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Development and Testing of a Single-Ended Distributed Temperature Sensing System at the Beowawe, Nevada Geothermal Reservoir

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ABSTRACT

Testing of "single-ended" optical fibers for monitoring temperatures in geothermal production began at the Beowawe, Nevada geothermal field in June 1996. High-temperature rated polyamide-coated fibers were badly damaged within weeks in flowing wells. Optical time domain reflectometry measurements show no appreciable degradation of replacement teflon-coated and polycarbon-coated fibers after 18 and 15 months of continuous service. Comparison of the DTS temperature data with research-quality conventional temperature logs shows that considerable care must be taken in obtaining the optical fiber data if repeatable temperatures within 1 to 3°F are desired. These data demonstrate that the long-term cooling trend of all three Beowawe production wells has greatly diminished or ceased entirely.

Introduction

As geothermal fields age or injection augmentation programs are implemented, the probability of reservoir or production well cooling increases and more intensive temperature monitoring is desirable. Free flowing wells with two phase conditions in the upper part of the wellbore are the most difficult and costly to monitor. Data must be acquired below the flash point, which can be several thousand feet below the wellhead. Historically, monitoring has required traversing the wellbore with a temperature logging tool. Long-term monitoring with conventional tools seems to inevitably result in a number of different logging tools and vendors being utilized. Questions of individual tool calibrations greatly complicate the interpretation of differing data sets. Such complications are particularly vexing if the intent is to confidently measure temperature differences of one or two°F over a period of months to years.

The advent of distributed optical fiber temperature sensing (DTS) systems offers an opportunity for obtaining temperatures deep in flowing or static wells with the same installed equipment for a period of years. It also has the potential to substantially reduce field monitoring costs in that a logging truck with a high-temperature cable is not required for data collection. DTS systems, with very small diameter fibers, can easily be integrated with pressure monitoring equipment and/or chemical inhibition systems in a variety of downhole hardware configurations serving multiple purposes.

DTS Background

Distributed optical fiber temperature sensing is based on the optical time domain reflection concept. The DTS technique uses the optical fiber as the sensing element with the intensity of the Raman back-scattered light of a laser pulse as a temperature-dependent parameter. The method allows temperature to be measured instantaneously along an optical fiber with an exact allocation of temperature to distance because of the known velocity of light propagation in the fiber (Forster et al., 1997).

DTS systems need to be calibrated. This has normally meant using a fiber-specific calibration function that is dependent on the fiber properties and their temperature dependence. The calibration has been accomplished by heating a defined length of the fiber on the surface in a constant temperature environment. Raw DTS data contain some scatter which can be smoothed by averaging combinations of data points or multiple DTS logs obtained over a period of minutes.

DTS Geothermal Experience

The DTS technique is quite new to the geosciences, with its first wellbore application in 1992 (Hurtig et al., 1993). In 1993 DTS measurements were made in two static geothermal wells in Japan (Sakaguchi and Matsushima, 1995) to depths of 5742' and 464°F using a loop system with both ends of the loop being alternately injected with a laser pulse. These static logs agreed to within 3 to 5°F with conventional prior temperature data. Sakaguchi and Matsushima also installed a DTS system in a well for 69 hours before, during, and after an injection test at temperatures up to 383°F.

In the United States in 1994 and 1995 suites of temperature logs were obtained with various logging tools in static nongeothermal wells (Wisian et al., 1996, Forster, et al., 1997). These data showed that the DTS technique is capable of providing information with a limiting resolution of 0.1°C and a limiting precision of 0.3°C. These values are adequate for monitoring the temperature trends of geothermal production wells, assuming the equipment reliably operates with similar resolution in hotter environments.

The only DTS logs made in geothermal wells in the United States so far have been at Beowawe, Nevada beginning in June 1996 and in one shallow well at Steamboat Hot Springs in July 1996 (Pruett, 1996).

Beowawe Background and DTS System Design

All three production wells at the Beowawe, Nevada geothermal field have undergone extensive and well documented cooling (Benoit and Stock, 1993, Benoit, 1997). Obtaining flowing temperature logs from these wells has historically been relatively expensive and also requires that the carbonate scale inhibition system, consisting primarily of 1/4" O. D. stainless steel capillary tubing, be pulled and rerun before and after each log.

The Beowawe production wells have three characteristics which made them ideal for long-term testing of DTS systems. The wells have relatively shallow flash points of 500 to 800' below the surface so DTS systems need not be very long. The wells have moderate temperatures of 340 to 365°F at the flash point and they already had retrievable downhole hardware for carbonate scale inhibition to support and protect the optic fiber. A change in injection strategy in early 1994 was anticipated to moderate the temperature decline and it was with considered important that the temperature of the wells be closely monitored.

DTS data have most commonly been collected through a loop system where both ends of the optic fiber are at the surface and a laser pulse can be alternately launched into each end to determine the measurement repeatability. The existing scale inhibition system hardware at Beowawe did not readily allow the required 2 inch minimum radius at the bottom of the 1/4" tubing for a loop. The optic fiber was therefore designed as a simple single strand with one end at the bottom of the tubing and one end at the surface.

The installed hardware consists of an optic fiber with a diameter of 155 μm installed in a 1/8" O. D. stainless steel capillary tubing which is sealed on the bottom. The 1/8" cap tubing is installed inside a 1/4" O. D. stainless steel cap tubing. The inhibition chemical is pumped through the annulus between the 1/8" and 1/4" cap tubing strings. The 1/8" cap tubing isolates the optic fiber from both the geothermal fluid and the scale inhibition chemical. No attempt was made to purge the air or any associated water vapor from the inside of the 1/8" tubing.

The initial optical fibers installed were multimode graded index fibers manufactured by Spectran (Product Code TCU-MEO5OH). They have a PYROCOAT™ coating rated to over 572°F. These fibers are referred to as polyimide-coated.

Initial DTS and Conventional Measurements

Immediately prior to the first polyimide-coated fibers being installed by Pruett Industries, conventional flowing temperature logs were obtained with Pruett's small diameter surface readout equipment. A comparison of these June 1996 surface readout logs with the first DTS results show that the DTS reported temperatures at depths of 1100 or 1200' were from 1.1 to 2.9 °F lower than the surface readout log temperatures (Figures 1, 2, and 3). In December 1996 a different surface readout tool reported temperatures slightly lower than the DTS logs. The variable scatter of the DTS logs in Figures 1, 2, and 3 simply reflect different averaging techniques.

Comparison of the June and December 1996 Pruett conventional logs and DTS data with 1994 and 1995 TASCO conventional temperature data (Figure 4) shows a substantial offset in the cooling trends of the wells. This is a classical case of the difficulty in working with detailed temperature data collected from different tools and/or vendors. An optimistic, and incorrect, interpretation of the June 1996 data on Figure 4 could be that the cooling trend actually stopped in late 1995. However, the June and December 1996 conventional Pruett data, indicate the temperature decline in all three wells continued throughout 1996. From just these data, it is not possible to say which, if either of the 1996 or pre 1996 data, are closest to being correct. Relative temperatures between the three wells are consistent in all data sets. Overall discontinuities between 1995 and 1996 data are 3 to 6°F.

Polyimide-Coated Fiber Degradation

Over a period of weeks all three polyimide-coated optic fibers began producing obviously erroneous data. As these fibers are rated by the manufacturer to over 572°F, this deterioration is presumably not solely temperature related. Four surveys in well Ginn 2-13 over three months are typical of the progressive deterioration in data quality (Figure 5). The questionable profiles clearly show a "knee" at the flash point depth which indicates that the fiber is at least partially operational below the flash point depth.

There are many possible causes of the damage. Inspection of one damaged polyimide-coated fiber by Sandia National Laboratory (Randy Norman, pers comm.) with a scanning electron microscope showed that the coating had most likely been damaged by mechanical abrasion on the surrounding stainless steel capillary tubing. Electron energy spectrums from an electron scanning microscope on damaged sections of fiber show the presence of iron and chromium, presumably resulting from abrasion on the 1/8" stainless steel tubing enclosing the optical fiber. These elements were not found on scans of undamaged fiber. This damage presumably allows light to escape, putting the calibration in error.

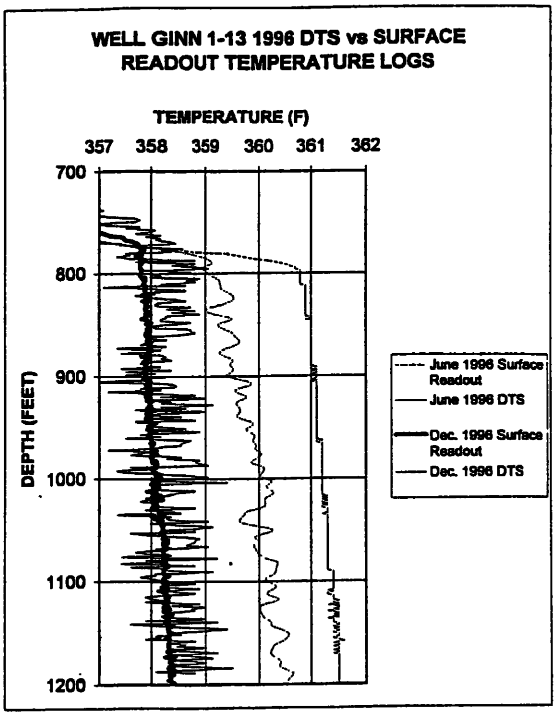
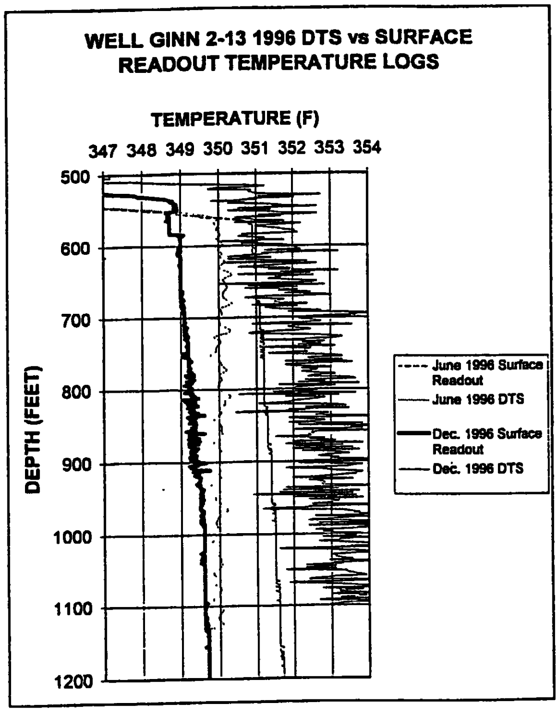


Figure 1.



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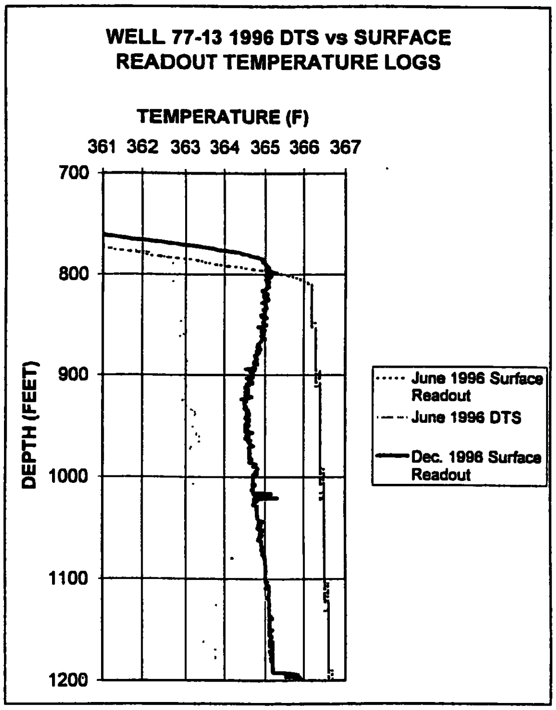

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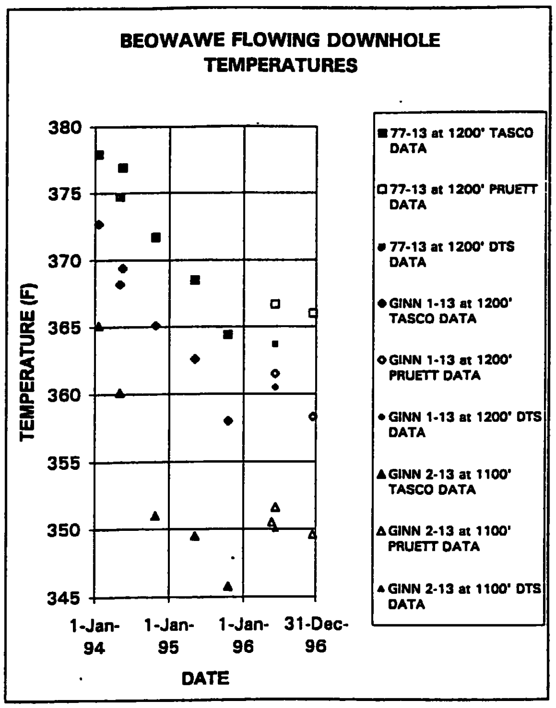

Figure 4.

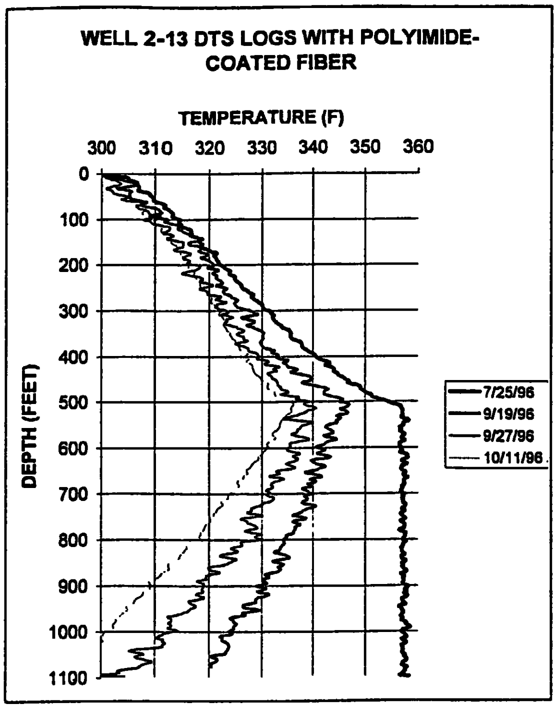

Figure 5.

Optical transmission spectra from the degraded polyamide coated fiber were compared to spectra from new polyamide coated fiber. The ratio of the degraded to new fiber transmittance (Figure 6) shows loss over all wavelengths measured and distinct loss peaks at 1.4 and 2.2 microns. These loss peaks are consistent with published wavelengths of hydroxide contamination (Murata, 1987). A possible mechanism of contamination is hydrogen diffusing into the fiber core and reacting with oxygen in the silica at the elevated temperatures to form hydroxide (Lemaire, 1993). This mechanism may be more likely to occur if the fiber coating is damaged.

Teflon and Polycarbon-Coated Fibers

With the discovery of the failing fibers a search was made for fibers with more robust coatings. A Dow Corning manufactured fiber (no longer available as of early 1998) with a teflon coating was installed in the Ginn 1-13 well on Sept. 19, 1996 (and transferred to well 77-13 on Aug. 12, 1997). The first data from this teflon-coated fiber produced reasonable results in terms of absolute temperatures below the flash point (Figures 7 and 1). However, over the next 9 months difficulties in generating consistent or reproducible results were the norm. The selected profiles on Figure 7 (others were obtained but are not included) show more or less the proper shape but the absolute values of temperatures below the flash point vary by up to 20°F. This pattern suggests that the fiber is operating properly and that some aspect of the measurement technique was incorrect.

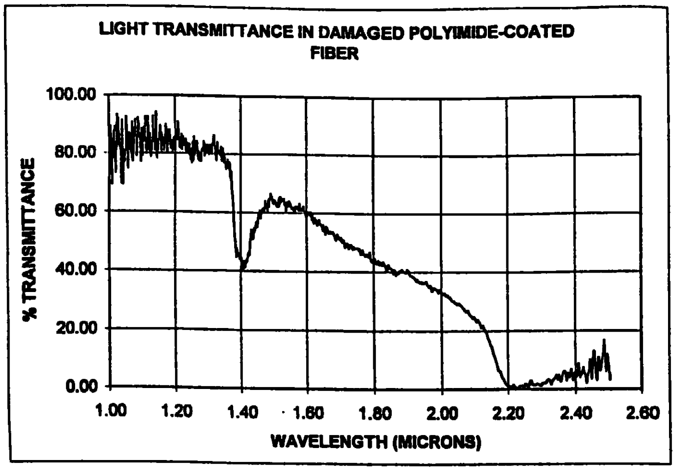

Figure 6.

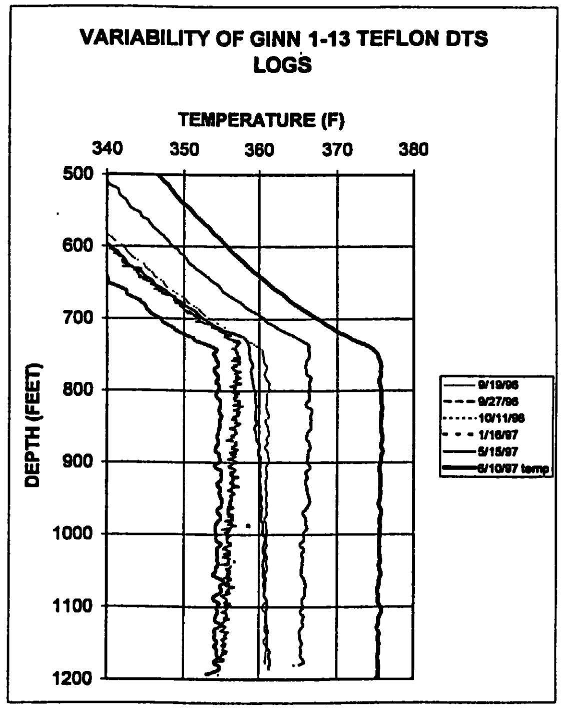

Figure 7.

In obtaining these DTS data a 200 foot length of fiber on the surface which was heated in air to a constant temperature of 100°F and this served as a calibration reference. This type of calibration or the technique utilized may be inadequate to obtain consistent quality information.

On Dec. 16, 1996 a Spectran manufactured fiber (Product code TCU-MEO50J)with a Hermetic/PYROCOAT™ coating was installed in the Ginn 2-13 well. This new fiber, referred to as polycarbon- coated, also produced an unacceptably broad range of temperatures below the flash point (Figure 8). The fact that both new (and different) fibers produced the same inconsistent data clearly suggested that the measurement technique needed improvement.

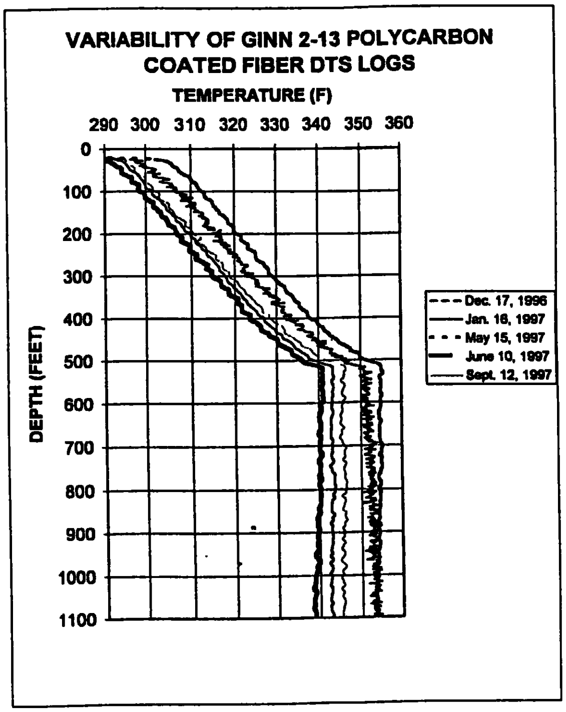

Figure 8.

To reduce the scatter in reported temperatures below the flash point a single point calibration method was devised to adjust the reported fiber temperature in the wellhead to the measured wellhead temperature. This has resulted in much more consistent data being collected after June 1997.

On March 11, 1998 a new chemically resistant Spectran fiber (product code SL 50/125/155 Chemical Resista) was installed in the Ginn 1-13 well. This fiber incorporated a thermocouple in the upper part of the system so that a more precise wellhead reference temperature could be obtained. The fiber was easily calibrated to this temperature, however, the initial log with this system showed an anomalously high temperature gradient below the flash point (Figure 9).

Conventional Confirmatory Logging

By the spring of 1997 it was clear that repeatable data were not being obtained with the DTS systems and it was also believed that the replacement fibers in Ginn 1-13 and Ginn 2-13 were not deteriorating. As it had been approximately 1 ½ years since independent logs were obtained from the three wells, arrangements were made for Sandia, Southern Methodist University, and the U. S. Geological Survey to obtain flowing logs in the wells. These served two purposes, as a reference point for calibrating and working with the DTS systems, and to accurately characterize the temperature decline of the reservoir.

Conventional logs were obtained by Southern Methodist University (SMU), Sandia, and the U. S. Geological Survey in the Ginn 1-13 well between June 13 and November 18, 1997. These three conventional logs agree to within 1°F of each other (Figure 9). The two 1997 DTS logs on Figure 9 vary by 1 to 1.5°F from each other and in general are slightly hotter than the conventional logs. The March 1988 DTS log was obtained with a different fiber and has an abnormally high gradient below the flash point. This most recent DTS log has the highest temperatures and it is possible (Wisian et al., 1998) that this well has warmed slightly over the past year.

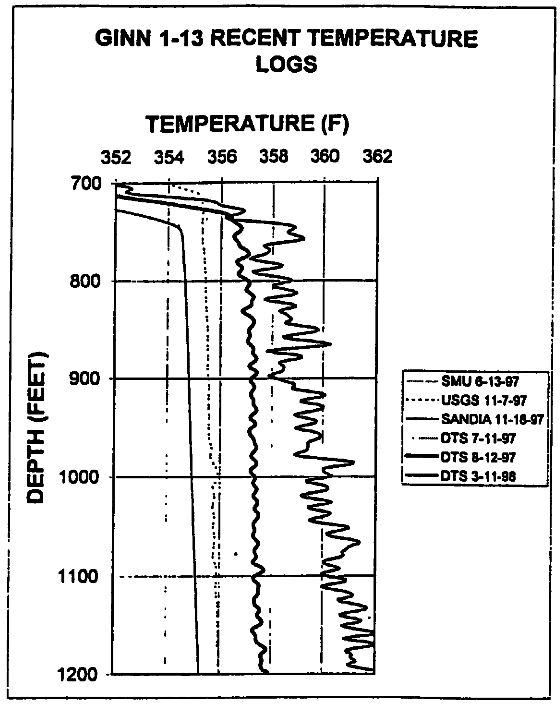

Figure 9.

In June 1997 SMU and Sandia conventionally logged the Ginn 2-13 well with memory tools (Figure 10). These two logs vary by about 1°F below the flash point. A log by the USGS in Nov. 1997 encountered some difficulties with a leaking cable. However, this suspect log is in reasonable agreement with the other conventional logs and is included on Figure 10. Since June 1997, DTS logs with the polycarbon-coated fiber are in reasonable agreement with the conventional logs and have a temperature spread of 2 to 3°F below the flash point. The recent DTS logs in the 2-13 well show a repeatable wavy pattern below the flash point.

In September 1997 the teflon coated fiber from the Ginn 1-13 well was transferred to the 77-13 well so that it could be subjected to the environment of a much higher flow rate well. Recent conventional and DTS logs from 77-13 (Figure 11) have exceptionally good agreement to within 1°F.

OTDR Testing of Fibers

On March 11 and 12, 1998 optical time domain reflectometery (OTDR) traces were taken from all fibers in the Beowawe wells. These fibers had been in service for less than one day in well Ginn 1-13, 15 months in well Ginn 2-13, and 18 months in well 77-13. Figure 12 shows the ODTR traces from the Corning silicon/teflon fiber and partially degraded Spectran polyamide fiber in well 77-13. The amplitude of the OTDR data indicate the amount of reflected light as a function of distance. The amplitude peaks represent connections between the OTDR, a patch cable, the fiber in the well, and the end of the fiber. The viability of each fiber was assessed by comparing the loss per kilometer to the manufacturer's new fiber specification. This comparison demonstrated no degradation of the Corning fiber in well 77-13 or the Spectran fiber in Ginn 2-13 after 18 and 15 months of continuous service. Some degradation of the polyimide coated fiber is obvious on Figure 12.

Recent Fluid Temperature Changes with Time

The most recent good quality logs obtained at Beowawe indicate that the cooling trend in all three wells has greatly diminished, if not entirely ceased (Figure 13). The most recent DTS data are in good agreement with conventional logs and should now therefore be producing quality data. Many individual DTS data points and the 1996 Pruett conventional log data (shown on Figure 4) are not included on Figure 13. Some of these logs agree closely with the recent conventional logs, while others are clearly erroneous (Figs 7 and 8). To avoid personal bias none of the questionable data obtained in 1996 and early 1997 are shown on Figure 13. Unfortunately, this does not allow detailed insight into the cessation of the cooling trends.

Conclusions

After considerable effort the single-ended DTS systems installed in the three Beowawe production wells appear to be producing temperature data of reasonable quality at depths to 1200' and temperatures as high as 360°F. The polyimide coated optical fibers that have been previously utilized in short-term logging operations to considerably higher temperatures and depths deteriorated within a matter of weeks. Polycarbon-coated and teflon-coated fibers have now been continuously tested for periods of 15 and 18 months and appear capable of surviving for many years under these conditions.

Considerable care must be taken in calibrating the fibers. It is possible to obtain temperature logs with the correct shape but absolute values can be off by as much as 10°F. By calibrating the fiber to a known temperature in the wellhead it is hoped that more accurate data can be obtained. Properly calibrating the fibers so that repeatable data are obtained is the most important unfinished task at Beowawe.

Research quality temperature logs obtained by SMU, Sandia, and the U. S. Geological Survey agree to within about 1°F of each other. Comparison of the recent DTS data with these logs has demonstrated that recently collected DTS data are within 1 to 3°F of "true" temperatures. Unfortunately, difficulties with the DTS measurements in 1996 and early 1997 overlapped the cessation of the cooling trends in the productions wells so it is not known if this event was abrupt or gradual in nature. These DTS systems should substantially lower the temperature monitoring costs of the Beowawe geothermal field.

Acknowledgments

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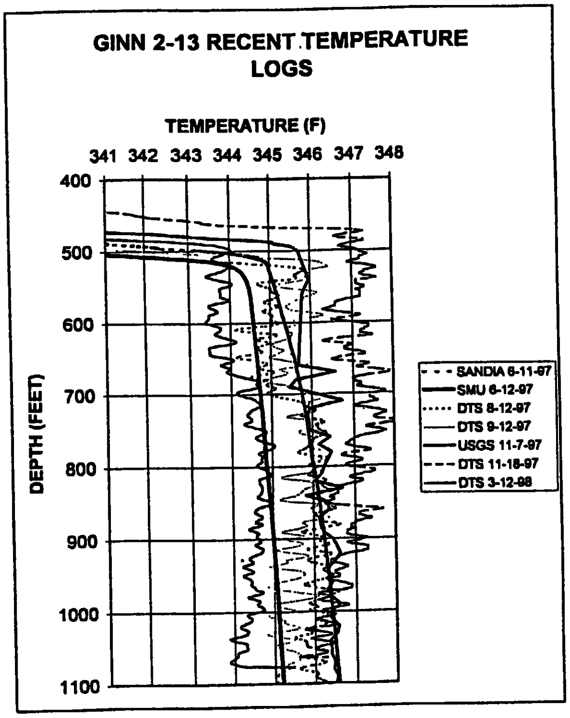

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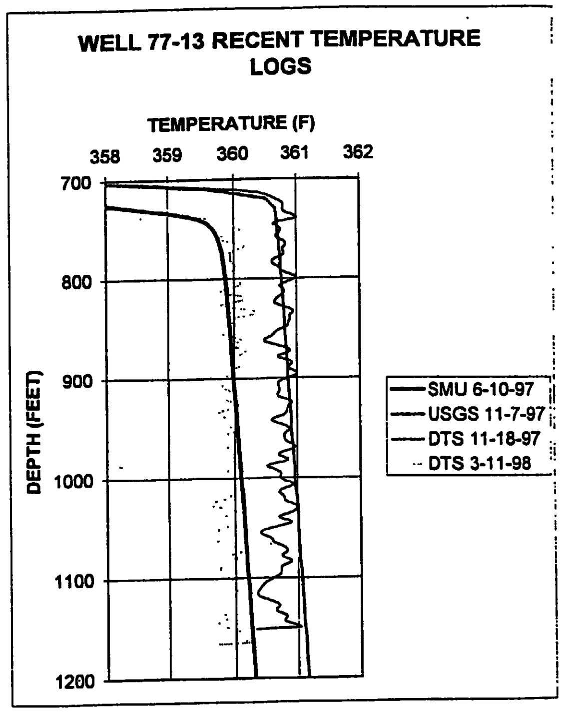

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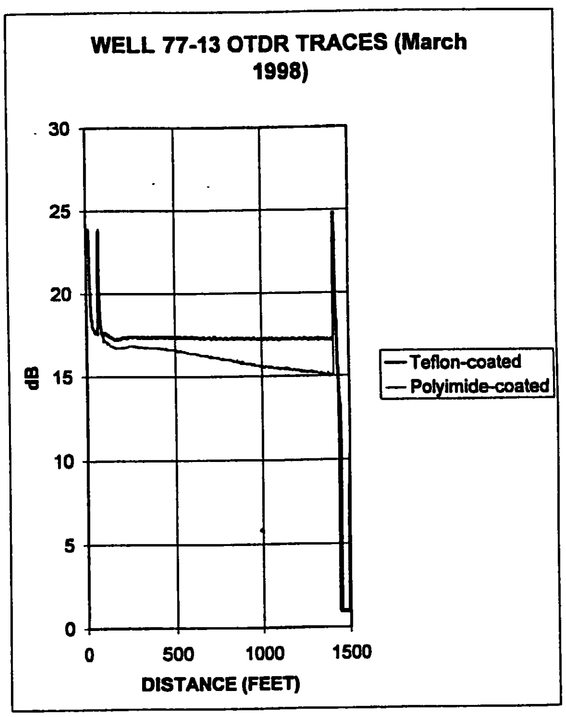

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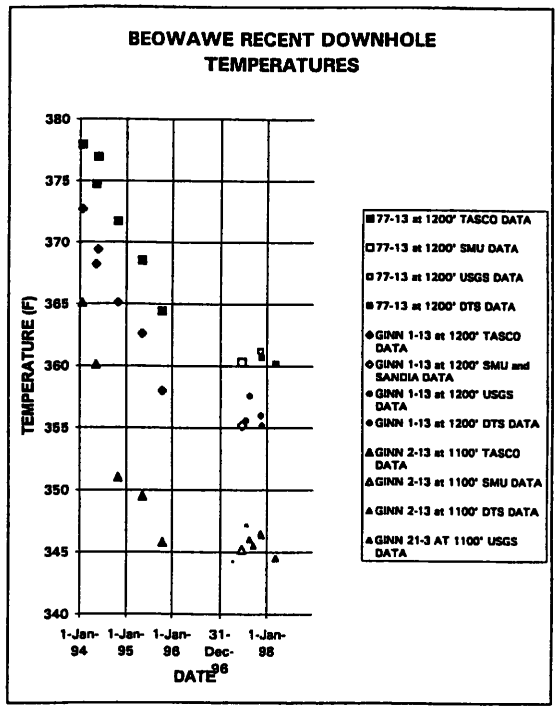

Figure 13.