NVO-1229-105 Part I

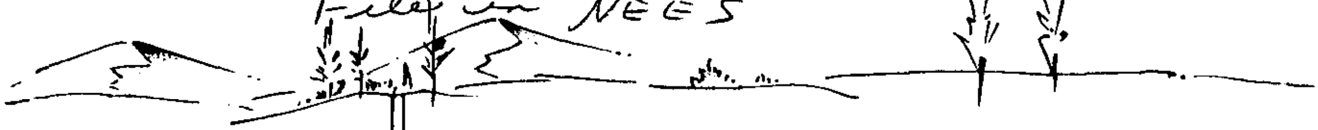
NV-63-1

EVALUATION OF THE PROJECT SHOAL SITE
FALLON, NEVADA
FOR DISPOSITION, INCLUDING IDENTIFICATION OF RESTRICTIONS
Part I

by

M. C. Gardner
W. E. Nork

Classified Part II of this document in Shoal Event File in NEES



April 1970

Contract AT(29-2)-1229

U. S. ATOMIC ENERGY COMMISSION
NEVADA OPERATIONS OFFICE
LAS VEGAS, NEVADA

HYDROGEOLOGY

ISOTOPES

PALO ALTO LABORATORIES

4062 Fabian Street
Palo Alto, California 94303

EVALUATION OF THE PROJECT SHOAL SITE
FALLON, NEVADA
FOR DISPOSITION, INCLUDING IDENTIFICATION OF RESTRICTIONS

PART I

by

M. C. Gardner
W. E. Nork

Submitted to:
U. S. Atomic Energy Commission
Nevada Operations Office
Las Vegas, Nevada

June 1970

Contract AT(29-2)-1229

M. C. Gardner,
Project Leader

P. R. Fenske,
Project Manager

Hydrogeology Section
TELEDYNE ISOTOPES
Palo Alto Laboratories
4062 Fabian Street
Palo Alto, California 94303

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

ABSTRACT

The site of the Project Shoal underground nuclear detonation was studied to develop criteria and recommendations for disposal of the site. Disposal of a nuclear event site should be considered from the standpoint of security, radiological safety, and structural safety in a logical sequence of criteria application.

The chimney contains melt and debris whose analysis might reveal classified information. However, access to the chimney would require extensive drilling. Exclusion of drilling and mining from the site is recommended. Security considerations would not prevent release of the site to public domain.

There are no radioactive materials at the site surface. Subsurface radioactive materials are confined to the rubble chimney and possibly some radiating fractures. Isolation of the radioactive area will continue into the foreseeable future. Further collapse of the present chimney roof to the ground surface is improbable, except in case of a major earthquake.

Granitic rocks of the Sand Springs Range are in a local water recharge area. The potentiometric surface is above the rubble chimney. Water moves very slowly through fractures, and no radionuclides above Concentration Guide levels are forecast to enter the areas' alluvial formations.

The site is recommended for release except for drilling and mining restrictions within a specified area.

Inclusion of the site into the Fallon Naval Auxiliary Air Station is recommended.

1.0 INTRODUCTION

1.1 Purpose and Organization of Report. This report is submitted in accordance with U. S. Atomic Energy Commission (AEC) plans for evaluation of nuclear test sites for possible post-shot disposal from AEC supervisory and security administration. Specifically, the report describes the study and evaluation of the site of the Shoal nuclear event, presents the evaluation criteria applied to the site, and contains recommendations for site disposal.

To facilitate use of this report, classified material has been extracted and placed in a separate section, Part II.

1.2 Shoal Site Evaluation Method. To enable systematic evaluation of current Shoal site conditions, general criteria were developed for the evaluation of nuclear-event site disposal. From these criteria, a method of systems analysis was established for applying these criteria and interpreting the results thereof. The criteria and systems analysis are explained in paragraphs 1.3 and 1.4 of this report. In order to conduct the analysis, existing literature and other data on the Shoal detonation were collected and evaluated. On-site inspection and measurements were made to verify reports and certify physical conditions at the site. Quantitative data were lacking for some ground-water parameters. Conclusions affected by these parameters were therefore based on the most conservative source term and dispersion parameters, and on best scientific interpretations of local geology and hydrology.

1.3 Site Disposal Criteria and Analysis. Three problem areas must be considered in the disposal of any nuclear event site. They are security, radiological safety, and structural safety. Combinations of these problem areas provide the following eight possible nuclear-event site conditions:

1. Security, radiological safety and structural safety problems
2. Security and radiological safety problems
3. Security and structural safety problems
4. Security problems
5. Radiological safety and structural safety problems
6. Radiological safety problems
7. Structural safety problems
8. No technical problems.

The types of site range from those whose problems include security, that the AEC may not want to release, to sites with no problems that would interfere with release of the site to the general public. Two approaches appear satisfactory for upgrading the sites for disposal purposes. Remedial action can be applied to overcome some or all of the problems, or restrictions that would circumvent some or all of the problems could be placed upon the use of the sites. Figure 1 is a diagram of the general criteria, based on these considerations, for disposal of a nuclear-event site.

Remedial measures or restrictions relevant to each of the problem areas will vary with the effects of the detonation, depth of burial, host rock characteristics, position of the potentiometric surface relative to the explosion zone, and climate. Combinations of these factors with the eight types of site conditions already mentioned provide nearly two hundred different possible types of nuclear-event site. Some criteria, perhaps many, are not significant for a specific site. Others will be significant.

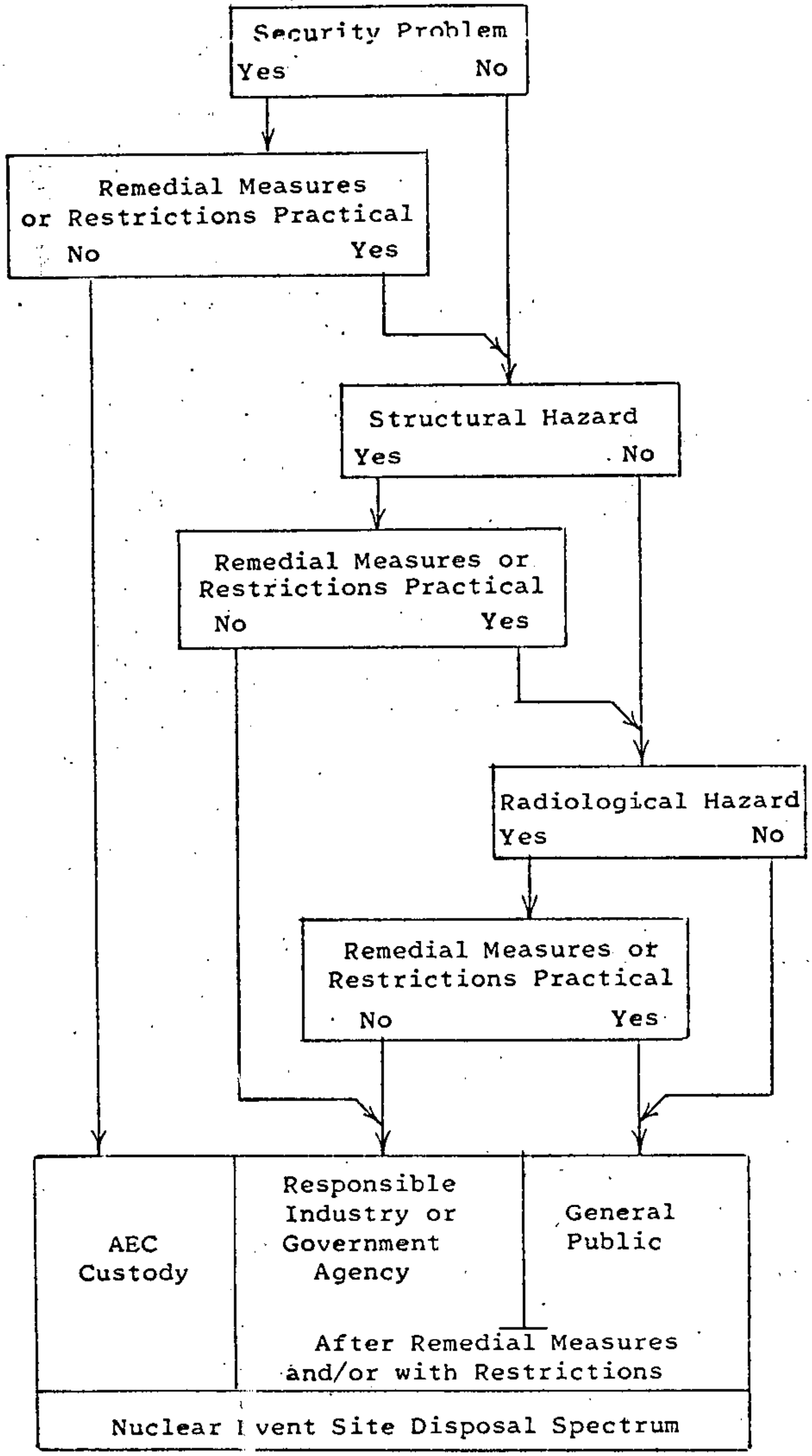


Figure 1

Criteria For Nuclear Event Site Disposal

1.4 Systems Analysis Methods. Figure 2 is a flow chart showing the systems analysis method of applying the criteria shown in Figure 1. Direction of systems analysis is indicated by arrow paths. This method progressively applies new criteria based upon factors revealed by the application of previous criteria. Each subject sub-topic is analyzed and reached logically according to physical and radiochemical indications from predecessor criteria. Significant path directions are taken according to the go/no-go design of the flow chart, thereby minimizing subjective analysis of safety parameters.

Results of the systems analysis as applied to the Shoal site are contained in Section 3 of this report.

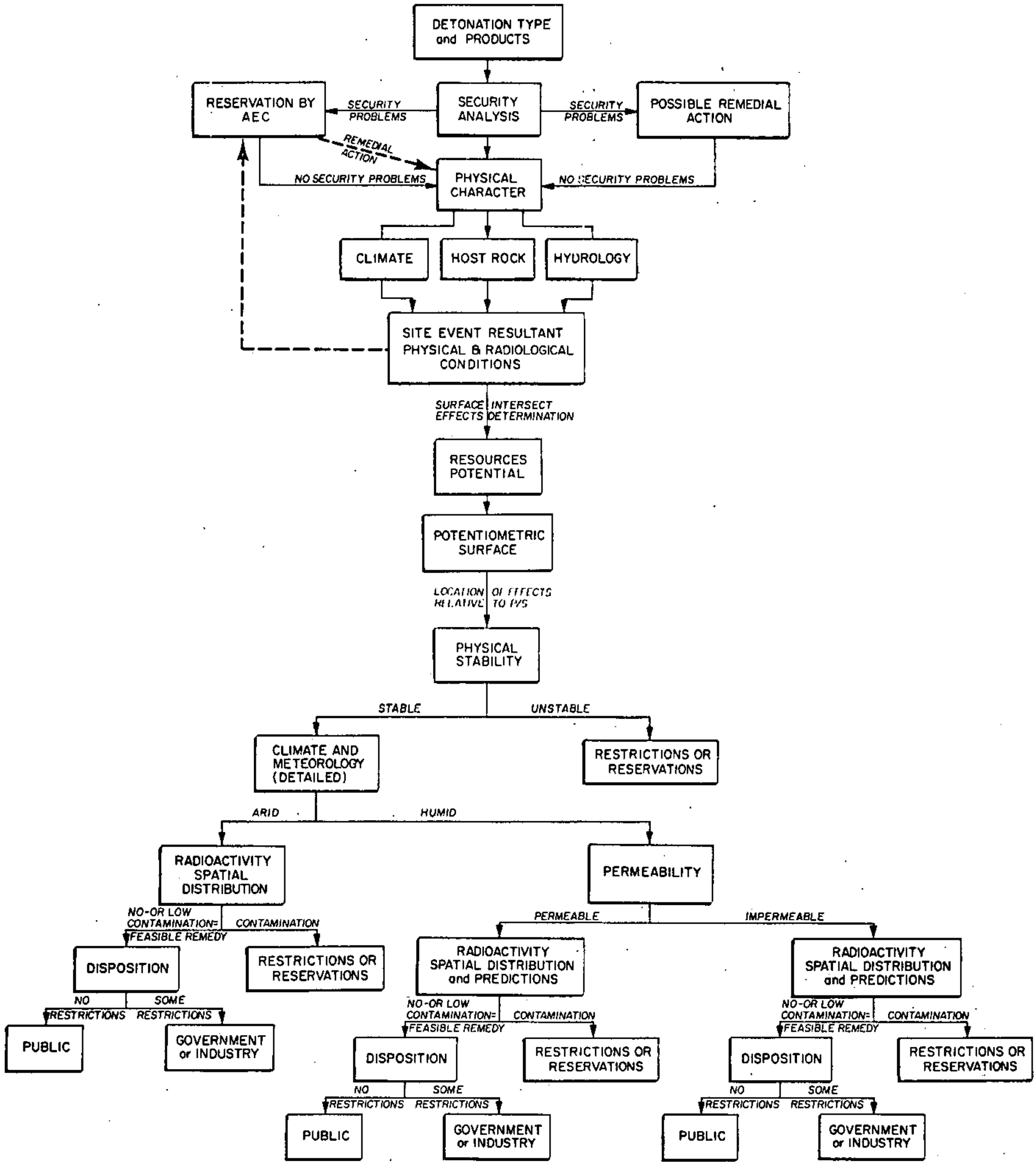


Figure 2

Flow Chart - Systems Analysis of Nuclear-Event Site for Possible Disposal

2.0 SHOAL SITE LOCATION AND TERRAIN

The Shoal site consists of a four-square-mile (10.4 square kilometer) area around Ground Zero (GZ), withdrawn by the Bureau of Land Management from public domain land and assigned to the exclusive use of the Atomic Energy Commission. It is located in west central Nevada, about 45 kilometers southeast of Fallon. Access is afforded by good paved roads off U. S. Highway 50. The nearest commercial jet airport is at Reno, Nevada, about 150 road kilometers west of the Shoal test site. A military airport is located at the Naval Auxiliary Air Station, Fallon, Nevada. Figure 3 shows location of the test site, and Figure 4 shows the topography.

Sand Springs Range is a north-south trending mountain mass in the Great Basin Section of the Basin and Range physiographic province. Total relief between the range and valleys is about 500 meters. The working point is at a buried depth of 367 meters below surface, and is therefore nearly at grade with the valley floors. The Range is bounded on west and east by steep slopes which result from erosion of high angle northeast and northwest faults. The Range's eastern side is less steep than the western. Canyons on the eastern side are long and wide, contrasting with canyons on the western side which are short, narrow, and steep walled. Eastern access is therefore easier. Temperate, semi-arid climate weathers Cretaceous granitic core rocks and Paleozoic and Mesozoic metamorphosed marine sediments to form a deeply dissected mountain landscape.

Ground Zero is at the crest of the Range on a minor intramountain plateau named Gote Flat which is about 800 meters wide. Outcrops are frequent. No permanent water bodies or streams exist. A major intermittent drainage course in GZ Canyon leads east to Fairview Valley. Sparse, low vegetation covers the area. The ground slopes steeply west to Four Mile Flat and east to Fairview Valley.

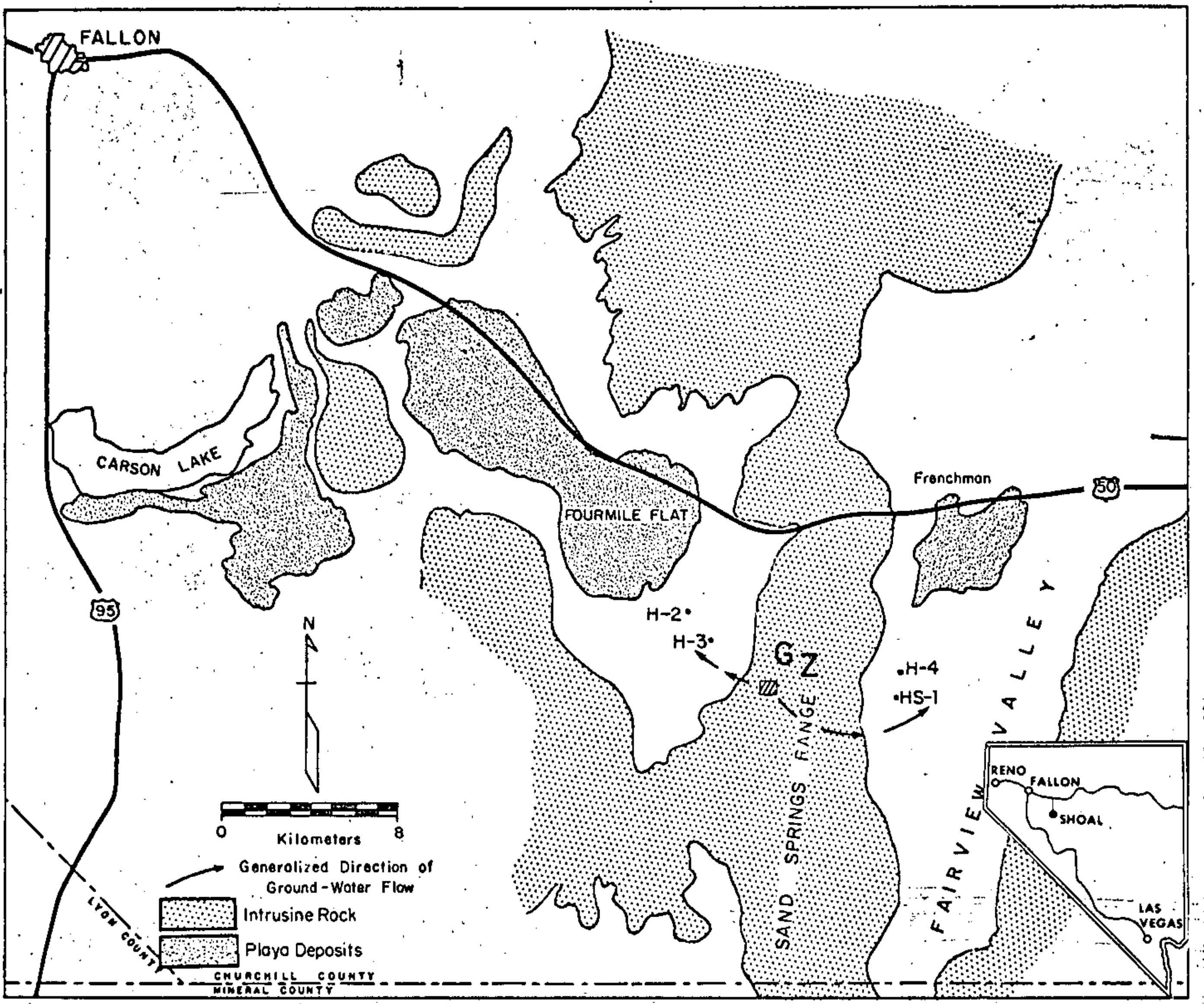


Figure 3. Site of the Shoal Event, Regional Plan View.

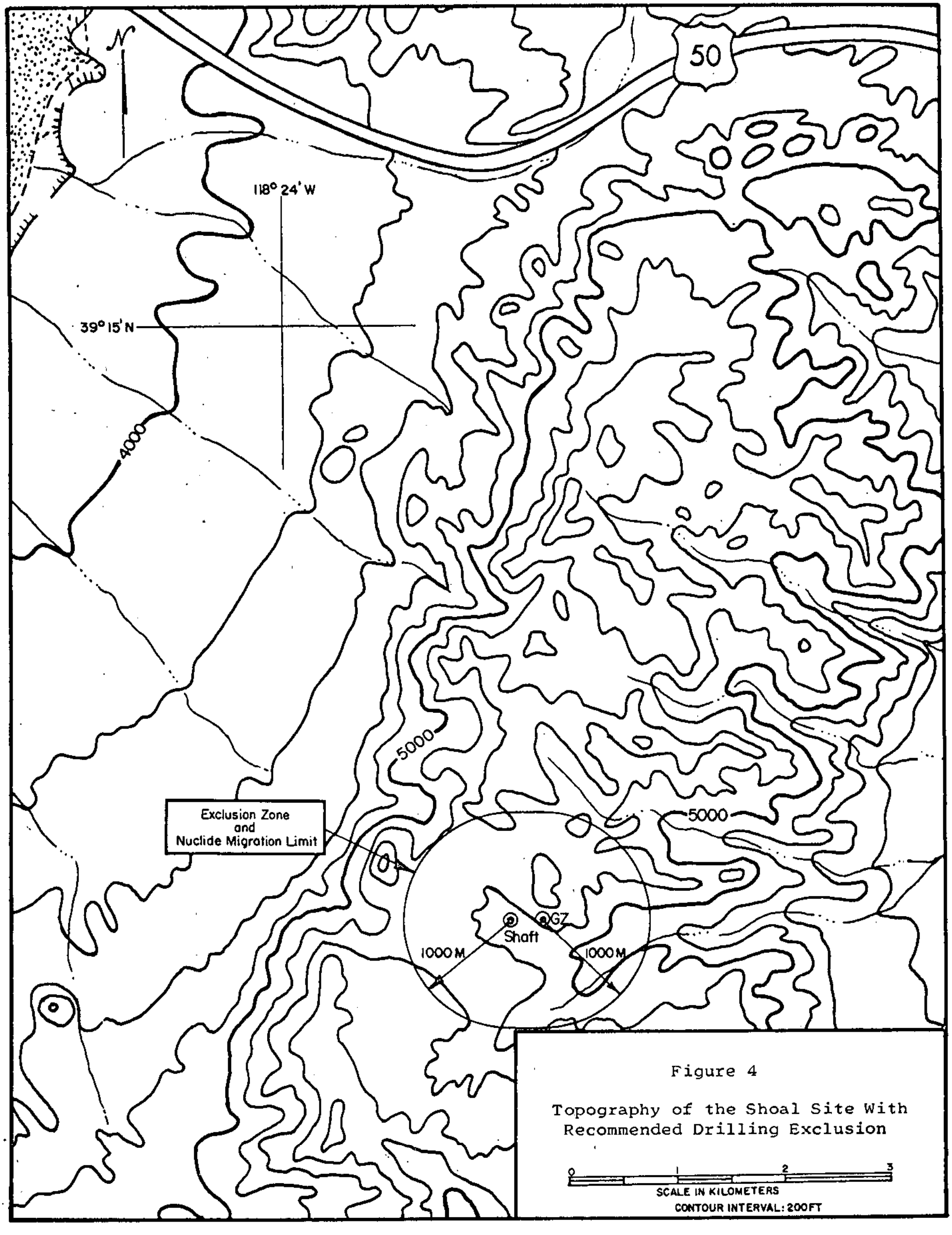


Figure 4

Topography of the Shoal Site With Recommended Drilling Exclusion

Ground Zero is located at North 1,620,170, East 557,544 (Nevada Grid Coordinates) (Sec. 34, T16N, R32E, MDB&M). The shaft head is located 305 meters west of GZ, with surface elevations at 1611 and 1594 meters, respectively. A mud pit is located at the head of the creek at the east edge of the GZ pad.

3.0 APPLICATION OF CRITERIA TO SHOAL SITE

3.1 Detonation Type and Products. The Shoal event consisted of a 12.5 ± 0.5 kiloton yield nuclear detonation which occurred on October 26, 1963. The device was placed into a buttonhook design space in granitic rocks 367 meters below ground surface. Emplacement was via a shaft, a 305-meter drift, and a 12 meter raise and drill hole. Device products are described in Part II of this report.

3.2 Security Analysis. The details of the Shoal event yield and resultant nuclide generation are presented in the classified section (Part II) of this report. However, for a general security analysis it is sufficient to observe that the event utilized a combination of fission components which resulted in possibly classified debris. The chimney contains melt and debris which may reveal classified information by sampling and analysis. Therefore, any potential for unauthorized access to the chimney must be considered to be a breach of security.

The shaft is protected by a massive concrete cover, and all drill holes other than PS #1 have been grouted. If PS #1 were filled and plugged, effective access to the melt and debris could be accomplished only by drilling through more than 400 meters of rock.

The Shoal site security problem could be satisfactorily neutralized by remedial action and restrictions. The remedial action would consist of filling and plugging PS #1. Restrictions would consist of prohibiting drilling or mining in the restricted area. Section 5 of this report expands on the methods of accomplishing these restrictions.

3.3 Physical Character. The physical character of the site takes into consideration natural and man-made environment. The natural environmental conditions are climate and meteorology, terrain, host rock, and hydrology. The man-made environment was produced by the device yield, configuration, and device products.

3.3.1 Climatology and Meteorology. The Shoal site is the sub-humid to semi-arid region of Nevada's Great Basin. Annual rainfall varies from about 13 centimeters in valleys to about 30 centimeters in high mountain ranges. Data from the U. S. Weather Bureau's local climatological summaries from Fallon and from Eastgate (40 km east of the Shoal site) are presented in Table I. Most precipitation in mountains occurs in the form of winter snows. At Eastgate, elevation 1,505 meters, annual precipitation averages 13.7 cm. Eastgate is less than 75 meters lower than the Shoal site, but is further east toward rain-shadowed interior basins. About 20 cm was considered a valid estimate for annual precipitation at the Shoal site. Less than five percent may infiltrate consolidated rocks and recharge the groundwater reservoir (Cohen, 1963).

Extreme diurnal temperature fluctuations occur, often exceeding 50°F. Maximum temperatures exceed 100°F in July and August; minimum temperatures of less than 0°F occur in December and January.

No disposal safety problems are inferred from meteorological conditions. No radioactive objects which are water soluble or flood transportable have been left at the Shoal site surface, nor buried at shallow depths.

3.3.2 Geology and Host Rock. The Shoal event occurred in typical Basin-Range terrain, consisting of fault-block mountains and valleys. The Sand Springs Range trends north-south with irregular boundaries defined by high-angle northeast and northwest trending faults. The Range is comprised of metamorphosed Paleozoic and Mesozoic marine sediments surrounding a central granitic intrusive body of Cretaceous age. Tertiary and Quaternary volcanic rocks overlie the crystalline rocks locally and numerous aplite-pegmatite dikes are evident in the western and central part of the range. The aplite-pegmatite dikes, as well as the granitic and metamorphic rocks, are intruded by younger andesite and

TABLE I

CLIMATOLOGICAL DATA, SHOAL SITE VICINITY

Average Monthly and Annual Precipitation, in Centimeters, at Two Stations Near Dixie Valley, Nevada

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Eastgate 1/	1.21	.99	1.77	.94	2.28	1.37	.99	1.65	1.87	1.09	1.77	1.32	17.20
Fallon 2/	1.44	1.77	1.42	1.27	1.60	1.07	.43	.30	.51	1.24	.89	1.7	13.66

1/ Elevation 1,506 meters. In sec. 25, T. 17 N., R. 36 E. Period of record 1949-1950, 1957-1961.

2/ Elevation 1,189 meters. In sec. 6, T. 18 N., R. 29 E., 40 kilometers west of project area. Period of record 1908-1962.

Average Monthly and Annual Temperatures, in Degrees Fahrenheit, at Two Stations Near Dixie Valley, Nevada

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Eastgate 1/	32.4	38.9	42.2	49.0	56.3	68.2	64.1	70.6	62.8	51.4	39.4	35.5	51.7
Fallon 2/	30.4	36.0	42.5	50.6	57.5	65.3	72.8	70.3	62.4	52.0	39.5	32.7	51.0

1/ Period of Record 1957-1961.

2/ Period of Record 1931-1965.

rhyolite dikes, which typically occupy prominent structural openings. East of the range, geophysical surveys indicate that Fairview Valley contains Tertiary and Quaternary alluvial and aeolian sediments as much as 1765 meters thick. Four Mile Flat is a pediment west of the Sand Springs Range consisting of alluvial fans, pediment sand and gravels, and aeolian and playa deposits. This sediment is underlain by a relatively shallow west-sloping crystalline basement. The unconsolidated deposits thicken westward to about 395 meters.

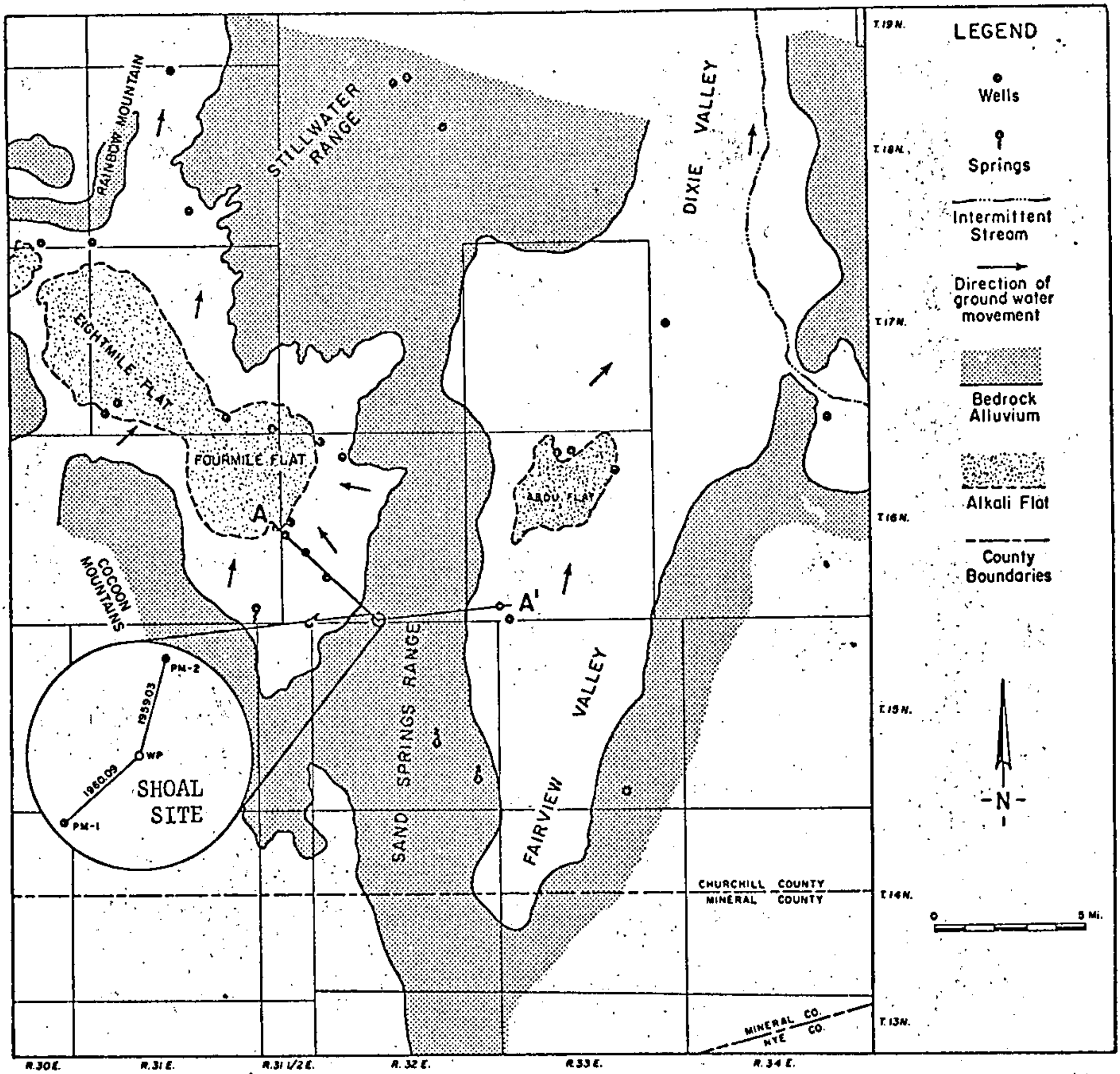
Deposition of Paleozoic and early Mesozoic marine strata was interrupted by several episodes of folding and thrust faulting. The range's gross features were formed by emplacement of the granitic intrusion in the project area, regional uplift in the latest Mesozoic age, volcanism and sedimentation in the middle and late Tertiary Period, and normal faulting extending into the late Pliocene Epoch. The present morphology of the region is the consequence of erosion and intermittent uplift of mountain ranges, and alluvial deposition (fluvial, lacustrine, aeolian) in adjacent valleys during the Pleistocene and Recent Epochs.

An active tectonic history is evidenced by several prominent structural features. Folding appears mainly in metamorphic rocks at the south end of the range but is not a prominent feature. However, evidence of intermittent faulting is present both in the high-angle northeast- and northwest-trending faults which define the Sand Springs Range boundaries, and in faults and associated joint patterns which are conspicuous within the range itself. The northwest-trending faults and accompanying parallel joints are quite prominent, and aplite-pegmatite, andesite, and rhyolite dikes are intruded along these breaks. Generally offsetting these faults and associated dikes is a system of northeast-trending faults. The northeast-trending faults, many of which contain gouge and brecciated wall rock, are accompanied by closely-spaced, well-developed parallel fracture cleavage. At the north end of the range, a thrust fault which dips north cuts the metamorphic rocks, but direction of movement along the thrust is not discernible.

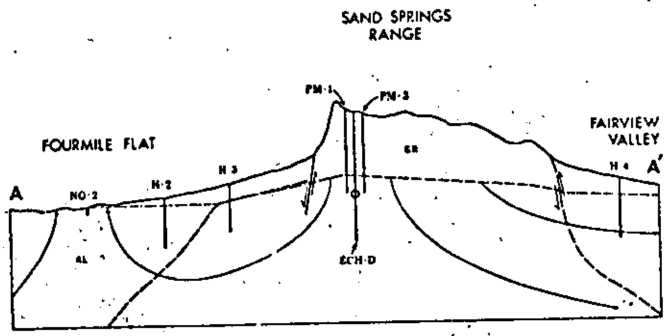
The area has continued to be active seismically. Tremors and strong shallow focus earthquakes are documented by the U. S. Coast and Geodetic Survey (USC&GS) and U. S. Geological Survey (USGS). Special attention was gained by the region contiguous with the Sand Springs Range in 1954. A tremor measured VII in intensity on the Mercalli (1931) scale, and resulted in significant local fissures and ridges.

3.3.3 Hydrology. Historic Shoal hydrologic safety studies and interpretations of radionuclide transport stressed ground-water movement in Fairview Valley and Four Mile Flat alluvial aquifers, rather than in the granitic host rock. Earlier comprehension of Shoal site hydrology including media permeability and porosity might have provided information and hydraulic potential data in the recharge zone that may have made extensive valley studies inconsequential. In this report, we are primarily concerned with the test site, controlled by AEC proprietorship, and not with water movement in distant valleys. Consequently, there will only be brief review of valley hydrology herein, including most recent well sampling and analyses for radioactivity.

3.3.3.1 Hydrologically Significant Drainage and Topography. The Sand Springs Range, Four Mile Flat, and Fairview and Dixie Valleys constitute a local ground-water system. This fact was recognized by Cohen and Everett, Nork, and others, and explained definitively by Maxey. The highest part of the Sand Springs Range is a ground water divide and recharge area (Figure 5). Water moves from the range to Four Mile Flat and to Fairview Valley and from Fairview Valley north to Dixie Valley. Dixie Valley and Four Mile Flat are discharge areas. In Four Mile Flat, flow is west to northwest, and terminates in the center of a closed basin and system discharge area about 10 kilometers west of the Sand Springs Range. Water in Four Mile Flat and Dixie Valley is lost principally by evaporation near the ground surface.



Regional flow system of Sand Spring Range and environs – plan view.



Regional flow system of Sand Spring Range and environs – cross section.

Figure 5. Ground Water Flow of the Region Near the Shoal Site (from Maxey, 1968).

3.3.3.2 Ground Water. The main consideration in this study involved ground water in crystalline rocks of the Sand Springs Range. Test and construction holes drilled into the rocks at the Shoal site indicate that ground water exists, and that a regional water table could be drawn at about 300 meters below surface at the Shoal site. The piezometric surface slopes toward Four Mile Flat and Fairview Valleys.

3.3.3.2.1 Crystalline Rocks of the Sand Springs Range. The intrusive and metamorphic rocks, which are the host media at the Shoal site, can be viewed as a unit with the same integrity as any other geologic formation, notwithstanding argument about whether connected pores or fractures provide a measured permeability. A recent work by Maxey (1968) proposed that "although the rocks in themselves may be nearly impermeable, they have been broken up to such a degree by tectonic stresses that the whole mountain mass can be regarded as a single hydrologic unit with hydrologic properties of a very coarse gravel filled with clay and silt. The medium is just as homogeneous and isotropic on a large scale as is a permeameter filled with sand on a small scale." U. S. Bureau of Mines (USBM) laboratory tests of a sample of "firm granite" from the emplacement hole resulted in permeability data. Permeability of the sample to gas was 1.7×10^{-6} darcys, and to water about 0.7×10^{-6} darcys. Fluid flow probably occurred in the microfracture system since no other porosity was apparent microscopically.

The metamorphic and intrusive rocks which comprise the Sand Springs Range have little capacity to transmit water. In hydrologic test holes which penetrated at least one hundred meters of the saturated granite of the range, low (0.3 liters/sec) pumping rates rapidly depressed water levels, which attests to the low transmissive capacity of the fractured rock. Bailer tests were conducted in several wells in the granite (ECH-D, PM-1, PM-2, PM-3, PM-8, and USBM-TH-1). With respect to determination of a representative transmissivity coefficient (T) for the fractured granite aquifer, recovery curves derived from these tests ranged from very complex to inconclusive. Well H-3 on the west slope of the Sand Springs Range, which penetrated granite below a veneer of alluvium, also was tested. A credible range of values for the coefficient of transmissivity in the granite, based upon these tests, was 0.02 to 0.2 cm^2/sec. The thickness of the more prolific saturated fractured aquifer at well ECH-D was about 200 meters, and this value is assumed to be representative of the granite aquifer. Dividing this thickness into the above transmissivity coefficients results in an apparent hydraulic conductivity of from 10^{-6} to 10^{-5} cm/sec for the granite. Figure 6 shows drill holes.

The specific capacities of wells HS-1 and H-4 were calculated to be 0.37 and 0.5 liter/sec/meter of drawdown, respectively. These values were moderately low for the derived transmissivity and storage coefficients. This could have resulted from incomplete well development or because specific capacities tend to decrease with duration of pumping, and thus the values represented end-of-test results. Another possibility was that hydrologic boundary effects may have been realized because of the proximity of the pumping wells to the much less transmissive crystalline rocks of the Sand Springs Range. This would decrease the relative yields from the wells as the end of the testing was approached, and could produce the effect of lowering specific capacity.

Observations in connection with the underground operation permit several generalizations. First, the water at depth in the granite occurs in structural openings. Second, the inability of most of the structural openings to sustain a continuous flow indicates that water movement in the mass of granite is quite restricted. Initial "flush" production may have resulted in part from disturbances to the granite during mining and drilling operations. Third, zones exist which contain large quantities of water, and along which relatively unrestricted water movement may occur. The amount of water produced by well DDH-EL, on the order of 4 x 10^7 liters prior to grouting, provides a rough measure of the possible relative importance of such zones to the occurrence and movement of water.

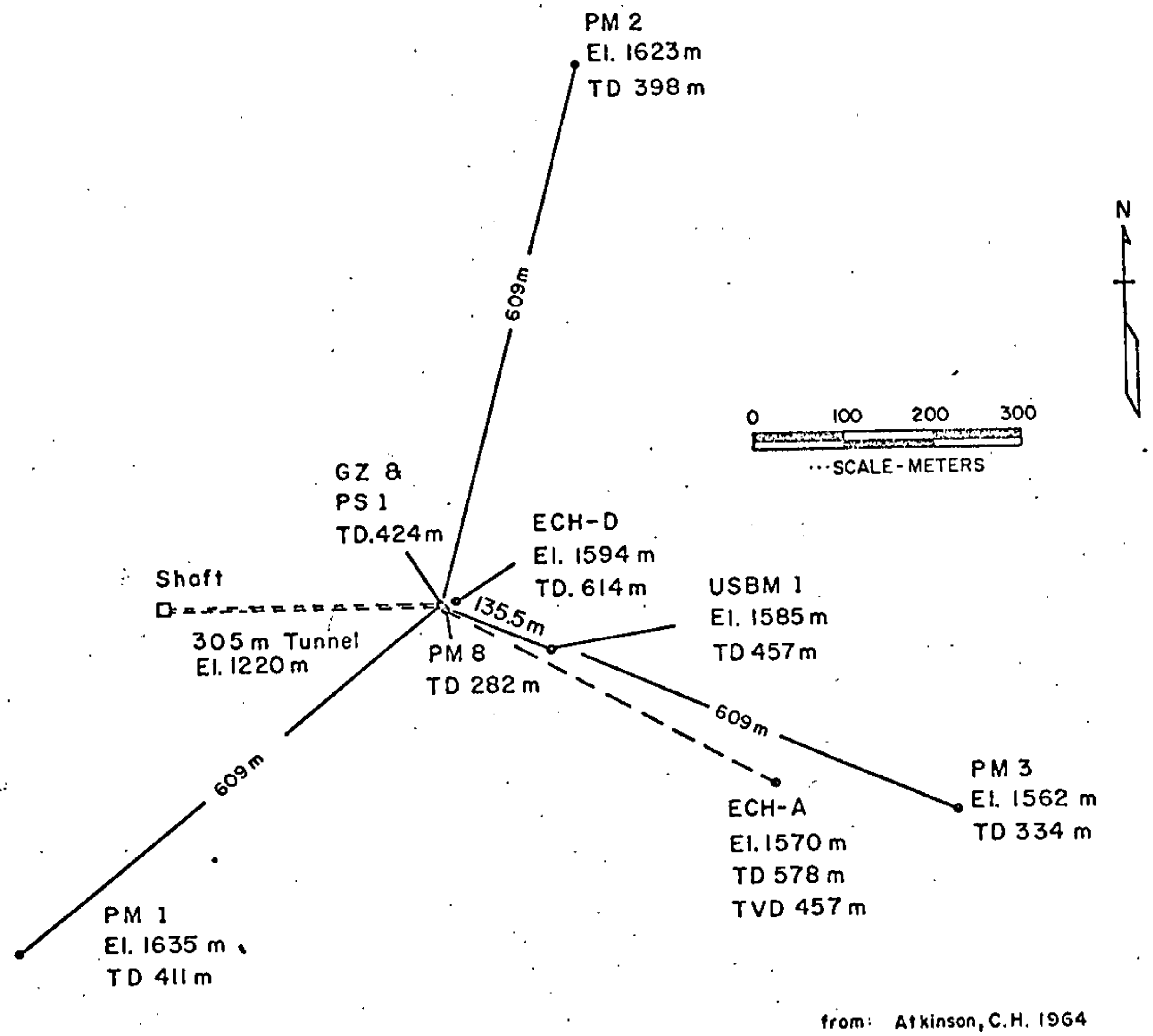


Figure 6. Drill Hole Locations, Shoal Test Site

Data on the water level in the granite near ground-zero have been obtained for six drill holes (PM-1 through PM-3, PM-8, ECH-D, USBM hole) and the emplacement shaft. Observed levels fell within a 165-meter interval, between about 1235 and 1400 meters elevation, and included variations both between and within individual holes. Water level declines were noted subsequent to hydrologic bailing tests and further drilling and deepening of holes. Potentials commonly decrease with depth in recharge areas. The decline of water levels observed during drilling may possibly have reflected adjustment of the water column to lower hydraulic potentials at depth. This is evidence for downward components of ground-water flow. In at least several instances, drilling and testing activities are believed to have influenced adversely the validity of the measured levels, and may account to an unknown degree for variations in water level between and within holes.

Because of the apparent consistence of values derived in the preceding analyses, the value $K' = 10^{-5}$ cm/sec will be used as an average hydraulic conductivity for the mass of the granite. This is consistent with values projected from analyses of well-yield and water injection data for several crystalline rocks (Davis, 1963). Higher conductivity values indicated in the early recovery portion of the test on PM-3 may have been associated with a highly fractured zone at the bottom of the hole. The water-bearing zone in well DDH-E1 could have a conductivity as much as four or five orders of magnitude greater than that of the mass of the granite or on the order of 10^{-1} to 1 cm/sec.

It is not possible to compute with assurance the rate of groundwater movement in the Sand Springs Range crystalline complex. The apparent hydraulic conductivity was approximated, but the hydraulic gradient in these rocks is uncertain and the effective porosity of fractures and joints can only be estimated. On the basis of available information, rate of movement is considered to be extremely low. The significance and effect of ground water flow velocities on estimates of nuclide transport is discussed below, with reasonable assurance that a very conservative safety view has been taken.

A local dewatered zone was created in the Sand Springs Range granite aquifer by 1) removal of water which seeped into the Shoal underground workings during construction, and 2) creation of new, unsaturated pore space of the explosion cavity-collapse chimney. It is also possible that temporary displacement of ground water surrounding the point of detonation occurred due to high pressures created by the blast. This dewatered region was not in equilibrium with the ambient hydraulic potential field. The aquifer responded by moving toward a stabilized state, and ground water flowed inward toward the hydraulic potential sink of the dewatered zone.

Radionuclides in solution may migrate beyond the rubble chimney through molecular diffusion during aquifer adjustment. However, large-scale transport of radiocontaminated ground water should not occur until water in the underground workings and rubble chimney is in or near equilibrium with the surrounding environment. One may reasonably assume that the equilibrium water level will very nearly approach the pre-Shoal-detonation potentiometric surface.

In order to estimate a probable rubble chimney fill-up rate and total fill-up period, the following approximations and assumptions were made:

1) The underground workings are located on a lower horizon than much of the rubble chimney and would consequently fill with in-flowing ground water before the bulk of the chimney. The drift complex has an approximate volume of 2200 cubic meters (366 m long x 6 m^2 drift cross section). The total length was 396 meters for both east and west drifts; however, about 30 meters of this length was incorporated into the rubble chimney as a result of the detonation.

2) Void space to be filled with ground water increases upwards in the rubble chimney as a result of lesser compaction by overlying collapse materials. In addition, the infill or recovery rate is not constant. As the chimney fills, hydraulic head differences will decrease, bringing about a decrease in recovery rate. However, the decreasing rate is uniform with respect to time.

3) The lower part of the rubble chimney and underground workings filled with ground water simultaneously. Initial infill was relatively rapid due to the presumably steep hydraulic gradient between the base of the chimney and the more or less stable water level in granite at some distance away from GZ, and in part as a result of the comparatively smaller volume of pore space to be filled in the lower chimney.

4) The undistrubed granite medium hydraulically connected with the rubble chimney is more or less uniformly fractured and fractures are evenly distributed, thereby approaching homogeneity. The apparent water level recovery rates observed in post-shot investigations were low, suggesting that neither the water-bearing zone tapped by Well DDH-E1, nor any similar zone, was breached as a result of the detonation. Response of such an aquifer is considered similar to a porous medium when large volumes of water-bearing rock are involved.

The fractures are oriented NE-SW and NW-SE, whereas local-regional ground-water gradients are E-W. Most fractures are steeply dipping to vertical and observed water levels indicate that potential values decrease with depth. Taken together, these controls could easily result in gross isotropic flow.

5) An essentially uniform fracture network implies uniform and constant permeability and transmissivity.

6) The granite body is of sufficient areal extent to be considered hydraulically infinite.

7) The Shoal rubble chimney probably does not fully penetrate the aquifer; however, total saturated thickness of the aquifer is unknown. It is probable that total saturated thickness is less than one magnitude greater than the chimney height. Distortion of flow paths at the chimney bottom would be minor due to slow flow rate.

8) The rubble-chimney/drift complex is essentially a localized sink and flow to it would be radial. Gross fracture flow is governed by the smallest of interconnected fractures, resulting in laminar flow.

Assuming an initial inflow rate in the granite of $Q = 300\ cm^3/sec$, which is about the same as the last recorded inflow rate prior to the detonation, fill-up time in the drift complex would be about 80 to 100 days. Although infill may be relatively rapid in the lower chimney, the rate of infill would decrease with time. Calculations indicate that total rubble chimney fill-up may take on the order of 12 years.

When aquifer restabilization is approached, essentially natural ground-water conditions should prevail, and flow will again be downward and outward from the central part of the Sand Springs Range. There will be convergence of flow toward the more permeable rubble chimney in the more or less uniform granite aquifer. Divergence of flow downgradient away from the chimney will occur. Flow rate of radioacontaminants in ground water away from the chimney will be governed, however, by hydraulic and chemical-exchange properties of undisturbed granite.

Available hydrologic test data indicates that extremely low ground-water velocities normally exist in the granite aquifer. An approximation of the rate of movement may be derived by substitution of several already suggested values in the velocity equation

$$\bar{v} = \frac{K' I}{p} \qquad (1)$$

where

$\bar{v}$ = possible average ground water velocity in the granite

K' = apparent hydraulic conductivity in cm/sec

I = hydraulic gradient

p = porosity of the fractured granite.

Using the estimated values K' = 10^{-5} cm/sec, I = 0.015, and p = 0.001, equation (1) gives a velocity of 1.5 x 10^{-4} cm/sec for worst-case conditions. Using K' = 10^{-6} cm/sec and p = .01, equation (1) gives a lower estimated velocity limit of 1.5 x 10^{-6} cm/sec.

The cross-cutting fracture network precludes the possibility of straight-line flow of ground water. More likely, circuitous path would be taken in a general downgradient direction. However, this long path may be compensated for by interconnection locally with fractures of high permeability and, consequently, possibly high velocity, such as one penetrated by well DDH-E1. The possibility that any one of these high permeability fractures extends uninterrupted for the entire breadth of the Sand Springs Range is extremely remote. Any such feature would probably either pinch out, be offset by another less permeable fracture, or be truncated by one or more low permeability intersection fractures.

The fracture network and location of possible high velocity flow fractures is too complex for a detailed aquifer flow analysis. It is believed that interconnection with any high velocity feature would be compensated for by the circuitout ground-water flow path. It is reasonable to conclude, therefore, that straight-line flow with average velocities of between 1.5 x 10^{-6} and 1.5 x 10^{-4} cm/sec closely approximates the actual transmission of ground water through the granite. With these velocities, flow along even the most direct path to alluvium would take a significantly long period of time. For example, flow to the vicinity of H-3 and H-2 on the west side of the Sand Springs Range (Figure 1), a distance of about 4500 meters, would take a minimum of 95 years and a maximum of 9500 years. However, the potentiometric gradient in the granite, and fracture frequency, indicate possibility of a southeasterly flow toward Fairview Valley. Southeasterly flow would take an even longer period to leave the granite system (University of Nevada, 1965). Calculations resulted in less than 1000 meters of total movement. These calculations were based on a physical retardation rate (K_d) of one (1.0) for tritium (H^3), a porosity of one (1.0) percent, flow velocity of 0.5 to 5 meters in 10 years for the granitic rocks, and total elapsed time of 130 years to decay the estimated H^3 concentration to Concentration Guide (CG)* level. The equations used are

$$V' = V_g B \qquad (2)$$

$$B = \frac{1}{1 + \frac{1 - p}{p} K_d} \qquad (3)$$

where

V' = retarded flow velocity

V_g = unretarded flow velocity

B = retardation factor

K_d = retardation constant

For V_g = 5.0 m/10 yr, B = 65 meters; for V_g = 0.5 m/10 yr, B = 650 meters.

---

* CG's are reference concentrations as given in November 8, 1968, revision of USAEC Manual, Chapter 0524, Standards for Radiation Protection, Annex A, Table II, Column 2, reduced by a factor of three to be consistent with standards applicable to Individuals and Population Groups in Uncontrolled Areas. These guides are applied in accordance with instructions in TN NV 0500-23, May 12, 1969. CG is analogous to the previous term MPC.

3.3.3.2.2 Alluvial Deposits of Fairview Valley and Four Mile Flat. Alluvial fill in valleys east and west of the Sand Springs Range contains and transmits appreciable quantities of ground water. The regional potentiometric surface has been established by wells drilled, tested, and produced in the valleys (HS-1, H-2, H-3). Intersection of the potentiometric surface and ground surface occurs in Four Mile Flat.

Lithologic drilling logs and aquifer hydraulic properties obtained from well discharge tests in wells HS-1, H-4, and H-2 (University of Nevada, 1965) indicated that confined hydraulic conditions exist in alluvium in both Fairview Valley and Four Mile Flat. Hydraulic potentials in the valleys were consistently lower than those observed in wells in the granite of the Sand Springs Range. Water levels observed in drilling, although not entirely conclusive, suggested a decrease in potential with depth in the saturated granitic rocks of the Sand Springs Range. The natural flow pattern, therefore, appeared to be downward in the range with lateral movement of ground water from saturated crystalline rocks toward valley fill material in east- and west-bounding valleys.

Two pumping tests were conducted in test hole H-2 in Four Mile Flat (Figure 3) in order to determine aquifer properties, but neither test was conclusive. Recovery data from the second of these tests indicated a transmissivity coefficient of about 110 cm^2/sec for the valley fill.

Hydrologic investigations were conducted in wells HS-1 and H-4 in Fairview Valley (Figure 3), testing two separate confined zones in the alluvium, i.e., an upper zone between 94 and 161 meters depth, and a lower zone between 174 and 209 meters depth. Transmissivity coefficients derived from these tests were 24.6 cm^2/sec and 16 cm^2/sec for the upper and lower zones, respectively. These moderately low values were attributed to incomplete well development, end of test results after much pumping, and/or hydrologic boundary effects caused by proximity of pumping wells to less transmissive rocks of the Sand Springs Range.

The hydraulic gradient (I) in alluvium of Fairview Valley between Well HS-1 and Frenchman Station, about 4.75 kilometers north of HS-1, was 0.00057. The apparent hydraulic conductivity, K', was about 3.7×10^{-3} cm/sec. Although no reliable value of effective porosity (p) was known, it probably ranged from 10 to 20 percent. Therefore, average interstitial velocity ($\bar{v}$) of ground water in Fairview Valley alluvium, from equation (1), the velocity equation, is 2.1×10^{-5} cm/sec. For an estimated p = 20 percent, $\bar{v} = 1.1 \times 10^{-5}$ cm/sec., or 11.4 feet per year.

In Four Mile Flat, the hydraulic gradient, I, was about 0.00028, the apparent hydraulic conductivity, K', was estimated to be about 5.6×10^{-3} cm/sec and the porosity, p, was between 10 and 25 percent. The average interstitial pore velocity of ground-water movement in Four Mile Flat sediments is therefore 1.6×10^{-5} cm/sec. For an estimated 25 percent porosity, $\bar{v} = 6.2 \times 10^{-6}$ cm/sec., or 6.4 feet per year.

3.3.3.2.3 Local Shoal Site Hydrology. Shoal emplacement workings and underground drill holes (Figure 7) intersected numerous joints, fracture cleavages, and faults in granite. Below about 325 meters in the workings (elevation 1290 meters) many of these structural features were saturated and supported a small inflow of water, in most cases less than 0.6 to 1 liter/sec. Flow decreased rapidly with time, and several weeks prior to detonation, with one or two minor exceptions, inflow from individual points had diminished to minor seepage or ceased completely. During final stages of underground construction, four horizontal fault-definition holes explored the granite for about 30 meters around the working point (WP), but little water was produced and flow had ceased prior to detonation. Just prior to detonation, pumps were producing about 0.3 liter/sec from the shaft sump. All drill holes had been grouted and this flow was seepage across the granite-drift interface.

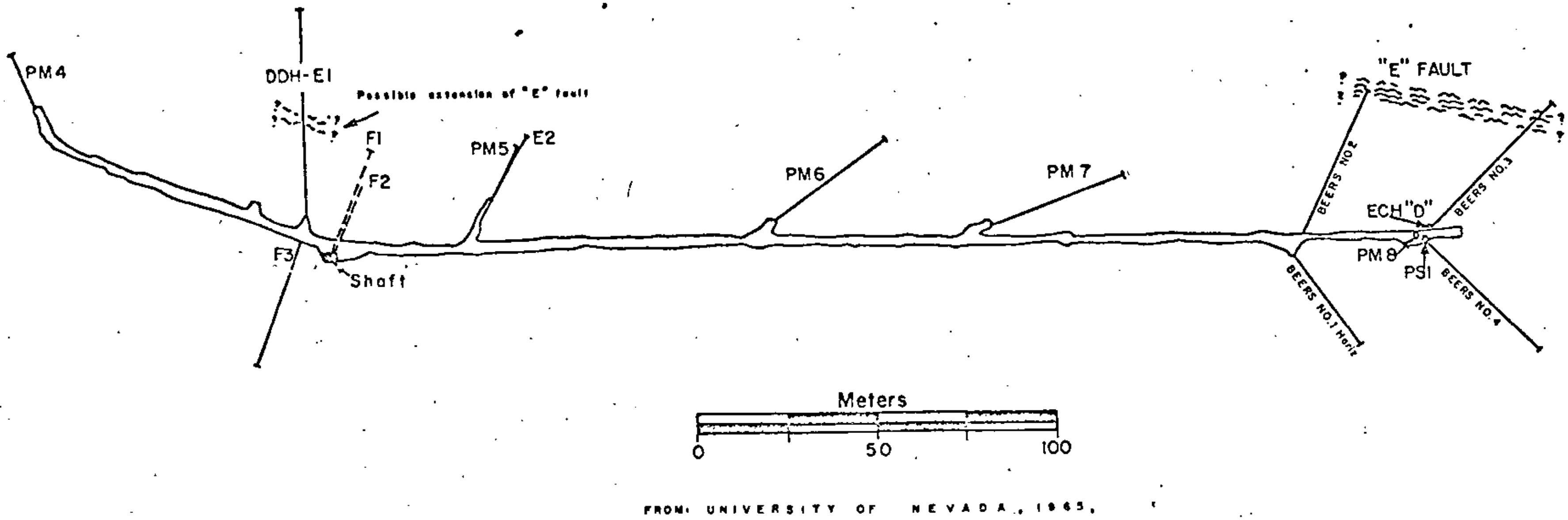


Figure 7. Plan View, Shoal East and West Drift

Diamond drill hole-E1 (DDH-E1) produced a substantial continuous flow of water for two months from a zone somewhat over 30 meters north of the west drift. Flow commenced at about 13 liters/sec and had declined to about 4 liters/sec when the drill hole was grouted prior to the Shoal detonation. Flow from DDH-E1 was responsible for most of the water pumped from the shaft-drift complex during underground construction. The mode of occurrence of this water is not clear, but may have been related to a possible underground extension of the west to northwest-trending "E" fault. No natural large-scale communication existed between this water zone and the underground workings. Conclusions and generalizations have been stated in Section 3.3.3.2.1 with regard to crystalline rock hydrology.

Post-shot investigations of ground water conditions in the chimney area were abortive because of the marginal condition of the PS#1 hole and subsequent failure of the hole for test purposes. The radionuclide presence and transport discussions in Section 4 of this report describe possible movement toward and out from the detonation point, and integrate total activity, decay, and absorption for each isotope.

3.4 Site Event-Correlated Physical and Radiological Conditions.

The detonation resulted in the formation of a cavity which immediately collapsed to produce a residual rubble-filled chimney 26 meters in radius and 118 meters high, according to Korver, 1964. A small void space 11 meters high was at the apex of the chimney. The chimney and ground have been apparently stable for the past five years. The ground surface was physically affected by the blast by uplift to a maximum .5 meters at ground zero. Spalling occurred with a depth of 120+ meters and a radius of 794 meters. A fracture radius of 41 meters was implied from drilling which encountered unbroken granite at a depth of 408 meters. U. S. Bureau of Mines drill hole No. 1, 135.5 meters southeast of GZ was offset at a depth of 345 meters; lateral shock-induced fractures therefore may have extended to 5.2 times the radius of the cavity, according to Atkinson, 1964. Figure 8 depicts the effects zone.

The detonation therefore, is in the category of collapsed chimney without surface intersect. The matrix bulked as collapse occurred so that the void space created by the detonation was scattered throughout the chimney. Repose occurred before the surface was reached. The bulking has provided physical stability by the "shrinking stope" process. A bulking factor of 1.33 to 1.44 was calculated for Shoal (Berry and Hakala, 1968). In granitic rock, addition of fluid or earth tremors would be unlikely to cause consolidation, further settling, and surface intersection. A seismic event focused nearby could conceivably result in a surface-intersecting rift only if it were of an intensity which would normally produce severe damage.

The site can be declared radiochemically safe before examination of other parameters, insofar as natural access to the melt area via fractures, rifts, or a chimney is concerned. Man-made access routes, namely drill holes and the shaft and drift complex, have been sealed. Water entering the chimney would become radioactive. However, water which has leaked into the chimney through fractures caused by detonation, and water intersected during construction and ineffectively grouted, also has been made inaccessible. Radiation released during drillback in 1963 was negligible, and is discussed in Section 4. The chimney apparently reached equilibrium pressure with the atmosphere; a pressure gauge emplaced on PS#1 registered zero (0) psig during a site visit in September 1968.

3.5 Resources Potential.

3.5.1 Mineral Deposits and Prospects.

No mines were active in the Sand Springs Range in 1963. Small contact metasomatic tungsten deposits had been prospected, but none were found to be economic ore bodies. An inactive gold-silver mine, the Summit

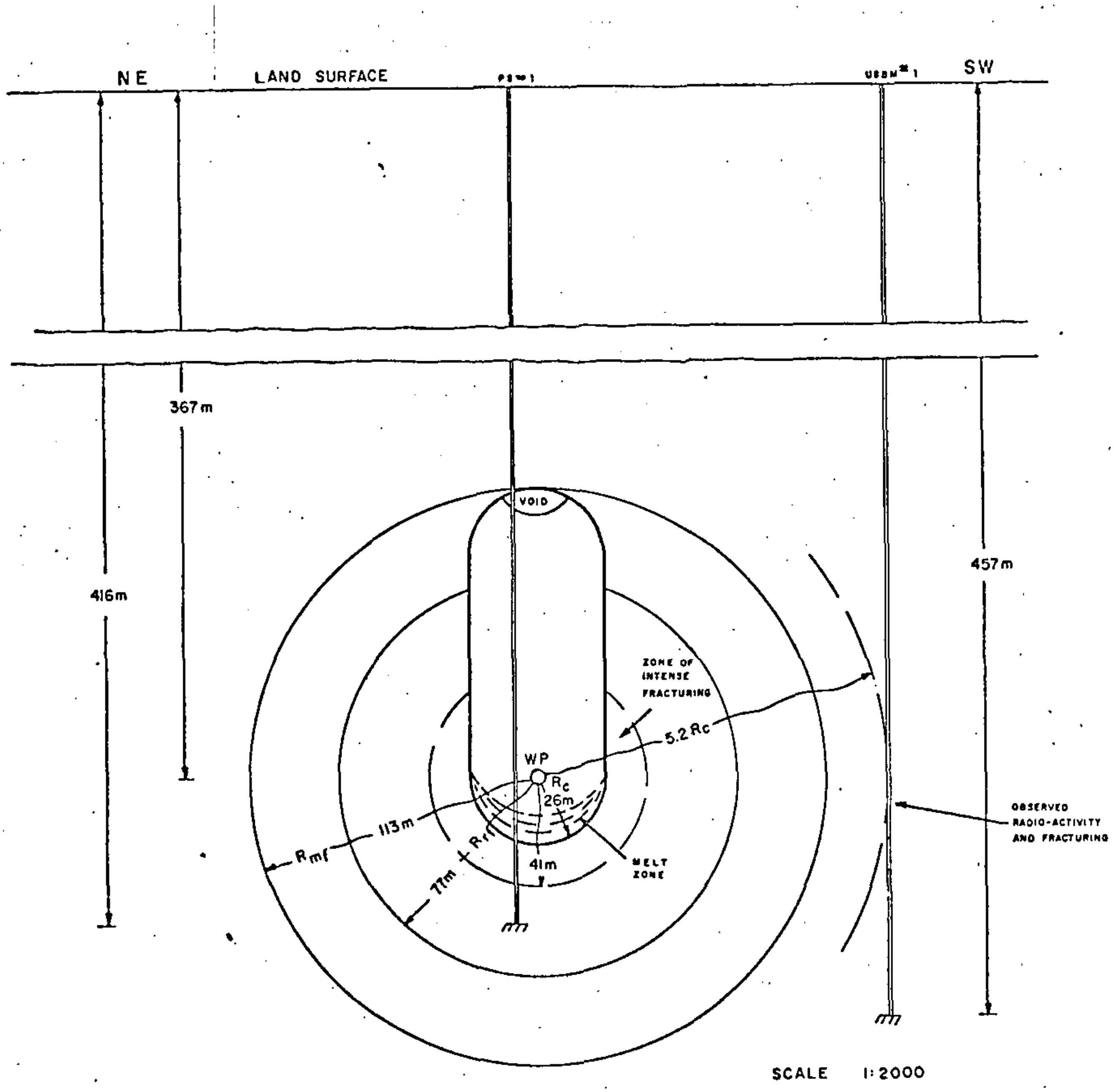


Figure 8. Shoal Rubble Chimney and Explosion Effects

King mine, was located in the range south of U. S. Highway 50. Veins occurred which have produced several million dollars worth of gold and silver. A cyanide mill on the property recovered metals from the ore. Some silica-rich pegmatite outcrops have also been prospected but not mined. The history of mining activity indicates that as metal values increase, and geophysical prospecting becomes more sophisticated and successful, the Sand Springs Range will be re-surveyed if permission can be obtained. The ECH-A and ECH-D drill holes did not intersect ore in the Sand Springs Range granitic rock, according to drilling records. Since no indications of ore have been found during site exploration, it may be assumed that no significant restraint of exploration or mining progress would occur by prohibiting prospecting and claims on the site.

3.5.2 Bombing and Gunnery Practice Range. The Shoal site is an enclave in the Fallon U. S. Naval Auxiliary Air Station (USNAAS) bombing ranges in Fairview Valley and the Sand Springs Range. The USNAAS would apparently be glad to incorporate the site into its ranges to provide expansion of target facilities and to prevent access by civilian personnel to places near active ranges. Traffic and other activities near training missions implies a danger both to civilians on the ground and to airmen attempting to avoid a tragedy. Release to proprietorship of the air station provides routine posting and patrol by a government agency without cost to the AEC.

3.5.3 Other Uses. Grazing over the land including the gunnery ranges and the Shoal site has not been altered by the detonation, and is not likely to be affected by disposition. The land is mostly unfenced and cattle were grazing on the test site in early 1964. The rangeland is used each year until early summer, when cattle are driven north to greener pastureland.

No high density industrial centers are nearby which might place demands on the Shoal site for communications facilities, industrial locations, or residences. No population was displace by use of the site for the detonation. No recreational suitability exists, except for seasonal hunting.

4.0 RADIOACTIVITY DISTRIBUTION

Detonation of the Shoal device produced a spectrum of radioisotopes obtained by fission processes, and left other radioactive debris from unburned fuel elements. The catalog of radionuclides produced is contained in Part II of this report. Practically all of the debris remained trapped below ground in the collapsed cavity area. The spatial distribution is indicated in paragraph 4.3.

4.1 Surface Physical Refuse - Radioactive. No radiation was detected above ground on D Day. Any gaseous radioisotopes were at such a low level of concentration as to be undetectable by ordinary instrumentation. No venting of particulate debris occurred. During post-shot drilling, contaminated material was restricted to the drill-rig casing, vent line, chip and dust collection tank of the vent line, and filters. Contaminated soil and cuttings near the GZ drill hole and mud pit were scraped from the surface, mixed with clean soil to reduce activity levels, and buried under several feet of uncontaminated soil, (Eubank, 1963). A visit to the Shoal site in September 1968, and inspection of the GZ and mud pit areas using a sensitive survey meter detected no radioactivity above background. No items were observed that required burial or shipment off-site for radiation safety reasons.

4.2 Subsurface Radioactive Materials - Event Manifestations. Radioactive materials produced by detonation of the Shoal nuclear device are described and listed in Part II of this report. The device's fuel characteristics, efficiency, and radionuclide products may be calculated from post-shot radioisotope identification and amount, as well as from noted fuel components. Post-shot investigations and water sampling for safety purposes have produced unclassified information useful for disposal purposes. Data is presented and discussed in Section 4.3 and Table II.

4.3 Spatial Distribution of Radionuclides.

4.3.1 Crack Formation and Melt Injection. Small amounts of radioactivity were found in air below a plug at 125 meters depth in the USBM hole. A single sample obtained by passing 1.7×10^7 cc of air through a cryogenic filter during post-shot clean out obtained analyses which showed 1) xenon^{133}, 8×10^{-4} μCi, 2) iodine^{131}, 2.2×10^{-4} μCi, and 3) cesium^{137}, trace (Atkinson, 1964).

From the analyses, radioactivity was assumed to extend 135.5 meters, or 5.2 times the cavity radius. However, one reference point does not provide a conclusive radius determination for radioactive fracturing. Non-spherical distribution of fracturing and radionuclide injection may have occurred. Estimated radius of radioactive fracturing is 77 meters, based on observations at the Nevada Test Site.

Calculation of quantities and identity of the radionuclides produced in the Shoal detonation required consideration of the total yield, external neutron fluxes, and chemical elements exposed to flux. For the purpose of completeness in Part I, nonclassified conservative estimations of tritium, strontium^{90}, and cesium^{137} production are discussed below.

4.3.2 Radionuclides in the Ground Water System. Tritium is produced by neutron activation of lithium^6, $Li^6(n,\alpha)\ H^3$. A lithium concentration of 25 ppm was found in the Shoal granite by the University of Nevada (1965). Ten times this amount (250 ppm), acted on by a 13 kiloton plutonium-239 fueled event, was used for possible total tritium production calculation. Activation computations used procedures described by Carnahan (1964) and Castagnola (1967). Therefore, 1) 301×10^4 curies of H^3 were produced primarily by neutron activation of the granite, 2) H^3 was not sorbed on a geologic matrix preferentially to water, and only retarded physically, and 3) H^3 was chemically combined as water and will be uniformly mixed with about 4.2×10^{10} ml of water when Shoal's rubble chimney is filled to the regional water table. Infill of the rubble chimney requires about 12 years from shot time. The concentration in the chimney would be 4.2×10^{-1} μCi/ml.

Strontium^{90} and Cs^{137} may be considered as the two other nuclides of greatest possible contamination consequence. About 2.4×10^3 curies of Cs^{137} and 1×10^3 curies of Sr^{90} were produced by the detonation. In the unlikely event that 90 percent of the production was not incorporated in the insoluble melt, then utilizing 1) conservative distribution coefficients (K_d) for Sr^{90} and Cs^{137} of 1.5 and 20.0 ml/g, respectively, and 2) calculating concentration according to

$$C = \frac{A(\mu Ci)}{K_d \; Mr(g) \; Vaq(ml)} \qquad (4)$$

where

C = concentration of the radionuclide in the aquifer,

A = activity,

Mr(g) = grain density of rubble rock,

V = volume of water,

then $C^{Sr^{90}} = 7.8 \times 10^{-4}$ μCi/ml, and

$C^{Cs^{137}} = 1.7 \times 10^{-4}$ μCi/ml.

Actual concentration values of H^3, Sr^{90} and Cs^{137} in a sample taken from the chimney void, probably representing condensate, are listed in Part II.

The concentrations of Sr^{90}, Cs^{137}, and H^3 upon infill of the rubble chimney could exceed the maximum permissible concentration for radioactivity in effluents released to uncontrolled areas for average exposure of an exposed population group. (AEC Manual, Standards for Radiation Protection.) Calculation of possible concentrations of nuclides and comparison with acceptable levels in water are shown in Table II. However, as described in paragraph 3.3.3, the rate of ground-water migration in the granite is low. Nuclide concentrations greater than acceptable levels would therefore be confined to the vicinity of the explosion zone, even taking into account the possibility of initial explosion distribution of nuclides along fractures more than one hundred meters into the granite. Tritium transported as tritiated water is not retarded by chemical interaction with the geologic medium and it is considered very unlikely that a level greater than one CG would extend more than one thousand meters from the explosion zone prior to radioactive decay and dilution by mixing to less than one CG. Transport of Sr^{90} and Cs^{137} will be retarded by chemical interaction with granite, and aqueous transport of these nuclides will be even more restricted than tritium.

TABLE II. LIMITING AQUEOUS CONCENTRATIONS OF NUCLIDES AND ACCEPTABLE LEVELS

Nuclide	Possible Concentration in Rubble Chimney Water at Infill, μCi/ml	Acceptable Concentration, Chapter 0524, μCi/ml
Sr^{90}	7.8×10^{-4}	1×10^{-7}
Cs^{137}	1.7×10^{-4}	7×10^{-6}
H^3	4.2×10^{-1}	1×10^{-3}

Consideration of about 5000 meters transport distance to the nearest ground-water use point, relatively slow ground-water movement, radioactive decay of nuclides, retardation by geologic media in the case of Sr^{90} and Cs^{137}, and dilution by mixing with uncontaminated water, indicates that no radiocontamination problem will arise from the Shoal event.

Other nuclides listed in Part II either are incorporated in the relatively insoluble melt and therefore unavailable to ground water, or have sufficiently high K_d values to be sorbed in place. Real concentrations in the chimney may be different from those calculated above; assumed uniform distribution of explosion debris, percent exclusion of nuclides from the melt, and mixing of nuclides in the rubble chimney is unlikely.

4.4 Shoal Water Sampling Results, 1968. Post-detonation water samples have been periodically collected from wells and springs near the Shoal site by the U.S. Public Health Service (USPHS) and Desert Research Institute (DRI). The samples have been analyzed and counted for various radionuclides. Tritium, gross gamma and gross beta have received special attention. Effects of natural radiation have been subtracted from results. Data from this repeated sampling and analysis have indicated that no radioactivity has left the Shoal chimney area and migrated into regional water resources (Earth Sciences Division, H-NSC, 1965). One set of analyses in 1965 did provide an anamolous data point, but investigation indicated that a laboratory procedure was responsible. Subsequent resampling of the questionable water points has confirmed background level activity. New water samples were analyzed during the research phase of this study, and the results are shown in Table III, Gross Activities of Shoal Area Spring and Well Water, July 1968. Concentrations found for tritium and gross activities were orders of magnitude below one CG level. No leading edge of contamination had evidently reached the sampled points. There was very little radiochemical background data from Shoal area waters, but that which did exist was in the same range as the 1968 data.

TABLE III

GROSS RADIOACTIVITIES OF SHOAL AREA SPRING AND WELL WATER, JULY 1968

Site	Collection Date 1968	Tritium (as HTO) T.U.	Dissolved Solids: β, γ Total pCi/l	Dissolved Solids: β, γ Less K^{40} pCi/l	Dissolved Solids: α pCi/l	Dissolved Solids: K mg/l	Suspended Solids: β, γ pCi/l	Suspended Solids: α pCi/l
WP-2	2 July	<300	200 ± 8	0 ± 8	N.D.	95	<1	<0.5
WP-7	2 July	<300	147 ± 5	3 ± 5	N.D.	75	<1	<0.5
WP-11	2 July	<300	776 ± 36	14 ± 36	N.D.	375	1.5 ± 1.1	2.0 ± 0.7
WP-17	2 July	<300	19 ± 2	12 ± 2	56 ± 11	4.0	1.2 ± 0.6	<0.5
Well H-2	2 July	<300	82 ± 6	0 ± 6	N.D.	38	<1	<0.5

Notes

Calibration: The gross beta, gamma activities are reported as the Cs^{137} equivalent. The gross alpha activities are reported as the U^{233} equivalent.

K^{40}: The gross beta, gamma data on the dissolved solids are corrected for the contribution due to K^{40}.

Counting Errors: The uncertainty values represent the statistical counting errors only, calculated at the 95% confidence level.

Suspended Solids: Separated by filtration through 0.45 micron membrane.

Detection Limits: Based on three standard deviations above the background count rate.

Units & Abbreviations:
- pCi/l - picocuries per liter (1 pCi/l = 1 x 10^{-9} microcuries per milliliter)
- mg/l - milligrams per liter
- K - potassium concentration
- β, γ - beta, gamma gross activity
- α - alpha gross activity
- T.U. - tritium units (1 T.U. = 3.26 pCi/l, <300 T.U. = <9.78 x 10^{-7} μCi/ml
- N.D. - not determined

5.0 DISPOSITION RECOMMENDATIONS

5.1 Condition Summary.

5.1.1 Radioactivity. There are no radioactive materials at the site surface. High-level concentrations of radioactivity at the Shoal site were largely confined to a melt and rubble mixture in the collapsed cavity. By far the greatest part of the radioactivity was trapped in the insoluble melt in the lowest 10 meters of the chimney. Some radionuclides, mostly gases, may have been injected into fractures as far as 135 meters from the shot point. Minor amounts of material were liberated into the air during drillback, or were flushed to the surface on drill equipment or in circulating cuttings. All equipment was decontaminated and/or removed from the Shoal site. Gaseous radionuclides dispersed at drilling time. Some short-lived radionuclides fixed by filters were mixed with clean soil and buried in the mud pit area beneath uncontaminated soil.

Recommended exclusion zones include the drift and shaft because communication may have existed. Dispersion in aqueous solution would most likely include the mined areas. The shaft is protected by a massive concrete cover and other drill holes are grouted.

Calculation of concentration, water velocity through the rock matrix, retardation, and sorption indicate that no radionuclides above the one CG level will enter the alluvial formations in valleys adjacent to the Sand Springs Range.

Measurements in situ are not available to further refine the judgments; a significant expense would be incurred to re-open the shaft or post-shot hydrologic test hole, record concentration of radioactivity, and perform geophysical measurements of rock and construction items. Disposition with some minimum restrictions accomplishes the same objective of protection of public life and property in an economic and expedient manner.

5.1.2 Physical Stability. Present conditions indicate stability of the rubble chimney, limitation of chimney height, maintenance of integrity of shafts, drill holes, drift and construction materials, and good grout to casing bonds with surrounding rock.

5.2 Disposition. Based upon the flow path indicated in preceding sections, it is recommended that the ground surface at the Shoal site be released without restrictions to public movement after clean-up and construction operations to remove trash and seal drill hole PS #1. Reservation by the AEC of access to subsurface areas is required as a security measure. The exclusion area is designated in Figure 4.

Disposition by release to the Fallon USNAAS for inclusion into restricted target range areas is recommended. Recent resurgence of minerals exploration activities throughout Nevada would make effective withdrawal of the area from public domain a convenience to avoid drilling and geophysical testing applications after claim registration by prospectors.

Identification of the site could consist of an historical marker.

BIBLIOGRAPHY

1. Atkinson, Charles H., Subsurface Fracturing from a Nuclear Detonation in Granite, PNE-3001, Bureau of Mines, 1964.

2. Biggan, J. W. and Nielsen, D. R., "Some Comments on Molecular Diffusion and Hydrodynamic Dispersion in Porous Media." J. of Geophys. Res. Vol. 67. At. A. August 1962.

3. Berry, R. H. and Hakala, W. W., A Study of Chimneys and Subsidence Craters Created by Underground Nuclear Explosions, NVO-1163-162, Environmental Research Corporation, 1968.

4. Boardman, C. R., Rabb, D. D., and McArthur, R. D., "Responses of Four Rock Mediums to Contained Nuclear Explosions." J. of Geophys. Res. Vol. 69, No. 16, August 1964.

5. Carnahan, C. L. and P. Kruger, Production of Long-Lived Fission Products and Thermal Neutron-Induced Radionuclides in Underground Nuclear Explosions, Hazleton-Nuclear Science Corporation, HNS-22, March 1963.

6. Carnahan, C. L., A Procedure for the Calculation of Neutron Activation of an Infinite Homogeneous Medium, Hazleton-Nuclear Science Corporation, HNS-1229-54, September 1964.

7. Carnahan, C. L., Unpublished Tables of Explosion-Produced Radionuclides, October 1964.

8. Cohen, P. and Everett, D. E., A Brief Appraisal of the Ground Water Hydrology of the Dixie-Fairview Valley Area, Nevada, November 1963.

9. Davis, Stanley N., and Turk, L. J., Some Hydrogeologic Characteristics of Crystalline Rocks, Hazleton-Nuclear Science Corporation, 1963.

10. Dolan, P. J., Calculated Abundances and Activities of the Products of High Energy Neutron Fission of Uranium-238. Analysis Division Headquarters Defense Atomic Support Agency. DASA 525. May 1959.

11. Earth Sciences Division, Hazleton-Nuclear Science Corporation, Post-Shot Hydrologic Safety, VUF-1014, October 1965.

12. Eubank, B. F. and Ward, A. W., On-Site Health and Safety Report, Reynolds Electrical and Engineering Co., Inc. VUF-1012, June 1964.

13. Kingsley, W. H., et al., Radiological Safety, Sandia Corporation, VUF-1005, June 1964.

14. Korver, J. A., Boardman, C. R., and Rawson, D. E., The Shoal Postshot Environment, Lawrence Radiation Laboratory, SDK 65-5, August 1965.

15. Maxey, George B., "Hydrogeology of Desert Basins," in Ground Water, Vol. 6, No. 5, September-October 1968.

16. Rawson, D. E., Industrial Applications of Contained Nuclear Explosions, UCRL-14756. Lawrence Radiation Laboratory, Livermore, California, July 1966.

17. Southwestern Radiological Health Laboratory, Final Report of Off-Site Surveillance, Dept. of HEW, PUS, VUF-1009, September 1964.

18. University of Nevada, Report 2 - Geological, Geophysical, and Hydrological Investigations of the Sand Springs Range, Fairview Valley, and Four Mile Flat, Churchill County, Nevada, Part 2, Nevada Bureau of Mines, 1963.

19. University of Nevada, Geological, Geophysical, Chemical, and Hydrological Investigations of the Sand Springs Range, Fairview Valley, and Four Mile Flat, Churchill County, Nevada, VUF-1001 Final Report, Nevada Bureau of Mines, 1965.

20. U. S. Atomic Energy Commission Nevada Operations Office, Safety Involving Detonation of Nuclear Devices, NVO-28, May 1966.