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GEOTHERMAL RESOURCES AT NAVAL PETROLEUM RESERVE-3 (NPR-3), WYOMING

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ABSTRACT

Naval Petroleum Reserve #3 is located at Teapot Dome field in Natrona County, Wyoming. The structure is a typical Laramide asymmetrical drape fold, bounded on the west by a basement-involved blind thrust fault. Commercial oil production occurred in the early 1920s for a brief period, followed by a long shut-in period. NPR-3 was opened to full field development in 1976. An abundance of relatively fresh hot water (180° - 200° F) is produced in association with Pennsylvanian Tensleep oil from depths of about 5000 ft. Water supply wells drilled to the underlying Mississippian Madison Limestone yielded rates exceeding 20 MBWPD flowing at formation temperatures projected to be about 230° F.

Artesian flow of the Teapot Dome geothermal system is caused by forced convection resulting from recharge in the Big Horn Range located 90 miles NW. The Big Horn recharge area represents a hydraulic head of about 8000 vertical ft above the NPR-3 surface. Pumping could increase rates by factors in the range of two to four. The geothermal gradient of 25° F per 1000 ft of depth at NPR-3 is 9% higher than the average for the Southern Powder River Basin. Fractured Precambrian basement granitic rocks at depths of 7000 ft and more may yield large volumes of water at temperatures exceeding 250° F. Gross power potential at NPR-3 from 130 MBWPD at 220° F would be 76 MW.

SUMMARY

NPR-3 is an operating oil field owned and operated by the U. S. Department of Energy, located near Casper, Wyoming. As primary oil production at NPR-3 declines, the Department of Energy is looking forward to providing a demonstration site for alternative energy technology applications in stripper oil field settings. NPR-3 is an excellent test site for wind and solar power generation projects. Geothermal energy, however, is the only asset that will provide a baseline load, which is critical in an oil field setting.

NPR-3 currently conducts surface disposal of about 40 MBWPD as 190° F waste water associated with oil production. The wasted heat on a daily basis is equivalent to gross 22 MW of electrical power, although only a small percentage is usable with current technology. RMOTC testing partners predict about 300 KW of usable power from the current co-produced throughput. Substantially more power could be produced from deeper formations using wells specifically designed for hot water production.

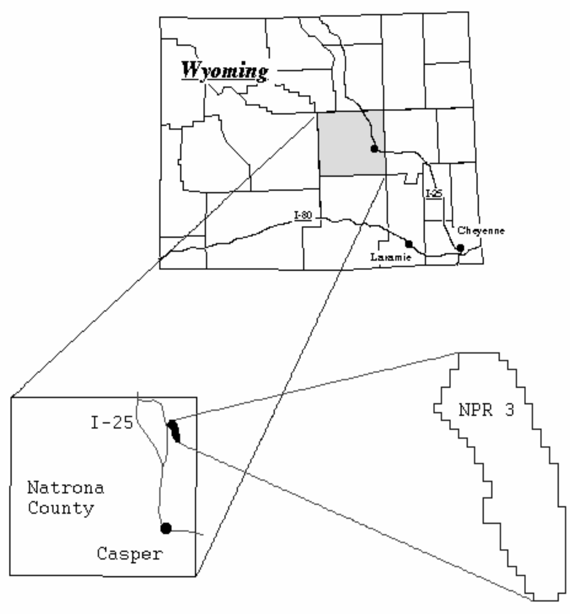

Figure 1. Location of NPR-3.

Introduction

NPR-3 is located at Teapot Dome field near Casper, Wyoming (Figure 1). The stripper oil field and RMOTC are owned by the U. S. Government and operated by the U. S. Department of Energy, under the Office of Fossil Energy. Cumulative production is

28 MMBO and 60 BCFG. Current production is 300-400 BOPD, from 700 active wells.

RMOTC was formed in 1994 to take advantage of unused or under-used facilities in a producing field. More than 175 projects of all scales have been successfully conducted at RMOTC since its inception. Though tests have been conducted over a wide variety of disciplines, RMOTC specializes in industry-funded projects that promise improved oil recovery and stripper field efficiencies.

As oil recovery costs continue to increase and primary production declines at NPR-3, the DOE is looking forward to a wide variety of cost-sharing partnerships involving stripper oil field-based alternative energy. These projects include wind, solar, and geothermal technologies. Of these energy sources, geothermal is the only asset that can provide base load electrical power.

Stratigraphy and structure of NPR-3

Teapot Dome is an asymmetrical anticline of Laramide age, and is a southern extension of the much more productive Salt Creek anticline (Curry, Jr., 1977). A blind eastward-dipping thrust fault bounds the relatively steep southwest flank. The structure formed on the western flank of the Powder River Basin (Figure 2).

Rocks of the Late Cretaceous Mesa Verde and Steele Shale Formations are exposed on the surface at NPR-3. Rocks at depth include Early Cretaceous, Late Jurassic, Triassic, Permian, Pennsylvanian, Mississippian, Cambrian, and Precambrian ages. Oil producing zones include the Shannon Sandstone of the Steele Shale Formation (±500 ft depth), fractured Steele Shale and Niobrara Formations (1000-2000 ft depth), Late Cretaceous Frontier Formation (±3000 ft depth), Early Cretaceous Dakota and Lakota Sandstone Formations (±3900 ft depth), and Pennsylvanian-Permian Tensleep Sandstone Formation (±5400 ft depth). Hot water for field

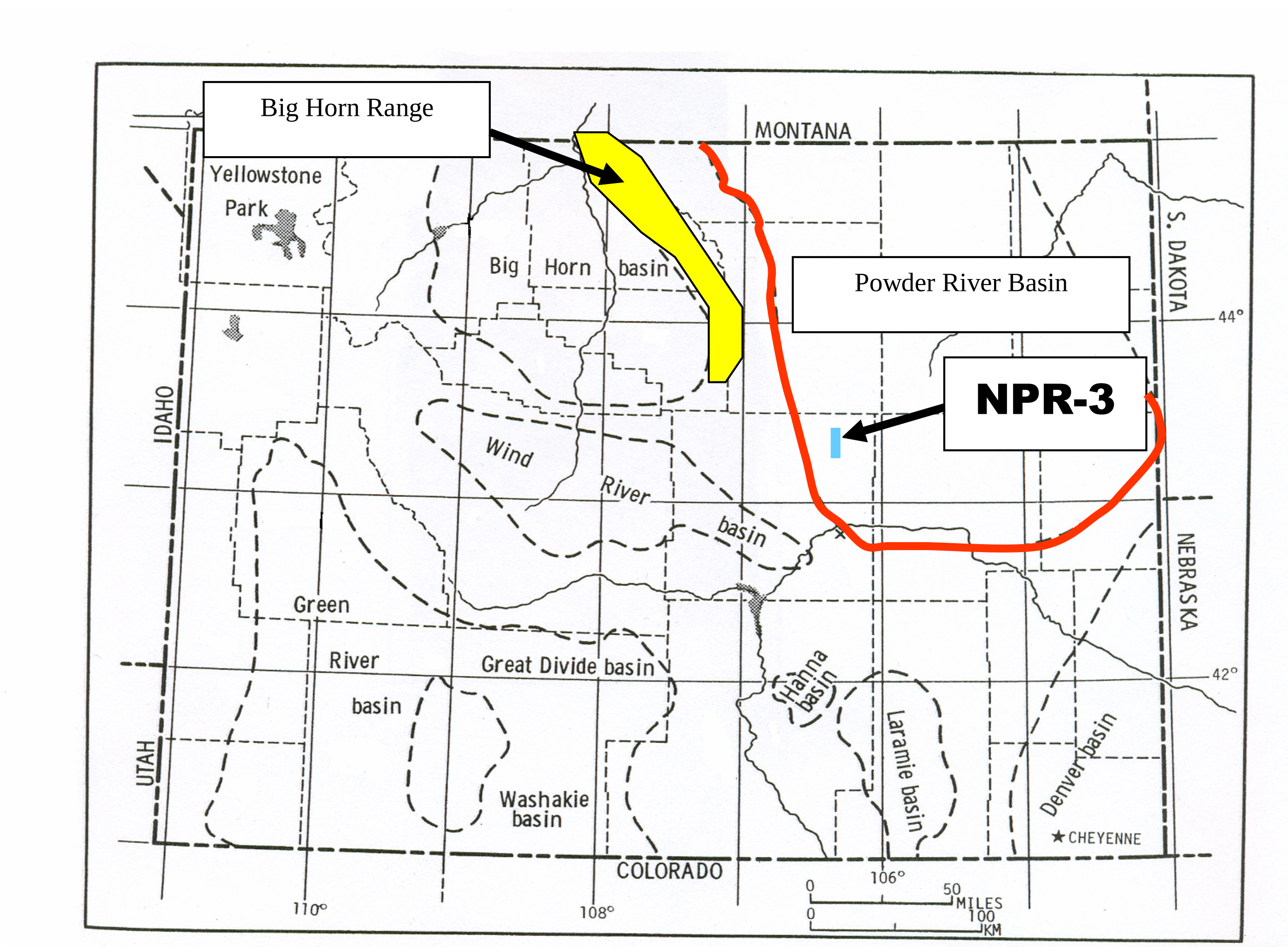

Figure 2. NPR-3 is located on the west flank of the Powder River Basin. The Big Horn recharge area is about 90 miles north of NPR-3.

purposes is produced from the Mississippian Madison Limestone Formation (±6000 ft depth). Basement rock is composed of Precambrian granitic rocks at depths of 7000 ft and greater.

The western flank of the NPR-3 structure dips at 30° - 40° SW, while the eastern flank dips at 4° - 10° NE. A series of basement-cored faults extend through the Early Cretaceous section, one of which forms a trap for the Tensleep oil reservoir. Late Miocene-age normal faults cross the anticline obliquely and control oil production in Cretaceous rocks. These faults likely sole out in the Triassic Chugwater Group.

ORIGINS OF GEOTHERMAL WATER AT NPR-3

Data from DOE's National Renewable Energy Laboratory (NREL) shows the Powder River Basin (including NPR-3) to be within an area of low temperature (<212°F) geothermal potential (Figure 3) (Green and Nix, 2006). NREL claims such low temperatures are suitable for direct heating only. Modern binary power plants, however, have shown capabilities at temperatures as low as 165° F, and would have great potential at NPR-3.

Research by the Wyoming Geological Survey indicates the average geothermal temperature gradient in the Powder River Basin is 22° F per 1000 ft of depth (Buelow and others, 1986). Temperature data from the Tensleep Formation (203° F) suggests a temperature gradient of 25° F per 1000 ft at NPR-3. By extrapolation, the Mississippian Madison Limestone would be 230° F, with basement rocks exceeding 250° F. The unusually high temperature gradient at NPR-3 is due to forced convection heating and circulation from relatively shallow hot water sourced from the Big Horn Mountain Range located

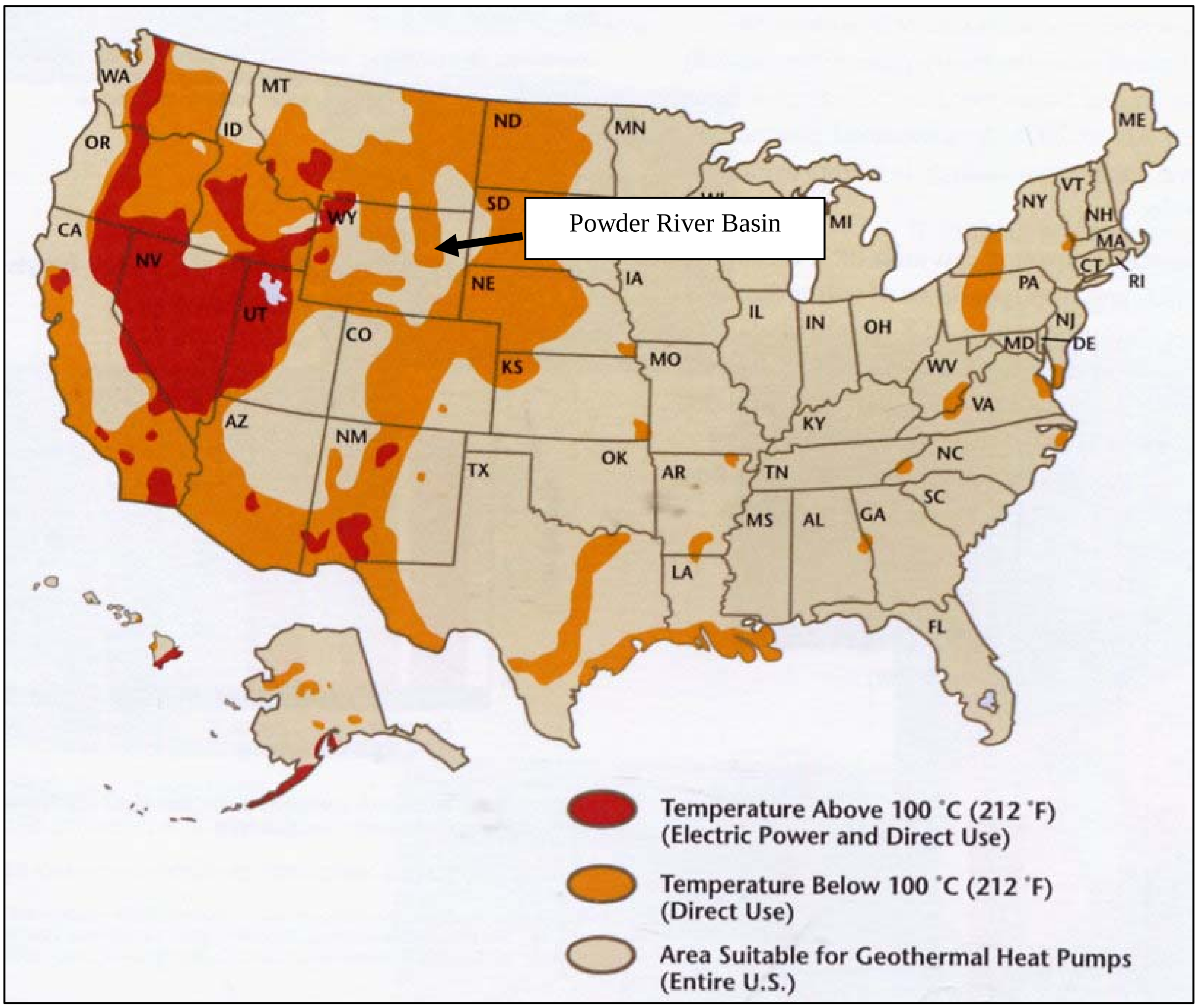

Figure 3. Geothermal heat flow map of the U. S. The Powder River Basin (including NPR-3) is shown to have low temperature geothermal potential. Although the area is described as being suitable for direct use only, modern binary power generating units have demonstrated success with temperatures as low as 165° F. From Green and Nix, 2006.

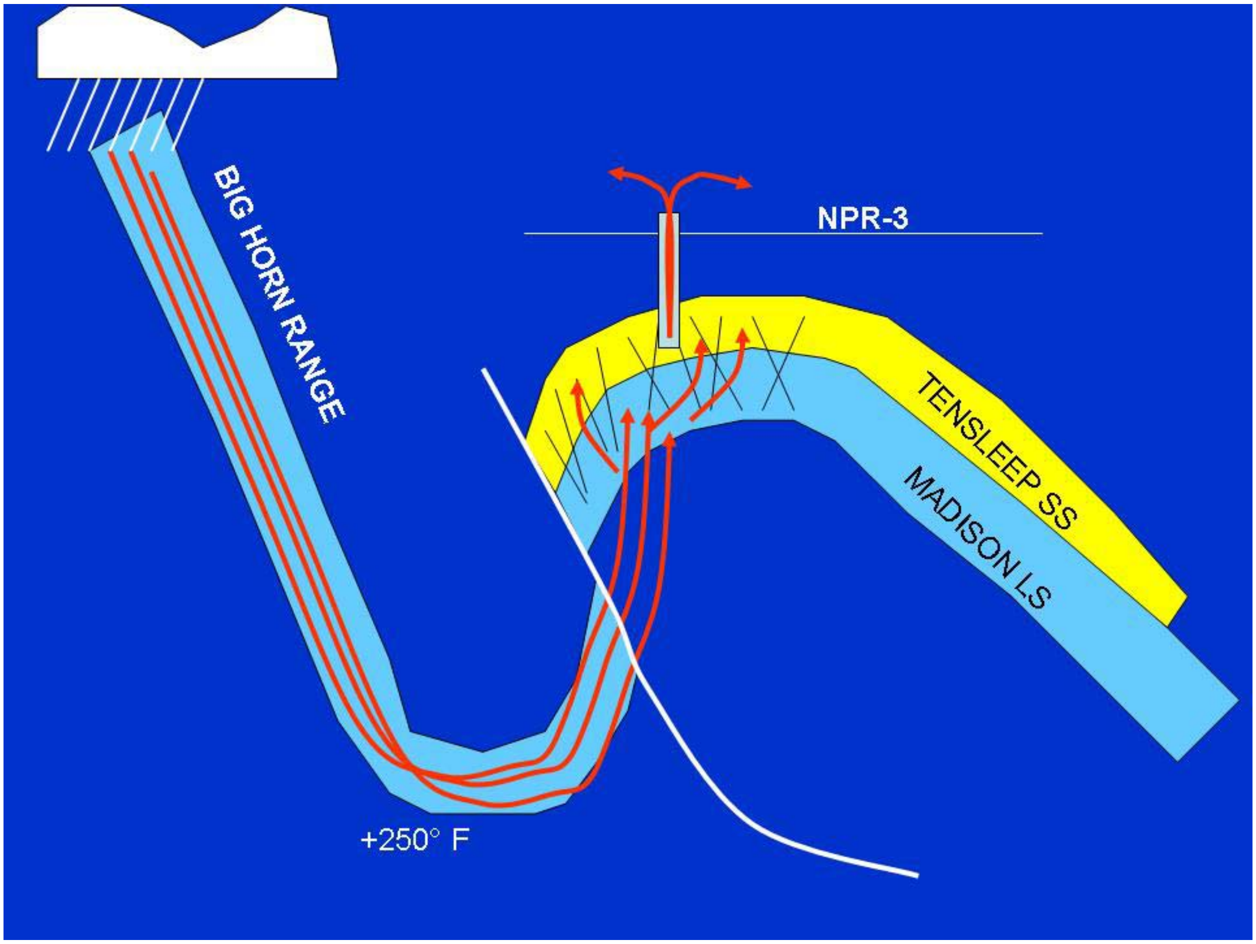

Figure 4. Generalized diagram showing the recharge pathway between the Bighorn Mountain Range (90 miles NW of NPR-3) and NPR-3. Recharge of shallow rocks is by forced convective circulation through fractures associated with Laramide style folding.

about 90 miles NW of the field (Figures 2 and 4).

NPR-3 GEOTHERMAL ASSETS AND INFRASTRUCTURE

Hot water produced with oil is currently being discharged into Little Teapot Creek (Figure 5). The total discharge rate is typically 40 MBWPD. The rate can vary depending on the number of wells on production. Most water comes from seven Tensleep wells, with rates ranging between 2000 and 5000 BWPD per well. Although NPR-3 Tensleep wells exhibit artesian flow, submersible pumps are required to obtain fluid flow volumes necessary for economic oil production rates. Fluid temperature at the Tensleep manifold output is 190° F. Calculations by United Technologies Corporation and RMOTC engineers calculate an equivalent daily power of 22 MW gross being dispersed in NPR-3's water disposal process. Despite what appears to be a high loss of energy, only a small portion of this heat can realistically be converted into electrical power.

Several geothermal production companies have expressed interest in demonstration projects at NPR-3 using the disposal throughput as a way to recover heat from oil field waste water. Project proposals include the application of binary power plant technology, and using working fluids such as R-134A refrigerant or isobutene. The concept of capturing waste heat from oil field water is being actively researched and promoted in the Gulf Coast area through produced and geopressured water (McKenna and others, 2005). Here, huge volumes of hot produced water are being disposed of in the subsurface, and electrical costs are high (McKenna and others, 2005). Oil field produced water (typically <212° F) is defined as low temperature for the purposes of geothermal power production (Green and Nix, 2006). New technologies involving binary power units, such as at Chena Hot Springs, Alaska, have demonstrated the capability of economic power generation from low temperature sources (Green and Nix, 2006).

Figure 5. Discharge of produced waste water at NPR-3. The discharge rates are typically 40 MBWPD. Tensleep manifold outlet temperature is 190° F. The warm water has created a unique habitat for plants and animals in the Little Teapot Creek drainage.

Other sources of hot water at NPR-3 include two water supply wells completed in the Madison Limestone Formation. These wells, 17-WX-21 and 75-WX-3 (Figure 6), have artesian flow, and supply hot water for field use. The wells have seven-inch casing cemented through the Tensleep, with open hole through the Madison Limestone Formation. Well 17-WX-21 was tested on a line restricted by valves with flow at 20 MBWPD. An NPR-3 production manager predicted open (un-restricted) flow rates of 35 MBWPD for 17-WX-21, and 10 MBWPD for 57-WX-3. The manager also suggested that Madison water production rates could be increased by factors of between two and four if submersible pumps were used. If all available wells were optimized for hot water production, the power potential at NPR-3 could exceed 76 MW. Wells designed specifically for hot water production from the Madison and deeper formations (i.e., Cambrian sandstones) could provide enough hot water for significantly more electrical power.

A major engineering issue facing oil field geothermal power generation is the availability of cooling fluids for the condensation phase of the working fluid in a binary system. One advantage NPR-3 has over Gulf Coast oil fields is a much lower average seasonal ambient temperature. At NPR-3, air cooling of the working fluid would be feasible for seven to nine months of the year. In the summer, additional cooling may be required, possibly by circulating water through unused buried pipelines throughout NPR-3.

Another possible engineering issue involved with oil field waste water is that of scale buildup in lines, valves, and vessels where temperature and pressure drops cause precipitation of dissolved solids. The chemistries of Tensleep and Madison Formation waters are shown in Figures 7 and 8. Note that Madison water has a TDS of 6900 PPM, more than twice that of Tensleep water (3200 PPM). Madison water also exhibits sharply higher sodium and bicarbonate levels than Tensleep water.

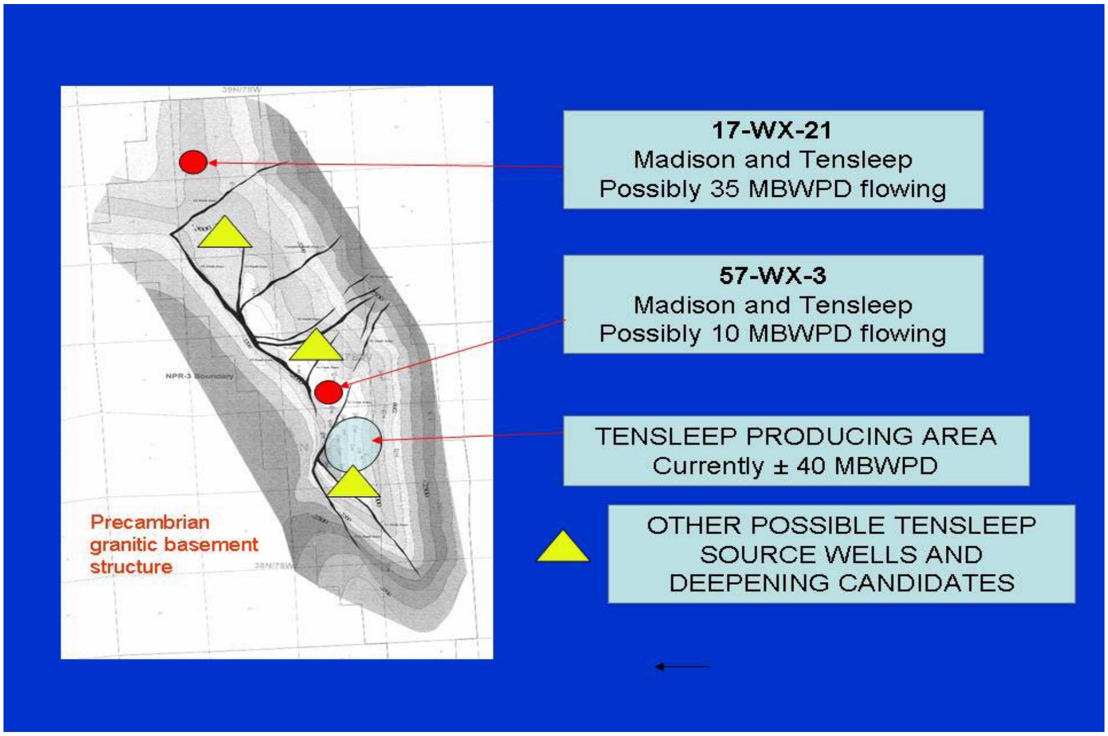

Figure 6. Basement time-structure map interpreted from 3D seismic data. Shown are locations of hot water sources at NPR-3, including the Tensleep producing area, available Tensleep wells for deepening, and two Madison wells currently used for field hot water supply.

NPR-3 production personnel have reported minor calcium carbonate scale buildup in some Tensleep production facilities, valves, and gathering lines. There has been, however, no indication that scale from Tensleep water has caused significant oil field production problems.

At the low temperature geothermal power generation facility at Chena Hot Springs in Alaska, scale is controlled by periodic treatments with scale inhibitors (Bernie Karl, Chena Hot Springs Resort, personal communication, 2006). A demonstration geothermal power project at RMOTC can be specifically designed to quantify scale issues. In response, different types of scale remediation technologies can be applied and evaluated.

NPR-3 TENSLEEP WATER	NPDES #2 Discharge (Tensleep Only)		
Cations	mg/L	meq/L	Other
Potassium	90.3	2.31	
Sodium	642	27.9	
Calcium	268	13.4	
Magnesium	34.2	2.81	
Iron-Total	0.55	0.02	
Anions			
Sulfate	887	18.5	
Chloride	870	24.5	
Carbonate	<1	0	
Bicarbonate	148	2.43	
Hydroxide			
Nitrogen, Ammonia as N			
Nitrogen, Nitrate + Nitrite as N			
Solids			
TDS @180C	3220		
Total Solids, NaCl Equivalents	2200		
Chloride as NaCl	1430		
NaCl % of TDS			42.1
Sample Conditions			
pH (s.u.)			7.93
Ionic Strength (u)			268
Accuracy (Sigma)			-1.23
Other Properties			
Calcium Hardness asCaCO3	669		
Magnesium Hardness as CaCO3	141		
Total Hardness as CaCO3	810		
Sodium Adsorption Ratio	9.79		
Specific Gravity	1		
Conductivity (uhmo/cm)			4740
Resistivity, 68F (Ohm meter)			2.11
Probabled Mineral Residue, Dry			
NaCl	1360		
CaSO4			
Na2SO4	389		
Ca(HCO3)2	197		
MgSO4	169		
KCl	98.7		
Organics			
O&G (Total Recoverable)	2.2		

Figure.7. Chemistry report for produced water from the Tensleep Formation at 180° F.

NALCO

REPORT OF WATER ANALYSIS

Company	Fenix & Scisson, Inc. Naval Petroleum Reserve #3 Casper, WY	Date	12/22/80
		Analysis No.	80RD109B
		Sampling Date	12/2/80
		Date Sample Rec'd.	12/2/80

Sample Marked Madison Source Water; 2nd Wall Creek Waterflood Pump St.#1

DISSOLVED SOLIDS	mg/l	meq/l	RESULTS AS COMPOUNDS	mg/l
Cations				
Sodium, Na (Calc.)	1,758	76.44	as NaCl	
Calcium, Ca	316	15.80	as $CaCO_3$	790
Magnesium, Mg	51	4.20	as $CaCO_3$	210
Barium, Ba	0	0	as $BaSO_4$	0
Cations Total	2,125	96.44		
Anions				
Chloride, Cl	1,032	29.10	as NaCl	1,700
Sulfate, SO_4	1,352	28.12	as Na_2SO_4	2,000
Carbonate, CO_3	0	0	as $CaCO_3$	0
Bicarbonate, HCO_3	2,391	39.22	as $CaCO_3$	1,960
Anions Total	4,775	96.44		
Total Dissolved Solids (Calc.)	6,900			
Total Iron, Fe	19.5		as Fe	19.5
Acidity to Phenolphthalein, CO_2	145		as $CaCO_3$	330
Dissolved Oxygen	0.1			
Sulfide, as H_2S	12.5			

OTHER PROPERTIES		$CaCO_3$ STABILITY INDEX	
pH	6.9	@ 70° F.	+ 0.73
Specific Gravity	1.004	@ 120° F.	+ 1.35
Turbidity (JTU)	--	@ 160° F.	+ 1.81
Temperature	159°F	Method of Stiff & Davis	

Remarks:
Oxygen content was 0.1 ppm at the source well (17Wx21) and in the water-flood plant at the pump suction. Sulfate reuding bacteria were 10-100 colonies/ml.

cc: M. Harker

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Figure 8. *Chemistry report for water from the Madison Formation at 159° F. These data show Madison water to have a TDS of 6900 PPM, which is more than twice that of Tensleep water (Figure 7).*

FUTURE GEOTHERMAL DEVELOPMENT CONCEPTS AT NPR-3

The Madison reservoir is considered to be an infinite pressure sink, and a huge reservoir of hot water. Reservoir pressure in the Tensleep Formation, thought by NPR-3 engineers to be in pressure communication with the Madison, has remained unchanged over a 30-year period of Tensleep production. The Madison hot water resource would be best exploited with large-diameter wells specifically designed to produce high volumes of water.

Geothermal water sources deeper than the Madison include Cambrian sandstones and fractured basement granite. A recent RMOTC project proposal put forth the concept of artificially fracturing granitic basement rocks, and circulating water within a pattern of producing and injection wells. The project proposed large diameter wells drilled to depths of 8,000 ft- 12,000 ft or more. Temperatures would exceed 300° F, and specialized drilling and completion equipment would be required. The cost of drilling and completing these deep wells in granite, combined with the necessary frac jobs, would be exceedingly large. Large volumes of geothermal water will require similarly large volumes of cooling water. Sources for cooling water on NPR-3 will become problematic as power generation capacity increases. The field has many miles of unused pipelines that could be used for cooling loops, using the low ambient temperature of the soil as a heat sink.

Wells completed in the Cambrian sandstone may prove to be the most productive. Geothermal water moving through primary porosity and permeability of a sandstone matrix has more efficient heat transfer than fractured limestone or granite with only secondary permeability and porosity. If ever fully developed, these deep hot water reservoirs could make RMOTC a significant geothermal power supplier in central Wyoming.

After passing through the power unit heat exchangers, geothermal water can be circulated for direct heating of NPR-3 buildings and for improved oil recovery projects in depleted oil reservoirs at NPR-3. Ultimately, used geothermal water will likely be disposed of in subsurface reservoir rocks or on the surface. Previously unknown and untested high-quality sandstones such as the eolian dune field of the Jurassic Morrison Formation discovered by 3D seismic interpretation (Milliken and Koepsell, 2002) may also provide opportunities for subsurface disposal.

CONCLUSIONS AND RECOMMENDATIONS

The Rocky Mountain Oilfield Testing Center has been recognized by the geothermal power industry as a potential world class demonstration site for the recovery of waste heat from co-produced oil field water. At NPR-3, an estimated 22 MW of heat energy is being wasted on a daily basis. At 3 KW per private household, that's enough energy to supply 7000 homes in Wyoming. Although only a small percentage of this wasted energy can be efficiently recovered with current technology, it underscores the opportunities for development of alternative energy throughout the petroleum industry from similar heat sources that are being otherwise wasted.

A staged plan for geothermal power testing and demonstration projects at NPR-3 could include:

- The use of existing produced water that is currently being disposed of.
- Bringing existing Madison and idle Tensleep wells on production to provide additional hot water.
- In a test well, deliverability tests in the Madison limestone, Cambrian sandstones, and Precambrian fractured granite.
- The drilling of additional wells along basement-cored fault zones for the sole purpose of hot water production in highly fractured rocks.
- The installation of several power plants with individual capacities of 1 MW or more.
- The utilization of other alternative energy sources, such as brine pools, for heat augmentation.

ABBREVIATIONS

BCFG	Billion cubic feet of gas
BO	Bbls of oil (42 U.S. gallons/bbl)
BOPD	Bbls of oil per day (42 U.S. gallons/bbl)
BWPD	Bbls of water per day (42 U.S. gallons/bbl)
°F	Temperature in Fahrenheit
KW	Kilowatt (one thousand watts) of electrical power
M	A factor of 1000
MW	Megawatt (one million watts) of electrical power
PPM	Parts per million
TDS	Total dissolved solids

CONVERSION FACTORS

°C = 0.56(°F - 32°)

10 MBWPD ≈ 300 Gallons Per Minute

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