Overview: The Geopressured-Geothermal Resource

Geothermal energy resources are present in several forms, which can be distinguished from one another as: hydrothermal (available ground water is heated by hot rock formations adjacent to magma), petrothermal (near magma, hot-dry rock formations) and Geopressured-Geothermal (GPGT) (Seni, 1993 [21]). GPGT energy is available in the reservoir brines of certain sedimentary basins and should be distinguished from the other two geothermal energies which are typically associated with volcanic (igneous) formations.

GPGT aquifers form when reservoir waters, trapped within lenticular sedimentary bodies between shale formations, are hydrologically isolated by subsidence and rapid burial. The rapid compaction of the shale and the consequent entrapment and thermal expansion of excess water (from shale dewatering) within these sedimentary formations, enclosed within the shale, tends to overpressure and heat the trapped reservoir waters. Characteristic of GPGT reservoirs are their high temperature and pressure gradients (°F per ft of depth and psi per ft of depth respectively). The pressure gradient of GPGT formations will typically approach that of lithostatic (~1 psi/ft), which approximates the effective pressure of the rock overburden, versus a normal hydrostatic gradient (~0.465 psi/ft) which approximates the effective pressure of a typical ground-water column. In some GPGT reservoirs (e.g., California "superpressured" systems) the pressure gradient exceeds lithostatic, where it is believed that tectonic stresses add to the overpressure. However the tectonically assisted GPGT reservoirs may not yield as high a temperature gradient as the geopressured regions resulting primarily from rapid compaction and shale dewatering (Geothermix, 1993 [16]); in addition to expelling water and generating natural gas, the morphic conversion of montmorillonite clays into illite shale, a developmental component of GPGT reservoirs, is an exothermic reaction (Dorfman, 1988 [4]).

The GPGT reservoir brines are highly pressured and hot, ranging from 1000 to 4000 psi and from 250 to 500°F flowing surface pressure and temperature respectively. The brines are entrained with natural gas, varying from 20 to 100 scf/bbl. The brines can be recovered via typical well-bores, at high flow rates ranging from 15,000 to 40,000 bpd. The available energies are: (1) the mechanical energy of the high pressure flowing brine; (2) the brine's thermal energy via heat exchange; and (3) the chemical energy of the natural gas which can be withdrawn from the brine in a standard gas separator. According to U.S. Geological Survey (USGS) estimates, there are 5,700 quads of recoverable gas and 11,000 quads of available thermal energy in the Gulf Coast GPGT basin alone (quad=E15 BTU) (Wallace, 1978 [3]). For comparison, the U.S. total annual energy consumption for 2003 is estimated at 100 quads[1].

The GPGT brine water and salts are additional resources. The quantity of salts and minerals dissolved in the GPGT reservoir brine, or total dissolved solids (TDS), ranges from 3,500 to 200,000 ppm. The majority of the TDS are Sodium Chloride, with lesser amounts of Calcium, Potassium, and other trace elements. Generally there is an inverse relationship between brine TDS and brine gas content since the solubility of gas in water decreases with increasing salinity. Consequently, since the solution gas in the GPGT brines is typically at saturation levels, the GPGT brines with the higher Gas-to-Water-Ratio (GWR) are associated with lower TDS. As the surrounding shale dewaters,

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[1] Energy Information Administration, http://www.eia.doe.gov/emeu/aer/eh/frame.html

the expelled water cuts the TDS and thereby allows more gas to evolve into solution. As the GPGT overpressure is relieved, e.g., due to reservoir production, the otherwise incomplete morphic shale conversion is allowed to continue, thereby expelling more water, exothermically generating more heat, and allowing for the absorption of more gas into the reservoir fluid. This continued reaction may contribute to the extraordinary flow longevity of GPGT reservoirs.

There are at least seven known GPGT basins in the U.S. and approximately 60 others worldwide (Dorfman, 1988 [4]). Figure 1.2-1 shows a map of the U.S. GPGT basins. The largest U.S. basin is in the Gulf Coast region with the second largest in the Central Valley of California. Figure 1.2-2 shows a map of the GPGT basins within six major reservoir regions in California, and Figure 1.2-3 shows a map of the GPGT basins in the Gulf Coast region.

The U.S. Department of Energy (DOE) initiated the Geopressured-Geothermal Research Program in 1974 to define the magnitude and recoverability of GPGT energy in the U.S. Under this program, five deep GPGT research wells were flow tested in the Texas-Louisiana Gulf Coast region during 1979–1992. Three of the DOE GPGT test wells are indicated on Figure 1.2-3. These flow tests demonstrated the GPGT reservoir production longevity, ranging from 5 to 7 years at sustained flow rates from 20,000 to 40,000 bpd (Negus-de Wys, 1990 [2]; Riney, 1991 [6]; Riney, 1993 [7]). The relatively high GPGT reservoir production can be attributed to several mechanisms, e.g., fault-enhanced fluid communication, and shale dewatering. While the site-specific GPGT drive mechanisms are still open to interpretation, most agree that the GPGT basins have outperformed conventional reservoir models (Ramsthaler, 1988 [8]; Riney, 1988 [9];

John, 1989 [10]). The last of the DOE test wells was plugged in December, 1993 (Rinehart, 1994 [11]; DOR, 1994 [12]).

Under the direction of the DOE's Idaho National Engineering Laboratory (currently called Idaho National Laboratory), the Industrial Consortium for the Utilization of the Geopressured-Geothermal Resource was established in January, 1990. The purpose for the consortium was to provide a forum for GPGT technology transfer and to assist in the commercialization of the GPGT resource. Some of the data used in developing the GEM GPGT conversion systems were taken from the consortium's proceedings and references (Jan.,1990; Feb.,1991). The consortium also provided a good forum for reviewing some of the early GEM system concepts (Nitschke, 1990 [13]; Lunis, 1991 [14]; Nitschke, 1991 [15]). The DOE ended funding for the GPGT program in 1992, officially ending the consortium. Additional Gulf Coast GPGT data have been compiled by the Bureau of Economic Geology at the University of Texas at Austin and the Louisiana Geological Survey. Data pertaining to California's GPGT potential can be found in an investigative report by GeothermEx, Inc., under contract to the California Energy Commission (CEC) (GeothermEx, 1993 [16]).

For a California implementation of the GEM TEOR systems, the GPGT well would be located in California's Great Valley region (Figure 1.2-2). To date, the GeothermEx, Inc. report (1993 [16]) is the best data compilation for estimating the performance of California's GPGT reservoirs (i.e., pressure, temperature, gas content, TDS, etc.). For the sake of estimating performance it is assumed that the California GPGT wells will perform similarly to the Gulf Coast GPGT wells, a sampling of which data are shown in Table 2.1.1-1.

Annotated References

2. Negus-de Wys, J., Hart, G.F., Kimmell, C.E., and Plum, M.M.; **The Feasibility of Recovering Medium to Heavy Oil Using Geopressured-Geothermal Fluids**, Proceedings, v.2, Industrial Consortium for the Utilization of the Geopressured-Geothermal Resource, Feb., 1991, pp. 1-92.

   The paper discusses GPGT application for TEOR (direct GPGT flood), including criteria for successful TEOR, formation reactions, budgetary assumptions, and a discussion of collocational (heavy oil and GPGT) studies cited for south Texas, Louisiana, and CA. The Alworth field of south Texas (Mirando Trend, 18° gravity oil, ~1B bbls potential) is used to case-study a *GPGT-direct TEOR method* (CALDES TEOR utilizes a binary-fluid approach driven by waste heat and recovered gas) with an Upper Wilcox GPGT source (13,000 – 16,000 feet depth, T>250°F, 20,000–70,000 mg/L NaCl, 26%-30% porosity, e.g., Hulin flow rates 20,000 bpd, high GWR). Used as primary source to establish the baseline TEOR water injection ratio (i.e., water injected bbls per bbl recovered heavy oil).

3. Wallace, R.H. et al; **Assessment of Geopressured-Geothermal Resources in the Northern Gulf of Mexico Basin**, Assessment of Geothermal Resources of the United States, U.S. Geological Survey Circular 790, 1978, pp. 132-155.

   Primary source for characterization (pressure and temperature gradients, salinity, gas content) and quantity estimates of energies in GPGT reservoirs, primarily in the Gulf Coast region. The source includes a discussion of GPGT geological data, including formation and (potential) drive mechanisms.

4. Dorfman, M.H.; **Geopressured-Geothermal Energy and Associated Natural Gas**, Proceedings, 11th Annual Energy Source Conference and Exhibit, 1988, pp. 97-101.

   Source provides a discussion of the processes by which natural gas evolves into GPGT waters, with geological progression of events, and a discussion of potential drive mechanisms for GPGT reservoirs. Additional source for GPGT characterization, and discussion of the DOE GPGT test program.

5. Negus-de Wys, J. and Dorfman, M.H.; **The Geopressured-Geothermal Resource: Transition to Commercialization**, Proceedings, v.1, Industrial Consortium for the Utilization of the Geopressured-Geothermal Resource, Jan. 10, 1990, pp. 11-39.
   Discussion of University of Texas at Austin (UTA) analysis of the Gladys-McCall GPGT test well; provides estimates of GPGT reservoir volumes and production well performance (4B bbls and 40,000 bpd for 5 years respectively) and GWR (e.g., 62–100 scf/bbl for south Texas).

6. Riney, T.D.; **Analysis of Preliminary Testing of Willis Hulin Well No.1**, S-Cubed Technical Report for the U.S. Department of Energy Geothermal Division, Lawrence Berkeley Laboratory Contract No.DE-AC03-76SF00098, Sept. 1991.
   Test report of the Willis Hulin No.1 GPGT flow test for the DOE (Gulf Coast Louisiana), including: flow test results, fluid and formation properties, well bore calculations and reservoir simulations. Source for GPGT reservoir modeling correlation.

7. Riney, T.D. and Owusu, L.A.; **Well Test Analysis and Reservoir Modeling of Geopressured-Geothermal Systems, Includes Topical Reports on Analyses for: Pleasant Bayou Well No.2 and Gladys McCall Well No.1**, S-Cubed Final Report for the U.S. Department of Energy Geothermal Division, Lawrence Berkeley Laboratory Contract No.DE-AC03-76SF00098, Subcontract No.4584310, Feb. 1993.
   Same type of analysis and source material as [6] for the Pleasant Bayou Well No.2 (Texas Gulf Coast near Houston) and the Gladys McCall Well No.1 (Louisiana Gulf Coast).

8. Ramsthaler, J. and Plum, M.; **Future for Geopressured-Geothermal Resources**, ASME Geothermal Energy Symposium, Jan.10-13, 1988.
   Discussion of the Bureau of Economic Geology at the UTA GPGT data. Case study of the economics and operational considerations for a gas-sale GPGT application flow test of the Willis Hulin; estimates break-even price for gas at $4.60 for a 60 scf/bbl GWR; waste brine disposal costs questionable.

9. Riney, T.D.; **Gladys McCall Geopressured Reservoir Analysis-June 1987**, Journal of Energy Resources Technology, v.110, Transactions of the ASME, Dec. 1988.

Production history and reservoir analysis of the Gladys McCall GPGT DOE flow test. Source for correlative data for reservoir simulations, e.g., skin factors. Porosity and permeability established via lab tests to be 0.168 and 83 md respectively.

10. John, C.J.; **Geology of the Gladys McCall Geopressured-Geothermal Prospect, Camaron Parish, Louisiana**, Louisiana Geological Survey, 1989.

    Further characterization of the Gladys McCall test well: ~300°F, 32 scf/bbl GWR, 94,000 ppm TDS. No detrimental effects observed from GPGT production and disposal. Discussion how flow performance greatly exceeds conventional models.

11. Rinehart, B.N.; **Geothermal Well Site Restoration and Abandonment of Wells: DOE Gladys McCall Test Site and DOE Willis Hulin Test Site**, Idaho National Engineering Laboratory, EG&G Idaho, Inc., Contract DE-AC07-76ID01570, Aug. 1994.

    Plug and abandon reports for subject test wells. Source for various operational information, e.g., regarding well re-entry, salvage value, plug and abandon costs, etc.

12. DOR Engineering, Inc.; **Final Report on Well Plug and Abandonment Operations and Wellsite Restoration, U.S. DOE Geopressured-Geothermal Program, Louisiana and Texas Wells**, for EG&G Idaho, Inc., Aug. 30, 1994.

    Same type of data and use as noted for [11].

13. Nitschke, G.S. and Harris, J.A.; **Production of Fresh Water and Power From Geopressured-Geothermal Reservoirs**, Proceedings v1, 1st Annual Meeting of the Industrial Consortium for the Utilization of the Geopressured-Geothermal Resource, Jan.10, 1990, pp. 89-105. (also published in: Proceedings, 9th Miami International Congress on Energy and Environment, December, 1989)

    Early conceptual work leading to the CALDES proposal. Discusses distilled water, gas, and electricity production from GPGT conversion system (near term) and construction of solar ponds for seawater desalination (long term).

14. Lunis, B.C., Negus de-Wys, J., Plum, M.M., Lienau, P.J., Spencer, F.J., and Nitschke, G.S.; **Applying Geopressured-Geothermal Resources is Feasible**, Proceedings v1, 2nd Annual Meeting of the Industrial Consortium for the Utilization of the Geopressured-Geothermal Resource, Feb. 1991, pp. 83-138.

Discussion of various direct uses for GPGT energy, including the work discussed in [13], with projected economics. Other discussed uses include power generation, agriculture/aquaculture benefits, and direct applications for low grade heat (e.g., pollutant removal, kilning, chemical processes).

15. Nitschke. G.S.; **The California Design: Concept Overview and Demonstration Outline**, Submitted to the Industrial Consortium for the Utilization of the Geopressured-Geothermal Resource, July 1, 1991.

    The earliest version of the CALDES concept; GPGT conversion for solar powered ROD only, i.e., does not include the CALDES GPGT TEOR. Discussion of economics, engineering calculations and estimating tools, and various systems configurations. Includes conceptual deployment of pipeline grid and fault stress control subsystems, with gas lift calculations, injection/production scenarios, etc.

16. GeothermEx, Inc.; **A Survey of Potential Geopressured Resource Areas in California: Final Report**, for the California Energy Commission, March 1993.

    The GPGT data for California are relatively sparse, however this report provides a good review and compilation of GPGT estimates, based on oil and gas well data, primarily using shale resistively logs as done for identifying Gulf Coast GPGT (but using different correlations, included in the source)[2]. The source estimates that

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[2] Author's note: It should be borne in mind that an oil & gas well driller/operator would view the onset of GPGT as a negative consequence (i.e., salt water flood of payzone, drilling and/or production problems, etc.) and hence avoid drilling GPGT zones (i.e., focus on horizons above GPGT zone) or use weight mud, drill through, and cement off GPGT encroachment. Therefore, solely using oil and gas drilling and well log data to assess GPGT resources may paint an overly conservative picture, as the true GPGT pays are seldom, if ever, intentionally encountered and/or flow tested (e.g., the measured temperature might be confounded with other zones, salinity not representative of cleaned-up reservoir flow, pressures not corrected for skin factors, etc.) Hence care must be taken when analyzing the data to ensure that correct weighting is given to particular well logs, e.g., data from wells which penetrate known GPGT horizons should be accorded strongest weighting for parameter

California GPGT reservoirs contain 10–100 scf/bbl GWR due to lower salinity (10,000–40,000 ppm versus ~100,000+ for the Gulf Coast). It is also noted in the source that, unlike Gulf Coast reservoirs, California reservoirs are subjected to tectonic stresses, which can vary markedly and have a significant impact on overpressure; the source notes that zones exhibiting superpressure (at or exceeding lithostatic) are likely due in part to tectonic stresses. The study identifies at least 70 geopressured and eight superpressured pools in California.

21. Seni, S.J. and Walter, T.G.; **Geothermal and Heavy-Oil Resources in Texas: Direct Use of Geothermal Fluids to Enhance Recovery of Heavy Oil**, Bureau of Economic Geology Geological Circular 93-3, University of Texas at Austin, 1993.
    The publication[3] consolidates the GPGT TEOR proposals from [17-20]. The source provides heavy oil production data for south Texas, including an excellent summary of the geology and reservoir characteristics (e.g., porosity, permeability, GWR, oil saturation, etc.). It is noted that typical heavy oil recovery efficiencies are 20%–35%, i.e., most of the oil is yet to be recovered; the feasibility of direct GPGT injection TEOR is discussed, noting that the high salinity GPGT brines may limit the swelling of interspersed smectite clays and therefore be advantageous for water-flood TEOR. The appendices include a listing of suitable abandoned gas wells in south Texas for reentry as GPGT producers.

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correlation, etc. While it is believed that such attention was taken with the Gulf Coast data, which conclusions are likewise supported by the DOE GPGT test wells, it is not evident that such consideration was accorded the subject assessment, nor are there any GPGT tests to corroborate the correlations. This is only noted here as a caution and not a criticism of the data or methods, and it is proposed that these estimates be utilized in the absence of actual test well data.

[3] The Bureau of Economic Geology, University of Texas at Austin, is an excellent resource for GPGT data. http://www.beg.utexas.edu/index.html (current Summer 2006)

22. Bebout, D.G., Loucks, R.G., and Gregory, A.R.; **Frio Sandstone Reservoirs in the Deep Subsurface Along the Texas Gulf Coast: Their Potential for Production of Geopressured-Geothermal Energy**, Bureau of Economic Geology, The University of Texas at Austin, Report of Investigation No.91, 1978.

    Detailed geologic data for the Frio GPGT fairways in south Texas, including data for the Chocolate Bayou basin in Brazoria County, Texas, the reservoir utilized by one of the DOE GPGT test wells, Pleasant Bayou No.2; salinities, projected flow rates, permeability, porosity, etc., are given.

23. Bebout, D.G., Weise, B.R., Gregory, A.R., and Edwards, M.B.; **Wilcox Sandstone Reservoirs in the Deep Subsurface Along the Texas Gulf Coast: Their Potential for Production of Geopressured-Geothermal Energy**, Bureau of Economic Geology, The University of Texas at Austin, Report of Investigation No.117, 1982.

    Same type of data as noted in [22] for the Wilcox GPGT fairways in south Texas.

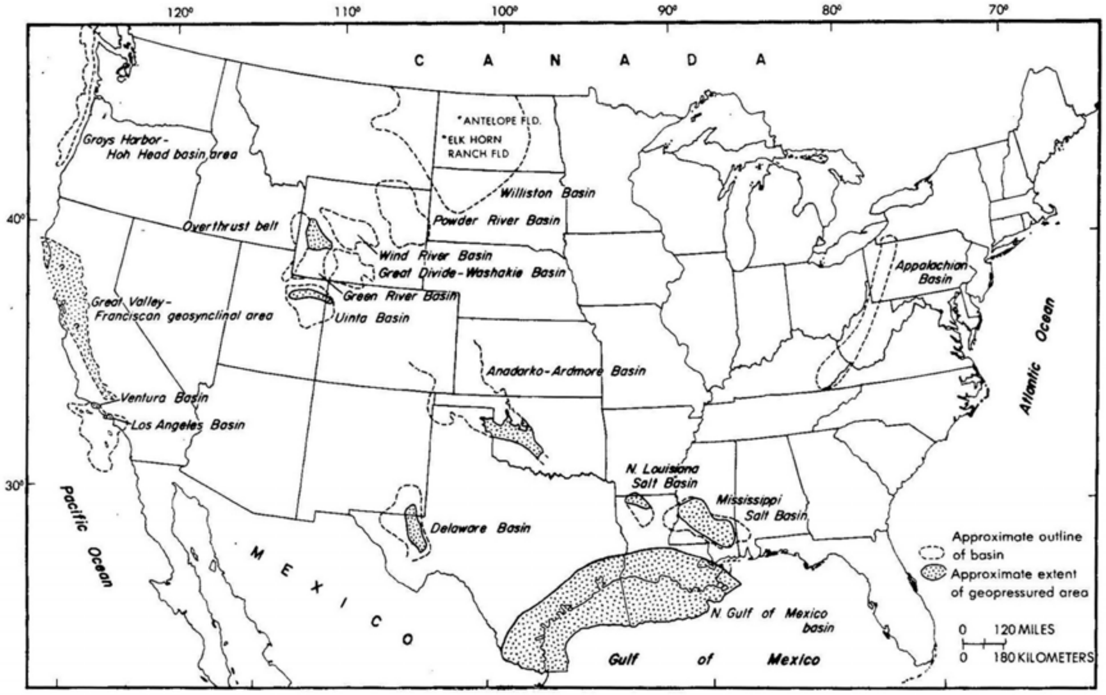

Figure 1.2-1: Geopressured-Geothermal Basins of the United States [4]

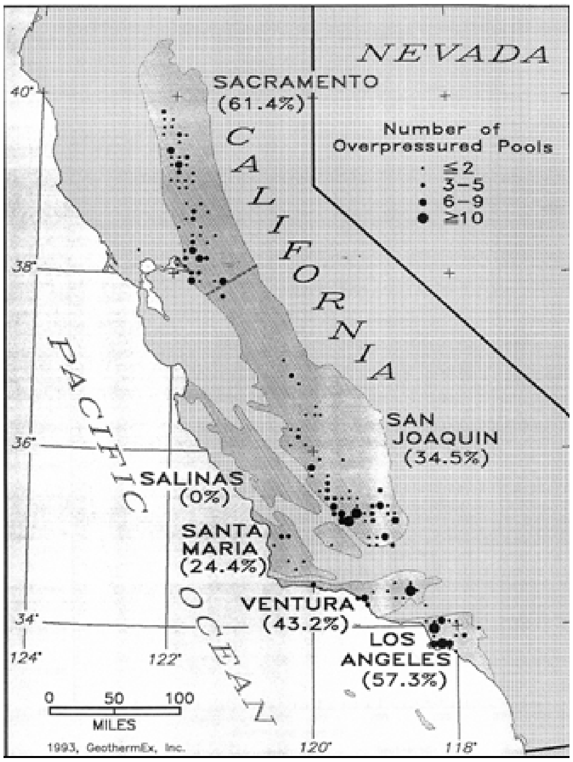

Figure 1.2-2: California Geopressured-Geothermal Basins [16]

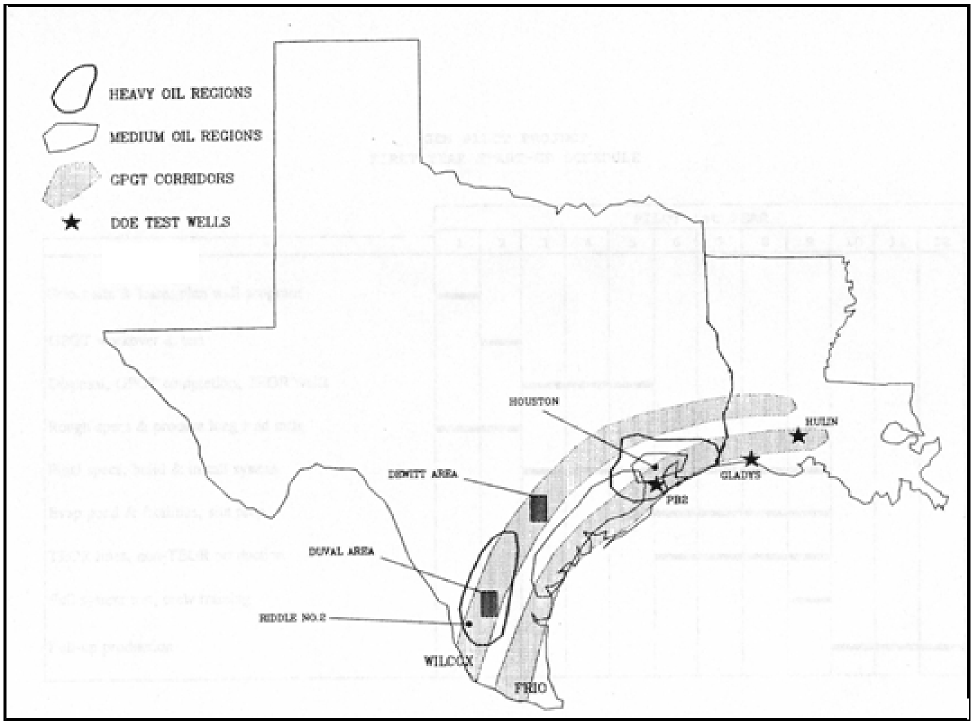

Figure 1.2-3: Gulf Coast GPGT Basins, Texas Medium-Heavy Oil Reservoirs [21]

Table 2.1.1-1: South Texas and Gulf Coast GPGT Characteristics [5,6,23]

GPGT Corridors/Formations→		**Wilcox**		**Frio**		**Miocene**
Regions/Wells→	**Case 5**	**DeWitt**	**Duval**	**PB2***	**Hulin***	**Gladys***
depth (ft)	*10,000*	12,000	12,000	16,465	21,546	15,831
flow rate (bpd)	*20,000*	20,000	10,000	20,000	15,000^	40,000
temperature (°F)	*300*	300	340	290	330	270
surface pressure (psi)	*3000*	3500	4000	3000	3500	2000
TDS (ppm)	*35,000*	60,000	30,000	127,000	195,000	95,000
GWR (scf/bbl)	*60*	80	50**	24	34	27
permeability (milidarcy)	*50*	50	~1	200	20	64
porosity (%)	*20*	20	15	19	18	24

*** DOE test well** **** Riddle No.2** **^ casing limited**