JBIS Volume 75 2022 pages 315-320

KEN WISIAN Bureau of Economic Geology, The University of Texas at Austin, 10611 Exploration Way, Austin, Texas, USA 78758
Email ken.wisian@beg.utexas.edu

Geothermal Energy on Solar System Bodies

As humanity expands into the solar system, power will be needed for fixed installations. For spacecraft to date this has meant solar panels or Radioisotope Thermoelectric Generators (RTGs) – a fission source. Each of these power sources have drawbacks; solar is subject to the inverse square law of decreasing solar flux with distance, while fission sources emit radiation that must be protected against with shielding mass and distance. One possibility with potential for powering installations on planetary bodies, particularly the outer solar system, is geothermal generation. All that is needed to produce geothermal energy is an exploitable temperature differential between a source and a sink. This technology has been producing electricity on Earth for more than 100 years from temperature differences of about 125°C or greater. On many icy bodies this differential would come from the difference between the surface temperature and a subsurface liquid body (ocean). The rims of polar region craters on the Moon offer a near-term potential geothermal development using ThermoElectric Generators and the ~150°C difference between the sunlit and permanently shadowed sides. While significant engineering issues remain in producing this energy, the potential, particularly on icy bodies is on the order of Megawatts of power generation per well. **Keywords:** Geothermal Power, Icy Moons, Energy, Polar Craters, Ocean, Thermo-electric Generator

1 INTRODUCTION

1.1 Problem

The solar system from the Earth out (including the Moon) is the direction that most human activity and potential exploration and settlement will proceed. Other than perhaps the clouds of Venus, no substantial settlement inward of Earth's orbit is seriously contemplated at this time. Earth outward however, there is already serious work ongoing for colonizing Mars [1] and establishing Moon bases [2] as well as extensive exploration of the outer solar system, especially regarding the search for life in subsurface oceans of the icy moons of Jupiter and Saturn.

Human and even robotic exploration and settlement will need power. While some power sources will need to be portable, the bulk power for facilities will come from fixed power stations akin to power plants on Earth.

Nearly all space probes to date have been powered by either photovoltaics (solar cells) or Radioisotope Thermoelectric Generator (RTG) systems [3-5]. Each of these have major downsides. Solar power suffers from the inverse square law – the solar flux decreases as the square of the distance from the sun. Thus, while Mars might still have sufficient solar irradiance to provide power for the limited needs of a lander, by the time you are at Jupiter, over five times further from the Sun than Earth, the solar irradiance is less than 1/25th that at Earth. At Earth the solar irradiance is approximately 1.37 kW/m2, 583 W/m2 at Mars and only 50 W/m2 at Jupiter. While the decrease in solar flux can be compensated for by a corresponding increase in solar panel size, there is a practical limit to this path.

RTGs have been the preferred power source for all deep space probes to date [4, 6]. These are radioactive sources that produce heat via the energy released in fission decay events. The temperature difference of more than 800 K between the source and ambient space is converted into electricity through a thermocouple (RTG). RTGs are long-lasting – witness the decades of service of the Pioneer and Voyager probes. RTGs, though, have their own negative issues. First, as a fission battery, they gradually decline in power due to the half-life of the radioactive materials in the RTG. The Pioneer probes, as an example, had an initial power output of 155 W. After 29 years the radioactive output was at 80% of initial, however total system output was only 65 W [7]. This substantial additional decline beyond radioactive decay is attributed to thermocouple degradation. Also, a fission power source has a relatively high energy density but is also relatively dense. Further, biological beings and even electronics require shielding and/or distance from the radiation source – thus creating a mass penalty. Since mass is the most significant driver of cost in space travel, this is a major downside.

Fission reactors, as opposed to RTGs, have seen more limited use in space. The U.S. launched one in 1965 and intended to put one on the Moon with Apollo 13 [3]. The USSR launched 33 fission reactor-powered satellites between 1967 and 1988 [8]. Generally, fission reactors suffer from the same issues as RTGs, but are also more complicated. Further, both RTGs and fission reactors eventually require fuel resupply as well as disposal of the hazardous waste.

Regardless of the relative advantages and disadvantages of various power sources, another, perhaps overriding, priority is the resilience and reliability of your power sources, especially when you are days to years from help. In this case a diversity of sources would substantially reduce risk. For this reason alone, new sources of power deserve further study.

1.2 Solution

Geothermal power generation – generating power from the naturally occurring heat of the Earth (through a temperature differential over a distance) has been exploited for electricity for over a century [9] and for heat (e.g. baths) for thousands of years [10, 11]. It is proposed here to broaden the definition of geothermal power to include power produced from the heat of, or at, any body, not just the Earth, capable of sustaining an exploitable temperature difference under any configuration that utilizes the geology of the body. This definition will now include other terrestrial planets (e.g. Mars) and icy bodies in the outer solar system (moons and dwarf planets).

Conventional geothermal systems are a mature technology on Earth and one of the cleanest energy sources in use today [12]. An improved paradigm of zero emission, deep closed-loop geothermal systems is in trials now. Which type of geothermal power system is best applied will depend on the specific geologic setting, economic, environmental and other policy considerations. Economically viable geothermal power generation on Earth currently needs a temperature difference of at least 100°C and preferably 150°C or greater [9]. The enthalpy of water, the typical medium of heat transfer, increases non-linearly with temperature, up to the critical point [13], thus higher temperatures yield better than linear growth in extractable energy.

Multiple icy moons in the outer solar system such as Enceladus and Europa appear to have subsurface oceans of liquid saline water at temperatures at or above the freezing point [14] while their surface temperatures are around –200°C (Table 1.). These bodies are prime candidates for geothermal power generation. Other bodies have very different compositions, that could still hold significant temperature differentials. Io has active sulfuric volcanoes driven by a greater than 1,000 K temperature difference [15]. Titan has a liquid hydrocarbon cycle, much like the water cycle on Earth but operating at significantly lower temperature. Pluto on the other hand shows evidence of nitrogen ice convection, implying a still to be determined temperature drive [16-18].

What all these bodies have in common is a temperature difference in or across the crust of the body. Such a temperature difference is exploitable to generate energy – this is the basic idea of extracting work from heat that underlies most power generation [9]. For geothermal power on Earth this temperature difference is generally between ambient air (for simplicity let's assume 0°C) and at least 100°C above ambient. While H2O is the most common fluid used to carry the heat, other liquids are used or have good potential depending on the minimum and maximum temperatures for the cycle. CO2 and organic molecules are used, often in multiple stages, to extract energy from a heat stream. There are other fluids like liquid nitrogen that can function in these roles over lower temperature ranges in the outer solar system [19]. The details of power generation are not explored here, but the reader is referred to DiPippo [9] and Glassey [20] as starting points.

Mars is an example of a body with less determined geothermal potential. While it was certainly geologically active in the past (witness the largest volcano in the solar system), it is a much smaller body than the Earth and appears to be geologically senescent. However, there is potential for localized areas of elevated temperature due to remnant geologic activity or perhaps large meteor strikes. Also, there is evidence of ongoing water floods or ice melts on an annual basis though it is not clear what the dynamics of this activity are [21]. Geothermal power for Mars settlement has been proposed [22-24]. Mars however has a low crustal heat flow about 20 mW/m2 [25] relative to Earth's typical 30-60 mW/m2 . The corresponding temperature gradients, on the order of 10 K/km, would require very difficult drilling to great depths to reach a temperature differential adequate for power generation. This does not rule out geothermal power, but it likely makes viable geothermal systems like those found on Earth, very rare on Mars. This, in turn, would require significant exploration and the citing of facilities and colonies where the geothermal system is as opposed to where other priorities might dictate.

2 GEOTHERMAL POWER GENERATION

Geothermal Power is generated by harvesting the naturally occurring heat of a body. On Earth "conventional" geothermal power is generated by drilling (often kilometers) into the crust to tap into a hot water flow or steam system, bringing the hot fluid to the surface and running it through a generating turbine to produce electricity [20]. These systems are tied to either shallow magmatic activity or fault systems that allow water to circulate very deep in the crust and be heated to >150°C. A new emerging paradigm in geothermal power, enabled by engineering advances, decouples power generation from specific geologic settings and simply drills deep enough anywhere on the Earth to reach sufficiently high temperatures. A fluid is then usually circulated in an engineered closed or semi-closed loop with a large surface contact area to harvest the heat and bring it to the surface for power generation [20].

The key to geothermal power on the icy moons and similar bodies in the solar system is the presence of a shallow subsurface liquid body. Shallow is a relative term here and could be as deep as 100 km or more subsurface. Naturally though, the shallower, the better, and oceans that are a few kilometers subsurface present a near-best-case scenario.

The efficiency of any heat engine relates how much useful work is output for a given amount of heat energy input and according to the second law of thermodynamics:

where εmax = the maximum thermodynamic efficiency, and $Thot$ and $Tcold$ (in Kelvin) are the source and sink temperatures respectively

If on Earth, 200 K difference between hot and cold reservoirs can provide only 40% maximum efficiency. The same ΔT on an icy moon gives >70% Carnot efficiency due to the cold side approaching closer to zero degrees Kelvin (K) and reducing the numerator substantially. This higher efficiency means that the same power on the icy moon can be generated by using much smaller working fluid mass flow rates. This in turn allows for more compact equipment and lower-mass infrastructure than required on Earth.

Io, Enceladus and Europa show clear signs of volcanic activity. “Volcanic” in this case refers to any fountaining, flowing or geysering of molten material from the subsurface. While on Earth the molten material is rock of one sort or another (geothermal geysers are another matter), on an ice body, the molten “rock” is water. In the case of Io, which is unique in composition, the molten “rock” is sulfur and sulfur compounds (Table 1). The important point is that where these types of outflow features are present, the distance between the liquid reservoir (with its associated high temperature) and the surface and reducess to zero. As is discussed below, the depth to the source heat can be a significant engineering factor, thus, depending on the stability of the geology and other practicalities, the drilling depth to the heat source can be quite small and easily reached. On some moons, such as Ganymede and Callisto, where outflow has not been detected, there is still evidence of past outflow resurfacing parts of the moons and crustal thinning tectonics that would at least reduce the depth to ocean on these bodies [26].

Pluto is a special case. It is a very cold body with no giant planet nearby to exert tidal stresses to heat its interior, but there is a relatively large moon, Charon, that might have a similar effect. Pluto displays clear evidence of tectonic activity and slow-motion ice convection as well as less certain subsurface oceans [17, 27].

2.1 Geothermal potential on solar system bodies

It appears that the subsurface oceans in the outer solar system are mostly water and salts with a complex mixture of other minerals and organic molecules included [14]. While these impurities and the pressure of being under kilometers of ice affect the freezing temperature of the ocean liquid, in rough terms and for the “back of the envelope” purpose here, we can assume a minimum temperature of the oceans of 0°C.

The surface temperature of the outer solar system bodies varies significantly. A rough average surface temperature is 100 K or –173°C (Table 1). Thus, if the ocean water can be brought to the surface with little or no heat loss, then you will have a 173 K (°C) source-sink temperature difference – enough to make a terrestrial geothermal power engineer quite happy.

Table 1 shows key characteristics of selected outer solar system bodies. While the surface temperatures are relatively well measured, the potential crustal thicknesses are poorly constrained by modeling morphology and geophysical features. Fig. 1 shows a representative cross section through an icy moon with a single coaxial flow well drilled through the crust into the ocean. In this schematic the heat from the ocean is transferred via a heat exchanger to a working fluid which drives the electrical generation. A couple of points are relevant to mention:

1. Crustal thickness is an average and there could be places on each of these worlds where crustal thickness goes to zero (as per the mid-ocean ridges on Earth). While penetrating a few kilometers of ice with a melt-probe is foreseeable, drilling (melting) through 100 km of ice would be a stretch technologically.
2. Regardless of the drilling depth required, the keys will be; a) bringing the ocean fluid to the surface with minimal heat loss or b) using a downhole heat exchanger and an engineered fluid to then carry heat to the surface.
3. Impurities could substantially lower the melting point of water. This would make oceans more likely and thicker but would also reduce the heat content of the fluid. For the calculations in this paper, pure H2O is used. The likely mineral salts thought to be present in the subsurface oceans have little impact on water properties, but in the case of ammonia (NH3) and methane (CH4), possible impurities, particularly from Saturn outward [28], could lower the solidus by as much as 100 K [29].
4. Io is a unique body due to a high silicate composition and extreme tidal heating. It is therefore somewhat more analogous to the Earth than the other bodies. It has molten mafic rock, and volcanoes. These in turn drive the volcanic plumes that have been observed, but these are thought to be mostly sulfur compounds, not water. Given an approximately 1,400 K magma body 50 km down yields temperature gradient on the order of 25°C/km – similar to Earth. Thus, given the similarities to Earths geothermal setting and geology, the geothermal technology developed for

Geothermal Energy on Solar System Bodies

Fig.1 A geothermal well system on an icy body with a subsurface ocean. The temperature difference between the ocean and the surface is used to drive a turbine (or a TEG) and generate electricity. Many engineering options are available: shown here is a heat exchanger extending into the ocean to transfer heat to the surface.

TABLE 1: Key properties of selected outer solar system bodies

Body	**Avg Surface Temp, °K**	**Depth to Ocean, km**	**Ocean Composition**
Io [15, 30, 31]	110	50	Mafic silicates
Europa [29, 32, 33]	102	3-80 (6-20)	Brine
Ganymede [32, 34]	110	75-100	Brine
Callisto [32, 35]	134	75-100	Brine
Titan [32]	94	50-150	Brine
Enceladus [32, 36, 37]	75	12-70	Brine
Pluto [27-29]	44	180-260	Brine