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The Roles and Functions of a Lunar Base Nuclear Technology Center

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Abstract

This paper describes the roles and functions of a special Nuclear Technology Center which is developed as an integral part of a permanent lunar base. Numerous contemporary studies clearly point out that nuclear energy technology will play a major role in any successful lunar/Mars initiative program and in the overall establishment of humanity's solar system civilization. The key role of nuclear energy in providing power has been recognized. A Nuclear Technology Center developed as part of a permanent lunar base can also help bring about many other nuclear technology applications, such as producing radioisotopes for self-illumination, food preservation, waste sterilization, and medical treatment; providing thermal energy for mining, materials processing and agriculture; and as a source of emergency habitat power. Designing such a center will involve the deployment, operation, servicing and waste product management and disposal of megawatt class reactor power plants. This challenge must be met with a minimum of direct human support at the facility. Furthermore, to support the timely, efficient integration of this Nuclear Technology Center in the evolving lunar base infrastructure, an analog of such a facility will be needed here on Earth.

Introduction

Where do you get cobalt-60 on the Moon to radiation process life support system wastes? How do we most effectively decommission and dispose of a central nuclear power plant on the Moon? The answers to these important questions and others involving the expanded use of nuclear technology in space can be found in the timely development of a lunar base Nuclear Technology Center.

The need for nuclear power as an integral part of a permanent lunar base is now widely recognized.[1,2,3,4] There are numerous interesting applications of nuclear power as part of such a base including[5]:

- stationary base power for base operations,
- power for mobile operations,
- emergency life support power,
- production of radioisotopes for lunar "biosphere" activities (e.g. waste stream treatment, food preservation, medical waste sterilization, etc.), self-illumination light sources, space industries, and medical treatment, and
- nuclear process heat for industrial, agriculture and life support applications.

The lunar base Nuclear Technology Center (NTC) suggested here would explore, develop, demonstrate and utilize advanced automation and robotics techniques to minimize the need for direct lunar worker interactions, while providing safe, reliable and maintainable nuclear technology applications including power, thermal energy and radioisotope production. The following automation and robotic areas would be included: artificial intelligence, expert systems, robotics, teleoperation, telepresence, and automation. According to the NASA Advanced Technology Advisory Committee[6]:

<u>teleoperation</u>--involves the study and use of manipulators which receive instructions from a human operator and perform some action based on those instructions at a location that is remote from the operator;

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telepresence--involves a teleoperation situation in which the operator has sufficient cues to stimulate the sensations that would be experienced in performing the operations manually, i.e. without any teleoperation device; and

automation--involves use of machines that rely on artificial intelligence, robotics, or teleoperations.

The lunar base Nuclear Technology Center will also be supported by a major terrestrial "analog" facility. This terrestrial analog facility would combine the robotic and automation experiences of the marine and terrestrial nuclear activities with the unusual demands and requirements imposed by the lunar environment, including an approximate three light second round trip time to Earth at optic velocity.[7]

The proposed lunar base NTC would evolve in a series of stages along with the overall lunar base infrastructure--eventually becoming a major constituent of the emerging lunar economy. Economic activities would include the sale of radioisotopes produced in space, the refueling of advance space nuclear power systems, space radiation protection services, thermonuclear fusion research, nuclear astronomy services, and the decommissioning and disposal of space nuclear power plants.

The lunar base NTC, through extensive interaction with its terrestrial analog facility, will eventually address and encompass all the potential aerospace uses of nuclear technologies and nuclear phenomena, including research and development, scientific inquiry, resource exploration, engineering test demonstrations, and the development, manufacture and delivery of space-qualified nuclear systems for user applications throughout cislunar and inter-planetary space. The proposed lunar base Nuclear Technology Center could also serve as the space location for the preparation for and response to space-based nuclear emergency situations (e.g., a premature shutdown of a nuclear electric propulsion cargo ship) and to manage the proper disposal of expended nuclear powered space systems.[8]

Lunar Base Requirements

Lunar base power requirements need to meet the requirements of a continuing and evolving presence on the Moon and to act as a learning facility for Mars exploration and settlements. Megawatts of power will be needed for Moon and Mars settlements to process in situ resources. Oxygen for habitations, oxygen and hydrogen for propellants, materials for structures and manufacturing are some of the high power demands. In addition, the central base power system provides a back up to the habitat power system. This power system could also provide power for mobile system in such configurations as an energy source for regenerative fuel cells or as a source of radioisotopes. If the power plant is properly located, it can provide process heat directly or use a thermochemical pipeline to transfer thermal energy for heating regolith or for extracting other materials and processing them into finished products. Many processes have been examined[9,10], all of which require significant amounts of electrical power. A table of projected planetary power requirements is given in Table 1.[11]

The requirements are, therefore, for megawatts of power, lifetimes of possibly 30 years, low mass to minimize transportation cost with specific mass on the order of 100 W/kg at 1 MW, reliability of greater than 0.95 that the power plant will be operational when needed throughout its lifetime, and a minimum of direct lunar worker operations. The reactor should also be flexible to provide not only power, but also thermal energy if required for process heat and radioisotopes for such uses as given in Table 2.

Because of its close proximity to Earth while presenting a hostile planetary environment, the Moon is an ideal location to learn what is necessary to live and work on Mars. However, there are some significant differences between lunar and Martian environments that need to be taken into account. For instance, Mars has an atmosphere with more than 95% CO_2 and may have unfrozen groundwater. These environmental circumstances do not exist on the Moon. It is important in designing a lunar Nuclear Technology Center to keep in mind that one long-term objective is Mars. Another major difference between establishing a power plant on the Moon and Mars is communication times. The Moon is less than three seconds (at speed of light round trip) response from the time a command is given to perform some function and an acknowledgement that the command has been received; Mars could take up to 40 minutes for the same communication interaction. Thus, for a sound learning experience using the Moon, this communication delay must be taken into account. The lunar NTC will teach us how to perform such robotic operations as unloading the power system from a cargo

PLANETARY SURFACE STATIONARY POWER REQUIREMENTS

Mission	Power Level	Life
Human-Tended Lunar Observatory	< 100 kW	Years (Sustained)
Initial Human Sortie Mission	< 100 kW	< 60 Days
Human Outpost	100-600 kW	Years (Sustained)
Human Base (With Resource Processing)	2-20 MW	Years (Sustained)

PLANETARY SURFACE OPERATIONS

Human-Tended Lunar Observatory	Initial Human Sortie Missions	Human Outpost	Human Base (with Resource Processing)
Very Low Frequency Radio Array	Habitat (2-4 Crew)	Habitat (15 Crew)	Habitat (24 Crew)
Optical Very Large Array	Laboratory	Additional Labs	Research Facilities
Stellar Monitoring Telescopes	Science Experiments	Extended Science	Sustained Science
Moon-Earth Radio Interferometer	LOX* Pilot Plant Production	In-Situ Resources	Increased LOX
Solar Observatory	Site Preparation	CELSS* Research	Metals Production
Radio Telemetry for SETI*	Rovers/Trailers	Surface Surveys	Manufacturing
Local Geological Traversos in Unpressurized Rover	Lander/Ascent Vehicle		Ceramics Production
			Food Production
Geophysical Stations			Product Export

*LOX = Liquid Oxygen
CELSS = Controlled Ecological Life Support System
SETI = Search for Extraterrestrial Intelligence

Table 1 Projected Planetary Power Requirements

vessel, siting, setting up the power plant, operations, servicing, and disposal; experiences of great value to developing a Mars base.

The proposed lunar Nuclear Technology Center will be based on automated teleoperated set up and operation. This is especially important for Mars operations, where it is necessary to know that surface power is available to the crew when they arrive. Lunar operations will be used to demonstrate the success of these activities.

Aerospace safety considerations and demonstration are important aspects of a lunar Nuclear Technology Center. Astronauts and the surrounding facilities must be protected from nuclear radiation and contamination. The reactor integrity must be maintained as part of these requirements; a loss-of-coolant accident that could result in a core disruption accident must be avoided. In case the power plant is the primary or secondary habitat energy source, continuing operations are necessary if it can be

Need	Radioisotope
Portable Power	^{238}Pu, ^{252}Cf, ^{242}Cm, ^{90}Sr, ^{137}Cs
Medical	^{99}Mo, ^{133}Xe, ^{99m}Tc
NDE Inspection, hard γ	^{60}Co, ^{192}Ir
Waste Treatment, hard γ	^{60}Co
Food Preservation, hard γ	^{60}Co, ^{137}Cs
Lighting, β+phosphor lamps	^{85}Kr

Table 2 Radioisotope Applications

achieved without major power plant damage. The power plant should be able to continue to operate successfully with two failures in active elements and one failure in structural elements.

Since power is such an important aspect of future space activities, this paper now focuses on the role of a lunar Nuclear Technology Center (and its terrestrial analog) in developing a viable nuclear power infrastructure on the Moon.

System Description

Power Plant

A number of building blocks can be used in developing a power plant to meet the requirements described in the previous section. For this paper, we have chosen to use SP-100 reactor elements and the NASA Lewis Research Center Stirling cycle for the building blocks. The power plant is a continuation of the concept known as PHLIPR described in reference [12]. The reactor consists of a moderator plug with six power elements (see Figure 1). Each power module terminates into a heat exchanger element. This heat exchanger element can be mated to a Stirling power conversion system, thermochemical pipeline to transfer thermal heat, or other possible power conversion elements such as thermoelectrics or Rankine cycle engines. The fuel assemblies (see Figure 2) include a control rod in each bundle of 36 lithium heat pipes. A protective shell or coating will be used to protect the bundle against dust or outgassing on the Moon and from the Martian atmosphere. The moderator element includes holes for producing selected radioisotopes for use in the items outlined in Table 2. The moderator plug can be suspended within a pressure vessel to allow for easy removal later, if desired, and to retain any radioactive materials in case of accidents.

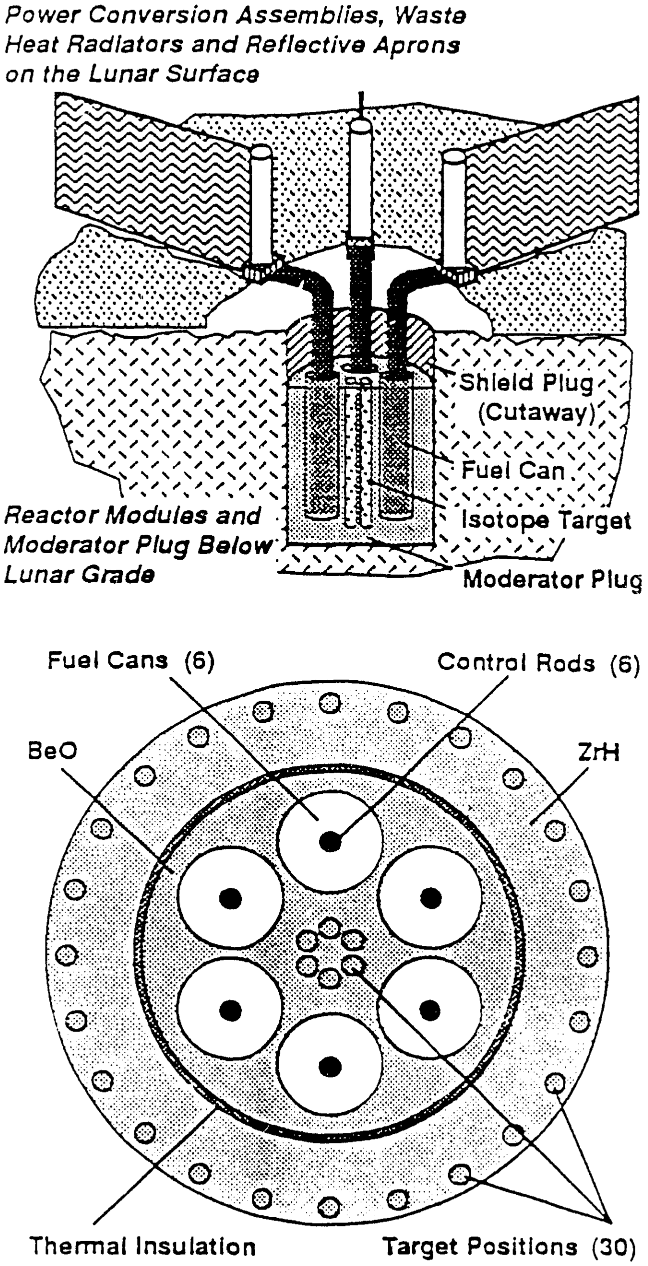

Figure 1 PHLIPR Reactor Concept

A major design problem facing the NTC is to develop assemblies and thermal interfaces such that the heat exchanger to the power conversion or power extraction element can be assembled and eventually disassembled using advanced automation and robotic techniques. Also, redundant heat removal is necessary to accommodate possible loss-of-coolant accidents or failures in a single loop. A heat exchanger is located at the termination of the core bundle heat pipes. This heat exchanger is currently envisioned as a lithium bath with the outside walls double layers and arranged as heat pipes. This provides redundant walls for containment and uniform distribution of thermal energy throughout the heat exchanger. To avoid loss of lithium at 1400 K, the lithium bath should be hermetically sealed. This might be accomplished with the fuel bundle heat pipes being plugged in as a unit into the top of the heat exchanger and sealed with a screw type fitting using a malleable refractory metal for a seal. Advantage can be taken of the Moon's gravity (similarly advantage will be taken of Mars gravity). The lithium bath container can be attached to the outer moderator core vessel for support and alignment. A common bath can serve all the fuel modules and power

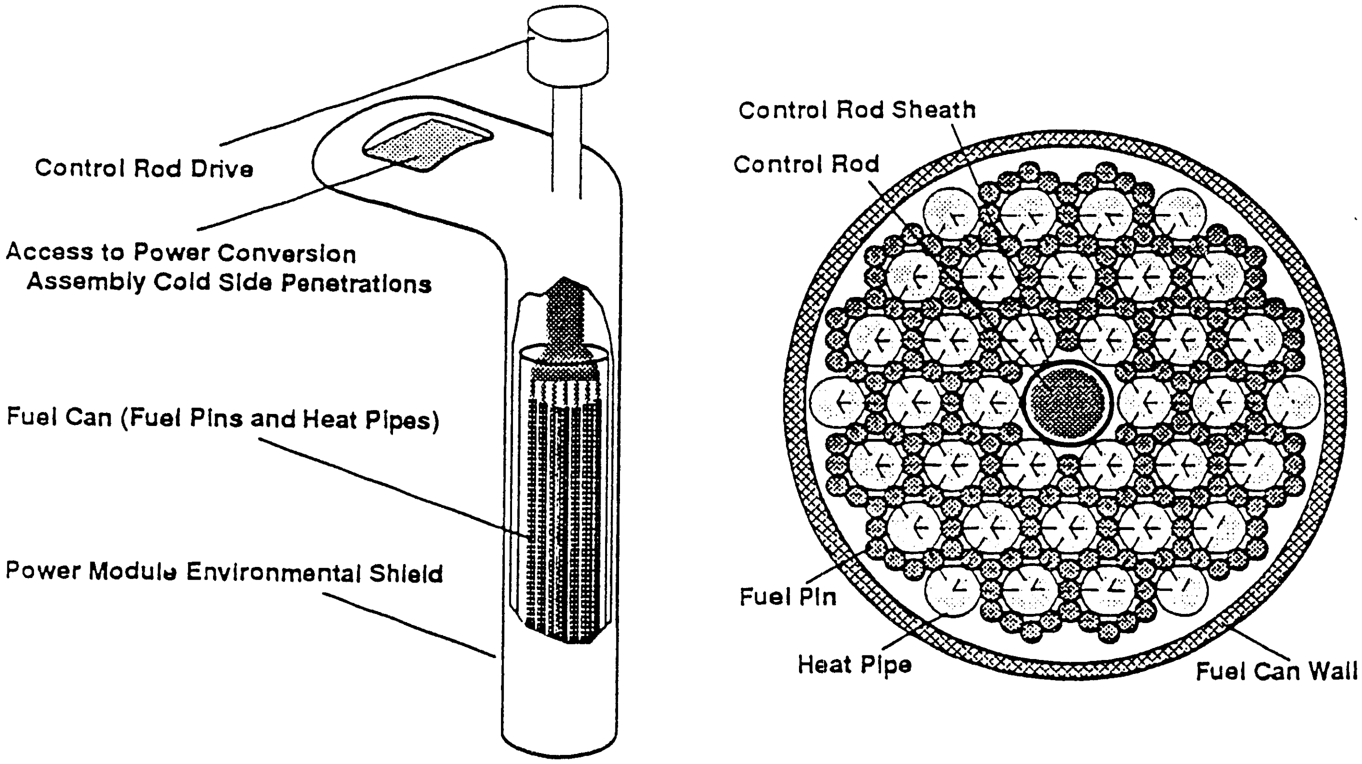

Figure 2 Fuel Module

conversion modules to avoid overheating the core if a power conversion or radiator element is lost. This arrangement will allow continued operation of the other power conversion modules.

For power, the outlet of the heat exchanger is mated to a Stirling engine using the same type of fixture as on the inlet. The Stirling engine can have its own integral radiator as part of the unit or use a heat exchanger to isolate it from the radiator.

Installation

Within the context of an evolving lunar NTC, power plant elements would be delivered to the Moon in subassemblies. With proper design and development, these will be roboticly unloaded using the lunar logistics infrastructure system that will be needed to unload other lunar cargo. The robots will move the power plant subassemblies to the power system location. This should be an essentially routine process considering the need to do this for other types of cargo. Since the reactor will not be radioactive nor in a configuration that it could achieve criticality, no special handling is anticipated.

Assembling the reactor is a challenge and one of the first major automation and robotic design and development tasks of the proposed NTC. The area around where the power plant is to be assembled must be leveled using a robotic excavator with a blade attachment. If the regolith is mostly dust, provision will need to be made to either develop something to stabilize it when equipment is installed or it will need to be scrapped down to a level that provides firm structural support. An excavator will be used to dig a trench for the reactor. This trench should be sufficiently deep to a have the core completely below grade and such that radiation scatter is not along the surface. The moderator core vessel will than be placed in the trench. This operation can use the cargo unloader. The regolith from the trench will be backfilled around the moderator core outer vessel. Again, the NTC will explore ways of using lunar excavation and logistics equipment to assemble the first lunar reactor power system.

The fuel/converter lithium heat exchanger will be installed on the reactor containment vessel using the unloader. This will provide a known geometry for the fuel assemblies and the core vessel will provide structural support for the heat exchanger.

The first fuel assembly will be inserted into the core moderator element, again using the unloader vehicle. The control drive will be tested. There is no possibility that the reactor can go critical, since there is not enough fuel in the core at this point.

A power conversion element will next be inserted by the first fuel assembly in the lithium bath heat exchanger. This will take advantage of planetary gravity. In the first installation step, the surface was prepared for this operation. The Stirling engine, assuming this is what is being used, will be lowered into place using the unloader vehicle.

Similarly, arrangements can be made for a heat exchanger between the Stirling engine and the radiator. The radiator will be a fold-out type that sits vertically from the ground.

This procedure is repeated for each of the other five fuel assembly bundles. Care must be taken to never have more than one control rod removed at a time as the amount of fuel in the core increases.

Lithium will than be added to the heat exchanger containers. The lithium can be in the form of solid pellets and several containers attached at evenly distributed points around the heat exchanger. After mounting the lithium containers, valves at the bottom of the containers can be opened using a telerobotic device to allow the lithium into the heat exchanger.

Operations

After assembly and checkout, the reactor control elements are withdrawn to make the reactor critical using an automated feedback control system. The temperature is increased sufficiently to melt the lithium in the heat exchanger and the system is checked that everything is functioning normally. The power conversion and heat rejection elements are also monitored to ensure that they are functioning properly while at low power. Once these conditions are satisfied, the reactor can be brought to the operational power level desired.

This power plant can provide a full range of power from a few kilowatts to megawatts. The plant would normally be operated at some steady state level with load resistors to regulate power during transient operations. The steady state level should be one capable of handling peak conditions for significant periods of time.

Servicing

As part of the engineering and operational experience developed under the NTC, the reactor is designed to be serviced during operations or shutdown. Servicing during operations maybe necessary to ensure that there is always a backup power system for the habitat on the Moon and eventually Mars. Therefore, it is desirable to be able to operate the reactor with one fuel module removed. The current PHLIFR concept does this. The heat exchangers have been designed in the concept to allow removal of subassemblies like the Stirling engines or radiators while the reactor is running. Radiation hardened teleservicing equipment will be needed for these operations.

Disposal

Since the NTC is taking a long-term perspective of space nuclear technology applications, the proposed nuclear power system has been designed for removal of subassemblies for disposal. Even the core moderator module can be removed without removing the containment vessel surrounding it. These elements can be transported to a disposal site for burial. This will require a radiation-hardened remotely operated vehicle. On the Moon, since there is no subsurface water, almost any site will be acceptable. For Mars, geological mapping will be needed to avoid selecting a disposal site where groundwater might exist.

Isotope Production

Radioisotopes will be a primary by-product of reactors operated for power and/or heat on planetary surfaces. Through evolving NTC functions, isotope production capability will be factored into advanced lunar reactor designs from the start. Cold, non-radioactive (e.g., thulium-169 or cobalt-59) target material will be initially shipped from Earth, activated at the space reactor, and repackaged for use. As lunar mining operations increase, much of the target feedstock can be produced from raw materials mined on the Moon near the reactor, eliminating much of the cost of shipment from Earth. High grade steel and special alloys used in target cladding and end-product fabrication will continue to be shipped from Earth for the foreseeable future.

One of the considerations in the design of a nuclear reactor for both power production and radioisotope production is sufficient decoupling to avoid shutdown from mechanisms associated with radioisotope production. The facility design includes means for transfer of samples into hot cells and for intermediate storage. Finally, it provides for waste processing and final storage as needed. In order to produce radioisotopes in space or on the Moon, the nuclear reactor must be designed to allow for the continuous addition and removal of targets. This design approach also makes provisions for robotically handling the radioisotopes after removal from the reactor. Extensive processing facilities are not considered acceptable. Radioisotopes produced need to be to the greatest extend possible in a form that can go directly from the reactor to the application.

The initial reactor core loading can include radioisotope irradiation target assemblies. These assemblies could be designed for ease of handling and compatibility with end-use devices. Such target assemblies will probably include heavy isotopes in the fuel regions for the production of Pu-238 and Cf-252 and loadings in the poison regions for the production of Co-60 and Ir-192. The latter isotopes can support construction activities and geological exploration and mining operations. As the facilities under construction are transformed into laboratories, machine shops, etc., the demand will expand to include the heavy radioisotopes and specialty isotopes, such as Ni-63. As medical facilities are expanded, the demand will increase for such short-lived isotopes as Tc-99m (from Mo-99) for neutron sources for radiography and small-scale neutron activation devices. Isotopes will play an increasingly important role in space exploration and development; especially if produced in space.

Building A Terrestrial Demonstration Facility

Because of the need to use extensive automation and robotics, it is important to build a simulator here on Earth to help design, demonstrate, test and even operate all phases of the operations and installations. Such a facility could be used to simulate the key aspects of the space environment. Use of such a facility as the Contained Test Facility (CTF) and Loss-Of-Flow Test Facility (LOFT) at the Idaho National Engineering Laboratory provides facilities that can meet the terrestrial reactor safety and environmental safety standards. CTF is a shielded facility 97 m wide, 78 m long and 30 m at its peak that was originally built to accommodate nuclear powered aircraft. The floor could be covered with simulated lunar regolith to perform ground operations under simulated Moon conditions. The scale of CTF makes it possible to approximate lunar conditions (except for vacuum and gravity) for large scale operations. This includes low humidity and lunar day-night conditions. Reactors can be set up in a manner similar to that planned for lunar operations. If safety and environmental laws can not be satisfied, the LOFT facility located next to CTF can be used. This facility (See Figure 3 and 4 for size and layout of LOFT) is certified for reactor operations. Heat transfer to CTF from LOFT can be accomplished using thermochemical pipelines.

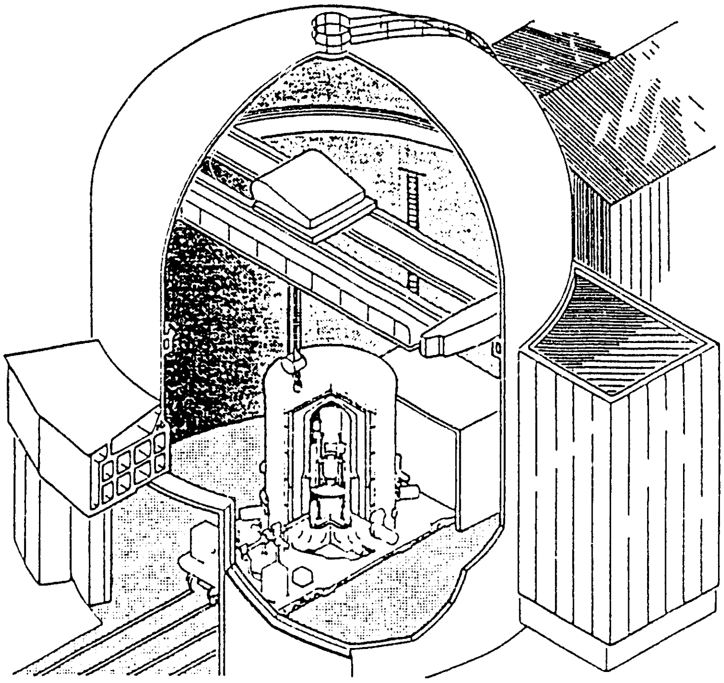

Figure 3 Layout of LOFT Facility

Conclusions

Nuclear Technology Centers on the Moon and Mars will greatly expand the capabilities to explore and settle these planetary bodies. A staged development for establishing such a Center has been described. All of the functions of the Center can be accommodated. A terrestrial analog facility is also important for testing and validating NTC activities for Moon or Mars. This might be accomplished in a shielded facility like the Contained Test Facility at the Idaho National Engineering Laboratory.

- Existing reactor test facility (located next to CTF)
- Containment building for reactor testing
  - heat rejection 55 MW(t)
  - 39.3 m height, 21.4 m diameter
- Connect to CTF by thermochemical pipe line (one approach)

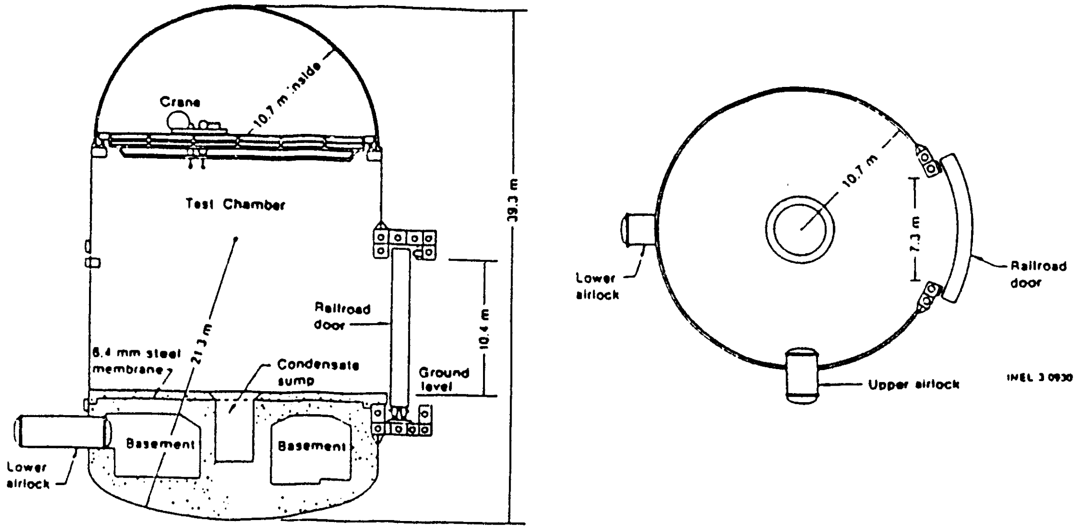

Figure 4 Size of LOFT Facility

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