Multi-Megawatt Gas Turbine Power Systems for Lunar Colonies

Albert J. Juhasz
Glenn Research Center, Cleveland, Ohio

December 2006

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to *help@sti.nasa.gov*

- Fax your question to the NASA STI Help Desk at 301–621–0134

- Telephone the NASA STI Help Desk at 301–621–0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076–1320
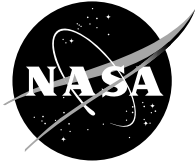
Multi-Megawatt Gas Turbine Power Systems for Lunar Colonies

Albert J. Juhasz
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

December 2006

Acknowledgments

This work was conducted at NASA Glenn Research Center Thermal Energy Conversion Branch.

Level of Review: This material has been technically reviewed by technical management.

Multi-Megawatt Gas Turbine Power Systems for Lunar Colonies

Albert J. Juhasz
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

A concept for development of second generation 10 MWe prototype lunar power plant utilizing a gas cooled fission reactor supplying heated helium working fluid to two parallel 5 MWe closed cycle gas turbines is presented. Such a power system is expected to supply the energy needs for an initial lunar colony with a crew of up to 50 persons engaged in mining and manufacturing activities. System performance and mass details were generated by an author developed code (BRMAPS). The proposed pilot power plant can be a model for future plants of the same capacity that could be tied to an evolutionary lunar power grid**.**

Nomenclature

A_r radiating area, m^2
C_p working fluid specific heat, J/kg-K
D   average sun-to-lunar orbit distance ($1.496*10^{11}$m)
h_r gas heat transfer coefficient, W/m^2- K
L   Solar Luminosity ($3.86*10^{26}$ W)
$\dot{m}$ working fluid mass flow rate, kg/s
P_{IC} compressor Inlet Pressure, mPa
P_{OC} compressor Outlet Pressure, mPa
P_{IT} turbine Inlet Pressure, mPa
P_{OT} turbine Outlet Pressure, mPa
T_e, T_s equilibrium surface or space sink Temperature, K
T_{win} wall surface temperature at Radiator duct inlet, K
T_{wex} wall surface temperature at Radiator duct exit, K
α cycle temperature ratio; α = solar absorptivity (eq. (1) only)
ε radiator surface emissivity
ε_R regenerator effectiveness
γ specific heat ratio of working fluid
η_b cycle heat input efficiency;
η_c isentropic efficiency of compressor (function of polytropic efficiency, pressure ratio, γ)
η_t isentropic efficiency of turbine (function of polytropic efficiency, pressure ratio, γ)
η_{th} thermodynamic cycle efficiency
σ Stefan-Boltzmann constant ($5.67*10^8$ W/m^2-K^4)

I. Introduction

Ever since the first lunar landing over 36 years ago, establishment of a permanent lunar presence by humans has been an intriguing concept. Establishment of initial lunar outposts which would gradually evolve into bases and eventually human colonies has been the topic of numerous studies (Eckart ed. 1999). Lunar bases and colonies would be strategic assets for development and testing of space technologies required for further exploration and colonization of favorable places in the solar system, such as Mars.

Specifically, the establishment of lunar mining, smelting and manufacturing operations for the production of oxygen, Helium 3 and metals from the high grade ores (breccias) of asteroid impact sites in the Highland regions would result in extraordinary economic benefits for a cis-lunar economy that may very likely exceed expectations. For example, projections based on lunar soil analyses show that average metal content mass percentage values for the highland regions is the following (Eckart, op. cit.): Al, 13 percent; Mg, 5.5 percent; Ca, 10 percent; and Fe, 6 percent. The iron content of the "Maria" soil has been shown to reach 15 percent.

In time technologies culminating in effective utilization of these lunar resources would enable more ambitious projects such as construction of optical and radio astronomy facilities. Besides the tremendous benefits resulting from the absence of radio interference on the lunar far side, operation of a lunar radio telescope (RT) as an element of a "Very Large Baseline Array" (VLBA) could be integrated with an earth based telescope system. The separation distance of such a system would be some thirty times wider than the maximum possible separation of earth based telescopes. Since telescope resolving power is determined by the ratio of wavelength-to-baseline separation distance, resolutions for the RT system at centimeter scale wavelengths would approach values of less then 10^{-5} arc seconds, thus permitting detailed observations on disks of nearby solar size stars (Zeilick and Gaustad, 1990).

Regarding optical astronomy the far side of the lunar surface would be the best site for an observatory in the Solar System. A key requirement for the establishment of permanent human presence on the lunar surface is a reliable power system to supply energy demands for life support, science, and operational requirements. Since such a power system is to provide continuous output through the 29.5 day synodic month, half of which receives no sunlight unless the power plant is located at the poles, the advantage of a heat source independent of the sun is obvious. Several studies have been performed using the lunar regolith soil as a thermal energy storage medium integrated with a solar power system. The conclusion reached was that while thermal energy could be stored as relatively low temperature sensible heat, high temperature latent heat storage necessary for a viable dynamic power system would require an elaborate heat distribution, storage, and retrieval network of such technological complexity that the concept was judged to be impractical.

To circumvent the energy storage problems associated with solar power, energy conversion systems using nuclear heat sources offer definite advantages for lunar power plants. In this report the author discusses a 10 MWe conceptual lunar power plant design utilizing two 5 MWe CBC (Closed Brayton Cycle) helium gas turbine power systems operating in parallel with each other and in series with a single high temperature gas reactor (HTGR).

A lunar power plant of up to 30 MWe capacity utilizing turbo-alternator engine modules was discussed in a previous report (Juhasz and Sawicki, 2005). In that report it was concluded that, due to the large radiator area requirement a 10 MWe power plant composed of two parallel 5 MW CCGT power systems drawing on a single reactor for their thermal energy supply, would greatly simplify the radiator configuration. To facilitate the cycle heat rejection process, a unique approach to lowering lunar daytime sink temperatures based on the analysis of Bien and Guentert (1969) using a light weight (~0.25 kg/m^2) aluminized plastic cover in the vicinity of the radiator is proposed. Conversely, a method for generating excess power during the lunar night, when sink temperatures are very low, could be utilized as discussed by Juhasz and Sawicki (2005). Before discussing the conceptual design of a lunar power system, a brief review of the lunar thermal environment is in order.

II. Lunar Temperature Environment during Synodic Month

The lunar environmental sink temperatures over the synodic month from full moon to the next full moon, as seen from earth, are shown in figure 1. Lunar midday temperatures can be computed from a relatively simple relationship based on the solar luminosity, and lunar surface emissivity and absorptivity to solar radiation as shown in equation (1)

$$T_e = \sqrt[4]{(\alpha/\varepsilon)\left(L/\left(4\pi\sigma D^2\right)\right)} \tag{1}$$
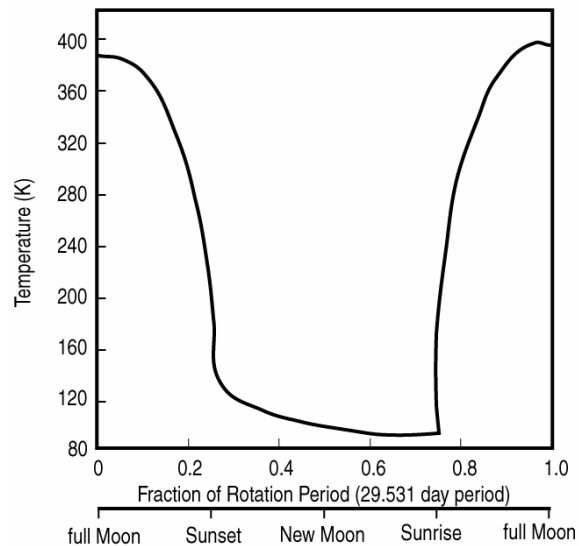
Figure 1.—Lunar surface temperatures
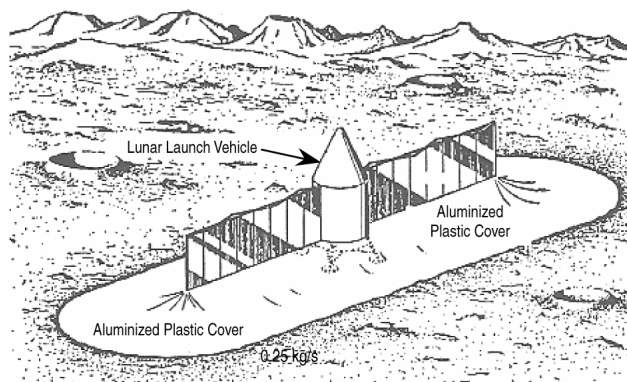variation—lunar noon to noon.

Figure 2.—Power system with in-line radiator and
reflective cover on moon (Bien and Guentert).

It is understood that "full moon" as viewed from earth actually is lunar midday at a central longitude location on the side of the moon facing earth. A more detailed procedure which includes infrared radiation from Earth during the lunar night is given by Juhasz (2001), who obtained lunar night temperatures of 70 K. Regarding figure 1, surface temperatures are seen to drop from about 385 K at noon to near 120 K at sunset, then to just over 80 K before sunrise. Temperatures then (in terms of lunar time) rapidly climb to the previously quoted noontime, or "full moon" values. A close examination of the temperature profile shows that lunar surface temperatures are at 360 K or above for about 28 percent of the synodic month, which is more than 8 earth days. Obviously, heat rejection to such high sink temperature levels would require very large radiator surface areas. Fortunately, as explained below, the sink temperature can be lowered by the use of an aluminized sheet of plastic, which can be spread out over the lunar surface in the vicinity of the radiator as proposed by Bien and Guentert (op. cit.) and illustrated in figure 2. In this concept the vertically oriented radiator wings, emanating on both sides of a centrally located vehicle, which contains the nuclear reactor/shield heat source and the gas turbine power system, are aligned in the lunar equatorial plane thus ensuring that negligible solar radiation is incident on the radiator, because the inclination of the mean lunar equator to the ecliptic is only ~1.6°. Even if the

outpost or base were to be located not at the lunar equator, but within a latitude range of ±30°, the lowering of sink temperature and corresponding radiator reduction could still be achieved by tilting the radiator relative to the local vertical at an angle equal to the local latitude. Of course the direction of tilt would be towards the lunar equator.

As will be shown in section IV.B of this paper, placing the reactor below ground level for permanent power plant installations will permit the lunar soil to provide some of the neutron and gamma shielding requirement for the energy conversion and radiator sub-systems. In addition, an exclusion zone of up to 2 km radial distance from the reactor is advisable for human crew personnel. Maintenance and repairs within the exclusion zone will need to be carried out by remotely controlled devices or autonomous robots. The aluminized sheet mentioned above, having a low solar absorptivity (near 0.12), would replace the high lunar surface absorptivity, α, in the vicinity of the radiator which may be as high as 0.9. Since accumulation of lunar dust on the reflective cover would reduce its effectiveness, attention will have to be paid to preventing transport of lunar material onto the cover by robots or crew. This can be done by keeping one or two "maintenance" robots permanently positioned on the cover, near its edge, so that no crossing of the lunar soil-to-cover boundary is necessary.

It is this high solar absorptivity which leads to the high lunar day sink temperatures for a vertical radiator when the sun is directly overhead. Based on the mathematical analysis of re-radiating and reflecting surfaces a chart as shown in figure 3 was constructed. Use of this chart allows accurate estimation of sink temperature as a function of "cover length-to-radiator height" ratio with radiator temperature as a parameter.

Note that the lowest of the three radiator temperatures, namely 333 K, would be impossible without the cover, since the sink temperature is already at 334 K. Figure 3 also shows that for a radiator height of 1 m a cover with about 6 m on each side would be sufficient to lower daytime sink temperatures to no more than 230 K.

The reference value of ~340 K for a horizontal radiator with $\alpha/\varepsilon = 0.55$ was confirmed by the *TSCALC* code (Juhasz, 2001, op cit.) to agree with the previously given value. Use of this code showed that the minimum lunar night sink temperatures would drop to 70 K.
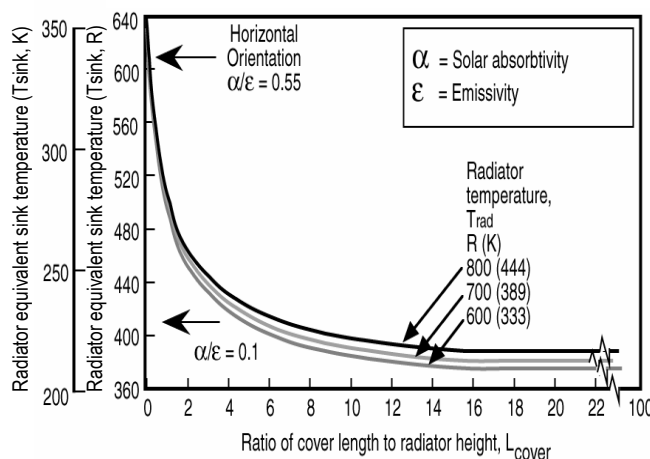

Figure 3.—Effect of cover length and radiator temperature on
equivalent sink temperature (Bien and Guentert).

III. Closed Cycle Gas Turbine (CCGT) Power System Conceptual Designs

As envisioned for purposes of this study, lunar power plants with nuclear reactor heat sources will likely evolve from a power output of a few tens of kWe for an early outpost to multi-megawatt levels to meet the needs of a lunar colony of 50 to 60 individuals productively engaged in mining and manufacturing operations. As discussed previously (Juhasz and Sawicki, 2005) power plant output would need to grow from about 20 kWe to multi megawatt levels. For this study, a CCGT lunar power plant, also referred to as a CBC (Closed Brayton Cycle) power system, was conceptually designed. The system configuration comprised a single high temperature gas reactor heat source typified by the pellet reactor proposed by Juhasz, El-Genk and Harper (1992). This reactor heats the He working fluid supplied to two 5 MWe CBC units, each with their in-line flat plate radiator mounted vertically. Assuming the radiator being surrounded by the aluminized sheet discussed above day time sink temperature was set at 230 K. Using the BRMAPS code (Juhasz, 2005), a preliminary conceptual preliminary design of a lunar power plant was laid out by replacing the SP-100 thermoelectric conversion system with a CBC, as suggested in figure 4. It should be understood that this study represents the first step in a number of design iterations before final detailed design is arrived at.
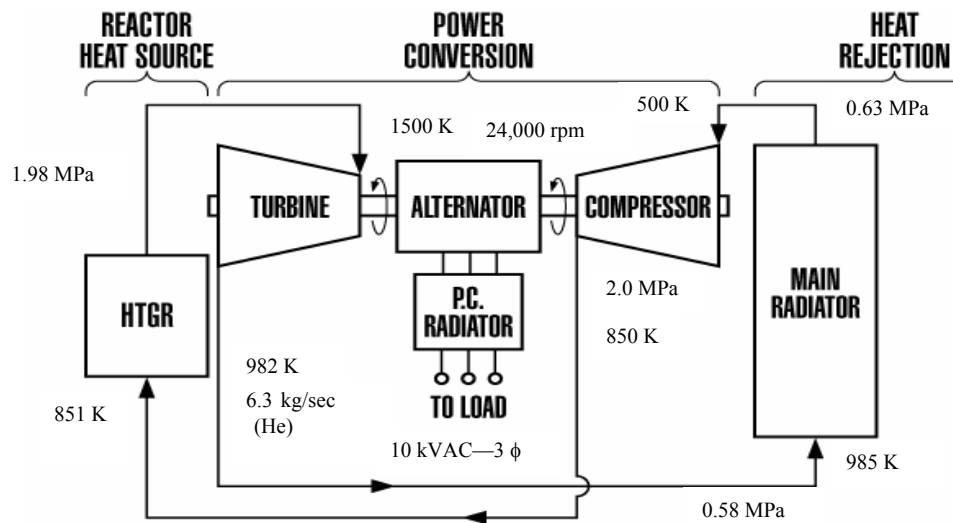

Figure 4.—Simplified baseline schematic for one of two parallel 5 MWe lunar He CBC turbo-alternators for a 10 MWe plant. Thermodynamic cycle efficiency = 24 percent.

IV. Mathematical Analysis of Closed Brayton Cycle

The analysis of the proposed power system configuration was performed using the computational procedures contained in BRMAPS. This code contains a key sub-routine which performs a triple objective non-linear optimization procedure using generalized reduced gradient techniques to identify the three cycle operating conditions at which maximum thermodynamic efficiency, minimum radiator area, and minimum system mass are obtained. Salient theoretical expressions derived for determining the needed objective functions are given below:

A. Thermodynamic Cycle Efficiency—η_{th}

With cycle efficiency defined as the net work output, i.e., the difference between turbine work and compressor work, divided by the cycle input thermal energy, the author derived the expression given in equation (2) for the CBC thermodynamic efficiency, η_{th}.

$$\eta_{th} = \frac{\eta_b\left(\frac{\Theta_T - 1}{\Theta_C}\right)\left(\alpha\eta_t - \frac{\Theta_C}{\eta_C}\right)}{\alpha(1-\varepsilon_R) + \varepsilon_R\eta_t\alpha\left(1 - \frac{1}{\Theta_T}\right) + \varepsilon_R - 1 + \frac{1}{\eta_C}\left(1 - \Theta_C + \Theta_C\varepsilon_R - \varepsilon_R\right)} \tag{2}$$

where

$$\Theta_C = (P_{OC}/P_{IC})^{(\gamma-1)/\gamma} \text{ is the compressor pressure ratio parameter} \tag{3}$$

and

$$\Theta_T = (P_{IT}/P_{OT})^{(\gamma-1)/\gamma} \text{ is the turbine pressure ratio parameter} \tag{4}$$

Note that due to cycle pressure loss the "loss pressure ratio," $(P_{IT}/P_{OT})/(P_{OC}/P_{IC}) \sim 0.94$ for a regenerated cycle with $\varepsilon_R = 0.95$. For a non-regenerated cycle the ratio is in the 0.975 to 0.985 range.

B. Radiating Area

Similarly, an analysis of gas turbine working fluid being cooled in a radiator duct led to the following expression for radiating area required for a CBC space power system.

$$A_r = \dot{m}\cdot C_p \cdot \left[\frac{1}{h_r}\cdot\ln\left(\frac{T_{win}^4 - T_s^4}{T_{wex}^4 - T_s^4}\right) + \frac{1}{\left(4\cdot\sigma\cdot\varepsilon\cdot T_s^3\right)}\cdot\left[\ln\frac{(T_{win}-T_s)\cdot(T_{wex}+T_s)}{(T_{wex}-T_s)\cdot(T_{win}+T_s)} - 2\cdot\left(\tan^{-1}\cdot\frac{T_{win}}{T_s} - \tan^{-1}\cdot\frac{T_{wex}}{T_s}\right)\right]\right] \tag{5}$$

Note that the actual radiator sail area depends on the view factor to the space background. Thus a flat plate surface radiating from both sides would have a sail area value equal to half that determined by equation (5). To allow for heat pipes damaged by micrometeoroids over mission life, the value for A_r was incremented by 20 percent.

C. Power System Mass

The individual masses for key sub-systems and components shown in figure 4 were determined by use of empirical mass models, taking into account certain theoretically derived parameters such as

working fluid mass flow rate, thermal power, fluid temperatures, and transport properties. Overall system mass then became the sum of component masses. The non-regenerated cycle working fluid was a pure He inert gas, heated to 1500 K turbine inlet temperature by a "High Temperature Gas Reactor" (HTGR) without an intervening liquid-to-gas heat exchanger. For the conditions shown, the turbo-alternator rotor speed was computed at 24,000 rpm. Cycle state points were computed for the minimum mass pressure ratios (near 3.5), assuming a polytropic efficiency of 0.90 for both, the compressor and turbine. The alternator is located on the same shaft with the compressor and turbine and it generates 3ϕ, 440 VAC current at 600 Hz, using three pole pairs. Due to this higher frequency, the mass of electrical components is significantly lower than for conventional power at 60 Hz. A detailed description of the 5 MWe turbo-alternator dimensions and operating conditions is shown in table 1.

TABLE 1.—PARAMETERS OF 5 MWe HELIUM TURBO-COMPRESSOR (TC)
TO BE COUPLED WITH A 3-PHASE 6 POLE AC (600 Hz) ALTERNATOR

Parameter	Compressor	Turbine
Average hub radius, m	0.13	0.262
Casing diameter, m	0.33	0.7
Axial stages	14	8
Length, m	0.85	0.32
Design rotor speed, rpm	24,000	
Total rotor shaft length, m	1.8	
He mass flowrate, kg/sec	6.25	
Compressor pressure ratio[1]	3.2	
Max. operating pressure, MPa	2.1	
Turbine inlet temp., K	1,500	

V. Conceptual 10 MW Power System With Twin 5 MWe Helium Turbo-Compressors

Assuming that advances in high temperature materials technology (i.e., refractory metals and ceramics) will enable CCGT turbine inlet temperatures in the 1500 K range, a simple (non-regenerated) CBC cycle utilizing HTGR is proposed as shown in the simplified schematic featured in figure 4. The HTGR heat source could be of the "pellet bed" design as described by Juhasz et al. (1992). The energy conversion system utilizes multi-stage axial compressor and turbine technology adapted from aircraft engine or stationary power generating applications, but modified for pure helium (He) working fluid. Note that this non-regenerated cycle uses direct heating of the helium working fluid by a gas reactor and the heat rejection at the low temperature side of the schematic would be accomplished by passing the He working fluid directly over light weight Carbon-composite (Juhasz and Bloomfield, 1992) heat pipe evaporators which protrude into the flow passage of the radiator duct. The high emissivity C-C condenser sections of the heat pipes thermally communicate with high conductivity and emissivity radiating surfaces for the final step in the space heat rejection process. An important feature illustrated by the cycle schematic is the complete absence of any heat exchangers. This should lead to lower overall system mass and cost and to higher reliability due to the smaller number of series connected components, whose system reliability will be the product of the unit reliabilities of its series connected components. The price for the reduced mass and complexity is reduced cycle efficiency, which is 24 percent as shown in figure 4. This efficiency value is about 10 percent lower than could have been obtained with regenerated cycles of 95 percent effectiveness. But the mass of each of the two recuperators for the 5 MWe CBC loops would be about 6200 kg, for a total system mass increase of 12.4 tonnes.

The conceptual design for a helium turbo-compressor rotor capable of supplying shaft power to a 5 MWe alternator is shown in figure 5. The dimensions were obtained using a one dimensional analysis
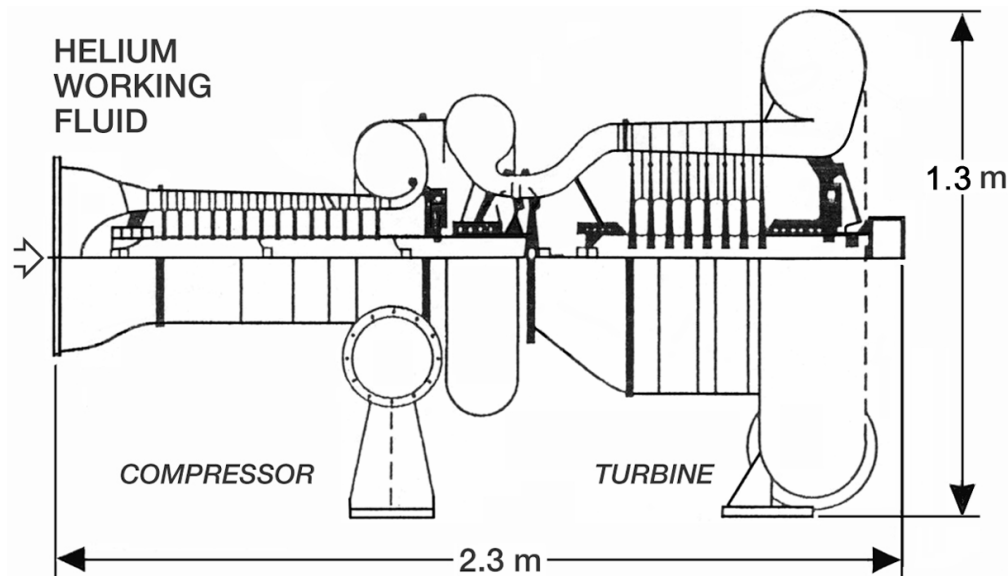
Figure 5.—Helium turbo-compressor of 5 MWe power output.

TABLE 2.—10 MW (2 PARALLEL 5MWe) BRAYTON SYSTEM COMPONENT MASS BREAKDOWN

Component	Component mass kg	Component mass (Percent of mass)
Reactor	8,540	19.8
Instrument shield	8,180	19 0
Source heat exchanger and pump	0	0
Recuperator	0	0
Turbo-alternators (2 total)	9,650	22.4
Instrumentation and controls (2)	1,000	2.3
Main radiator (2)	6,160	14.3
Auxiliary radiators (2)	440	1.0
Radiator HX, ducting, misc., and structure	9,200	21.2
Total System Mass (kg)	43,170	100

which was incorporated as a subroutine in the BRMAPS code suite. As a function of operating pressure level, working fluid mass flow rate, and molecular weight, this routine computes the number of stages, diameter, and rotor speed. Subroutine output results were validated against known dimensions and specifications for a 40,000 hp ground power machine using air working fluid in the compressor, and a mixture of air and combustion products of a hydrocarbon fuel as the working fluid for the turbine. Rotor dimensions and operational details are given in table 1 and the system mass distribution for major components and the overall mass for a 10 MWe lunar power plant are shown in table 2. The change of the working fluid molecular weight from 29 for air to 4 for He required that the flow passage area be decreased with an increase in the design speed and the number of axial stages in both the compressor and turbine.

Note that a separate study focusing on the alternator armature rotor dynamics, including radial magnetic bearing suspension for a 1/6 G lunar environment will need to be conducted at a future date. It should be noted that magnetic bearings have been demonstrated to operate at over 800 K (Provenza et al.

2003) in 1 G earth gravity. The reduced lunar gravity environment should simplify magnetic suspension of the rotor. As already mentioned, the conceptual design of a 10 MWe lunar power plant would use two turbo-compressors, each sized to drive an alternator (not shown) at 5 MWe terminal output. The alternators could be mounted on the same or on adjacent platforms and connected to the turbine shaft by a coupling. Since each of the two turbo-alternator sets would be positioned on either side of the reactor heat source in an opposed configuration, their rotational moments of inertia would cancel each other. Thus unbalance torques transmitted to the mounting platform would be minimized or cancelled. With the rotor design speed of 24,000 rpm, the frequency of the generated 3 phase AC current will be 600 Hz for a six pole alternator. Terminal voltage could be 10 kVAC.

VI. 10-Megawatt Lunar Power Plant Installation

As discussed in a prior paper (Juhasz and Sawicki 2005), the base load power output could be enhanced by taking advantage of variations in the lunar equilibrium sink temperature in the immediate vicinity of the vertically oriented heat rejection radiator surfaces. With the reactor and conical frustum shield buried below the surface as shown in figure 6, dual turbo-alternator sets can be thermally integrated with a single reactor in a manner such that their vertically oriented radiators are "in-line" i.e., in a single plane, so that the radiating surfaces do not "see" each other, meaning that the view factor between them is zero. This configuration can be accomplished at a reasonable radiator size by using power generator modules to ~5 MWe with two "in-plane" turbo-alternator modules per heat source as indicated in figure 6, thus giving 10 MWe output for each power plant As shown, each of the two flat plate radiators with two sided heat rejection has a sail area of 1200 m^2, which translates into a 240 m length for a 5 m height. The heat pipe radiator design envisioned would utilize the thermo-siphon effect by positioning individual heat pipes so that their evaporator sections are at the bottom of the radiator. Thus the lunar gravity field would be harnessed to aid the return working fluid condensate from the condenser to the evaporator.
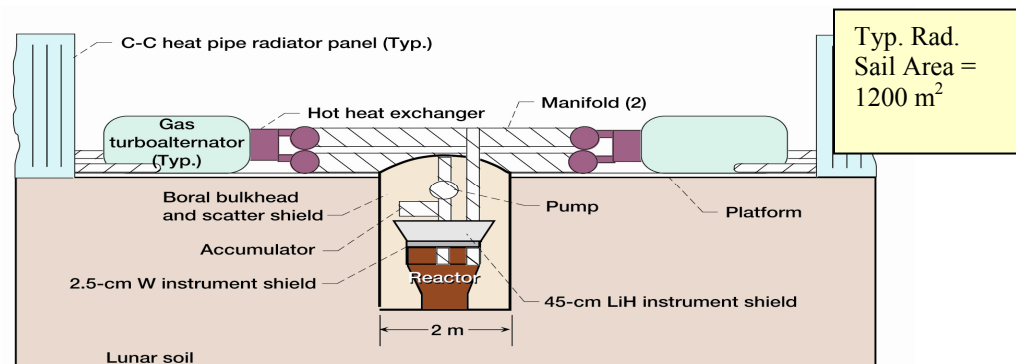

Figure 6.—Section showing subsurface reactor installation supplying thermal input to dual 5 MWe gas turbines each equipped with a flat plate heat pipe radiator.

VII. Conclusions

A lunar 10 MWe CBC power plant with a gas reactor heat source provided by two high efficiency 5 MWe turbo-alternators each of which would require a radiator with a sail area of about 1200 m^2. At 5 m radiator height the length would be reduced to ~240 m in lieu of ~1500 m for a 30 MWe unit. As lunar bases evolve into colonies, each with a 10 MW power plant, electrical interconnection of these electrical energy sources into a power grid would be a logical next step. For permanent lunar colonies, capable of supporting several hundred humans engaged in lunar mining and manufacturing activities, a power generation concept comprising a number of multi- megawatt power plants is proposed. Terrestrial power grids containing a number of power generating sources could serve as a model for an integrated lunar power system, especially concerning proven techniques of synchronizing the three phase AC power output of several power plants. Power distribution to various loads could be accomplished using copper, or aluminum alloy wiring for the IOC configuration. However, as HTS (high temperature superconducting) technology is further developed, appropriate utilization of this technology based on either YBCO (yttrium-barium-cobalt) or BSCO (barium-strontium-cobalt) could lead to significant reductions in transmission line mass.

References

Bien, D.D., and Guentert D.C.: "A Method for Reducing the Equivalent Sink Temperature of a Vertically Oriented Radiator on the Lunar Surface," NASA TM X-1729, Jan. 1969.

Eckart, P. ed.: "The Lunar Base Handbook," Mc Graw Hill Companies Inc., 1999.

Juhasz, A.J.; and Bloomfield, H.S.: "Development of Lightweight Radiators for Lunar Based Power Systems," NASA TM 106604, May, 1994. Presented at the 24th ICES, Friedrichshafen, Germany, June 20–23, 1994.

Juhasz, A.J.; and Sawicki, J.T: "Lunar Surface Power Systems with Fission Reactor Heat Sources," NASA/TM—2005-214003, November 2005.

Juhasz, A.J., El – Genk, M.S., and Harper, W.B.: "Closed Brayton Cycle Power Systems with a High Temperature Pellet Bed Reactor Heat Source for NEP Applications," NASA TM 105933, Oct. 1992.

Juhasz, Albert J.: "An Analysis and Procedure for Determining Space Environmental Sink Temperatures with Selected Computational Results." NASA/TM—2001-210063, Jan. 2001.

Juhasz, A.J. "Analysis and Numerical Optimization of Gas Turbine Space Power Systems with Nuclear Fission Reactor Heat Sources" Doctoral Dissertation, Cleveland State University, May 25th, 2005.

Zeilik, M. and Gaustad, J. "Astronomy—The Cosmic Perspective" 2nd Edition, John Wiley & Sons, 1990.

Provenza, A.J.; Montague, G.T.; Jansen, M.J.; Palazzolo, A.B.; Jansen, R.H. "High Temperature Characterization of a Radial Magnetic Bearing for Turbomachinery," Proceedings of ASME/GTI Turbo Expo 2003, June 3 16–19, 2003, Atlanta, Ga., USA.

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 2006	Technical Memorandum

4. TITLE AND SUBTITLE

Multi-Megawatt Gas Turbine Power Systems for Lunar Colonies

5. FUNDING NUMBERS

WBS 22–973–90–01

6. AUTHOR(S)

Albert J. Juhasz

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–15789

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2006-214658
AIAA–2006-4117

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories: 44, 37, and 59

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A concept for development of second generation 10 MWe prototype lunar power plant utilizing a gas cooled fission reactor supplying heated helium working fluid to two parallel 5 MWe closed cycle gas turbines is presented. Such a power system is expected to supply the energy needs for an initial lunar colony with a crew of up to 50 persons engaged in mining and manufacturing activities. System performance and mass details were generated by an author developed code (BRMAPS). The proposed pilot power plant can be a model for future plants of the same capacity that could be tied to an evolutionary lunar power grid.

14. SUBJECT TERMS

Space nuclear power; Lunar power; Nuclear power plants

15. NUMBER OF PAGES

16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	