UPGRADING AMERADA-TYPE SURVEY CLOCKS FOR HIGH-TEMPERATURE
GEOTHERMAL SERVICE*

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ABSTRACT

The "Amerada" type subsurface recording gauges have been used by the oil and gas industry for many years. These mechanical logging instruments are currently used by the growing geothermal industry. As the gauges were designed for service in low-temperature oil and gas wells, a significant number of failures are occurring at elevated geothermal temperatures. The spring-driven mechanical survey clocks appear to be the primary cause of these failures. The clock mechanisms tend to stop or lock-up when exposed to temperatures as high as 300°C.

This report summarizes a project that was undertaken to upgrade the survey clocks to 300°C capability. The major problems causing clock failure were determined and were rectified by minor modifications and lubrication of the moving parts. Several clocks so modified performed reliably, both during laboratory oven tests and during field tests performed in actual geothermal wells at temperatures up to 330°C.

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Introduction

Development of the earth's high temperature geoenery resources requires well logging to determine essential physical properties of the well. Methods for obtaining this information are limited in high temperature application by technical deficiencies, because the logging tools in current use were developed for the oil and gas industry. Such instruments rarely encounter temperatures above 150°C; however, geothermal wells are typically above 180°C and some range up to 350°C.

The "Amerada-type" subsurface recording gauges have been used to measure temperature and pressure in the oil and gas industry for over 40 years. These gauges are relatively inexpensive, and they are run on a slickline wire, requiring no complex instrumentation, electric cable, or cablehead. They are also widely used by the growing geothermal industry. However, at the elevated temperatures of geothermal wells, significant reductions in reliability and tool life have been reported.

Of primary concern to users of Amerada-type instruments is the clock mechanism, which is simply a spring-driven system. Most instrument failures are caused by the clock; in high-temperature applications it stops before completion of its designed time cycle.

At present there is a great need within the geothermal industry for Amerada-type instruments that will run reliably at temperatures up to 300°C or higher. The survey clocks seem to be the weak link for high-temperature operation. Thus, a project to upgrade the clocks to 300°C capability would significantly enhance the reliability of the instruments for geothermal service. However, because of the large number of instruments in use by geothermal producers, this upgrading should be accomplished with a minimum of redesign and rework.

Instrument Operation

The Amerada-type gauge consists of three main parts: clock, recording section, and sensing element. The sensing element is a helically wound bourdon tube (Figure 1). This gauge, completed one way, is a pressure-measuring device; completed another way, it is a temperature-measuring device. The recording section produces a record of pressure (or temperature) changes over a period of time determined by the hour range of the clock used.

Figure 1. Subsurface Pressure Recording Instrument:
Cutaway View

Pressure-Gauge Operation

Pressure from the well is sensed by the bellows-bourdon liquid-filled tube system. Pressure change causes the free end of the bourdon tube to rotate. This rotation is transmitted to the stylus assembly by means of the stylus shaft. The chart carrier is carried past the stylus at a controlled rate determined by the spring-driven clock. A recording of pressure and time is made in one passage of the stylus across the face of the chart, with no overlapping. The recording by the stylus is an inscribed line on the chart. Pressure is determined by measuring the exact distance of this mark from a reference line, and converting this distance to pressure by use of calibration data furnished with each pressure element.

Temperature-Gauge Operation

Temperature of the well fluids surrounding the gauge is sensed by the volatile liquid-filled bulb-bourdon tube element that replaces the pressure element for temperature measurement. The vapor pressure of the filling liquid, which is directly related to temperature, is exerted inside the bourdon tube, causing its free end to rotate. Temperature recording is made in exactly the same way as pressure recording.

Temperatures are read from the chart by measuring the distance from a reference line to the stylus mark made at that temperature.

Clock Operation

Figure 2 shows a cutaway view of the internal mechanisms of the survey clock. The manually wound mainspring assembly provides power, which is transmitted through the gear train to the balance and pallet-fork assembly, regulating the beat of the clock. The rotation of the clock shaft is then translated into the vertical motion of the chart carrier by means of the coupler assembly, lead screw, and push rods.

Figure 2. Survey Clock

Clock Performance Analysis

Initial testing was done in the laboratory to assess the high-temperature performance of the clocks, independent of the recording mechanisms. In normal operation, the vertical movement of the chart carrier and push rods exerts a gravitational force on the clock shaft through the coupler assembly. Usually, this gives the clock power in addition to that provided by the mainsprings. However, since this is not always the case, the clocks should be designed to operate reliably independent of this added power.

All of the tests and evaluations were performed at 300°C (572°F) with several clocks provided by Kuster Company and by Geophysical Research Corporation (GRC). The clocks were tested as soon as they were received; each one failed to operate for the prescribed length of time. Two major problems were detected: either the friction through the gear train became excessive or the escapement locked up. These problems were attacked simultaneously.

The high friction problem was caused by:

1. Rubbing at the contact surfaces of the pinion and wheel interfaces.
2. Excessive loading between the miter gear and the first wheel pinion, due to the 90° change of load direction.
3. Sliding friction between the coils of each of the mainsprings.
4. The bearing surfaces and the mainspring barrels rubbing against the mainspring shaft.
5. Contact at the pivot and jewel interfaces.

The escapement lock-up problem was caused by the pallet and fork shifting at high temperature. The fault is in the design of the "L"-style escapement assembly plates and the way the escapement is adjusted. As shown in Figure 3, the escapement is adjusted by bending the arms of the escapement plate. These arms contain the hole jewels for the pallet-fork shaft. This adjustment is very critical and can vary only slightly from an optimum position without causing lockup or disengagement of the escapement. The shifting of the pallet-fork assembly is caused by the bending of the escapement plates when the escapements are adjusted at room temperature. This takes the plate material from its elastic state past the yield point; upon heating, the plates relax (shift) to a new stable position. There is also some thermal expansion of the pallet and fork; although normal, this expansion must be taken into consideration when adjusting the escapement.

In all the laboratory temperature tests with the clocks, there was an increase of end play in the balance assembly. Subsequently, all balance end-play adjustments were made at room temperature to obtain a minimum of end play at the higher geothermal temperatures.

Figure 3. "L" Style Escapement Assembly

Upgrading Procedure

The following step-by-step procedure was established for upgrading the Amerada-type clocks for operation at 300°C (527°F):

1. Round the end of the pivot to a full radius on the wheel side of the first miter wheel (Figure 4).
2. Insert a cap jewel (or cap plate) on the back side of the hole jewel for the miter wheel. Set the cap jewel to a depth that will allow the rounded pivot to carry the load instead of the pivot shoulder. This reduces the friction from the large pivot shoulder to a point loading on the rounded pivot.
3. Apply Electrofilm (Lubri-Bond "A"* or equivalent) solid-film lubrication to
 - All gear and wheel teeth of the gear train
 - Mainspring drive shaft and miter-gear shaft, excluding the clutch-spring area (this application applies only to Kuster clocks)
 - The pallet faces and slot end of the pallet and fork assembly
 - The escape wheel and pinion.

Follow the manufacturer's instructions for applying and curing of the dry film.

4. Mix one part Vydax AR** to 20 parts Freon TF

* Trade mark of Electrofilm, Inc, North Hollywood, CA. Contains resin, molydisulfide, and graphite.

** Trade marked by E. I. DuPont Company, Wilmington, DE. Contains fluorotelomer.

5. Dip the following parts in the mixture:

- All gear train wheels and pinions
- The mainspring drive-shaft bearing (GRC clock only)
- All mainspring bearings and mainsprings. Do not remove mainsprings from their barrels, but dip each spring as a unit.
- The pallet and fork assembly
- The escape wheel and pinion

Follow the manufacturer's instructions for curing the parts after application.

6. Assemble the clock mechanism with the exception of the balance assembly and the pallet-fork assembly. Wind up the mainsprings and let the gear train spin down several times to burnish the dry-film lubrication at the contact points. Some dry film sluffing will occur at this stage. Remove the sluffing by brushing or blowing the loose particles out of the mechanism.
7. Reassemble the clock, including the balance and pallet-fork assemblies, and apply DuPont's Krytox 143 AD* oil to all pivot and jewel interfaces, excluding the balance assembly. Apply power by winding up the mainsprings and let the clock run through its total time cycle several times at room temperature to seat everything.
8. An oven test can now be made to check performance at high temperature. Insert the clock into a suitable oven (300°C capability), leaving the outer cover off the clock. Let it run for a complete time sequence. Check the escapement while it is hot, and adjust if necessary. After the temperature run, remove the clock from the oven and let it cool to room temperature. Recoil all pivot and jewel interfaces, excluding the balance. Replace the cover; the unit is now ready for service in the instrument package.

Figure 4. Miter Gear and Wheel Assembly

* Made by E. I. DuPont Company, Wilmington, DE.

Lubrication

The basis for using the Electrofilm Lubri-Bond "A" dry-film lubricant for reducing the friction was through past experience at Sandia Labs with other small mechanisms that had similar friction problems; these were rectified by using a dry-film lubricant. The Lubri-Bond "A" brand was used because of its availability. There are probably other brands that would give the same results, as long as the basic ingredients (resin, molydisulfide, and graphite) remain the same.

DuPont's Krytox 143 AD oil is used because of its good high temperature characteristics. This oil has a fairly high viscosity at room temperature, but a lower viscosity at elevated temperatures. When it evaporates, it does not contaminate the hairspring. Unlike the Kuster clock oil and Pioneer-10 oil, which left a shellac-type residue upon heating, DuPont's Krytox 143 AD left no hardened film. The Krytox oil evaporated completely from the pivot and jewel interfaces after 24 to 30 h at the 300°C temperature. For this reason it is important to reoil the clocks after each high temperature run.

It was difficult to run the 48-h clock through its total time, even with the Electrofilm and Krytox applied; the clock would run 30 to 38 h and then stop. Another lubrication that has been used with some success on other small instruments was tried; Vydax AR is a mixture of fine particles of teflon suspended in a Freon TF carrier. This was applied by the previously mentioned technique to the 48-h clock; the clock then ran for 60 h.

While the clocks were tested, a torque reading was taken on a tooth of the wheel preceding the escape wheel on both the unmodified and the modified clocks. The readings were taken at room temperature and at 300°C. Torque levels for the unmodified clocks were considerably lower at high temperatures than at room temperature. By applying all of the techniques listed for modifying the clocks, the high temperature torque was brought back up, and sometimes exceeded the original torque noted on the clocks at room temperature.

Alternate Escapements

A modified Hamilton Watch Company escapement (balance wheel, escape wheel, and pallet-fork assembly) was installed in a Kuster 12-h clock (Serial No. 20641) to determine if better high-temperature reliability could be achieved with a different escapement and balance assembly than the "L" style currently used.

The Hamilton escapement assembly performed well in several downhole tests, but has a basic weakness--loosening of the balance wheel from the balance staff under high-temperature cycling. The wheel is pressed onto the staff and held tightly by a mechanical interference fit. The adaptation of this balance and escapement assembly would be a major modification and would increase the cost of the clocks. Since performance of the regular "L"-type balance and escapement assembly was satisfactory, work was discontinued on the modified balance assembly.

Field Testing Upgraded Clocks

After modifications on the clocks were completed, they were tested in complete instruments in actual geothermal wells. The clocks upgraded for field testing were

- Kuster 12 h, Serial No. 20640
- Kuster 12 h, Serial No. 20641
- Kuster 3 h, Serial No. 20614
- GRC 12 h, Serial No. 7841
- GRC 48 h, Serial No. 7842

Two different wells were used to test these instruments. The first, a low-temperature source, was located at East Mesa, CA and was operated by Republic Geothermal. The maximum temperature encountered was 170°C. The second well was located at Cerro Prieto in northern Mexico. This facility is owned and operated by Mexico's Comisión Federal de Electricidad (CFE). The maximum temperature of this well approached 330°C.

Republic Geothermal Test

Republic Geothermal ran well surveys to obtain pressure buildup and drawdown data, important parameters in assessing the production potential of a well. For these surveys, two pressure gauges were connected in tandem with a universal subjoint--a common practice among the users of the Amerada-type instruments because of the unreliability of a single gauge.

Each of the modified clocks was tested twice, some in conjunction with unmodified clocks owned by Republic Geothermal. All the surveys were taken at the 1,500-m level. The results of the tests, along with postmortem analyses are as follows:

Kuster 12 h, No. 20640 --

Test 1: The instrument was left in the well about 17 h. Upon retrieval and disassembly, it was observed that the seal on the recording section had failed, allowing brine to enter. Although the inner workings were exposed to the brine, the clock had completed its cycle and a successful survey chart was obtained.

Test 2: A 12-h survey was made as a second test of the clock. Krytox oil was applied to the pivots of the clock before testing. The seal failed; however, the clock had been able to complete its cycle. A complete chart recording of the well pressure was obtained.

Postmortem: No damage to the clock was noted. The general condition of the clock was good. The clock was then cleaned and oiled.

Kuster 12 h, No. 20641 --

Test 1: This Kuster clock with the modified escapement was left in the well for a 9-h survey. After the log was completed, the instrument was disassembled to retrieve the recorded chart. The chart and inner mechanisms were wet, indicating leakage into the instrument. The chart carrier had traversed barely half of the distance required for a complete survey. The lead screw mechanism was jammed up and may have caused the stoppage. The clock would not start for a second test.

Postmortem: Stoppage was caused by the balance wheel coming loose from the balance staff. There was some deterioration of the dry-film lubrication. The pivots were dry of oil.

Kuster 3 h, No. 20614

Test 1: The Kuster 3-h clock was used to obtain a temperature survey of the well. The clock ran satisfactorily and a good survey was obtained.

Test 2: A 2-h stabilizing test was made using the 3-h Kuster clock. Reports indicated that the clock ran for only 1 h. Neither test showed whether the clock had been exposed to brine through seal leakage.

Postmortem: Corrosive liquid had entered the unit. Rust was found on several wheels and pivots. The clock was cleaned and dry-filmed. Vydax was then applied and the mechanism was oiled.

GRC 12 h, No. 7841 --

Test 1: This test was run in tandem with the second test of clock No. 20640 during a 12-h pressure survey. After completion of the survey and upon disassembly of the instrument, the clock was seen to have completed its time cycle. No leakage into the instrument was observed.

Test 2: After Test 1, the clock was reoiled and placed back into the well for a second 12-h survey. Before the clock was rewound, it was partially disassembled and oiled with Krytox oil. When the clock was reassembled, one of the gears would not seat properly in the pivot hole. The clock worked for only 4-1/2 h.

Postmortem: Noticeable loss of power through the gear train was observed. This was traced to binding of the pivot point in question. Also, the pallet-fork assembly had shifted, causing excessive friction in the escapement parts.

GRC 48 h, No. 7842

Test 1: This GRC 48-h clock was used during a 12-h test. Upon disassembly of the instrument after retrieval, the chart carrier had traversed only 2 in. of the full 5-in. scale. As the clock was still running, it was rewound, taking 5-1/2 of the maximum 15 turns to complete the winding. This represents exactly the 18 h the clock had been running from the initial windup.

Test 2: A full 48-h test was made of the clock during a pressure buildup survey in the well. Krytox oil was applied to all pivots before reinsertion into the instrument. The clock ran satisfactorily for the full extent of the test.

Test 3: The clock was used for a third survey. However, the seal leaked and the clock did not run properly.

Postmortem: Rust residue appeared on gears, pallet, and balance assembly. Actual stoppage was caused by a rusty balance pivot. The balance assembly was replaced and the clock was prepared for future use.

A review of the test results shows that each of the modified clocks performed well. Most of the failures that did occur were attributed to leakage of fluid past the seals on the recording section. This was a major problem throughout the test program.

Although the temperature of the well did not allow for an extreme temperature test (300°C), the modified clocks performed well at 170°C , whereas some unmodified clocks also tested did not perform satisfactorily.

Cerro Prieto Test

By request of Lawrence Berkeley Laboratories (LBL), arrangements were made to field test the modified clocks at Cerro Prieto, Mexico. This was part of an agreement between LBL and CFE for logging development and reservoir assessment. CFE has a large inventory of Kuster logging instruments. It has reported limited success in long-term logging operations. Temperatures in the Cerro Prieto well approach 330°C and the brine is very corrosive. Well logging is currently restricted to a maximum of 2 to 3 h downhole because of greatly decreased reliability during long-term surveys.

Two separate tests were run, each with a temperature and pressure instrument connected in tandem. The initial test, for 2 h, was only to check operation of the equipment and any effect the brine had on the instrument materials. The second test was run for a full 12 h to check the complete range of the clocks used.

Test 1: 2-h Soak Test. The two instruments were lowered to 1500 m. The temperature was about 320°C . The modified clocks used were Kuster No. 20640-12 h and Kuster No. 20641-12 h. After the test was complete, the instruments were retrieved and disassembled. There was no leakage around the seals, and the clocks were still running. A successful survey was obtained.

Test 2: 12-h Complete Survey. The two clocks used for this full term test were the Kuster No. 20640 and the GRC No. 7841. When the test was complete, the instruments were retrieved and disassembled. Each of the gauges had an obvious leakage past the seals. The GRC clock ran

to full term. In the gauge containing the Kuster clock, the chart carrier had travelled only halfway, giving a 6-h survey.

Postmortem: Kuster No. 20640. This clock showed evidence of liquid penetration. Plates were more blackened than usual. There was a deterioration of the dry-film lubricant on the gear train. All three mainsprings were broken. Cause of the failure could have been either the broken mainsprings or increased friction due to leakage. One mainspring was broken after Test 1 and was replaced.

Kuster No. 20641. The balance wheel was loose on the balance staff. This could have caused failure on a longer term test. Four of the train-wheel jewels were cracked.

GRC No. 7841: The clock was in fairly good condition. However, all three mainsprings were broken. This failure occurred after the full term on the clock since the chart carrier had completed its travel.

The testing program at Cerro Prieto was limited because of extensive corrosion damage to the internal parts of the recording sections as a result of the seal leakage. Thus, the 3-h and 48-h clocks were not tested. The three clocks used did perform well and showed that the modifications increased the reliability of the clocks at the high temperatures encountered. A problem did arise in the failures of the mainsprings. Several of the mainsprings became very brittle and broke into several pieces. It is not currently known whether the cause of the embrittlement was from exposure to high temperatures or to the corrosive brine. No indication of embrittlement occurred as a result of the initial laboratory oven tests.

Cleaning Procedure

Because of the elevated temperatures encountered during field testing, it was essential to keep the clocks clean. This was especially important if the clocks had been exposed to hot brine through seal leakage. The cleaning procedure used on all of the clocks was as follows:

1. Disassemble the clock. Do not remove the mainsprings from the mainspring barrels.
2. Place the clock parts into a glass or stainless-steel beaker. Fill the beaker with trichloroethylene to cover all parts. Insert the beaker into an ultrasonic cleaning machine containing a coupling fluid. Clean for 5 to 10 min.
3. Remove the beaker from the cleaner and drain off the liquid. Place all of the clock parts on a clean tissue.
4. Refill the beaker with isopropyl alcohol and repeat the procedure with the sonic cleaner. Clean for about 5 min.

5. Remove the clock parts from the alcohol and place them in a flat glass tray. Insert the tray into a 75°C oven for 30 min to dry the parts.
6. Remove the parts from the oven. When they cool, the clock is ready for assembly.

The cleaning method outlined above is currently used at Sandia Laboratories for cleaning other small mechanisms. Other methods may work as well. It is important while cleaning the parts not to handle them with bare hands, which will etch the metal parts; this etching is accelerated at high temperatures. Use nylon, plastic, or rubber gloves to handle all parts.

Generally, if a clock is not compromised by a leaky instrument package, it should be cleaned after four runs of 12 h each. After each run, the clock should be opened and the pivots oiled with Krytox 143 AD oil. At that time the condition of the clock should be checked for possible deterioration of the dry-film lubricant and the Vydax coating. If the mating surfaces of the gears show lack of dry-film lubrication, the clock should be cleaned. Dry-film lubricant and Vydax should be reapplied, following the procedure given.

Conclusions and Recommendations

The method of upgrading the Amerada-type clocks as addressed in this paper has greatly increased the performance and reliability of the clocks for use in high-temperature geothermal wells. Special emphasis was placed on obtaining long-term reliability (12-48 h). The modified clocks performed consistently well, during both the lab-oven tests and the actual field testing.

Two additional areas are currently being investigated at Sandia Laboratories to further improve the clocks. One is the mainspring breakage problem which was a major concern during the tests run at Cerro Prieto.

The second area is in pursuing a better, more permanent type of dry-film lubricant for the gear train. Evaluations will be made on such materials as teflon coating, Vitrolube, and sputtered molydisulfide containing antimony trioxide or nickel.

After completion of the analysis and testing of the modified clocks, several suggestions can be made to better manufacture the clocks for high-temperature capability:

1. Place a cap jewel behind the first miter wheel and round the end of the pivot. This modification was shown in Figure 4.
2. Use stainless-steel or nickel plating for all wheels and pinions. The brass wheels currently used in the Kuster clocks react at high temperature, leaving a copper residue on the surface of the wheels.

3. If possible, use roller bearings on the mainspring drive shaft. These are currently used on the GRC clocks; they cause less friction than the bushings.
4. Make the balance staff and balance roller pin out of a stainless-steel material. When fluid enters the clock mechanism due to a leaky instrument seal, the balance staff and roller pin are attacked by rust; this requires a replacement of the entire balance assembly.

The clock is only one part of the complete recording instrument, and there are other problems which can arise. One such problem is failure of the seal in the recording section; this failure allows corrosive borehole fluid to enter the instrument. The present seal design includes an elastomeric o-ring acting as a back-up to a face-sealed german silver seal. Many seal failures have been observed even during low-temperature tests, with no apparent damage to the o-rings. At high temperature, the o-rings were noticeably degraded. Seal leakage is a major problem and can quickly cause irreversible degradation to the clock mechanisms and other parts within the recording section. Further work should be initiated to improve the seal design.

Another problem that can cause stoppage of the clock was traced to the lead screw and nut assembly. This mechanism was frequently jammed, usually after leakage had occurred. However, it also jammed after Test 1 at Cerro Prieto, although no leakage had occurred. A film residue left on the screw assembly after evaporation of the Kuster clock oil (applied at the factory) had caused the trouble. Kuster clock oil is not recommended for high temperature use.

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