Chapter 8

Other Strategic Considerations for Geothermal in Texas

Space and Defense

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> ***The interdisciplinary synergies between space, defense, and subsurface energy production are key to Texas leading the future of geothermal.***

I. Introduction

Geothermal, with its clean, baseload energy, generated using the abundant heat in Earth's crust, has been an inconsequential part of the energy mix of the United States and the world for more than one hundred years, as has been detailed in other Chapters of this Report. However, as described in this Report, recent developments, many in Texas, have positioned geothermal for quick growth. Advances in exploration, drilling and well construction, and production technologies are poised to revolutionize the accessibility of geothermal energy. These developments will break the geographical constraints that have held geothermal back for a century, enabling the next generation of geothermal development, anywhere demand for energy exists.

Geothermal energy can make a significant impact in both Texas and beyond, as a source of clean energy that will become increasingly cost competitive with wind and solar as we drill deeper and hotter wells. At temperatures exceeding 200 °C (392 °C), where the potential for cost parity with other renewables is in line of sight, well longevity and integrity, and energy conversion efficiency, will be dependent on the use of the toughest, temperature hardened materials available. The aerospace industry and its developments in extreme temperature materials holds the potential to increase the market size and deployment potential of geothermal, positioning it as a highly scalable, primary, baseload alternative energy source. Technologies developed at the National Space

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and Aeronautics Administration ("NASA") and the U.S. Department of Defense ("DOD") may benefit the industry greatly as we look to realize the potential of this large and ubiquitous energy resource beneath our feet.

In this Chapter, we describe how defense and space technologies may both benefit from, and provide benefit to, the growth and scale of geothermal energy. We also highlight how geothermal technologies may lead to new developments and capabilities in aerospace and space exploration, and how materials from aerospace can be adapted to improve well construction and, ultimately, energy production efficiency in geothermal systems.

II. Defense

DOD and critical infrastructure (such as water supply and hospitals) have a critical need for safe, secure, reliable power. Unfortunately, civilian power grids are notable for their susceptibility to deliberate attacks, the effects of aging infrastructure, and natural disasters (Narayanan, et al., 2020). Advances in technology have increased the susceptibility of power grids world-wide to disruption. Cyberattacks on facilities are an increasing threat as power systems are automated, but it is not just high-tech attacks that present problems. There have been many examples around the world where terrorist groups use physical attacks on power infrastructure to cause blackouts (NRC, 2012, NPR, 2022).

While the incidence of these attacks in the United States has been lower than other less stable regions, in 2013, a sophisticated physical attack on a California transmission substation awakened the power industry to its vulnerability from close-in threats (Smith, 2014). In 2022, an attack on substations in North Carolina shut down power to more than 10,000 people (Morris, 2022), and another such incident followed months later in Washington State on Christmas Day (Domonoske, 2023). For these serious liabilities, the use of commercial power grids for defense and critical infrastructure represents a massive, systemic, and strategic vulnerability in Texas, the United States, and the world.

A. Geothermal and U.S. National Security

Constructing geothermal power plants "inside the wire" at DOD facilities, using proven and emerging technologies, can provide a real solution to their dependence on civil power grids with a cost-effective, resilient, clean energy that is less vulnerable to attack and natural disaster. Unlike Conventional Hydrothermal Systems, next generation scalable geothermal concepts like Advanced Geothermal Systems ("AGS"), Engineered Geothermal Systems ("EGS"), and Multi-System Hybrids, are likely to be deployed to meet demand at DOD facilities, due to their ability to be developed anywhere. These next generation geothermal plants possess significant advantages over commercial power from off-site or other on-site solutions, such as:

- **Physical Security:** Location inside the fence-line is relatively secure, and includes the ability to easily ramp-up security as needed under threat warning;
- **Baseload Energy Supply**: Geothermal power is "always on" and can be load following;
- **Self-Contained**: Unlike conventional standby generators, no outside resources for resupply are needed, with decades-long operational lifetimes, and relatively low operations and maintenance costs;
- **Scalable**: If more power is needed, in many cases, more wells can be drilled;
- **Safe**: No combustion or radioactivity is involved in operation;
- **Green, Clean, and Renewable**: AGS and Hybrid Geothermal Systems are expected to emit no pollution/greenhouse gasses, and have the potential to be carbon-negative through sequestration of additional carbon in the heat-exchange path; and
- **Electro-Magnetic Pulse ("EMP") Resiliency**: Extremely short electricity transmission distance to load (co-location) greatly reduces vulnerability to EMP induced power surges.

Note that while this Section is focused on Defense, most of these advantages would apply to critical civilian infrastructure as well. Military base applications will be the use case addressed here for simplicity, and because DOD geothermal development has experienced some notable steps forward in Texas, with at least one project, Ellington Field, funded to the detailed design phase at this time (Richter, 2021), with additional projects in the works.

DOD is an ideal early adopter of next generation geothermal technologies. While conventional hydrothermal geothermal is a relatively mature technology, the next generation, scalable geothermal paradigm is not. It

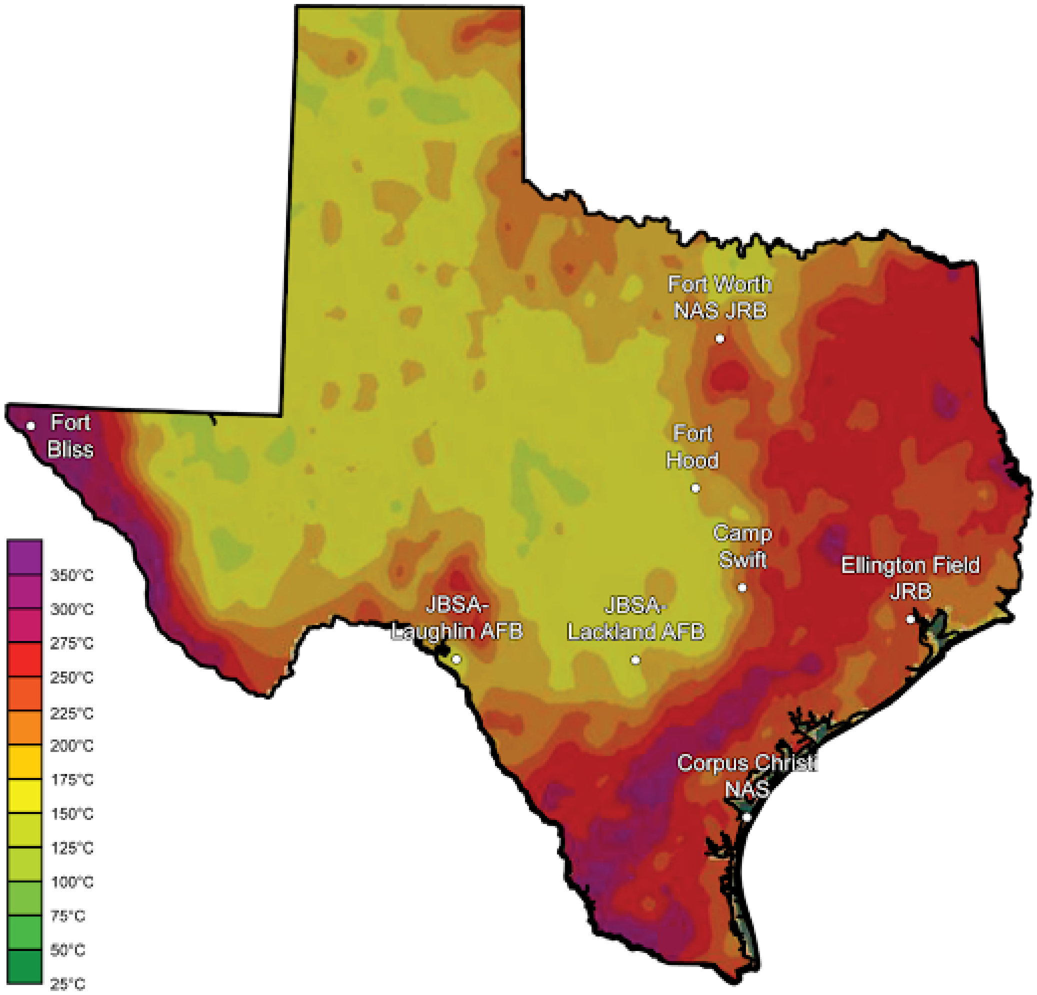

Figure 8.1. Selected military facilities overlaid with temperatures at 5.9 miles (9.5 kilometers). Multiple major DOD installations are in attractive geothermal areas in coastal, East, and West Texas. *Source: Adapted from Blackwell, et al., 2006.*

is a set of emergent technologies, all of which are in the prototyping and pilot stage. This suggests an opening for DOD to lead the way because: 1) DOD can and does, prioritize operational effectiveness over cost effectiveness when it is mission critical, 2) secure, resilient power supply is mission critical to everything DOD does; and 3) the military is accustomed to working with and furthering cutting-edge technologies.

But by themselves, these two factors will not be sufficient to sustain DOD's attention. What is required is scalability. DOD has been using and managing a Conventional Hydrothermal System in the western United States for decades. This is accomplished through the Navy Geothermal Program Office, which technically has led for all DOD geothermal projects. However, this program, like the current geothermal industry, is focused on conventional hydrothermal geothermal, and has experienced very little growth over the years.

Currently, DOD is being approached at many levels in a scattered and uncoordinated fashion by companies pitching geothermal projects, including power production projects and Direct Use geothermal for building heating and cooling. Next generation, scalable geothermal concepts have the potential to be applied across almost all of the Earth's surface, breaking free of the current very tight geographical restrictions that are often limiting factors for Conventional Hydrothermal Systems. The potential to power every military installation, not only in the United States, but globally, provides the scalability that will make it worth DOD's while to invest time and money into the next generation geothermal space.

Figure 8.2. The U.S. Air Force has described geothermal as a first priority energy solution for base energy innovation (OEA, 2022), and a critical solution to address energy reliability and resiliency at military installations around the world. *Source: Stock photography.*

Given DOD's increasing interest in next generation geothermal concepts, the next question that arises is the preferred location of geothermal deployments on military bases. As DOD is an ideal early adopter of next generation geothermal technologies, Texas is an ideal sandbox in which to develop and pilot them. Texas is the world's energy epicenter, and has led multiple energy revolutions. It has the right combination of industry, research institutions, startups, eager off-takers, a favorable subsurface policy and regulatory environment, and geothermal resources to lead once again in this next generation of geothermal development and deployment. Multiple DOD geothermal projects are brewing, from concept to funded projects, that implicate or will be located in the State of Texas. The project that has advanced furthest is an Air Force Work Project ("AFWERX") funded effort to build a three megawatt geothermal power plant on Ellington Air Force Base ("Ellington") on the Southside of Houston, previously mentioned in this Chapter. This site was selected as a first proof of concept/commercial project for multiple reasons:

- **A High Quality Geothermal Resource**: The project is in a zone of elevated temperatures and pressures, the Gulf Geopressure Zone (see Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development), where only moderate drilling depths are needed to reach 150 to 200 °C (302 to 392 °F) temperatures;
- **A Base of Reasonable Size**: Ellington is a relatively small base, with low power needs suitable for a pilot project;
- **Room for the Rig**: There is ample open space for a drilling rig onsite (though little space is actually required);
- **A Need for Resilience**: High-priority, no-fail missions take place on the base;
- **Fast Decision-Making**: As an Air National Guard Base, Ellington has a relatively "flat" chain of command, resulting in quicker decision making; and
- **Houston as an Epicenter**: A successful project in Houston, the epicenter of the petroleum industry, will gain traction amongst ecosystem partners in a way that a project in the western United States would not.

The project is currently nearing completion of Phase 2, the detailed design phase (Cariaga, 2021).

B. The Way Forward with Defense

In the winter of 2021, as a result of Winter Storm Uri, the Texas power grid experienced a massive failure. Exposed by this grid collapse were mis-prioritizations of critical infrastructure power needs. A revision of critical infrastructure needs, cross-linked with geothermal potential is a clear first step to building a strategy for maximum and optimized geothermal deployment in Texas for DOD. Parallel, but distinct, would be the same effort for the dozens of large and small military installations across the State of Texas. As described in Chapter 4, The Texas Geothermal Resource: Regions and Geologies Ripe for Development of this Report, there is also a need for methodical data collection in promising, but under-explored (i.e., non-oil and gas producing) areas. Finally, favorable policy and incentives at the Federal, State and local level have been critical to the success of previous emergent industries, and will be so for geothermal as well.

It is important to remember that although Texas is widely known as an oil and gas State, it easily jumped into the lead as the number one wind energy producer in the United States via a relatively small shift in State policy (Galbraith and Price, 2013). These policies are considered in further detail in Chapter 11, Geothermal, The Texas Grid, and Economic Considerations and Chapter 12, Policy, Advocacy, and Regulatory Considerations in Texas of this Report.

Following through on the DOD critical infrastructure potential of geothermal power in Texas would be a win-win for DOD, the State, and its budding geothermal industry. It will position Texas and its industries as the world leader in a major emerging and wide-open energy field, and improve civil and national security. A comprehensive State Department and DOD strategy for deploying geothermal power for military and critical infrastructure is clearly called for, starting with prioritization of the possible projects.

III. Space

Texas is endowed with the history of a robust and thriving energy industry, but as discussed in Chapter 9, The Texas Startup and Innovation Ecosystem of this Report, Texas has also been fertile ground for some of the world's great technological innovations and discoveries in nanotechnology, materials science, geoscience, and industrial engineering. Texan inventions like the tricone drill bit, the microchip, 3-D printing, and the lithium-ion battery are all innovations that have had a profound impact on business, society, and the way we live and interact. They are the products of a uniquely Texan spirit for exploration and discovery, which has pushed the limits of human achievement for over a century.

With the Johnson Space Center, SpaceX, Blue Origin, and the Houston Spaceport within its borders, technology transfer from aerospace to the burgeoning Texan geothermal industry is a handshake away. While commercial space efforts are making significant strides in many of the research and development areas discussed below, we will focus for the purpose of this Chapter on technology flow to and from NASA, and the impact that technology transfer in this area may have on the trajectory of geothermal in Texas.

A. The Transfer of Materials From Aerospace to Geothermal

Carbon composites are widely used in high performance systems. Just about all modern aircraft contain some amount of composite material currently. The light weight, formability, and high strength of composites make them excellent materials for aerospace applications (Zhang & Zhao, 2016). These materials also have potential in geothermal well construction, particularly in highly corrosive environments. However, temperature tolerances limit use in geothermal applications. Composites are currently being deployed in the oil and gas industry in a number of different tool applications. They are especially useful for corrosion protection when dealing with a combination of high-temperature and corrosive well fluids. The composites used in oil and gas, however, currently have temperature limitations that restrict their use in the industry (Badeghaish, et al., 2019). Thus, technology transfer from NASA's thermal protection systems could spur a new generation of composites that would enhance how and where we can develop geothermal systems.

Figure 8.3. Artist rendering of an atmosphere reentry vehicle on descent. Skin temperatures on reentry vehicles as well as hypersonic aircraft can reach well over a thousand degrees. *Source: NASA, 2022.*

Developments in high-temperature materials at NASA have been a cornerstone for space exploration since before the Apollo moon landings. This robust materials development history has led to a spectrum of exotic materials for the thermal protection of spacecraft. In Apollo, the Thermal Protection System ("TPS") was an ablative resinous material in a fiberglass honeycomb matrix (Natali, et al., 2017). It was designed to protect the Saturn V command module as the spacecraft re-entered the atmosphere, reaching speeds up to 25,000 miles per hour (40,000 kilometers per hour). Development in TPS changed course slightly with the space shuttle program, where ceramic tiles were an essential component to the TPS.

More recently, the Parker Solar Probe, launched in 2018, boasts a non-ablative foamed carbon heat shield designed to withstand extraordinary extremes in temperature and heat (Congdon, 2021). The Parker spacecraft is actively studying the sun and solar flares, and is designed for temperatures higher than 1,200 °C (2,192 °F). NASA's tradition of excellence, and breadth in high-temperature materials continues into future missions, as non-ablative thermal protection systems and high-temperature power systems are being designed for NASA's next missions to the extremely inhospitable environment of Venus.

Tough conditions are run of the mill in geothermal, where drilling temperatures can exceed 300 °C (572 °F), and pressures can easily exceed 5,000 pounds per square inch. Additionally, the extreme vibration loads of launch and reentry are roughly comparable to the downhole environment, both during drilling and production. Thus, aerospace materials meeting these performance metrics could be game-changers in geothermal systems where very high-temperatures, in combination with corrosive fluids, challenge the best materials available.

Beyond the composite materials that are already in use in aircraft and spacecraft are 3-D printed composites. There are enormous performance benefits that are being realized through multi-material 3-D printing. The research arm of NASA has been developing methods in 3-D printed geomaterials in a process called In-Situ Resource Utilization ("ISRU"). These technologies, along with those developed in the oil and gas industry in 3-D printing cements and cement composites, can be used to develop a new generation of Thermal Protection Systems, both for the aerospace and geothermal industries.

Figure 8.4. NASA's VERITAS and DAVINCI's missions will develop the vehicles, materials and instrumentation for missions to Venus in the 2028-2030 timeframe with a total budget of $1 billion. The average surface temperature of Venus is 465 °C (869 °F). *Source: NASA, 2008.*

B. Heat Management in Space

Spacecraft can be exposed to massive swings in temperature, and extremes in radiation energy and flux. Thermal management is critical to the engineering of space faring vehicles. In space vehicles, temperature regulation depends on phase-transfer fluids, thermoelectrics, and the intentional inclusion of reflective, absorptive, and emissive materials. The development of these thermal management materials has evolved over decades at NASA, and the opportunity is ripe for technology transfer to the geothermal industry.

NASA's VERITAS and DAVINCI+ missions will launch between 2028 and 2030 to study the surface and atmosphere of Venus. The surface temperature of Venus averages about 465 °C (869 °F), with an atmospheric pressure roughly 92 times that on Earth. High temperature electronics developed at NASA have been designed for 600 °C (1,112 °F), with silicon-carbide based transistors at NASA's Glenn Research Center (Francis, et al., 2018). Technologies in high-temperature materials and electronics will be developed further for the Venus landers and probes, to tackle the extreme environmental conditions in the atmosphere of Venus.

Thermoelectrics are materials that are improving rapidly and could significantly benefit geothermal energy systems, in tuning the systems for maximum efficiency (Glavin, 2020). These materials take a temperature differential and turn it into electrical energy. By scavenging waste heat in geothermal power generators, thermoelectrics offer the possibility of greater overall efficiency in geothermal electricity generation.

C. Nanotechnology and Higher Performance

Nanotechnology has its roots deep in the heart of Texas, from the Nobel prize winning discovery of carbon-60, the soccer ball shaped carbon allotrope, at Rice University in 1985 (Smalley, 1997). Currently all the major universities in Texas have significant nanotechnology programs. Now a multi-billion-dollar industry, nanotechnology offers the possibility of improving the efficiency of geothermal energy generation.

There are many examples of the applicability of nanotechnology in geothermal systems. For instance, research in the use of nanofluids in geothermal heat exchangers, fluids endowed with highly conductive particles each sized 10 million times smaller than a penny, offer the promise of boosting system efficiencies (Boul & Ajayan, 2020; Ponmani, et al., 2013). Additionally, the composite technologies described earlier can benefit from the inclusion of nanomaterials. Nanomaterials can be used to make composites stronger, stiffer, smarter, and even self-healing. Major research and development programs have been striving for decades to bring nanoelectronics and the use of nanomaterials in energy and power to consumer markets, and military and space applications alike.

Nobel prize winning research at the University of Texas at Austin in lithium-ion batteries has led to many great innovations from which we now benefit, from our cell phones, tablets, and laptops, to appliances and vehicles (Ponmani, et al., 2013). The engineering of these devices at the nanoscale offer higher temperature tolerances and greater storage capacities, which will extend the temperature limits of sensors in the geothermal environment. Geothermal monitoring while drilling, and structural health monitoring of geothermal wells, is important for the longevity of the geothermal well, and for the reduction of potential environmental impacts associated with well construction and energy production.

High temperature tolerant electronics may make it possible for us someday to have a real time heat and structural health map for geothermal wells made available on a smartphone. Further, the U.S. Army Futures Command has launched a major, $210 million facility at the Texas A&M University Rellis campus, which includes in its mission high-temperature and high g-load electronics development (TAMU, 2019). The potential technology transfer from the military to geothermal, and vice versa from this effort is high.

The Materials Science and NanoEngineering Department at Rice University is now under a five year $30 million contract with the Army to develop a new class of high-temperature military-grade electronics based on synthetic diamond (Semiconductor Today, 2019). Developments in Radio Frequency communications are beneficial in geothermal for data communications within the wells. Developments in these and other materials offer the possibility of structural health monitoring in geothermal wells having temperatures greater than 200 °C (392 °F). Currently, temperature limitations in electronics limit the applicability of structural health monitoring in both the geothermal and oil and gas industries.

D. Remote Sensing

Sensors embedded into geothermal wells, drill strings, and logging tools are obvious applications for new sensor technologies. Perhaps a less obvious application is remote sensing from the air. Many unconventional plays in the United States experience gas leaks during production, which reduce and in some cases negate any climate benefit of gas for energy generation, compared to coal and oil. In the case of accidents and blowouts, methane emissions are a serious cause for concern.

Data is being collected from the air and from satellites, by monitoring instruments like the Tropospheric Monitoring Instrument ("TROPOMI") onboard the Sentinel-5 Precursor satellite. The data that TROPOMI is collecting ultimately offers time resolved region-specific methane emissions around the world (Pandey, et al., 2019). Measurements from TROPOMI and other Earth-orbiting satellites offer the extended monitoring capabilities that are likely to influence regulations and policies throughout the world.

The University of Texas at Austin's Bureau of Economic Geology owns and operates airborne instrument survey systems, which offer this kind of imaging, known as multi-spectral imaging. They also collect time-resolved, region-specific methane emissions. This imaging can be used to map surface alteration mineralogy of geothermal sites, in the case of long-term subsidence and uplift of geothermal areas related to exploitation of reservoirs. In addition, multispectral imaging has also been used in the survey of geothermal wells to assess the environmental impact. Studies of the spectral response of vegetation and lichens in proximity to conventional geothermal wells and power stations can be used to assess impacts by hydrogen sulfide, mercury, and other potential contaminants from the wells.

E. The Transfer of Oil, Gas, and Geothermal Technologies to NASA Missions

As humans continue to explore space, and missions to other planets and moons increase in their duration and complexity, power systems ranging from solar power to nuclear, wind, and geothermal will be evaluated for their reliability and suitability in supporting NASA's operations. Drilling for geothermal energy in space has been the topic of serious study by experts in space exploration, particularly for colonization and human habitats on moons and other planets (Wisian, 2022; Badescu & Zacny, 2015; Badescu, 2009). In order to make geothermal power a possibility in this context, high fidelity automated well construction must be enabled. It is widely regarded in the ISRU community that the future of mining on other planets, moons, and asteroids will most likely resemble future mines on earth. Large mining companies are currently developing automation technologies for automated drilling and mining (Badescu, 2009). Automation and digitalization in construction even now extends to housing, where the Austin-based company, ICON, is building neighborhoods of 3-D printed homes (ICON, 2022). And as we saw in Chapter 6, Oil and Gas Industry Engagement in Geothermal of this Report, there is broad consensus in the oil and gas industry that rig automation and digitalization is the future of geothermal drilling.

At Rice University, developments in 3-D printing for well construction applications have had a focus on tough, temperature tolerant, corrosion resistant materials (Boul & Thaemlitz, 2021). 3-D printing is not just a natural method for ISRU of building structures, but also a method to build stronger, more resilient materials for harsh environments. 3-D printing offers a method combining digitalization and automation to build wells and other building structures remotely, ultimately with full automation. With the oil and gas, geothermal, and aerospace industries all requiring high performance in harsh environments, opportunities for transfer of technologies and expertise from oil and gas or geothermal are plenty.

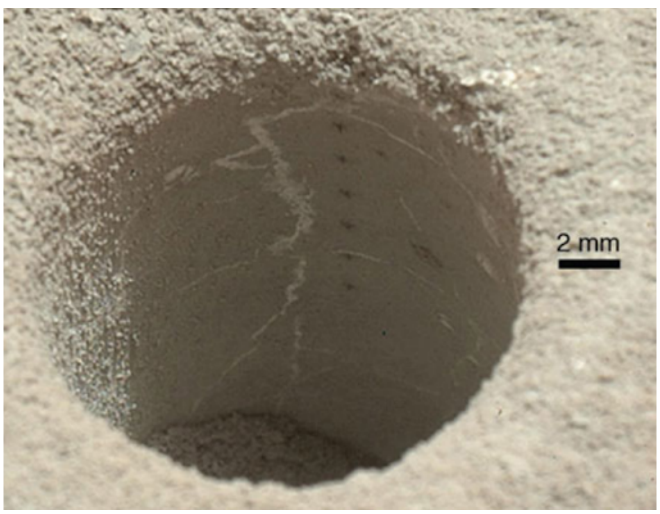

Figure 8.5. A hole drilled by the Mars Science Laboratory ("MSL") on the Curiosity rover. A vertical array of pits can be seen on the side of the hole in the rock, referred to as "John Klein." These pits resulted from the ChemCam tool ("LIBS") to give a composition of the drilled rock (Badescu & Zacny, 2015). *Source: NASA, 2022.*

In planetary exploration, drilling is necessary to acquire subsurface samples for in-situ analysis or return to Earth. With knowledge of the composition of the surface and subsurface, it may be possible to utilize these resources for energy and for building structures. The drill on the Curiosity rover is the first autonomous extraterrestrial drill to be deployed on another planet since the 1980's, when the Venera missions were deployed to study the surface of Venus. It is also the first autonomous drill deployed on another planet to drill through solid rock. An image of one of the holes drilled on Mars by the MSL is provided in Figure 8.5. Compositional analysis by the Mars Science Laboratory ("MSL") determined the presence and depth dependence of the concentrations of calcium oxide, calcium sulfate, and silica – all useful building materials.

The exploration of Venus in the manner that Mars is being studied for resources will require enhanced drilling capabilities, which match those needed on some of the hottest geothermal wells on Earth, those greater than 300 °C (572 °F) (Badescu & Zacny, 2015). Table 8.1 shows that the survival times of the Venus landers was greatly limited by the inhospitable environment of the planet. There were, however, four landers which were able to acquire surface samples. For example, Venera 14 was successfully drilled to a 1.2 inch (three centimeter) depth, and gathered a sample for an X-ray fluorescence spectrum in a chamber kept at 30 °C (86 °F). The sample was determined to be of similar composition to the basaltic rocks on Earth in mid-ocean ridges. This was all done with technology from the 1980's. Developments in high-temperature drilling and automation in recent years can help to determine the composition of such extreme environments as those on Venus. Further developments in high-temperature materials will likely greatly increase the surface time of robotic vehicles on the surfaces of such planets.

Research and development activity in 3-D printing for well construction in oil and gas has been driven by the recognition that on average, approximately 20 percent of all constructed wells in the industry require costly remediation within a 30-year period (Daccord, et al., 2006). In normal operations, failures of these kinds can result in the loss of a well and considerable hazard to field personnel (Plank, 2011). Longevity is particularly important in geothermal wells, where operators look for well lifetimes much longer than the 30-year lifetime for a typical oil or gas well.

Table 8.1. Venus landers, their surface time on Venus, and sample acquisition success. *Source: Badescu & Zacny, 2015.*

Surface landed mission	Lanuch Year	Surface time* (min)	Surface sample acquision capabilites
Venera 7	1970	23	No
Venera 8	1972	50	No
Venera 9	1975	53	No
Venera 10	1975	65	No
Venra 11	1978	95	Yes. Failed to deposit sample
Venra 12	1978	110	Yes. Failed to deposit sample
Pioneer Venus 2	1978	60	No
Venera 13	1981	127	Yes
Venera 14	1981	57	Yes
Vegra 1 Lander	1984	56	Yes. Activated during descent by error
Vega 2 Lander	1984	57	Yes

The mining of minerals and harvesting of energy are mission critical for NASA in establishing lunar bases or colonies on other celestial bodies. They are necessarily integrated with life-support systems in human space travel. Failure rates of 20 percent are not tolerable in human spaceflight. The precision that is possible with 3-D printing, in addition to the superior toughness in the structures built through 3-D printing, can lead to higher fidelity in well construction. Furthermore, the development of automation in these systems can also transfer directly into mining of materials and automation thereof.

A new class of hypervelocity impact-resistant structures is being developed to broaden the toolset for building wells through 3-D printing (Sajadi, et al., 2019b). The structures combine fracture toughness into load-bearing lightweight structures made from simple thermoplastics. It is the printed architecture of these materials that give them their remarkable toughness. The application of the 3-D printed structures is envisioned not just for oil and gas applications, but also for aerospace applications and development of lightweight armor. The technology is readily tailored to increasing the strength to weight ratio of aerospace composites, and potentially to improvements in a material's thermal tolerance.

Building from research and development activities in 3-D printing of oil and gas wells, smart 3-D printing technologies can be extended to NASA's efforts in ISRU. It is widely recognized that the exploration and colonization of planets and moons beyond our own is an endeavor that will require the use of resources local to the regions of the bases or colonies (Badescu & Zacny, 2015; Badescu, 2009). The manufacture of materials and energy powering longer term missions through ISRU will be essential for the sustainability of long-term missions. 3-D printing of oil well cements (Sajadi, et al., 2019a) and multimaterial cement composites (Sajadi, et al., 2021) has taught us many lessons which can be applied to the building of a Martian base from Martian regolith, for example (Yashar, et al, 2019). 3-D printing is enabling a digitization and automation of construction (Craveiroa, et al., 2019). The construction is not limited to habitats, but extends to wells and mineral mining structures and systems (Zacny, 2012; Zacny & Bar-Cohen, 2009).

There are many other aspects related to additive manufacturing that would be impactful transfers into NASA's missions. The 3-D printing of metals, for example, has undergone major developments in the oil and gas industry. High performance alloys, such as Inconel, can now be printed into parts for gas turbines, compressors, downhole tools, and sensors (Burns & Wangenheim, 2019). Further development of these technologies can make it possible to mine resources and utilize them for energy production remotely and through automation. They are also useful in hybrid smart systems with sensors and communication systems that are directly integrated with building structures.

F. Geothermal Power in Space

Texas is and has been a leader in government driven, and also now private space exploration and related technology development. Texas is also driving hard into the new geothermal paradigm. Combining these two areas yields geothermal in space. Remember that the essential ingredient for a geothermal system is a temperature differential, generally in the 100 to 250 °C range. Multiple solar system bodies have geologic settings where these differentials might be observed.

The moon is our closest celestial body. The surface "soil" of the moon has a thermal conductivity orders of magnitude lower than typical rocks here on Earth (Yu & Fa, 2016; Grott, et al., 2010). This low conductivity can drive very high thermal gradients of short distances, and not just vertically. The heat flow in the crust of the moon is generally low. Additionally fluids, particularly water, are likely to be quite precious, to the point that an Engineered Geothermal System might not be practical. However thermoelectric (or Seebeck) generators, as discussed further in other Chapters, might be able to generate usable amounts of power without any fluids, or even moving parts, required. Lastly, the need for deep drilling could be avoided by taking advantage of the greater than 200 °C (392 °F) temperature difference at the rim of lunar polar craters. These craters have near zero temperature inside the permanently shadowed interior, while half the time enjoying temperatures more than 200 °C (392 °F) warmer on the sunward lip of craters (Figure 8.6). This is a usable temperature difference for geothermal applications (Wisian, 2022).

Mars has no active tectonics, and while geothermal potential cannot be ruled out, it will likely be very restricted geographically, and relatively low-temperature. As you move further out in the solar system to Jupiter, Saturn, and beyond, the solar flux falls off dramatically, making solar power less attractive. Radioactive power sources of one sort or another have potential, but also significant drawbacks. Thus, geothermal power becomes particularly attractive in the outer solar system. While the gas giants are not settlement targets, their moons are. Lo (a moon of Jupiter) is the most volcanically active body in the solar system, but its sheer level of activity will likely prohibit long-term occupation, and thus will not be considered here.

The remaining (spherical) moons around the gas and ice giants, as well as minor planets such as Pluto and Eros are mostly ice, and this presents an opportunity. Many of the icy bodies in the solar system appear to have subsurface oceans of water (with an indeterminate amount of other constituents in solution). These oceans appear in at least some instances to be "planet"-wide. The net result of these configurations is an ocean top at or near 0 °C (32 °F) and an average surface temperature around -200 °C (-328 °F), with kilometers of ice in between (Figure 8.6). Setting aside the considerable engineering challenges, this is a constant 200 °C (392 °F) differential – a resource that would make a terrestrial geothermal engineer quite happy.

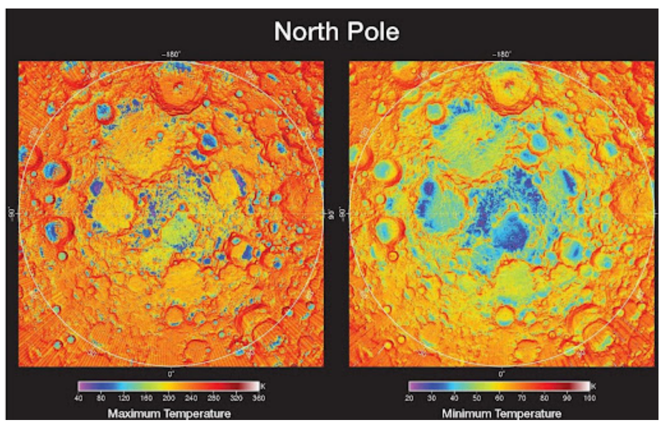

Figure 8.6. Maximum and minimum temperatures at the Moon's North Pole as measured by the Lunar Reconnaissance Orbiter. *Source: NASA, 2014.*

G. A Way Forward with Space

The aerospace, oil and gas, and geothermal industries have developed remarkable technologies, which have been advancing the possibilities within their individual domains. It is the space between the industries where perhaps some of the most exciting developments and applications can be realized. Each industry has developed

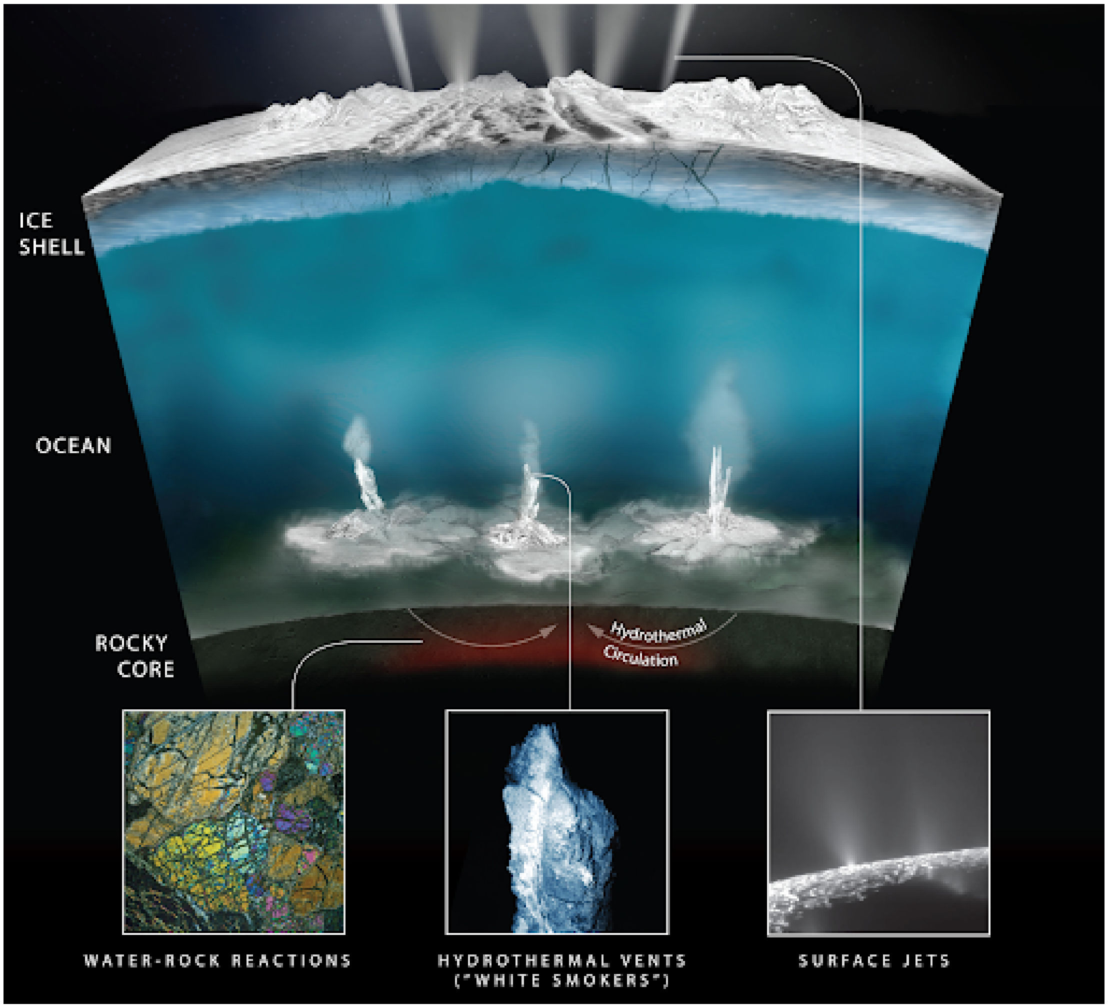

Figure 8.7. Generalized structure of outer solar system icy bodies. *Source: NASA, 2017.*

technologies which are of potential mutual benefit to the other. And beyond established technologies that may readily transfer are research and development activities, which translate well into aerospace and space exploration technology development activities. There may be no better time than now to unlock the potential that we have in establishing Texas as the leader in geothermal power through inter-industry and interdisciplinary collaboration and technology transfer.

IV. Conclusion

Texas has a long history of world-leading science and technology innovation across three major industries, subsurface energy production, defense, and space. The interplay and reinforcing synergy of leading-edge developments in space (both government and commercial), and defense, along with emergent geothermal start-ups, existing energy companies, and academic researchers, is exciting and loaded with near-term potential. This unique convergence of strengths will enable Texas to lead the world in the geothermal revolution.

Conflict of Interest Disclosure

Ken Wisian serves as an Associate Director of The Bureau of Economic Geology, Jackson School of Geoscience at the University of Texas at Austin, and is compensated for this work. His main area of research for 30 plus years in geothermal systems. Outside of this role, Ken Wisian certifies that he has no affiliations, including board memberships, stock ownership and/or equity interest, in any organization or entity with a financial interest in the contents of this manuscript, and has no personal or familial relationship with anyone having such an affiliation or financial interest.

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