Final Report

Texas Geothermal Assessment for the I35 Corridor East

EXECUTIVE SUMMARY

The impressive extent of the thermal energy available to Texans lying beneath the ground became evident through the 2004 publication of the Geothermal Map of North America. The high volumes of saltwater produced during hydrocarbon production, combined with the high temperatures found in Texas at depth, provide an ideal mix of resources from which to produce electricity from geothermal energy. Although previous investigations into the geothermal resource potential along the Gulf Coast -h Tch tce us successful demonstration project in 1989-90, the business environment was not yet supportive of renewable energy (John et al. 1998) and the geothermal energy potential remained untapped. In 2010, we have a convergence of ideal economic forces, political climate, and technological advancements for using existing hydrocarbon production infrastructure as a means of generating baseload, renewable electricity for Texans.

Geothermal energy is a baseload renewable resource located in close proximity to where the majority of Texas citizens live. The development of this resource requires an understanding of both the business model and geologic structures involved. The existing infrastructure and expertise of the oil and gas industry in this area affords us the opportunity to leverage that investment and combine geothermal energy production with hydrocarbon and waste heat production. The interest from the business community is evidenced by the successful SMU Geothermal Conferences, which drew hundreds of participants, as well as by the number of companies installing systems throughout the Gulf Coast.

We achieved our stated project goal of defining geothermal resources through improved understanding of subsurface temperatures. The focus of study was the area of Texas generally east of Interstate 35 because of the overlap between high heat flow levels, the location of major Texas population centers, and the availability of numerous oil and gas field data. Both new and existing temperature data from oil and gas wells were collected, collated, and analyzed. Corrections to non-equilibrium BHT temperatures were compared with in situ well measurements to improve the accuracy of temperature readings.

Within the area of study, different temperature characteristics were observed by region. South Texas has the highest measured temperatures (in excess of 300 °F) at depths of 10,000 to 12,000 feet. The Gulf Coast geopressured areas have the most accessible energy potential, because of the large fluid volumes, entrained gas, and artesian flow. East Texas, while dominated by shallower drilling (typically less than 10,000 feet) and waterflood fields, possesses a crust with high natural radioactivity in the granites (such as associated with the Sabine Uplift). This is indicates the elevated temperatures needed for geothermal energy can be expected at depth. The drilling in North Central Texas is currently predominantly in the Barnett shale formation, averaging 7,000 to 8,000 feet. Beneath the Barnett shale formation, lays the Ellenberger limestone, which has temperatures in the 200 to 250ûF range and can produce water volumes in the 20,000 to 50,000 barrels per day range, based on injection well capacity. In short, all of the areas studied, while yielding different results, showed remarkable promise for geothermal energy potential.

In addition to the report detailing the extensive work done collecting, collating, and analyzing temperature data from oil and gas wells, we have included information from four conferences hosted by SMU on 'Geothermal Energy Utilization Associated with Oil and Gas Development'. As mentioned, a successful development of this resource requires an appreciation for the business potential as well as the geologic potential, which these conferences sought to combine. The full archive of the conference presentations and related papers are posted on the SMU Geothermal Laboratory website. Additionally, the website contains information developed to assist companies starting a geothermal project and a list of resources to contact for assistance.

The outcome of the temperature assessment work and the outreach projects, such as the conferences and web resources, has led to several projects in our general area reaching development stage. Among them:

- Universal GeoPower LLC and the U.S. Department of Energy (DOE) have a geothermal demonstration project in Liberty county, near Houston, designed to generate 250 KW of power using a watered-out and abandoned oil well from a Pratt & Whitney binary generation system.
- Louisiana Geothermal LLC and the DOE have a second demonstration project in Cameron Parish.
- Gulf Coast Green Energy, with a grant from the Renewable Partnership to Secure Energy for America (RPSEA), is deploying an ElectraTherm Green Machine in Jones County, MS on a Denbury Resources Inc. owned well. It is expected to generate 30-50 KW.
- Hilcorp Energy Company and Cleco Power LLC are in development on a project in western Louisiana, also using the ElectraTherm Green Machine.
- The GeoPower Texas Company has acquired Texas General Land Office geothermal leases for development of off-shore wells near Galveston, Brazoria, and Matagorda Counties.

Conclusion: The next five years will be crucial to gain enough momentum to establish a geothermal industry in Texas. There are currently over 200,000 active wells in Texas. That is 200,000 potential sources of cost-competitive, renewable, baseload, clean energy to Texans. We have a window of opportunity to leverage our state's investment in the oil and gas industry while the economic forces, political pressures, and available technology are aligned towards a common goal of renewable energy. Additional resources of time and dollars would be well spent on exploiting the geothermal energy potential of Texas.

INTRODUCTION

For a century, Texas has been a leading energy producing state. Its abundance of oil and gas has existing hydrocarbon service industry productive long after the wells cease to produce hydrocarbons. Geothermal development can also enhance Texas' ability to produce hydrocarbons at lower costs, for longer periods of time, and to extract gas in locations where it is presently uneconomic. Areas in Texas with the greatest geothermal potential directly correlate with the active hydrocarbon production areas of the eastern and southern portions of the state. They are located near the large urban areas of Dallas-Fort Worth, Houston, San Antonio, and Corpus Christi. The majority of oil and gas fields in these regions are connected to the power grid, with existing major transmission lines often directly overhead allowing for convenient grid connections for the geothermal power development to use the existing power line system.

This geothermal assessment focuses on temperature mapping of wells with depths of over 7000 feet, capable of electrical generation in the eastern half of Texas (located between interstate I-35 and the eastern border of Texas). This area covers North, East, and South Texas, as well as the Texas Gulf Coast. This regional focus was chosen because of the collocation of existing oil and gas fields with higher heat flow areas (Figure 1) as shown on the Geothermal Map of North America, (Blackwell and Richards, 2004a) and described in general resource analyses by Blackwell et al. (2006) and Negraru et al. (2008). The assessment of existing and new temperature data, along with the changes in geothermal technology, illuminates the compelling reasons Texas has for developing its geothermal potential.

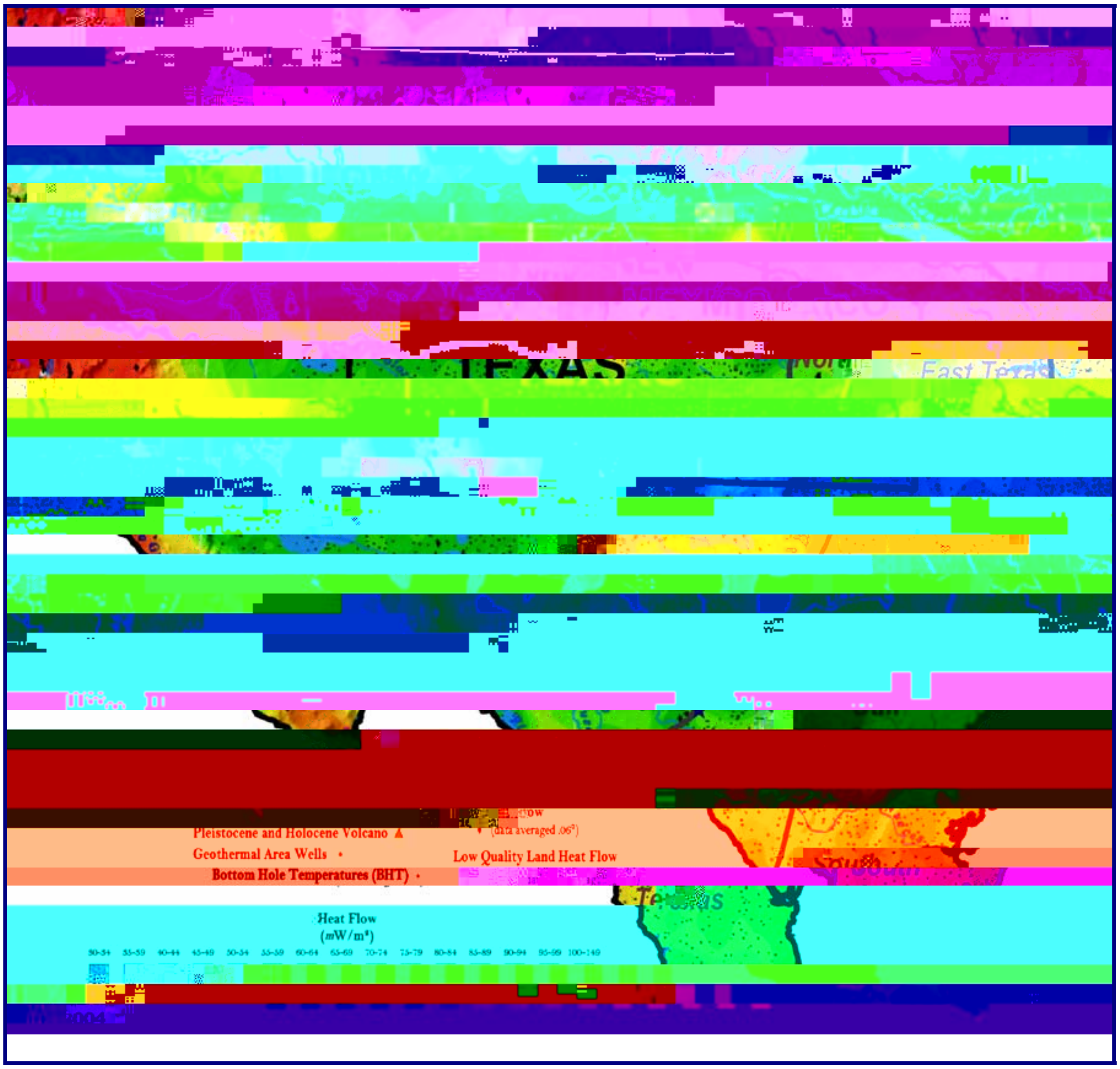


Figure 1. South-central portion of the Geothermal Map of North America (Blackwell and Richards, 2004a) with the Texas State boundary highlighted and the areas discussed in report.

OVERVIEW OF PREVIOUS REPORTS

Geothermal power production could be at the leading edge of Texas energy development for this century. Texas has been building its geothermal resource knowledge base since the early 1900s, as shown by temperature data collected by Plummer and Sargent (1931) and Spicer (1964) from early oil wells typically between 2500 and 5000 feet deep.

Starting in the mid 1970s, the oil embargo resulted in concentrated studies of geopressured - geothermal resources in Texas. Grants of approximately $200 million were awarded by the U.S. Department of Energy (DOE). The primary goals of these studies were to: define the extent of the geopressured reservoirs; determine the technical feasibility of reservoir development, including downhole, surface and disposal technologies; establish the economics of production; identify and mitigate adverse environmental impacts; identify and resolve legal and institutional barriers, and determine the viability of commercial exploitation of this resource (John et al., 1998). This previous research revealed massive geothermal and geopressured resources in Texas. It concluded with the successful demonstration of geopressure electrical generation conducted by the DOE at Pleasant Bayou, Brazoria County in 1989-90 (Shook, 1992; John et al., 1998). Technical feasibility was demonstrated, but momentum was lost during the period of low energy prices between 1985 and 2003.

As part of the geothermal studies C.M. Woodruff investigated geothermal energy in central Texas throughout the 1970s to the early 1990s. His research focused primarily on the mid-depth ranges of geothermal resources (5000 feet to the surface), and aquifers associated with low to moderate

North America (Blackwell and Richards, 2004a); a review of the geothermal resources in the South Central portion of the United States (Negraru et al., 2008); and the use of Enhanced Geothermal Systems (EGS) in the United States with each individual state's resources categorized (Tester et al., 2006; Blackwell et al., 2006). Additionally, a resource study of oil and gas well data examines the geothermal resource potential in West Texas (Erdlac, 2006).

These studies prove conclusively that geothermal resources exist. Geopressure continues to be viewed as an integral part of the Texas geothermal resource. A search for "geopressure and Texas" on the Office of Science and Technology Information website, results in over 300 publications[5]. As a single option, the geopressured resource holds the largest potential for electrical development in Texas. Geothermal understanding of this geopressured resource has changed little since the completion of studies in the 1990s, but technology and energy economics have continued to evolve. Therefore, past geologic research is of the utmost importance as a knowledge base for this and any future geothermal assessment or development project. A review of the multiple geopressure related publications and references is provided in Appendix A.

GENERALIZED REGIONAL GEOLOGY

Throughout geologic time Texas has experienced multiple periods of uplift and regional seas covering the surface creating the numerous layers of sediments. The depth to basement determines the maximum thickness of sedimentary layers, and therefore the maximum depth of drilling for oil and gas wells. The eastern half of the state was part of the collision between the North American tectonic plate and the European-African-South American plate that formed the supercontinent Pangaea. This event folded and faulted the sediments now exposed in the Appalachian Mountains, the Ouachita Mountains in southwestern Arkansas and southeastern Oklahoma, and the Marathon region near Big Bend National Park in West Texas. Originally a

As North America rifted away from Europe/South America during the break up of Pangaea, fault zones formed which still impact Texas. The Balcones fault zone was created along the Texas Craton and slightly further south-east the Luling-Mexia fault zones were created. Today these are zones of weakness that allow warm fluids to rise quickly along them and create elevated temperatures in the deeper fresh water aquifers such as the Trinity, Hosston, and Edwards (Woodruff et al., 1982). The newly formed East Texas and Gulf Coast basins were buried by thick deposits of Middle Jurassic marine salt and sediments. Igneous oceanic crust formed in the Gulf Coast Basin during the Late Jurassic. The boundary between oceanic and continental crust lies beneath the present-day Texas continental margin, but its exact location is unknown. Jurassic and Cretaceous deposits formed broad carbonate shelves that were periodically buried in places by deltaic sandstones and shales at the edge of the widening Gulf of Mexico. Mobilization of the salt from evaporates formed salt domes in East Texas and the Gulf Coast. The deposition along the Texas Gulf Coast continental shelf continue to build new land mass towards the Gulf of Mexico, as it continues to do today. Area of deposition shifted over time across the Gulf Coast. The sediment flow was dominated from the western side of the Gulf Coast (now South Texas and Central Gulf Coast) during the Eocene and Oligocene (~55 - 23 MA). It gradually shifted eastward, where it is today with sediment primarily from the North and East (Mississippi Delta) (Salvador, 1991, Figure 2).

Sea level has fluctuated continuously throughout the geologic past. During the most recent glacial advances, the sea levels were 300 to 450 feet lower than today (an interglacial period), because so much sea water was contained in the ice sheets. The climate was both more humid and cooler than that of today, and the largest Texas rivers carried more water and sediment to the Gulf of Mexico. These deposits underlie the initial fifty miles or more of the Gulf Coastal plain inland from the current shoreline. Approximately 3,000 years ago sea level reached its modern position, and the coastal features that are present today, such as the deltas, lagoons, beaches, and barrier islands, have formed since that time (Sellards, et al., 1933).

Figure 2. Location of Cenozoic depocenters, northwestern Gulf of Mexico from oldest to youngest: Late Paleocene, Eocene, Oligocene, Early to Late Miocene, Pliocene, Pleistocene, (Salvador, 1991).

Gulf Coast Geology

The Gulf Coast is known for its geopressured - geothermal resources located along the coastal regions of both Texas and Louisiana. The region is approximately 100 miles (160 km) wide and 750 miles (1,200 km) long onshore and encompasses roughly an equivalent area offshore (Wallace et al., 1979; Davis et al., 1981). The pattern of geopressured formations in Texas consists of roughly concentric bands of sediment, trending parallel to the Gulf of Mexico coastline. The regional dip is Gulfward, with formations becoming progressively younger and thicker in the downdip direction towards the Gulf Coast.

The formation of geopressured strata along the Gulf Coast resulted from the rapid sediment deposition over the last 65 million years at each successive position of the continental margin into the rapidly subsiding Gulf of Mexico basin. Sequences of prograding deltas deposited sand on top of unconsolidated shales (water-laden clays and silt) and salt deposits. The weight of the overlying sands caused large scale slumping along growth faults and the sands became hydrologically isolated by the surrounding, less permeable shales. With progressive burial, the pressure of the saline fluids trapped within the sandstones increased, becoming greater than hydrostatic, (0.465 psi/ft) and eventually approaching lithostatic pressure (~1.0 psi/ft, Davis et al, 1981). As a result of the high pressure, the sands are very porous and permeable for their depth. These geopressured sands contain entrained methane. Wells drilled into this geopressured sand flow artesian (naturally) to the surface. Water temperature can range from 190°F (88°C) to over 400°F (205°C). This water is an important resource because it contains three forms of energy: 1) thermal from the high temperatures; 2) hydraulic from the high fluid flow pressure; and 3) chemical from the dissolved methane in the fluids.

A number of distinct clastic wedges within the Gulf Coast have been identified for their resource potential in the onshore portion of the geopressured zone. Foremost among these are the Upper Claiborne Group, Wilcox Group, Vicksburg and Frio Formations (Figures 3 and 4).

Figure 4. Geothermal corridors of primary geothermal favorability at depth shown in brown fill. (Bebout et al., 1983). Front of the Ouachita Overthrust Belt is drawn as a solid line in Texas and dashed in

when the area fluctuated from an inland sea to land. The salt formations were deeply buried by

the TX RRC Oil and Gas Districts 1 though 6. The SMU-TX RRC database contains the following information on 4,887 wells: 1) latitude and longitude (NAD 27); 2) county; 3) API and TX RRC surface and bottom well ID numbers; 4) type of well (oil/gas/both) and production status as of 2006; 5) bottom hole temperature (BHT); 6) depth of measurement; 7) elevation; 8) time since circulation; 9) field name and operator. SMU-TX RRC data are mostly from wells drilled during the 2000s, with some wells from the 1990s. As such, this database reflects a snapshot of current drilling activities in the east portion of Texas and is a random dataset based on availability of well logs on the TX RRC website.

The second largest dataset available is the Texas subset of the American Association of Petroleum Geologist (AAPG) Geothermal Survey of North America GSNA) Well Data (AAPG, 1994). This dataset was collected for the United States as part of the Geothermal Gradients Map of North America (DeFord and Kehle, 1976) from oil and gas wells drilled before 1972. This database includes 2,498 wells that are used in this assessment.

The key difference between the two oil and gas datasets is the areal distribution of the data. The SMU-TX RRC data were collected using recent online information based on what was submitted. As a result there are clusters of data in fields where many new wells were drilled and other areas with few points. The AAPG Geothermal Survey Well Data were collected on a more even distribution. Because of this difference in approach, it is possible to create maps both on a regional scale and, in some instances, at a local county-field scale.

Other data sets used include the Gulf Coast Geopressure data (Gregory et al., 1980), the Hunt Oil Company Fairway Field data in Anderson and Henderson Counties (Hunt Oil and Kweik, this report), the Freestone County well data (Burns, 2004) and the USGS GEOTHERM shallow database (Bliss, 1983).

The Gulf Coast Geopressure data (Gregory et al., 1980) include 654 well data points with the following available parameters: well number, total depth, bottom-hole temperature (BHT), formation, sand thickness, porosity, fluid pressure, water salinity, and methane solubility. The report data were converted to digital for this and future studies. These data are helpful in modeling 3-D aspects of the Gulf Coast because of the included geologic information.

The Fairway Field (located in Anderson and Henderson counties) data were collected for this assessment through collaboration with Hunt Oil Company. Well data were collected from the Hunt Oil Company files to characterize the thermal regime, review the history of the field and to investigate possible changes in temperature over time. The data collected include 216 wells with production data, 2,241 pressure tests, and 30 wells with injection data. These wells were drilled over a 40 year period from 1965 to 2005.

A previously detailed thermal study was completed on Freestone County as part of a SMU Masters Thesis (Burns, 2004) with the well data collected from oil and gas well log headers. There are 174 well locations with some wells having up to four interval temperature measurements.

The USGS GEOTHERM shallow database for Texas (Bliss, 1983) was sent to us for inclusion in this assessment by Janet Abbot of Spa Waters of Texas, who has some of the original data records. The data set contains primarily shallow wells (<5,000 ft) and spring chemistry data. Because these wells are shallow and therefore not suitable for electrical production, they were not used in the resource evaluation. This data set is included in Appendix B.

Table 1. Data set information used in this assessment.

Name of Data Set	Author, year	Number of Wells	Area of Coverage
SMU Geothermal Laboratory Texas RRC Oil/Gas Temperature Database			

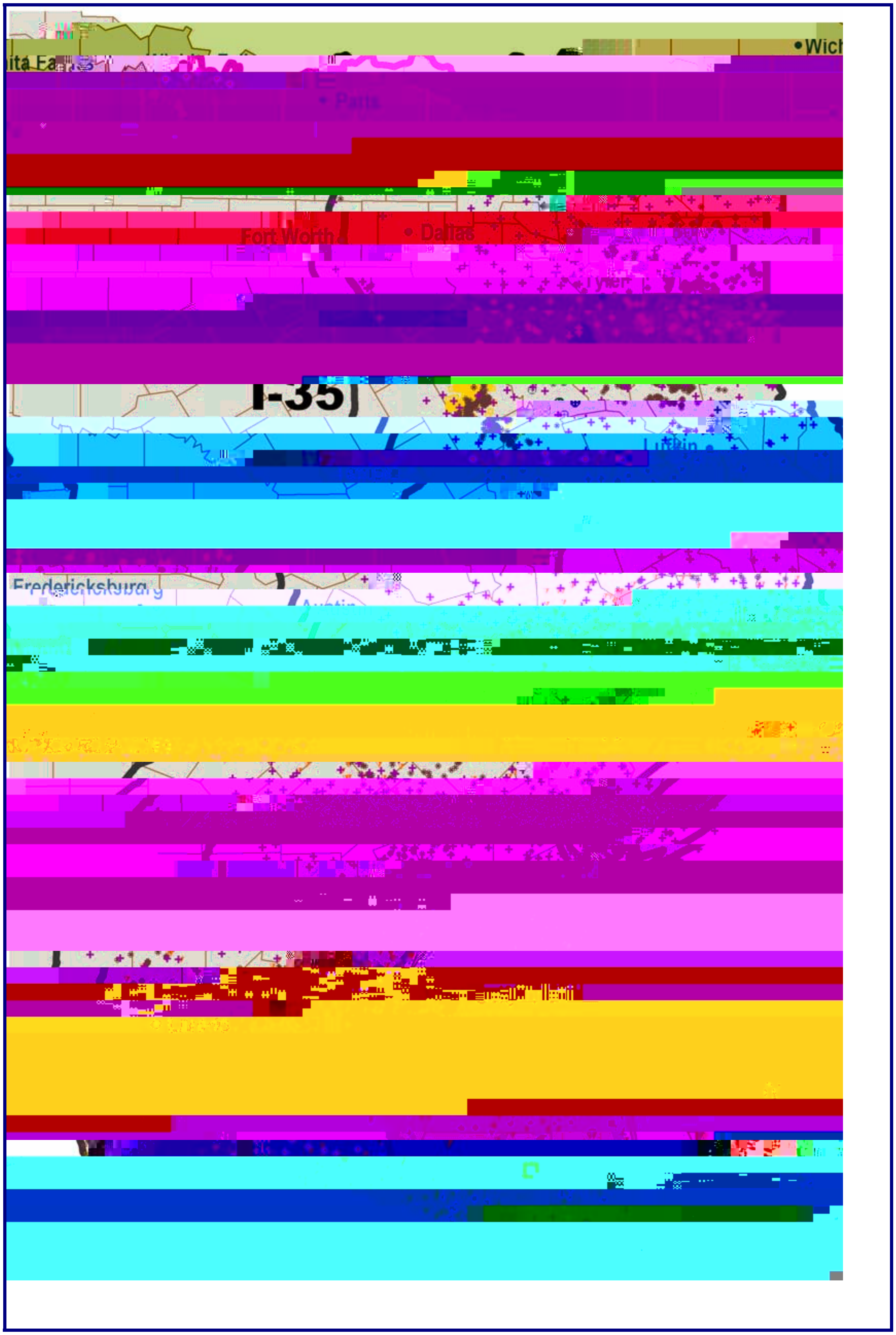


Figure 7. The locations of different data sets used in this assessment.

DATA CORRECTIONS

The temperature data in this assessment are from oil and gas wells. In order to give value to the data, multiple steps were taken to determine data accuracy and correct for differences in raw data versus in-situ temperatures. In a best case scenario, the temperatures would be from measurements of wells at equilibrium with high precision, high resolution equipment (Wisian et al, 1998). This is rarely possible. To improve the value of the collected data, corrections were made to the data and comparisons of the corrected data were made with more accurate methods. This section describes the data and these corrections and comparisons.

While drilling a well, fluid is injected and circulated from the surface to the drill bit in order to

A comparison of the SMU-Harrison equation and the Kehle equation shows the largest difference at shallow depths, i.e., 4.5 °F at 6,000 feet, with the SMU-Harrison correction the lesser of the two. At depths of 12,000 feet or greater, the corrections are the same. The SMU-Harrison equation is used to correct BHTs between depths of 3,000 and 12,900 feet. Deeper than 12,900 feet the BHT data were given a linear increase starting with the maximum value of the SMU-Harrison correction (34.3°F) and increasing slightly by 0.05°F every 500 feet. The deeper wells are expected to have longer times between drilling circulation and BHT measurements. As a result, the correction is assumed to not increase at the same rate as the shallower depths.

In order to assess the validity of the calculated in-situ temperature, the values were checked against wells in Texas logged by the SMU Geothermal Laboratory. The well locations (Republic, Chapman, Garcia, and West Ranch) were chosen because of their equilibrium temperatures logs made with high-accuracy, high precision temperature logging equipment (Figures 8 and 9; Wisian et al., 1996 and 1998; Blackwell and Richards, 2004; and Negraru et al., 2008). An additional temperature log from the Pleasant Bayou well (DOE #2) was used. That well was logged in 1988 by Panex (Randolph et al., 1992).

The difference between the well log header BHT values, the Harrison corrected temperature values, and the equilibrium well measured temperature - depth curves is shown in Figures 9 a - f. The BHT data were selected within ±0.5° of latitude and longitude (~30 mile radius) around the equilibrium well location. By limiting the distance from the equilibrium well, the data are assumed to be most comparable. The equilibrium temperature graphs show that the well log header BHTs are generally too cold in comparison to the in-situ temperature. After applying the SMU-Harrison correction, the data fall more tightly around the logged equilibrium temperature line.

The West Ranch well (Figure 9d) has the poorest correlation to the corrected data. This limited correlation could be due to the influence of shallow water sources for waterflooding of the West Ranch field to push the oil out of the deeper formations. The West Ranch well was measured by

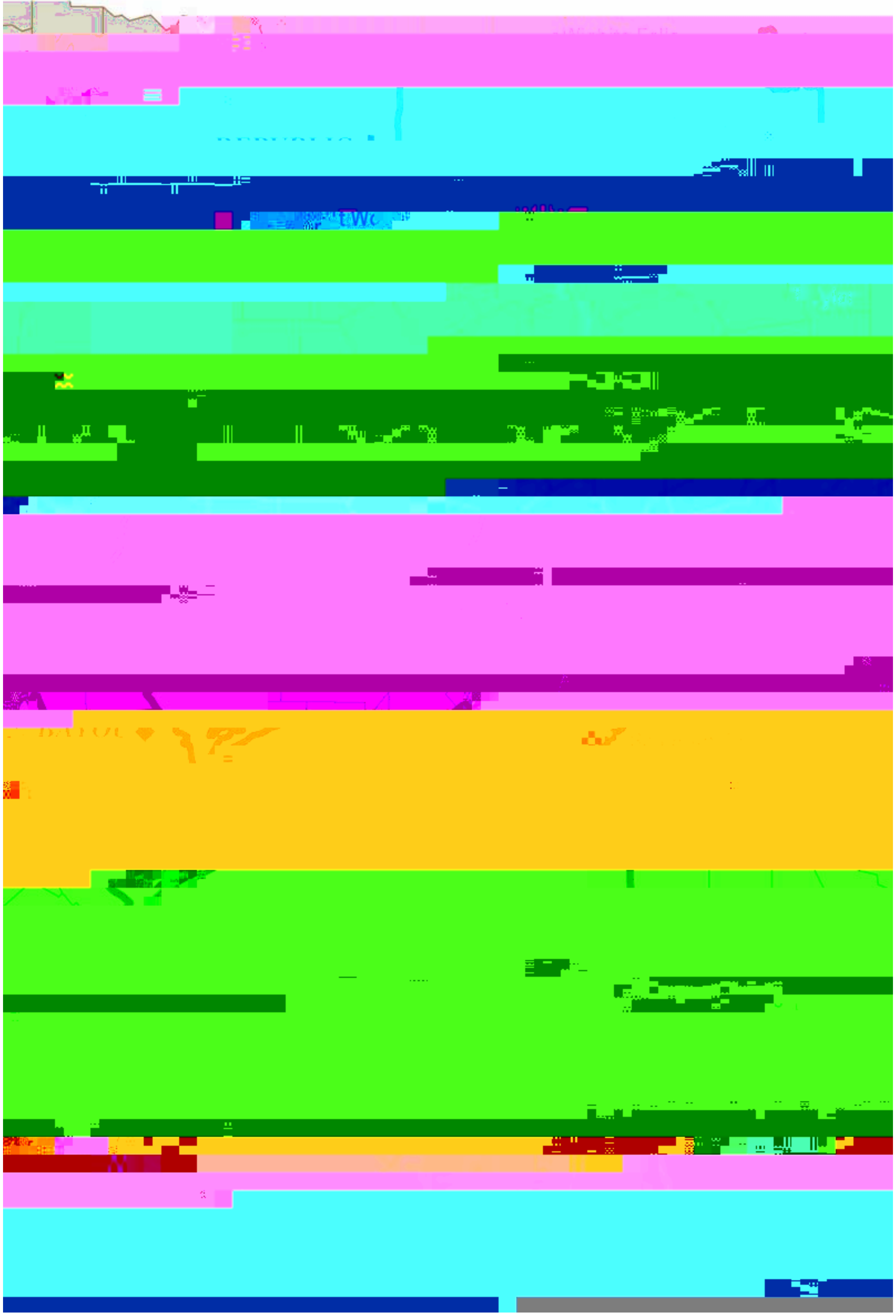
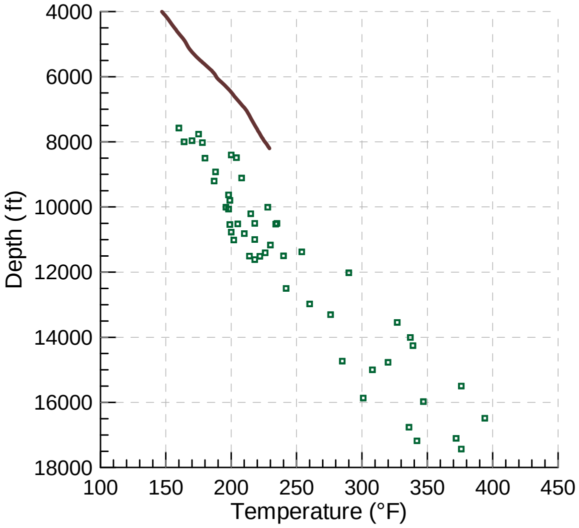
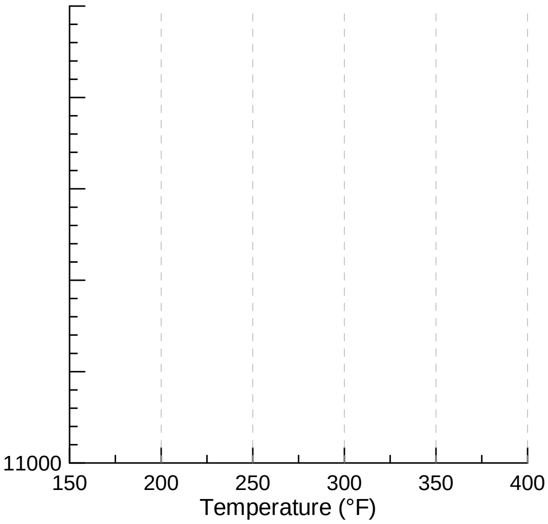


Figure 9 (a - e). Equilibrium temperature data are shown as a black line, the log header BHT values in the area shown as a square symbol, and the corrected BHT values are shown as a cross symbol.




11000
150
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250
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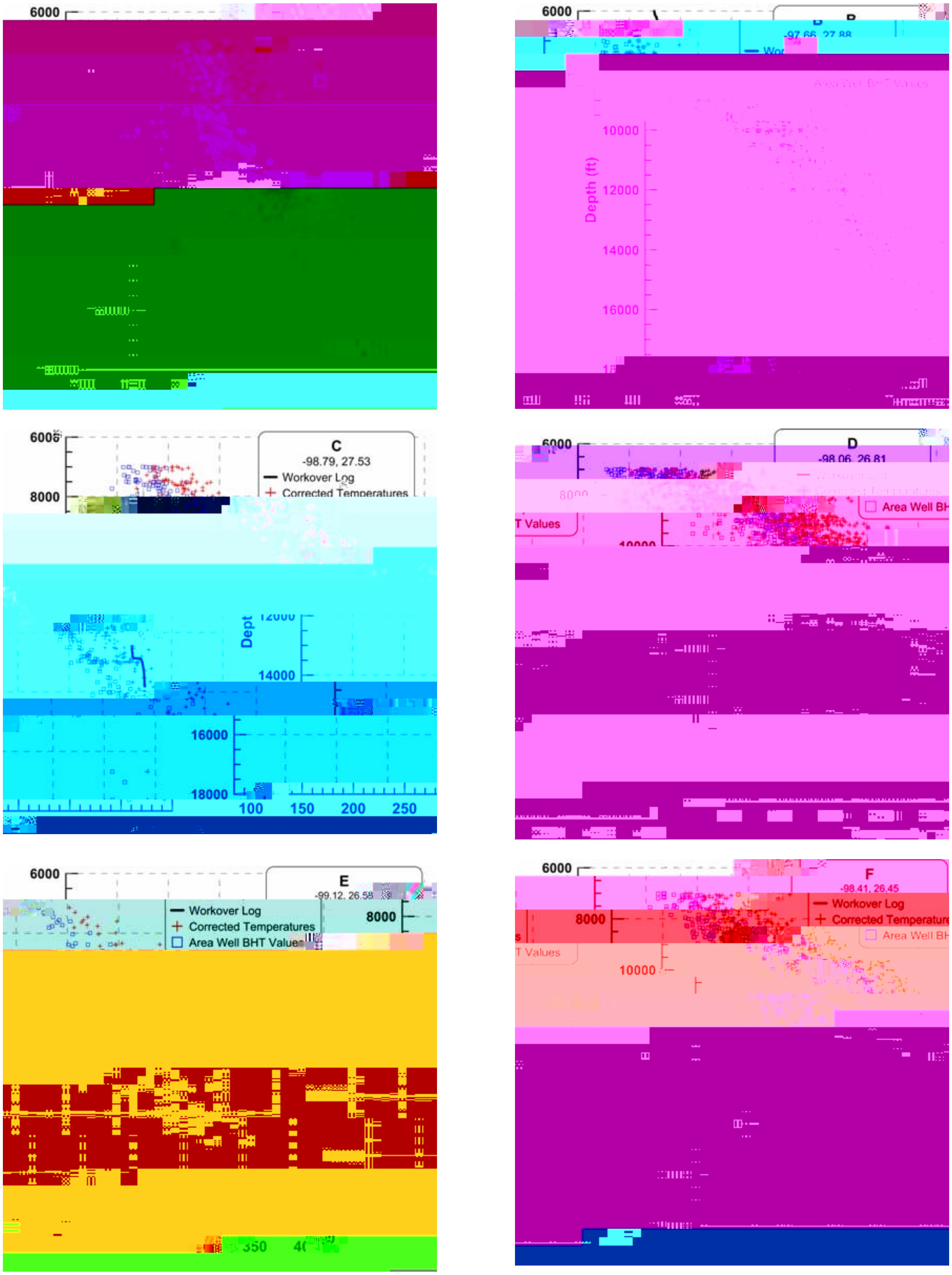
350
400
Temperature (°F)

Figure 10 (a - f). The workover well temperature log is shown as a black line, uncorrected BHT values within an area of ±0.5 longitude and latitude are shown as a square, and the corrected well temperatures are shown as a cross. Locations are shown by letter on Figure 8.



The curves shown in Figure 10 are also helpful to understand the temperature profiles for the wells in the fields around each workover well. The graphs also show the variation in the temperature trends according to the geological structure as depicted by Figure 10 D where there are two geothermal trends in the area, one colder than the regional. Information about the reservoir thicknesses can be depicted by the depths plotted as shown by breaks in the data (Figure A). The temperature -depth graphs in Figure 10 show that most areas in South Texas are over 300°F, even uncorrected BHT measurements, by 14,000 ft.

Pressure Data

For the Fairway Field area, pressure data from the production well records were used as a second comparison of the application of the SMU-Harrison correction on the SMU-TX RRC data points in Anderson and Henderson counties (Figures 11 & 7). The SMU-Harrison corrected BHT data follow the general trend of the pressure data with values slightly warmer than the uncorrected (blue triangles). There is an outlier group of data at 10,000 feet that are related to a variety of disturbances and recording errors. Pressure data are an improved parameter to use for estimating in-situ values when available over well log BHTs. This is because pressure data are collected with a temperature measurement throughout the life of the well. These are not considered an exact in-situ temperature because the well is active and has usually been flowing. They do represent values not influenced by drilling fluids, so are considered close to undisturbed (Kehle et al., 1970; Erkan et al., 2007). The pressure data contain numerous values for a specific well which can then indicate a reasonable spread of temperatures at that depth. These temperatures usually vary 10 to 25°F for a similar depth measurement as shown by the sample set of wells in Figure 12.

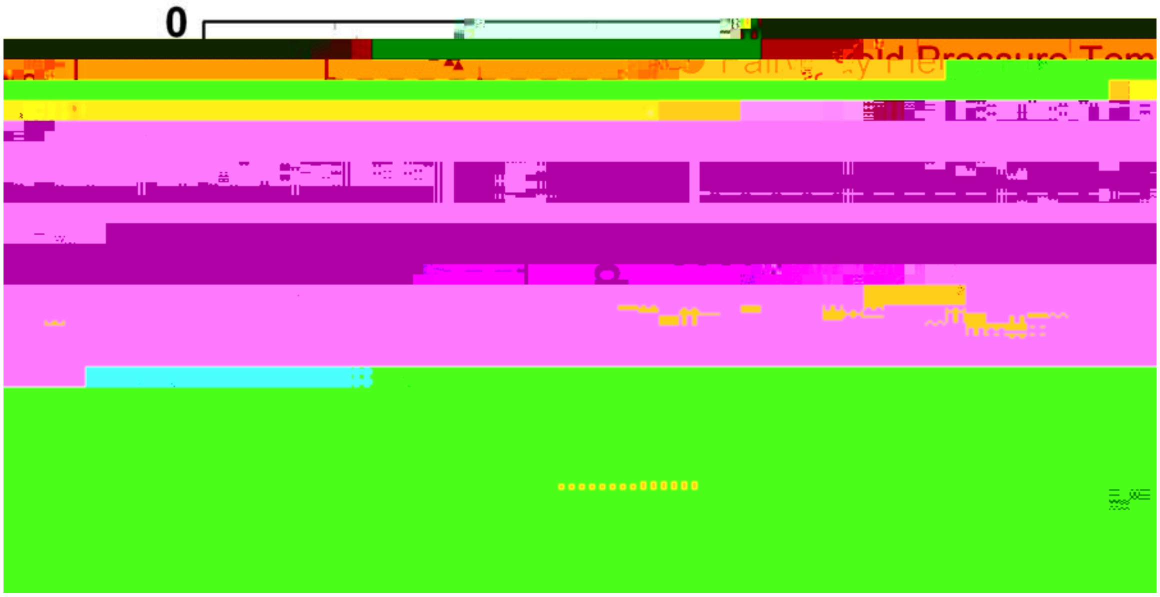
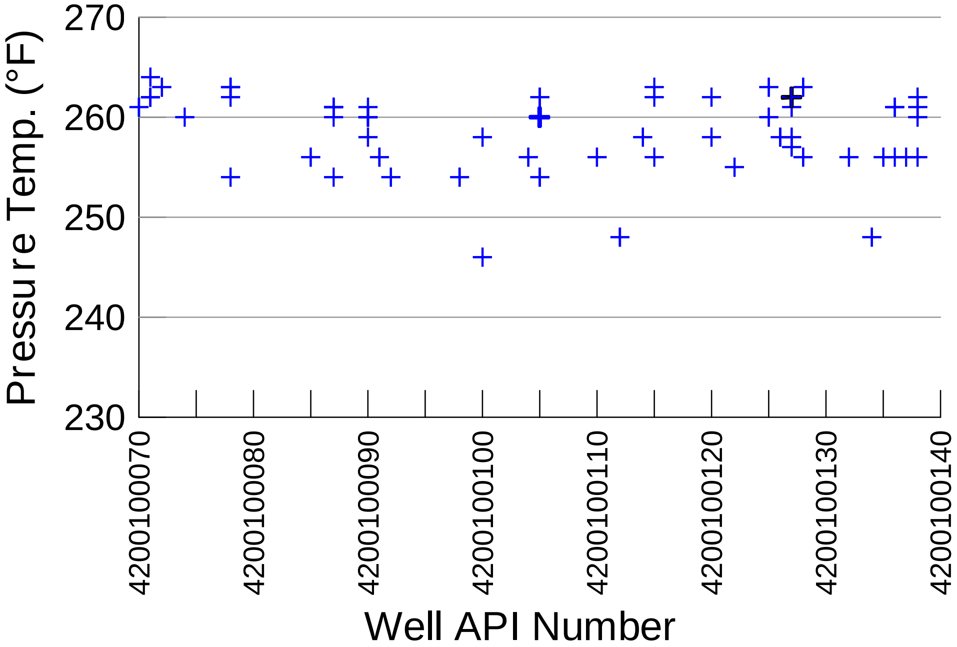


Figure11. The corrected SMU-TX RRC BHT data (diamonds) located within or near the Fairway Field, the averaged Fairway Field pressure/temperatures data (circles), and the uncorrected Fairway Field BHT data (triangles) are plotted. The trend of the pressure temperatures and corrected temperatures are similar except within the reservoir zone at approximately 10,000 feet.



ANALYSIS OF THE DATA

The data from the SMU-TX RRC database, the AAPG Geothermal Well Survey (AAPG, 1994), Gulf Coast Geopressure database (Gregory et al., 1980), Freestone County (Burns, 2004), and Fairway Field (Hunt Oil Company and Kweik, this report) were used to generate a series of temperature maps of the area of the study at various depths and at different scales. The maps were produced using software which developed a 3-dimensional lattice and second program for 2-dimensional grids. The 3-dimensional lattice is able to take into consideration the gradients of data in all directions to create smooth contour maps of temperatures at specific depths. These maps represent the general trend of the data and regional temperatures. Depths are slices of the lattice for a specific interval (Figure 13 a to h) shown at 1,000 feet intervals between the depths of wells are completed between 12,000 and 13,000 feet (Figure 15). Wells in this depth range are

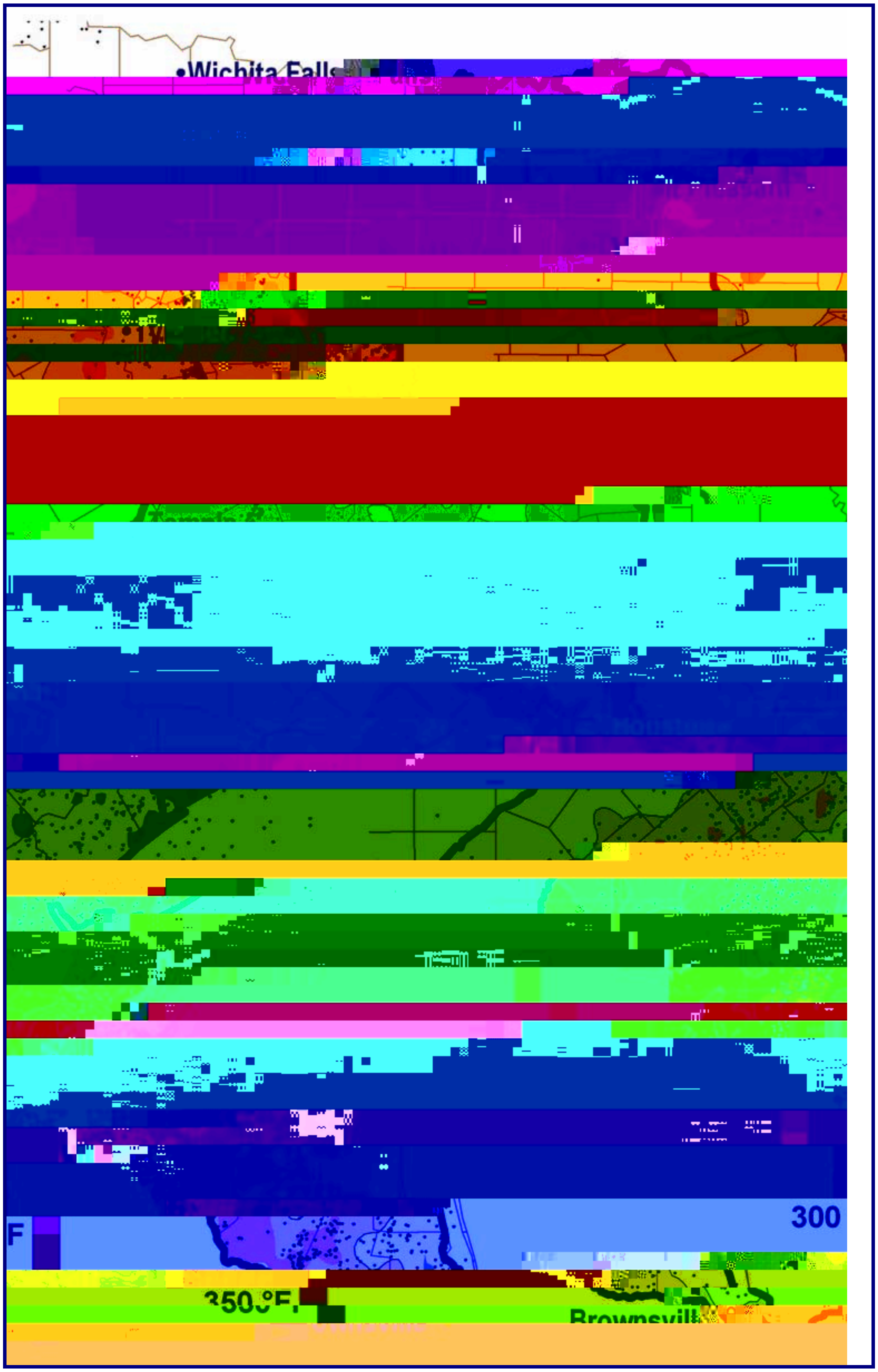


Figure 14a. Map of detailed corrected temperatures at 9,000 feet. Data are shown as small dots.

Figure 15. Histogram of drilling depth versus number of wells for the study area.

3. The surface temperature variation from summer to winter (and in some instances day to day) impacts the well temperature by changing the drilling fluid temperature. Temperatures are further altered by the duration of circulated drilling fluid and drilling conditions.

Table 2. Interval depth with average and maximum temperatures for that 1,000 feet interval.

Depth Range Feet	Number of Wells	Average Uncorrected Temperature °F	Average Corrected Temperature °F	Maximum Corrected Temperature °F
12,000 - 13,000	879	263	299	363
13,000 - 14,000	628	283	320	430
14,000 - 15,000	330	304	340	423
15,000 - 16,000	159	306	349	420
16,000 - 17,000	107	319	361	422
17,000 - 18,000	60	319		

Figure 16. Well locations with depth between 13,000 to 24,000 feet. The color of the symbol repre s

scheme, where a large volume of natural gas was injected into the field to help recover even more oil (Figure 18). However, this injection was halted in 2000, due to the rise in natural gas prices. The gas was then recovered. The production of the stored natural gas eliminated the need for water injection. In 2000, Fairway entered its current stage, which includes dehydrating the field under a pressure depletion drive to induce a blowdown phase with high water flow (David Luttner, personal communication).

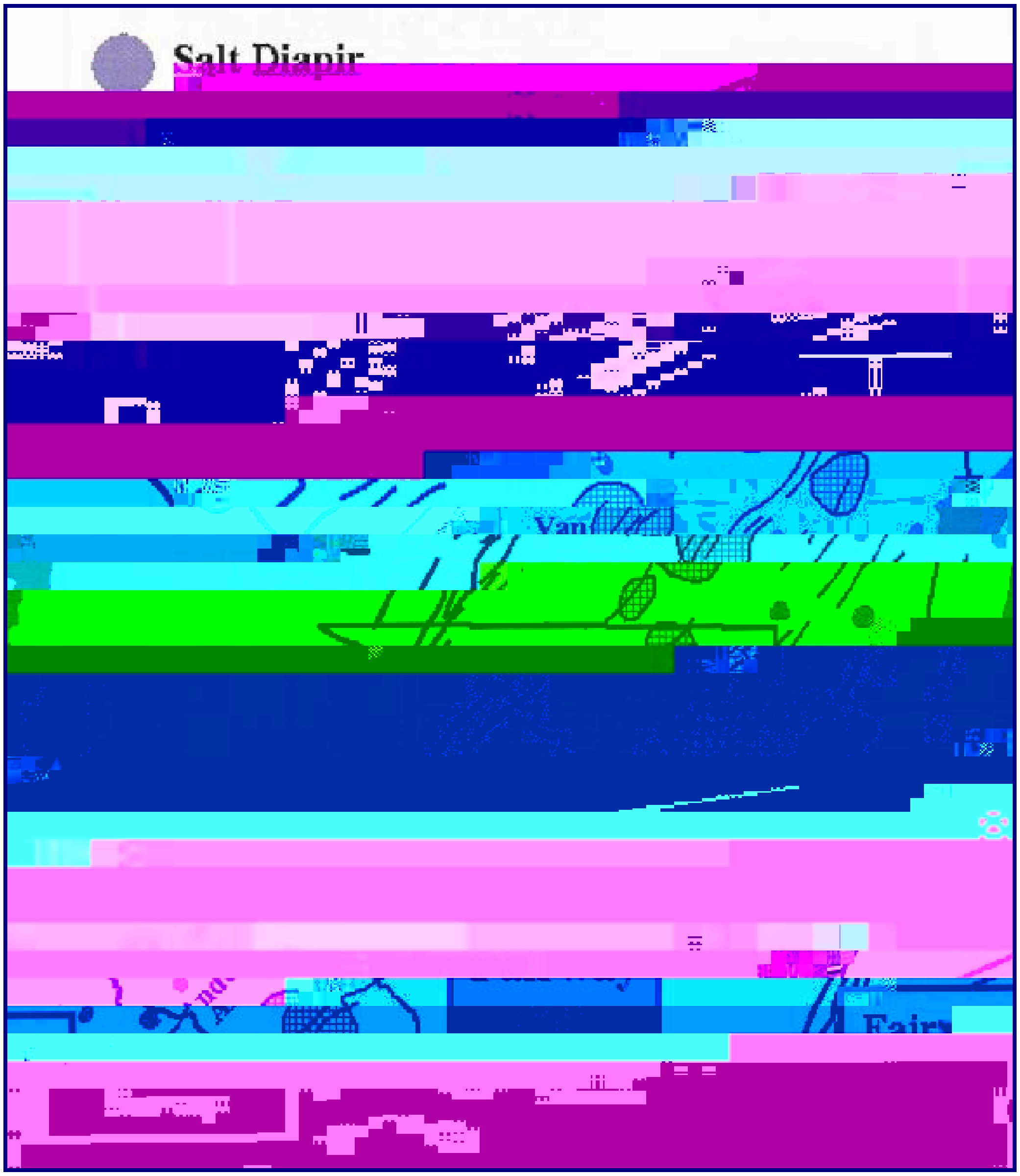
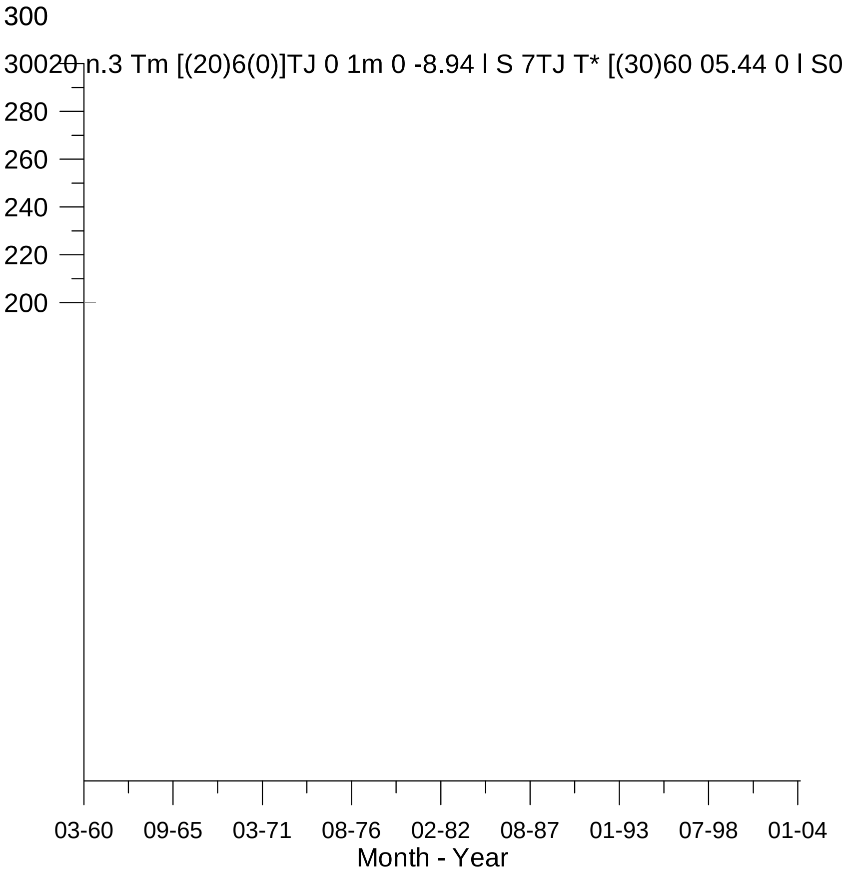


Figure 17. Overview map of the location of Fairway Field in East Texas, Henderson and Anderson Counties, the base is from Seni and Jackson (1983)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280
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240
220
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03-60
09-65
03-71
08-76
02-82
08-87
01-93
07-98
01-04
Month - Year

GEOTHERMAL RESOURCE UTILIZATION

This eastern Texas geothermal assessment focused on the moderate to high temperature geothermal resources accessible through depths typically associated with hydrocarbon wells. The advantages of using oil and gas wells/fields are: 1) the geothermal and oil and gas industries have overlapping knowledge bases that can build on each other's expertise to improve both industries; 2) existing oil field data are accessible for initial reservoir review and understanding, reducing exploration costs compared to conventional geothermal systems; 3) oil and gas fields have the existing infrastructure necessary for geothermal project development, i.e., roads, well pads, electrical connections to the grid, etc.; 4) the new binary turbine designs for distributed energy production makes them easier to plug and play with oil/gas wells; 5) oil and gas fields are normally in a state of flux with wellsieTxm essary

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Since Texas has extensive and diverse geothermal resources for electrical production, it is helpful to divide them into three categories for discussion: 1) geothermal-geopressured resources; 2) coproduced fluids; and 3) enhanced geothermal systems.

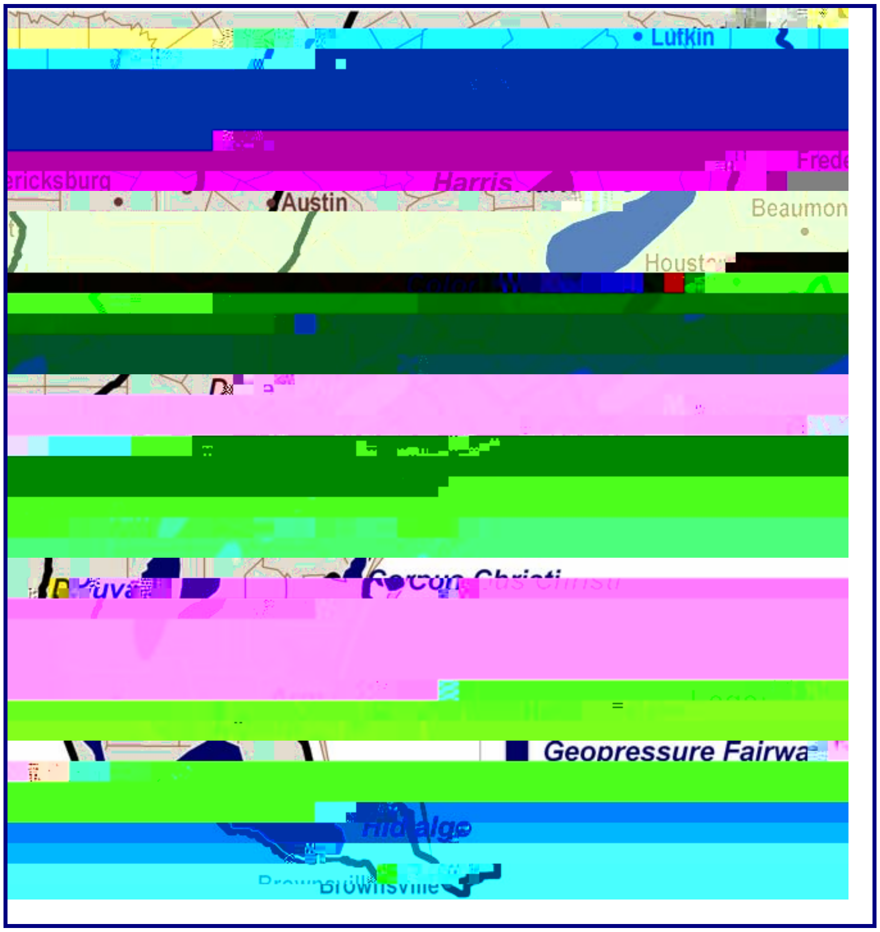

Figure 20. Geothermal - geopressured fairways as depicted by Bebout et al. (1982; 1983).

Table 3. Summary of the physical characteristics of the six Wilcox geopressured geothermal fairways (Table 4, Bebout et al., 1982). * SWC = Side wall core; ** DC = Diamond core

Wallace et al. (1979) estimated that over 2,000 exajoules (EJ) of recoverable thermal energy and methane are contained within the Texas Gulf Coast geopressured deposits. Uncertainties about the reservoir mechanics, the connectedness of the geopressured zones, and their capability to produce brine for extended periods of time, ar

Coproduced Resources

Coproduced geothermal resources are directly integrated into the production of oil and gas. Coproduction uses a well for the purpose of both the extraction of oil and/or gas and the heat from the fluids for electricity. The electricity can be used on-site or sold to the grid. Traditionally the fluid (brine) is trucked off or directly reinjected at an expense to the project. Locations where the fluids are directly injected on-site are the “low-hanging-fruit” for coproduction sites. The business plan incorporates the brine water as an economic commodity to allow for longer hydrocarbon production from a well. This type of development is the best case scenario for the utilization of the geothermal resource from an oil and gas field because of the minimal additional expense - primarily the installation of binary turbines. Fields which currently use waterflooding to increase hydrocarbon production from deep formations could be an initial focus point for geothermal development.

The second scenario for coproduction is the end of the life of oil and/or gas wells or “stripper’ wells. In these cases the well produces adequate hydrocarbon volumes to be economically viable until at some point of increasing production of brine water it is no longer economic. Rather than abandoning the well, to keep it economical the well could be converted to coproduction to recover the additional expense of the produced brine. This conversion allows a greater percentage of the hydrocarbons from the field to quantification of brine available is primarily a result of the research completed during the 1970s to 1990s geopressured - geothermal studies for the Gulf Coast Region. Areas such as East Texas where the technique of waterflooding is used to extract more oil and gas have current information on fluid injection volumes. Thus, it is certain that far more fluids presently exist stranded in oil and gas fields than the current records show.

Fluids Produced and Injected

Texas is the nation's number one oil and gas producer with more than 216,000 active oil and gas wells statewide. Along with these are the injection and disposal wells which return the produced water and frac fluids from these oil and gas wells. Texas has more than 50,000 permitted oil and gas injection and disposal wells.[7] Disposal wells inject fluid into an underground interval that is not producing oil and gas. Injection wells reinject fluids into the same or similar reservoir, from which the fluids originated, usually for secondary recovery of the oil. Operators use secondary recovery techniques when an oil field's recovery rate has decreased. One technique of secondary recovery, sometimes known as waterflooding, injects produced saltwater into a reservoir to reestablish sufficient pressure that will allow an operator to recover additional amounts of oil.

The quantity of water an individual oil and gas well produces is not recorded by the Railroad Commission. However, there is a section on the TX RRC W10 Form for "Daily Water" and some operators fill it in. Review of the records between 1994 and 2007 from this form includes over 12,000 wells for Districts 1 - 6 (Figure 22). Using the 12,000 wells as indicators of production depths with the most available water, there are two peaks, one between 5,000 to 7,000 feet and a second between 9,000 to 11,000 feet (Figure 23). Based on the total water produced, highest flow rates are produced at depths less than 7,000 feet and most likely have too low a temperature for electrical production (Figure 23). Of the 12,000 wells there are only three wells [API # 4223902390 (Jackson Co.), 4249900386 (Brazoria Co.), 4203931304 (Wood Co.); Figure 24] with recorded daily water production values of

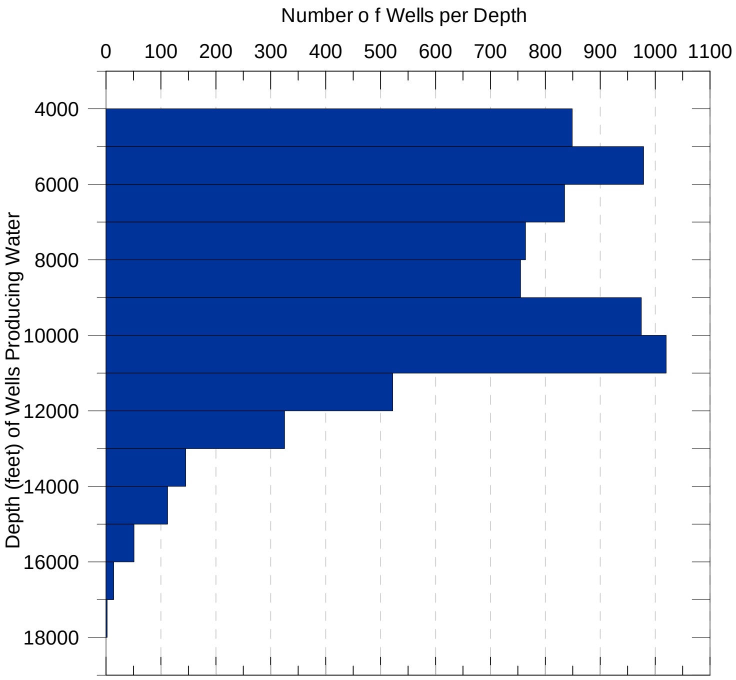

Figure 22. Histogram of recorded well daily water production (TX RCC form W10) for Districts 1 - 6.

The counties with the highest total volumes of combined injection and disposal are shown in Table 4. These are based on the records from the H10 form of the Texas RRC.[8] Figure 24 is a map of eastern Texas with the county water volumes. Guadalupe County near San Antonio has the largest volumes for 2007 and more than double the per well injection rate. In East Texas, Gregg and Upshur Counties are the two counties with the highest injection rates. Johnson County, in North-Central Texas, is unique in going from no disposal in wells in 2002 to having the 10th largest volume in 2007. The amount of fluid a formation has injected into it gives an indication as to how much is available for production. Therefore, deep (>10,000 ft) injection wells with high disposal rates are considered one initial indicator of where to explore for geothermal development.

Table 4. The total volume of well injection and disposal in barrels (BBLS) for each county during the years 2002 and 2007.

COUNTY	2002 BBLS	BBLS/day '02	2007 BBLS	BBLS/day '07	# of wells	BBLS/well '07
BRAZORIA	76,018,663	208,270	82,961,267	227,291	114	727,730
CALDWELL	85,350,824	233,838	126,802,271	347,403	82	1,546,369
FORT BEND	40,404,936	110,698	2,988,225	8,187	98	30,492
GREGG	162,441,485	445,045	171,657,048	470,293	68	2,524,368
GUADALUPE	137,000,401	375,344	316,642,226	867,513	54	5,863,745
HARRIS	41,152,107	112,745	37,261,790	102,087	149	250,079
JACKSON	55,276,969	151,444	44,467,697	121,829	133	334,344
JOHNSON	0	-	65,750,533	180,138	24	2,739,606
MONTGOMERY	39,537,722	108,323				

Figure 24. Map of eastern Texas with counties shaded according to their combined injection and disposal volumes.

Available Wells

There are various methods of exploration to determine which wells within a field are the “low-hanging-fruit” for geothermal exploration. The ability to extend the life of a field and use existing wells leads to the review of wells in line for plugging and abandonment. During the last three years, there have been 19,328 wells plugged in Texas (Table 5). For the I-35 study area which includes RRC Districts 1 - 6, there have been 2,684 wells abandoned in 2009 alone. By comparing data within the SMU-TX RRC Database, 47% were deeper than 10,000 feet and 54% were greater than 250°F. Therefore, it is estimated that 45 to 55% of the wells abandoned in 2009 were capable of geothermal energy production. If 50% of these wells (from Districts 1 - 6) were converted and had a minimal energy output of at least 250 kW, eastern Texas could continuously generate 335,500 kW (33.5 MW) of base load power. Using the current availability for geothermal power plants at 94%, then 2,762,641,200 kW/hours of electricity per year could be produced from the wells instead of them being plugged. That is enough for 8,400 homes or a whole county in some cases.

Table 5. Texas RRC Summary of Drilling, Completions, and Plugging Reports for 2009.

	2009	2008	2007	1	2	3	4	5	6
Drilling Overview									

allows for a binary turbine to be installed between the two wells with minimal infrastructure changes necessary. As shown in Table 5, the quantity of the fluid being injected or disposed of is huge. For the combined volumes of Districts 1 - 6 the total amount was 2,172,701,192 barrels in 2007. The average barrels per well was 364,242. Over half of the fluid was used for secondary recovery. There are currently 2,237 secondary recovery injection wells in District 1 - 6 that could be reviewed for depth and interconnection within the hydrocarbon field to see if they are injecting the 2008 Texas electrical consumption rate of 32,525 thousand megawatt-hour (MWh)[9]. Even modest utilization of this EGS resource is capable of supplying a large portion of the state’s energy on a permanent baseload basis.

Direct Uses of Geothermal Resources

Many of the wells in Texas are drilled to depths where the temperatures are less than 200°F. In these situations, the water production can be reviewed for specific economic applications. Use of the warm to hot water for commercial applications or community space heating is referred to as “Direct Use”. For instance, John et al., (1998) determined the following applications from the Gulf Coast geothermal - geopressured wells: the heating of houses, sulfur extraction, coal desulfurization, chemical processing, extraction of chemicals from brine, water desalination, fish rearing, greenhouse heating, cane sugar processing, lumber drying etc2 Tw 205/,,-5pan <</MCID 1 >>BD.7

heavy oil in South Texas. To determine how much of the resource was left, they compared the overall sizes and extraction rates of different reservoirs. Thus "medium- and heavy oil reservoirs constitute 10% of the large oil reservoirs in Texas, their cumulative production represents only 8.4% of the production from the large oil reservoirs. The 1.6% difference is a result of the lower average productivity and is equivalent to a difference of 629 MMbbls (1.0×10^8 m^3) (or 1.6% x total cumulative production of large reservoirs in Texas)." This is one resource target still available for production in conjunction with geothermal energy development.

The heavy-oil reservoirs are concentrated in the Jackson Group, Cole sandstone, whereas medium-oil reservoirs are concentrated in the Government Wells, Lorna Novia, and Mirando sandstones within the same area. The medium oil resource is larger than the heavy oil resource. This allows for a multi-level resource development using medium oil, heavy oil and geothermal resources. The geothermal resources reach temperatures of over 350°F and are below the oil reservoirs.

The San Miguel 'D' sandstone (2,100 feet depth) was targeted for heavy oil research in the early 1980s, when Exxon and Conoco produced 417,673 barrels from pilot plants (Ewing, 2005). The viability of using the geothermal-geopressured resources was studied again in 1991 as part of a Department of Energy research project (Negus-de Wys et al., 1991). The conclusions at that time were that the break-even price for oil needed to be $14/barrel and gas $2 per thousand cubic feet. Using those figures, at the time there would be a payback in less than two years. The study included a pilot project using the Alworth Field in South Texas and the Wilcox Formation for a water source at fluid temperatures of 250°F to 500°F between 16,000 and 18,000 feet. Seni and Walter (1994) continued to study the heavy oil extr

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The most recent legislation is the Texas House Bill 4433, September 2009, which is an exemption from the severance taxes on oil and gas incidentally produced in association with the production of geothermal energy. The Texas Comptroller office is working on the determination of incidentally.

Business Development

Leasing and development of geothermal projects have been occurring for the last 40+ years in the United States. Yet the business plan for developing low-temperature (< 300°F) geothermal projects in areas outside of the Western United States is still considered “risky” (Dunn, 2010).

195°F fluid from a series of oil striper wells in the Tea Pot Dome field, Wyoming. This installation was the first commercial application of coproduction. In recent years, new products have entered the electrical power market with designs starting as low as 180 to 200°F in Texas

Developing existing hydrocarbon fields into geothermal electrical production has the quickest potential for tapping into the thermal energy resource stored under Texas.

The Future of Geothermal Report (Tester et al., 2006) suggests Enhanced Geothermal Systems (EGS) could be a sustainable source of energy. There will be initially high costs for development that will then decrease as technology, knowledge, and market growth improve. Texas has the resources to be one of the proving grounds for EGS through use of deep sedimentary basins, and

Using information from existing oil and gas wells, tens of thousands of temperature data points can be used as an exploration tool for defining the most accessible resource locations. The temperatures from well log records can be corrected for in-situ temperatures, or pressure temperature data can be used as a proxy for equilibrium temperature. Although temperature at depth is only the initial starting point for reviewing potential resources, the extent of BHT data in

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Appendix A

Water, produced at a rate of 20,000 to 40,000 barrels per day, will probably have to be disposed of by injection into shallower sandstone reservoirs. More than 10 billion barrels of water are in place in these sandstone reservoirs of the Austin Bayou Prospect; there should be approximately 400 billion cubic feet of methane in solution in th

Geothermal Program Review X, 1992: The theme of the review, “Geothermal Energy and the Utility Market -- The Opportunities and Challenges for Expanding Geothermal Energy in a Competitive Supply Market,” focused on the needs of the electric utility sector. Geothermal energy, with its power capacity potential of 10 GWe by the year 2010, can provide reliable, environmentally clean electricity which can help offset the projected increase in demand. The six technical sessions included presentations by the relevant field researchers covering DOE-sponsored R&D in hydrothermal, hot dry rock, and geopressured energy. Individual projects are processed separately for the databases.

Gregory et al., 1980: The objective of this project was to appraise the total volume of in-place methane dissolved in formation waters of deep sandstone reservoirs of the onshore Texas Gulf Coast within the stratigraphic section extending from the base of significant hydrocarbon production (8000 ft) to the deepest significant sandstone occurrence. The area of investigation is about 50,000 mi^2. Factors that determine the total methane resource are reservoir bulk volume, porosity, and methane solubility; the latter is controlled by the temperature, pressure, and salinity of formation waters. Regional assessment of the volume and the distribution of potential sandstone reservoirs was made from a data base of 880 electrical well logs, from which a grid of 24 dip cross sections and 4 strike cross sections was constructed. Solution methane content in each of nine formations or divisions of formations was determined for each subdivision. The distribution of solution methane in the Gulf Coast was described on the basis of five reservoir models. Each model was characterized by depositional environment, reservoir continuity, porosity, permeability, and methane solubility.

Griggs, 2004: This study shows commercial production of geopressured-geothermal aquifers is feasible under reasonable assumptions of natural gas and electricity price. However, the near-term likelihood of large-scale developments of geopressured aquifers is low. Factors that reduce the chance of near-term development include the availability of better exploration prospects, an uncertainty in current technology, and the lack of any current geothermal geopressured aquifer research programs. The medium-term development of geopressured aquifers relies on the sustainability of high natural gas prices, the application and acceptance of new technologies, and diversification of conventional exploration and production companies and electric utility companies. The long-term development of geopressured aquifers depends on the scarceness of conventional hydrocarbons.

Jackson et al., 1993:This report outlines the types of data, data sources and measurement tools

John et al., 1998, Volume 2B: This volume describes the following studies: Design well program; LaFourche Crossing; MG-T/DOE Amoco-Fee No. 1 (Sweet Lake); Environmental

Vicksburg Formation in the Lower Texas Gulf Coast is not prospective. Reservoir quality in the Frio Formation increases from very poor in lowest Texas, to marginal into the Middle Texas Gulf Coast and to good through the Upper Texas Gulf Coast. The Frio Formation in the Upper Texas Gulf Coast has the best deep-reservoir quality of any unit along the Texas Gulf Coast.

Loucks et al., 1981: This study discusses variable intensity of diagenesis as the factor primarily responsible for contrasting regional reservoir quality of Tertiary sandstones from the upper and lower Texas coast. Detailed comparison of Frio sandstone from the Chocolate Bayou/Danbury Dome area, Brazoria County, and Vicksburg sandstones from the McAllen Ranch Field area, Hidalgo County, reveals that extent of diagenetic modification is most strongly influenced by (1) detrital mineralogy and (2) regional geothermal gradients. The regional reservoir quality of Frio sandstones from Brazoria County is far better than that of Vicksburg sandstones from Hidalgo County, especially at depths suitable for geopressured geothermal energy production. However, in predicting reservoir quality on a site-specific basis, locally variable factors such as relative proportions for porosity types, pore geometry as related to permeability, and local depositional environment must also be considered. Even in an area of regionally favorable reservoir quality, such local factors can significantly affect reservoir quality and, hence, the geothermal production potential of a specific sandstone unit.

Morton et al., 1983: This study focuses on structural styles that are conducive to the development of large geothermal reservoirs include blocks between widely spaced growth faults having dip reversal, salt-withdrawal basins, and shale-withdrawal basins. These styles are widespread on the Texas Gulf Coast. Detailed structural mapping at several horizons in selected study areas within the Frio growth-fault trend demonstrates a pronounced variability in structural style. At Sarita in South Texas, shale mobilization produced one or more shale ridges, one of which localized a low-angle growth fault trapping a wedge of deltaic sediments. At Corpus Christi, shale mobilization produced a series of large growth faults, shale-cored domed anticlines, and shale-withdrawal basins, which become progressively younger basinward. At Blessing, major growth faults trapped sands of the Greta/Carancahua barrier system with little progradation. At Pleasant Bayou, a major early growth-fault pattern was overprinted by later salt tectonics - the intrusion of Danbury Dome and the development of a salt-withdrawal basin. At Port Arthur, low-displacement, long-lived faults formed on a sand-poor shelf margin contemporaneously with broad salt uplifts and basins. Variability in styles is related to the nature and extent of Frio sedimentation and shelf-margin progradation and to the presence or absence of salt.

Nagihara and Jones, 2005:Eighty-two seafloor heat-flow measurements were recently obtained across the Mississippi Fan region in the deep the U.S.G.S., N.S.F., G.R.I., and possibly other areas within DOE. A research spin-off: a sensitive in-line benzene monitor has been designed by USL and will be tested in the near future. An in-

Appendix B

Data used in this Assessment

1. SMU Geothermal Laboratory, TX Railroad Commission data collected for this project. Included in this appendix.
2. AAPG Geothermal Survey Well Data, 1994. This can be purchased through the AAPG Bookstore, Product Code 482. It includes: A. Exploratory Well File (CSDE), 1950-1989; B. Geothermal Survey of North America (GSNA), 1972; and C. Correlation of Stratigraphic Units of North America (COSUNA)
3. Gulf Coast Geopressure data, Gregory et al., 1980. Included in this appendix.
4. Freestone County Well data, Burns, 2004. Included in this appendix.
5. Fairway Field data, Hunt Oil Company and Kweik, 2008. Company data not included.

Appendix C

Calculating the Potential Power from a Well

Calculating the potential power from the fluid temperatures and flow rates is the initial aspect to determining if a well/field should even be considered. The following materials from the Tester et al. (2006) Report, The Future of Geothermal Energy will assist in accomplishing this.

Using Figure 7.3 from Tester et al. (2006), the inlet and outlet temperatures can be used to determine the gross power output for a kilogram per second of fluid movement.

The 2006 Report used the example of 40°C (104°F) output (T_2) for its estimated power based on the yearly fluid for from the production of the oil and gas wells, as shown in Table 7.3. The

Oilfield Testing Center (RMOTC), Wyoming and is expected to be even hotter in Texas. In general the outlet temperature is generally about 10 to 40°C (18 to 72°F) cooler than the inlet temperature.

Within a State, well temperatures will vary greatly according to location and depth of resource. Table 7.3 from Tester et al., (2006) shows the MW capacity if all the flow is at each of the input temperature of 100°C, 140°C, or 180°C (212°F, 258°F, 355°F).

To convert from kg/s to gpm, depending on the method of conversion, the conversion rate is either 15.81 (using kg to pounds to gallons) or 15.85 (using kg to liters to gallons). Therefore in working with the different units the accuracy of the final number will vary according the number of digits and method of conversion.

Calculating Potential Flow

By using Darcy's Law, which expresses radial liquid flow into a borehole in units of barrels of liquid per day, the open-flow potential of a well can be determined (Harrison et al, 1982). This can be used to review the available wells in an oil and gas field to get initial numbers for how much production can be expected to flow from a formation according to the borehole sizes.

$$bbl/day \quad 7.07kh(P_e \quad P_w)/\ \mu\ln(r_e/r_w)$$

where bbls/day = barrels per day (42 gallons/barrel)

k = permeability in darcies

h = interval thickness in feet

P_e = 1 atmosphere in psi (14.7 psi)

P_w = formation pressure in psi

The table below shows the Excel spreadsheet with the equations for the calculation.

	B	C	D
	Average Daily Flow Rates	Input	Energy Content, MBTU
3	Average daily barrels of oil (US bbls)		=C3*42*0.14
4	Average daily gas (scf)		=C4*400/1000000
5	Average daily barrels of saltwater (US bbls)		=C5*159*(C6-75)*2.2/1000000
6	Average fluid temperature at the wellhead (°F)		
	Percent of energy in saltwater		=D5/(D3+D5+D4)*100
	Total energy possible from well		=SUM(D3:D5)

The next table shows numbers in the Excel spreadsheet with an example of the calculations.

B	C
Average Daily Flow Rates	Input

Appendix D

Business Report Questions

Organizations and Companies to Contact for Assistance

Companies with Low-Temperature Technology

Questions to Consider
Before Starting a Geothermal Venture

Executive Summary

The purpose of this document is to give those interested in developing geothermal resources and undertaking business ventures in the geothermal field an aid in the form of a basic checklist of things that should be considered when engaging in such a venture, in order to increase the probability of project success.

In any geothermal project there are four main areas that need to be considered in order to evaluate the potential success of the project. In the following pages we will expand

Geologic Investigation

“Does the resource exist?” This is the starting block for any geothermal venture, simply because you need to identify a geothermal resource and its characteristics before you can develop it.

What is the geology of the area?

- Geologic structure of the area
- Stratigraphic column and cross sections
- Are any local well logs available?
- Is seismic information available?
- Is a chemical analysis of the fluids available?

Does the geothermal resource exist?

- Where, at what depth, in what formation?
- What is the temperature, pressure, formation thickness, and flow rate of the resource?

Legal Investigation

Engineering Investigation

“Can the resource be efficiently harnessed?” Once the geologic resource is well understood, it becomes essential to find the most efficient way of harnessing its full potential in order to maximize plant output as well as financial gain.

What type of plant design is best suited for harnessing the resource?

- Dry steam, flash steam, or binary plant?
- Will the temperature, pressure, and fluid flow rate of my reservoir be able to support one of these plants?
- Can absorption chillers or other renewable energy types be incorporated?
- What diameter wells/ pipes do I need to produce my desired amount of energy?
- How many wells do I need to obtain my desired fluid flow rate to maximize power plant output?
- What insulation is needed in order to most efficiently transport the heat?
- What material should my casing/ pipes be made of to avoid corrosion, scaling, or other impurity related issues?

To what extent is reservoir engineering required in your resource?

- Do you need to fracture the formation in order to increase production?
- Does your reservoir require fluid injection such as an enhanced geothermal system (EGS)?

What working fluids will be involved in the plant operations?

- What refrigerants will be using in the binary systems?
- How much cooling fluid is neede and where will it come from?
- In the wells, pipes, and plant systems, what chemicals will be used to eliminate issues of scaling?

What will be required to run the plant?

- What electrical, computer, etc. systems are required in order to run the plant at its highest efficiency?
- What personnel will be needed to run the plant?
- What backup/ emergency systems will be installed in the case of a malfunction?
- What parameters will be collected on a regular basis?

How will the energy be transported from the plant to the desired market?

- What infrastructure is available to do this?
- Where is the closest utility transfer station?

Financial Investigation

"Can the project be financed?" Answering this question will be the true make or break of any business venture. If the numbers don't make sense, then the project won't make sense. Even in the case of green energy projects, there is no exception.

Opportunity Analysis

- Who will purchase the geothermal energy?
- What is the most profitable target market for your power generation— selling to the grid, distributed energy, coproduction, a combination of each?
- If gas is produced, will it be sold to a pipeline, used in a fuel cell, or in a turbine?
- How much energy is need to satisfy the site demand?
- What are the resources already available?
- How can profits be maximizes from these resources?
- Can a Power Purchase Agreement be secured? At what price, for how many years?
- Who is the competition?
- What is the price to beat of the competitor?
- How will this project be financed (debt/equity)?
- What is the source of capital?
- What is the cost of capital?
- What financial risks are associated with the project?
- Was a Strengths, Weaknesses, Opportunities, and Threats (SWOT) Analysis completed?
- What is the anticipated performance of the plant?

Cost Analysis

What are the Exploration Cost?

- Seismic surveys, well logging and data, geologic analysis and flow tests, chemical analysis of geothermal fluids, etc.
- What are the drilling costs (drill rig, well fracturing, personnel, casing, etc.)?
- Is it possible to recomplete an existing well?
- What is the cost to recomplete a well?
- What is the estimated lifespan of a well?
- Production well (new): drilling costs, casing costs, emplacement of the wellhead, preparing the site for power plant installation.
- Production well (existing): work-over costs of well, perforation of casing, formation fracturing.
- Where will the injection well be located, designed and drilled to necessary depth, casing, injection pump, etc.?
- What are the development costs for infrastructure on and off site?

What are the Legal Costs?

- Legal costs associated with zoning, siting, drilling permits and mineral right procurement.
- Legal costs associated with rules and regulations

Geothermal Agencies and Business Contacts for Texas

Organizations Assisting Renewable Energy Development

Geothermal Energy Association
Karl Gawell
209 Pennsylvania Ave., SE
Washington, D.C. 20003
karl@geo-energy.org
www.geo-energy.org
P: 202-454-5264

Geothermal Resources Council
Curt Robinson
P.O. Box 1350
Davis, CA 95617
grc@geothermal.org
www.geothermal.org
P: 530-758-2360

Research Partnership to Secure Energy for America (RPSEA)
Michael Ming
1650 Highway 6, Suite 300
Sugar Land, TX 77478

Companies with Low Temperature Technology Geothermal Power Plants

Pratt & Whitney Power Systems
Michael Ronzello
400 Main Street
East Hartford, CT 06108
michael.ronzello@pw.utc.com
www.pw.utc.com
P: 860-727-2465

Gulf Coast Green Energy
Loy Sneary
2200 Avenue A, Suite 103
Bay City, TX 77414
loys@sbcglobal.net
www.gulfcoastgreenenergy.com
www.electratherm.com
P: 888-448-2112

ORMAT Technologies, Inc.
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P: 775-356-9029

Turbine Air Systems
Halley Dickey
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Deluge, Inc.
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Linear Power Ltd.
Robert Hunt
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Long Beach, MS 39560
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228-363-0736

Engineering Power Plants

Power Engineers
Kevin Wallace
3940 Glenbrook Drive
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Condenser- Cooling Towers

Tranter
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Dry Coolers Inc.
Bob Antaya
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Oxford, MI 48371
bob@drycoolers.com
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Reservoir Engineering

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