

COMMUNICATIONS AND COMMAND FOR A LUNAR NUCLEAR POWER PLANT

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Summary Extensive lunar exploration will require the establishment of relatively long-term lunar bases. The power demands and the high fuel transportation costs to support these bases will necessitate the utilization of nuclear power plants. In the following paper, the lunar exploration base is briefly described. The economics of electrical power production on the Moon are discussed and the need for a nuclear power plant is established. A power plant configuration is shown. Communications and command requirements are presented and the communications and command system is described.

Introduction The Office of the Chief of Engineers (O. C. E.) Corps of Engineers, has directed the Westinghouse Electric Corporation in a study* of a lunar surface nuclear power plant in support of the National Aeronautics and Space Administration, Lunar Exploration System-Apollo (LESA) Program. The conceptual design for a lunar nuclear power plant communications and command system herein described was developed in conjunction with the O. C. E. directed study. The Apollo mission will accomplish the initial lunar exploration, but extensive lunar exploration will require the establishment of more nearly permanent lunar surface bases. The Westinghouse concept of an essentially fully developed lunar base is shown in Figure 1.

Description of Base The transport vehicle assumed for all of the payloads shown in Figure 1 is the Saturn V, which would carry about 25,000 pounds of unmanned payload. The nuclear power supply (1) would produce about 100 kilowatts of electric power from a turbine generator powered by a nuclear reactor. The entire plant would be contained in a single Saturn V payload section, which measures about 20 feet in diameter by 30 feet in height. The nuclear unit provides power for life support, fuel and oxygen regeneration, and operation of communication equipment. A regeneration unit (2) processes the chemical fuels of secondary power supplies. For example, water produced by the fuel

* Engineering Study of a Nuclear power Plant for Lunar Exploration System for Apollo (U.S. Army Corps of Engineers Contract DA-49-129-ENG(NASA)-1

cells of the roving vehicle is broken down by electrolysis into oxygen and hydrogen, which are then liquefied, stored cryogenically, and reused. Personnel shelters (3) accommodate six men each, or even up to twelve each in an emergency. They have complete life-support systems and use power from either the nuclear supply or from a backup fuel-cell supply in the shelter. Each shelter has a parabolic antenna for video and data transmission and communication with the Earth. A tall mast on each supports VHF antennas for communication with men outside the shelters and with the two-man lunar roving vehicle (4) when in line-of-sight range. Lunar excursion modules (LEM) (5) are vehicles in which men arrive on the Moon and return to a lunar orbit. In lunar orbit, the ascent module rendezvous with an Apollo spacecraft for the return to Earth. Expended lunar excursion module descent stages (6) are left on the lunar surface when the ascent stages depart. A 500-foot mast supports the ground-wave propagation antenna (7) used for over-the-horizon lunar surface communications. Small two-wheel resupply trailers transport materials, equipment, and food among units of the base. Logistics vehicles (8) transport the roving vehicle, resupply trailers, and resupply payloads from Earth to the lunar base.

The initial NASA LESA study considered four levels of lunar base development:

- (1) Three-man crew, three months duration
- (2) Six-man crew, six months duration
- (3) Twelve-man crew, twelve months or longer duration
- (4) Eighteen-man crew, twenty-four months duration, or longer.

The energy requirement for each of the bases was estimated. Bases 1 and 2 require relatively little energy and, considering all problems, fuel cells supplemented by solar cells for shelter power during the lunar day, will most economically supply the required power. For Bases 3 and 4, it quickly became apparent that a nuclear power plant is essential. Hydrogen, oxygen fuel cells require nearly one pound of reactants for each kilowatt hour of output. Transportation cost to the lunar surface is estimated at \$5000 per pound. Based upon this estimate, the energy cost using fuel cells for Bases 3 and 4 would be millions of dollars a day and a nuclear power plant would become an economic necessity.

Power Plant Description Figure 2, “Functional Diagram of Lunar Nuclear Power Plant”, illustrates the operation of the plant. The primary fluid, liquid potassium is circulated through the reactor and to the boiler where heat is transferred to the secondary mercury loop which operates in a Rankine cycle. In the Rankine cycle, the fluid is vaporized, drives a turbine, is condensed, pumped up to boiler pressure, and returned to the boiler. One of the unusual features of this plant is the manner in which heat is removed from the condenser in the secondary loop. On the Moon, heat must be rejected by radiation, and since meteoroids may puncture the radiator with resultant loss of fluid,

it is not feasible to have the secondary fluid go through the radiator. To remove the heat, there are about 200 independent reflux condensing tubes. By having a large number of independent radiator loops, several meteoroid punctures can occur with only a small effect on the complete system. As can be seen from the block diagram, there are duplicate secondary loops, pumps, etc. Reliability requirements dictate this redundancy; however, where these components are in parallel, only one operates at a time. The design capacity of the power plant shown is 100 kw electrical.

Power Plant Control and Operation Power plant control is automatic. Base personnel have initiation and intervention capabilities. In view of the communication lag time, the possibility of temporary Earth-Moon communication outages, and the requirements of safety, extensive reliance cannot be placed upon Earth systems or personnel for control purposes (although they have the same intervention and initiation capability as lunar personnel), but large savings in operational labor can be effected by allowing the Earth system to assume the burdensome plant monitoring and data accumulation function. During normal operation lunar base personnel have the option of activating a reactor SCRAM (rapid shutdown) on high gamma levels at the base, or when an incipient unsafe condition exists during a period of interruption in Earth-Moon communications. A recorder positioned at the base will be activated to record plant data for transmission to Earth at a later time, should such an interruption occur. Large changes in load, which for economic reasons should not be accommodated by the ballast load, can also be made by lunar personnel. A similar option is available to Earth personnel.

The plant would be automatically shut down (SCRAMMED) under unsafe conditions. No manual action is required to base personnel except to initiate restart of the plant, which could also include remotely controlled draining of a failed secondary loop and filling the alternate secondary loop. The plant startup time is about 20 to 25 minutes, not including diagnosis which, in the case of a SCRAM, would be performed by Earth personnel. The switchover to redundant valves and pumps in the secondary loop can be accomplished automatically with little effect on the plant electrical load.

Communications and Command System A nuclear power plant operating on the lunar surface in support of a lunar exploration system presents an unprecedented communications and command problem. Though the challenge is great, techniques and hardware presently in use and under development, when properly applied, can meet the requirements. The design presented herein is based upon the best currently available information with regard to lunar nuclear power plant design and existing and planned Earth-Moon communications networks. Since this background information is preliminary, a definitive design of the communications and command system is not possible at this time. The purpose of this effort is to contribute to the definition of both the nuclear power plant system design and the lunar exploration system communication and command system design.

General Approach In considering the nuclear power plant communications and command subsystem, certain broad design philosophies have been developed; they are:

- (1) Maximization of reliability is the most important requirement,
- (2) Wherever practical, failure analysis capability should be included.
- (3) The communications and command subsystem is not the pacing item in a lunar nuclear power plant development program. Hardware and techniques not presently foreseen will become available well before the production design must be fixed. These new techniques and hardware can be incorporated into reiterations of the design.
- (4) In order to develop the overall subsystem design, it is necessary to make assumptions in many areas because the detailed information required to justify comprehensive engineering analyses is not available. An example of one of these assumptions is that the data words will be eight binary bits in length. In the final design, longer data words or data words of several different lengths may be used.
- (5) The techniques indicated in the functional block diagrams are in all cases conventional. More sophisticated telemetry techniques, such as on-site editing, or adaptive schemes using variable data formats were considered. The advantages of these techniques are reduced bandwidth and, as a consequence, reduced power requirements. The primary disadvantage is additional complexity, generally resulting in reduced reliability. To evaluate the applicability of adaptive telemetry or other bandwidth reducing schemes, the system requirements must be well-defined.
- (6) The communications and command hardware will make maximum use of molecular electronic, integrated circuitry techniques. These techniques will be state-of-the-art well before the 1971- 75 period. Molecular electronics offer minimum weight, volume, and power consumption and maximum reliability. Redundancy, where required, becomes quite practical due to very small weight, volume, and power consumption.

Requirements Estimates of monitoring requirements, in the form of signal lists were prepared by those engineers responsible for the design of the nuclear power plant. Approximately 1300 points must be monitored during the operational phase. The required number is somewhat less during the standby phase. (Due to limited Saturn V launch capability all lunar base payloads maybe required to survive an unattended standby period of six months to one year before the base becomes operational). The major difference in monitoring requirements is that only intermittent sampling, perhaps once every 100 hours, is required during standby. The self-monitoring requirements of the communications and control system must be added to the nuclear plant requirement. These, and a spares allowance, are estimated to total an additional 100 points. Requirements for time multiplexed data during operation are approximately 600 points each sampled once every ten seconds. An examination of the monitoring requirements

for standby and operation has shown that independent monitoring systems are not justified. Sampling rates will be changed for the two phases.

Implementation During standby on the lunar surface, an S-Band (approximately 2300 mc) command receiving system will operate continuously. Every 100 hours, upon command from Earth, the system will transmit a status check directly to Earth. Three scans of the data will require approximately one hour. This system will use an omnidirectional (hemispherical coverage) antenna and is independent of all other lunar payloads. The data will be demultiplexed and automatically compared in the available Earth station computers to identify those points which are outside established limits. The data will be stored and displayed on Earth as desired. When the system is about to become operational, the sampling system will be commanded into continuous operation and the sampling rate increased by a factor of ten. One master frame containing every data point will be transmitted every 100 seconds. Six hundred points will be sampled every second. During startup, continuous monitoring of the rate of change of reactor power will be conducted.

All of this data will be transmitted from the power plant to the lunar control station in the shelter using a VHF link. The data will then be frequency multiplexed with data from the shelter and other payloads and sent to Earth on an S-Band link. The shelter will be capable of limited monitoring and control and data storage (magnetic tape recording) will be available at the shelter. Normally, all commands to the nuclear payload will be sent directly from Earth. Limited emergency command from the shelter will also be possible. The data received at the Earth station will be continuously monitored and when out of tolerance data is detected, alarms will be initiated. All received data will be recorded. Selected data will be retransmitted to the central terrestrial station, using the Earth network.

Communications and Command System Functional Diagram The telemetry, communications, and command equipment which is located in the nuclear power plant is shown in Figure 3, "Lunar Nuclear Power Plant Telemetry and Communications System". This equipment, in conjunction with the communications equipment in the shelter provides the capability for the remote monitoring of the power plant status and integrity during the standby phase (prior to base habitation), the command and monitoring of the power plant status and integrity following a shutdown. The system provides the capability for remote monitoring and command both from the Earth and the lunar shelter except during the lunar standby phase, prior to base habitation, in which case, monitoring and command can be accomplished only from Earth.

Telemetry System The telemetry system in the nuclear power plant payload is capable of operating in three different modes with each mode corresponding to a distinct operational phase of power plant activity. The three phases of power plant activity are:

- (1) Standby, prior to base habitation and following a plant shutdown
- (2) Power plant start-up and shutdown
- (3) Power plant normal operation.

The operating modes and the capability of the telemetry system corresponding to these phases of power plant activity are:

- (1) Standby
592 quantities--each sampled once every 10 seconds
800 quantities--each sampled once every 1000 seconds
Data Rate--480 bits/sec
- (2) Start-up and Shutdown
592 quantities--each sampled once every second
800 quantities--each sampled once every 100 seconds
Data Rate--4800 bits/sec
3 quantities continuously monitored--100 cps each
- (3) Normal Operation
Same as Start-up and Shutdown except the continuously monitored signals are not required.

Common pulse code modulation (PCM) telemetry equipment will be utilized for all three operating modes. The sampling rates will be changed between standby and start-up. This is accomplished by providing the programmer with the capability of generating two sets of timing signals. The PCM telemetry equipment shown accepts both high level (0-5v) and low level (0-40mv) conditioned analog inputs and digital inputs. The outputs of these high level and low level analog multiplexers are serial pulse amplitude modulated (PAM) signals. The output of the low level analog multiplexer is amplified to the 0 to 5v level in the low level amplifier. The master multiplexer accepts the serial PAM output of the high level multiplexer and the amplified serial PAM output of the low level analog multiplexer and combines them into a single serial PAM output. The serial PAM output of the master multiplexer is converted into a pulse PCM signal in the analog to digital converter. The analog-to-digital converter digitizes the analog input to an 8-bit binary code; each 8-bit binary word is read out in parallel. The digital multiplexer combines the parallel digital inputs from the analog to digital converter, the digital inputs from the digital sensors, and the proper synchronization signals from the programmer into a single serial PCM output. The output bit rate is 480 bits/sec during the standby phase and 4800 bits/sec during the start-up and normal operation and shutdown phases.

Standby During the standby phase, prior to base habitation, only the S-Band receiver operates continuously. On command from Earth, the monitoring system is placed in operation, the PCM output of the digital multiplexer phase modulates the S-Band transmitter, and the phase modulated signal is fed to the omni-directional antenna through the duplexer for transmission to Earth. The output of the S-Band transmitter is nominally 1 watt. This value of transmitter power is based on the use of coherent phase shift keying (PSK) modulation and on achieving an error probability of 10^{-3} (one error in 1000 bits) for the Moon-to-Earth transmission bit rate of 480 bits/ sec.**

Start-up and Operate During the normal operation phase and the standby phase following a plant shutdown, the PCM output of the digital multiplexer passes through the summing network and frequency modulates the 100 mw VHF transmitter. It is then fed through the VHF duplexer to the whip antenna on top of a 100-foot extendible (DeHavilland STEM) antenna mast for transmission to the shelter and relay to the Earth through the shelter S-Band communications system. During start-up the PCM output of the digital multiplexer is fed to the FM summing network. The FM summing network combines this signal with the frequency modulated outputs of the subcarrier oscillators containing the high frequency analog signals (reactor period, etc.). The frequency multiplexed output of the FM summing network then frequency modulates the 100-mw VHF transmitter. The transmitter output is fed through the VHF duplexer to the whip antenna for the transmission to the shelter and relay to the Earth through the shelter S-Band communications system.

Command System Alternate control of the nuclear power plant payload will be from the Earth through the S-Band command system. Control capability is also provided from the shelter through the VHF command system. The VHF command system is used both for reception of commands originating at the shelter and reception of commands originating at the Earth and relayed through the shelter. This second function of the VHF command system provides a back-up capability should the primary S-Band command system in the power plant payload fail. Both the S-Band and VHF command systems will be digital systems. The command equipment in the power plant payload for the two systems will be identical except for the receivers. During the standby phase, prior to base habitation, the S-Band command system is used exclusively. Its primary function is to initiate periodic status checks of the power plant payload and to command control point resets following a status check. The reactor will be prepared for the start-up manually or automatically by remote command. In either case, received commands will initiate command routines stored in the programmer. The programmer will be capable of executing upon command two hundred sets of sequential command routines, each routine consisting of an average of five separate commands. After full scale operation is

** See J. W. Thatcher, "Deep Space Communications", Space/Aeronautics, Vol. 42, No. 1, July '64, for an exposition of existing and planned N.A. S.A. deep space communication capabilities.

automatically achieved, the commands to change power levels, shift to the other secondary loop, etc., can be transmitted from Earth or from the shelter. The programmer will accept these commands and initiate the desired control sequence. The programmer will also execute control of the communications and command systems, shifting to redundant equipment automatically and by command from Earth when required.

Weight and Power Requirements Based upon the use of microelectronic integrated circuitry, the weight of the electronic equipment shown in Figure 3 is estimated to be approximately 13 pounds. The S-Band antenna weight is approximately 2 pounds and the VHF antenna and 100-foot extendable mast total 10 pounds. The weight of transducers and wiring are not included. Wiring capable of withstanding high temperatures would add appreciably to the overall weight. Power consumption estimates are:

Standby, Continuous	0.1 W
Transmit Standby Status Check (duty cycle approximately 1%)	8.6 W
Operate, Continuous	6.9 W

Lunar Surface Communication Center The communications center on the lunar surface will be located at the manned shelter and will relay to Earth all data from the numerous LESA payloads, including the nuclear power supply. Limited monitoring of the relayed data will be possible at the central station. Magnetic tape recording will be included to permit scheduled and emergency storage of data should contact with the Earth be lost. The capability for limited emergency commands to other lunar payloads will be provided. The central communication center will also include the required monitoring, control and data transmission, including video, for the shelter and crewmen. The lunar surface communications center, acting as a relay point between the various payloads and Earth offers a number of advantages:

- (1) The use of the VHF transmission system from the remote payload to the center, reduces the effective radiated transmitter power (product of r-f power radiated and antenna gain) required at each payload.
- (2) It is not necessary to use independent S-Band carriers for each payload, since all data will be frequency multiplexed at the central station and transmitted to Earth on a single carrier.
- (3) The central station will employ a high gain S-Band antenna, thus minimizing the number of high power S-Band transmitters used in the lunar base.
- (4) The tracking antennas and higher power transmitters are at the manned site and available for maintenance and replacement.

Reliability The communication and command system of a lunar base could be substantially implemented today using available hardware. Weight, power consumption, and volume would be large when compared to 1972 equipment. The nuclear power plant communication and command subsystem presents a very different reliability problem in the communications and control area. Not only must the long t e r m I u n a r surface storage requirement be met, but also, unlike the other lunar surface units, the react o r radiation hazard necessitates unattended operation of the reactor communication and control equipment even when the base is manned. In addition, the cost of shutdown of the nuclear power plant is measured in millions of dollars per day. The reliability demands of space programs in communications and other areas are well known and much of this country's technological effort is presently devoted to the problem. The solution, in the final designs will be to employ the least demanding approach, the most reliable hardware and intelligent use of redundancy.

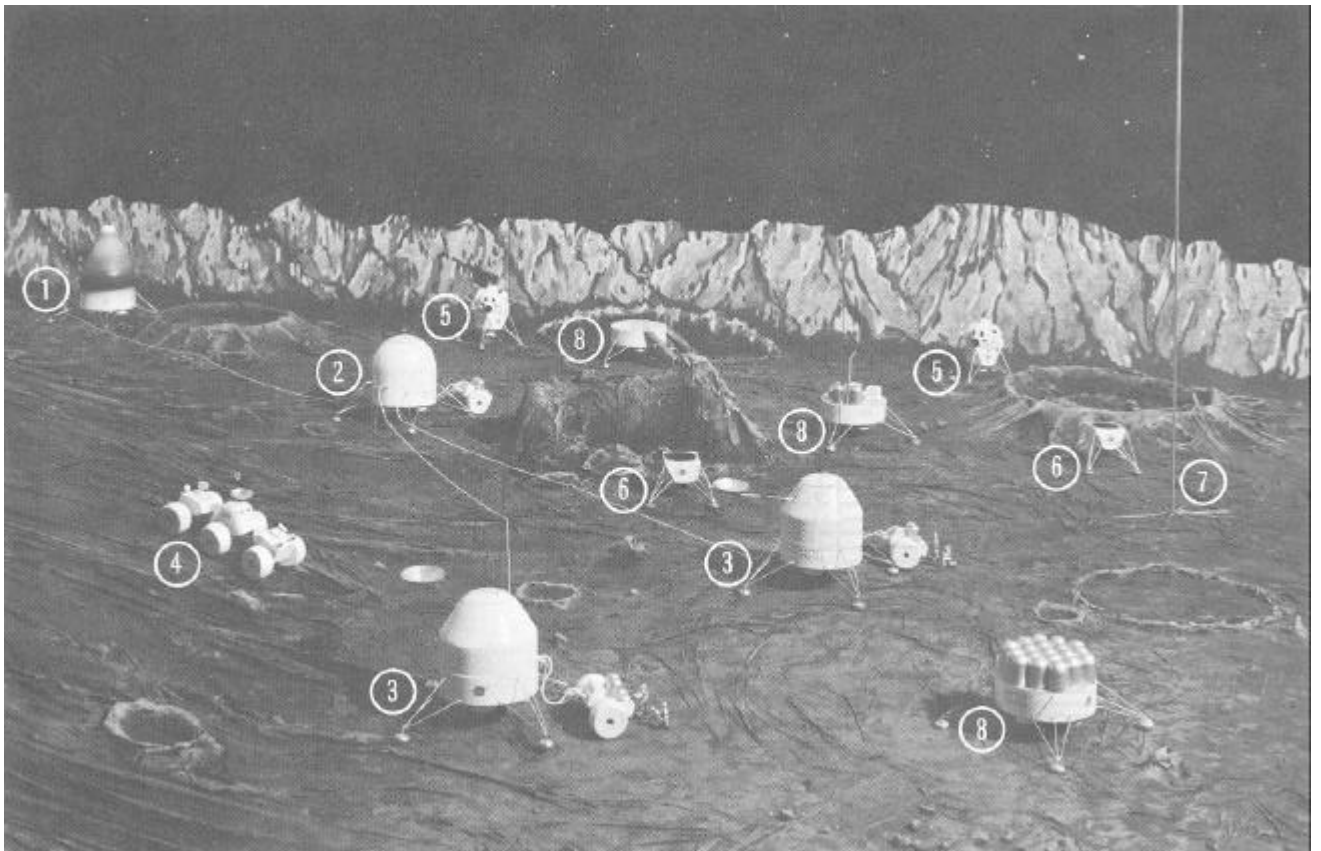


Figure 1. Westinghouse Lunar Base

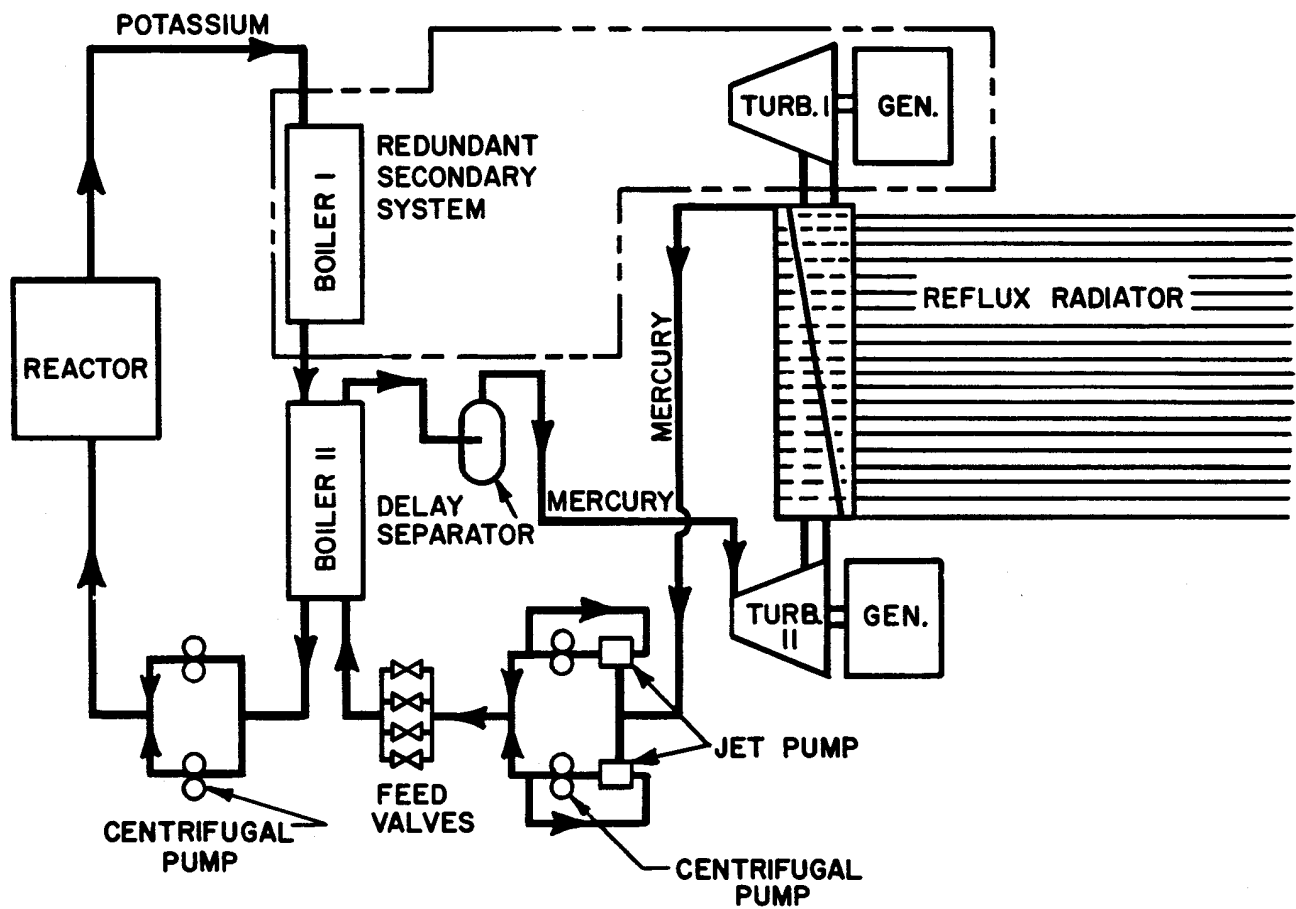


Figure 2. Functional Diagram of Lunar Nuclear Power Plant

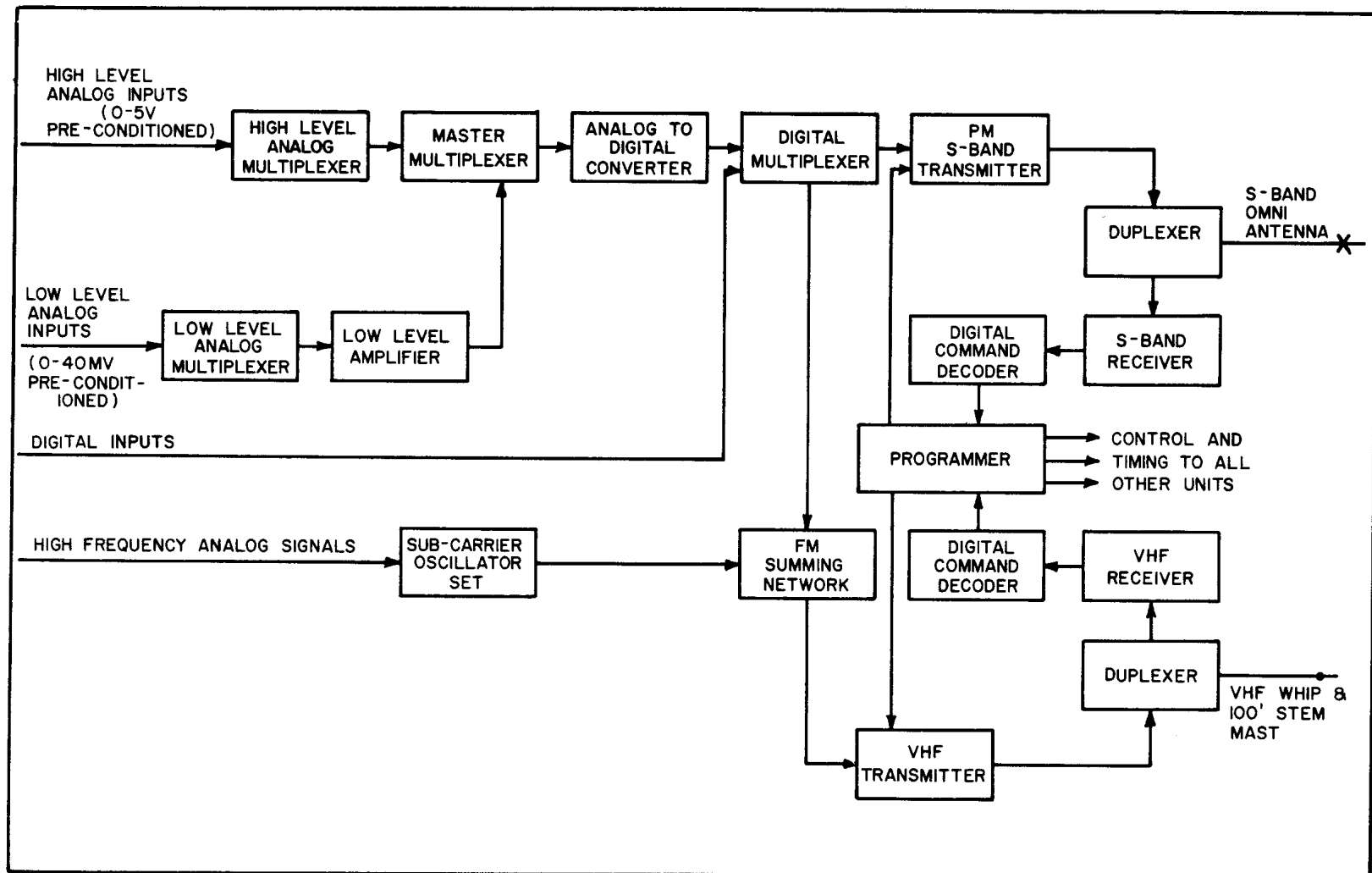


Figure 3. Nuclear Power Plant Telemetry and Communications System Functional Block Diagram