theoretically, it is possible that the calcite at Yucca Mountain is composed of the two types: older hydrothermal and younger, formed by rain waters. This would mean, however, that methods applied by the DOE and USGS researches studying this calcite are not capable of distinguishing between these two origins. None of the most detailed studies published by them indicates an option for this calcite of being polygenetic. I view the possibility of such interpretation of being correct as remote.

## *6.10. Evaluation of the "slow continuous deposition" model*

Models of "continuous" mode of deposition and the "remarkably constant" 1 to 5 mm per million years deposition rates postulated by the USGS researchers for the Yucca Mountain calcite (Neymark et al., 1998; Paces et al., 1998, etc.) raise serious questions.

It appears that physical plausibility of this model has never been seriously analyzed and the model as a whole was not developed beyond a vague concept. Here is the best descriptions of the suggested mechanism of mineral deposition I have found so far:

> *"To explain bladed calcite textures and the presence of opal at crystal tips, solutions must transport ions to crystal extremities, where solutions reach oversaturation in mineral constituents. A depositional environment consistent with observed textures involves water moving down connected fractures as sheets*

> *or films where it can enter intersected rock cavities. Interaction between the liquid and an independently migrating gas phase at these sites result in $CO_2$ evasion or evaporation, oversaturation of mineral components in solution, and precipitation of slow-growing secondary minerals." (Paces, et al., 1998, p. 38).*

Firstly, I have observed under the microscope up to four distinct depositional episodes in some of my samples. These episodes are separated by hiatuses (dissolution, deposition of impurities, deposition of opal or quartz). Examples are shown in Figs. 11 and 27-B.

My observations are consistent with early, as well as recently published observations of the USGS scientists:

> *"The cathodoluminescence studies have revealed at least 4 major stages of calcite deposition in some samples, commonly separated by dissolution unconformities." (Whelan et al., 1994, p. 2741)*

or

> *"Secondary mineralization sequences in the UZ may be sorted into early, middle, and late stages ... A sparsely distributed early stage consists of silica phases ... locally associated with sparry, but often corroded, calcite. Main stage mineralization contains blocky to thick-bladed calcite +/-opal, frequently with dusty growth zones marked by abundant semi-opaque inclusions. Late stage calcite, again locally with opal, occurs as euhedral, clear, thin-bladed, spade- or fan-shaped crystals and as overgrowth on older calcite." (Whelan and Moscati, 1998).*

Therefore, petrographic features clearly indicate that: (a) there have been several stages of calcite deposition at Yucca Mountain, and (b) that depositional environment changed with time (at times, the fluids even become corrosive and dissolved calcite). This is inconsistent with the theory of "continuous deposition of calcite at a remarkably constant rate through the last 7-9 million years".

Now, let us make a simple calculation. Many of my samples contain large, 20 to 100 microns, all-gas inclusions (see Figs. 10, 11, 14, 15, 26, 29, and 33). They were trapped as gases immiscible with aqueous fluid. If the rate of calcite precipitation was 1 mm per million years, as suggested by the USGS researchers, it would take some 20,000 to 100,000 years to create a 20 to 100 micron-thick layer of calcite (such as shown in Fig. 11) in which inclusion is trapped. It is inconceivable that a gas bubble would remain in the same position for 100,000 years "waiting" until it becomes overgrown by calcite. Even if one invents some mechanism to "glue" the bubble to the growing surface, during such an extended period of time it would be destroyed by diffusion.

The problematic "continuous" concept becomes even more problematic when we apply it to the unsaturated environment (as the USGS researchers do). In the unsaturated zone aqueous fluids are supposed to move down as thin sheets along the surfaces of the interconnected air-filled fractures. The air is not stagnant in these fractures; it moves in response to changes of barometric pressure (for Yucca Mountain it is shown by recent studies in the tunnel). Accordingly, the $CO_2$ degassing or intake occurs in water films. Since the deposition of calcite is mostly controlled by the regime of $CO_2$, the rate of deposition would be expected to vary drastically in such a system. The amount of percolating water would be correspondingly variable. (The time of calcite formation spans several major climatic changes; therefore significant changes in the rate of atmospheric precipitation are expected.) Finally, an "unsaturated" setting cannot explain the newly obtained fluid inclusion data presented in this report.

My conclusion is that the hypothesis of "continuous deposition of calcite at a very constant and low rate" is in contradiction with empirical data (textures, petrographic observations, fluid inclusions) and does not comply with basic physical laws.

## *6.11. Ages of secondary minerals at Yucca Mountain*

One sample analyzed by fluid inclusion method yielded the average age of about 160,000 years (see Section 5.3). This date should be considered as an estimate. A large sample, weighing ~4.5 gm, was analyzed.

Publications of the USGS scientists indicate that calcite and particularly opal at Yucca Mountain were formed over extended period of time of about 7-9 million years (Paces et al., 1998; Neymark et al,. 1998). The latest parts of calcite crusts, however, were found to be deposited quite recently (in terms of geological time). Paces et al. (1998) determined ages as young as 20,000-28,000 of years and older for calcite samples removed from the ESF.

Whelan and Stuckless (1992) and Whelan et al. (1994) reported U-series ages of 310, 280, 227, 190, 185, 170, 142, 30, and 26 and $^{14}C$ ages of 45, 44, 43, 42, 40, 39, and 21 (in thousands of years) for calcite samples recovered from drill cores from the upper 400 m of the Yucca Mountain vadose zone. Scarce fluid inclusion measurements reported for calcite from these boreholes (7 temperatures measured by Edwin Roedder; DOE, 1993) range from 57 to 114 °C (sample depth from 178 to 347 m). The outer layers in two samples were dated at ~21,000 and 45,000 years (radiocarbon dating).

Unfortunately, the fluid inclusion method was not used in characterization activities at Yucca Mountain to the extent it should have been used. As a result, the DOE currently possesses extensive database of ages measured on secondary minerals, the origin of which is not constrained by fluid inclusion studies. The absence of adequate fluid inclusion information limits usefulness of this database.

In the absence of the data on samples containing fluid inclusions, no strong conclusion can be drawn regarding the age of hydrothermal activity at Yucca Mountain. However in general, mineral-forming process for calcite and opal from ESF is reasonably well-constrained by the DOE dating (i.e., from ~7-9 million years to ~20,000 years).

In process of the reviewing of this report, an argument was made that calcite with elevated temperatures may be related to old, several million years old, parts of calcite. Because of this old age, the thermal-water origin of this calcite does not imply any potential threat to the suitability of the site.

This suggestion is in agreement with petrographic observations in a sense that the elevated-temperature inclusions are typically found closer to the contact with tuff (i.e., in older parts of calcite). The argument, however, is flawed. Hydrothermal origin of calcite is important mostly because it indicates saturated environment of formation. Outer parts of crystals in the Yucca Mountain calcite, do not typically contain two-phase inclusions; however, they do not contain inclusions typical of vadose zone, either. On top of that, they have a number of other features (see section 6.5) giving a compelling evidence of the saturated environment of formation.

On the basis of the available data, formation of calcite-opal-quartz-fluorite mineralizaion at Yucca Mountain can be envisaged as deposition in saturated zone from waters with elevated temperature. The temperature decreased at the latest stages of mineral formation; saturated environment of the deposition, however, persisted.

More data need to be obtained in order to constrain the timing of this fossil hydrothermal (lukewarm) activity. The relatively youthful age of the later stages of this activity, however, is fairly certain.

## *6.12. Implications of the data obtained from fluid inclusions on the Yucca Mountain Total System Performance Assessment*

The possibility that saturated thermal environment may occur at certain stage of the planed repository life needs to be fully appreciated. This should lead to a re-consideration of many key-elements of the Total System Performance Assessment for the Planed Yucca Mountain repository. As far as I am concerned, the scenario of repository flooding by thermal waters is not considered in any of the recent versions of the TSPA.

One example emphasizing the importance of such re-assessment is the issue of the waste package degradation. It was explicitly stated in the Third Interim Report of the Peer Review Panel on the TSPA[7] that:

> *"No rational materials selection can be made without knowledge of the characteristics of the waters in contact with the waste packages. These characteristics include: temperature, pH, Eh and ionic concentrations (Cl, $SO_4$, $NO_3$, $CO_3$, $Fe^{+++}$, Ca, etc.)."*

Clearly, decisions based on the typical meteoric water compositions found in the Yucca Mountain subsurface will be inadequate in case of the intrusion of the deep-seated thermal fluids into the repository zone.

Also emphasized in the Report is the fact that the most corrosion-resistant and recently chosen as a base-case option, alloy C-22

> *"...is susceptible to localized corrosion only when wet in a critical temperature range. If C-22 remains passive in this range, its anticipated life, prior to penetration, is thousands of years. If it is not passive, then its life, prior to penetration, is as little as a few tens of years."*

Therefore:

> *"There is a need to determine the critical temperature range, and the times in this range when different scenarios can occur."*

Such vital determination cannot be made without scientifically sound and sufficiently detailed understanding of the hydrological history of Yucca Mountain.

Fluid inclusion studies may provide necessary information with regard to the expected compositions and temperatures of waters in contact with the waste packages. Coupled fluid inclusion, isotopic and absolute-age studies are required for determining the pattern and timing of the past excursions of thermal waters into the repository zone.

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[7] Available from the web page of the Yucca Mountain Site Characterization Project at http://www.ymp.gov/nonjava/index.htm

## 7. Conclusions and recommendations

Although the presence of fluids with elevated temperatures (ca. 35-75 °C) within the modern unsaturated zone at Yucca Mountain in the geological past is reasonably certain, this conclusion only indicates the possibility of the hazard for the potential high-level nuclear waste site. Much more data need to be acquired and analyzed in order to assess the degree of this hazard. Specifically, three questions need to be addressed:

1. What is the age and what was the recurrence period (if any) of the hydrothermal activity?

2. What was the volume of fluids involved at different stages of this activity? and

3. What was the spatial structure of ancient hydrothermal system?

This may be accomplished through concerted effort of researchers, involving:

a). Detailed fluid inclusion studies in calcite and other mineral phases from the ESF as well as from drill cores. Such study may provide important information on the spatial structure of the ancient hydrothremal system;

b). Careful dating of calcite samples hosting fluid inclusions with elevated homogenization temperatures. Such study would constrain the temporal structure of ancient hydrothermal system; and

c). Detailed isotopic study of mineral phases (C, O, Sr, He) may provide important information on the pattern of fluid migration, origin of fluids, etc.

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Of course, as the author of the report I am solely responsible for its contents and conclusions, any omissions and any errors that may remain.

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GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Sodium Abundance data of water samples from Fourth Quarter Results in the Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF: 306448

DTN: LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4.
Experiment denotes data set.

```
***************************************************************************
ROW#   Q  SODIUM ABUNDANC  LOCATION         DATE             TEMPERATURE
          E                                                  °C
          mg/L
***************************************************************************

1      Y  12.20            SHT Hole 16      02/27/1997       47.60
2      Y  11.00            SHT Hole 16      05/22/1997       51.20
```

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```
GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Silicon Abundance data of water samples from Fourth Quarter Results in the
Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF:  306448

DTN:  LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4.
Experiment denotes data set.

****************************************************************************
ROW#   Q  SILICON ABUNDAN  LOCATION          DATE             TEMPERATURE
          CE                                                   °C
          mg/L
****************************************************************************

1      Y  14.50            SHT Hole 16       02/27/1997       47.60
2      Y  15.20            SHT Hole 16       05/22/1997       51.20
```

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GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Calcium Abundance data of water samples from Fourth Quarter Results in the Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF: 306448

DTN: LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4. Experiment denotes data set.

```
***************************************************************************
ROW#    Q  CALCIUM ABUNDAN  LOCATION          DATE              TEMPERATURE
           CE                                                   °C
           mg/L
***************************************************************************

1       Y  8.65             SHT Hole 16       02/27/1997        47.60
2       Y  7.70             SHT Hole 16       05/22/1997        51.20
```

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## GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Potassium Abundance data of water samples from Fourth Quarter Results in the Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF: 306448

DTN: LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4.
Experiment denotes data set.

| ROW# | Q | POTASSIUM ABUNDANCE mg/L | LOCATION | DATE | TEMPERATURE °C |
|---|---|---|---|---|---|
| 1 | Y | 3.30 | SHT Hole 16 | 02/27/1997 | 47.60 |
| 2 | Y | 2.30 | SHT Hole 16 | 05/22/1997 | 51.20 |

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```
GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Sulfur Abundance data of water samples from Fourth Quarter Results in the
Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF:  306448

DTN:  LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4.
Experiment denotes data set.

****************************************************************************
ROW#    Q  SULFUR ABUNDANC  LOCATION         DATE             TEMPERATURE
           E                                                  °C
           mg/L
****************************************************************************

1       Y  0.20             SHT Hole 16      02/27/1997       47.60
2       Y  0.21             SHT Hole 16      05/22/1997       51.20
```

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```
GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Sulfate Abundance data of water samples from Fourth Quarter Results in the
Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF:  306448

DTN:  LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4.
Experiment denotes data set.

************************************************************************
ROW#    Q  SULFATE ABUNDAN  LOCATION         DATE            TEMPERATURE
           CE                                                °C
           mg/L
************************************************************************

1       Y  <2               SHT Hole 16      02/27/1997      47.60
2       Y  <2               SHT Hole 16      05/22/1997      51.20
```

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# Site and Engineering Properties

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GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Nitrite Abundance data of water samples from Fourth Quarter Results in the Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF: 306448

DTN: LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4.
Experiment denotes data set.

| ROW# | Q | NITRITE ABUNDANCE mg/L | LOCATION | DATE | TEMPERATURE °C |
|---|---|---|---|---|---|
| 1 | Y | <2 | SHT Hole 16 | 02/27/1997 | 47.60 |
| 2 | Y | <2 | SHT Hole 16 | 05/22/1997 | 51.20 |

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GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Phosphate Ion Abundance data of water samples from Fourth Quarter Results in the Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF: 306448

DTN: LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4. Experiment denotes data set. Phosphate Ion Abundance has a negative three charge.

```
****************************************************************************
ROW#    Q  PHOSPHATE ION A  LOCATION          DATE              TEMPERATURE
           BUNDANCE                                             °C
           mg/L
****************************************************************************

1       Y  <2               SHT Hole 16       02/27/1997        47.60
2       Y  <2               SHT Hole 16       05/22/1997        51.20
```

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GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Nitrate Abundance data of water samples from Fourth Quarter Results in the Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF: 306448

DTN: LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4. Experiment denotes data set.

| ROW# | Q | NITRATE ABUNDANCE mg/L | LOCATION | DATE | TEMPERATURE °C |
|---|---|---|---|---|---|
| 1 | Y | <2 | SHT Hole 16 | 02/27/1997 | 47.60 |
| 2 | Y | <2 | SHT Hole 16 | 05/22/1997 | 51.20 |

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```
GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Lithium Abundance data of water samples from Fourth Quarter Results in the
Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF:  306448

DTN:  LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4.
Experiment denotes data set.

****************************************************************************
ROW#   Q  LITHIUM ABUNDAN  LOCATION          DATE              TEMPERATURE
          CE                                                   °C
          mg/L
****************************************************************************

1      Y  <0.01            SHT Hole 16       02/27/1997        47.60
2      Y  <0.01            SHT Hole 16       05/22/1997        51.20
```

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GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Boron Abundance data of water samples from Fourth Quarter Results in the Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF: 306448

DTN: LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4.
Experiment denotes data set.

```
****************************************************************************
ROW#   Q  BORON ABUNDANCE  LOCATION          DATE              TEMPERATURE
          mg/L                                                 °C
****************************************************************************

1      Y  0.66             SHT Hole 16       02/27/1997        47.60
2      Y  0.93             SHT Hole 16       05/22/1997        51.20
```

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GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Iron Abundance data of water samples from Fourth Quarter Results in the Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF: 306448

DTN: LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4.
Experiment denotes data set.

| ROW# | Q | IRON ABUNDANCE mg/L | LOCATION | DATE | TEMPERATURE °C |
|---|---|---|---|---|---|
| 1 | Y | 0.30 | SHT Hole 16 | 02/27/1997 | 47.60 |
| 2 | Y | 0.03 | SHT Hole 16 | 05/22/1997 | 51.20 |

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```
GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Aluminum Abundance data of water samples from Fourth Quarter Results in
the Single Heater Test at the ESF on 02/27/1997 and 05/22/1997.

TDIF:  306448

DTN:  LL971006604244.046

FOOTNOTES: Location is Single Heater Test - Hole 16, Interval 4.
Experiment denotes data set.

***************************************************************************
ROW#   Q  ALUMINUM ABUNDA  LOCATION         DATE              TEMPERATURE
          NCE                                                 °C
          mg/L
***************************************************************************

1      Y  <0.06            SHT Hole 16      02/27/1997        47.60
2      Y  <0.06            SHT Hole 16      05/22/1997        51.20
```

MOL.19980507.0363

# Baseline Gas Sampling in the DST

Laura DeLoach, Marina Chiarappa, Roger Martinelli, and Bill Glassley
Lawrence Livermore National Laboratory

Revision 1, March 4, 1998

## Introduction

Characterization of the rock-fluid interactions in the DST will play an important role in understanding the performance of waste package materials and radionuclide transport through the altered zone of a repository. Consequently, the chemistry of fluids and gases originating in the pore space of the rock and the changing compositions observed with time and temperature will be targeted for study in the chemistry boreholes of the DST.

The chemical holes have been lined with SEAMIST (Science Engineering Associate Membrane Insitu Sampling Technology) liners that allow gas and fluid from the pore spaces of the rock walls to be sampled on-site periodically. The concentrations of certain chemical species in the gases and fluids sampled at those locations will then be analyzed back in the laboratory. The baseline sampling of the rock-pore gases (prior to heater turn-on) is described.

## Proposed Baseline Gas Sampling

The intent of the original gas sampling plan was to establish a background baseline of the rock pore gas chemistry using at least three sets of sample analyses obtained during the pre-heat phase. However, the actual baseline sampling has been modified to a single set of gas samples collected during pre-heat. The change resulted from the following factors:

i. The Seamist liner installation was completed late in the pre-heat stage delaying sample collection of baseline gases.
ii. The first gas samples to be collected were obtained during simultaneously ongoing air permeability testing in the adjacent hydrology boreholes. Mine air and tracer gas injected into nearby boreholes potentially corrupted sampled gases such that the gas analyses would not be suitable to establish baseline.
iii. Gas sampling opportunities were further reduced because the baseline-scheduled heater turn-on date was advanced.

## Gas Collection Procedure:

The procedure for gas collections was tested and employed during two sampling trips. It utilized gas tight syringes for the immediate on-site collection and injection of the collected gases into previously evacuated stainless steel vessels for their containment and transport to the analytical labs.

A gas sampling plan was devised to draw gas from the tubing mounted on the SEAMIST liners within the chemistry boreholes in increasingly "pore-space-rich" aliquots. Gas present in the length of the teflon-tubing at the time of initial sampling correspond to the SMF bar-coded designations that are reported in controlled scientific notebook, #00342.

Results from a previous sample collecting trip obtained when the SEAMIST liners were not fully inflated and during a time of air permeability testing were considered corrupted (see ii under Proposed Baseline Gas Sampling). Although not appropriate for establishing baseline compositions, the analyses were completed and will be presented in a later report.

## Gas Analysis Summary (Reported In Volume Percent)

**12/2/97 Samples**

| Sample Name | Nitrogen | Oxygen | Argon | Carbon Dioxide | Carbon Monoxide | Methane | Helium | Hydrogen | Total % |
|---|---|---|---|---|---|---|---|---|---|
| #54-1A | 77.46% | 21.55% | 0.95% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1B | 76.94% | 22.07% | 0.94% | 0.04% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1C | 76.96% | 22.02% | 0.94% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1D | 77.38% | 21.65% | 0.92% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1E | 77.19% | 21.86% | 0.93% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1F | 77.15% | 21.86% | 0.92% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #54-3A | 77.49% | 21.55% | 0.93% | 0.04% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3B | 76.92% | 22.11% | 0.92% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3C | 76.79% | 22.15% | 0.93% | 0.13% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3D | 77.26% | 21.76% | 0.91% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3E | 77.14% | 21.73% | 0.91% | 0.22% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3F | 77.52% | 21.50% | 0.91% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #54-5A | 77.00% | 22.03% | 0.93% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5B | 76.93% | 22.09% | 0.93% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5C | 77.46% | 21.57% | 0.92% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5D | 77.21% | 21.82% | 0.92% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5E | 77.14% | 21.87% | 0.92% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #56-1A | 77.85% | 21.22% | 0.90% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1B | 77.50% | 21.54% | 0.91% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1C | 77.64% | 21.39% | 0.91% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1D | 75.02% | 23.89% | 1.01% | 0.08% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1E | 77.63% | 21.42% | 0.92% | 0.03% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #56-3A | 78.12% | 20.94% | 0.92% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3B | 77.43% | 21.59% | 0.91% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3C | 77.66% | 21.39% | 0.92% | 0.03% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3D | 77.56% | 21.48% | 0.92% | 0.04% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3E | 77.48% | 21.57% | 0.92% | 0.03% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| OD-1 | 77.36% | 21.65% | 0.92% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.00% |
| HD-1 | 77.12% | 21.86% | 0.93% | 0.09% | <0.50% | <0.01% | <0.01% | <0.01% | 100.00% |

MOL.19980521.0002

LL 930408304244
058

# First Quarter Chemical Borehole Studies in the Drift Scale Test

*(milestone SP2640M4)*

**Laura DeLoach, Roger Martinelli, Marina Chiarappa, and Bill Glassley**
**Lawrence Livermore National Laboratory**

**April 9,1998**

## Introduction

The chemistry boreholes of the Drift Scale Test (DST) have been designed to gather geochemical information and assess the impact of thermal perturbations on gas and liquid phases present in pore spaces and fractures within the rock. There are a total of ten boreholes dedicated to these chemical studies. Two arrays of five boreholes each were drilled from the access/observation drift (AOD) in planes which run normal to the heater drift and which are located approximately 15 and 45% of the way along the length of the drift as measured from the bulkhead. The boreholes each have a length of about 40 meters and have been drilled at low angles directed just above or just below the heater plane. In each array, three boreholes are directed at increasingly steeper angles (< 25°) above the line of wing heaters and two are directed at shallow angles below the wing heater plane.[1]

To assess the geochemical changes as a function of time and position, the boreholes have each been lined with two different sampling liner systems. Both employ SEAMIST™ liner technology (Science Engineering Associate Membrane In-situ Sampling Technology) which is an instrumentation and fluid sampler emplacement technique designed for in-situ hydrologic characterization and monitoring investigations. It uses an inverting, pneumatically-deployed tubular membrane to install sampling devices and instruments in uncased boreholes. For each chemistry borehole of the DST, one SEAMIST™ liner has been installed with Teflon tubing lines run to various depths and ending at the collar of the hole with a port for sampling the gases originating from the rock walls. In the same hole and adjacent to this liner, a second liner has been installed with a linear array of highly absorbent pads for the collection of pore and condensate water samples; electrical resistance is measured in the pads to indicate wetness. The two liners, installed side-by-side, are inflated to effectively seal the rock walls of the borehole and thereby limit the accessibility of the sampling sites to the air from the drift. The fluids are collected on 10 pads positioned approximately every 4 meters along the length of the hole, and six Teflon tubing lines (three pairs) are equidistantly-placed along the length to collect the pore space gases. The positions of the pads and ports within the boreholes are summarized in Table 1.

Gas samples and damp pads are collected from the boreholes and taken for chemical analyses. The gaseous phases are analyzed for the volume percent of atmospheric constituents (predominantly $N_2$, $O_2$, Ar, and $CO_2$). The pads are analyzed for a suite of ions typical of the total dissolved solids found in ground water samples from the vicinity of Yucca Mountain. The chemical composition of the gases and liquids will be analyzed throughout the heating phase of the Drift Scale Test and the results will be considered as a function of time and location with respect to the heaters in the heated drift. The schedule and the analytical protocols for the two systems are described in this report. The available results for the first few months of heating are presented.

## SEAMIST™ Gas Sampling in the DST

The general procedure for collecting gases from the chemistry boreholes is to use gas-tight syringes to draw in gas through the Teflon tubing and to inject the sample into previously-evacuated, stainless steel vessels. The gas initially present in the tubing is expected to represent a mixture of the rock gas from pores and fractures in the borehole walls as well as atmospheric mine air diffused in from the sampling port that opens into the AOD. In order to collect sample rich in the rock gases, the tubing has to be depleted of this "compositionally-mixed" air that is present initially and refilled with the desired rock gases from the borehole walls. This process occurs when the gas-tight syringe creates a slight vacuum on the tubing as the plunger is drawn back during sample collection, then the gases from the rock pore spaces and fractures refill the line to equalize the pressure. Samples enriched in the rock gases from the walls of the borehole would be those pulled after multiple draws of the syringe.

A series of gas samples are collected for a given borehole and port as follows: the volume of gas determined to be present in the tubing (estimated from the diameter and length of the tube) is first removed in several small aliquots which are individually collected into evacuated vessels. With the full volume of the line removed, two additional samples are drawn from the same port, and these are collected into two more stainless steel vessels. All of these samples are returned for analyses. For comparison, gas samples of the AOD mine air are also collected directly into the evacuated stainless steel vessels simply by opening the main valve for filling, and heater drift atmosphere is collected from a sampling port accessible on the bulkhead itself. All vessels are labeled with Sample Management

Facility (SMF) identifiers and packed for their transport to the gas mass spectrometry lab at LLNL.

## Gas Analysis by Gas Mass Spectrometry

The collected gas samples are analyzed on a VG 30-01 gas analytical mass spectrometer for the volume percent of $N_2$, $O_2$, Ar, $CO_2$, CO, $CH_4$, He and $H_2$. In addition, the presence of molecules with molecular weight of 160 or less are identified from the scan, but not quantified. The determinations are made by the mass abundance and the cracking pattern for the various components. Levels of detection for the VG 30-01 are 0.01%, with the exception of CO which is detectable at levels of 0.05%. A standard deviation for each gas component is determined from the differences of the predicted partial pressures and those observed. Water vapor itself is not analyzed.

Each trip to the DST requires multiple gas sampling vessels to be available, clean and evacuated. As a consequence, samples cannot be archived, nor held for additional future analyses. The LLNL gas mass spectrometry lab, currently performs all gas analyses, as well as evacuation and leak-testing of the vessels used for these gas studies.

## SEAMIST™ Sampling of Pore Fluids in the DST

The composition of water in the pore space and moving through the fractures of rock during the DST will be assessed from the fluid which contacts the array of absorbent pads of each SEAMIST™ liner system. The pads are situated approximately every 4 meters along the length of each borehole and tightly pressed against the rock walls of the borehole with the inflation of the liners. Any moisture and/or condensate which result from the heating activities, may contact and be wicked into the pads at the various locations. Thus, the potential to analyze the fluid chemistry with respect to time and space is inherently built into the experimental design.

To determine whether pads have taken on moisture during the test, a measurement is made and recorded by the data collection system DCS which directly relates to the pad's electrical resistance. The electrical resistance of the pads would vary significantly depending on whether they are measured when dry or wet. Thus, plots of resistance over time may be used to determine when the resistance has dropped dramatically for any of the pads thereby reflecting the wetting process.

Contrary to the sampling strategy for the gas collection in the DST, the collection of water (i.e. the absorbent pads) from the SEAMIST™ liner system requires the complete removal of a liner from the particular borehole. Each of the pads are collected from the liner (not just the suspected "damp" ones) and another liner with clean pads is reinstalled and inflated. During collection the pads need to be minimally handled and exposed in order to prevent contamination and limit evaporation. On the other hand, it will be important to accurately document the condition of the pads with respect to apparent moisture content (e.g. comparing wet and dry weights), adhering rock particulates (potentially affecting both weight and analyte concentration), apparent distribution of moisture across a pad (if inhomogeneous), and other physical observations which may be relevant to the analyses to be performed. The pads will then be stored and transferred in clean, air-tight bags and made available for immediate preparation and analysis at qualified chemistry labs at LLNL .

## SEAMIST™ Pad Analytical Strategy

The water composition determined from the SEAMIST™ pads collected in the DST will be analyzed using several methods and therefore will necessitate sectioning each of the pads among the tests to obtain complete analytical data for the different locations represented by the pads characterized. The suite of inorganics to be included for analysis can be grouped into three categories: 1) metals or cations , 2) anions, and 3) carbonates. The metals are: Aluminum (Al), Boron (B), Calcium (Ca), Iron (Fe), Magnesium (Mg), Lithium (Li), Sodium (Na), Potassium (K), Sulfur (S), Silicon (Si), and Strontium (Sr). The oxidative states of the metals are not critical since the metal analysis will quantify the total metals present regardless of the oxidative state species (although it is assumed that they are in the cation conformation). The anions are Fluoride ($F^-$), Chloride ($Cl^-$), Bromide ($Br^-$), Nitrite ($NO_2^-$), Nitrate ($NO_3^-$), Phosphate ($PO_4^{3-}$), and Sulfate ($SO_4^{2-}$). The final analyte is Carbonate ($CO_3^{2-}$). The oxidative state of the anions is critical, because analyses will be specifically for the anion species. Carbonates will be analyzed separately from the other anions due to analytical difficulties in performing carbonate analysis along with the analyses of the other analytes.

The analytical method of Inductively Coupled Plasma (ICP) will be utilized to obtain cation concentrations, including Al, B, Ca, Fe, Mg, Li, Na, K, S, Si, and Sr. Samples destined for ICP will be prepared through an acid extraction procedure. The anions will be analyzed by Ion Chromatography (IC). IC will provide the concentrations of $F^-$, $Cl^-$, $Br^-$, $NO_2^-$, $NO_3^-$, $PO_4^{3-}$, and $SO_4^{2-}$. Samples destined for IC analyses will be prepared by a water extraction procedure. For $CO_3^{2-}$ analyses separate pad sections will be submitted for an infrared (IR) analysis technique where $CO_2$ is liberated from the carbonate and quantified. The carbon dioxide generated by acidification of the pad material is directly proportional to the carbonate present. For each technique employed, appropriate controls and matrix blanks will be documented.

## Available Sample Analyses from DST First-Quarter Heating

Gas sampling from the chemical study boreholes in the DST has occurred approximately every 4-6 weeks, in coordination with the air permeability studies and tracer gas testing conducted by LBNL. The focus of the sampling efforts has been the lower borehole array (series ESF-HD-CHE- 1,2...5), located closest to the bulkhead end of the heater drift. Samples have been collected from those boreholes that are closest to the heaters, and from the gas sampling ports in them that are most proximal to the heaters. The data from the first two collecting trips since heaters were turned on are presented in Tables 2 and 3. The baseline data from a previously submitted report are repeated here for comparison; see Table 4. These data must all be considered preliminary at this time, since the complete QA requirements have not been satisfied. Nevertheless, all data were collected on a fully calibrated system by acceptable methods employed in gas mass spectrometry labs and are expected to be Q-pedigreed according to QARD procedures.

Sample designations used in the milestone reports utilize an abbreviated borehole number (52-56 and 69-73) and reference to one of six possible ports located on each liner. The actual sample locations may be determined using the information provided in Table 1. The samples increase alphabetically for multiple and sequential samples drawn from a single hole and port; according to the procedure described, the last sample will best represent the rock gas chemistry. All samples can also be identified with a unique SMF bar-coded number which is tracked in controlled notebook #00342. Finally, atmospheric gas samples collected from within Alcove 5 are listed according to the location drawn, so that OD refers to the observation drift in the vicinity of the lower series of chemistry boreholes, CD refers to the connecting drift or the area between the bulkhead and the AOD, and HD is a reference to the heater drift samples collected from the ports accessible in the bulkhead itself.

To date, the absorbent liner systems used for water collection have not been pulled. No water chemistry data are available for this first quarter heating report.

## References

[1]. Civilian Radioactive Waste Management System and Operating Contractor (OCRWM M&O), 1996, "Test, design, plans, and layout for the first ESF thermal test,"

Rev. 1, BAB000000-01717-4600-00025, TRW Environmental Safety System, Inc., Las Vegas, NV 89109.

**Table 1. Distance of gas sampling ports and absorbant pads (in meters) from the collar of each borehole.**

| ESF-HD-CHE-sensors | Hole #52 ...CHE-1 | Hole #53 ...CHE-2 | Hole #54 ...CHE-3 | Hole #55 ...CHE-4 | Hole #56 ...CHE-5 | Hole #69 ...CHE-6 | Hole #70 ...CHE-7 | Hole #71 ...CHE-8 | Hole #72 ...CHE-9 | Hole #73 ...CHE-10 |
|---|---|---|---|---|---|---|---|---|---|---|
| ports 1,2 | none* | none | 35.0 | 31.0 | 35.0 | 34.0 | 35.0 | 35.1 | 35.1 | 35.1 |
| ports 3,4 | 17.1 | 15.0 | 18.9 | 18.9 | 18.9 | 18.0 | 18.9 | 18.9 | 18.9 | 18.9 |
| ports 5,6 | 1.2 | 1.2 | 3.1 | 3.1 | 3.1 | 2.1 | 3.1 | 3.1 | 3.1 | 3.1 |
| absorber 1 | none | none | 39.0 | none | none | none | none | 39.0 | none | none |
| absorber 2 | none | none | 35.1 | 35.1 | 35.1 | none | none | 35.1 | 35.1 | none |
| absorber 3 | 31.1 | none | 31.1 | 31.1 | 31.1 | none | none | 31.1 | 31.1 | 31.0 |
| absorber 4 | 27.1 | none | 27.1 | 27.1 | 27.1 | none | none | 27.1 | 27.1 | 27.1 |
| absorber 5 | 22.9 | none | 22.9 | 22.9 | 22.9 | none | none | 22.9 | 22.9 | 22.9 |
| absorber 6 | 18.9 | none | 18.9 | 18.9 | 18.9 | 18.9 | 19.0 | 18.9 | 18.9 | 18.9 |
| absorber 7 | 14.9 | 15.0 | 14.9 | 14.9 | 14.9 | 15.0 | 15.0 | 14.9 | 14.9 | 14.9 |
| absorber 8 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 |
| absorber 9 | 17.1 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 |
| absorber 10 | 3.1 | 3.0 | 3.1 | 3.1 | 3.1 | 3.0 | 3.0 | 3.1 | 3.1 | 3.1 |

* the designation "none" results from a shortened liner with respect to other holes: in one case the hole itself is shorter (#55), but most cases are because the liner was blocked from full extension.

**Table 2. Jan. 13, 1998 gas sample analyses determined by analytical gas mass spectrometry.***
**All results are expressed in mole (volume) percent.**

| Sample Name | Nitrogen | Oxygen | Argon | Carbon Dioxide | Carbon Monoxide | Methane | Helium | Hydrogen | Total % |
|---|---|---|---|---|---|---|---|---|---|
| 54-1A | 76.69% | 22.33% | 0.95% | 0.03% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1B | 77.36% | 21.67% | 0.93% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1C | 77.04% | 21.99% | 0.93% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1D | 77.02% | 22.00% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1E | 76.91% | 22.11% | 0.93% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1F | 76.90% | 22.09% | 0.94% | 0.07% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 54-3A | 76.86% | 22.15% | 0.93% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3B | 76.88% | 22.12% | 0.93% | 0.08% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3C | 77.58% | 21.45% | 0.92% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3D | 77.48% | 21.56% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3E | 77.37% | 21.66% | 0.92% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3F | 77.33% | 21.70% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 55-1A | 77.37% | 21.66% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1B | 77.77% | 21.26% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1C | 77.73% | 21.31% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1D | 77.50% | 21.53% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1E | 77.54% | 21.50% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1F | 77.65% | 21.41% | 0.89% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 55-3A | 77.43% | 21.60% | 0.91% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3B | 77.32% | 21.71% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3C | 77.46% | 21.58% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3D | 77.46% | 21.53% | 0.91% | 0.09% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3E | 77.34% | 21.69% | 0.91% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3F | 77.65% | 21.41% | 0.90% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 56-1A | 77.81% | 21.26% | 0.90% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-1B | 77.61% | 21.45% | 0.90% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 56-1D | 77.53% | 21.51% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-1E | 77.48% | 21.56% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-1F | 77.34% | 21.71% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 56-3A | 76.73% | 22.30% | 0.92% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3B | 77.35% | 21.70% | 0.90% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3C | 77.37% | 21.66% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 56-3E | 76.83% | 22.12% | 0.93% | 0.12% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | | | | | | | | | |
| HD-1 | 77.54% | 21.49% | 0.91% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| HD-2 | 77.46% | 21.56% | 0.92% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| HD-3 | 77.43% | 21.61% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| OD-1 | 77.43% | 21.54% | 0.91% | 0.12% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |

** these data are preliminary since the QA requirements are not complete*

*shaded rows represent sample vessels which may have opened during transit*

**Table 3.** Feb. 19, 1998 gas sample analyses determined by analytical gas mass spectrometry.*
All results are expressed in mole (volume) percent.

| Sample Name | Nitrogen | Oxygen | Argon | Carbon Dioxide | Carbon Monoxide | Methane | Helium | Hydrogen | Total % |
|---|---|---|---|---|---|---|---|---|---|
| 54-1A | 77.61% | 21.41% | 0.91% | 0.07% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1B | 77.29% | 21.74% | 0.91% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1C | 77.20% | 21.84% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1D | 77.23% | 21.80% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1E | 77.41% | 21.62% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1F | 77.33% | 21.72% | 0.91% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 54-3A | 77.68% | 21.34% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3B | 77.53% | 21.50% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3C | 77.41% | 21.61% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3D | 77.48% | 21.55% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3E | 77.43% | 21.59% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3F | 77.41% | 21.62% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 55-1A | 77.38% | 21.65% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1B | 77.37% | 21.65% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1C | 77.38% | 21.65% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1D | 77.25% | 21.79% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1E | 77.28% | 21.75% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1F | 77.18% | 21.85% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 55-3A | 77.22% | 21.81% | 0.93% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3B | 77.23% | 21.74% | 0.92% | 0.10% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3C | 77.27% | 21.76% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3D | 77.26% | 21.77% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3E | 77.48% | 21.56% | 0.92% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3F | 77.35% | 21.69% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 56-3A | 75.83% | 23.20% | 0.93% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3B | 76.46% | 22.56% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3C | 76.82% | 22.22% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3D | 76.89% | 22.09% | 0.92% | 0.10% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3E | 76.82% | 22.18% | 0.93% | 0.06% | <0.50 | <0.01 | <0.01 | [redacted] | 100.0% |
| 56-3F | 76.64% | 22.37% | 0.92% | 0.07% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| CD-1 | 76.64% | 22.37% | 0.92% | 0.07% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| HD-1 | 77.26% | 21.77% | 0.91% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| OD-1 | 77.25% | 21.76% | 0.92% | 0.07% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| ** these data are preliminary since the QA requirements are not complete* | | | | | | | | | |
| | | | | | | | | | |

**Table 4. Dec. 2, 1997 gas sample analyses determined by analytical gas mass spectrometry.***
**All results are expressed in mole (volume) percent.**

| Sample Name | Nitrogen | Oxygen | Argon | Carbon Dioxide | Carbon Monoxide | Methane | Helium | Hydrogen | Total % |
|---|---|---|---|---|---|---|---|---|---|
| #54-1A | 77.48% | 21.55% | 0.95% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1B | 76.94% | 22.07% | 0.94% | 0.04% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1C | 76.98% | 22.02% | 0.94% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1D | 77.38% | 21.65% | 0.92% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1E | 77.19% | 21.86% | 0.93% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1F | 77.15% | 21.86% | 0.92% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #54-3A | 77.49% | 21.55% | 0.93% | 0.04% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3B | 76.92% | 22.11% | 0.92% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3C | 76.79% | 22.15% | 0.93% | 0.13% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3D | 77.26% | 21.76% | 0.91% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3E | 77.14% | 21.73% | 0.91% | 0.22% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3F | 77.52% | 21.50% | 0.91% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #54-5A | 77.00% | 22.03% | 0.93% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5B | 76.93% | 22.09% | 0.93% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5C | 77.46% | 21.57% | 0.92% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5D | 77.21% | 21.82% | 0.92% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5E | 77.14% | 21.87% | 0.92% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #56-1A | 77.85% | 21.22% | 0.90% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1B | 77.50% | 21.54% | 0.91% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1C | 77.64% | 21.39% | 0.91% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1D | 75.02% | 23.89% | 1.01% | 0.08% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1E | 77.63% | 21.42% | 0.92% | 0.03% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #56-3A | 78.12% | 20.94% | 0.92% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3B | 77.43% | 21.59% | 0.91% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3C | 77.66% | 21.39% | 0.92% | 0.03% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3D | 77.56% | 21.48% | 0.92% | 0.04% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3E | 77.48% | 21.57% | 0.92% | 0.03% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| OD-1 | 77.36% | 21.65% | 0.92% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.00% |
| HD-1 | 77.12% | 21.86% | 0.93% | 0.09% | <0.50% | <0.01% | <0.01% | <0.01% | 100.00% |

* these data are preliminary since the QA requirements are not complete

# First Quarter Chemical Borehole Studies in the Drift Scale Test

*milestone SP2640M4*
*Rev. 1, May 19,1998*

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## Introduction

The chemistry boreholes of the Drift Scale Test (DST) have been designed to gather geochemical information and assess the impact of thermal perturbations on gas and liquid phases present in pore spaces and fractures within the rock. There are a total of ten boreholes dedicated to these chemical studies. Two arrays of five boreholes each were drilled from the access/observation drift (AOD) in planes which run normal to the heater drift and which are located approximately 15 and 45% of the way along the length of the drift as measured from the bulkhead. The boreholes each have a length of about 40 meters and have been drilled at low angles directed just above or just below the heater plane. In each array, three boreholes are directed at increasingly steeper angles (< 25°) above the line of wing heaters and two are directed at shallow angles below the wing heater plane.[1]

To assess the geochemical changes as a function of time and position, the boreholes have each been lined with two different sampling liner systems. Both employ SEAMIST™ liner technology (Science Engineering Associate Membrane In-situ Sampling Technology) which is an instrumentation and fluid sampler emplacement technique designed for in-situ hydrologic characterization and monitoring investigations. It uses an inverting, pneumatically-deployed tubular membrane to install sampling devices and instruments in uncased boreholes. For each chemistry borehole of the DST, one SEAMIST™ liner has been installed with Teflon tubing lines run to various depths and ending at the collar of the hole with a port for sampling the gases originating from the rock walls. In the same hole and adjacent to this liner, a second liner has been installed with a linear array of highly absorbent pads for the collection of pore and condensate water samples; electrical resistance is measured in the pads to indicate wetness. The gas sampling liner is installed and pressurized to effectively seal the rock walls of the borehole and thereby limit the accessibility of the sampling sites to the air from the drift. The fluids are collected on 10 pads positioned approximately every 4 meters along the length of the hole, and six Teflon tubing lines (three pairs) are equidistantly-placed along the length to collect the rock gases. The positions of the pads and ports within the boreholes are summarized in Table 1.

Gas samples and damp pads are collected from the boreholes and taken for chemical analyses. The gaseous phases are analyzed for the volume percent of atmospheric constituents (predominantly $N_2$, $O_2$, Ar, and $CO_2$). The pads are analyzed for a suite of ions typical of the total dissolved solids found in ground water samples from the vicinity of Yucca Mountain. The chemical composition of the gases and liquids will be analyzed throughout the heating phase of the Drift Scale Test and the results will be considered as a function of time and location with respect to the heaters in the heated drift. The schedule and the analytical protocols for the two systems are described in this report. The available results for the first few months of heating are presented.

## SEAMIST™ Gas Sampling in the DST

The general procedure for collecting gases from the chemistry boreholes is to use gas-tight syringes to draw in gas through the Teflon tubing and to inject the sample into previously-evacuated, stainless steel vessels. The gas initially present in the tubing is expected to represent a mixture of the rock gas from pores and fractures in the borehole walls as well as atmospheric mine air diffused in from the sampling port that opens into the AOD. In order to collect sample rich in the rock gases, the tubing has to be depleted of this "compositionally-mixed" air that is present initially and refilled with the desired rock gases from the borehole walls. This process occurs when the gas-tight syringe creates a slight vacuum on the tubing as the plunger is drawn back during sample collection, then the gases from the rock pore spaces and fractures refill the line to equalize the pressure. Samples enriched in the rock gases from the walls of the borehole would be those pulled after multiple draws of the syringe.

A series of gas samples are collected for a given borehole and port as follows: the volume of gas determined to be present in the tubing (estimated from the diameter and length of the tube) is first removed in several small aliquots which are individually collected into evacuated vessels. With the full volume of the line removed, two additional samples are drawn from the same port, and these are collected into two more stainless steel vessels. All of these samples are returned for analyses. For comparison, gas samples of the AOD mine air are also collected directly into the evacuated stainless steel vessels simply by opening the main valve for filling, and heater drift atmosphere is collected from a sampling port accessible on the bulkhead itself. All vessels are labeled with Sample Management Facility (SMF) identifiers and packed for their transport to the gas mass spectrometry lab at LLNL.

## Gas Analysis by Gas Mass Spectrometry

The collected gas samples are analyzed on a VG 30-01 gas analytical mass spectrometer for the volume percent of $N_2$, $O_2$, Ar, $CO_2$, CO, $CH_4$, He and $H_2$. In addition, the presence of molecules with molecular weight of 160 or less are identified from the scan, but not quantified. The determinations are made by the mass abundance and the cracking pattern for the various components. Levels of detection for the VG 30-01 are 0.01%, with the exception of CO which is detectable at levels of 0.05%. A standard deviation for each gas component is determined from the differences of the predicted partial pressures and those observed. Water vapor itself is not analyzed.

Each trip to the DST requires multiple gas sampling vessels to be available, clean and evacuated. As a consequence, samples cannot be archived, nor held for additional future analyses. The LLNL gas mass spectrometry lab, currently performs all gas analyses, as well as evacuation and leak-testing of the vessels used for these gas studies.

## SEAMIST™ Sampling of Pore Fluids in the DST

The composition of water in the pore space and moving through the fractures of rock during the DST will be assessed from the fluid which contacts the array of absorbent pads of each SEAMIST™ liner system. The pads are situated approximately every 4 meters along the length of each borehole and tightly pressed against the rock walls of the borehole with the inflation of the sealing liner. Any fluid and/or condensate which result from the heating activities, may contact and be wicked into the pads at the various locations. Thus, the potential to analyze the fluid chemistry with respect to time and space is inherently built into the experimental design.

To determine whether pads have taken on moisture during the test, a measurement is made and recorded by the data collection system (DCS) which directly relates to the pad's electrical resistance. The electrical resistance of the pads would vary significantly depending on whether they are measured when dry or wet. Thus, plots of resistance over time may be used to determine when the resistance has dropped dramatically for any of the pads thereby reflecting the wetting process.

Contrary to the sampling strategy for the gas collection in the DST, the collection of water (i.e. the absorbent pads) from the SEAMIST™ liner system requires the complete removal of a liner from the particular borehole. Each of the pads are collected from the liner (not just the suspected "damp" ones) and another liner with clean pads is reinstalled. During collection the pads need to be minimally handled and exposed in order to prevent contamination and limit evaporation. On the other hand, it will be important to accurately document the condition of the pads with respect to apparent moisture content (e.g. comparing wet and dry weights), adhering rock fragments (potentially affecting both weight and analyte concentration), apparent distribution of moisture across a pad (if inhomogeneous), and other physical observations which may be relevant to the analyses to be performed. The pads will then be stored and transferred in clean, air-tight bags and made available for immediate preparation and analysis at qualified chemistry labs at LLNL .

## SEAMIST™ Pad Analytical Strategy

The water composition determined from the SEAMIST™ pads collected in the DST will be analyzed using several methods and therefore will necessitate sectioning each of the pads among the tests to obtain complete analytical data for the different locations represented by the pads characterized. The suite of inorganics to be included for analysis can be grouped into three categories: 1) metals or cations , 2) anions, and 3) carbonates. The metals are: Aluminum (Al), Boron (B), Calcium (Ca), Iron (Fe), Magnesium (Mg), Lithium (Li), Sodium (Na), Potassium (K), Sulfur (S), Silicon (Si), and Strontium (Sr). The oxidative states of the metals are not critical since the metal analysis will quantify the total metals present regardless of the oxidative state species (although it is assumed that they are in the cation conformation). The anions are Fluoride ($F^-$), Chloride ($Cl^-$), Bromide ($Br^-$), Nitrite ($NO_2^-$), Nitrate ($NO_3^-$), Phosphate ($PO_4^{3-}$), and Sulfate ($SO_4^{2-}$). The final analyte is Carbonate ($CO_3^{2-}$). The oxidative state of the anions is critical, because analyses will be specifically for the anion species. Carbonates will be analyzed separately from the other anions due to analytical difficulties in performing carbonate analysis along with the analyses of the other analytes.

The analytical method of Inductively Coupled Plasma (ICP) will be utilized to obtain cation concentrations, including Al, B, Ca, Fe, Mg, Li, Na, K, S, Si, and Sr. Samples destined for ICP will be prepared through an acid extraction procedure. The anions will be analyzed by Ion Chromatography (IC). IC will provide the concentrations of $F^-$, $Cl^-$, $Br^-$, $NO_2^-$, $NO_3^-$, $PO_4^{3-}$, and $SO_4^{2-}$. Samples destined for IC analyses will be prepared by a water extraction procedure. For $CO_3^{2-}$ analyses separate pad sections will be submitted for an infrared (IR) analysis technique where $CO_2$ is liberated from the carbonate and quantified. The carbon dioxide generated by acidification of the pad material is directly proportional to the carbonate present. For each technique employed, appropriate controls and matrix blanks will be documented.

## Available Sample Analyses from DST First-Quarter Heating

Gas sampling from the chemical study boreholes in the DST has occurred approximately every 4-6 weeks, in coordination with the air permeability studies and tracer gas testing conducted by LBNL. The focus of the sampling efforts has been the lower borehole array (series ESF-HD-CHE- 1,2...5), located closest to the bulkhead end of the heater drift. Samples have been collected from those boreholes that are closest to the heaters, and from the gas sampling ports in them that are most proximal to the heaters. The data from the first two collecting trips since heaters were turned on are presented in Tables 2 and 3. The baseline data from a previously submitted report are repeated here for comparison; see Table 4. These data must all be considered preliminary at this time, since the complete QA requirements have not been satisfied. Nevertheless, all data were collected on a fully calibrated system by acceptable methods employed in gas mass spectrometry labs and are expected to be Q-pedigreed according to QARD procedures.

Sample designations used in the milestone reports utilize an abbreviated borehole number (52-56 and 69-73) and reference to one of six possible ports located on each liner. The actual sample locations may be determined using the information provided in Table 1. The samples increase alphabetically for multiple and sequential samples drawn from a single hole and port; according to the procedure described. All samples can also be identified with a unique SMF bar-coded number which is tracked in controlled notebook #00342. Finally, atmospheric gas samples collected from within Alcove 5 are listed according to the location drawn, so that OD refers to the observation drift in the vicinity of the lower series of chemistry boreholes, CD refers to the connecting drift or the area between the bulkhead and the AOD, and HD is a reference to the heater drift samples collected from the ports accessible in the bulkhead itself.

The data collected to date are very similar to atmospheric chemistry, with slightly higher $CO_2$ content. Atmospheric $CO_2$ is 0.033 ± 0.001 per cent by volume (exclusive of water vapor) as generally reported (e.g. in the *CRC Handbook of Chemistry and Physics*). The data for the chemistry boreholes reflect a $CO_2$ content which averages ~0.06 %. Nevertheless, these values are similar to the average value observed for the $CO_2$ content sampled in the observation drift.

The data are currently only available for the baseline and the first two months of the test. Figure 1 is a plot of the $CO_2$ content for representative gas samples collected from particular sampling sites over time. Not surprisingly, trends in the data are not yet indicated. Ultimately, the intent will be to examine composition as a function of time and space, but more data are needed.

To date, the absorbent liner systems used for water collection have not been pulled. Although the DCS records numbers which are related to each pad's resistance, the information are not treated as data per se; the plots of resistance with respect to time are studied to determine whether significant changes in resistance have been measured, and accordingly, whether the trends result from wetting of the pads. Interpretation of these resistance plots, however, has not been straightforward during this first quarter of heating for several reasons. Spikes have been observed in the plots of resistance which have been traced to sudden loss of pressure, as when the sealing liners are deflated for any period of time. In certain instances, broken connections appear to be indicated, presumably as a consequence of difficulties encountered entering the liners into the boreholes. Furthermore, the instrumentation systems were not complete in all boreholes at the start of heating, nor were connections completed with the DCS prior to heater turn-on for the baseline readings. For these reasons, the first absorber liners will be pulled and replaced at convenient intervals until supplementary data can be collected from laboratory studies of the absorber pads themselves.

## References

[1]. Civilian Radioactive Waste Management System and Operating Contractor (OCRWM M&O), 1996, "Test, design, plans, and layout for the first ESF thermal test," Rev. 1, BAB000000-01717-4600-00025, TRW Environmental Safety System, Inc., Las Vegas, NV 89109.

Figure 1. The average $CO_2$ concentration for representative borehole gas samples and for drift atmospheres during first quarter heating.

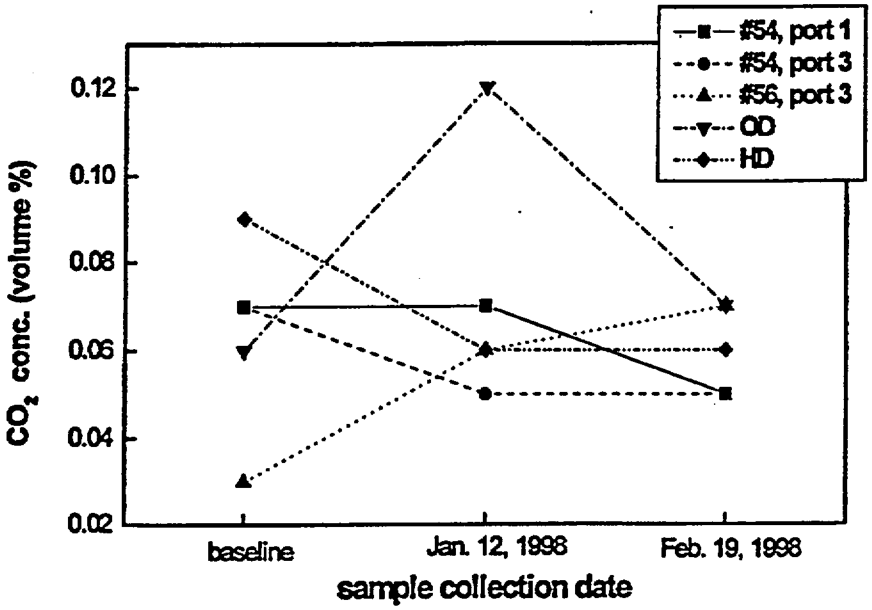

Table 1. Distance of gas sampling ports and absorbant pads (in meters) from the collar of each borehole.

| ESF-HD-CHE-sensors | Hole #52 ...CHE-1 | Hole #53 ...CHE-2 | Hole #54 ...CHE-3 | Hole #55 ...CHE-4 | Hole #56 ...CHE-5 | Hole #69 ...CHE-6 | Hole #70 ...CHE-7 | Hole #71 ...CHE-8 | Hole #72 ...CHE-9 | Hole #73 ...CHE-10 |
|---|---|---|---|---|---|---|---|---|---|---|
| ports 1,2 | none* | none | 35.0 | 31.0 | 35.0 | 34.0 | 35.0 | 35.1 | 35.1 | 35.1 |
| ports 3,4 | 17.1 | 15.0 | 18.9 | 18.9 | 18.9 | 18.0 | 18.9 | 18.9 | 18.9 | 18.9 |
| ports 5,6 | 1.2 | 1.2 | 3.1 | 3.1 | 3.1 | 2.1 | 3.1 | 3.1 | 3.1 | 3.1 |
| absorber 1 | none | none | 39.0 | none | none | none | none | 39.0 | none | none |
| absorber 2 | none | none | 35.1 | 35.1 | 35.1 | none | none | 35.1 | 35.1 | none |
| absorber 3 | 31.1 | none | 31.1 | 31.1 | 31.1 | none | none | 31.1 | 31.1 | 31.0 |
| absorber 4 | 27.1 | none | 27.1 | 27.1 | 27.1 | none | none | 27.1 | 27.1 | 27.1 |
| absorber 5 | 22.9 | none | 22.9 | 22.9 | 22.9 | none | none | 22.9 | 22.9 | 22.9 |
| absorber 6 | 18.9 | none | 18.9 | 18.9 | 18.9 | 18.9 | 19.0 | 18.9 | 18.9 | 18.9 |
| absorber 7 | 14.9 | 15.0 | 14.9 | 14.9 | 14.9 | 15.0 | 15.0 | 14.9 | 14.9 | 14.9 |
| absorber 8 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 |
| absorber 9 | 17.1 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 |
| absorber 10 | 3.1 | 3.0 | 3.1 | 3.1 | 3.1 | 3.0 | 3.0 | 3.1 | 3.1 | 3.1 |

* the designation "none" results from a shortened liner with respect to other holes: in one case the hole itself is shorter (#55), but most cases are because the liner was blocked from full extension.

**Table 2.** Jan. 13, 1998 gas sample analyses determined by analytical gas mass spectrometry.*
All results are expressed in mole (volume) percent.

| Sample Name | Nitrogen | Oxygen | Argon | Carbon Dioxide | Carbon Monoxide | Methane | Helium | Hydrogen | Total % |
|---|---|---|---|---|---|---|---|---|---|
| 54-1A | 76.69% | 22.33% | 0.95% | 0.03% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1B | 77.36% | 21.67% | 0.93% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1C | 77.04% | 21.99% | 0.93% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1D | 77.02% | 22.00% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1E | 76.91% | 22.11% | 0.93% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1F | 76.90% | 22.09% | 0.94% | 0.07% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 54-3A | 76.86% | 22.15% | 0.93% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3B | 76.88% | 22.12% | 0.93% | 0.08% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3C | 77.58% | 21.45% | 0.92% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3D | 77.48% | 21.56% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3E | 77.37% | 21.66% | 0.92% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3F | 77.33% | 21.70% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 55-1A | 77.37% | 21.66% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1B | 77.77% | 21.26% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1C | 77.73% | 21.31% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1D | 77.50% | 21.53% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1E | 77.54% | 21.50% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1F | 77.65% | 21.41% | 0.89% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 55-3A | 77.43% | 21.60% | 0.91% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3B | 77.32% | 21.71% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3C | 77.46% | 21.58% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3D | 77.46% | 21.53% | 0.91% | 0.09% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3E | 77.34% | 21.69% | 0.91% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3F | 77.65% | 21.41% | 0.90% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 56-1A | 77.81% | 21.26% | 0.90% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-1B | 77.61% | 21.45% | 0.90% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-1C | 77.31% | 21.72% | 0.92% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-1D | 77.53% | 21.51% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-1E | 77.48% | 21.56% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-1F | 77.34% | 21.71% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 56-3A | 76.73% | 22.30% | 0.92% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3B | 77.35% | 21.70% | 0.90% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3C | 77.37% | 21.66% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3D | 77.09% | 21.93% | 0.92% | 0.08% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3E | 76.83% | 22.12% | 0.93% | 0.12% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3F | 77.15% | 21.87% | 0.92% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| HD-1 | 77.54% | 21.49% | 0.91% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| HD-2 | 77.46% | 21.56% | 0.92% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| HD-3 | 77.43% | 21.61% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| OD-1 | 77.43% | 21.54% | 0.91% | 0.12% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |

** these data are preliminary since the QA requirements are not complete*

*shaded rows represent sample vessels which may have opened during transit*

**Table 3.** Feb. 19, 1998 gas sample analyses determined by analytical gas mass spectrometry.* All results are expressed in mole (volume) percent.

| Sample Name | Nitrogen | Oxygen | Argon | Carbon Dioxide | Carbon Monoxide | Methane | Helium | Hydrogen | Total % |
|---|---|---|---|---|---|---|---|---|---|
| 54-1A | 77.61% | 21.41% | 0.91% | 0.07% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1B | 77.29% | 21.74% | 0.91% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1C | 77.20% | 21.84% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1D | 77.23% | 21.80% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1E | 77.41% | 21.62% | 0.91% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-1F | 77.33% | 21.72% | 0.91% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 54-3A | 77.68% | 21.34% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3B | 77.53% | 21.50% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3C | 77.41% | 21.61% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3D | 77.48% | 21.55% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3E | 77.43% | 21.59% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 54-3F | 77.41% | 21.62% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 55-1A | 77.38% | 21.65% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1B | 77.37% | 21.65% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1C | 77.38% | 21.65% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1D | 77.25% | 21.78% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1E | 77.28% | 21.75% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-1F | 77.18% | 21.85% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 55-3A | 77.22% | 21.81% | 0.93% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3B | 77.23% | 21.74% | 0.92% | 0.10% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3C | 77.27% | 21.76% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3D | 77.26% | 21.77% | 0.93% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3E | 77.48% | 21.56% | 0.92% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 55-3F | 77.35% | 21.69% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| 56-3A | 75.83% | 23.20% | 0.93% | 0.04% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3B | 76.46% | 22.56% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3C | 76.82% | 22.22% | 0.92% | 0.05% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3D | 76.89% | 22.09% | 0.92% | 0.10% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| 56-3E | 76.82% | 22.18% | 0.93% | 0.06% | <0.50 | <0.01 | <0.01 | 0.01% | 100.0% |
| 56-3F | 76.64% | 22.37% | 0.92% | 0.07% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| | | | | | | | | | |
| CD-1 | 76.64% | 22.37% | 0.92% | 0.07% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| HD-1 | 77.26% | 21.77% | 0.91% | 0.06% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |
| OD-1 | 77.25% | 21.76% | 0.92% | 0.07% | <0.50 | <0.01 | <0.01 | <0.01 | 100.0% |

* *these data are preliminary since the QA requirements are not complete*

**Table 4. Dec. 2, 1997 gas sample analyses determined by analytical gas mass spectrometry.***
**All results are expressed in mole (volume) percent.**

| Sample Name | Nitrogen | Oxygen | Argon | Carbon Dioxide | Carbon Monoxide | Methane | Helium | Hydrogen | Total % |
|---|---|---|---|---|---|---|---|---|---|
| #54-1A | 77.48% | 21.55% | 0.95% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1B | 76.94% | 22.07% | 0.94% | 0.04% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1C | 76.98% | 22.02% | 0.94% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1D | 77.38% | 21.65% | 0.92% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1E | 77.19% | 21.86% | 0.93% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-1F | 77.15% | 21.86% | 0.92% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #54-3A | 77.49% | 21.55% | 0.93% | 0.04% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3B | 76.92% | 22.11% | 0.92% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3C | 76.79% | 22.15% | 0.93% | 0.13% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3D | 77.26% | 21.76% | 0.91% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3E | 77.14% | 21.73% | 0.91% | 0.22% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-3F | 77.52% | 21.50% | 0.91% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #54-5A | 77.00% | 22.03% | 0.93% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5B | 76.93% | 22.09% | 0.93% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5C | 77.46% | 21.57% | 0.92% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5D | 77.21% | 21.82% | 0.92% | 0.05% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #54-5E | 77.14% | 21.87% | 0.92% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #56-1A | 77.85% | 21.22% | 0.90% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1B | 77.50% | 21.54% | 0.91% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1C | 77.64% | 21.39% | 0.91% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1D | 75.02% | 23.89% | 1.01% | 0.08% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-1E | 77.63% | 21.42% | 0.92% | 0.03% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| | | | | | | | | | |
| #56-3A | 78.12% | 20.94% | 0.92% | 0.02% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3B | 77.43% | 21.59% | 0.91% | 0.07% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3C | 77.66% | 21.39% | 0.92% | 0.03% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3D | 77.56% | 21.48% | 0.92% | 0.04% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |
| #56-3E | 77.48% | 21.57% | 0.92% | 0.03% | <0.50% | <0.01% | <0.01% | <0.01% | 100.0% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| OD-1 | 77.36% | 21.65% | 0.92% | 0.06% | <0.50% | <0.01% | <0.01% | <0.01% | 100.00% |
| HD-1 | 77.12% | 21.86% | 0.93% | 0.09% | <0.50% | <0.01% | <0.01% | <0.01% | 100.00% |

* these data are preliminary since the QA requirements are not complete

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# 5. Gas and Water Chemistry

by **Nina Rosenberg, Laura DeLoach, Marina Chiarappa, Roger Martinelli, and William Glassley**

## 5.1 Introduction

As a consequence of heating the rock mass, complex chemical reactions between the fluids and minerals present may be expected. The chemistry studies in the Drift-Scale Test (DST) have been designed to gather geochemical information and assess the impact of thermal perturbations on gas and liquid phases present in pore spaces and fractures within the rock. Compositional changes in the pore fluids reflect dissolution and precipitation processes that implicate changes in flow paths and movement rates. By studying such chemical changes, better understanding and modeling of the nature and evolution of these rock-water interactions may be expected, and confidence may be built in models that will (of necessity) be used to predict and assess repository performance.

To assess the geochemical changes as a function of time, temperature, and position, ten chemistry boreholes have each been lined with two different sampling liner systems. Both employ SEAMIST™ liner technology (Science Engineering Associate Membrane In-situ Sampling Technology) which is an instrumentation and fluid sampler emplacement technique designed for in-situ hydrologic characterization and monitoring investigations. Gas samples and damp pads are collected from the boreholes and analyzed chemically. The gaseous phases are analyzed for the volume percent of atmospheric constituents (predominantly $N_2$, $O_2$, Ar, and $CO_2$). The pads are analyzed for a suite of ions typical of the total dissolved solids found in ground water samples from the vicinity of Yucca Mountain. Samples of the gas and moisture present in the heater drift atmosphere will also be collected through the plumbed ports on the bulkhead. The chemical composition of all the gases and liquids collected will be analyzed throughout the heating phase of the DST and the results will be reported as available.

## 5.2 Description of Chemistry Boreholes

Ten boreholes, two arrays of five boreholes each (52–56 and 69–73), are designated as chemistry boreholes (**Figure 5-1**). These boreholes were drilled from the access/observation drift (AOD) in planes that run normal to the heater drift (HD) and that are located approximately 15% and 45% of the way along the length of the drift, respectively, as measured from the bulkhead (see Figure 1-3 in the Introduction section). Each of the boreholes is about 40 m long and has been drilled at low angles directed just above or just below the heater plane. In each array, three boreholes are directed at increasingly steeper angles (< 25°) above the line of wing heaters, and two are directed at shallow angles below the wing heater plane.

**Figure 5-1. Chemistry Boreholes 52–56 and 69–73.**

Each chemistry borehole has been lined with two different sampling liner systems. Both employ SEAMIST™ liner technology, which uses an inverting, pneumatically deployed, tubular membrane to install sampling devices and instruments in uncased boreholes. One SEAMIST™ liner has been installed with Teflon™ tubing lines run to various depths and sequentially multiplexed into the system sample pump through an expansion unit. The system sample pump dries the sample gas and then circulates the gas through each individual sensor at a constant flow and pressure. The Gas Analyzer is currently being used in the DST to measure $O_2$ and $CO_2$. $CO_2$ is measured by an infrared sensor and $O_2$ is measured by a paramagnetic sensor.

The presence of significant moisture in the HD air required the addition of a water trap, which provided an opportunity to condense and collect water. In these cases, the volume of this water is quantified, pH measured, and a sample collected for transport to LLNL for chemical analysis.

### 5.3.3 SEAMIST™ Pad Sampling and Analysis

When a SEAMIST™ absorber liner is removed, the pads are visually inspected for apparent moisture content and noteworthy physical variations. The pads are stored in clean, air-tight bags and sent to LLNL for chemical analysis.

Each pad is sectioned for three sets of inorganic analyses:

- **Metals or cations:** The total amount present regardless of the oxidative state is quantified via inductively coupled plasma (ICP). Samples are prepared through an acid-extraction procedure.
  - Aluminum (Al)
  - Boron (B)
  - Calcium (Ca)
  - Iron (Fe)
  - Magnesium (Mg)
  - Lithium (Li)
  - Sodium (Na)
  - Potassium (K)
  - Sulfur (S)
  - Silicon (Si)
  - Strontium (Sr)
- **Anions:** Analysis is by ion chromatography (IC). Samples are prepared by a water-extraction procedure.
  - Fluoride ($F^-$)
  - Chloride ($Cl^-$)
  - Bromide ($Br^-$)
  - Nitrite ($NO_2^-$)
  - Nitrate ($NO_3^-$)
  - Phosphate ($PO_4^{3-}$)
  - Sulfate ($SO_4^{2-}$)
- **Carbonates:** Carbonate ($CO_3^{2-}$) will be analyzed via an infrared analysis technique where $CO_2$ is liberated from the carbonate and quantified. The carbon dioxide generated by acidification of the pad material is directly proportional to the carbonate present.

## 5.4 Results

### 5.4.1 Gas Data

Gas data are reported in volume percent, exclusive of water vapor. Therefore, to determine total $CO_2$ or $O_2$ in the gas phase, these values need to be multiplied by the ratio air/(air + water vapor).

All gas data must be considered preliminary at this time because the complete quality-assurance requirements have not been satisfied. Nevertheless, all data were collected on a fully calibrated system by acceptable methods employed in gas mass-spectrometry labs or according to manufacturer specifications and are expected to be Q-pedigreed according to QARD procedures.

#### *5.4.1.1 Discrete Gas Data*

Gas sampling from the chemical study boreholes in the DST has occurred approximately monthly since the start of the test, in coordination with the air-permeability studies and tracer-gas testing conducted by Lawrence Berkeley National Laboratory (LBNL). The focus of the sampling efforts has been the chemistry boreholes that are closest to the heaters and from the gas-sampling ports in them that end nearest the heaters.

Data are reported for gas samples collected between December 1997 and April 1998 and are presented in Table 5-2 through Table 5-6. $CO_2$ is perhaps slightly elevated with respect to atmospheric levels, which are typically around 0.03%. A plot of average $CO_2$ values for samples collected between December 1997 and April 1998 is shown in Figure 5-2. The tabulated data and the plotted graphs, however, suggest that $CO_2$ fluctuates with time. Although additional samples were collected in late May and early June, analyses of those samples are not yet available. No data were reported above detection limits for CO, $CH_4$, He, and $H_2$, so these components have been omitted from the tables.

Figure 5-2. Percent $CO_2$ for discrete gas samples collected between December 1997 and April 1998. These are averaged values based on samples "D", "E", and "F" (in the case of boreholes gases) or averages of all the measured values for atmospheric samples collected during a particular trip.

#### *5.4.1.2 Real-Time, Near-Continuous Gas Data*

Real-time, near-continuous $CO_2$ and $O_2$ data were collected over several days in April from the HD and the CD and again in June from the HD, the CD, the AOD, and several borehole locations. Borehole locations included chemistry Boreholes 54 (ports 1, 3 and 5) and 55 (ports 1 and 3) and hydrology Borehole 59, zone 4 (close to 54-1). These data are presented in Table 5-7 through Table 5-18 and in Figure 5-3 through Figure 5-11.

Figure 5-3. Gas analyses of heater-drift atmosphere, sampled during April 1998.

In Figures 5-3 through 5-6, three channels each sample and measure $O_2$ and $CO_2$, but the differences among the channels are insignificant.

Figure 5-4. Gas analyses of heater-drift atmosphere, sampled during June 1998.

**Figure 5-5. Gas analyses of connecting-drift atmosphere, sampled during April 1998.**

**Figure 5-6. Gas analyses of connecting-drift atmosphere, sampled during June 1998.**

**Figure 5-7. Gas analyses of Borehole 54, sampled during June 1998. $O_2$ and $CO_2$ readings appear to depend on sampling port.**

**Figure 5-8. Gas analyses of Borehole 55, sampled during June 1998. Differences between the two channels measuring $O_2$ and $CO_2$ are insignificant.**

**Figure 5-9. Gas analyses of hydrology Borehole 59, zone 4, sampled during June 1998. A slight trend toward higher $O_2$ and $CO_2$ values is measured over this time period.**

**Figure 5-10. $CO_2$ analyses of hydrology Borehole 59 and nearby chemistry Borehole 54.**

**Figure 5-11. Gas analyses of access/observation-drift atmosphere, sampled during June 1998. Three channels each sample and measure $O_2$ and $CO_2$ and do not display significantly different values.**

These data definitively show that there is a time dependence to the $CO_2$ and $O_2$ levels measured. An initial examination of the HD atmospheric-pressure readings corresponding to the same time interval would not appear to support a direct relation (Figure 5-12). This is consistent with observations of occasional elevated $CO_2$ readings from the discrete gas samples collected on a monthly basis.

**Figure 5-12. $CO_2$ levels observed in the heater-drift atmosphere and air-pressure readings obtained during corresponding time intervals.**

These data also show that $CO_2$ levels in the HD, the CD, the AOD, and the chemistry boreholes are still not significantly different from ambient levels. Measurements for hydrology Borehole 59, zone 4, is, however, significantly elevated (~0.4–0.6%), consistent with LBNL gas measurements. This provides confidence in our analytical methods, but suggests that drift air is diluting the samples we collect from the chemistry boreholes. We are currently investigating possible leakage of the pressurized liners into the chemistry boreholes.

Table 5-19 gives the details on the water collected during the gas sampling and the temperature and relative humidity of the HD at the start of sampling, as noted from the large information display by the bulkhead. Using the temperature and humidity data available, calculations of the moisture present in the HD atmosphere were compared with the amount of water collected; these values agreed, to a rough approximation.

### 5.4.2 Water Chemistry and Moisture Distribution Data

To date, the absorbent liner systems used for water collection have been pulled from Boreholes 55 (April 20, 1998) and 56 (May 5, 1998). Borehole 55 contained a large amount of water and all the pads showed signs of being saturated at some point in time. All were wet during removal except for pad 6, located ~19 m down the borehole. The location is in good agreement with neutron data from Borehole 69 (at approximately the same orientation as Borehole 55), which shows a drying region at about the same depth. Pads from Borehole 56 were also damp but not saturated, as was observed from Borehole 55. Both liners had contacted mud, and solid particulates adhered to the pads, potentially complicating the chemical analysis of the fluids.

All the water samples collected to date from gas sampling in April and June and from the SEAMIST™ pads from Borehole 55 and 56 are currently being analyzed. pH data from these samples are reported in Table 5-20. All pH measurements are between 7.1 and 8.6.

## 5.5 Tables

**Table 5-1.** Distance of gas-sampling ports and absorbent pads (in meters) from the collar of each borehole.

| ESF-HD-CHE- | Hole 52 | Hole 53 | Hole 54 | Hole 55 | Hole 56 | Hole 69 | Hole 70 | Hole 71 | Hole 72 | Hole 73 |
|---|---|---|---|---|---|---|---|---|---|---|
| sensors | ...CHE-1 | ...CHE-2 | ...CHE-3 | ...CHE-4 | ...CHE-5 | ...CHE-6 | ...CHE-7 | ...CHE-8 | ...CHE-9 | ...CHE-10 |
| ports 1, 2 | none[*] | none | 35.0 | 31.0 | 35.0 | 34.0 | 35.0 | 35.1 | 35.1 | 35.1 |
| ports 3, 4 | 17.1 | 15.0 | 18.9 | 18.9 | 18.9 | 18.0 | 18.9 | 18.9 | 18.9 | 18.9 |
| ports 5, 6 | 1.2 | 1.2 | 3.1 | 3.1 | 3.1 | 2.1 | 3.1 | 3.1 | 3.1 | 3.1 |
| absorber 1 | none | none | 39.0 | none | none | none | none | 39.0 | none | none |
| absorber 2 | none | none | 35.1 | 35.1 | 35.1 | none | none | 35.1 | 35.1 | none |
| absorber 3 | 31.1 | none | 31.1 | 31.1 | 31.1 | none | none | 31.1 | 31.1 | 31.0 |
| absorber 4 | 27.1 | none | 27.1 | 27.1 | 27.1 | none | none | 27.1 | 27.1 | 27.1 |
| absorber 5 | 22.9 | none | 22.9 | 22.9 | 22.9 | none | none | 22.9 | 22.9 | 22.9 |
| absorber 6 | 18.9 | none | 18.9 | 18.9 | 18.9 | 18.9 | 19.0 | 18.9 | 18.9 | 18.9 |
| absorber 7 | 14.9 | 15.0 | 14.9 | 14.9 | 14.9 | 15.0 | 15.0 | 14.9 | 14.9 | 14.9 |
| absorber 8 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 |
| absorber 9 | 17.1 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 |
| absorber 10 | 3.1 | 3.0 | 3.1 | 3.1 | 3.1 | 3.0 | 3.0 | 3.1 | 3.1 | 3.1 |

[*] The designation "none" results from a shortened liner with respect to other holes; in one case (Borehole 55) the hole itself is shorter, but most cases arise from the liner being blocked from full extension.

Table 5-2. **Analyses for discrete gas samples collected December 2, 1997.[a]**
**All results are expressed in mole (volume) percent and are not corrected for water vapor.**

| Sample[b] | Nitrogen | Oxygen | Argon | Carbon dioxide |
|---|---|---|---|---|
| 54-1A | 77.48 | 21.55 | 0.95 | 0.02 |
| 54-1B | 76.94 | 22.07 | 0.94 | 0.04 |
| 54-1C | 76.98 | 22.02 | 0.94 | 0.06 |
| 54-1D | 77.38 | 21.65 | 0.92 | 0.05 |
| 54-1E | 77.19 | 21.86 | 0.93 | 0.02 |
| 54-1F | 77.15 | 21.86 | 0.92 | 0.07 |
| 54-3A | 77.49 | 21.55 | 0.93 | 0.04 |
| 54-3B | 76.92 | 22.11 | 0.92 | 0.05 |
| 54-3C | 76.79 | 22.15 | 0.93 | 0.13 |
| 54-3D | 77.26 | 21.76 | 0.91 | 0.07 |
| 54-3E | 77.14 | 21.73 | 0.91 | 0.22 |
| 54-3F | 77.52 | 21.50 | 0.91 | 0.07 |
| 54-5A | 77.00 | 22.03 | 0.93 | 0.05 |
| 54-5B | 76.93 | 22.09 | 0.93 | 0.05 |
| 54-5C | 77.46 | 21.57 | 0.92 | 0.06 |
| 54-5D | 77.21 | 21.82 | 0.92 | 0.05 |
| 54-5E | 77.14 | 21.87 | 0.92 | 0.07 |
| 56-1A | 77.85 | 21.22 | 0.90 | 0.02 |
| 56-1B | 77.50 | 21.54 | 0.91 | 0.06 |
| 56-1C | 77.64 | 21.39 | 0.91 | 0.06 |
| 56-1D | 75.02 | 23.89 | 1.01 | 0.08 |
| 56-1E | 77.63 | 21.42 | 0.92 | 0.03 |
| 56-3A | 78.12 | 20.94 | 0.92 | 0.02 |
| 56-3B | 77.43 | 21.59 | 0.91 | 0.07 |
| 56-3C | 77.66 | 21.39 | 0.92 | 0.03 |
| 56-3D | 77.56 | 21.48 | 0.92 | 0.04 |
| 56-3E | 77.48 | 21.57 | 0.92 | 0.03 |
| OD-1 | 77.36 | 21.65 | 0.92 | 0.06 |
| HD-1 | 77.12 | 21.86 | 0.93 | 0.09 |

[a] These data are preliminary because QA requirements are not complete.
Table entries for CO, $CH_4$, He, and $H_2$ have been omitted because all are reported undetectable.

[b] Samples are assigned a unique descriptive tracking identifier for each trip, but are identified in tables by borehole and port.

Table 5-3. Analyses for discrete gas samples collected January 13, 1998.[a] All results are expressed in mole (volume) percent and are not corrected for water vapor.

| Sample [b] | Nitrogen | Oxygen | Argon | Carbon dioxide |
|---|---|---|---|---|
| 54-1A | 76.69 | 22.33 | 0.95 | 0.03 |
| 54-1B | 77.36 | 21.67 | 0.93 | 0.04 |
| 54-1C | 77.04 | 21.99 | 0.93 | 0.04 |
| 54-1D | 77.02 | 22.00 | 0.93 | 0.05 |
| 54-1E | 76.91 | 22.11 | 0.93 | 0.04 |
| 54-1F | 76.90 | 22.09 | 0.94 | 0.07 |
| 54-3A | 76.86 | 22.15 | 0.93 | 0.06 |
| 54-3B | 76.88 | 22.12 | 0.93 | 0.08 |
| 54-3C | 77.58 | 21.45 | 0.92 | 0.04 |
| 54-3D | 77.48 | 21.56 | 0.91 | 0.05 |
| 54-3E | 77.37 | 21.66 | 0.92 | 0.06 |
| 54-3F | 77.33 | 21.70 | 0.92 | 0.05 |
| 55-1A | 77.37 | 21.66 | 0.92 | 0.05 |
| 55-1B | 77.77 | 21.26 | 0.92 | 0.05 |
| 55-1C | 77.73 | 21.31 | 0.91 | 0.05 |
| 55-1D | 77.50 | 21.53 | 0.91 | 0.05 |
| 55-1E | 77.54 | 21.50 | 0.91 | 0.05 |
| 55-1F | 77.65 | 21.41 | 0.89 | 0.06 |
| 55-3A | 77.43 | 21.60 | 0.91 | 0.08 |
| 55-3B | 77.32 | 21.71 | 0.92 | 0.05 |
| 55-3C | 77.46 | 21.58 | 0.91 | 0.05 |
| 55-3D | 77.46 | 21.53 | 0.91 | 0.09 |
| 55-3E | 77.34 | 21.69 | 0.91 | 0.06 |
| 55-3F | 77.65 | 21.41 | 0.90 | 0.04 |
| 56-1A | 77.81 | 21.26 | 0.90 | 0.04 |
| 56-1B | 77.61 | 21.45 | 0.90 | 0.04 |
| 56-1C | 77.31 | 21.72 | 0.92 | 0.06 |
| 56-1D | 77.53 | 21.51 | 0.91 | 0.05 |
| 56-1E | 77.48 | 21.56 | 0.91 | 0.05 |
| 56-1F | 77.34 | 21.71 | 0.91 | 0.05 |
| 56-3A | 76.73 | 22.30 | 0.92 | 0.06 |
| 56-3B | 77.35 | 21.70 | 0.90 | 0.05 |
| 56-3C | 77.37 | 21.66 | 0.92 | 0.05 |

| Sample [b] | Nitrogen | Oxygen | Argon | Carbon dioxide |
|---|---|---|---|---|
| 56-3D | 77.09 | 21.93 | 0.92 | 0.06 |
| 56-3E | 76.83 | 22.12 | 0.93 | 0.12 |
| 56-3F | 77.15 | 21.87 | 0.92 | 0.06 |
| HD-1 | 77.54 | 21.49 | 0.91 | 0.06 |
| HD-2 | 77.46 | 21.56 | 0.92 | 0.06 |
| HD-3 | 77.43 | 21.61 | 0.91 | 0.05 |
| OD-1 | 77.43 | 21.54 | 0.91 | 0.12 |

[a] These data are preliminary because QA requirements are not complete.
Shaded rows represent sample vessels which may have opened during transit.
Table entries for CO, $CH_4$, He, and $H_2$ have been omitted because all are reported undetectable.

[b] Samples are assigned a unique descriptive tracking identifier for each trip, but are identified in tables by borehole and port.

Table 5-4. **Analyses for discrete gas samples collected February 19, 1998.[a]**

**All results are expressed in mole (volume) percent and are not corrected for water vapor.**

| Sample [b] | Nitrogen | Oxygen | Argon | Carbon dioxide |
|---|---|---|---|---|
| 54-1A | 77.61 | 21.41 | 0.91 | 0.07 |
| 54-1B | 77.29 | 21.74 | 0.91 | 0.06 |
| 54-1C | 77.20 | 21.84 | 0.91 | 0.05 |
| 54-1D | 77.23 | 21.80 | 0.91 | 0.05 |
| 54-1E | 77.41 | 21.62 | 0.91 | 0.05 |
| 54-1F | 77.33 | 21.72 | 0.91 | 0.04 |
| 54-3A | 77.68 | 21.34 | 0.93 | 0.05 |
| 54-3B | 77.53 | 21.50 | 0.93 | 0.05 |
| 54-3C | 77.41 | 21.61 | 0.93 | 0.05 |
| 54-3D | 77.48 | 21.55 | 0.93 | 0.05 |
| 54-3E | 77.43 | 21.59 | 0.93 | 0.05 |
| 54-3F | 77.41 | 21.62 | 0.93 | 0.05 |
| 55-1A | 77.38 | 21.65 | 0.93 | 0.05 |
| 55-1B | 77.37 | 21.65 | 0.93 | 0.05 |
| 55-1C | 77.38 | 21.65 | 0.92 | 0.05 |
| 55-1D | 77.25 | 21.79 | 0.92 | 0.05 |
| 55-1E | 77.28 | 21.75 | 0.92 | 0.05 |
| 55-1F | 77.18 | 21.85 | 0.93 | 0.05 |
| 55-3A | 77.22 | 21.81 | 0.93 | 0.04 |
| 55-3B | 77.23 | 21.74 | 0.92 | 0.10 |
| 55-3C | 77.27 | 21.76 | 0.93 | 0.05 |

| Sample [b] | Nitrogen | Oxygen | Argon | Carbon dioxide |
|---|---|---|---|---|
| 55-3D | 77.26 | 21.77 | 0.93 | 0.05 |
| 55-3E | 77.48 | 21.56 | 0.92 | 0.04 |
| 55-3F | 77.35 | 21.69 | 0.92 | 0.05 |
| 56-3A | 75.83 | 23.20 | 0.93 | 0.04 |
| 56-3B | 76.48 | 22.56 | 0.92 | 0.05 |
| 56-3C | 76.82 | 22.22 | 0.92 | 0.05 |
| 56-3D | 76.89 | 22.09 | 0.92 | 0.10 |
| 56-3E [c] | 76.82 | 22.18 | 0.93 | 0.06 |
| 56-3F | 76.64 | 22.37 | 0.92 | 0.07 |
| CD-1 | 76.64 | 22.37 | 0.92 | 0.07 |
| HD-1 | 77.26 | 21.77 | 0.91 | 0.06 |
| OD-1 | 77.25 | 21.76 | 0.92 | 0.07 |

[a] These data are preliminary because the QA requirements are not complete.

[b] Samples are assigned a unique descriptive tracking identifier for each trip, but are identified in tables by borehole and port.

[c] 0.01 $H_2$ was reported for sample 56-3E; other table entries for CO, $CH_4$, He, and $H_2$ have been omitted because all are reported undetectable.

Table 5-5. Analyses for discrete gas samples collected March 25, 1998.[a]
All results are expressed in mole (volume) percent and are not corrected for water vapor.

| Sample [b] | Nitrogen | Oxygen | Argon | Carbon dioxide |
|---|---|---|---|---|
| 54-1A | 77.51 | 21.50 | 0.94 | 0.05 |
| 54-1B | 77.40 | 21.59 | 0.94 | 0.07 |
| 54-1C | 77.47 | 21.52 | 0.94 | 0.07 |
| 54-1D | 77.52 | 21.46 | 0.94 | 0.07 |
| 54-1E | 77.29 | 21.70 | 0.95 | 0.06 |
| 54-1F | 77.41 | 21.57 | 0.95 | 0.07 |
| 54-3A | 77.13 | 21.88 | 0.94 | 0.05 |
| 54-3B | 77.08 | 21.93 | 0.94 | 0.05 |
| 54-3C | 77.62 | 21.39 | 0.94 | 0.05 |
| 54-3D | 77.13 | 21.88 | 0.94 | 0.05 |
| 54-3E | 77.14 | 21.87 | 0.94 | 0.05 |
| 54-3F | 77.12 | 21.90 | 0.94 | 0.05 |
| 55-1A | 77.07 | 21.94 | 0.94 | 0.05 |
| 55-1B | 77.06 | 21.95 | 0.94 | 0.05 |
| 55-1C | 77.12 | 21.89 | 0.94 | 0.05 |
| 55-1D | 77.10 | 21.90 | 0.94 | 0.05 |

| Sample [b] | Nitrogen | Oxygen | Argon | Carbon dioxide |
|---|---|---|---|---|
| 55-1E | 77.28 | 21.73 | 0.94 | 0.05 |
| 55-1F | 77.13 | 21.89 | 0.94 | 0.05 |
| 55-3A | 77.04 | 21.97 | 0.94 | 0.04 |
| 55-3B | 77.07 | 21.94 | 0.94 | 0.05 |
| 55-3C | 77.11 | 21.89 | 0.94 | 0.05 |
| 55-3D | 77.04 | 21.97 | 0.94 | 0.05 |
| 55-3E | 77.08 | 21.93 | 0.94 | 0.05 |
| 55-3F | 77.02 | 21.99 | 0.94 | 0.05 |
| 56-3A | 77.15 | 21.86 | 0.94 | 0.04 |
| 56-3B | 77.39 | 21.63 | 0.94 | 0.04 |
| 56-3C | 77.28 | 21.73 | 0.94 | 0.05 |
| 56-3D | 77.30 | 21.70 | 0.94 | 0.05 |
| 56-3E | 77.26 | 21.75 | 0.94 | 0.05 |
| 56-3F | 77.25 | 21.76 | 0.94 | 0.05 |
| 71-1A | 77.33 | 21.68 | 0.95 | 0.04 |
| 71-1B | 77.45 | 21.54 | 0.93 | 0.08 |
| 71-1C | 77.41 | 21.59 | 0.93 | 0.07 |
| 71-1D | 77.42 | 21.57 | 0.94 | 0.08 |
| 71-1E | 77.38 | 21.61 | 0.94 | 0.07 |
| 71-1F | 77.43 | 21.56 | 0.94 | 0.07 |
| 71-3A | 77.21 | 21.82 | 0.94 | 0.03 |
| 71-3B | 77.22 | 21.80 | 0.94 | 0.04 |
| 71-3C | 78.09 | 20.91 | 0.95 | 0.04 |
| 71-3D | 77.49 | 21.52 | 0.95 | 0.04 |
| 71-3E | 77.38 | 21.63 | 0.94 | 0.05 |
| 71-3F | 77.33 | 21.69 | 0.94 | 0.04 |
| HD-1 | 77.47 | 21.51 | 0.94 | 0.09 |
| HD-2 | 77.44 | 21.56 | 0.94 | 0.06 |
| OD-1 | 77.31 | 21.70 | 0.94 | 0.05 |

[a] These data are preliminary because the QA requirements are not complete.
Table entries for CO, $CH_4$, He, and $H_2$ have been omitted because all are reported undetectable.

[b] Samples are assigned a unique descriptive tracking identifier for each trip, but are identified in tables by borehole and port.

Table 5-6. Analyses for discrete gas samples collected April 21, 1998.[a]

All results are expressed in mole (volume) percent and are not corrected for water vapor.

| Sample[b] | Nitrogen | Oxygen | Argon | Carbon dioxide |
|---|---|---|---|---|
| 54-1A | 77.41 | 21.60 | 0.93 | 0.07 |
| 54-1B | 76.94 | 22.07 | 0.94 | 0.05 |
| 54-1C | 77.40 | 21.52 | 0.93 | 0.16 |
| 54-1D | 76.80 | 22.21 | 0.94 | 0.05 |
| 54-1E | 76.91 | 22.09 | 0.93 | 0.07 |
| 54-1F | 76.83 | 22.19 | 0.93 | 0.05 |
| 54-3A | 77.58 | 21.46 | 0.92 | 0.04 |
| 54-3B | 77.42 | 21.61 | 0.93 | 0.05 |
| 54-3C | 77.34 | 21.67 | 0.93 | 0.06 |
| 54-3D | 77.36 | 21.65 | 0.92 | 0.06 |
| 54-3E | 77.35 | 21.66 | 0.93 | 0.07 |
| 54-3F | 77.34 | 21.68 | 0.93 | 0.05 |
| 56-1A | 77.83 | 21.19 | 0.92 | 0.06 |
| 56-1B | 77.48 | 21.54 | 0.93 | 0.06 |
| 56-1C | 77.57 | 21.45 | 0.92 | 0.05 |
| 56-1D | 77.61 | 21.40 | 0.92 | 0.07 |
| 56-1E | 77.64 | 21.39 | 0.92 | 0.05 |
| 56-1F | 77.72 | 21.32 | 0.92 | 0.05 |
| 56-3A | 76.24 | 22.73 | 0.95 | 0.07 |
| 56-3B | 77.23 | 21.79 | 0.94 | 0.05 |
| 56-3C | 77.30 | 21.72 | 0.93 | 0.06 |
| 56-3D | 77.24 | 21.78 | 0.93 | 0.05 |
| 56-3E | 77.50 | 21.51 | 0.93 | 0.06 |
| 56-3F | 77.64 | 21.37 | 0.93 | 0.07 |
| HD-1 | 77.50 | 21.52 | 0.93 | 0.06 |
| HD-2 | 77.44 | 21.55 | 0.93 | 0.09 |
| OD-1 | 77.33 | 21.67 | 0.93 | 0.07 |

[a] These data are preliminary because the QA requirements are not complete. Table entries for CO, $CH_4$, He, and $H_2$ have been omitted because all are reported undetectable.

[b] Samples are assigned a unique descriptive tracking identifier for each trip, but are identified in tables by borehole and port.

Table 5-7. $CO_2$ (mole [volume] percent) by time, connecting drift, April 1998.

| Date and time | CD-1 | Date and time | CD-2 | Date and time | CD-3 |
|---|---|---|---|---|---|
| 4/21/98 10:44 | 0.05 | 4/21/98 10:50 | 0.05 | 4/21/98 10:57 | 0.05 |
| 4/21/98 11:24 | 0.06 | 4/21/98 11:30 | 0.06 | 4/21/98 11:37 | 0.06 |
| 4/21/98 12:23 | 0.04 | 4/21/98 12:30 | 0.04 | 4/21/98 12:36 | 0.04 |
| 4/21/98 13:03 | 0.04 | 4/21/98 13:10 | 0.03 | 4/21/98 13:16 | 0.03 |
| 4/21/98 13:43 | 0.03 | 4/21/98 13:50 | 0.03 | 4/21/98 13:56 | 0.03 |
| 4/21/98 14:23 | 0.03 | 4/21/98 14:30 | 0.03 | 4/21/98 14:36 | 0.03 |
| 4/21/98 15:03 | 0.03 | 4/21/98 15:10 | 0.03 | 4/21/98 15:16 | 0.03 |
| 4/21/98 15:43 | 0.04 | 4/21/98 15:50 | 0.04 | 4/21/98 15:56 | 0.03 |
| 4/21/98 16:23 | 0.04 | 4/21/98 16:30 | 0.03 | 4/21/98 16:36 | 0.04 |
| 4/21/98 17:03 | 0.03 | 4/21/98 17:10 | 0.03 | 4/21/98 17:16 | 0.04 |
| 4/21/98 17:43 | 0.04 | 4/21/98 17:50 | 0.04 | 4/21/98 17:56 | 0.04 |
| 4/21/98 18:23 | 0.03 | 4/21/98 18:30 | 0.03 | 4/21/98 18:36 | 0.03 |
| 4/21/98 19:03 | 0.03 | 4/21/98 19:10 | 0.03 | 4/21/98 19:16 | 0.03 |
| 4/21/98 19:43 | 0.03 | 4/21/98 19:50 | 0.03 | 4/21/98 19:56 | 0.03 |
| 4/21/98 20:23 | 0.04 | 4/21/98 20:30 | 0.03 | 4/21/98 20:36 | 0.04 |
| 4/21/98 21:03 | 0.04 | 4/21/98 21:10 | 0.04 | 4/21/98 21:16 | 0.04 |
| 4/21/98 21:43 | 0.04 | 4/21/98 21:50 | 0.04 | 4/21/98 21:56 | 0.04 |
| 4/21/98 22:23 | 0.04 | 4/21/98 22:30 | 0.04 | 4/21/98 22:36 | 0.04 |
| 4/21/98 23:03 | 0.04 | 4/21/98 23:10 | 0.04 | 4/21/98 23:16 | 0.04 |
| 4/21/98 23:43 | 0.04 | 4/21/98 23:50 | 0.04 | 4/21/98 23:56 | 0.04 |
| 4/22/98 0:23 | 0.04 | 4/22/98 0:30 | 0.04 | 4/22/98 0:36 | 0.04 |
| 4/22/98 1:03 | 0.04 | 4/22/98 1:10 | 0.04 | 4/22/98 1:16 | 0.04 |
| 4/22/98 1:43 | 0.04 | 4/22/98 1:50 | 0.04 | 4/22/98 1:56 | 0.04 |
| 4/22/98 2:23 | 0.04 | 4/22/98 2:30 | 0.04 | 4/22/98 2:36 | 0.04 |
| 4/22/98 3:03 | 0.04 | 4/22/98 3:10 | 0.03 | 4/22/98 3:16 | 0.04 |
| 4/22/98 3:43 | 0.04 | 4/22/98 3:50 | 0.04 | 4/22/98 3:56 | 0.04 |
| 4/22/98 4:23 | 0.04 | 4/22/98 4:30 | 0.04 | 4/22/98 4:36 | 0.03 |
| 4/22/98 5:03 | 0.03 | 4/22/98 5:10 | 0.04 | 4/22/98 5:16 | 0.04 |
| 4/22/98 5:43 | 0.03 | 4/22/98 5:50 | 0.03 | 4/22/98 5:56 | 0.03 |
| 4/22/98 6:23 | 0.03 | 4/22/98 6:30 | 0.03 | 4/22/98 6:36 | 0.03 |
| 4/22/98 7:03 | 0.03 | 4/22/98 7:10 | 0.03 | 4/22/98 7:16 | 0.03 |
| 4/22/98 7:43 | 0.03 | 4/22/98 7:50 | 0.03 | 4/22/98 7:56 | 0.03 |
| 4/22/98 8:23 | 0.03 | 4/22/98 8:30 | 0.03 | 4/22/98 8:36 | 0.04 |
| 4/22/98 9:52 | 0.03 | 4/22/98 9:58 | 0.03 | 4/22/98 10:05 | 0.03 |
| 4/22/98 10:32 | 0.03 | 4/22/98 10:38 | 0.04 | 4/22/98 10:45 | 0.04 |

| Date and time | CD-1 | Date and time | CD-2 | Date and time | CD-3 |
|---|---|---|---|---|---|
| 4/22/98 11:12 | 0.04 | 4/22/98 11:18 | 0.04 | 4/22/98 11:25 | 0.04 |
| 4/22/98 11:52 | 0.04 | 4/22/98 11:58 | 0.04 | 4/22/98 12:05 | 0.03 |
| 4/22/98 12:32 | 0.04 | 4/22/98 12:38 | 0.03 | 4/22/98 12:45 | 0.04 |
| 4/22/98 13:12 | 0.04 | 4/22/98 13:18 | 0.03 | 4/22/98 13:25 | 0.03 |
| 4/22/98 13:52 | 0.03 | 4/22/98 13:58 | 0.04 | 4/22/98 14:05 | 0.03 |
| 4/22/98 14:32 | 0.03 | 4/22/98 14:38 | 0.02 | 4/22/98 14:45 | 0.02 |
| 4/22/98 15:12 | 0.02 | 4/22/98 15:18 | 0.02 | 4/22/98 15:25 | 0.02 |
| 4/22/98 15:52 | 0.02 | 4/22/98 15:58 | 0.02 | 4/22/98 16:05 | 0.02 |
| 4/22/98 16:32 | 0.02 | 4/22/98 16:38 | 0.02 | 4/22/98 16:45 | 0.02 |
| 4/22/98 17:12 | 0.02 | 4/22/98 17:18 | 0.02 | 4/22/98 17:25 | 0.02 |
| 4/22/98 17:52 | 0.02 | 4/22/98 17:58 | 0.02 | 4/22/98 18:05 | 0.02 |
| 4/22/98 18:32 | 0.02 | 4/22/98 18:38 | 0.02 | 4/22/98 18:45 | 0.02 |
| 4/22/98 19:12 | 0.01 | 4/22/98 19:18 | 0.01 | 4/22/98 19:25 | 0.01 |
| 4/22/98 19:52 | 0.02 | 4/22/98 19:58 | 0.01 | 4/22/98 20:05 | 0.02 |
| 4/22/98 20:32 | 0.02 | 4/22/98 20:38 | 0.02 | 4/22/98 20:45 | 0.02 |
| 4/22/98 21:12 | 0.01 | 4/22/98 21:18 | 0.01 | 4/22/98 21:25 | 0.01 |
| 4/22/98 21:52 | 0.02 | 4/22/98 21:58 | 0.02 | 4/22/98 22:05 | 0.01 |
| 4/22/98 22:32 | 0.02 | 4/22/98 22:38 | 0.02 | 4/22/98 22:45 | 0.02 |
| 4/22/98 23:12 | 0.01 | 4/22/98 23:18 | 0.01 | 4/22/98 23:25 | 0.01 |
| 4/22/98 23:52 | 0.02 | 4/22/98 23:58 | 0.02 | 4/23/98 0:05 | 0.02 |
| 4/23/98 0:32 | 0.02 | 4/23/98 0:38 | 0.02 | 4/23/98 0:45 | 0.02 |
| 4/23/98 1:12 | 0.02 | 4/23/98 1:18 | 0.01 | 4/23/98 1:25 | 0.01 |
| 4/23/98 1:52 | 0.01 | 4/23/98 1:58 | 0.01 | 4/23/98 2:05 | 0.01 |
| 4/23/98 2:32 | 0.01 | 4/23/98 2:38 | 0.01 | 4/23/98 2:45 | 0.01 |
| 4/23/98 3:12 | 0.01 | 4/23/98 3:18 | 0.01 | 4/23/98 3:25 | 0.01 |
| 4/23/98 3:52 | 0.01 | 4/23/98 3:58 | 0.01 | 4/23/98 4:05 | 0.01 |
| 4/23/98 4:32 | 0.01 | 4/23/98 4:38 | 0.01 | 4/23/98 4:45 | 0.01 |
| 4/23/98 5:12 | 0.01 | 4/23/98 5:18 | 0.01 | 4/23/98 5:25 | 0.01 |
| 4/23/98 5:52 | 0.01 | 4/23/98 5:58 | 0.01 | 4/23/98 6:05 | 0.01 |
| 4/23/98 6:32 | 0.01 | 4/23/98 6:38 | 0.01 | 4/23/98 6:45 | 0.01 |
| 4/23/98 7:12 | 0.01 | 4/23/98 7:18 | 0.01 | 4/23/98 7:25 | 0.01 |
| 4/23/98 7:52 | 0.01 | 4/23/98 7:58 | 0.01 | 4/23/98 8:05 | 0.01 |
| 4/23/98 8:32 | 0.01 | 4/23/98 8:38 | 0.01 | 4/23/98 8:45 | 0.01 |
| 4/23/98 9:12 | 0.02 | 4/23/98 9:18 | 0.02 | 4/23/98 9:25 | 0.02 |
| 4/23/98 9:52 | 0.02 | 4/23/98 9:58 | 0.02 | 4/23/98 10:05 | 0.02 |
| 4/23/98 10:32 | 0.02 | 4/23/98 10:38 | 0.02 | 4/23/98 10:45 | 0.02 |

| Date and time | CD-1 | Date and time | CD-2 | Date and time | CD-3 |
|---|---|---|---|---|---|
| 4/23/98 11:12 | 0.02 | 4/23/98 11:18 | 0.02 | 4/23/98 11:25 | 0.02 |
| 4/23/98 11:52 | 0.01 | 4/23/98 11:58 | 0.01 | 4/23/98 12:05 | 0.01 |
| 4/23/98 12:32 | 0.01 | 4/23/98 12:38 | 0.01 | 4/23/98 12:45 | 0.01 |

Table 5-8. $CO_2$ (mole [volume] percent) by time, heater drift, April 1998.

| Date and time | HD-1 | Date and time | HD-2 | Date and time | HD-3 |
|---|---|---|---|---|---|
| 4/21/98 10:24 | 0.04 | 4/21/98 10:31 | 0.05 | 4/21/98 10:37 | 0.05 |
| 4/21/98 11:04 | 0.05 | 4/21/98 11:11 | 0.05 | 4/21/98 11:17 | 0.05 |
| 4/21/98 12:04 | 0.04 | 4/21/98 12:10 | 0.04 | 4/21/98 12:17 | 0.04 |
| 4/21/98 12:44 | 0.04 | 4/21/98 12:50 | 0.04 | 4/21/98 12:57 | 0.04 |
| 4/21/98 13:24 | 0.03 | 4/21/98 13:30 | 0.03 | 4/21/98 13:37 | 0.03 |
| 4/21/98 14:04 | 0.03 | 4/21/98 14:10 | 0.03 | 4/21/98 14:17 | 0.03 |
| 4/21/98 14:44 | 0.03 | 4/21/98 14:50 | 0.03 | 4/21/98 14:57 | 0.03 |
| 4/21/98 15:24 | 0.03 | 4/21/98 15:30 | 0.03 | 4/21/98 15:37 | 0.03 |
| 4/21/98 16:04 | 0.03 | 4/21/98 16:10 | 0.03 | 4/21/98 16:17 | 0.04 |
| 4/21/98 16:44 | 0.04 | 4/21/98 16:50 | 0.04 | 4/21/98 16:57 | 0.04 |
| 4/21/98 17:24 | 0.04 | 4/21/98 17:30 | 0.03 | 4/21/98 17:37 | 0.04 |
| 4/21/98 18:04 | 0.04 | 4/21/98 18:10 | 0.04 | 4/21/98 18:17 | 0.04 |
| 4/21/98 18:44 | 0.04 | 4/21/98 18:50 | 0.04 | 4/21/98 18:57 | 0.04 |
| 4/21/98 19:24 | 0.04 | 4/21/98 19:30 | 0.04 | 4/21/98 19:37 | 0.04 |
| 4/21/98 20:04 | 0.03 | 4/21/98 20:10 | 0.04 | 4/21/98 20:17 | 0.04 |
| 4/21/98 20:44 | 0.04 | 4/21/98 20:50 | 0.04 | 4/21/98 20:57 | 0.04 |
| 4/21/98 21:24 | 0.04 | 4/21/98 21:30 | 0.04 | 4/21/98 21:37 | 0.04 |
| 4/21/98 22:04 | 0.04 | 4/21/98 22:10 | 0.04 | 4/21/98 22:17 | 0.04 |
| 4/21/98 22:44 | 0.04 | 4/21/98 22:50 | 0.04 | 4/21/98 22:57 | 0.04 |
| 4/21/98 23:24 | 0.04 | 4/21/98 23:30 | 0.04 | 4/21/98 23:37 | 0.04 |
| 4/22/98 0:04 | 0.04 | 4/22/98 0:10 | 0.04 | 4/22/98 0:17 | 0.04 |
| 4/22/98 0:44 | 0.04 | 4/22/98 0:50 | 0.04 | 4/22/98 0:57 | 0.04 |
| 4/22/98 1:24 | 0.04 | 4/22/98 1:30 | 0.04 | 4/22/98 1:37 | 0.04 |
| 4/22/98 2:04 | 0.04 | 4/22/98 2:10 | 0.04 | 4/22/98 2:17 | 0.04 |
| 4/22/98 2:44 | 0.04 | 4/22/98 2:50 | 0.04 | 4/22/98 2:57 | 0.04 |
| 4/22/98 3:24 | 0.04 | 4/22/98 3:30 | 0.04 | 4/22/98 3:37 | 0.04 |
| 4/22/98 4:04 | 0.04 | 4/22/98 4:10 | 0.04 | 4/22/98 4:17 | 0.04 |
| 4/22/98 4:44 | 0.04 | 4/22/98 4:50 | 0.04 | 4/22/98 4:57 | 0.04 |
| 4/22/98 5:24 | 0.04 | 4/22/98 5:30 | 0.04 | 4/22/98 5:37 | 0.04 |
| 4/22/98 6:04 | 0.04 | 4/22/98 6:10 | 0.04 | 4/22/98 6:17 | 0.04 |

| Date and time | HD-1 | Date and time | HD-2 | Date and time | HD-3 |
|---|---|---|---|---|---|
| 4/22/98 6:44 | 0.04 | 4/22/98 6:50 | 0.03 | 4/22/98 6:57 | 0.04 |
| 4/22/98 7:24 | 0.03 | 4/22/98 7:30 | 0.03 | 4/22/98 7:37 | 0.04 |
| 4/22/98 8:04 | 0.04 | 4/22/98 8:10 | 0.04 | 4/22/98 8:17 | 0.04 |
| 4/22/98 8:44 | 0.04 | 4/22/98 8:50 | 0.04 | 4/22/98 8:57 | 0.04 |
| 4/22/98 9:32 | 0.04 | 4/22/98 9:39 | 0.03 | 4/22/98 9:45 | 0.03 |
| 4/22/98 10:12 | 0.03 | 4/22/98 10:19 | 0.03 | 4/22/98 10:25 | 0.03 |
| 4/22/98 10:52 | 0.03 | 4/22/98 10:59 | 0.03 | 4/22/98 11:05 | 0.03 |
| 4/22/98 11:32 | 0.06 | 4/22/98 11:39 | 0.05 | 4/22/98 11:45 | 0.06 |
| 4/22/98 12:12 | 0.09 | 4/22/98 12:19 | 0.07 | 4/22/98 12:25 | 0.09 |
| 4/22/98 12:52 | 0.11 | 4/22/98 12:59 | 0.09 | 4/22/98 13:05 | 0.09 |
| 4/22/98 13:32 | 0.09 | 4/22/98 13:39 | 0.09 | 4/22/98 13:45 | 0.09 |
| 4/22/98 14:12 | 0.08 | 4/22/98 14:19 | 0.07 | 4/22/98 14:25 | 0.07 |
| 4/22/98 14:52 | 0.06 | 4/22/98 14:59 | 0.06 | 4/22/98 15:05 | 0.05 |
| 4/22/98 15:32 | 0.06 | 4/22/98 15:39 | 0.05 | 4/22/98 15:45 | 0.05 |
| 4/22/98 16:12 | 0.05 | 4/22/98 16:19 | 0.05 | 4/22/98 16:25 | 0.05 |
| 4/22/98 16:52 | 0.05 | 4/22/98 16:59 | 0.05 | 4/22/98 17:05 | 0.05 |
| 4/22/98 17:32 | 0.04 | 4/22/98 17:39 | 0.05 | 4/22/98 17:45 | 0.04 |
| 4/22/98 18:12 | 0.04 | 4/22/98 18:19 | 0.04 | 4/22/98 18:25 | 0.04 |
| 4/22/98 18:52 | 0.04 | 4/22/98 18:59 | 0.04 | 4/22/98 19:05 | 0.04 |
| 4/22/98 19:32 | 0.04 | 4/22/98 19:39 | 0.03 | 4/22/98 19:45 | 0.03 |
| 4/22/98 20:12 | 0.03 | 4/22/98 20:19 | 0.03 | 4/22/98 20:25 | 0.03 |
| 4/22/98 20:52 | 0.03 | 4/22/98 20:59 | 0.03 | 4/22/98 21:05 | 0.03 |
| 4/22/98 21:32 | 0.03 | 4/22/98 21:39 | 0.03 | 4/22/98 21:45 | 0.03 |
| 4/22/98 22:12 | 0.03 | 4/22/98 22:19 | 0.03 | 4/22/98 22:25 | 0.03 |
| 4/22/98 22:52 | 0.03 | 4/22/98 22:59 | 0.03 | 4/22/98 23:05 | 0.03 |
| 4/22/98 23:32 | 0.03 | 4/22/98 23:39 | 0.03 | 4/22/98 23:45 | 0.03 |
| 4/23/98 0:12 | 0.03 | 4/23/98 0:19 | 0.03 | 4/23/98 0:25 | 0.03 |
| 4/23/98 0:52 | 0.03 | 4/23/98 0:59 | 0.03 | 4/23/98 1:05 | 0.02 |
| 4/23/98 1:32 | 0.03 | 4/23/98 1:39 | 0.02 | 4/23/98 1:45 | 0.02 |
| 4/23/98 2:12 | 0.02 | 4/23/98 2:19 | 0.02 | 4/23/98 2:25 | 0.02 |
| 4/23/98 2:52 | 0.02 | 4/23/98 2:59 | 0.02 | 4/23/98 3:05 | 0.02 |
| 4/23/98 3:32 | 0.02 | 4/23/98 3:39 | 0.02 | 4/23/98 3:45 | 0.02 |
| 4/23/98 4:12 | 0.02 | 4/23/98 4:19 | 0.02 | 4/23/98 4:25 | 0.02 |
| 4/23/98 4:52 | 0.02 | 4/23/98 4:59 | 0.02 | 4/23/98 5:05 | 0.02 |
| 4/23/98 5:32 | 0.02 | 4/23/98 5:39 | 0.02 | 4/23/98 5:45 | 0.02 |
| 4/23/98 6:12 | 0.02 | 4/23/98 6:19 | 0.02 | 4/23/98 6:25 | 0.01 |

| Date and time | HD-1 | Date and time | HD-2 | Date and time | HD-3 |
|---|---|---|---|---|---|
| 4/23/98 6:52 | 0.02 | 4/23/98 6:59 | 0.02 | 4/23/98 7:05 | 0.02 |
| 4/23/98 7:32 | 0.01 | 4/23/98 7:39 | 0.02 | 4/23/98 7:45 | 0.02 |
| 4/23/98 8:12 | 0.02 | 4/23/98 8:19 | 0.01 | 4/23/98 8:25 | 0.02 |
| 4/23/98 8:52 | 0.02 | 4/23/98 8:59 | 0.02 | 4/23/98 9:05 | 0.02 |
| 4/23/98 9:32 | 0.03 | 4/23/98 9:39 | 0.03 | 4/23/98 9:45 | 0.03 |
| 4/23/98 10:12 | 0.02 | 4/23/98 10:19 | 0.02 | 4/23/98 10:25 | 0.02 |
| 4/23/98 10:52 | 0.02 | 4/23/98 10:59 | 0.02 | 4/23/98 11:05 | 0.02 |
| 4/23/98 11:32 | 0.02 | 4/23/98 11:39 | 0.02 | 4/23/98 11:45 | 0.02 |
| 4/23/98 12:12 | 0.02 | 4/23/98 12:19 | 0.02 | 4/23/98 12:25 | 0.02 |
| 4/23/98 12:52 | 0.02 | 4/23/98 12:59 | 0.01 | | |

Table 5-9. $O_2$ (mole [volume] percent) by time, heater drift, April 1998.

| Date and time | HD-1 | Date and time | HD-2 | Date and time | HD-3 |
|---|---|---|---|---|---|
| 4/21/98 10:24 | 20.87 | 4/21/98 10:31 | 20.75 | 4/21/98 10:37 | 20.82 |
| 4/21/98 11:04 | 20.92 | 4/21/98 11:11 | 20.91 | 4/21/98 11:17 | 20.92 |
| 4/21/98 12:04 | 20.85 | 4/21/98 12:10 | 20.85 | 4/21/98 12:17 | 20.85 |
| 4/21/98 12:44 | 20.86 | 4/21/98 12:50 | 20.86 | 4/21/98 12:57 | 20.86 |
| 4/21/98 13:24 | 20.87 | 4/21/98 13:30 | 20.87 | 4/21/98 13:37 | 20.87 |
| 4/21/98 14:04 | 20.88 | 4/21/98 14:10 | 20.88 | 4/21/98 14:17 | 20.88 |
| 4/21/98 14:44 | 20.88 | 4/21/98 14:50 | 20.88 | 4/21/98 14:57 | 20.88 |
| 4/21/98 15:24 | 20.88 | 4/21/98 15:30 | 20.88 | 4/21/98 15:37 | 20.88 |
| 4/21/98 16:04 | 20.88 | 4/21/98 16:10 | 20.88 | 4/21/98 16:17 | 20.88 |
| 4/21/98 16:44 | 20.88 | 4/21/98 16:50 | 20.88 | 4/21/98 16:57 | 20.88 |
| 4/21/98 17:24 | 20.88 | 4/21/98 17:30 | 20.88 | 4/21/98 17:37 | 20.88 |
| 4/21/98 18:04 | 20.88 | 4/21/98 18:10 | 20.88 | 4/21/98 18:17 | 20.88 |
| 4/21/98 18:44 | 20.88 | 4/21/98 18:50 | 20.88 | 4/21/98 18:57 | 20.88 |
| 4/21/98 19:24 | 20.88 | 4/21/98 19:30 | 20.88 | 4/21/98 19:37 | 20.88 |
| 4/21/98 20:04 | 20.88 | 4/21/98 20:10 | 20.88 | 4/21/98 20:17 | 20.88 |
| 4/21/98 20:44 | 20.88 | 4/21/98 20:50 | 20.88 | 4/21/98 20:57 | 20.88 |
| 4/21/98 21:24 | 20.88 | 4/21/98 21:30 | 20.88 | 4/21/98 21:37 | 20.88 |
| 4/21/98 22:04 | 20.88 | 4/21/98 22:10 | 20.87 | 4/21/98 22:17 | 20.88 |
| 4/21/98 22:44 | 20.88 | 4/21/98 22:50 | 20.87 | 4/21/98 22:57 | 20.88 |
| 4/21/98 23:24 | 20.87 | 4/21/98 23:30 | 20.87 | 4/21/98 23:37 | 20.87 |
| 4/22/98 0:04 | 20.87 | 4/22/98 0:10 | 20.86 | 4/22/98 0:17 | 20.86 |
| 4/22/98 0:44 | 20.87 | 4/22/98 0:50 | 20.86 | 4/22/98 0:57 | 20.86 |
| 4/22/98 1:24 | 20.87 | 4/22/98 1:30 | 20.86 | 4/22/98 1:37 | 20.87 |

| Date and time | HD-1 | Date and time | HD-2 | Date and time | HD-3 |
|---|---|---|---|---|---|
| 4/22/98 2:04 | 20.86 | 4/22/98 2:10 | 20.86 | 4/22/98 2:17 | 20.86 |
| 4/22/98 2:44 | 20.86 | 4/22/98 2:50 | 20.86 | 4/22/98 2:57 | 20.86 |
| 4/22/98 3:24 | 20.86 | 4/22/98 3:30 | 20.86 | 4/22/98 3:37 | 20.86 |
| 4/22/98 4:04 | 20.87 | 4/22/98 4:10 | 20.86 | 4/22/98 4:17 | 20.86 |
| 4/22/98 4:44 | 20.87 | 4/22/98 4:50 | 20.86 | 4/22/98 4:57 | 20.86 |
| 4/22/98 5:24 | 20.87 | 4/22/98 5:30 | 20.86 | 4/22/98 5:37 | 20.86 |
| 4/22/98 6:04 | 20.86 | 4/22/98 6:10 | 20.86 | 4/22/98 6:17 | 20.86 |
| 4/22/98 6:44 | 20.86 | 4/22/98 6:50 | 20.86 | 4/22/98 6:57 | 20.86 |
| 4/22/98 7:24 | 20.86 | 4/22/98 7:30 | 20.86 | 4/22/98 7:37 | 20.86 |
| 4/22/98 8:04 | 20.86 | 4/22/98 8:10 | 20.86 | 4/22/98 8:17 | 20.86 |
| 4/22/98 8:44 | 20.86 | 4/22/98 8:50 | 20.86 | 4/22/98 8:57 | 20.86 |
| 4/22/98 9:32 | 20.84 | 4/22/98 9:39 | 20.83 | 4/22/98 9:45 | 20.84 |
| 4/22/98 10:12 | 20.84 | 4/22/98 10:19 | 20.84 | 4/22/98 10:25 | 20.84 |
| 4/22/98 10:52 | 20.84 | 4/22/98 10:59 | 20.83 | 4/22/98 11:05 | 20.83 |
| 4/22/98 11:32 | 20.83 | 4/22/98 11:39 | 20.82 | 4/22/98 11:45 | 20.82 |
| 4/22/98 12:12 | 20.8 | 4/22/98 12:19 | 20.8 | 4/22/98 12:25 | 20.8 |
| 4/22/98 12:52 | 20.78 | 4/22/98 12:59 | 20.78 | 4/22/98 13:05 | 20.78 |
| 4/22/98 13:32 | 20.77 | 4/22/98 13:39 | 20.77 | 4/22/98 13:45 | 20.77 |
| 4/22/98 14:12 | 20.75 | 4/22/98 14:19 | 20.75 | 4/22/98 14:25 | 20.75 |
| 4/22/98 14:52 | 20.74 | 4/22/98 14:59 | 20.74 | 4/22/98 15:05 | 20.73 |
| 4/22/98 15:32 | 20.73 | 4/22/98 15:39 | 20.72 | 4/22/98 15:45 | 20.72 |
| 4/22/98 16:12 | 20.72 | 4/22/98 16:19 | 20.71 | 4/22/98 16:25 | 20.71 |
| 4/22/98 16:52 | 20.69 | 4/22/98 16:59 | 20.69 | 4/22/98 17:05 | 20.68 |
| 4/22/98 17:32 | 20.67 | 4/22/98 17:39 | 20.66 | 4/22/98 17:45 | 20.66 |
| 4/22/98 18:12 | 20.65 | 4/22/98 18:19 | 20.64 | 4/22/98 18:25 | 20.64 |
| 4/22/98 18:52 | 20.62 | 4/22/98 18:59 | 20.61 | 4/22/98 19:05 | 20.6 |
| 4/22/98 19:32 | 20.58 | 4/22/98 19:39 | 20.56 | 4/22/98 19:45 | 20.56 |
| 4/22/98 20:12 | 20.53 | 4/22/98 20:19 | 20.52 | 4/22/98 20:25 | 20.52 |
| 4/22/98 20:52 | 20.5 | 4/22/98 20:59 | 20.49 | 4/22/98 21:05 | 20.5 |
| 4/22/98 21:32 | 20.49 | 4/22/98 21:39 | 20.49 | 4/22/98 21:45 | 20.49 |
| 4/22/98 22:12 | 20.49 | 4/22/98 22:19 | 20.48 | 4/22/98 22:25 | 20.48 |
| 4/22/98 22:52 | 20.48 | 4/22/98 22:59 | 20.48 | 4/22/98 23:05 | 20.48 |
| 4/22/98 23:32 | 20.48 | 4/22/98 23:39 | 20.47 | 4/22/98 23:45 | 20.48 |
| 4/23/98 0:12 | 20.48 | 4/23/98 0:19 | 20.47 | 4/23/98 0:25 | 20.47 |
| 4/23/98 0:52 | 20.48 | 4/23/98 0:59 | 20.47 | 4/23/98 1:05 | 20.47 |
| 4/23/98 1:32 | 20.47 | 4/23/98 1:39 | 20.47 | 4/23/98 1:45 | 20.47 |

| Date and time | HD-1 | Date and time | HD-2 | Date and time | HD-3 |
|---|---|---|---|---|---|
| 4/23/98 2:12 | 20.47 | 4/23/98 2:19 | 20.47 | 4/23/98 2:25 | 20.47 |
| 4/23/98 2:52 | 20.47 | 4/23/98 2:59 | 20.47 | 4/23/98 3:05 | 20.47 |
| 4/23/98 3:32 | 20.47 | 4/23/98 3:39 | 20.47 | 4/23/98 3:45 | 20.47 |
| 4/23/98 4:12 | 20.47 | 4/23/98 4:19 | 20.47 | 4/23/98 4:25 | 20.47 |
| 4/23/98 4:52 | 20.47 | 4/23/98 4:59 | 20.47 | 4/23/98 5:05 | 20.47 |
| 4/23/98 5:32 | 20.47 | 4/23/98 5:39 | 20.47 | 4/23/98 5:45 | 20.47 |
| 4/23/98 6:12 | 20.47 | 4/23/98 6:19 | 20.47 | 4/23/98 6:25 | 20.47 |
| 4/23/98 6:52 | 20.47 | 4/23/98 6:59 | 20.47 | 4/23/98 7:05 | 20.47 |
| 4/23/98 7:32 | 20.47 | 4/23/98 7:39 | 20.47 | 4/23/98 7:45 | 20.47 |
| 4/23/98 8:12 | 20.47 | 4/23/98 8:19 | 20.47 | 4/23/98 8:25 | 20.47 |
| 4/23/98 8:52 | 20.47 | 4/23/98 8:59 | 20.47 | 4/23/98 9:05 | 20.47 |
| 4/23/98 9:32 | 20.47 | 4/23/98 9:39 | 20.46 | 4/23/98 9:45 | 20.47 |
| 4/23/98 10:12 | 20.47 | 4/23/98 10:19 | 20.46 | 4/23/98 10:25 | 20.46 |
| 4/23/98 10:52 | 20.47 | 4/23/98 10:59 | 20.46 | 4/23/98 11:05 | 20.46 |
| 4/23/98 11:32 | 20.47 | 4/23/98 11:39 | 20.46 | 4/23/98 11:45 | 20.47 |
| 4/23/98 12:12 | 20.47 | 4/23/98 12:19 | 20.46 | 4/23/98 12:25 | 20.47 |
| 4/23/98 12:52 | 20.47 | 4/23/98 12:59 | 20.46 | | |

Table 5-10. $O_2$ (mole [volume] percent) by time, connecting drift, April 1998.

| Date and time | CD-1 | Date and time | CD-2 | Date and time | CD-3 |
|---|---|---|---|---|---|
| 4/21/98 10:44 | 20.89 | 4/21/98 10:50 | 20.91 | 4/21/98 10:57 | 20.91 |
| 4/21/98 11:24 | 20.93 | 4/21/98 11:30 | 20.93 | 4/21/98 11:37 | 20.93 |
| 4/21/98 12:23 | 20.86 | 4/21/98 12:30 | 20.87 | 4/21/98 12:36 | 20.87 |
| 4/21/98 13:03 | 20.88 | 4/21/98 13:10 | 20.88 | 4/21/98 13:16 | 20.89 |
| 4/21/98 13:43 | 20.89 | 4/21/98 13:50 | 20.89 | 4/21/98 13:56 | 20.89 |
| 4/21/98 14:23 | 20.89 | 4/21/98 14:30 | 20.89 | 4/21/98 14:36 | 20.89 |
| 4/21/98 15:03 | 20.89 | 4/21/98 15:10 | 20.89 | 4/21/98 15:16 | 20.89 |
| 4/21/98 15:43 | 20.88 | 4/21/98 15:50 | 20.88 | 4/21/98 15:56 | 20.89 |
| 4/21/98 16:23 | 20.89 | 4/21/98 16:30 | 20.89 | 4/21/98 16:36 | 20.89 |
| 4/21/98 17:03 | 20.89 | 4/21/98 17:10 | 20.89 | 4/21/98 17:16 | 20.89 |
| 4/21/98 17:43 | 20.89 | 4/21/98 17:50 | 20.89 | 4/21/98 17:56 | 20.89 |
| 4/21/98 18:23 | 20.9 | 4/21/98 18:30 | 20.9 | 4/21/98 18:36 | 20.9 |
| 4/21/98 19:03 | 20.9 | 4/21/98 19:10 | 20.9 | 4/21/98 19:16 | 20.9 |
| 4/21/98 19:43 | 20.9 | 4/21/98 19:50 | 20.89 | 4/21/98 19:56 | 20.89 |
| 4/21/98 20:23 | 20.89 | 4/21/98 20:30 | 20.89 | 4/21/98 20:36 | 20.89 |
| 4/21/98 21:03 | 20.89 | 4/21/98 21:10 | 20.89 | 4/21/98 21:16 | 20.89 |

| Date and time | CD-1 | Date and time | CD-2 | Date and time | CD-3 |
|---|---|---|---|---|---|
| 4/21/98 21:43 | 20.89 | 4/21/98 21:50 | 20.89 | 4/21/98 21:56 | 20.89 |
| 4/21/98 22:23 | 20.88 | 4/21/98 22:30 | 20.88 | 4/21/98 22:36 | 20.88 |
| 4/21/98 23:03 | 20.88 | 4/21/98 23:10 | 20.88 | 4/21/98 23:16 | 20.88 |
| 4/21/98 23:43 | 20.88 | 4/21/98 23:50 | 20.88 | 4/21/98 23:56 | 20.88 |
| 4/22/98 0:23 | 20.88 | 4/22/98 0:30 | 20.88 | 4/22/98 0:36 | 20.88 |
| 4/22/98 1:03 | 20.88 | 4/22/98 1:10 | 20.88 | 4/22/98 1:16 | 20.88 |
| 4/22/98 1:43 | 20.88 | 4/22/98 1:50 | 20.88 | 4/22/98 1:56 | 20.88 |
| 4/22/98 2:23 | 20.88 | 4/22/98 2:30 | 20.87 | 4/22/98 2:36 | 20.88 |
| 4/22/98 3:03 | 20.88 | 4/22/98 3:10 | 20.88 | 4/22/98 3:16 | 20.88 |
| 4/22/98 3:43 | 20.88 | 4/22/98 3:50 | 20.87 | 4/22/98 3:56 | 20.88 |
| 4/22/98 4:23 | 20.88 | 4/22/98 4:30 | 20.88 | 4/22/98 4:36 | 20.88 |
| 4/22/98 5:03 | 20.88 | 4/22/98 5:10 | 20.88 | 4/22/98 5:16 | 20.88 |
| 4/22/98 5:43 | 20.88 | 4/22/98 5:50 | 20.88 | 4/22/98 5:56 | 20.88 |
| 4/22/98 6:23 | 20.88 | 4/22/98 6:30 | 20.88 | 4/22/98 6:36 | 20.88 |
| 4/22/98 7:03 | 20.88 | 4/22/98 7:10 | 20.88 | 4/22/98 7:16 | 20.88 |
| 4/22/98 7:43 | 20.88 | 4/22/98 7:50 | 20.88 | 4/22/98 7:56 | 20.88 |
| 4/22/98 8:23 | 20.88 | 4/22/98 8:30 | 20.88 | 4/22/98 8:36 | 20.88 |
| 4/22/98 9:52 | 20.85 | 4/22/98 9:58 | 20.85 | 4/22/98 10:05 | 20.85 |
| 4/22/98 10:32 | 20.85 | 4/22/98 10:38 | 20.84 | 4/22/98 10:45 | 20.84 |
| 4/22/98 11:12 | 20.84 | 4/22/98 11:18 | 20.83 | 4/22/98 11:25 | 20.83 |
| 4/22/98 11:52 | 20.83 | 4/22/98 11:58 | 20.82 | 4/22/98 12:05 | 20.82 |
| 4/22/98 12:32 | 20.8 | 4/22/98 12:38 | 20.8 | 4/22/98 12:45 | 20.8 |
| 4/22/98 13:12 | 20.79 | 4/22/98 13:18 | 20.79 | 4/22/98 13:25 | 20.79 |
| 4/22/98 13:52 | 20.78 | 4/22/98 13:58 | 20.77 | 4/22/98 14:05 | 20.77 |
| 4/22/98 14:32 | 20.77 | 4/22/98 14:38 | 20.77 | 4/22/98 14:45 | 20.77 |
| 4/22/98 15:12 | 20.76 | 4/22/98 15:18 | 20.75 | 4/22/98 15:25 | 20.75 |
| 4/22/98 15:52 | 20.74 | 4/22/98 15:58 | 20.74 | 4/22/98 16:05 | 20.74 |
| 4/22/98 16:32 | 20.72 | 4/22/98 16:38 | 20.72 | 4/22/98 16:45 | 20.72 |
| 4/22/98 17:12 | 20.71 | 4/22/98 17:18 | 20.7 | 4/22/98 17:25 | 20.7 |
| 4/22/98 17:52 | 20.68 | 4/22/98 17:58 | 20.68 | 4/22/98 18:05 | 20.68 |
| 4/22/98 18:32 | 20.66 | 4/22/98 18:38 | 20.65 | 4/22/98 18:45 | 20.65 |
| 4/22/98 19:12 | 20.62 | 4/22/98 19:18 | 20.61 | 4/22/98 19:25 | 20.61 |
| 4/22/98 19:52 | 20.58 | 4/22/98 19:58 | 20.58 | 4/22/98 20:05 | 20.56 |
| 4/22/98 20:32 | 20.54 | 4/22/98 20:38 | 20.53 | 4/22/98 20:45 | 20.53 |
| 4/22/98 21:12 | 20.52 | 4/22/98 21:18 | 20.52 | 4/22/98 21:25 | 20.52 |
| 4/22/98 21:52 | 20.51 | 4/22/98 21:58 | 20.5 | 4/22/98 22:05 | 20.5 |

| Date and time | CD-1 | Date and time | CD-2 | Date and time | CD-3 |
|---|---|---|---|---|---|
| 4/22/98 22:32 | 20.5 | 4/22/98 22:38 | 20.49 | 4/22/98 22:45 | 20.49 |
| 4/22/98 23:12 | 20.5 | 4/22/98 23:18 | 20.5 | 4/22/98 23:25 | 20.5 |
| 4/22/98 23:52 | 20.5 | 4/22/98 23:58 | 20.49 | 4/23/98 0:05 | 20.49 |
| 4/23/98 0:32 | 20.49 | 4/23/98 0:38 | 20.49 | 4/23/98 0:45 | 20.5 |
| 4/23/98 1:12 | 20.49 | 4/23/98 1:18 | 20.49 | 4/23/98 1:25 | 20.49 |
| 4/23/98 1:52 | 20.49 | 4/23/98 1:58 | 20.49 | 4/23/98 2:05 | 20.49 |
| 4/23/98 2:32 | 20.49 | 4/23/98 2:38 | 20.49 | 4/23/98 2:45 | 20.49 |
| 4/23/98 3:12 | 20.49 | 4/23/98 3:18 | 20.49 | 4/23/98 3:25 | 20.49 |
| 4/23/98 3:52 | 20.49 | 4/23/98 3:58 | 20.49 | 4/23/98 4:05 | 20.49 |
| 4/23/98 4:32 | 20.49 | 4/23/98 4:38 | 20.49 | 4/23/98 4:45 | 20.49 |
| 4/23/98 5:12 | 20.49 | 4/23/98 5:18 | 20.49 | 4/23/98 5:25 | 20.49 |
| 4/23/98 5:52 | 20.49 | 4/23/98 5:58 | 20.49 | 4/23/98 6:05 | 20.49 |
| 4/23/98 6:32 | 20.49 | 4/23/98 6:38 | 20.49 | 4/23/98 6:45 | 20.49 |
| 4/23/98 7:12 | 20.49 | 4/23/98 7:18 | 20.49 | 4/23/98 7:25 | 20.49 |
| 4/23/98 7:52 | 20.49 | 4/23/98 7:58 | 20.49 | 4/23/98 8:05 | 20.49 |
| 4/23/98 8:32 | 20.49 | 4/23/98 8:38 | 20.49 | 4/23/98 8:45 | 20.49 |
| 4/23/98 9:12 | 20.48 | 4/23/98 9:18 | 20.48 | 4/23/98 9:25 | 20.48 |
| 4/23/98 9:52 | 20.48 | 4/23/98 9:58 | 20.48 | 4/23/98 10:05 | 20.48 |
| 4/23/98 10:32 | 20.48 | 4/23/98 10:38 | 20.48 | 4/23/98 10:45 | 20.48 |
| 4/23/98 11:12 | 20.47 | 4/23/98 11:18 | 20.49 | 4/23/98 11:25 | 20.48 |
| 4/23/98 11:52 | 20.48 | 4/23/98 11:58 | 20.49 | 4/23/98 12:05 | 20.49 |
| 4/23/98 12:32 | 20.48 | 4/23/98 12:38 | 20.48 | 4/23/98 12:45 | 20.48 |

Table 5-11. $CO_2$ (mole [volume] percent) by time, heater drift, June 1998.

| Date and time | HD-1 | Date and time | HD-2 | Date and time | HD-3 |
|---|---|---|---|---|---|
| 6/1/98 14:56 | 0.04 | 6/1/98 15:03 | 0.05 | 6/1/98 15:10 | 0.05 |
| 6/1/98 15:39 | 0.06 | 6/1/98 15:46 | 0.06 | 6/1/98 15:53 | 0.06 |
| 6/1/98 16:22 | 0.07 | 6/1/98 16:29 | 0.06 | 6/1/98 16:36 | 0.06 |
| 6/1/98 17:05 | 0.06 | 6/1/98 17:12 | 0.06 | 6/1/98 17:19 | 0.06 |
| 6/1/98 17:48 | 0.06 | 6/1/98 17:55 | 0.06 | 6/1/98 18:02 | 0.06 |
| 6/1/98 18:31 | 0.05 | 6/1/98 18:38 | 0.05 | 6/1/98 18:45 | 0.05 |
| 6/1/98 19:14 | 0.05 | 6/1/98 19:21 | 0.05 | 6/1/98 19:28 | 0.05 |
| 6/1/98 19:57 | 0.05 | 6/1/98 20:04 | 0.05 | 6/1/98 20:11 | 0.05 |
| 6/1/98 20:40 | 0.05 | 6/1/98 20:47 | 0.05 | 6/1/98 20:54 | 0.06 |
| 6/1/98 21:23 | 0.06 | 6/1/98 21:30 | 0.06 | 6/1/98 21:37 | 0.06 |
| 6/1/98 22:06 | 0.06 | 6/1/98 22:13 | 0.06 | 6/1/98 22:20 | 0.06 |
| 6/1/98 22:49 | 0.06 | 6/1/98 22:56 | 0.06 | 6/1/98 23:03 | 0.06 |
| 6/1/98 23:32 | 0.06 | 6/1/98 23:39 | 0.06 | 6/1/98 23:46 | 0.06 |
| 6/2/98 0:15 | 0.06 | 6/2/98 0:22 | 0.05 | 6/2/98 0:29 | 0.05 |
| 6/2/98 0:58 | 0.05 | 6/2/98 1:05 | 0.05 | 6/2/98 1:12 | 0.05 |
| 6/2/98 1:41 | 0.05 | 6/2/98 1:48 | 0.05 | 6/2/98 1:55 | 0.05 |
| 6/2/98 2:24 | 0.05 | 6/2/98 2:31 | 0.05 | 6/2/98 2:38 | 0.05 |
| 6/2/98 3:07 | 0.05 | 6/2/98 3:14 | 0.05 | 6/2/98 3:21 | 0.05 |
| 6/2/98 3:50 | 0.05 | 6/2/98 3:57 | 0.05 | 6/2/98 4:04 | 0.05 |
| 6/2/98 4:33 | 0.05 | 6/2/98 4:40 | 0.05 | 6/2/98 4:47 | 0.05 |
| 6/2/98 5:16 | 0.05 | 6/2/98 5:23 | 0.05 | 6/2/98 5:30 | 0.05 |
| 6/2/98 5:59 | 0.05 | 6/2/98 6:06 | 0.05 | 6/2/98 6:13 | 0.06 |
| 6/2/98 6:42 | 0.05 | 6/2/98 6:49 | 0.05 | 6/2/98 6:56 | 0.05 |
| 6/2/98 7:25 | 0.06 | 6/2/98 7:32 | 0.06 | 6/2/98 7:39 | 0.05 |
| 6/2/98 8:08 | 0.05 | 6/2/98 8:15 | 0.05 | 6/2/98 8:22 | 0.05 |
| 6/2/98 8:51 | 0.06 | 6/2/98 8:58 | 0.07 | 6/2/98 9:05 | 0.07 |

Table 5-12. $CO_2$ (mole [volume] percent) by time, connecting drift, June 1998.

| Date and time | CD-1 | Date and time | CD-2 | Date and time | CD-3 |
|---|---|---|---|---|---|
| 6/1/98 15:17 | 0.05 | 6/1/98 15:24 | 0.05 | 6/1/98 15:31 | 0.05 |
| 6/1/98 16:00 | 0.06 | 6/1/98 16:07 | 0.06 | 6/1/98 16:14 | 0.06 |
| 6/1/98 16:43 | 0.06 | 6/1/98 16:50 | 0.06 | 6/1/98 16:57 | 0.06 |
| 6/1/98 17:26 | 0.05 | 6/1/98 17:33 | 0.05 | 6/1/98 17:40 | 0.05 |
| 6/1/98 18:09 | 0.05 | 6/1/98 18:16 | 0.05 | 6/1/98 18:23 | 0.05 |
| 6/1/98 18:52 | 0.05 | 6/1/98 18:59 | 0.05 | 6/1/98 19:06 | 0.05 |
| 6/1/98 19:35 | 0.05 | 6/1/98 19:42 | 0.05 | 6/1/98 19:49 | 0.05 |
| 6/1/98 20:18 | 0.05 | 6/1/98 20:25 | 0.05 | 6/1/98 20:32 | 0.05 |
| 6/1/98 21:01 | 0.05 | 6/1/98 21:08 | 0.05 | 6/1/98 21:15 | 0.05 |
| 6/1/98 21:44 | 0.05 | 6/1/98 21:51 | 0.05 | 6/1/98 21:58 | 0.05 |
| 6/1/98 22:27 | 0.05 | 6/1/98 22:34 | 0.05 | 6/1/98 22:41 | 0.05 |
| 6/1/98 23:10 | 0.05 | 6/1/98 23:17 | 0.05 | 6/1/98 23:24 | 0.06 |
| 6/1/98 23:53 | 0.06 | 6/2/98 0:00 | 0.05 | 6/2/98 0:07 | 0.05 |
| 6/2/98 0:36 | 0.05 | 6/2/98 0:43 | 0.05 | 6/2/98 0:50 | 0.05 |
| 6/2/98 1:19 | 0.04 | 6/2/98 1:26 | 0.04 | 6/2/98 1:33 | 0.04 |
| 6/2/98 2:02 | 0.04 | 6/2/98 2:09 | 0.04 | 6/2/98 2:16 | 0.04 |
| 6/2/98 2:45 | 0.04 | 6/2/98 2:52 | 0.04 | 6/2/98 2:59 | 0.04 |
| 6/2/98 3:28 | 0.04 | 6/2/98 3:35 | 0.04 | 6/2/98 3:42 | 0.05 |
| 6/2/98 4:11 | 0.05 | 6/2/98 4:18 | 0.05 | 6/2/98 4:25 | 0.05 |
| 6/2/98 4:54 | 0.05 | 6/2/98 5:01 | 0.04 | 6/2/98 5:08 | 0.04 |
| 6/2/98 5:37 | 0.05 | 6/2/98 5:44 | 0.05 | 6/2/98 5:51 | 0.05 |
| 6/2/98 6:20 | 0.05 | 6/2/98 6:27 | 0.05 | 6/2/98 6:34 | 0.05 |
| 6/2/98 7:03 | 0.05 | 6/2/98 7:10 | 0.05 | 6/2/98 7:17 | 0.05 |
| 6/2/98 7:46 | 0.05 | 6/2/98 7:53 | 0.05 | 6/2/98 8:00 | 0.05 |
| 6/2/98 8:29 | 0.05 | 6/2/98 8:36 | 0.05 | 6/2/98 8:43 | 0.06 |
| 6/2/98 9:12 | 0.06 | 6/2/98 9:19 | 0.06 | 6/2/98 9:26 | 0.06 |

Table 5-13. $CO_2$ (mole [volume] percent) by time, access/observation drift, June 1998.

| Date and time | OD-1 | Date and time | OD-2 | Date and time | OD-3 |
|---|---|---|---|---|---|
| 6/2/98 13:13 | 0.04 | 6/2/98 13:20 | 0.03 | 6/2/98 13:27 | 0.04 |
| 6/2/98 14:10 | 0.04 | 6/2/98 14:17 | 0.04 | 6/2/98 14:24 | 0.04 |
| 6/2/98 15:07 | 0.03 | 6/2/98 15:14 | 0.04 | 6/2/98 15:21 | 0.04 |
| 6/2/98 16:04 | 0.04 | 6/2/98 16:11 | 0.04 | 6/2/98 16:18 | 0.04 |
| 6/2/98 17:01 | 0.03 | 6/2/98 17:08 | 0.03 | 6/2/98 17:15 | 0.03 |
| 6/2/98 17:58 | 0.03 | 6/2/98 18:05 | 0.02 | 6/2/98 18:12 | 0.02 |
| 6/2/98 18:55 | 0.02 | 6/2/98 19:02 | 0.02 | 6/2/98 19:09 | 0.02 |
| 6/2/98 19:52 | 0.01 | 6/2/98 19:59 | 0.01 | 6/2/98 20:06 | 0.01 |
| 6/2/98 20:49 | 0.04 | 6/2/98 20:56 | 0.04 | 6/2/98 21:03 | 0.04 |
| 6/2/98 21:46 | 0.05 | 6/2/98 21:53 | 0.05 | 6/2/98 22:00 | 0.05 |
| 6/2/98 22:43 | 0.05 | 6/2/98 22:50 | 0.05 | 6/2/98 22:57 | 0.05 |
| 6/2/98 23:40 | 0.05 | 6/2/98 23:47 | 0.05 | 6/2/98 23:54 | 0.05 |
| 6/3/98 0:37 | 0.05 | 6/3/98 0:44 | 0.05 | 6/3/98 0:51 | 0.05 |
| 6/3/98 1:34 | 0.05 | 6/3/98 1:41 | 0.05 | 6/3/98 1:48 | 0.05 |
| 6/3/98 2:31 | 0.05 | 6/3/98 2:38 | 0.04 | 6/3/98 2:45 | 0.04 |
| 6/3/98 3:28 | 0.05 | 6/3/98 3:35 | 0.04 | 6/3/98 3:42 | 0.04 |
| 6/3/98 4:25 | 0.05 | 6/3/98 4:32 | 0.05 | 6/3/98 4:39 | 0.05 |
| 6/3/98 5:22 | 0.05 | 6/3/98 5:29 | 0.05 | 6/3/98 5:36 | 0.05 |
| 6/3/98 6:19 | 0.05 | 6/3/98 6:26 | 0.05 | 6/3/98 6:33 | 0.05 |
| 6/3/98 7:16 | 0.06 | 6/3/98 7:23 | 0.06 | 6/3/98 7:30 | 0.06 |
| 6/3/98 8:13 | 0.06 | 6/3/98 8:20 | 0.06 | 6/3/98 8:27 | 0.07 |
| 6/3/98 10:12 | 0.03 | 6/3/98 10:19 | 0.03 | 6/3/98 10:26 | 0.03 |
| 6/3/98 11:16 | 0.03 | 6/3/98 11:23 | 0.03 | 6/3/98 11:30 | 0.03 |
| 6/3/98 12:20 | 0.03 | 6/3/98 12:27 | 0.03 | 6/3/98 12:34 | 0.02 |
| 6/3/98 13:24 | 0.04 | 6/3/98 13:31 | 0.04 | 6/3/98 13:38 | 0.04 |
| 6/3/98 14:28 | 0.04 | 6/3/98 14:35 | 0.05 | 6/3/98 14:42 | 0.05 |
| 6/3/98 15:32 | 0.04 | 6/3/98 15:39 | 0.05 | 6/3/98 15:46 | 0.05 |
| 6/3/98 16:36 | 0.04 | 6/3/98 16:43 | 0.04 | 6/3/98 16:50 | 0.04 |
| 6/3/98 17:40 | 0.04 | 6/3/98 17:47 | 0.04 | 6/3/98 17:54 | 0.03 |
| 6/3/98 18:44 | 0.04 | 6/3/98 18:51 | 0.04 | 6/3/98 18:58 | 0.04 |
| 6/3/98 19:48 | 0.04 | 6/3/98 19:55 | 0.04 | 6/3/98 20:02 | 0.04 |
| 6/3/98 20:52 | 0.05 | 6/3/98 20:59 | 0.05 | 6/3/98 21:06 | 0.05 |
| 6/3/98 21:56 | 0.05 | 6/3/98 22:03 | 0.05 | 6/3/98 22:10 | 0.05 |
| 6/3/98 23:00 | 0.06 | 6/3/98 23:07 | 0.05 | 6/3/98 23:14 | 0.05 |
| 6/4/98 0:04 | 0.05 | 6/4/98 0:11 | 0.05 | 6/4/98 0:18 | 0.05 |

| Date and time | OD-1 | Date and time | OD-2 | Date and time | OD-3 |
|---|---|---|---|---|---|
| 6/4/98 1:08 | 0.05 | 6/4/98 1:15 | 0.05 | 6/4/98 1:22 | 0.05 |
| 6/4/98 2:12 | 0.05 | 6/4/98 2:19 | 0.05 | 6/4/98 2:26 | 0.05 |
| 6/4/98 3:16 | 0.05 | 6/4/98 3:23 | 0.05 | 6/4/98 3:30 | 0.05 |
| 6/4/98 4:20 | 0.04 | 6/4/98 4:27 | 0.05 | 6/4/98 4:34 | 0.04 |
| 6/4/98 5:24 | 0.04 | 6/4/98 5:31 | 0.04 | 6/4/98 5:38 | 0.04 |
| 6/4/98 6:28 | 0.04 | 6/4/98 6:35 | 0.05 | 6/4/98 6:42 | 0.05 |
| 6/4/98 7:32 | 0.05 | 6/4/98 7:39 | 0.05 | 6/4/98 7:46 | 0.05 |
| 6/4/98 8:36 | 0.05 | | | | |

Table 5-14. $CO_2$ (mole [volume] percent) by time, Boreholes 54, 55, and 59, June 1998.

| Date and time | 54-1 | Date and time | 54-3 | Date and time | 54-5 |
|---|---|---|---|---|---|
| 6/2/98 12:38 | 0.05 | 6/2/98 12:45 | 0.03 | 6/2/98 12:52 | 0.04 |
| 6/2/98 13:35 | 0.05 | 6/2/98 13:42 | 0.03 | 6/2/98 13:49 | 0.04 |
| 6/2/98 14:32 | 0.09 | 6/2/98 14:39 | 0.04 | 6/2/98 14:46 | 0.04 |
| 6/2/98 15:29 | 0.1 | 6/2/98 15:36 | 0.03 | 6/2/98 15:43 | 0.04 |
| 6/2/98 16:26 | 0.1 | 6/2/98 16:33 | 0.04 | 6/2/98 16:40 | 0.04 |
| 6/2/98 17:23 | 0.1 | 6/2/98 17:30 | 0.02 | 6/2/98 17:37 | 0.04 |
| 6/2/98 18:20 | 0.09 | 6/2/98 18:27 | 0.02 | 6/2/98 18:34 | 0.03 |
| 6/2/98 19:17 | 0.08 | 6/2/98 19:24 | 0.01 | 6/2/98 19:31 | 0.02 |
| 6/2/98 20:14 | 0.07 | 6/2/98 20:21 | 0.01 | 6/2/98 20:28 | 0.05 |
| 6/2/98 21:11 | 0.11 | 6/2/98 21:18 | 0.05 | 6/2/98 21:25 | 0.05 |
| 6/2/98 22:08 | 0.11 | 6/2/98 22:15 | 0.05 | 6/2/98 22:22 | 0.06 |
| 6/2/98 23:05 | 0.11 | 6/2/98 23:12 | 0.05 | 6/2/98 23:19 | 0.06 |
| 6/3/98 0:02 | 0.11 | 6/3/98 0:09 | 0.05 | 6/3/98 0:16 | 0.06 |
| 6/3/98 0:59 | 0.11 | 6/3/98 1:06 | 0.05 | 6/3/98 1:13 | 0.06 |
| 6/3/98 1:56 | 0.11 | 6/3/98 2:03 | 0.05 | 6/3/98 2:10 | 0.05 |
| 6/3/98 2:53 | 0.11 | 6/3/98 3:00 | 0.04 | 6/3/98 3:07 | 0.05 |
| 6/3/98 3:50 | 0.04 | 6/3/98 3:57 | 0.04 | 6/3/98 4:04 | 0.05 |
| 6/3/98 4:47 | 0.08 | 6/3/98 4:54 | 0.05 | 6/3/98 5:01 | 0.06 |
| 6/3/98 5:44 | 0.05 | 6/3/98 5:51 | 0.05 | 6/3/98 5:58 | 0.06 |
| 6/3/98 6:41 | 0.06 | 6/3/98 6:48 | 0.05 | 6/3/98 6:55 | 0.06 |
| 6/3/98 7:38 | 0.07 | 6/3/98 7:45 | 0.05 | 6/3/98 7:52 | 0.06 |
| 6/3/98 9:37 | 0.03 | 6/3/98 9:44 | 0.03 | 6/3/98 9:51 | 0.04 |
| 6/3/98 10:41 | 0.02 | 6/3/98 10:48 | 0.02 | 6/3/98 10:55 | 0.03 |
| 6/3/98 11:45 | 0.03 | 6/3/98 11:52 | 0.02 | 6/3/98 11:59 | 0.03 |
| 6/3/98 12:49 | 0.04 | 6/3/98 12:56 | 0.03 | 6/3/98 13:03 | 0.04 |

| Date and time | 54-1 | Date and time | 54-3 | Date and time | 54-3 |
|---|---|---|---|---|---|
| 6/3/98 13:53 | 0.04 | 6/3/98 14:00 | 0.04 | 6/3/98 14:07 | 0.05 |
| 6/3/98 14:57 | 0.04 | 6/3/98 15:04 | 0.04 | 6/3/98 15:11 | 0.05 |
| 6/3/98 16:01 | 0.04 | 6/3/98 16:08 | 0.04 | 6/3/98 16:15 | 0.05 |
| 6/3/98 17:05 | 0.04 | 6/3/98 17:12 | 0.03 | 6/3/98 17:19 | 0.04 |
| 6/3/98 18:09 | 0.04 | 6/3/98 18:16 | 0.03 | 6/3/98 18:23 | 0.04 |
| 6/3/98 19:13 | 0.04 | 6/3/98 19:20 | 0.04 | 6/3/98 19:27 | 0.05 |
| 6/3/98 20:17 | 0.04 | 6/3/98 20:24 | 0.04 | 6/3/98 20:31 | 0.05 |
| 6/3/98 21:21 | 0.05 | 6/3/98 21:28 | 0.05 | 6/3/98 21:35 | 0.05 |
| 6/3/98 22:25 | 0.05 | 6/3/98 22:32 | 0.05 | 6/3/98 22:39 | 0.06 |
| 6/3/98 23:29 | 0.05 | 6/3/98 23:36 | 0.05 | 6/3/98 23:43 | 0.06 |
| 6/4/98 0:33 | 0.05 | 6/4/98 0:40 | 0.05 | 6/4/98 0:47 | 0.05 |
| 6/4/98 1:37 | 0.05 | 6/4/98 1:44 | 0.05 | 6/4/98 1:51 | 0.05 |
| 6/4/98 2:41 | 0.05 | 6/4/98 2:48 | 0.05 | 6/4/98 2:55 | 0.05 |
| 6/4/98 3:45 | 0.05 | 6/4/98 3:52 | 0.05 | 6/4/98 3:59 | 0.05 |
| 6/4/98 4:49 | 0.05 | 6/4/98 4:56 | 0.05 | 6/4/98 5:03 | 0.05 |
| 6/4/98 5:53 | 0.04 | 6/4/98 6:00 | 0.04 | 6/4/98 6:07 | 0.05 |
| 6/4/98 6:57 | 0.05 | 6/4/98 7:04 | 0.04 | 6/4/98 7:11 | 0.05 |
| 6/4/98 8:01 | 0.06 | 6/4/98 8:08 | 0.05 | 6/4/98 8:15 | 0.05 |

| Date and time | 55-1 | Date and time | 55-3 | Date and time | 59-4 |
|---|---|---|---|---|---|
| 6/2/98 12:59 | 0.03 | 6/2/98 13:06 | 0.03 | 6/3/98 9:30 | 0.41 |
| 6/2/98 13:56 | 0.03 | 6/2/98 14:03 | 0.03 | 6/3/98 10:34 | 0.41 |
| 6/2/98 14:53 | 0.04 | 6/2/98 15:00 | 0.03 | 6/3/98 11:38 | 0.42 |
| 6/2/98 15:50 | 0.03 | 6/2/98 15:57 | 0.03 | 6/3/98 12:42 | 0.43 |
| 6/2/98 16:47 | 0.03 | 6/2/98 16:54 | 0.03 | 6/3/98 13:46 | 0.46 |
| 6/2/98 17:44 | 0.03 | 6/2/98 17:51 | 0.02 | 6/3/98 14:50 | 0.47 |
| 6/2/98 18:41 | 0.01 | 6/2/98 18:48 | 0.02 | 6/3/98 15:54 | 0.47 |
| 6/2/98 19:38 | 0.01 | 6/2/98 19:45 | 0.01 | 6/3/98 16:58 | 0.48 |
| 6/2/98 20:35 | 0.04 | 6/2/98 20:42 | 0.04 | 6/3/98 18:02 | 0.49 |
| 6/2/98 21:32 | 0.05 | 6/2/98 21:39 | 0.05 | 6/3/98 19:06 | 0.51 |
| 6/2/98 22:29 | 0.05 | 6/2/98 22:36 | 0.05 | 6/3/98 20:10 | 0.53 |
| 6/2/98 23:26 | 0.05 | 6/2/98 23:33 | 0.05 | 6/3/98 21:14 | 0.55 |
| 6/3/98 0:23 | 0.05 | 6/3/98 0:30 | 0.05 | 6/3/98 22:18 | 0.57 |
| 6/3/98 1:20 | 0.05 | 6/3/98 1:27 | 0.05 | 6/3/98 23:22 | 0.58 |
| 6/3/98 2:17 | 0.05 | 6/3/98 2:24 | 0.04 | 6/4/98 0:26 | 0.59 |
| 6/3/98 3:14 | 0.05 | 6/3/98 3:21 | 0.04 | 6/4/98 1:30 | 0.59 |
| 6/3/98 4:11 | 0.05 | 6/3/98 4:18 | 0.05 | 6/4/98 2:34 | 0.61 |

| Date and time | 55-1 |
|---|---|
| 6/3/98 5:08 | 0.05 |
| 6/3/98 6:05 | 0.05 |
| 6/3/98 7:02 | 0.06 |
| 6/3/98 7:59 | 0.06 |
| 6/3/98 9:58 | 0.03 |
| 6/3/98 11:02 | 0.02 |
| 6/3/98 12:06 | 0.03 |
| 6/3/98 13:10 | 0.03 |
| 6/3/98 14:14 | 0.04 |
| 6/3/98 15:18 | 0.04 |
| 6/3/98 16:22 | 0.04 |
| 6/3/98 17:26 | 0.04 |
| 6/3/98 18:30 | 0.04 |
| 6/3/98 19:34 | 0.04 |
| 6/3/98 20:38 | 0.05 |
| 6/3/98 21:42 | 0.05 |
| 6/3/98 22:46 | 0.05 |
| 6/3/98 23:50 | 0.05 |
| 6/4/98 0:54 | 0.05 |
| 6/4/98 1:58 | 0.05 |
| 6/4/98 3:02 | 0.05 |
| 6/4/98 4:06 | 0.05 |
| 6/4/98 5:10 | 0.05 |
| 6/4/98 6:14 | 0.05 |
| 6/4/98 7:18 | 0.05 |
| 6/4/98 8:22 | 0.05 |

| Date and time | 55-3 |
|---|---|
| 6/3/98 5:15 | 0.05 |
| 6/3/98 6:12 | 0.05 |
| 6/3/98 7:09 | 0.05 |
| 6/3/98 8:06 | 0.05 |
| 6/3/98 10:05 | 0.02 |
| 6/3/98 11:09 | 0.02 |
| 6/3/98 12:13 | 0.02 |
| 6/3/98 13:17 | 0.03 |
| 6/3/98 14:21 | 0.04 |
| 6/3/98 15:25 | 0.04 |
| 6/3/98 16:29 | 0.04 |
| 6/3/98 17:33 | 0.03 |
| 6/3/98 18:37 | 0.03 |
| 6/3/98 19:41 | 0.04 |
| 6/3/98 20:45 | 0.05 |
| 6/3/98 21:49 | 0.05 |
| 6/3/98 22:53 | 0.05 |
| 6/3/98 23:57 | 0.05 |
| 6/4/98 1:01 | 0.05 |
| 6/4/98 2:05 | 0.05 |
| 6/4/98 3:09 | 0.05 |
| 6/4/98 4:13 | 0.05 |
| 6/4/98 5:17 | 0.04 |
| 6/4/98 6:21 | 0.04 |
| 6/4/98 7:25 | 0.05 |
| 6/4/98 8:29 | 0.05 |

| Date and time | 59-4 |
|---|---|
| 6/4/98 3:38 | 0.61 |
| 6/4/98 4:42 | 0.62 |
| 6/4/98 5:46 | 0.62 |
| 6/4/98 6:50 | 0.63 |
| 6/4/98 7:54 | 0.64 |

Table 5-15. $O_2$ (mole [volume] percent) by time, heater drift, June 1998.

| Date and time | HD-1 | Date and time | HD-2 | Date and time | HD-3 |
|---|---|---|---|---|---|
| 6/1/98 13:36 | 20.85 | 6/1/98 13:43 | 20.88 | 6/1/98 13:50 | 20.87 |
| 6/1/98 14:19 | 20.96 | 6/1/98 14:26 | 20.97 | 6/1/98 15:10 | 20.88 |
| 6/1/98 14:56 | 20.86 | 6/1/98 15:03 | 20.87 | 6/1/98 15:53 | 20.91 |
| 6/1/98 15:39 | 20.91 | 6/1/98 15:46 | 20.91 | 6/1/98 16:36 | 20.93 |
| 6/1/98 16:22 | 20.92 | 6/1/98 16:29 | 20.92 | 6/1/98 17:19 | 20.94 |
| 6/1/98 17:05 | 20.94 | 6/1/98 17:12 | 20.93 | 6/1/98 18:02 | 20.94 |
| 6/1/98 17:48 | 20.94 | 6/1/98 17:55 | 20.94 | 6/1/98 18:45 | 20.94 |
| 6/1/98 18:31 | 20.94 | 6/1/98 18:38 | 20.94 | 6/1/98 19:28 | 20.94 |
| 6/1/98 19:14 | 20.94 | 6/1/98 19:21 | 20.94 | 6/1/98 20:11 | 20.94 |
| 6/1/98 19:57 | 20.94 | 6/1/98 20:04 | 20.94 | 6/1/98 20:54 | 20.94 |
| 6/1/98 20:40 | 20.94 | 6/1/98 20:47 | 20.94 | 6/1/98 21:37 | 20.94 |
| 6/1/98 21:23 | 20.94 | 6/1/98 21:30 | 20.94 | 6/1/98 22:20 | 20.95 |
| 6/1/98 22:06 | 20.95 | 6/1/98 22:13 | 20.94 | 6/1/98 23:03 | 20.95 |
| 6/1/98 22:49 | 20.95 | 6/1/98 22:56 | 20.94 | 6/1/98 23:46 | 20.94 |
| 6/1/98 23:32 | 20.95 | 6/1/98 23:39 | 20.94 | 6/2/98 0:29 | 20.95 |
| 6/2/98 0:15 | 20.94 | 6/2/98 0:22 | 20.94 | 6/2/98 1:12 | 20.94 |
| 6/2/98 0:58 | 20.94 | 6/2/98 1:05 | 20.94 | 6/2/98 1:55 | 20.95 |
| 6/2/98 1:41 | 20.95 | 6/2/98 1:48 | 20.94 | 6/2/98 2:38 | 20.95 |
| 6/2/98 2:24 | 20.95 | 6/2/98 2:31 | 20.95 | 6/2/98 3:21 | 20.95 |
| 6/2/98 3:07 | 20.95 | 6/2/98 3:14 | 20.95 | 6/2/98 4:04 | 20.96 |
| 6/2/98 3:50 | 20.96 | 6/2/98 3:57 | 20.95 | 6/2/98 4:47 | 20.95 |
| 6/2/98 4:33 | 20.95 | 6/2/98 4:40 | 20.95 | 6/2/98 5:30 | 20.95 |
| 6/2/98 5:16 | 20.95 | 6/2/98 5:23 | 20.95 | 6/2/98 6:13 | 20.95 |
| 6/2/98 5:59 | 20.95 | 6/2/98 6:06 | 20.95 | 6/2/98 6:56 | 20.95 |
| 6/2/98 6:42 | 20.95 | 6/2/98 6:49 | 20.95 | 6/2/98 7:39 | 20.95 |
| 6/2/98 7:25 | 20.95 | 6/2/98 7:32 | 20.95 | 6/2/98 8:22 | 20.95 |
| 6/2/98 8:08 | 20.95 | 6/2/98 8:15 | 20.95 | 6/2/98 9:05 | 20.95 |
| 6/2/98 8:51 | 20.95 | 6/2/98 8:58 | 20.95 | | |

Table 5-17. $O_2$ (mole [volume] percent) by time, Boreholes 54, 55, and 59, June 1998.

| Date and time | 54-1 | Date and time | 54-3 | Date and time | 54-5 |
|---|---|---|---|---|---|
| 6/2/98 12:38 | 20.91 | 6/2/98 12:45 | 20.82 | 6/2/98 12:52 | 20.98 |
| 6/2/98 13:35 | 20.89 | 6/2/98 13:42 | 20.82 | 6/2/98 13:49 | 20.96 |
| 6/2/98 14:32 | 20.91 | 6/2/98 14:39 | 20.8 | 6/2/98 14:46 | 20.95 |
| 6/2/98 15:29 | 20.92 | 6/2/98 15:36 | 20.8 | 6/2/98 15:43 | 20.93 |
| 6/2/98 16:26 | 20.91 | 6/2/98 16:33 | 20.78 | 6/2/98 16:40 | 20.92 |
| 6/2/98 17:23 | 20.89 | 6/2/98 17:30 | 20.78 | 6/2/98 17:37 | 20.91 |
| 6/2/98 18:20 | 20.89 | 6/2/98 18:27 | 20.77 | 6/2/98 18:34 | 20.9 |
| 6/2/98 19:17 | 20.88 | 6/2/98-19:24 | 20.76 | 6/2/98 19:31 | 20.9 |
| 6/2/98 20:14 | 20.88 | 6/2/98 20:21 | 20.76 | 6/2/98 20:28 | 20.9 |
| 6/2/98 21:11 | 20.88 | 6/2/98 21:18 | 20.76 | 6/2/98 21:25 | 20.9 |
| 6/2/98 22:08 | 20.89 | 6/2/98 22:15 | 20.75 | 6/2/98 22:22 | 20.91 |
| 6/2/98 23:05 | 20.88 | 6/2/98 23:12 | 20.76 | 6/2/98 23:19 | 20.91 |
| 6/3/98 0:02 | 20.88 | 6/3/98 0:09 | 20.75 | 6/3/98 0:16 | 20.91 |
| 6/3/98 0:59 | 20.88 | 6/3/98 1:06 | 20.75 | 6/3/98 1:13 | 20.9 |
| 6/3/98 1:56 | 20.88 | 6/3/98 2:03 | 20.74 | 6/3/98 2:10 | 20.89 |
| 6/3/98 2:53 | 20.83 | 6/3/98 3:00 | 20.74 | 6/3/98 3:07 | 20.9 |
| 6/3/98 3:50 | 18.35 | 6/3/98 3:57 | 20.75 | 6/3/98 4:04 | 20.9 |
| 6/3/98 4:47 | 20.79 | 6/3/98 4:54 | 20.75 | 6/3/98 5:01 | 20.9 |
| 6/3/98 5:44 | 18.5 | 6/3/98 5:51 | 20.75 | 6/3/98 5:58 | 20.9 |
| 6/3/98 6:41 | 20.79 | 6/3/98 6:48 | 20.75 | 6/3/98 6:55 | 20.9 |
| 6/3/98 7:38 | 20.79 | 6/3/98 7:45 | 20.75 | 6/3/98 7:52 | 20.9 |
| 6/3/98 9:37 | 20.89 | 6/3/98 9:44 | 20.84 | 6/3/98 9:51 | 21 |
| 6/3/98 10:41 | 20.9 | 6/3/98 10:48 | 20.85 | 6/3/98 10:55 | 21 |
| 6/3/98 11:45 | 20.9 | 6/3/98 11:52 | 20.85 | 6/3/98 11:59 | 21 |
| 6/3/98 12:49 | 20.88 | 6/3/98 12:56 | 20.85 | 6/3/98 13:03 | 21 |
| 6/3/98 13:53 | 20.89 | 6/3/98 14:00 | 20.85 | 6/3/98 14:07 | 21.01 |
| 6/3/98 14:57 | 20.89 | 6/3/98 15:04 | 20.84 | 6/3/98 15:11 | 20.99 |
| 6/3/98 16:01 | 20.88 | 6/3/98 16:08 | 20.84 | 6/3/98 16:15 | 20.99 |
| 6/3/98 17:05 | 20.88 | 6/3/98 17:12 | 20.83 | 6/3/98 17:19 | 20.99 |
| 6/3/98 18:09 | 20.88 | 6/3/98 18:16 | 20.83 | 6/3/98 18:23 | 20.99 |
| 6/3/98 19:13 | 20.88 | 6/3/98 19:20 | 20.83 | 6/3/98 19:27 | 20.99 |
| 6/3/98 20:17 | 20.88 | 6/3/98 20:24 | 20.83 | 6/3/98 20:31 | 20.99 |
| 6/3/98 21:21 | 20.88 | 6/3/98 21:28 | 20.83 | 6/3/98 21:35 | 20.99 |
| 6/3/98 22:25 | 20.88 | 6/3/98 22:32 | 20.83 | 6/3/98 22:39 | 20.99 |
| 6/3/98 23:29 | 20.88 | 6/3/98 23:36 | 20.83 | 6/3/98 23:43 | 20.99 |

| Date and time | 54-1 | Date and time | 54-3 | Date and time | 54-5 |
|---|---|---|---|---|---|
| 6/4/98 0:33 | 20.88 | 6/4/98 0:40 | 20.83 | 6/4/98 0:47 | 20.99 |
| 6/4/98 1:37 | 20.88 | 6/4/98 1:44 | 20.83 | 6/4/98 1:51 | 20.99 |
| 6/4/98 2:41 | 20.88 | 6/4/98 2:48 | 20.83 | 6/4/98 2:55 | 20.99 |
| 6/4/98 3:45 | 20.88 | 6/4/98 3:52 | 20.83 | 6/4/98 3:59 | 20.98 |
| 6/4/98 4:49 | 20.88 | 6/4/98 4:56 | 20.82 | 6/4/98 5:03 | 20.98 |
| 6/4/98 5:53 | 20.87 | 6/4/98 6:00 | 20.82 | 6/4/98 6:07 | 20.98 |
| 6/4/98 6:57 | 20.87 | 6/4/98 7:04 | 20.83 | 6/4/98 7:11 | 20.97 |
| 6/4/98 8:01 | 20.86 | 6/4/98 8:08 | 20.82 | 6/4/98 8:15 | 20.98 |

| Date and time | 55-1 | Date and time | 55-3 | Date and time | 59-4 |
|---|---|---|---|---|---|
| 6/2/98 12:59 | 20.89 | 6/2/98 13:06 | 20.86 | 6/3/98 9:30 | 19.91 |
| 6/2/98 13:56 | 20.89 | 6/2/98 14:03 | 20.85 | 6/3/98 10:34 | 20.55 |
| 6/2/98 14:53 | 20.89 | 6/2/98 15:00 | 20.85 | 6/3/98 11:38 | 20.61 |
| 6/2/98 15:50 | 20.88 | 6/2/98 15:57 | 20.83 | 6/3/98 12:42 | 20.6 |
| 6/2/98 16:47 | 20.86 | 6/2/98 16:54 | 20.82 | 6/3/98 13:46 | 20.64 |
| 6/2/98 17:44 | 20.85 | 6/2/98 17:51 | 20.81 | 6/3/98 14:50 | 20.64 |
| 6/2/98 18:41 | 20.85 | 6/2/98 18:48 | 20.8 | 6/3/98 15:54 | 20.64 |
| 6/2/98 19:38 | 20.84 | 6/2/98 19:45 | 20.8 | 6/3/98 16:58 | 20.64 |
| 6/2/98 20:35 | 20.84 | 6/2/98 20:42 | 20.8 | 6/3/98 18:02 | 20.64 |
| 6/2/98 21:32 | 20.83 | 6/2/98 21:39 | 20.79 | 6/3/98 19:06 | 20.64 |
| 6/2/98 22:29 | 20.84 | 6/2/98 22:36 | 20.79 | 6/3/98 20:10 | 20.66 |
| 6/2/98 23:26 | 20.85 | 6/2/98 23:33 | 20.8 | 6/3/98 21:14 | 20.67 |
| 6/3/98 0:23 | 20.84 | 6/3/98 0:30 | 20.79 | 6/3/98 22:18 | 20.68 |
| 6/3/98 1:20 | 20.82 | 6/3/98 1:27 | 20.78 | 6/3/98 23:22 | 20.68 |
| 6/3/98 2:17 | 20.83 | 6/3/98 2:24 | 20.79 | 6/4/98 0:26 | 20.69 |
| 6/3/98 3:14 | 20.83 | 6/3/98 3:21 | 20.79 | 6/4/98 1:30 | 20.69 |
| 6/3/98 4:11 | 20.83 | 6/3/98 4:18 | 20.8 | 6/4/98 2:34 | 20.69 |
| 6/3/98 5:08 | 20.83 | 6/3/98 5:15 | 20.79 | 6/4/98 3:38 | 20.69 |
| 6/3/98 6:05 | 20.83 | 6/3/98 6:12 | 20.79 | 6/4/98 4:42 | 20.69 |
| 6/3/98 7:02 | 20.83 | 6/3/98 7:09 | 20.78 | 6/4/98 5:46 | 20.7 |
| 6/3/98 7:59 | 20.83 | 6/3/98 8:06 | 20.78 | 6/4/98 6:50 | 20.71 |
| 6/3/98 9:58 | 20.92 | 6/3/98 10:05 | 20.88 | 6/4/98 7:54 | 20.71 |
| 6/3/98 11:02 | 20.92 | 6/3/98 11:09 | 20.89 | | |
| 6/3/98 12:06 | 20.94 | 6/3/98 12:13 | 20.89 | | |
| 6/3/98 13:10 | 20.92 | 6/3/98 13:17 | 20.87 | | |
| 6/3/98 14:14 | 20.94 | 6/3/98 14:21 | 20.89 | | |
| 6/3/98 15:18 | 20.92 | 6/3/98 15:25 | 20.88 | | |

LB980420123142.005

# Chapter 3 Carbon Isotope Analyses of $CO_2$ Evolved During the Initial Stages of the Drift Scale Test

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## 3.1 Purpose

This preliminary study was completed to determine the potential utility of measuring the isotopic compositions of $H_2O$ vapor and $CO_2$ from the rock around the Drift Scale Test. In addition to providing background data for potential future studies, methods of sample collection and analysis were tested. As a scoping study, formal QA procedures had not yet been fully developed for sampling and analysis, so the data reported should be considered as not qualified.

## 3.2 Sampling

On Feb. 9-10, 1998, gas samples for isotopic analysis of CO2 and H2O vapor were collected from eight of the packed-off intervals in the hydrology holes collared on the Observation Drift of the Drift Scale Test (field numbers given in Table 1 correspond to the borehole and interval sampled). From each interval, approximately 0.5 liters of gas was collected in 1-liter Tedlar® bags after the sampling lines were purged for about 5 minutes. In one sample, YMP 77-3 (the highest temperature interval sampled), significant amounts of water condensed in the sampling lines and the Tedlar® bag. Minor condensation was also observed in the sampling lines when YMP 60-3 was collected. In addition to the samples from the hydrology holes, samples of tunnel air from the Observation Drift and of air from inside of the Heater Drift were collected. For both of these samples, larger amounts of gas (about 2 liters) were collected in 3-liter Tedlar® bags. The observation drift sample (YMP AO Drift Air) was collected next to the control module for the hydrology holes. The heater drift sample (YMP H Drift #2) was taken from port 2 (which extends to approximately the center of the heater drift) at the heater drift bulk head using a hand-held manual pump after purging the line for 2 minutes. Minor condensation of water was observed in the Tygon® tubing connecting port 2 to the Tedlar® bag during purging and sampling.

## 3.3 Analyses

In order to determine the best method for analyzing the isotopic compositions of the $CO_2$ in the samples, the amount of $CO_2$ in the samples was analyzed using the Li-Cor (infra-red analyzer) in the Amundson laboratory on the U.C. Berkeley campus. The $\delta^{13}C$ and $\delta^{18}O$ values of the $CO_2$ in the samples were then analyzed using two separate techniques at the Center for Isotope Geochemistry (CIG). First, analyses were done using the trace gas pre-concentrator on CIG's Isoprime continuous flow mass spectrometer. This is a new instrument, and the sampling protocols, blank effects, and other factors affecting the reliability of the results had not been fully determined when the samples were analyzed. For this reason, these analyses are not included with this report. $CO_2$ and $H_2O$ vapor were then separated cryogenically from the remaining gas in the samples. The isotopic composition of the $CO_2$ was then analyzed on CIG's Prism dual-inlet mass spectrometer (Table 1). Aliquots of $CO_2$ from three of the samples were also collected for $^{14}C$ analyses (which have not yet been finished). The $H_2O$ collected from the samples was sealed into glass tubes and has not yet been analyzed (the volumes collected were small and may not be adequate for analysis).

Table 1 - Isotope Data for $CO_2$ from Gas Samples Collected from Drift Scale Test.

| Field #[1] | Tracking #[2] | $\delta^{13}C_{VPDB}$[3] | $\delta^{18}O_{VSMOW}$[4] | T (°C) | $CO_2$ (ppmv) |
|---|---|---|---|---|---|
| YMP 57-3 | SPC 0052 7911 | -13.8 | 31.2 | 22.7 | 940 |
| YMP 59-3 | SPC 0052 7900 | -10.3 | 31.9 | 32.4 | 777 |
| YMP 60-3 [5] | SPC 0052 7906 | -8.0 | 22.9 | 49.3 | 927 |
| YMP 61-3 | SPC 0052 7914 | -11.6 | 30.2 | 31.1 | 1034 |
| YMP 74-4 | SPC 0052 7903 | -11.2 | 32.9 | 23.4 | 577 |
| YMP 77-3 | SPC 0052 7901 | -5.5 | 48.3 | 84.2 | 5960 |
| YMP 77-3 [5] | SPC 0052 7902 | -7.4 | 24.1 | 84.2 | 5960 |
| YMP 78-3 | SPC 0052 7913 | -11.3 | 30.7 | 39.9 | 2253 |
| YMP H Drift #2 | SPC 0052 7909 | -10.3 | 32.3 | 100.5 | 372 |
| YMP AO Drift Air | SPC 0052 7907 | -10.3 | 40.0 | 20.4 | 402 |

[1] Field # corresponds to sample numbers listed in field notebook (ID# YMP-LBNL-YWT-MC-2).

[2] Tracking # is YMP Sample Management Facility tracking number.

[3] Carbon isotope ratios are given as part per thousand or per mil (‰) variations relative to VPDB (Vienna PeeDee Belemnite), an internationally accepted standard for reporting carbon isotope data.

[4] Oxygen isotope ratios are given as part per thousand or per mil (‰) variations relative to VSMOW (Vienna Standard Mean Ocean Water), an internationally accepted standard for reporting oxygen isotope data.

[5] Samples collected in 150-cc metal canisters (as opposed to Tedlar® bags).

## 3.4 Analytical Results

The data for $CO_2$, cryogenically separated from the gas samples and analyzed on the CIG Prism, is given in Table 1. The samples taken from the tunnel and from within the heater drift had concentrations of $CO_2$ in the same range as atmospheric air (approximately 360 ppmv). The $\delta^{13}C$ values of the $CO_2$ in the tunnel and heater drift samples were identical (-10.3‰). This is also relatively close to the $\delta^{13}C$ value of atmospheric $CO_2$ (approximately -8‰).

The gas samples taken from boreholes all had higher concentrations of $CO_2$ than the samples from the tunnel. In general, the $CO_2$ concentrations increased with temperature, especially in the samples taken from the mid-drift holes (74-4 through 78-3). The $\delta^{13}C$ values of the $CO_2$ from the borehole interval also increased with temperature from -13.8‰ at 22.4°C to -5.5‰ at 84.2°C (Figure 1).

## 3.5 Discussion

The concentrations and $\delta^{13}C$ values of the $CO_2$ in the observation drift and the heater drift are similar to that of atmospheric $CO_2$. Most likely, this indicates that the $CO_2$ in both were primarily derived from ventilation air pumped into the tunnel. It is possible that there was a small contribution of $CO_2$ from combustion of low-$\delta^{13}C$ diesel fuel in the tunnel (at -30‰, a 10% contribution from this source could explain the shift from atmospheric $CO_2$ at -8‰ to the -10‰ values measured in the tunnel). Further sampling will attempt to quantify more accurately the sources of $CO_2$ in the tunnel air.

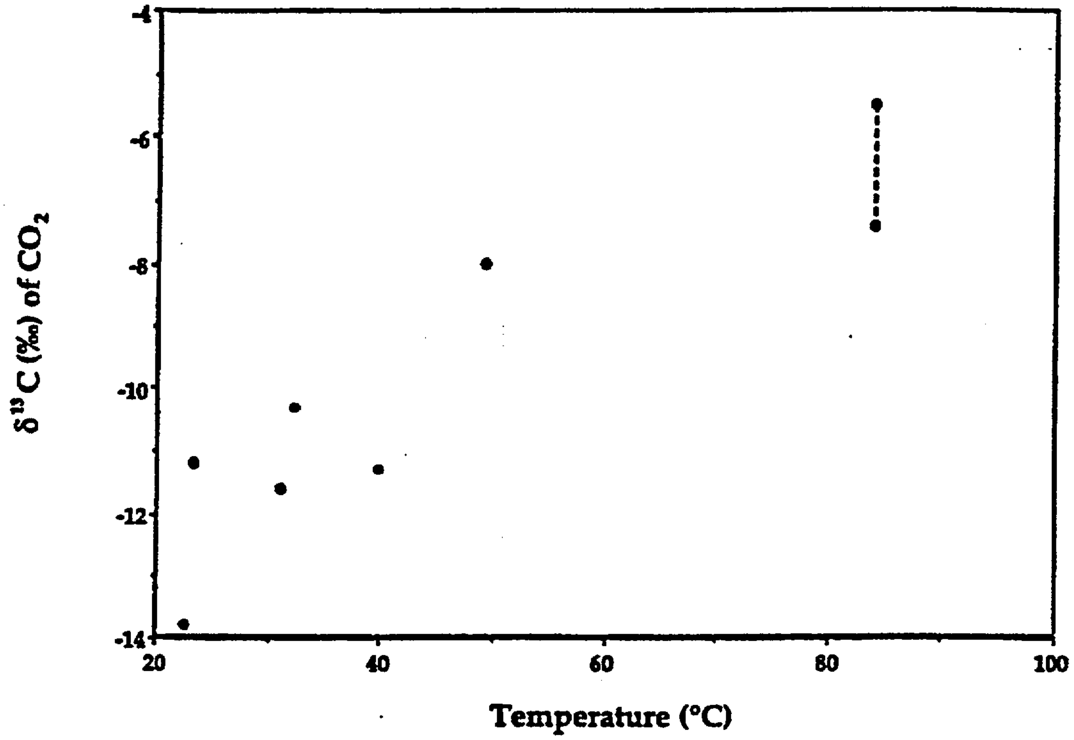

**Figure3-1.** Plot of the $\delta^{13}C$ values of $CO_2$ versus temperature for samples collected from the hydrology borehole intervals around the Drift Scale Test February 9-10, 1998. The dashed line connects data for two samples taken from the same interval by two different methods (the higher value was for a sample collected in a Tedlar® bag, and the lower value was for a sample collected in an evacuated stainless steel canister).

Somewhat surprisingly, the $CO_2$ in the rock does not appear to have been strongly affected by exchange with the tunnel air. Two calcite vein samples collected from the vicinity of the heater drift had $\delta^{13}C$ values of -6‰ (non-QA samples). If the $CO_2$ in the rock were in carbon isotopic equilibrium with these carbonates at 20°C, the $\delta^{13}C$ values of the $CO_2$ would be about -16‰ (Wigley et al., 1978). This is 2‰ lower than the lowest $\delta^{13}C$ value we measured, which is reasonably close, considering the uncertainties introduced as a result of the construction and air testing that has been done in the area. Measurements of the $^{14}C$ content of the $CO_2$ should help quantify the amount of contamination introduced with ventilation air (atmospheric $CO_2$ should have much higher concentrations of $^{14}C$ than anything in the rock or pore waters).

The increase in the concentration and $\delta^{13}C$ values of the $CO_2$ with temperature is consistent with degassing of $CO_2$ from the pore fluids in the rock as the temperature increases. Whether or not there has been any effect caused by dissolution or precipitation of calcite in the fractures is not yet clear.

## Reference

Wigley, T.M.L.; Plummer, L.N.; and Pearson, F.J. 1978. *Mass transfer and carbon isotope evolution in natural water systems. Geochim. et Cosmochim. Acta 42*, 1117-1139.

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# Site and Engineering Properties

**View Unit Descriptions**

GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Delta Carbon-13 Isotopic Ratio data from gas samples conducted during the heating phase, from the Drift Scale Test area, 06/04/1998 to 06/19/1998.

TDIF: 306921

DTN: LB980715123142.003

FOOTNOTES: The Delta Carbon-13 Isotopic ratio is derived from the Vienna PeeDee Belemnite carbonate standard.

| ROW# | Q | DELTA CARBON 13 ISOTOPIC RATIO permil | SPC NUMBER | SAMPLE NUMBER | TEMPERATURE °C |
|---|---|---|---|---|---|
| 1 | Y | -16.6 | SPC00527978 | YMP 57-3 | 23.1 |
| 2 | Y | -12.0 | SPC00527979 | YMP 58-3 | 30.1 |
| 3 | Y | -9.7 | SPC00527980 | YMP 59-3 | 51.3 |
| 4 | Y | -8.9 | SPC00527988 | YMP 59-4 | 49.4 |
| 5 | Y | -13.6 | SPC00527981 | YMP 74-3 | 23.7 |
| 6 | Y | -11.8 | SPC00527982 | YMP 75-3 | 27.9 |
| 7 | Y | -5.5 | SPC00527983 | YMP 76-3 | 52.2 |
| 8 | Y | -5.5 | SPC00527984 | YMP 77-3 | 98.1 |
| 9 | Y | -8.7 | SPC00527986 | YMP 78-3 | 64.4 |
| 10 | Y | -14.7 | SPC00527987 | YMP 185-3 | 25.4 |
| 11 | Y | -10.6 | SPC00527989 | YMP AO Drift Air | 22.0 |

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# Site and Engineering Properties

View Unit Descriptions

```
GEOCHEMICAL CHARACTERISTICS DATA REPORT

TABLE DESCRIPTION:
Delta Oxygen-18 Isotopic Ratio data from gas samples conducted during the
heating phase, from the Drift Scale Test area, 06/04/1998 to 06/19/1998.

TDIF:  306921

DTN:  LB980715123142.003

FOOTNOTES: The Delta Oxygen-18 Isotopic Ratio is derived from the Vienna
Standard Mean Ocean Water standard.

****************************************************************************
ROW#    Q  DELTA OXYGEN 18  SPC NUMBER        SAMPLE NUMBER       TEMPERATURE
            ISOTOPIC RATIO                                         °C

           permil
****************************************************************************

1       Y  29.5             SPC00527978       YMP 57-3            23.1
2       Y  29.1             SPC00527979       YMP 58-3            30.1
3       Y  26.6             SPC00527980       YMP 59-3            51.3
4       Y  25.8             SPC00527988       YMP 59-4            49.4
5       Y  30.1             SPC00527981       YMP 74-3            23.7
6       Y  29.0             SPC00527982       YMP 75-3            27.9
7       Y  25.2             SPC00527983       YMP 76-3            52.2
8       Y  21.1             SPC00527984       YMP 77-3            98.1
9       Y  23.4             SPC00527986       YMP 78-3            64.4
10      Y  22.0             SPC00527987       YMP 185-3           25.4
11      Y  36.4             SPC00527989       YMP AO Drift Air    22.0
```