Solar Generation of Electric Power at Lunar Pole

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An theoretical investigation of possibilities for an electric power station, appropriate for installation and use on the moon, late in the 20th century, leads to a tentative decision in favor of a solar driven Rankine cycle turboelectric system. Such a station would be located at one of the lunar poles, to take advantage of continuous sunlight for the collector, and continuous shade for the radiator, in close proximity. Gross thermodynamic characteristics of the system are investigated in a preliminary way.

INTRODUCTION

The present paper suggests one possible solution to the problem of continuously generating large quantities of electric power on the surface of the moon. It is not claimed to be an optimum solution, but is rather an outline of a system concept which would seem to merit serious consideration if certain basic assumptions turn out, in the light of future development, to be correct. The system concept, while perhaps novel when taken in its entirety, comprises nothing very new in the way of subsystems, assemblies, or components.

Ground Rules

Our study has to do with a power plant which might be built 20 or 30 years from now. Accordingly, our calculations are all in the nature of rough approximations. Thermodynamic computations are based on the usual first order idealizations --- pure adiabatic expansion of gases in a turbine, frictionless flow (zero pressure drop) in tubes and conduits, and all the rest.

No special allowance is made for the advances in power engineering technology which are bound to take place between now and the time when such a plant might be built. This paper aims to show up certain possibilities which will almost surely exist. If in the next few decades still more attractive possibilities are brought forward, so much the better; but that is not our present concern.

Basic Assumptions

1. There will be established a more or less permanent manned station, somewhere on the moon, before the end of the present century. There may even be several stations, in different locations.
2. Any such manned station will require a continuous supply of electric power, in the range of 100 to 1000 kw.

3. It will prove both feasible and advantageous to locate at least one such base in the near vicinity of the lunar north pole of south pole.

4. Natural resources locally available on or near the lunar surface will have been exploited, and a technology will have been developed, to a point such that simple metal fabrication and construction projects can be carried on with a minimum of support from earth. Only special equipment and materials (tools, instruments, optics, special alloys, etc.) will need to be brought from earth.

**DISCUSSION OF ASSUMPTIONS**

The above are perhaps bold assumptions; but the published literature affords abundant support, particularly for the first three. Many writers have argued the need for a "lunar colony". (See refs. 1-8, also bibliography in refs. 2 and 4, particularly). Especially forceful is the recent review by Arthur C. Clarke, citing the benefits to be expected in several widely differing categories:

- vacuum technology
- radio astronomy (lunar farside)
- logistics and supply to earth orbiting vehicles
- base of operations for further exploration of solar system

Among other interesting proposals by Clarke is that of a moon-based electrodynamic launching system. This idea has been further developed by Escher. Instantaneous electric power requirement for such a system, however, is extremely high (up to \(10^9\) watts or higher, per earth-ton of gross mass, accelerated to escape speed at 50 gravities), and would obviously require some kind of short term energy storage scheme, as well as a generating plant having a capacity suitably matched to that of storage device. The papers by Clarke and by Escher, in suggesting the need for large amounts of electric power on the moon, have provided a positive stimulus for the present study. Our proposal, however, falls far short of meeting the requirement implied by their electrical launch device.

Salisbury and Campen have considered in detail the relative merits of different possible locations for a permanent lunar colony. Green and co-authors have put forward the idea of a base at one of the lunar poles. They have, indeed, already pointed out a number of the factors which are important to the subject being treated in the present paper.

The general problem of designing a lunar power station can be approached in at least 2 different ways:

(a) One may first select the site for the lunar colony or base, thinking chiefly of the functions the base is to perform, then decide on an optimum scheme to supply power to a base in that particular location.

(b) One may determine what kind of electric power system, somewhere on the moon, would yield the greatest utility per dollar spent, then feed the result into the process of making a decision as to the site of the lunar base.
This paper takes the second approach. Our concern is with the situation which develops after the early phases of lunar exploration have been completed. The need will no longer be for a power station which is highly mobile, and neatly self-contained. Rather, to achieve maximum utility per dollar, one should seek to maximize the steady output per unit weight of equipment and material to be boosted from earth.

The endeavor to maximize this particular quantity leads to an overall design which differs markedly from that of power plants in the more usual categories — Earth-based public utility, manned or unmanned spacecraft. It may differ, too, from the designs appropriate to the very early permanent stations on the moon — stations deriving their entire support from earth.

Our treatment, while neither rigorous nor exhaustive, does lead to a tentative conclusion in favor of a solar-powered rankine cycle turboelectric installation at one or the other of the lunar poles. The chain of reasoning is set forth in the next section.

**STEPS TOWARD SYSTEM DEFINITION**

1. We recognize at least four possible prime sources of energy:
   a. Chemical fuels
   b. Heat from Lunar interior
   c. Solar energy
   d. Nuclear fuels

Both (a) and (b) seem unattractive. Present knowledge is not sufficient to warrant outright rejection of either; but the present expectation is strongly negative. Suitable unreacted chemicals probably do not exist, in any quantity, on the moon. Internal heat, while undoubtedly present, is a "low grade source". It is diffuse, thus difficult to exploit. Hence the choice would seem to lie between (c) and (d).

2. It is advantageous to use solar power on the moon if at all possible. The energy is free, and there is no interfering atmosphere. Hopefully, transportation cost from earth would be less for a solar system than for a nuclear power system, allowing for local (moon-based) fabrication of many bulky items in the solar collector and the radiator. The lesser hazard constitutes a further advantage.

3. The usual disadvantage of solar power, as compared to nuclear power, is the intermittency resulting from the day-night cycle. This disadvantage would almost* vanish if the solar collector could be located at the crest of a peak near one of the lunar poles. Certain of these crests enjoy almost* perpetual sunlight. (7,8,10)

*There would still be eclipses
4. From the above, it would appear that a solar installation is worth considering. There would still be a question how best to utilize the available solar energy.

5. With present technology, the outstanding possibilities are

a. thermoelectric conversion  
b. photovoltaic conversion (solar cells)  
c. thermionic conversion  
d. dynamic heat engine cycles

1. Stirling cycle  
2. Brayton cycle  
3. Rankine cycle

The direct conversion methods a, b, and c, are presently enjoying rapid development and improvement, particularly for spacecraft applications. They tend to be lightweight and compact. Broadly speaking, they have the advantage in the low power range, up to about 5 Kw. At higher power levels, dynamic heat engines show the better economy. Complete heat engine systems are complex and extensive, but this fact in itself is not necessarily a drawback, given a firm base of operations with plenty of space, and with available bulk raw materials. Moreover, heat engine technology is already well developed. A vast amount of engineering knowledge is immediately applicable. In all, the arguments in favor of the heat engine system seem to be decisive.

6. Choice amongst the 3 heat engine cycles will hinge largely on efficiency, and more particularly on power per unit weight. The Stirling cycle is the only one which matches the Carnot cycle in efficiency, but it has the drawback of utilizing reciprocating pistons in cylinders, not high speed turbines. Accordingly, in the power range above 25 Kw, it fails to compete favorably on a cost basis. Both the Rankine cycle and the Brayton cycle admit the use of turbines, and are therefore preferred in the power range presently of interest.

In recent years there has been much attention to the Brayton cycle for power plants operating under zero gravity. The working fluid remains in a gaseous state throughout the cycle, hence there is no problem of zero gravity boiling. In the absence of experimental data on boiling heat transfer under lunar gravity, one might assume that the situation on the moon would resemble the earth-based situation more closely than it does the zero gravity situation, and plan accordingly. On that basis, one would tend to prefer the Rankine cycle because of its inherently higher efficiency.

Actually, as will appear later, the analysis leads to a super-critical Rankine cycle, extending far into the superheat region. Such a cycle becomes, in effect, a sort of hybrid. In its heat absorption portion, it resembles the Brayton cycle; in the heat rejection portion, it is like an ordinary Rankine cycle with superheat. In any case, it seems best for now to look first at the Rankine cycle, bearing in mind that the Brayton cycle has not really been ruled out.
Solar energy is free, and is in constant supply. It can not be hoarded, nor turned off. Hence there is no direct reason for economizing in one's use of it. In a word, there is no incentive to achieve high efficiency for its own sake.

High efficiency remains a desirable attribute because it contributes to the achievement of high output per unit cost, as for example, by minimizing the size of the solar energy collector. Looking for ways to get high efficiency, one would normally try to arrange for a high temperature of heat absorption $T_1$ and a low temperature of heat rejection $T_2$.

In many situations, this broad classical principle has to be compromised, for one reason or another. (On earth, low temperature heat sinks are not readily available; in orbiting space vehicles, $T_2$ has to be kept fairly high so as to utilize a small, lightweight radiator structure.) At the lunar pole, such restrictions are greatly relaxed. The radiator can be placed in permanent shadow, allowing the rejection of heat to an almost black sky. This gives a low value for $T_2$, which in turn means a radiator of very large area. Such a thing would be prohibitive on a spacecraft; but on the moon, under our assumed conditions, it may be possible, even practicable.

Actually, for maximum ideal (Carnot) efficiency, the quantity to maximize is $(T_1 - T_2)/T_1$. Speaking generally, then, one can gain more by depressing $T_2$ than by elevating $T_1$. This fact can easily be lost sight of, since, commonly, there is a bottom limit, not very low, on $T_2$, and efficiency can be increased only by raising $T_1$. If, on the other hand, one could establish $T_2$ at an extremely low value, the inducement to increase $T_1$ would not be nearly so strong.

Absolute theoretical upper limit for $T_1$ is fixed by the temperature of the radiating surface of the sun ($\sim 5700^\circ$K), and is far above any temperature which can be practically utilized. Values of $T_1$ in the range of 2500 to 2800 °R have been suggested as being within reach by "reasonable extrapolation of current technology". Such temperatures, however, are well beyond those normally employed in earth-based power plants ($\sim 1000^\circ$F), and have been suggested for space-station power plants only because the need to keep $T_2$ high makes it necessary to keep $T_1$ still higher. Provisionally, one might settle for a value of $T_1$ somewhere between 800 °K (rule-of-thumb for the usual steam power plant) and 1500 °K (approximate maximum considered for spacecraft systems utilizing alkali metal vapors).

It is easier to reach a decision about $T_2$. Effective temperature of the black sky, complete with stars, has been estimated at 30 °K. This temperature, however, is much too low for a practical radiator on the Moon's surface. Allowance should be made for the temperature of lunar crust. Watson, Murray, and Brown have chosen the figure of 120 °K as a reasonable upper limit for the temperature of lunar surface in perpetual shadow. This figure allows for the effect of heat flow from the lunar interior; also, for heat flowing laterally through the crust from warmed areas. Some further allowance should be made, certainly, for the warming effect of the power plant operation itself. We therefore select, tentatively, the figure of 150 °K. At this temperature, one could reject heat not only by radiation to a black sky, but also, perhaps, by radiation.
and/or conduction downward to the surface. Some modification of this figure can be expected, once a choice of working substance has been made, and calculations on the radiator carried through. For the moment, however, we note the prospect of very high Carnot efficiencies. With $T_2 = 150 \, ^\circ K$,

\[
\text{Efficiency} = 81\% \quad (T_1 = 800 \, ^\circ K)
\]

\[
= 90\% \quad (T_1 = 1500 \, ^\circ K)
\]

The above figures underline the point already made about ideal operating temperatures. If we can get 81% efficiency (ideal) at an easy-to-handle 800 °K, and the input energy is free, why struggle to work at the high level of 1500 °K to gain only a small percentage?

**CHOICE OF WORKING FLUID**

To make a start somewhere, one might scan the list of substances capable of going through a gas-to-liquid change of phase at 150 °K or thereabouts, at some reasonable pressure. Such common atmospheric gases as Nitrogen (crit. temp. 127 °K) and Argon (crit. temp. 151 °K) are too volatile. The usual refrigerants ($\text{NH}_3$, $\text{SO}_2$, the various freons) are not volatile enough. Among the rare gases, however, are two likely candidates:

- **Krypton** (triple point, 116 °K, 548 Torr; critical point 209 °K, 54.3 atm)
- **Xenon** (triple point 161 °K, 612 Torr; critical point 290 °K, 58 atm)

Aside from the fact that these gases condense at approximately the desired temperature and pressure, there are three strong arguments in their favor:

1. Both gases, being monatomic, show a high value for $\gamma$, the ratio of specific heats. This fact, in turn, means that a large temperature range corresponds to a relatively small pressure range.

2. Krypton and Xenon are chemically inert. This characteristic at once removes all need to worry about corrosion or chemical instability.

3. There is reason to believe that both gases occur, albeit in a state of extreme attenuation, in the lunar "atmosphere". While we are not aware of any practical means of collecting a gas existing at such extraordinarily low density, one can hardly rule out the possibility that a means may be invented.

Saturation curves for Krypton and Xenon appear in figures 1 and 2. (Original data from ref. 12). Neither gas is quite right for condensing at the pre-selected temperature. At 150 °K, the saturation pressure for Krypton is 6.4 atmospheres --- somewhat higher than optimum. For Xenon, on the other hand, 150 °K lies below the triple point. Using this gas, one would probably choose to condense at $\sim 170 \, ^\circ K$ (1.3 atmospheres).
Conceivably, one might contrive some advantage from working with a mixture of Kr and Xe. Such a fluid, of course, would not behave as a "pure substance"; each element would tend to act in accordance with its own partial pressure. Eventually, the possibility should be considered, if only because the mixture of gases might be easier to come by than either gas by itself. One may reasonably expect that if either element is present on the moon, the other will be also. Any scheme to concentrate such extremely diffuse (and chemically inert) material would probably yield as its end product a mixture which one might prefer, in the interest of economy, not to have to separate into constituents. Parenthetically, the possibility of using mixed noble gases in a Brayton cycle has already been considered, by authors seeking to optimize the design of a space power plant in the 10-100 Kw range.

For the present, however, we put aside this line of thought, and consider the use of Xenon, with $T_2$ fixed at 170 °K. $P_2$, then, will be 1.3 atmospheres. If $P_1$ is established at 57.6 atmospheres (the critical pressure) then $T_1$, calculated by the perfect gas law, becomes approximately 775 °K. This figure lies comfortably within the range of practicality, and gives rise to a Carnot efficiency of 78%.

Actually, of course, the perfect gas law gives only a rough approximation for $T_1$. Vapor properties, derived experimentally, would furnish a much better base for calculation. But for Xenon, these properties appear to be available in the literature only through a small range of temperature.

With due allowance for the crudeness of this first approximation, and for a number of factors which have yet to be considered, one can draw two firm conclusions:

a. It would be feasible to use Xenon as the working fluid, over the entire temperature range from $T_1 = 800$ °K to $T_2 = 170$ °K. Pressures would be easily manageable throughout the cycle.

b. Xenon could be used in this way, and the cycle would still belong, technically, to the "Rankine cycle with superheat" classification; but the importance of the superheat portion would be far greater than usual. Indeed, during the heat input portion of the cycle the entire action takes place at constant pressure, not constant temperature, and the result is something more like the Brayton cycle than the Rankine cycle.

In consequence of item (b) above, the Xenon cycle would be considerably less efficient than a Carnot cycle between the same temperature limits. In figure 3B, the area $IJKL$, corresponding to heat added, is roughly trapezoidal. Comparison of area $IJKL$ (using the trapezoidal approximation) with area of heat rejection, $IJML$, leads to an estimate of thermodynamic efficiency of 65%. Even this may be optimistic, for the area $IJKM$ is not exactly a trapezoid. Undoubtedly, 60% would be a better figure.
There is, of course, a classic solution to the problem of making the Rankine cycle approximate the Carnot cycle, when the temperature range is wide: the binary vapor system. In the present situation, it is natural to think of a binary vapor cycle, wherein Xenon would be the low temperature fluid. The high temperature fluid, ideally, should be one having a vapor pressure of some 25 to 75 atmospheres at a conservative maximum temperature (\( \sim 800 \, ^\circ\text{K} \)) and about 1 atmosphere at a reasonable temperature for transfer of heat to Xenon, preferably somewhere below 290 \(^\circ\text{K}\), the Xenon critical. It quickly becomes evident, however, that no single fluid can meet these criteria. Mercury and the alkali metals satisfy the high temperature, but not the low temperature requirement. The reverse is true for \( \text{NH}_3 \), \( \text{SO}_2 \), and other common refrigerants.

Steam is a possibility, although the high critical pressure is a decided disadvantage. Among the many advantages are

a. Mature state of the art

b. Possibility of finding ice deposits at the lunar poles

Indeed, whether or not ice is found on the moon, it is obvious that a lunar colony must have water; if the power station can utilize a material which will necessarily be present anyway, the logistics and supply problems will become simpler by some amount. In fact, one might envision a scheme whereby the use of steam in the power plant is integrated with the "domestic" use of water by the lunar colony. The thermodynamic boil-expand-condense cycle becomes then the purification (distillation) cycle necessary for re-use of water by the life support system (just what a good power engineer would normally wish at all costs to avoid). To follow up on this possibility, one would of course have to design the boiler in a special way, to permit the continuous or short-term-periodic removal of the impurities in the feed water. It has been shown by Konikoff that a partially closed-cycle physico-chemical ecology can be devised whereby an initial supply of water is not only maintained, but slowly increased, due to indirect recovery of the water present in foodstuffs, provided these latter are continuously supplied in open cycle fashion. Since a pioneer moon colony will probably need to utilize partially closed systems at first, before it becomes feasible to switch over to a fully closed system, there could be built up, during the early stages of lunar colonization, a reserve of water which might become available, at the proper time, for use in the electric power plant.

In view of all that has been said about free solar energy, and the reasonably high efficiency of the supercritical Xenon Rankine cycle, it may be somewhat academic to push further in the search for a composite cycle, employing different substances in such a way as to realize the classic Rankine cycle pattern on the temperature-entropy diagram. Such a search, indeed, leads to a quaternary vapor cycle. Table 1 affords a synoptic view of temperature and pressure relations which could hold for a 4-fluid system, utilizing mercury, water, ammonia, and xenon.
Solar energy would be used directly to boil the mercury, at moderate pressure and conservative temperature, also to superheat the Mercury slightly. The superheat serves to ameliorate the erosion problem\textsuperscript{21}; moreover, as will be seen in the section on the section on the solar boiler, it is probably easier to design for superheat than for saturation. The superheat called for in Table 1 is very slight, thus avoiding the materials problems associated with high temperatures. One might prefer, however, to go to somewhat higher temperatures to prevent condensation of mercury within the turbine.

In either case the mercury exhausted from the turbine is condensed at a temperature convenient for boiling water. The action takes place in a heat exchanger wherein pressures on both sides are regulated to maintain an 11 °C temperature difference between condensing mercury and boiling water.

The resulting saturated steam is delivered to a separate solar furnace, where it acquires several hundred degrees of superheat. It then expands through a turbine to a temperature not far above that which will normally be maintained in the living spaces of the colony. Heat of condensing steam serves to boil the ammonia. Saturated NH\textsubscript{3} vapor takes on superheat, expands through a turbine to a temperature well below the critical for Xenon, where once again the condensation of the spent vapor boils the lower temperature liquid, and the final stage goes through the superheat, expansion, and condensation steps.

The system just described is indeed a complicated monstrosity, and certainly would not be adopted merely for the sake of conserving sun power (which is going to be wasted anyhow, in one way or another). The only real justification for considering the quaternary vapor cycle lies in the possibility that by its very complexity it may serve a number of auxiliary functions (temperature control, process heating, refrigeration, distillation, etc.) for the colony. A highly sophisticated control system might allow for both heating and cooling by diversion of the appropriate fluids, at the right places in the cycle. Such heating and cooling would constitute an efficient use of power resources, since the heat transfer would be always into a fluid which needed to pick up heat, or out of a fluid which needed to lose heat, in the normal process of operation of the cycle.

Finally, it may be remarked that the complexity of the quaternary system does not necessarily imply low reliability. On the contrary, its reliability could be greater than that of a single fluid system by the addition of a few relatively simple provisions for operation in alternate (degenerate) modes. Standby loops would need to be provided, such that the higher temperature fluids could, in emergency, flow through condensers radiating to space. Such an arrangement would cost very little additional because of the smaller radiator area needed for the higher temperature fluids. Similarly, provision would have to be made for utilization of the superheaters, in emergency, in place of the heat-exchange boilers. Sophisticated control would be necessary; but the principle is straightforward.
General principles of solar collector design are well understood, and have been reviewed in recent literature. Parabolic or paraboloidal reflectors would be preferable to lenses. The reflectors could be fabricated on the moon, of lightweight material; lenses might have to be lifted from earth. Moreover, the pitting of lenses by meteorites could be a problem. Parabolic reflector surfaces would also be vulnerable to meteorite puncture; but in the case of these latter, the degradation rate would undoubtedly be slower, and the difficulties of repair less severe.

Mackay has suggested an array of parabolic cylinders, each with its own boiler tube in the focal line. The entire array is caused to move as a unit, facing the sun; turbine, pump, radiator, and all accessories are mounted upon the single unified structure.

In the larger, more complex and more permanent installation presently under consideration, it would not be feasible to mount everything together. Instead, the design represented in figure 5 is suggested. This design would be appropriate to serve the heat-input portion of the Xenon Rankine cycle described earlier, and with some modification would be applicable to other cycles.

The boiler tubes stand vertically, in a bundle, at a point which is the center of symmetry in the plan view. These tubes would not have to rotate. The plumbing could be simple and permanent.

Closely surrounding the bundle of tubes there would be a cylindrical shell, to control radiation entering and leaving the tube assembly. This shell serves to block radiation from the tubes outward into space. There is, however, a relatively narrow slit running up and down the length of the shell. This slit permits entry of radiation from the mirror, and also, unavoidably, permits re-radiation outward from the tubes. The cylindrical shell must rotate with the apparent motion of the sun, the slit always facing directly away from the sun, toward the reflector.

The mirror would consist of highly reflective foil material in a layered construction, mounted upon a structural frame. The structural frame, in turn, would rest upon a circular track, upon which the entire assembly could roll. A simple optical sensor would govern the motion of the assembly, maintaining the axis of the parabolic reflector in constant alignment with the incoming rays from the sun.

Geometrically, the mirror would consist of two parts, the lower part being a parabolic cylinder and the upper part a matching paraboloid of revolution. Focal length would of course be the same for the two, and would be slightly less than the distance from the vertex of the parabola to the center of the boiler tube structure. The focal line (for the parabolic cylinder) and the focal point (for the paraboloid) would lie just inside the slit in the radiation shield which encloses the tube assembly.
In operation, the pressurized Xenon would be pumped in at the bottom of the tube structure and would slowly rise, expanding and picking up heat in the process. Since the concentration ratio is higher for the paraboloidal than for the parabolic reflector, the highest temperatures occur at the top. There would be a steady flow of heat from the top downward along the tubes, the heat also draining into the fluid, along the length of the tubes. The gas itself, upon reaching the top of the structure and acquiring there its maximum temperature, would then be forced to flow downward in a well insulated tube placed in the center of the bundle. Turbine is located underground, preferably close to the above described solar furnace assembly.

Suppose the dimensions of the mirror to be as follows:

- 20 meters, width of shadow
- 30 meters, height of cylindric elements
- 20 meters, diameter of rim of paraboloidal crown

Total projected area, available for trapping sunlight, would then be 818 square meters, minus some small amount due to the shadow of the absorber. At 1394 watts/meter\(^2\), this comes to \(\sim 1140\) kw gross energy input from the sun. Only a portion of this energy can be transferred to the working substance, depending initially on such factors as

\[ C, \text{ the concentration ratio} \]
\[ = \frac{\text{radiant flux density received by absorber}}{\text{radiant flux density impinging on concentrator}} \]

\[ N_c, \text{ the concentration efficiency} \]
\[ = \frac{\text{radiant energy entering slit}}{\text{radiant energy impinging on concentrator}} \]

and also, eventually, upon the temperature relationships existing between the absorber surfaces and the working fluid. The concentration ratio depends essentially upon the rim angle \(\Theta\) (73\(^\circ\), in our suggested design) and the width of the slit. A concentration ratio of 100 should be attainable, without undue difficulty, in that portion of the system wherein the focusing is two dimensional. In the "crown" portion, with 3 dimensional focusing, one can obtain concentration ratios far higher (\(\geq 15,000\)), with correspondingly high temperatures, if necessary. It is desirable, however, not to go to extremely high temperatures --- not only on account of materials limitations, but also to keep the re-radiation losses to a reasonable level. Temperatures should be just high enough to make for effective heat transfer from tube walls to fluid.

In the proposed design, the cylindric part of the system, by itself, could operate at 660 \(\text{K}\), (with the working fluid draining away 80\% of the available heat) or as high as 800 \(\text{K}\) (with only 50\% of the available heat being transferred to the fluid). Since in the proposed design there would be an extra-high temperature hot spot at the top of the assembly, temperatures down the length of the tube would be influenced accordingly. Exact analysis of system efficiency would best
be accomplished by a computer, considering the varying temperatures and gas densities from point to point in the flow line. However, in view of the flexibility resulting from the combination of 2 dimensional and 3 dimensional focusing, it seems altogether reasonable to expect an overall efficiency (gain in enthalpy divided by solar input) not far below the maximum considered by Mackay,¹⁷ say, about 80%. This leads to a figure of 910 Kw input to the thermodynamic cycle, which in turn would break down to something like

480 Kw useful output
400 Kw rejected in radiator
30 Kw miscellaneous losses

Reviewing the above, one might raise the question of scaling either up or down in capacity rating. Especially might one be interested in the possibilities in the upward direction. Since the reflector has to be mounted upon a slowly rotating platform, there is indeed a practical upper limit to its size and weight, even after all allowances are made for low gravity and the absence of weather. The alternative of using a number of solar furnaces, each of moderate size, has drawbacks also. Two or more furnaces placed in proximity to one another would introduce the problem of shading. Yet they could not be scattered far apart, and stay essentially at the crest of a single peak. Conceivably, one may find a small, high crater, near the pole, with walls fairly even all around. Using such a formation, one might possibly mount small furnaces at intervals about the rim, tolerate a certain amount of shading, and use the floor of the crater for the radiator. Eventually, however, this question will have to wait; our present knowledge will take us just so far.

**HEAT REJECTION**

To radiate heat at 170 °K, at the rate of 400 Kw, would require an enormous emitting surface.

\[
\text{Area} = \frac{400(10^3)}{\sigma \varepsilon (T_2^4 - T_0^4)}
\]

With suitable choice of units, the radiator area comes out in square meters:

\[
\begin{align*}
T_2 &= 170 \, °K \\
T_0 &= 30 \, °K \\
\sigma &= 5.67(10^{-8}) \, \text{watts/(m}^2 \, °K) \\
\varepsilon &= 0.95 \, \text{emissivity, dimensionless}
\end{align*}
\]

Area = 8,900 square meters
To build a radiator covering 2 acres of territory in a lunar crater would indeed be a formidable undertaking, although not really far out of line with the cost and difficulties elsewhere in the proposed power project. One could, of course, cut the radiator area in half by working at 200 °K instead of 170 °K. Indeed, the practical answer may lie in this direction. Meanwhile, however, any possibility of a reasonable alternative should be explored.

In the absence of liquids on the moon, the prospects are not bright. If, however, it turns out that thermal conductivity of surface layers in the shadowed craters is higher than expected, one might unload some part of the heat by conduction. The heat thus transmitted to the ground would still have to radiate away, at the characteristically slow rate; but one could at least economize somewhat on the cost of tubes, fins, and working fluid to fill the tubes.

Other schemes can doubtless be thought of, whereby bulk material on the moon's surface can be caused to absorb heat at low temperature. For example, a mining operation might involve sifting or sieving of powdery or granular material. Just possibly, the temperature differential of 50 degrees or better could be turned to account, in those situations where the material would have to flow in a trough or conveyor channel. The possibility of finding ice deposits in shadowed areas has already been mentioned. Either alone or in combination with other materials the ice might be caused to pick up heat from condensing xenon, as a preliminary to other steps in transporation or processing. Once again, we seem to have run onto a problem where little headway can be made until people have landed on the moon and begun the work of exploration.

RECAPITULATION

Main conclusions are summarized below:

1. A physical situation unique in the solar system is found in the rugged terrain of the lunar polar regions.

2. This special situation prompts the consideration of a special kind of electric power generating station, such as would be impossible elsewhere.

3. High theoretical efficiencies can result from the immediate proximity of perpetual sunlight and perpetual shadow; but the endeavor to capitalize on this resource leads to serious practical difficulties in the design of collectors and radiators.

4. Xenon has properties which make it a very desirable working fluid for a heat-engine cycle, especially if the lower end of the available temperature spectrum is to be exploited. Other rare gases, alone or in combination, should also be considered.

5. Design of the special power station can and should be strongly influenced by the possibility of integrating the power requirement with other requirements, ecological and industrial, of the colony.

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<td>(996)</td>
<td>(1025)</td>
<td>(176.5)</td>
<td>(440)</td>
<td>(0.77)</td>
</tr>
<tr>
<td>Second</td>
<td>H$_2$O</td>
<td>489</td>
<td>800</td>
<td>21</td>
<td>311</td>
<td>0.0645</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(420)</td>
<td>(980)</td>
<td>(309)</td>
<td>(100)</td>
<td>(0.95)</td>
</tr>
<tr>
<td>Third</td>
<td>NH$_3$</td>
<td>300</td>
<td>433</td>
<td>10.4</td>
<td>233</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(80)</td>
<td>(320)</td>
<td>(153)</td>
<td>(-40)</td>
<td>(10.4)</td>
</tr>
<tr>
<td>Fourth</td>
<td>Xe</td>
<td>222</td>
<td>350</td>
<td>10.8</td>
<td>170</td>
<td>1/3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-60)</td>
<td>(170)</td>
<td>(159)</td>
<td>(-154)</td>
<td>(19.1)</td>
</tr>
</tbody>
</table>

Temperatures are in degrees K, first line, and in degrees F, (second line).
Pressures are in standard atmospheres, first line, and in p.s.i.a., (second line).

- $T_B =$ boiling temperature
- $T_S =$ superheat temperature
- $T_2 =$ exhaust (condensation) temperature
- $P_1 =$ inlet pressure
- $P_2 =$ exhaust pressure
FIGURE 1  Saturated Liquid Line for Krypton
Pressure in Standard Atmospheres

Kelvin Temperature

Critical Point

Triple Point

FIGURE 2  Saturated Liquid Line for Xenon
FIGURE 3 Comparison of Rankine Cycles

A. Typical Rankine Cycle, Ideal

B. Xenon Cycle, Rankine with Superheat
Figure 4. Working Fluids

*Lunar Temperature in Perpetual Shadow*
Figure 5A. Plan View Solar Furnace Assembly
FIGURE 5B  Pictorial View, Mirror and Absorber