# Geothermal Exploration, Drilling, and Reservoir Assessment for a 30 MW Power Project at the Naval Air Station, Fallon, Nevada, U.S.A.

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## ABSTRACT

A moderate- to high-temperature geothermal reservoir, situated at economically exploitahle depths. has hecn identified at the Naval Air Station, Fallon. Nevada. **USA.** Based on (1) the analysis and interpretation of temperatures, thermal gradients. and heat flow determinations in shallow and intermediate-depth boreholes; (2) the assessment of hydrothermal alteration patterns in these boreholes: (3) the distrihution of trace mercury in surface soils; **(4)** the surface and suhsurface structural patterns indicated hy the position and orientation of lineaments. fractures, and faults in the area: and, (5) the interpretation of surface geophysical anomalies; a geothermal reservoir of 200°C was predicted to be encountered as shallow as 1,800 m. The reservoir rock type appears to he a pre-Tertiary hasement complex that is extensively fractured. as suggested hy surface fault patterns and the results of the trace mercury study. Chemical analyses of suhsurface fluids and fluid from a hot artesian well as well as Na-K-Ca geothermometry, indicate that the maximum estimated temperature of the reservoir is 187°C to 204°C. The flow test data on a deep production-type slim hole of 2,119 m total depth demonstrates the fracture permeability in the hasement complex and the productive capacity of the geothermal reservoir. The estimated temperature of the geothermal resource is 190°C to 220°C with the reservoir situated at **1,500** to 2,500 meters. Therefore, the reservoir heneath NAS Fallon should supply geothermal fluids in sufficient quantities at temperatures necessary for the economic development of a minimum of 30 MW geothermal electric power project.

## INTRODUCTION

The geothermal resource at NAS Fallon, Nevada (NAS Fallon) has been studied hy the U.S. Navy off and on since 1979. Geochemical studies of fluids, soil mercury studies, geophysical surveys, temperature gradient hole drilling, and intermediate depth drilling were all employed in an attempt to locate and then delineate a commercial-grade geothermal resource capable of supporting electrical power generation. These efforts culminated with the drilling of a moderately deep (2,119 m) production-type slim hole in August 1993 which was successfully flow-tested thereby confirming the existence of a moderate- to high-temperature geothermal resource.

All available geological, geochemical, geophysical, and petrophysical data are synthesized in this paper for the area located at the southeast comer of the main air facility at NAS Fallon, referred to as Mainside. Based on these data and the drilling results, an assessment of the power-generating potential of NAS Fallon is presented. Mainside was deemed the most probable location for power generation based on resource quality and similarity to known producing geothermal fields in the immediate area of western Nevada.

## GEOGRAPHY AND PHYSICAL SETTING

NAS Fallon is located in west-central Nevada immediately south of the small town of Fallon, approximately 100 km east of Reno, in the Carson Desert (Figure 1). Mainside covers approximately 32 km$^2$ or 3,200 hectares. The area of greatest geothermal interest lies at the southeast corner of the Mainside complex.

NAS Fallon is situated in the physiographic province known as the Basin and Range or the Great Basin (Grose and Keller, 1979). This province is characterized by linear mountain ranges and intervening alluvium-filled basins which strike more or less a few degrees east of north. They are also very regular in their spacing and relief (Figure 2). Two notable exceptions are the Carson Desert

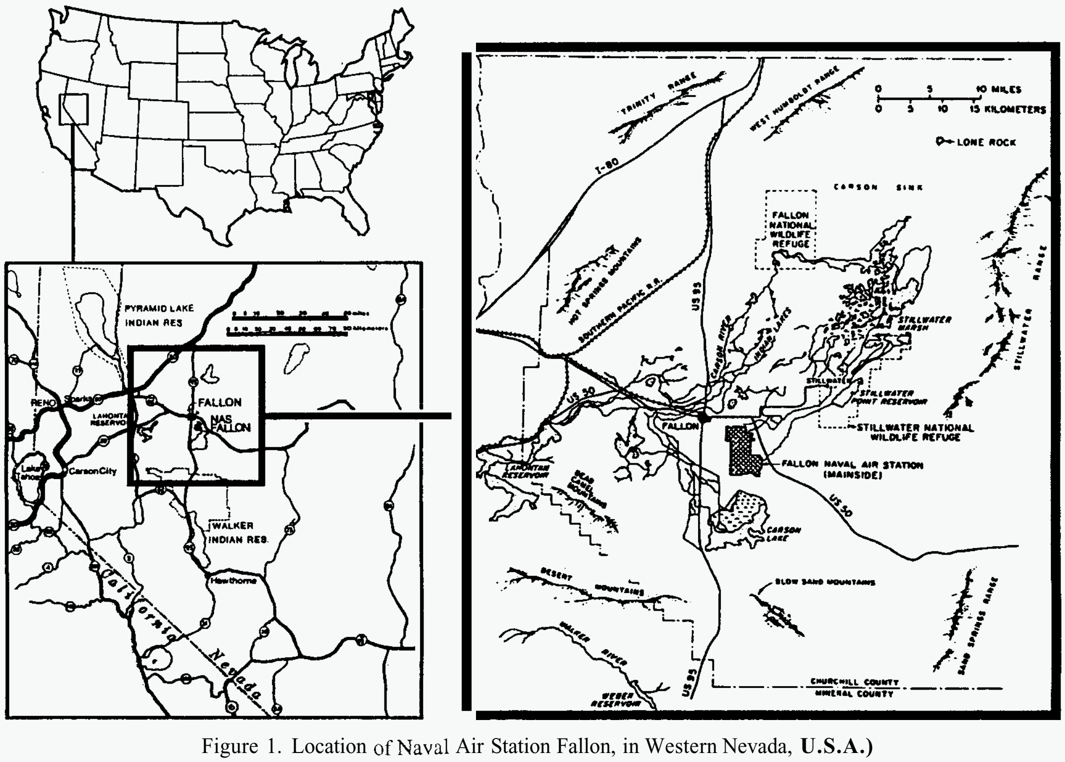



Figure 1. Location of Naval Air Station Fallon, in Western Nevada, **U.S.A.)**

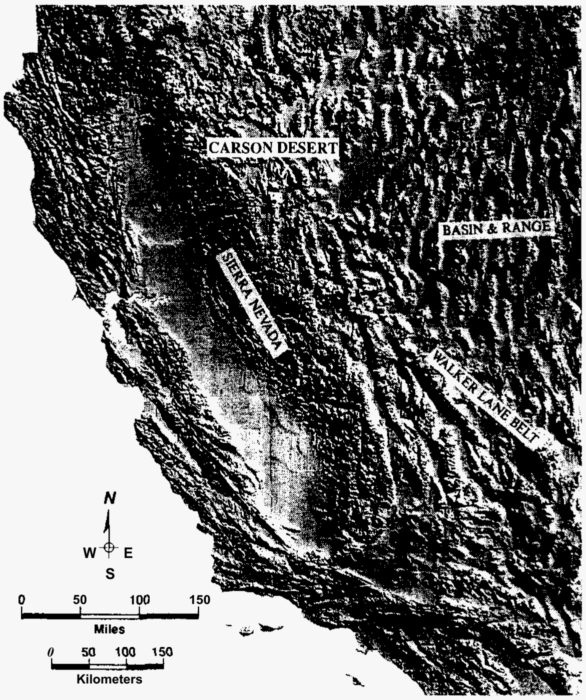



Figure 2. Digital Topographic Map of Southwestern **U.S.** The Carson Desert is the elliptically-shaped depression at the center top of the figure.

on the western side of the Basin and Range and the Sevier Desert on the eastern side. Both of these features are nearly equant in shape and are much larger in area than the average basin.

The Carson Desert is characterized by low annual rainfall, averaging slightly more than 12.5 cm per year. The basin is hydrologically closed which is to say that all drainage is internal, and there is no apparent connection with any of the adjacent basins (Katzenstein and Bjornstad, 1987).

## REGIONAL GEOLOGY AND STRUCTURAL SETTING

The Basin and Range province is best known for the large amount of well-documented Neogene crustal extension. Wernicke, et al., (1988) present data supporting up to 250 km overall crustal extension in the Basin and Range which amounts to an average of 133% in the area stretching from the western edge of the Colorado Plateau to the eastern margin of the Sierra Nevada. That extension is partitioned into strongly extended domains (upwards of 350%) and intervening areas of virtually no extension (Wemicke, 1992).

The topography of the Basin and Range was originally thought to be the product of movement along high-angle normal faults resulting in formation of a series of horsts and grabens (Stewart, 1971). **A** review of reflection seismic data by Anderson, et al (1983) resulted in three separate possible styles of deformation which could result in the topography seen today. One of these is the formation of asymmetric tilted fault blocks which are hounded on one side by listric faults which sole out into a master detachment surface at an average depth of approximately 15 km. Later crustal reflection and refraction data support this interpretation (von Tish, et al., 1985; Potter, et al., 1987) and it has generally become the accepted structural model for the Basin and Range province.

Volcanic activity occurred in the Carson Desert area during several periods extending from 43 to 0.02 Ma (Stewart and Carlson, 1976). Early Cenozoic volcanic rocks are deposited directly on top of Mesozoic sediments and metasediments. There are several well-documented rhyoliticvolcanic centers in eastern and south-central Nevada with ahundant and widespread lava flows and ash flow tuffs. The latest volcanism (since 6 Ma) consists of basaltic volcanic rocks confined to western Nevada. Vestiges **of** these hasaltic rocks outcrop in the Carson Desert, i.e., Rattlesnake Hill, Soda Lakes, Upsal Hogback, and Lone Rock, but they do not constitute a large volume of the total surface area (Bruce. 1980).

Mountain ranges surrounding the Carson Desert are composed of Mesozoic and Cenozoic volcanic rocks for the most part. The Stillwater Range on the eastern margin is a typical uplifted horst hlock consisting primarily of Jurassic and Triassic metasediments and sedimentary rocks overlain by Tertiary and Quaternary lava flows and tuffs. **A** few Jurassic-Triassic granitic rocks outcrop along the western edge of the range and a notable basic intrusive complex is found in the area of the Dixie Valley geothermal facility located approximately 60 km northeast of Mainside. The other smaller mountain ranges bordering the Carson Desert consist of volcanic flows, tuffs, and epiclastic rocks primarily of Miocene age (Stewart and Carlson, 1976).

The Carson Desert itself is a sediment-filled half-graben with a range-bounding fault on its eastern margin. The bulk of those sediments are lacustrine and eolian deposits associated with Plio-Pleistocene lakes which filled the valley. The fill ranges from a few hundred meters thick on the southern margin to more than 3,000 m in the northern part based on data from the Standard-Amoco Oil strat test well (Hastings, 1979). Lithologic units encountered in that well include lacustrine and fluvial clays, sands, and silts, eolian sands, volcanic flows, tuffs, and epiclastic deposits.

## SEISMICITY

NAS Fallon is located in an area that is considered moderately active from a tectonic point of view although no active faults have heen mapped on Mainside. Distribution of historic seismicity (Figure 3) from 1852 to 1989 in west-central Nevada show that the Carson Desert itself is nearly devoid of seismicity (U.S. Navy, 1991). Most of the earthquakes are located on the range hounding faults, i.e., the eastem and western margins of the Stillwater Range. Likewise, the vast majority of the events are Richter magnitude 3.0 or less. Most seismicity associated with geothermal anomalies is characterized by high frequencies and magnitudes in the range of -2.0 to 3.0 which could lead to the conclusion that there are no geothermal anomalies in the Carson Desert. However, based on available data, the producing geothermal sites appear to he aseismic in this area leading to the

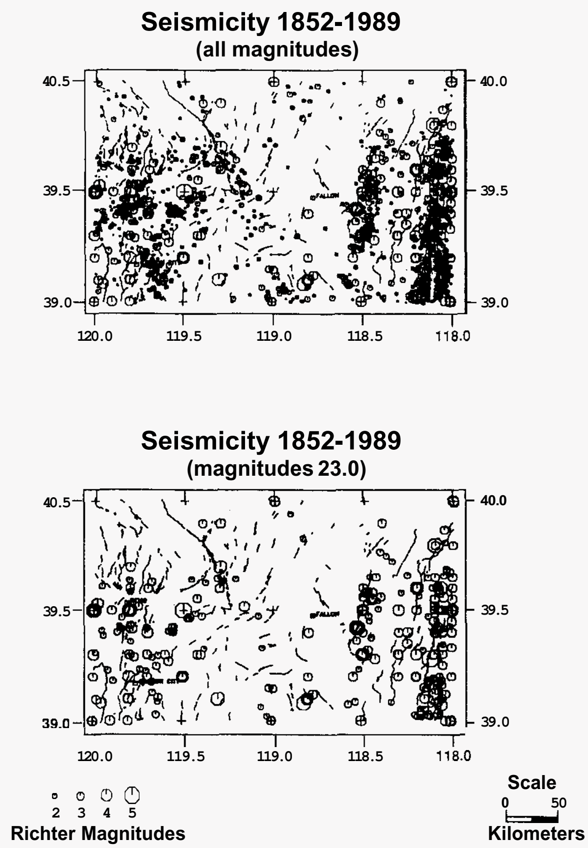



Figure **3.** Seismicity for the Region Surrounding Fallon. The upper plot shows epicenters for all magnitude earthquakes while the lower one shows only those greater than, or equal to, Richter magnitude 3.0. Data were ohtained from the Seismology Laboratory, University of Nevada at Reno.

conclusion that the paucity of events in the valley itself is a function of the type of instrumentation, the spacing, and emplacement of the seismometers. It is not, in this case, reflective of the presence of geothermal anomalies.

## REGIONAL GEOTHERMAL CONTEXT

Exploration for geothermal energy in Nevada began in 1950 with the drilling of the Rodeo well at Steamboat Springs approximately 15 km south of Reno (White, 1983). Since that time hundreds of boreholes have been drilled in Nevada in an attempt to locate and develop geothermal resources capable of producing electricity. These efforts have resulted in the identification of several moderate- to high-temperature geothermal locations in the northern Basin and Range (Edmiston, 1982; Benoit and Butler, 1983; Edmiston and Benoit, 1984). In fact, all of the commercial development to date in Nevada has been in the Basin and Range including three facilities, Desert Peak, Soda Lake, and Stillwater, in the Carson Desert. Of these, Desert Peak is significant because it is essentially a blind resource, i.e., there are virtually no surface thermal manifestations indicating a geothermal resource beneath the surface. Two sets of intersecting north-northeast and east-northeast striking faults provide the conduits for 204°C geothermal fluids in metamorphic and plutonic rocks at Desert Peak.

NAS Fallon lies in the northwestern portion of the Basin and Range which is characterized by abnormally high heat flow, a high frequency of hot springs, and abundant normal faulting (Grose and Keller, 1979). At least two hypotheses have been proposed to explain the high heat flow: high regional heat flow and decay of radioactive material in the shallow crust (Grose and Keller, 1979), and magmatic heating due to crustal thinning (Davis, 1979). Interpretation of COCORP seismic reflection lines in the northern Carson Sink show the crust as being approximately 20 km thick which is about one-half to one-quarter the normal thickness for continental lithosphere (Klemperer, et al., 1986). These data support the hypothesis of magmatic heating due to crustal thinning.

Heat flow measurements summarized by Lachenbruch and Sass (1978) for the Basin and Range show that the average value over the entire Carson Desert lies between 63 and 105 mW m$^{-2}$. These values are 1.5 to 2.5 times greater than normal continental lithosphere, and in local hot spots may exceed 5 times normal. Lachenbruch and Sass (1978) conclude that the high heat flow is the result of crustal thinning and convection from the asthenosphere, solid state stretching, and magmatic intrusion.

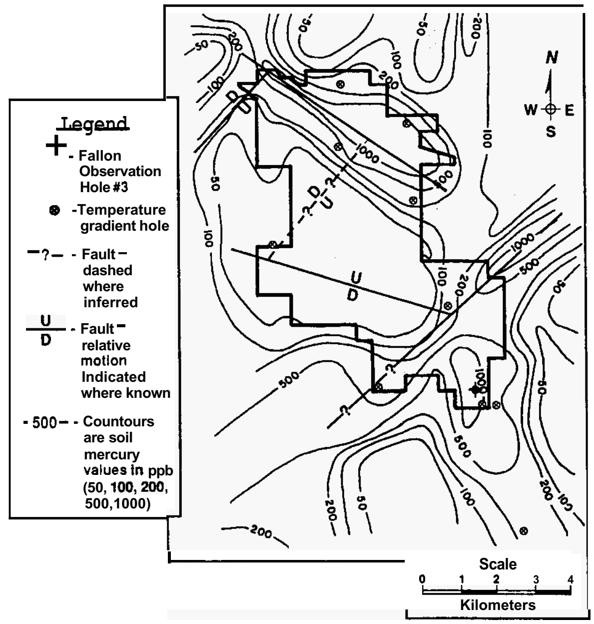
## PREVIOUS INVESTIGATIONS AT NAS **FALLON**

Investigation of the geothermal potential of NAS Fallon was initiated in the early 1970's by the **U.S.** Navy. General geological, geochemical, geophysical, and petrophysical studies were conducted at Mainside as well as outlying bombing ranges (Bruce, 1980; Bruce, 1981; Katzenstein and Danti, 1982; Katzenstein and Bjornstad, 1987; Monastero, et al., 1989). As a result of those investigations, the Navy has focused their resource assessment activities on Mainside.

Bruce (1980) summarized the first phase of exploration at Mainside concluding that there was a potential resource evidenced by a hot (77°C) artesian well located a few km south of the base. Using a Na-K-Ca geothermometer technique on water samples taken from that well, it was determined that the source water was as hot as 204°C. On the basis of those data, the Navy drilled four temperature gradient holes in the southeast comer of Mainside (Figure 4) in an attempt to delineate the thermal anomaly suggested by the artesian well. Thermal gradients in these holes ranged from 97°C km$^{-1}$ to 237°C km$^{-1}$ which are significantly above the regional average of 40°C km$^{-1}$ for the entire Basin and Range (Sass, et al., 1981).

Application of a Na-K-Ca geothermometer on fluids recovered from one of the Mainside thermal gradient holes yielded a value of 204°C for the source water. This is the same as that predicted from the artesian well south of Mainside.

A mercury trace element study conducted on soils yielded encouraging results with values in excess of 2000 pph which were collocated with high thermal gradients (Figure 4). It was postulated by Katzenstein and Danti (1982) that the pattern of the mercury anomalies in the southeast part of Mainside reflected the residue of geothermal fluids escaping from the reservoir along fault traces. Similarly high values for mercury in the northern portion of Mainside suggest the same type of leakage there, again associated with high thermal gradients.




igure 4. Composite Figure Showing Results of Mercury Soil Analysis, Location of Temperature Gradient Holes, FOH #3, and Structural Interpretation. (Adapted from Katzenstein and Bjornstad, 1987.)

In 1981, the Navy drilled the Fallon Observation Hole (FOH) #1 slim hole to a total depth of 617 m in the southeast corner of Mainside. When this hole reached thermal equilibrium, the bottom-hole temperature was 97°C with a temperature gradient of 139°C km$^{-1}$ which is, like the aforementioned artesian well, above the regional average for the Basin and Range (Sass, et al, 1981).

Subsequent gravity and magnetic surveys substantiate the idea that there might be a series of buried faults in the basement rocks and that there might be significant vertical displacement on some of them (Katzenstein and Danti, 1982). A broad, roughly circular magnetic high collocated with the mercury anomaly was identified in the central portion of Mainside. This feature was interpreted to reflect a thicker sequence of basaltic flows or possibly a cooled intrusion. The absence of positive correlation with a similar gravity anomaly prevents confirmation of any one of these ideas.

In 1986, a second slim hole, designated FOH #2, was drilled in close proximity to FOH #1. Total depth of this hole was 1,367 m with 681 m of unconsolidated sediments overlying 689 m of fractured volcanics (Katzenstein and Bjornstad, 1987). Based on mineralogy and petrology, it was determined that the volcanics probably were a northern extension of the Plio-Pleistocene Bunejug formation which consist of olivine basalts with interlayered tuffs, epiclastic deposits, and an occasional pyroxene andesite.

Evidence of hydrothermal alteration was found in FOH #2 in the form of pyritization, alteration of primary minerals, and traces of hydrogen sulfide. There was no evidence of steam nor was there any fluid flow from the slim hole. Based on analysis of the cores, however, abundant fracturing was documented. Logging of FOH #2 disclosed a bottom hole temperature of **155°C** with an aggregate gradient of 104°C km$^{-1}$. The temperature gradient was found to be conductive at the bottom of the hole which was an encouraging sign for further, deeper investigation.

## DEEP TEST HOLE **(FOH #3)**

The one remaining critical piece of information needed to document a viable economic geothermal resource at Mainside was provided with the drilling of a production-type slim hole, FOH #3, located immediately next to FOH #2 (Figure 4). This 2,119 m test hole penetrated essentially the same stratigraphic sequence as found in FOH #2 with the top of the volcanic sequence at 688 m and the top of the metamorphic/plutonic complex at 2,040 m.

A 17.78-cm diameter intermediate casing string was cemented in to **a** depth of 895 m and the hole was drilled to total depth (T.D.) with a 15.56-cm diameter bit. There were four lost circulation zones (Figure 5) between 2,072 m and T.D. with the largest taking 7,900 liters per hour. Geophysical logs were attempted in the open hole with no success. During the six-arm caliper run, the internal maximum recording thermometer registered a temperature of 233°C which caused severe damage to the tool. It was decided to run 11.43-cm diameter liner into the hole from 884 m to T.D. The liner was slotted (1.25 cm wide and 5 cm long) in the four lost circulation zones. After the liner was emplaced, **a** static temperature-pressure log **was** obtained and the maximum temperature recorded was 191°C. The temperature profile for the slim hole is shown in Figure 6.

The slim hole was successfully stimulated with liquid nitrogen in an attempt to induce flow. During a nine-hour test, fluid flowed from all four zones thereby demonstrating fracture permeability. Maximum fluid flow measured through a weir box reached **40** kg $sec^{-1}$ at a temperature of 109°C. The low flowing wellhead temperature was initially disappointing given the measured static downhole temperatures. A flowing pressure-temperature survey showed that cold tluids were entering the wellbore from the middle two perforation zones, inixing with the hot brines, and lowering the aggregate temperature substantially. In spite of the fluid mixing, steam Ilowed from the wellhead and the flash point was rapidly migrating up the wellhore when the flow test was terminated. The total volume of fluid produced during the test was 506,000 liters.

## RESERVOIR EVALUATION

The amount of electricity that can be generated at NAS Fallon will depend on the quality and quantity of the geothermal resource found during the reservoir delineation phase. Howcver, based on test results to date. it is clear that steam is present. Analysis of the available data show that these is a very high probability for sufficient steam to support a 30 MW power plant for up to 30 years.

Considering the thermal gradients, borehole temperatures, and geothermomcter values obtained at Mainside, there is a better than 95% probability of encountering a 190°C to 220°C resource at depths of less than 2,500 m. This does not take into account the probable temperature decline when the fluids are hrought to the surface although this drop may he as small as 2°C for large-capacity wells or as great as 15°C lor small-capacity wells. The precise amount of the temperature drop will vary with wellhore diameter, depth to production, etc. For the following calculations, a mass flow rate of 60 kg $sec^{-1}$ was assumed for production-type wells hased on a larger wellbore than that of FOH #3 where the measured flow rate was **40** kg $sec^{-1}$. However, the mass yield per well could vary from 30 kg $sec^{-1}$ to more than 250 kg $sec^{-1}$ hased on production levels at nearby geothermal power facilities. At Dixie Valley, for instance, production wells yield flow ranging from 100 to 232 kg $sec^{-1}$ of mass on a sustained basis (Benoit, 1987).

The conversion efficiency of thermal energy to electrical energy depends principally on the Camot thermodynamic efficiency, which ultimately limits the performance of any heat engine. Carnot efficiency increases with the temperature difference between the hot and cool reservoirs connected to the heat engine. In geothermal applications, the temperature of the cool reservoir which is the mean annual atmospheric temperature (12°C at Mainside) may he treated as a constant. This means that for a unit of electrical power, the required mass flow of geothermal fluid decreases as the reservoir temperature increases. Hence, for geothermal wells of equal deliverability and similar chemistry, the capital investment may also decrease with increasing reservoir temperature.

Based on drilling and llow rate test results for Mainside, producing wells can he expected to yield between 3 to 5 MWe each. The flow test on FOH #3 would have produced higher temperature geothermal fluids had the liner been pulled and blank inserted into those sections from which cold water was flowing. The fact that the flash point was migrating up the wellbore so rapidly during the flow test indicates that even though cold water entries were involved, the slim hole was still able to overcome that and produce steam and geothermal fluids.

The reservoir area is fairly pervasive beneath Mainside hased on the present geologic model of the geothermal system. It would appear from the stratigraphy and structure determined through drilling and geophysical work, that the reservoir is similar to that

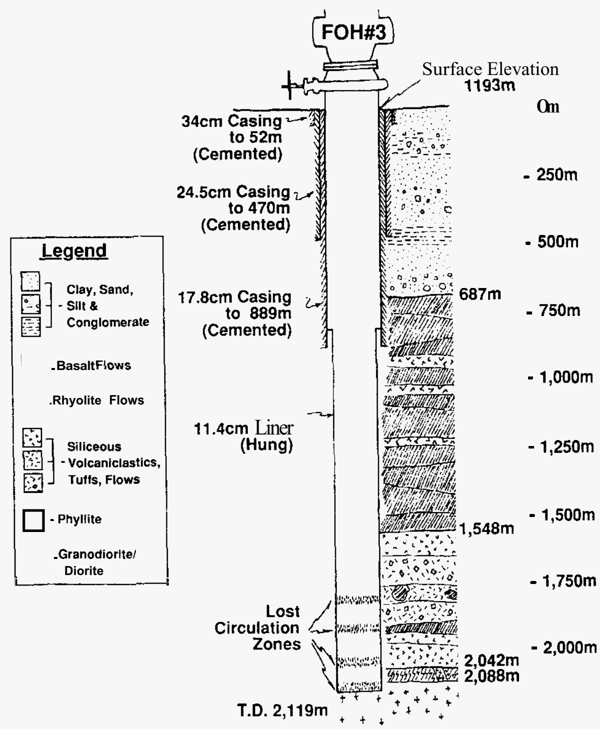



Figure 5. Schematic Diagram of FOH #3 Wellbore. Lost circulation at 1776-1789 m, 1881-1894 m, and 2002-2041 m, and 2094-T.D.

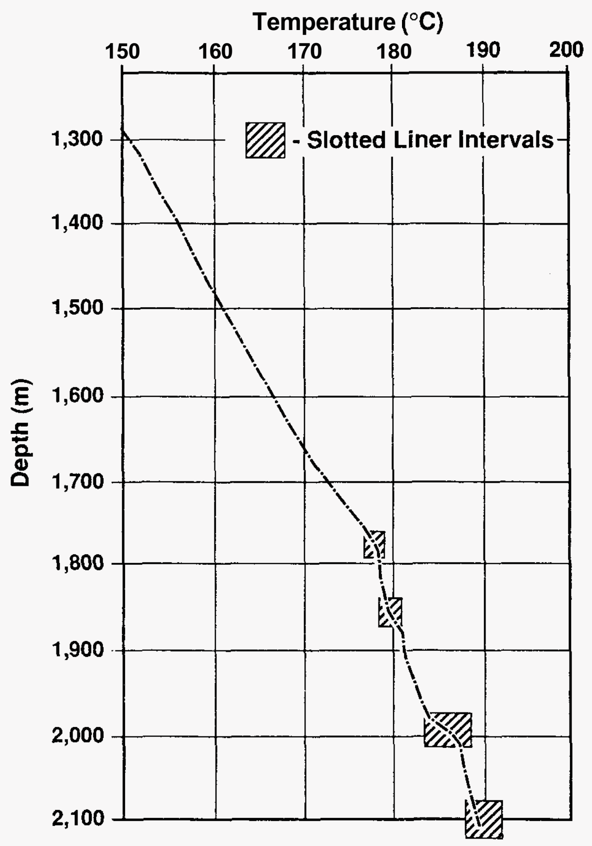



Figure 6. Fallon Observation Hole #3 Static Temperature Survey. Data acquired 48 hours after drilling was completed.

found at the nearby Desert Peak geothermal field. Production there is found in fractured crystalline basement rock and is located widely throughout the field.

For the purposes of estimating the size of the potential producing reservoir, 10% reservoir porosity was assumed. This is a conservative value given that wells in fractured crystalline rocks generally have 15% to 20% porosity in producing zones. It is further assumed that fracturing is reasonably pervasive throughout the area, which is the situation at Desert Peak. The total potentially productive area at Mainside is approximately 1,400 hectares with fractured reservoir rocks expected to occur on average hetween 1,500 and 2,500 m depth. As stated previously, wells are estimated to yield an average mass flow of 60 kg $sec^{-1}$ at temperatures of 185°C or greater, adjusted for a 5°C temperature loss in the wellhore. Using these values, it is estimated that there is sufficient geothermal resource beneath Mainside, NAS Fallon to generate 1,980 MWe-years of electrical power. Based on the assumption of a 30-year productive span, an installed capacity up to 66 MW could he supported which provides a 100% margin for the development of a 30 MW geothermal electric power generating facility at NAS Fallon.

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