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LUNAR NUCLEAR POWER FEASIBILITY STUDY

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C. A. Erdman
Tam Tran

Nuclear Engineering Division
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Contract No. NAS 9-17141

Final Report

November 1984

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I. INTRODUCTION AND BACKGROUND

The work reported here was performed under contract to NASA's Johnson Space Center (JSC) over the period of April 1984 through November 1984. NASA has identified a return to the lunar surface as one candidate mission for the year 2000. Suggested scenarios for lunar surface activities all involve substantial electrical power needs. The two main competitive electric power sources are solar and nuclear. The major disadvantage with solar power is the need to provide long term energy storage of up to 14 earth days, depending on where the base power system is located. However, solar power, and particularly photovoltaic solar units, offer a proven technology. The potential advantages for nuclear fission power sources are the reduced need for storage and, even ignoring storage, the large savings in total mass to be transported to the moon for initial electric power systems.

One scenario which defines overall power needs and the way in which nuclear fission power could contribute toward meeting those needs is illustrated in Figure 1. That figure was part of a JSC presentation to a Lunar Base Working Group at Los Alamos National Laboratory in April 1984. The four development phases cover a range of lunar activities ranging from unmanned excursions (Phase I) up through large scale manufacturing and utilization of Lunar Resources (Phase IV).

The three primary objectives identified for the current contract work were to 1) evaluate feasibility of utilizing nuclear fission power as the primary power source for a manned lunar base in the year 2000, 2) recommend preliminary design of such systems with adequate detail to provide estimates of critical quantities such as specific mass per unit power output, and 3) identify unique technology developments required for a lunar base nuclear power system. In order to implement those objectives, five specific tasks were defined as shown below:

A. Perform literature search on previous studies of nuclear fission power sources for lunar bases.

B. Assess current status of SP-100 project and associated technologies as they apply to lunar power systems up to 1 MWe in size.

C. Select overall system under near-term and/or proven technology constraints.

D. Select second system on basis of projected year 2000 technology.

E. Provide level A description, including conceptual drawings, of system of choice.

The results of task A were reported in the May monthly contract report. Several literature sources have been added to that earlier list. The complete list is included in this report as Appendix C, selected REFERENCES/BIBLIOGRAPHY. The numbering system used in that appendix will be used to reference documents throughout the remainder of this report. The other four tasks will be addressed in various sections in the remainder of this report, though not in the exact order listed above.

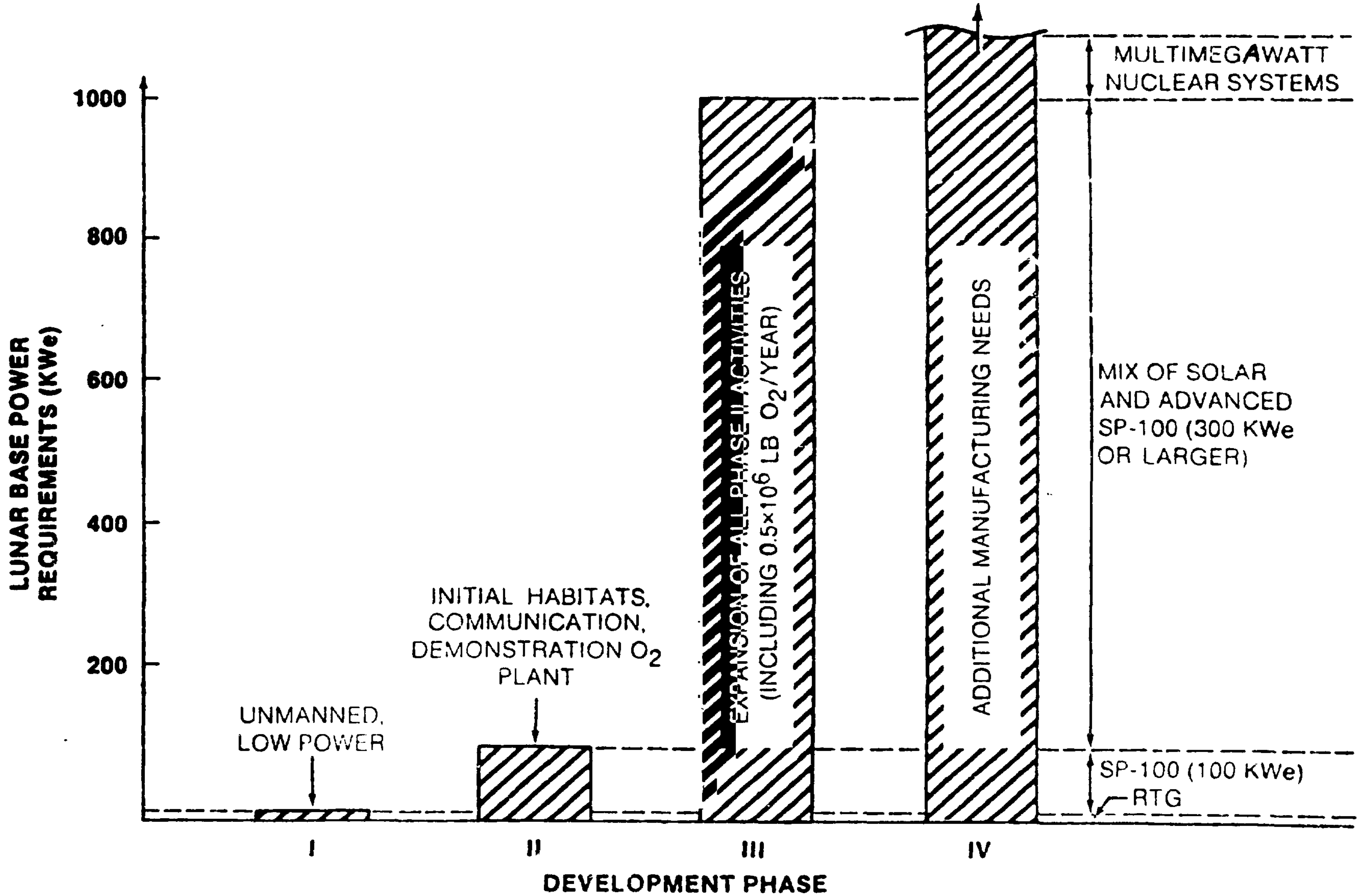

Figure 1. Role of Fission Power in Meeting Requirements of Lunar Base Development.

II. CURRENT STATUS OF SP-100 PROGRAM

There have been significant changes in the administrative structure of the SP-100 project since the beginning of this contract. The most important of these is that the SP-100 project has been folded into the Strategic Defense Initiative under the office of General Abramson. It is not clear at this point how the administrative structural change will affect either the timetable or the initial product of the SP-100 project. For the purposes of this report, it is assumed that the initial SP-100 system will be available for civilian missions such as power upgrade of the space station and a return-to-lunar-surface mission.

It is important to recognize that the SP-100 Program does not represent a single power system design either in terms of the types of subsystems or of the power level associated with the overall system. Nevertheless, a major goal appears still to be the development of a 100 kWe class space nuclear power system available for use in the early 1990s. At the same time, a view is being taken toward technology development for much larger, i.e. 1 to 100 MWe systems. A general conceptual configuration for an SP-100 power system is shown in Figure 2, which was also presented at the April 84 working group meeting in Los Alamos. Reference to this figure will be helpful in understanding further discussions of the SP-100 Program presented below.

The Program is now in the technology assessment and advancement phase. Current plans are to make a decision on space reactor system concepts by July of 1985 in order to move into the ground engineering system phase of development. The various reactor and power conversion systems still under consideration in the current phase are as follows:

1) A fast liquid-lithium cooled reactor coupled with a thermoelectric converter.

2) An in-core thermionic system with a pumped sodium-potasium coolant.

3) A low temperature reactor using liquid-metal-fast-reactor technology coupled with a Stirling system.

4) An advanced fast liquid-metal-cooled reactor coupled to a Brayton power conversion subsystem.

All four of those systems have the potential to meet the SP-100 requirements outlined in the next section. However, in order to do so, all of the systems will require technology advances. Of the four systems identified above, all but the first also have the potential to grow into one megawatt electric and higher power systems. The technical issues which must be resolved in each case in order to meet the initial requirements of the SP-100 program are also the main issues involved in scaling to the higher powers. Thus, a successful completion of the SP-100 Program based on any of the latter three systems should lead in a straightforward manner to a 1 MWe system.

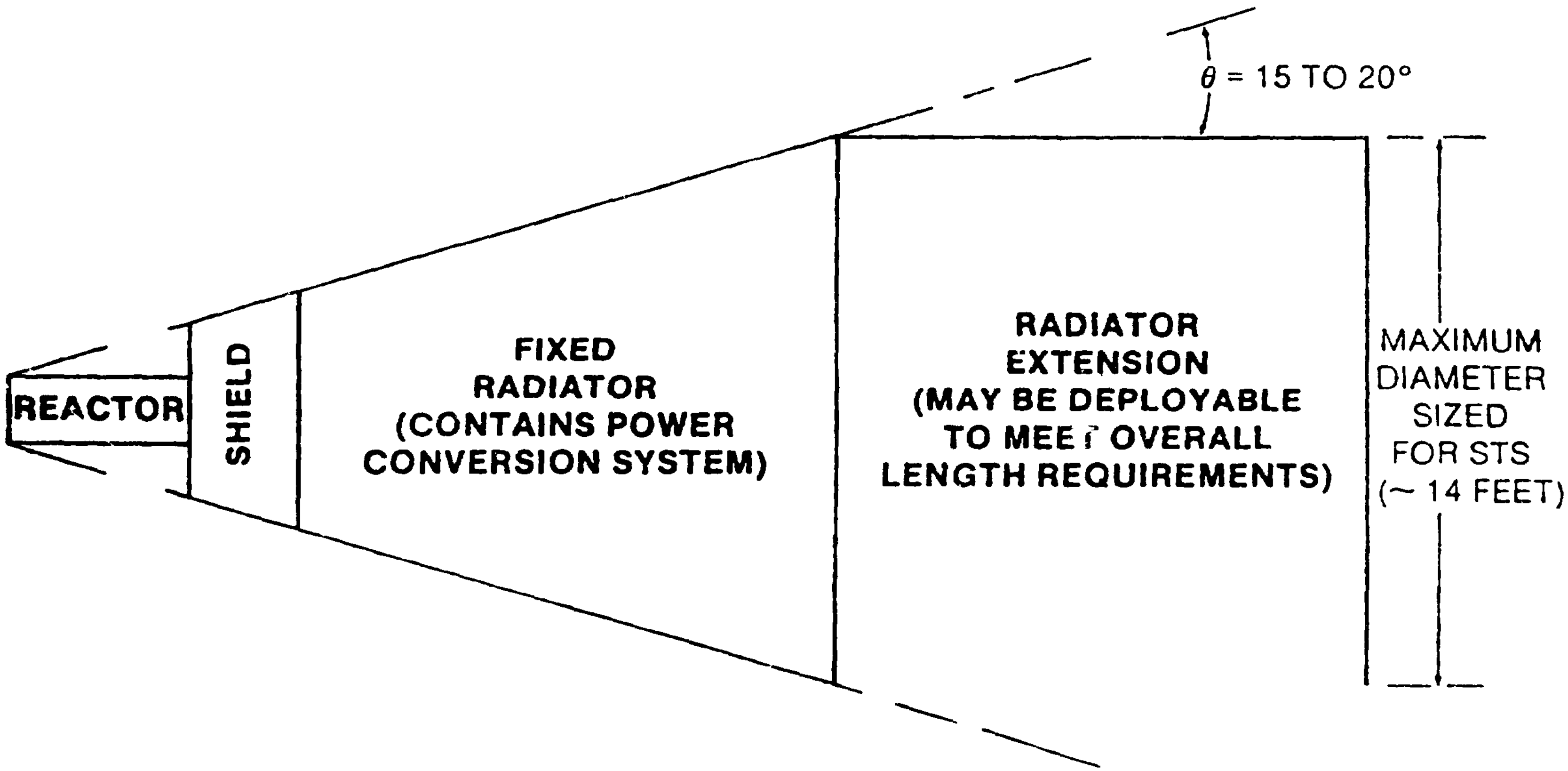

Figure 2. General Configuration of SP-100 System.

II. 1. Comparison With Typical Photovoltaic System

Assuming that the SP-100 Program were to produce a system which met all of the initial stated requirements, the resulting nuclear power system would have significant advantages over solar. The specific requirements are listed below:

- EOM (10 year length, 7 year full power operation) 100 KWe output
- .95 reliability for 2 years (initial system) to 7 years (later systems)
- 3000 kg mass limit
- Launch by STS with payload and propulsion system
- 1/3 of STS cargo bay volume
- All nuclear aerospace safety requirements plus STS launch safety requirements

The particular advantages of the resulting nuclear system over solar planar systems would derive from the overall mass savings. First there would be significant mass and cost savings with the nuclear because of the ability of the nuclear system to operate during the lunar night. No storage systems would be needed except for emergency power. However, even ignoring the cost of the storage hardware - both production and shipping - nuclear has significant advantages. Assuming that a continuous equivalent 100 KWe power availability is required, the cost of hardware and transportation can be compared for the solar and nuclear systems as shown below:

- HARDWARE

Solar: 200 kWe x \$.75M/kWe = \$150M

Nuclear: 100 kWe unit cost estimates vary from \$50M to \$150M for "copies" of SP-100

- TRANSPORTATION

Solar: $200 \text{ kWe} \times \frac{69 \text{ kg}}{\text{kWe}} \times \frac{\$12{,}000}{\text{lbm}} \times \frac{2.2 \text{ lbm}}{\text{kg}} = \$364\text{M}$

Nuclear: Assuming SP-100 requirement of 30 kg/kWe,

$$100 \text{ kWe} \times \frac{30 \text{ kg}}{\text{kWe}} \times \frac{\$12{,}000}{\text{lbm}} \times \frac{2.2 \text{ lbm}}{\text{kg}} = \$79.2\text{M}$$

- TOTAL COSTS

Solar: \$514M

Nuclear: \$129M to \$230M

II. 2. SP-100 Modification and Development Issues for Use on Lunar Surface

One overriding ground rule which was followed in looking at utilization of an SP-100 system for a lunar base is that the system would be landed on the lunar surface fully assembled and essentially ready to operate. Intervention by personnel was assumed to be minimal and restricted to such tasks as "plugging in" the remote power conditioning and control module (landed separately) and running power lines to the user. Tasks such as deploying radiators or excavating special shielding walls were precluded. A second ground rule was that modifications to the SP-100 system for adaptation to operation on the lunar surface should be minimal if not zero. These two rules were adhered to very closely.

Five specific issues were identified in connection with direct use of an unmodified SP-100 system on the lunar surface. These issues are all related to the fact that the SP-100 was designed for use in space in an unmanned situation. None of these issues appears limiting; however, some of them may require minor modifications to the basic SP-100 product.

1) Structural support and orientation of system on lunar surface
2) Radiator effectiveness
3) Reactor component temperatures
4) Use of lunar materials for shielding
5) Power delivery

Each of these issues is discussed briefly below.

1) General agreement to this point has been that the system should be oriented with the reactor down (see Figure 3) in order to make maximum utilization of the radiator (both inner and outer surface of upper sections). The reduced g field should allow a simple arrangement to support the system as sketched in Figure 3. Each pad would be required to support approximately 300 pounds. The landing vehicle would have a mostly open support platform so that the radiators primarily would view the lunar surface. Although little fuel would be left in the tanks following landing, the tanks should be vented before operation of the reactor.

2) Since the radiator does not "see" low temperature space on the moon, but will be designed that way for the SP-100 project, an evaluation was made of the effectiveness of the radiators near a sometimes hot lunar surface. Radiation heat transfer calculations involving thermal energy interchange between the lunar surface and the main radiators of the reactor system were carried out for various assumed heat rejection rates and heat rejection temperatures, i.e. for different proposed SP-100 systems. The model used to perform the calculations is described in Appendix A. In those calculations the assumption was made that there was a solar heat flux of 1400 watts/m^2 falling on the exposed lunar surface. Without the reactor present this would have resulted in a surface temperature (lunar noon) of approximately 400 K. The presence of the reactor system results in slightly higher lunar surface temperatures around the base of the reactor support system. Along with this, for a fixed heat rejection rate, the required radiator temperatures would be elevated above the SP-100 design temperature by 10-20 K depending on the specific system design.

These calculated results suggest that one of three alternatives might be considered. The first is simply to run the system at slightly higher temperature levels. If this were not judged to be an acceptable approach based on temperature limits within the total power system, the entire system could be derated by a few percent. As a third alternative, a slightly bigger radiator could be supplied to maintain the

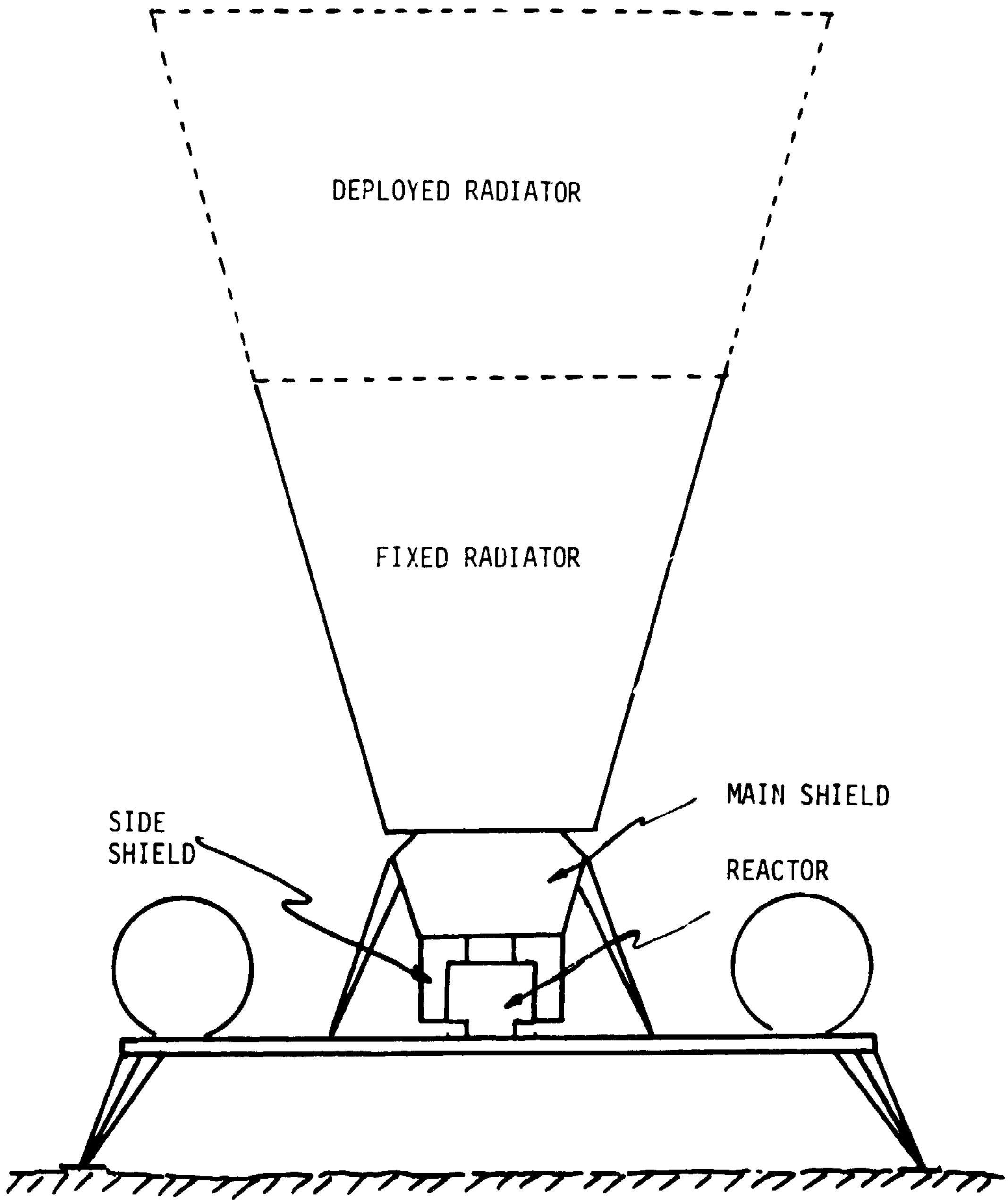

Figure 3. SP-100 orientation on lunar surface.

full rated power output. At any rate, this does not appear to be a serious problem. The radiator design temperatures for all of the systems under consideration are all significantly higher than the anticipated maximum lunar surface temperatures.

3) The design studies for SP-100 to this point have not provided sufficient detail to determine whether the reactor component temperatures would be seriously elevated by having the reactor containment located close to the hot lunar surface. In virtually all designs under consideration either beryllium or beryllium oxide materials are used in conjunction with absorbers in control drums surrounding the reactor core. The temperature restrictions on these beryllium components are more severe than on the reactor core fuel. This means that the system designs would rely (in a space environment) on a combination of insulation between the core and control drums plus radiative heat transfer from the sides of the reactor containment in order to maintain the proper radial temperature distribution within the components.

Simple arguments can be made to show that the radial temperature distribution should not be significantly affected by the presence of the lunar surface unless the reactor containment is buried in a small cavity or uncooled side shielding is added. The arguments are outlined below.

The useful upper limit temperature for beryllium metal is approximately 1075 K. To provide a margin of safety, assume beryllium temperatures are restricted to 1000 K. This means the outer surface of the containment could be at essentially this temperature. As long as there is sufficient thermal insulation between the core and the beryllium control drums to limit heat flow to a level which could be radiated from the 1000 K containment surface to the lunar environment, no problems would be anticipated. Consider how much insulation is required and whether this could easily be incorporated into the reactor design.

Even if the containment surface were radiating to a 700 K lunar surface (much higher than calculations of Appendix A indicate), the surface heat flux could be as high as 43 kW/m^2. To limit the heat flux for a 500 K temperature drop (1500 K cold leg return for GE baseline design minus 1000 K beryllium) to 43 KW/m^2 requires the equivalent of 2 to 3 mm of asbestos insulation. Thus, as long as the outer containment surface is able to radiate to anticipated lunar environments and a properly designed insulator is incorporated between the core and control drums, no temperature problems are anticipated.

4) In order to minimize exposure to personnel, the reactor system should be placed in a crater. The crater should have the following characteristics: a) its walls should be of sufficient height to provide the desired radiation protection for persons outside the crater, and b) the crater should be large enough in diameter (e.g. 100 m) and with a gentle enough slope (limited to a few degrees in the center) that the radiator temperature problems outlined in number 2) above are not aggravated. The option of burying the reactor in a cavity requires excavation and other site preparation and raises questions about radiative cooling of the reactor containment. Going on the basic ground rule that we simply wish to "drop" the reactor on the lunar surface with little surface intervention, this possibility was eliminated.

A second major consideration in placing the reactor near the surface is that backscattered radiation from the surface of the moon will result in increased radiation exposure (both neutron and gamma) to items located behind the shadow shield. This is not a problem in free space, where the shadow shield is designed specifically to account for radiation coming directly from the core and where there are no nearby reflecting surfaces.

Some simple experiments were run to try to estimate the increased radiation exposures that would be experienced behind the shadow shield due to reflection off the lunar surface. The results of those experiments are included in Appendix B. Design details of the experiments are also provided there. These experiments were run at a time when we did not have available detailed information on the geometry and the makeup of the shadow shield. Thus nonprototypic shield thicknesses were used, and the results are not directly applicable to the SP-100 system. This is especially true with regard to neutron doses. Nevertheless, based on the limited data it appears that backscattered fast and thermal neutrons could produce increased dose rates behind the shadow, perhaps by an order of magnitude, depending on the height of the system above the lunar surface. It does appear, however, that the increase in gamma doses under such geometry would not be significant, perhaps only the order of 10-20%. Of all the systems under consideration, the thermoelectric power conversion system would be most affected by this problem.

5) Power delivery was originally considered to be a problem, but this has been dismissed based on review of older reports which assumed rather long distances of power transport between the prime source and power modules and predicted only a few percent loss.

To summarize what came out of consideration of the 5 specific issues listed above, issue 4) seems to be the most important. As a result, a specific modification to the proposed shield designs for the various SP-100 programs was developed and is discussed below.

III. SYSTEM BASED ON PROJECTED YEAR 2000 TECHNOLOGY

The only current major effort in space reactor system technology advancement is that connected with the SP-100 Program. Thus year 2000 technology by default likely will be that available from the SP-100 Program. After examination of the current status of the program and the technology advances which must be made in order to meet its goals, we believe that it will be a severe test of the year 2000 technology to simply meet the current SP-100 Program requirements. In particular, consider the requirement of 30 kilograms mass/kilowatt of electric power. To reduce the mass per unit power to that range requires advances **both** in the reactor systems compared to current technology **and** in the power conversion systems. That statement is consistent with the assessment by Rockwell International[19] which concluded that, although a mass-to-power ratio of 30 kg/kWe may be met by 1997, it is not likely to be met until approximately 2001.

At this stage it is not clear which specific system will come out of the SP-100 program at that time. With at least four main systems and several variations on some of those systems under consideration, the major statements that could be made at this point are enveloping ones. Since the STS is all that is expected to be available to carry SP-100 into space, one can be fairly confident on volume and mass limits. Thus the SP-100 will look approximately like the sketch in Figure 2 and will be limited to approximately 3000 kg mass. To provide further projected design details requires a selection of a specific system. For purposes of this report, a selection was made. We selected the design proposed originally by General Electric[20] and made public at the Albuquerque conference in January 1984. There has been more information available to the public on this design than on most others, even though details are not available.

Since the Albuquerque conference, some modifications to the proposed design have been suggested. The most important of these is direct conductive coupling of the source heat pipe substrate to the thermoelectric device hot shoes. This will result in core temperature reductions of about 200 K while having little effect on the designed radiator temperatures.

III.1. Proposed Modification

We propose one modification to limit radiation field increases behind the shadow shield due to backscatter off the lunar surface. The modification simultaneously maintains desired radial temperature distribution within the containment. It is the introduction of cooled side shielding around the reactor. The side shield would incorporate low temperature heat pipes running from the shield/containment interface to the outer surfaces of the shield. Conceptual drawings of the fast liquid-lithium cooled reactor with thermoelectric converter and incorporating a side shield are shown in Figures 4 and 5. Figure 4 is a composite and adaptation of several figures from the paper by Katucki et al[20] presented at Albuquerque in January 1984. The reader is referenced to the paper for details of how the design stood at that time.

The side shield design must consider several characteristics of the core design and the various control and shielding materials. The melting point of the LiH used as neutron shielding is approximately 950 K. The useful upper temperature limit on beryllium is approximately 1075 K. A reasonable design goal is to maintain these materials at temperatures 100 K below their limits. That is why the short, low temperature heat pipes were incorporated into the side shield design.

It should not be necessary to include gamma shielding in the side shield. Also, the side shield does not need to be as thick as the shadow shield, since the backscattered radiation which passes through the side shield and reflects off the lunar surface is diffused by the distances from reactor to surface and back to the region above the shadow shield. A side shield thickness of 14 cm would reduce fast neutron leakage by about a factor of four, yet would fit directly below the edges of the shadow shield. The shield container would be an integral part of the reactor containment, and the heat pipes could be put in place before the LiH was poured. The intimate contact of shield and reactor containment would ensure desired temperature in the outer regions of the containment, since the LiH itself would be cooled to approximately 850 K.

The shield thickness of 14 cm would translate to approximately 160 kg of LiH, and the GE Baseline design[20] could accommodate the added mass and still be under the 3000 kg limit.

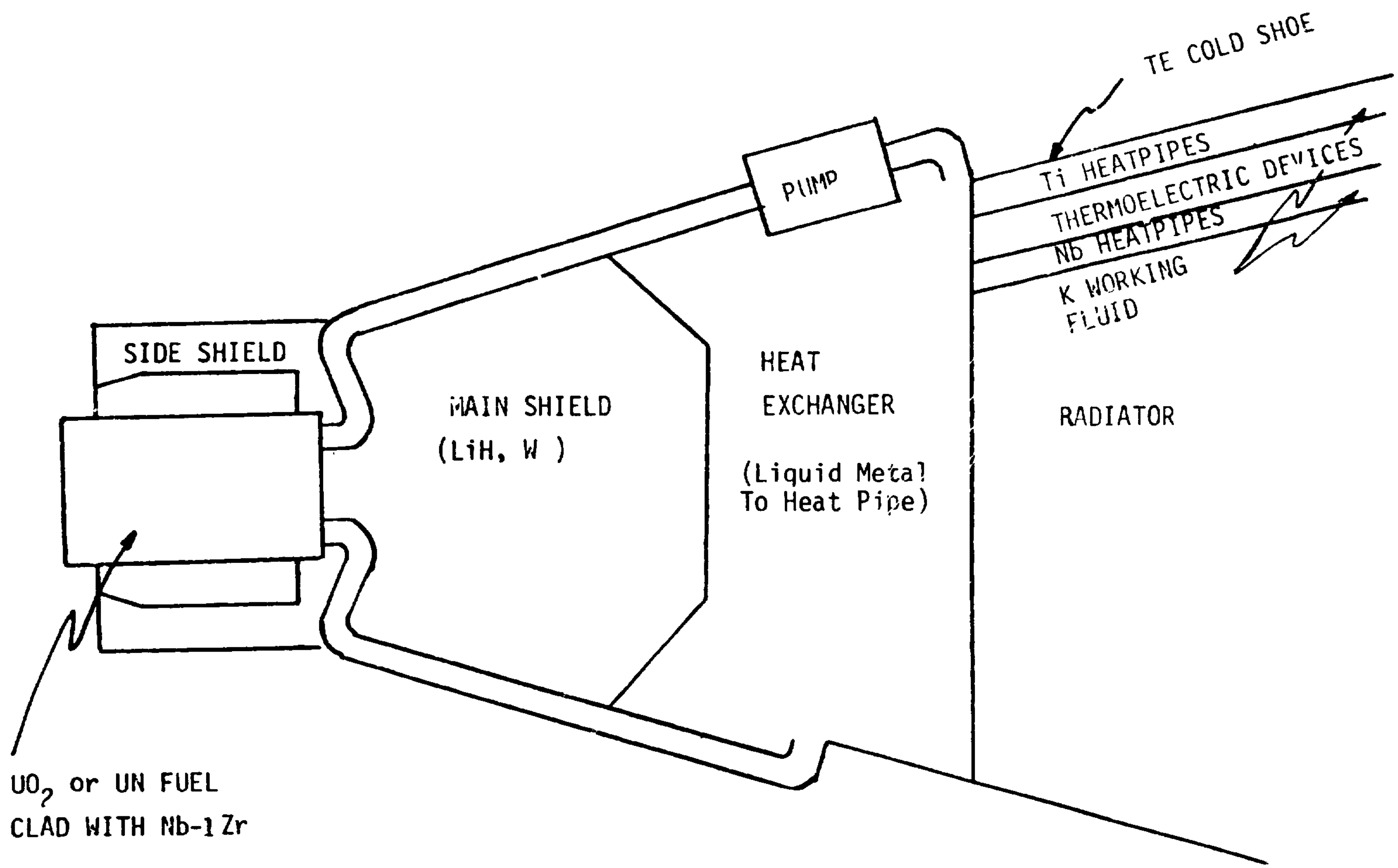

Figure 4. Conceptual Drawing of Proposed Thermoelectric SP-100 System with Side Shielding and Conductively Coupled Thermoelectric Device Hot Shoes (after Reference 20). Heat pipes and TE devices are not to scale. Ti Heat pipes extend to deployable radiator (not shown).

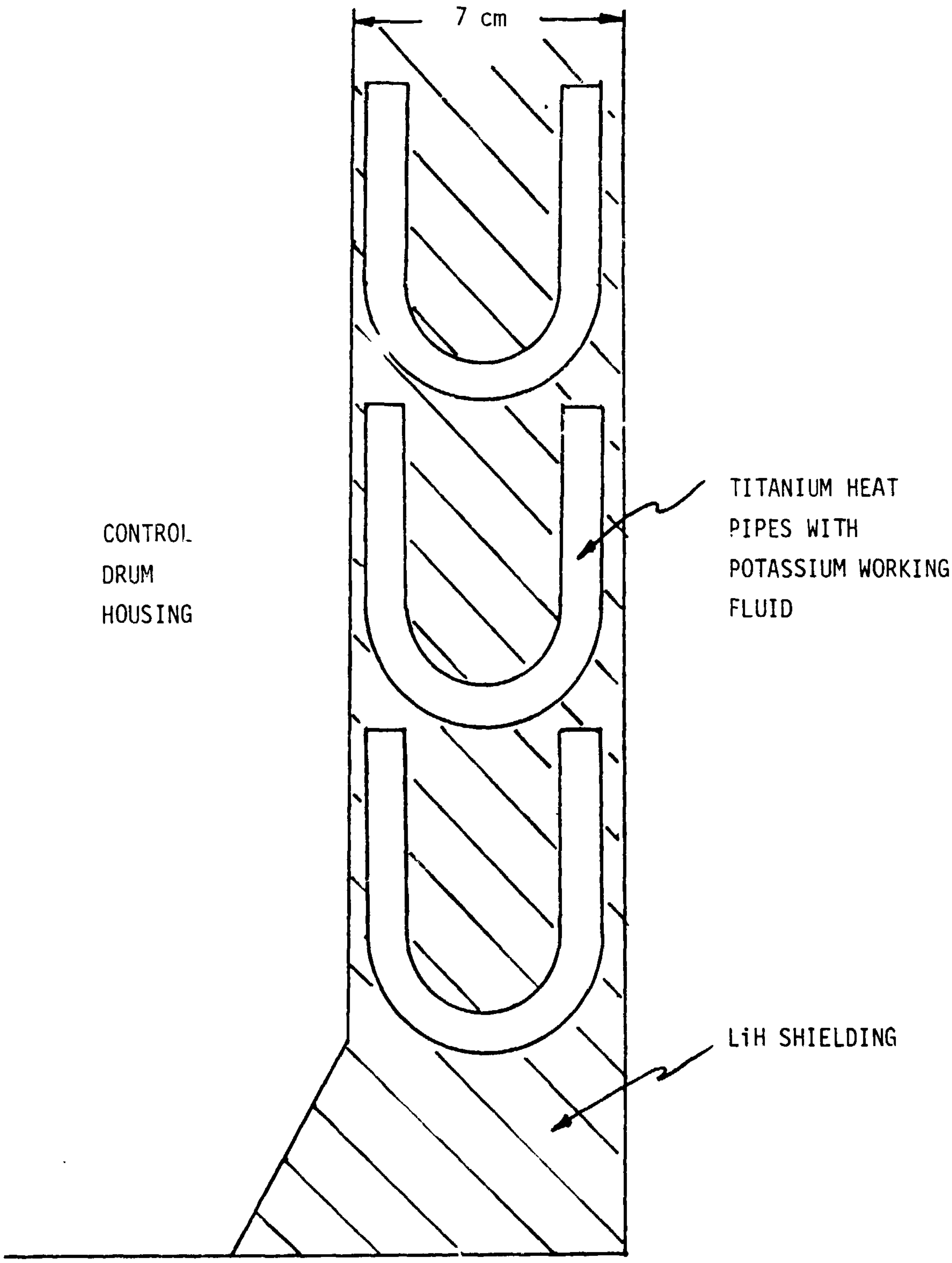

Figure 5. Cross section of bottom segment of side shield showing low temperature heat pipes imbedded in LiH. With twelve pipes at each axial location, the power per heat pipe would be well within current design limits.

IV. SYSTEM UTILIZING NEAR-TERM AND/OR PROVEN TECHNOLOGY

The concerns with advancing technology to meet SP-100 requirements are dominated by concern regarding high temperature preformance of various components, subsystems, and the overall system. The second greatest concern is for reliability of various mechanical elements in the core/power conversion train. Examples of these are mechanical pumps, rotating machinery, and mechanical bonds subject to thermal cycling. Static power conversion systems generally have an advantage over dynamic in this regard.

For reliable near-term technology the core design and operating perameters should conform closely to those of existing systems such as advanced liquid-metal-cooled fast reactor designs. This latter requirement translates to uranium oxide fuel clad with 316 stainless steel (or perhaps niobium-1% zirconium) and cooled with liquid sodium. The peak coolant temperatures under proven technology would be in the range of 850 to 900 K. However, these temperatures would be much too low for any system to come close to meeting space requirements. Backup designs, one proposed by General Electric and another using existing available commercial Brayton power conversion systems, would exhibit peak temperatures of the order of 1100 - 1150 K. We selected this value of 1150 K as an upper limit for design of systems based on near-term and/or proven technology. The immediate result of dropping power conversion inlet temperatures (or reactor outlet temperatures) to the 1100 K range is to effectively derate the systems on a kg/kWe basis or on a m^2 of radiator per kWe basis (derating means higher numbers in both catagories).

With 1100 K outlet temperatures from a sodium cooled reactor, the Brayton cycle was eliminated from consideration. The deciding factor was the need for an intermediate heat exchanger to heat the working gas as well as a heat exchanger to deliver rejected heat from the power conversion system to the radiators. (A gas radiator system was not considered acceptable based on mass and area constraints.) With highe acceptable system temperatures the Brayton cycle could again be competitiv

The system recommended for near-term and/or proven technology employs a static power conversion system and is very similar to the General Electric "Backup Design" presented at Albuquerque. The main differences would be as follows: reactor outlet temperatures in the range of 1100 to 1150 K; mechanical bonding of heat pipe substrate to thermocouple hot shoe; and fixed radiator (no deployable sections considered). The last change means that the system would not be able to meet the 6.1 meter length requirement of the SP-100 Program. However, by making the arbitrary decision to drop to a total electric output of 50 kilowatts, the increased length due to pure fixed radiator is only 2.6 meters, bringing the total length of the system in the cargo bay to approximately 8.75 meters.

The increased length of fixed radiator will not increase the total mass of the system. Also no low temperature heat pipes would be needed to couple the fixed and deployed radiators, since there is no deployed section. The mass savings in heat pipes would help offset the additional side shielding added, so the 3000 kilograms predicted for General Electric's backup system should still hold. The geometry of the proposed system is shown in Figure 6. The total length of the source heat pipes for this system would be approximately 7 meters.

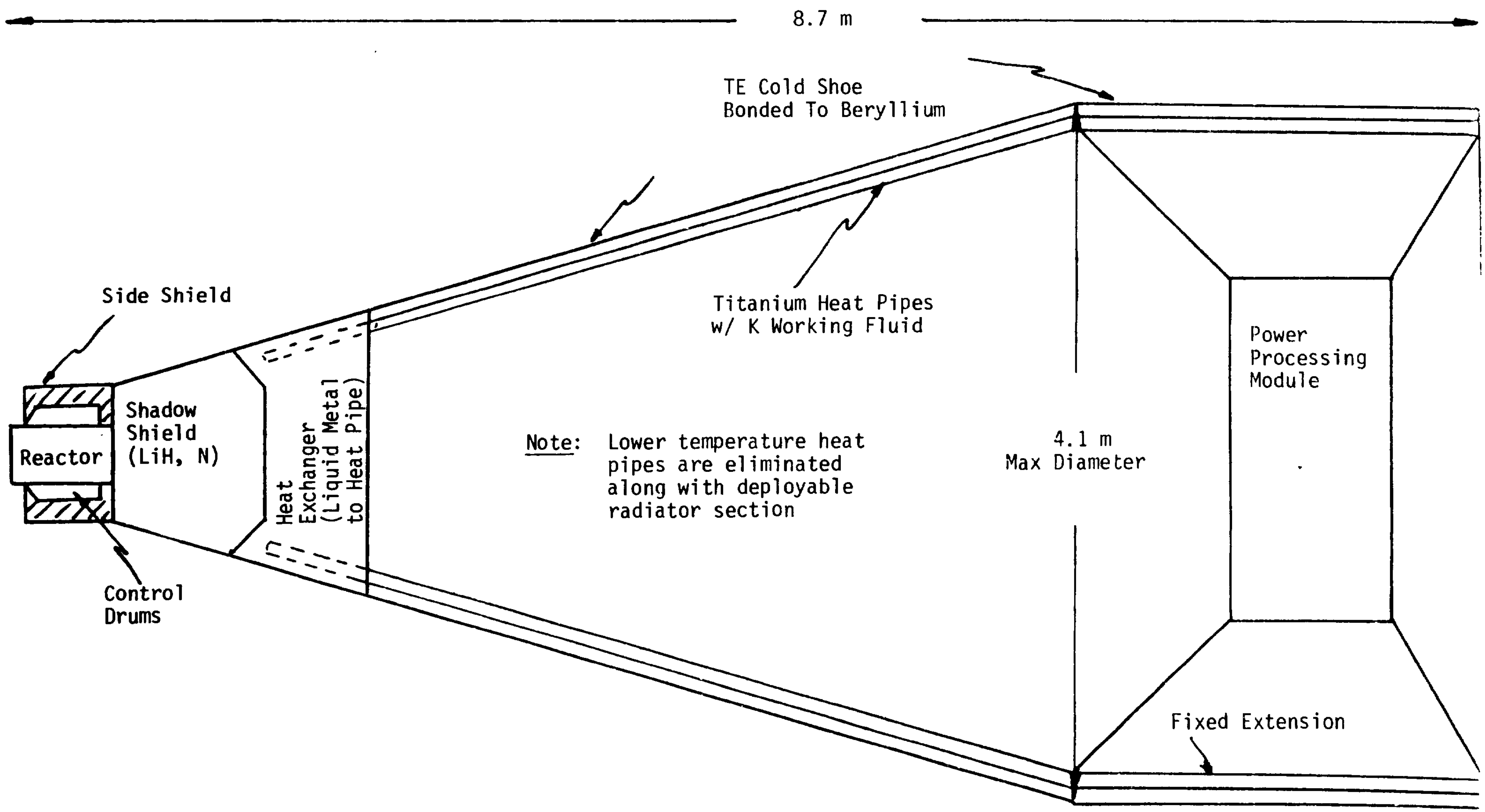

Figure 6. Near-term thermoelectric system utilizing sodium cooled reactor (1150 K outlet temperature) and low temperature radiator (760 K) with fixed extension.

Technical feasibility would center around three items: 1) development of heat exchanger for liquid sodium to heat pipe heat transfer, 2) mechanical bond of heat pipe substrate to thermoelectric hot shoe at 1100 K, and 3) steady state and dynamic operating characteristics of 7 meter heat pipes. All of these issues appear to be of a level of complexity such that they would permit resolution with reasonable certainty before the year 2000. Indeed, this is a very conservative approach for a 50 kilowatt electric system compared to the various proposed SP-100 systems to deliver 100 kWe. It is interesting to compare the cost and performance of this system with that of the planar solar photovoltaic system as addressed earlier in this report. Now the comparison is between a 50 kWe nuclear system and a 100 kWe solar system. Again storage costs are ignored for the solar system.

-HARDWARE

Solar: 100 kWe x \$.75M/kWe = \$75M

Nuclear: same estimates as for 100 kWe unit: \$50M to \$150M

-TRANSPORTATION

Solar: $100 \text{ kWe} \times 69 \frac{\text{kg}}{\text{kWe}} \times \frac{\$12{,}000}{\text{lbm}} \times \frac{2.2 \text{ lbm}}{\text{kg}} = \$182\text{M}$

Nuclear: $3000 \text{ kg} \times \frac{\$12{,}000}{\text{lbm}} \times 2.2 \frac{\text{lbm}}{\text{kg}} = \$79.2\text{M}$

-TOTAL COSTS

Solar: \$257M

Nuclear: \$129M to \$230M

Note that, even ignoring the storage issue, nuclear still appears competitive in this near-term technology state. Moreover, the estimates for hardware would most certainly go to the low end of the range of \$50M to \$15M listed for the nuclear option. Therefore, the nuclear system would probably still offer approximately a two to one cost advantage and an overall savings of the order of \$120M. At these reduced system requirements, the reliability and life of the nuclear system should be extendable to the range of current solar planar systems.

V. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Based on review of literature and on limited examination of nuclear power systems now proposed for space applications, it appears that a nuclear fission reactor powered system should be seriously considered as the first large (order of 50 kWe or greater) power system to be placed on a lunar base. With relatively minor modifications, the major one being addition of a cooled side shield, the proposed 100 kWe product of the SP-100 Program likely could be adapted for use on a lunear base. If the original SP-100 Program requirements were met by this reactor system, the nuclear system would have significant cost advantages over solar photovoltaic. Scaling to 1 MWe systems would follow fairly easily.

Even without the major technology advances needed to meet completely the SP-100 Program requirements, near-term and/or proven technology could produce a nuclear system which would show a competitive advantage over solar photovoltaic. This derated system would meet current program goals on mass limits, but would require slightly more volume in the STS cargo bay because of the use of completely fixed radiators. Selection of a static power conversion subsystem for the near-term technology design was driven partially by reliability concerns.

Any followup studies which look at design of a system specifically for lunar use would likely produce designs significantly different from those now under consideration for space power systems. For example, operation on the lunar surface in 1/6th earth g and with completely deployable radiators put in place on site suggests strong alternatives to current proposed space systems. Dynamic power conversion systems using the Rankine cycle and low temperature radiators would become very attractive. Use of lunar materials for shielding would decrease mass requirements significantly. A specific goal would be to utilize the technology from the current space power reactor system in defining a large power system to be assembled on a lunar base using automated machinery and robotics devices to the extent feasible with year 2000 technology.

APPENDIX A - RADIATOR EFFECTIVENESS FOR SPACE REACTOR SYSTEM USED ON LUNAR BASE

Since space reactors such as that being developed under the SP-100 Program are designed for use in free space, certain issues must be considered when the reactor system is used near the lunar surface. The issue addressed in this appendix is that of as-designed radiator effectiveness.

The system will likely be oriented with the reactor down and the major axis of the waste heat radiator cone vertical to the lunar surface. This arrangement allows for possible nuclear radiation shielding using lunar surface material, while also giving relatively good radiator geometry. Nevertheless, even with this arrangement the radiator will "see" the lunar surface in the radiative heat transfer process.

The surface will exhibit temperatures well above the equivalent sink temperatures seen by a power system in LEO. At points on the lunar surface near the base of the radiator cone the heat load from the radiator is likely to be comparable to that from the sun at lunar noon.

The resulting surface temperatures near the reactor are thus expected to be significantly greater than 400K (usual high noon temperature) during sustained reactor operation. This will reduce the effectiveness of the waste heat radiator and produce a need for either an increased radiator area or a higher radiator temperature or both.

A.1 Problem Geometry and Assumptions

Figure A.1 shows the geometry of the main reactor radiator relative to the lunar surface and identifies various symbols which are used in formulation of the radiation heat transfer expressions. All parts of the lunar surface not directly under the base of the radiator cone were assumed to see a solar heat flux of 1.393 kW/m(squared). This corresponds to the solar flux at the lunar noon. Both the radiator surface and the lunar surface were assumed to have an emissivity of unity. The inside of the upper part of the radiator cone (effectively the "deployed" radiator section as proposed by General Electric[20]) was assumed to be 60% effective as a radiator.

The lunar surface was assumed to be essentially perfectly insulating, i.e. all energy absorbed from the sun or from the reactor radiator was totally re-emitted. The radiator was assumed to have a uniform temperature. This is justified by designs which call for low temperature heat pipes covering the exterior of the radiator and coupling the fixed and deployed sections.

For a given set of calculations, the total thermal output from the radiator was fixed based on system design. The determination was then made of the temperature field on the lunar surface and of the uniform radiator surface temperature. These calculations require the development of rather complicated shape factors for differential areas on the lunar surface and differential areas on the radiator surface (again reference Figure A.1). The differential view factors are defined by the following equations:

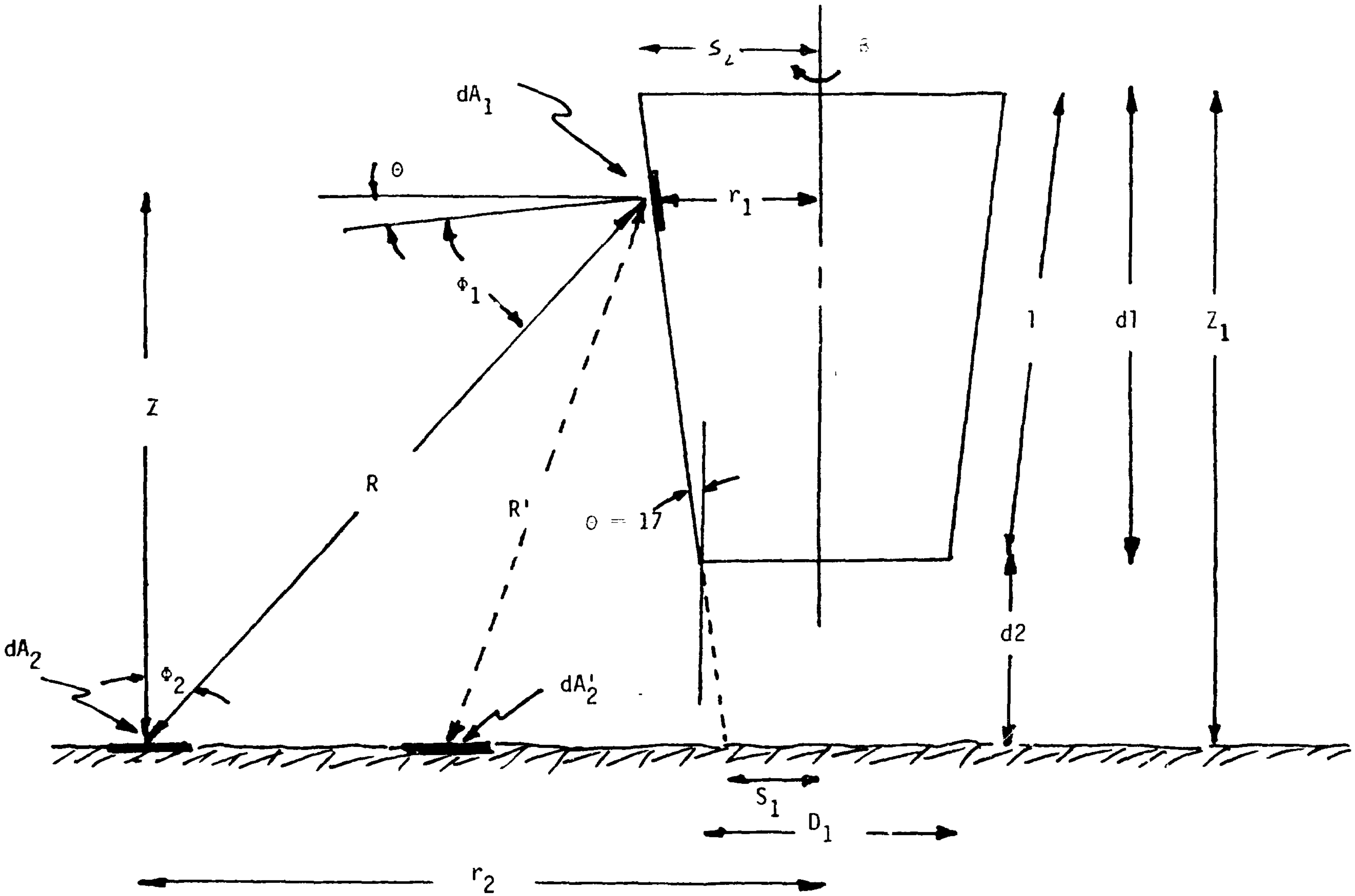

Figure A.1. Geometry and notation for formulation of radiator effectiveness analysis.

$$F_{dA_2A_1} = \int_{d_2}^{z_1} I \, dz \qquad (1)$$

$$I = \frac{2\alpha_1 [1 - (S_1/r_2)^2]^{1/2}}{(R^4 + 2R^2\alpha)[(R^2+\alpha) - \alpha(S_1/r_2)]} [\alpha_2(R^2+\alpha) + \alpha_3\alpha]$$

$$+ \frac{2\alpha_1}{(R^4+2R^2\alpha)^{3/2}} \cos^{-1}\left[\frac{-\alpha + (R^2+\alpha) S_1/r_2}{(R^2+\alpha) - \alpha S_1/r_2}\right] [\alpha_2\alpha + \alpha_3(R^2+\alpha)]$$

where,

$$\alpha = 2 r_1 r_2 \qquad (2.a)$$

$$\alpha_1 = \frac{r_1}{\pi \cos 17} \qquad (2.b)$$

$$\alpha_2 = z \cos 17 \, r_2 \qquad (2.c)$$

$$\alpha_3 = z^2 \sin 17 - z r_1 \cos 17 \qquad (2.d)$$

$$S_1 = D_1/2 - d_2 \tan 17 \qquad (2.e)$$

$$r_1 = z \tan 17 + S_1 \qquad (2.f)$$

$$R^2 = z^2 + (r_2 - r_1)^2 \qquad (2.g)$$

Then, if Q is the total heat rejected and E_S is the solar flux, the radiator temperature T_r is given by

$$T_R^4 = \frac{Q^* + \int_{A_2} F_{dA_2A_1} \alpha_R E_S \alpha_L dA_2}{[A_1(1+\xi\eta) - \int_{A_2} (F_{dA_2A_1})^2 \alpha_R \alpha_L dA_2] \sigma \epsilon_R} \qquad (3)$$

The lunar temperature distribution is as follows:

$$T_L^4 = \frac{E_S \alpha_2 + F_{dA_2A_1} \sigma T_R^4 \epsilon_R \alpha_L}{\sigma \epsilon_L} \qquad (4)$$

where

σ ≡ Stefan - Boltzman constant (5.a)

α_R, α_L ≡ absorptivities (5.b)

ϵ_R, ϵ_L ≡ emisivities (5.c)

ξ ≡ deployed area ratio (radiator) (5.d)

η ≡ radiative heat transfer fraction from the inside of the deployed radiator cone (5.e)

and,

$$Q^* = Q + E_S A_1 \sin 17 \qquad (6.)$$

The equations were verified by calculating the radiator temperature for large values of d2, which is the distant of separation of the base of the cone from the lunar surface. As d2 becomes very large, the radiator temperatures should approach the value for radiation into free zero temperature space. This behavior was verified for all cases.

The results of two parameter studies in which the distance d2 was varied are summarized below. In general, the results show that the radiator temperature is not strongly effected by the presence of the lunar surface.

A.2 Analysis of Baseline Design of Reference 20

In this analysis a total power of 2.1MW was assumed to be rejected from a radiator cone with a bottom diameter of 1.28 m and a total axial length of 6.115 m. A plot of radiator temperature versus height of radiator above lunar surface is presented as Figure A.2. Notice that as the radiator is moved farther and farther from the lunar surface, an asymtotic value of approximately 803 K is approached. This is lower than the predicted 843 K of Reference 20 primarily because an emissivity of unity was assumed here for the radiator surface. The most important point to note is that the radiator temperature increases by only approximately 10 K as the radiator cone is moved from effectively an infinite distance to a height of only 1.5 meter above the lunar surface. If desired, a short extension to the deployable radiator could be made to compensate for this temperature increase. Lunar surface temperatures peaked near the base of the reactor at values less than 600 K. At distances of 10 m or greater from the base of the cone, lunar surface temperatures were essentially that expected for only solar heat flux.

A.3 Lower Temperature Radiator Systems

The possibility that reactor systems utilizing lower heat rejection temperatures might be more dramatically affected by the presence of the lunar surface motivated a set of calculations which apply roughly to the "growth concept" of Reference 20. The total rejected power for this case was 326kW. Total radiator area was slightly less than that of the case discussed in section A.2. The radiator temperature in free space was approximately 580 K. For a radiator base elevation of 1.5 meters, this temperature increased to 597 K. Even in the extreme case of burying the reactor, shield, and heat exchanger and having the radiator bottom essentially level with the lunar surface, the radiator temperature only increased to 604 K.

Thus, even for extreme cases treated in this section, the increase in main radiator temperature, and therefore in overall system temperatures was not expected to be limiting. Slight increases in overall radiator area or decreases in power rating of system would accommodate any anticipated problems.

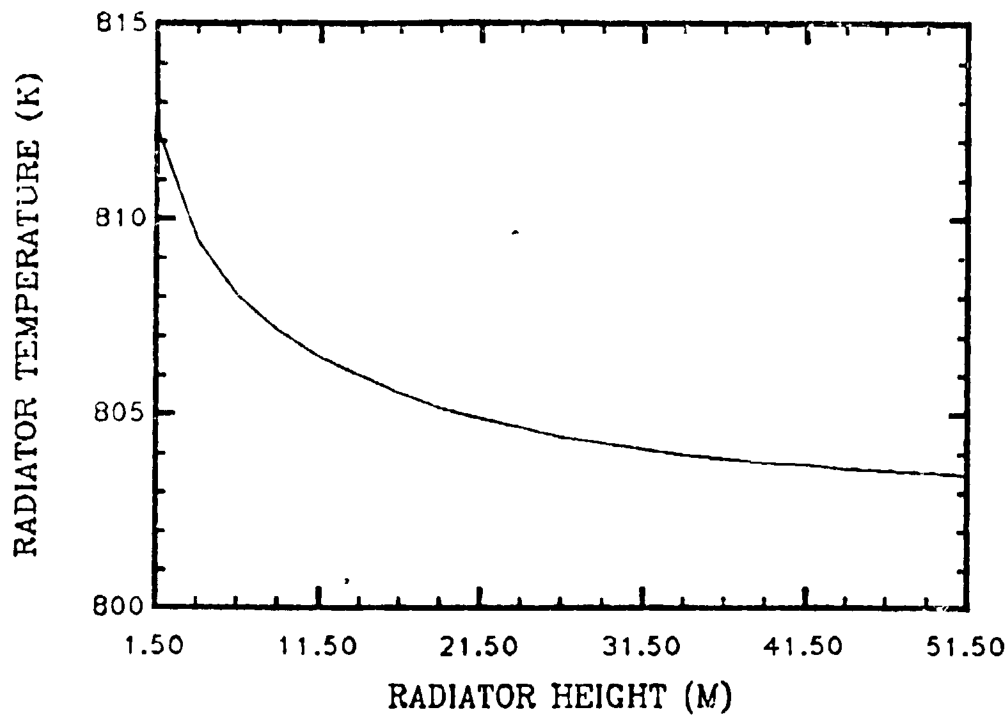

Figure A.2. Radiator temperature as a function of height of radiator above surface (d2) for the "Baseline" design of Reference 20.

APPENDIX B - BACKSCATTERING EXPERIMENT

B.1. Experiment Setup

An experiment was performed to assess the radiation buildup behind a shadow shield due to backscatter off of a nearby surface. A wooden tripod with pulley assembly was built as shown in Figure B.1. Paraffin and lead shields were fabricated and secured to the radiation sources as illustrated in Figure B.2.

A GM detector was used to detect gamma radiation. A B-10 detector with and without sleeve as shown in Figure B.3 was used to detect fast and thermal neutrons, respectively. A block diagram of the detector and counting system is given as Figure B.4.

B.2. Experiment Procedure

Measurements were first taken using the neutron source. The source and paraffin shield were positioned at various heights above the ground (at one foot increments). For each source height, the distance between the source and the detector was varied, and measurements were taken (30 second counts) with the fast neutron detector. Subsequently, one minute counts were taken at essentially the same locations with the thermal neutron detector. (The distance between source and detector was measured from the bottom surface of the source to the bottom surface of the detector.)

Next the neutron source was replaced with the gamma source, and the neutron detector was replaced with the gamma detector. Then the experiment outlined above was repeated for gamma measurements.

Background counts were taken at the end of each series of measurements for both the neutron and gamma detectors.

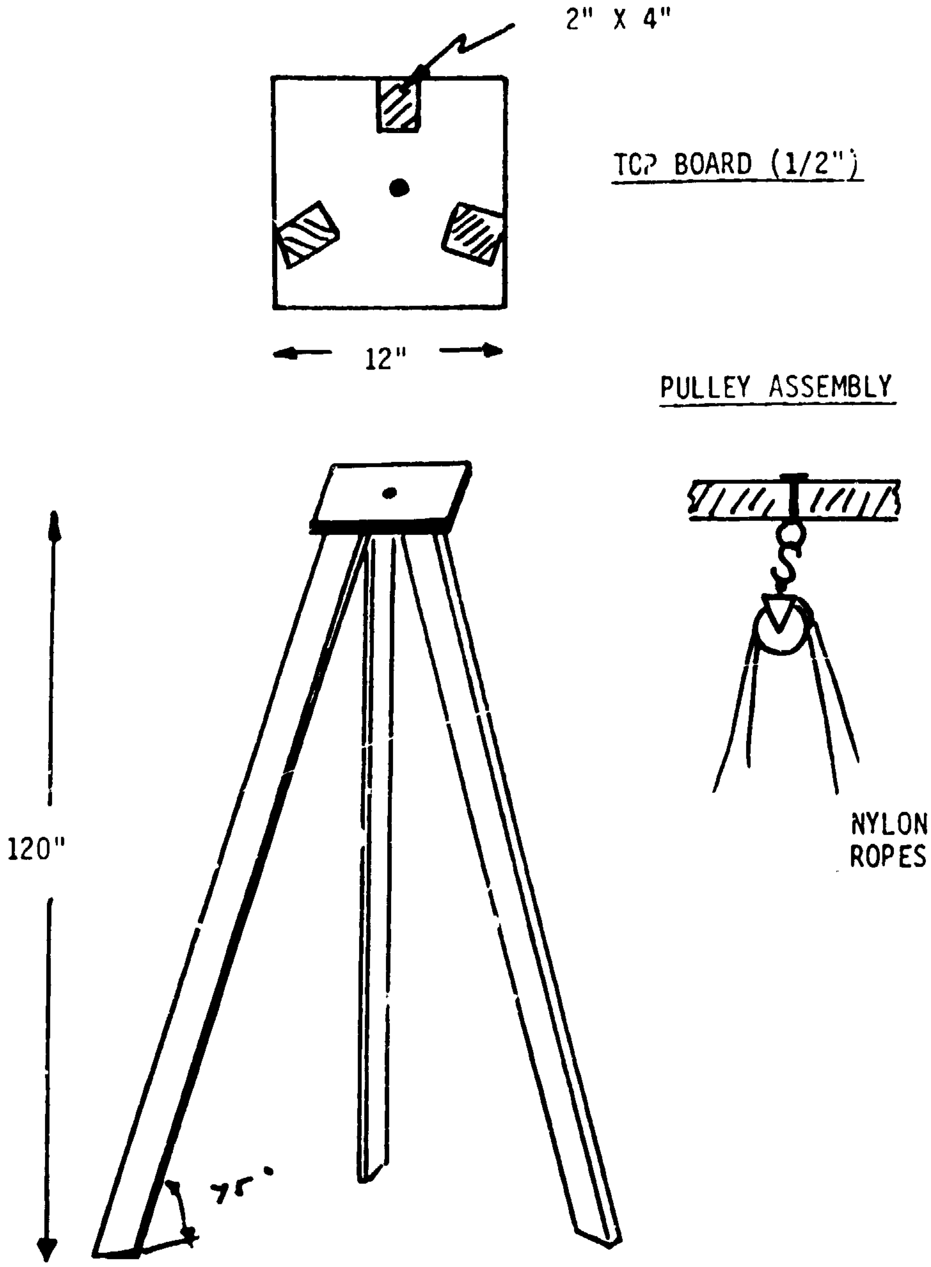

Figure B.1. Tripod and pulley assembly.

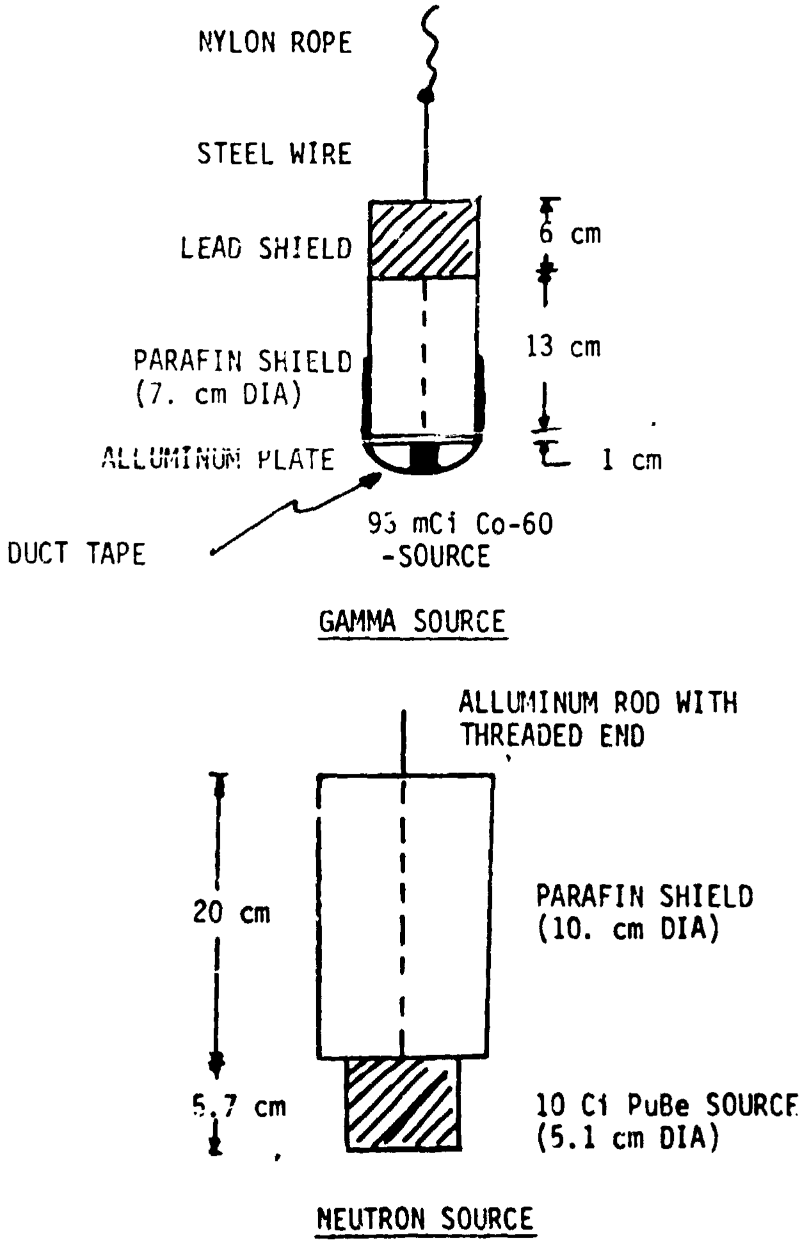

Figure B.2. Radiation shields and sources.

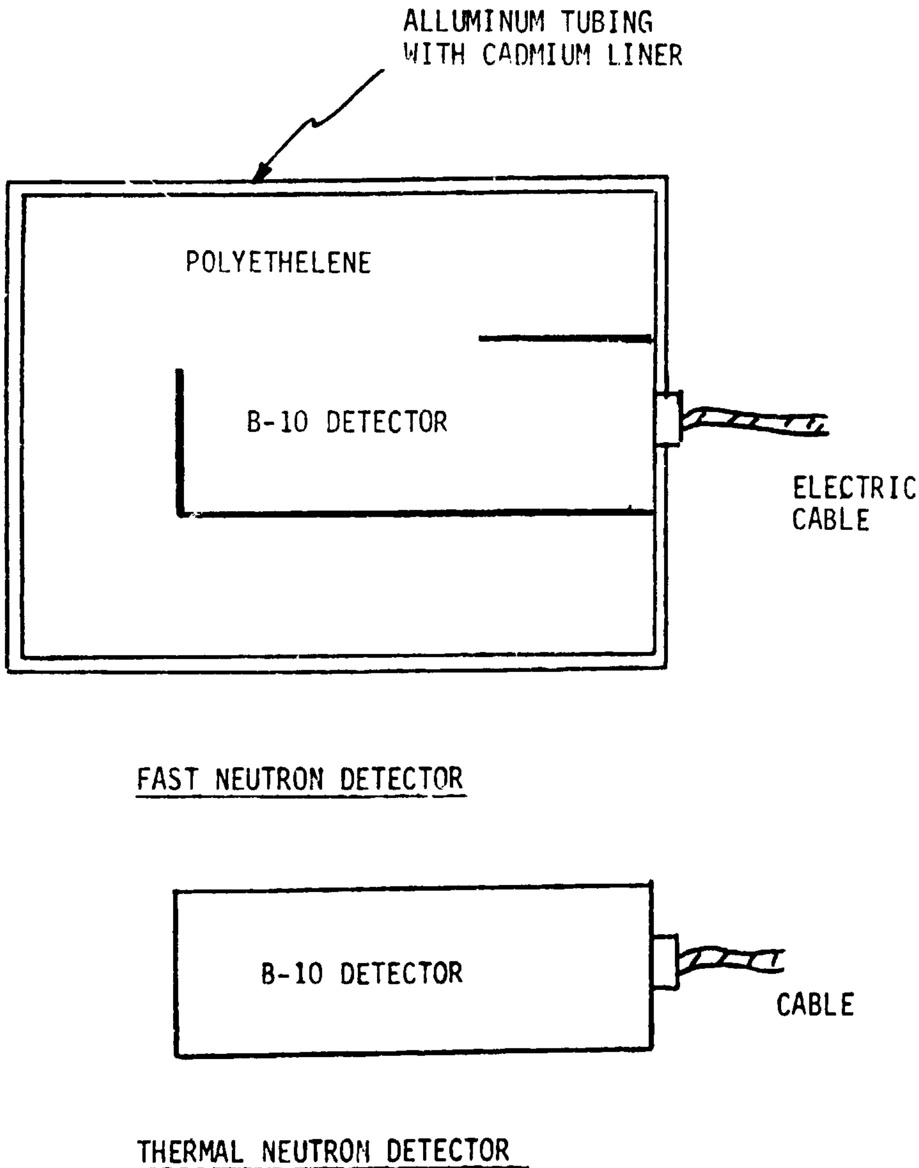

Figure B.3. Fast and thermal neutron detectors.

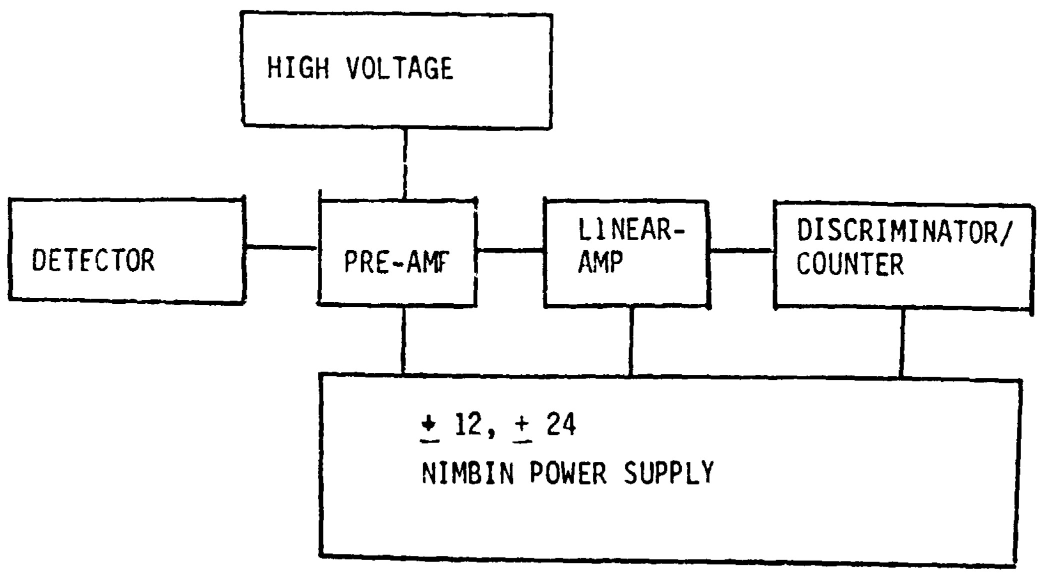

Figure B.4. Block diagram of detector hook-up.

B.3. Results

The following pages show results obtained from the experiments with neutron and gamma sources. Figures B.5, B.6 and B.7 show counts vs. detector/source separation at different source heights. Table B.1 is a tabulation of the experiment data.

TABLE B.1 EXPERIMENTAL MEASUREMENTS

A. Pu-Be Source (10 Ci)

1. Fast Neutron Measurements:

Background = 214 c/30 sec

	Source/Detector Separation (ft)	Counts/30 Second Minus Background
Source Height = 0.0 ft	1.0	1826
	1.5	1270
	2.0	930
	2.5	733
	3.0	499
	3.5	337
	4.0	316
	4.5	253
	5.0	213
Source Height = 1.0 ft	1.0	873
	1.5	846
	2.0	510
	2.5	558
	3.0	344
	3.5	348
	4.0	276
	4.5	222
	5.0	237
Source Height = 2.0 ft	1.0	624
	2.0	424
	3.0	238
	4.0	191
Source Height = 3.0 ft	1.0	410
	2.0	256
	3.0	133
Source Height = 4.0 ft	1.0	348
	1.5	289

2. Thermal Neutron Measurements:

Background = 60 c/60 sec

	Source/Detector Separation (ft)	Counts/60 Second Minus Background
Source Height = 0.0 ft	2.0	155[illegible]
	3.0	922
	4.0	641
	5.0	457
	6.0	417
	7.0	272
Source Height = 1.0 ft	2.0	806
	3.0	587
	4.0	460
	5.0	379
	6.0	279
Source Height = 2.0 ft	2.0	643
	3.0	420
	4.0	330
	5.0	255
Source Height = 3.0 ft	2.0	577
	3.0	359
	4.0	276
Source Height = 4.0 ft	2.0	505
	3.0	340

B. Co-60 Source (93 mCi)

Gamma Measurements:

Background = 700 c/30 sec

	Source/Detector Separation (ft)	Counts/30 Second Minus Background
Source Height = 0.0 ft	1.0	37578
	2.0	13665
	3.0	6276
	4.0	3590
	5.0	2334
	6.0	1650
	7.0	895
Source Height = 1.0 ft	1.0	12982
	2.0	6173
	4.0	2173
	5.0	1459
	6.0	916

	Source/Detector Separation (ft)	Counts/30 Second Minus Background
Source Height = 2.0 ft		
	1.0	7332
	2.0	3220
	3.0	1805
	4.0	1263
	5.0	861
Source Height = 3.0 ft		
	1.0	5495
	2.0	2174
	3.0	1308
	4.0	811
Source Height = 4.0 ft	1.0	4523
	2.0	1691
	3.0	916
Source Height = 5.0 ft	1.0	4488
	2.0	1377

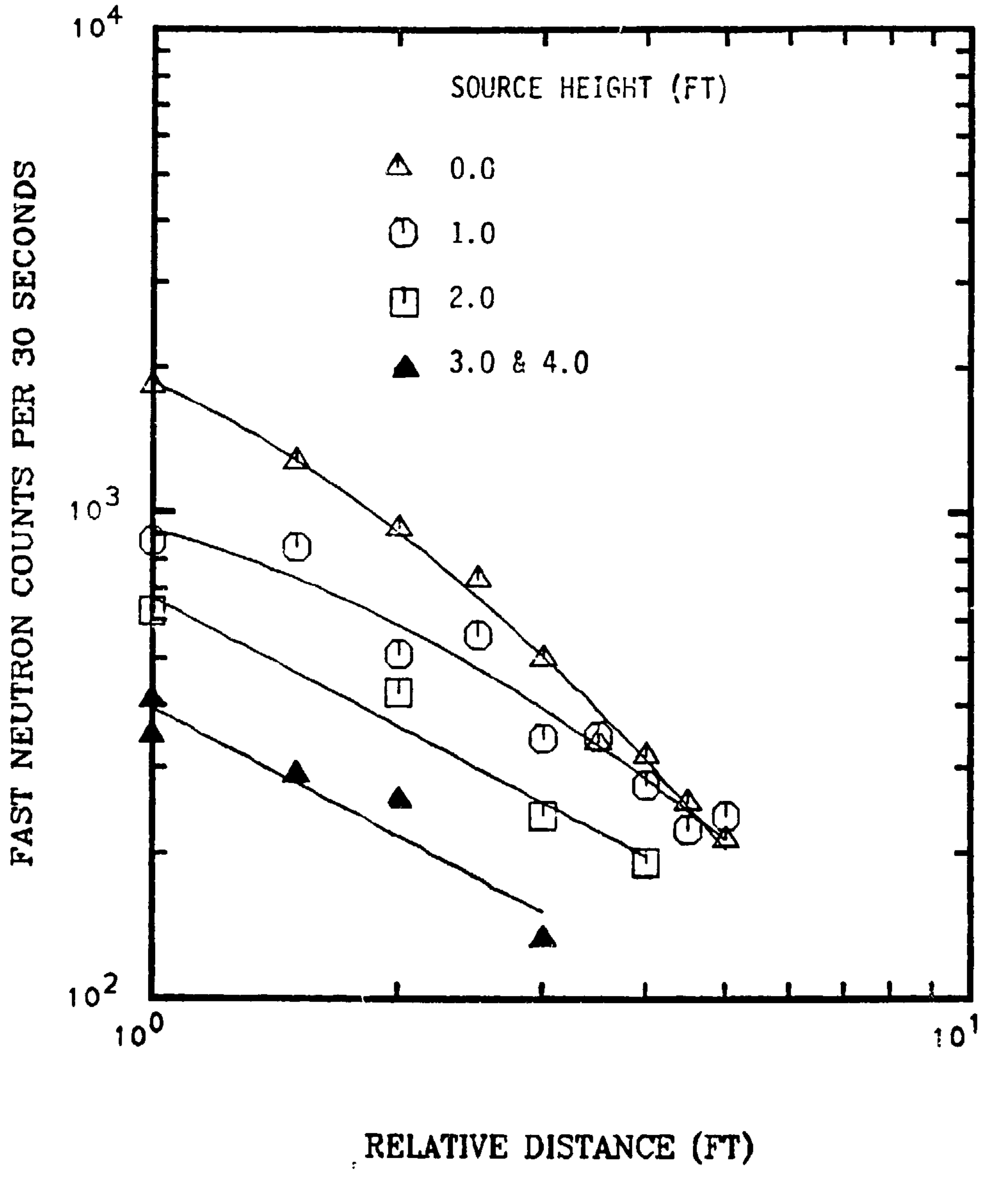

Figure B.5. Fast neutron count rates measured as a function of seperation distance between base of source and base of detector at different source heights above ground.

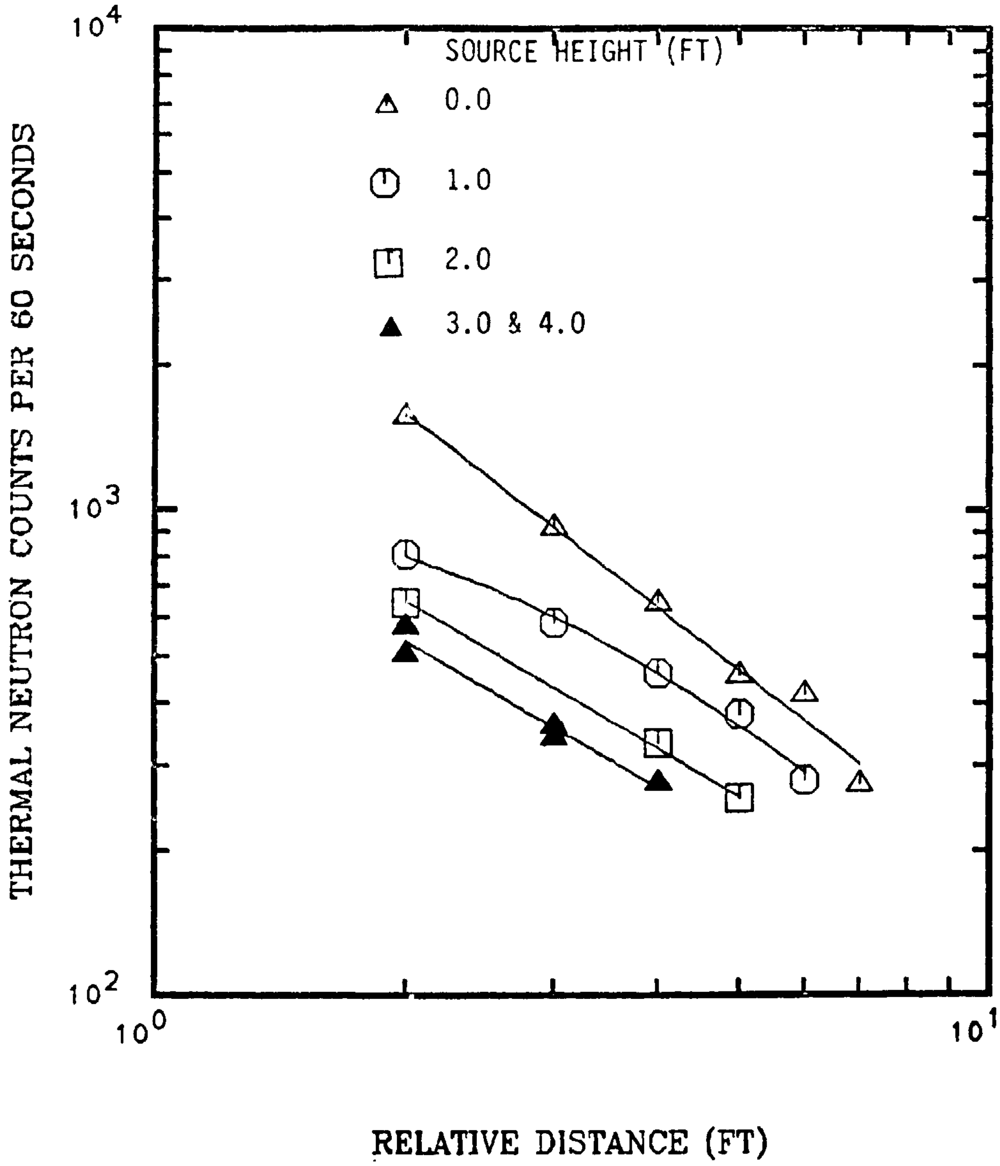

Figure B.6. Thermal neutron count rates measured as a function of seperation distance between base of source and base of detector at different source heights above ground.

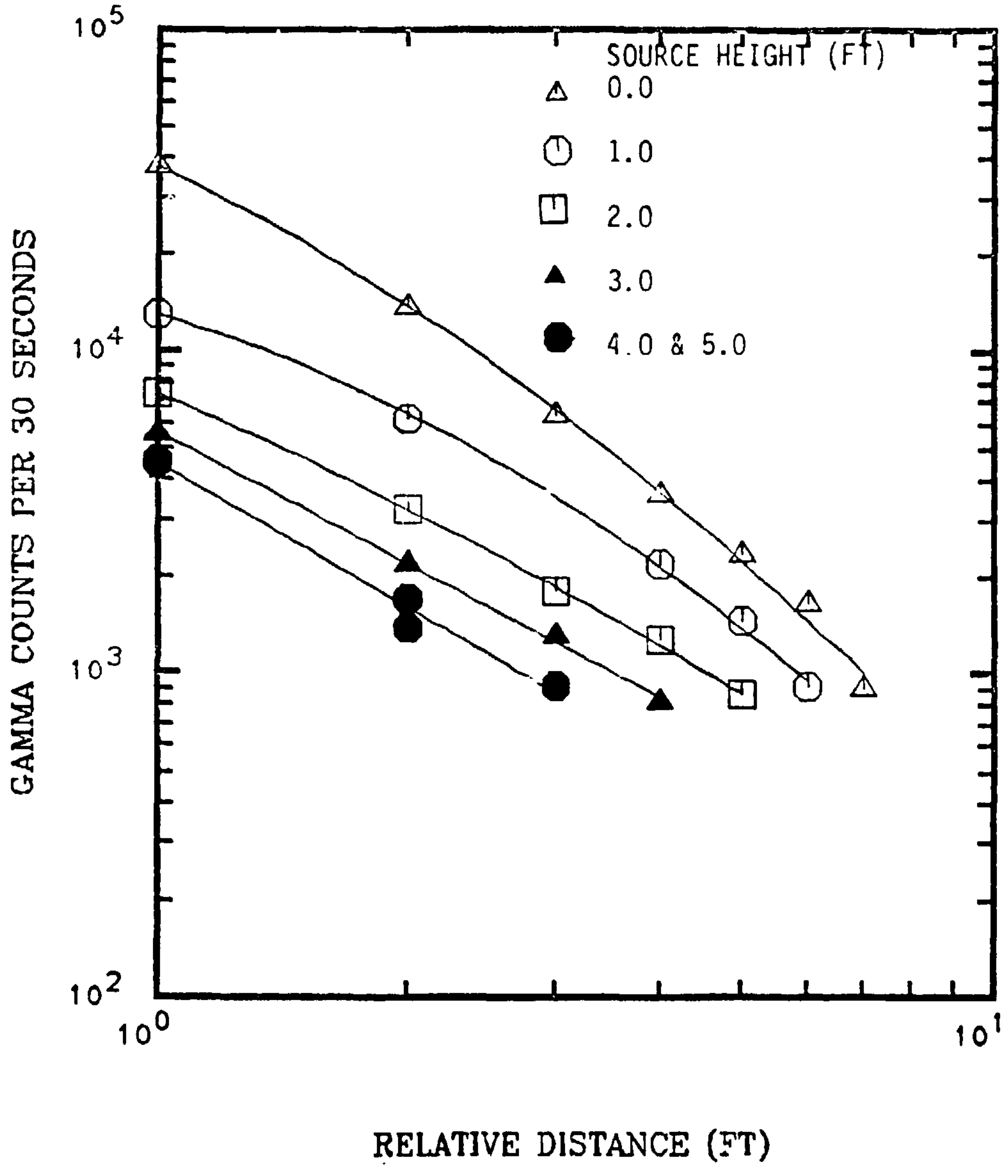

Figure B.7. Gamma count rates measured as a function of seperation distance between base of source and base of detector at different source heights above ground.

Tables B.2, B.3, and B.4 show coefficients for curve fits (using least squares method) to the points shown in Figures B.5, B.6, and B.7. The data were fitted according to the following formulas,

$$\ln(y) = \sum_i a_i \, (\ln x)^i \qquad (1)$$

$$\beta = \sigma^2 = \sum_i \frac{e_i^2}{N-n-1} \qquad (2)$$

where,

y = number of counts
x = the detector/source separation (ft)
β = σ^2, the square of the standard deviation
N = number of data
n = degree of the polynomial
e_i = deviation between actual and fitted curve values

TABLE B.2 FAST NEUTRON DATA EMPIRICAL FIT

Source Height (ft)	Polynomial Coefficients			
	a_0	a_1	a_2	β
0.0	7.5232	-0.76558	-0.37598	0.505×10^{-2}
1.0	6.8257	-0.46008	-0.28067	0.16×10^{-1}
2.0	6.5021	-0.88039	0.0	0.11×10^{-1}
3.0 & 4.0	5.9796	-0.87745	0.0	0.49×10^{-2}

TABLE B.3 THERMAL NEUTRON DATA EMPIRICAL FIT

Source Height (ft)	Polynomial Coefficients			
	a_0	a_1	a_2	β
0.0	8.2821	-0.13244×10^{1}	0.0	0.528×10^{-2}
1.0	6.9020	-0.79627×10^{-1}	-0.3421	0.337×10^{-2}
2.0	7.1628	-0.99814	0.0	0.337×10^{-3}
3.0 & 4.0	6.9698	-0.99257	0.0	0.308×10^{-2}

TABLE B.4 GAMMA DATA EMPIRICAL FIT

Source Height (ft)	Polynomial Coefficients			
	a_0	a_1	a_2	β
0.0	10.526	-1.2166	-0.33037	0.636×10^{-2}
1.0	9.4622	-0.74706	-0.3935	0.155×10^{-2}
2.0	8.9002	-1.1026	-0.13674	0.64×10^{-3}
3.0	8.6233	-1.3602	0.0	0.131×10^{-2}
4.0 & 5.0	8.3987	-1.4833	0.0	0.685×10^{-2}

B.4 Discussion

Note that at the maximum source heights where data was taken, the best fit polynomial is a linear curve in the above tables. The gradients for those linear curves are -0.88, -0.99, and -1.48. For the ideal case at very large source heights, the contribution from backscattering should be negligible. This, combined with the assumption of an isotropic point source, which would only apply at very large source to detector distances, should result in counts which are proportional to the inverse square of the separation distance between detector and source; thus on a log-log plot, the counts vs. distance curve for the ideal case would be a straight line of slope -2.0. This anticipated behavior is partially confirmed in the experiment, since the empirical fit for the gamma data produces a linear curve of slope -1.5. For the results involving fast neutrons, the anticipated behavior is also recognized for measurements with separation distances greater than 2 feet. At maximum source height the slope calculated using only the data with source/detector separations greater than 2 feet is -1.62. For thermal neutrons, the experimental results do not show the tendency toward inverse square dependence as in the case of gammas and fast neutrons. This is probably due to thermal neutron buildup in the shield as fast neutrons are thermalized. However as indicated by Figures B.8, B.9, and B.10 (plots of count rates vs. source height for fixed source/detector separation) all the measured count rates approach asymtotic values at source heights of 4 feet. These results show that backscattered radiation at this source-to-ground distance is negligible, assuming the measured count rates are from radiation passing through the shield and not from "sky shine".

The shield thickness of typical suggested SP-100 designs is the order of 75 cm, and the composition of the shield is lithium hydride and tungsten. This is quite different from the 20 cm of paraffin used in the experiment. Therefore, an attempt was made to extrapolate the experiment data for fast neutron and gamma backscattering to the SP-100 situation using simple removal cross sections and assuming an isotropic point source. This analysis did not produce satisfactory results, and we recommend a new set of experiments and/or detailed Monte Carlo calculations to resolve this issue.

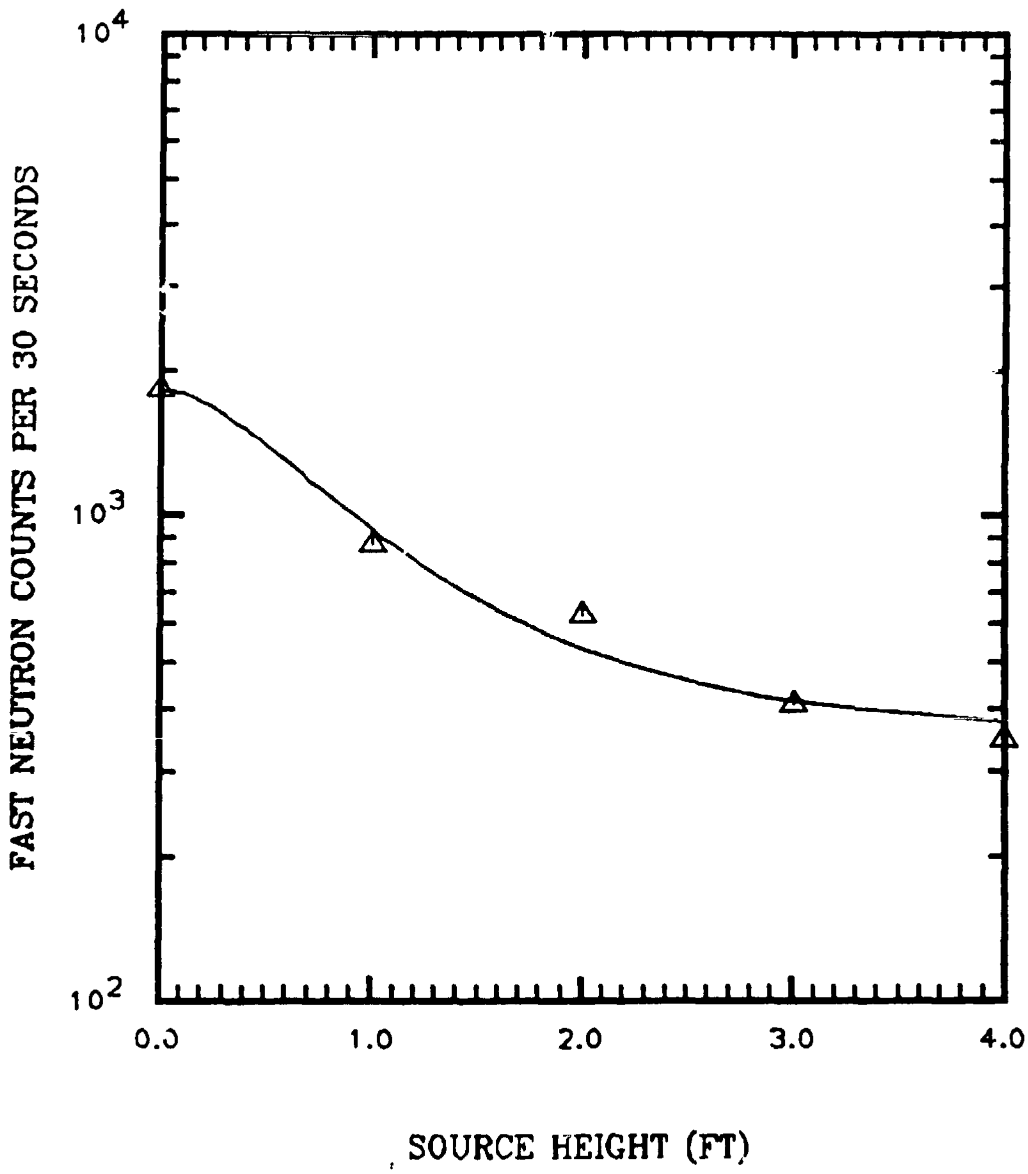

Figure B.8. Fast neutron count rates measured as a function of height of source above ground. Base of detector was located one foot from base of source.

Curve fit: $\ln y = 5.87 + 3.22 \exp(-x) - 1.59 \exp(-2x)$

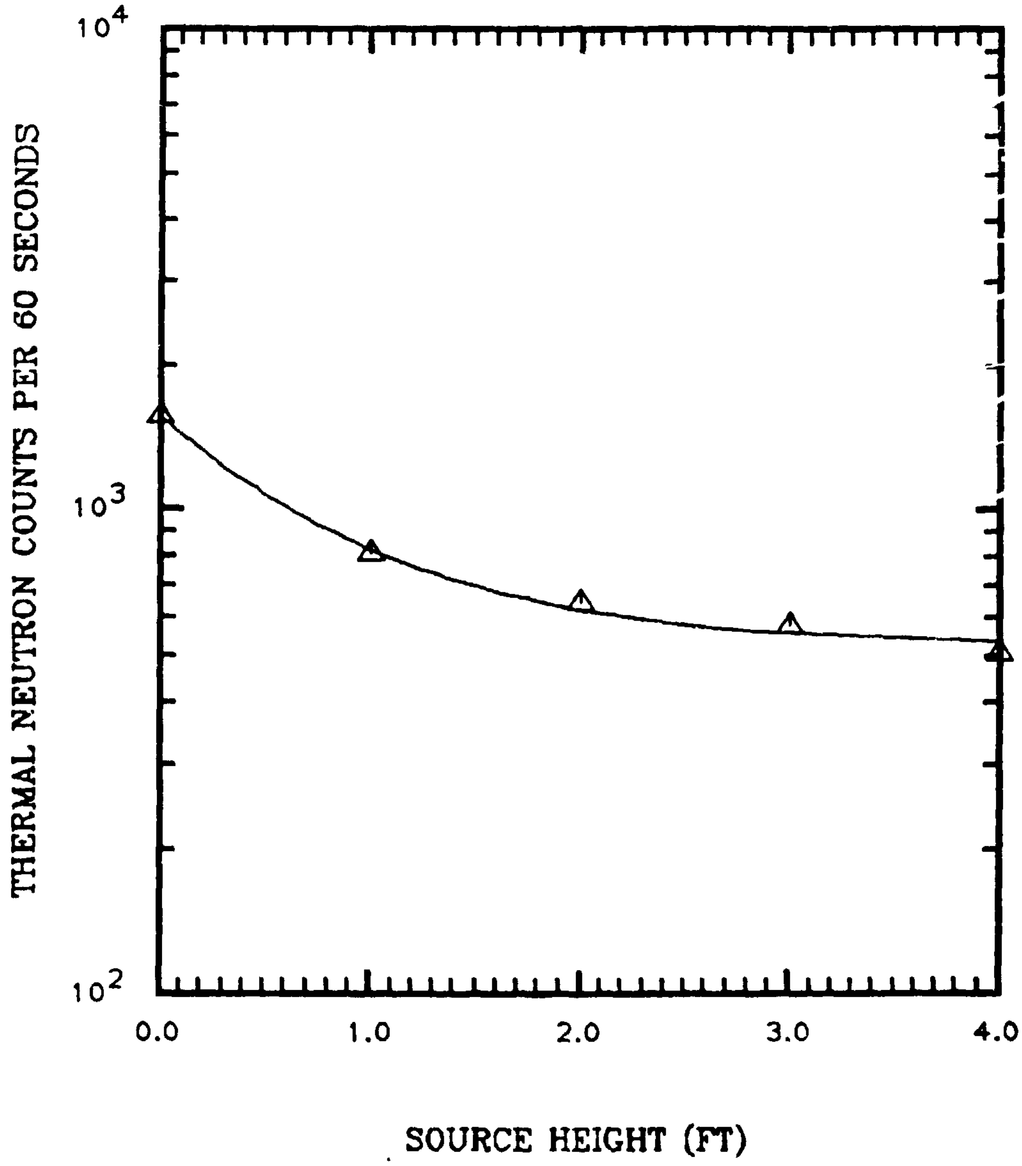

Figure B.9. Thermal neutron count rates measured as a function of height of source above ground. Base of detector was located two feet from base of source.

Curve fit: $\ln y = 6.25 + 1.34 \exp(-x) - .247 \exp(-2x)$

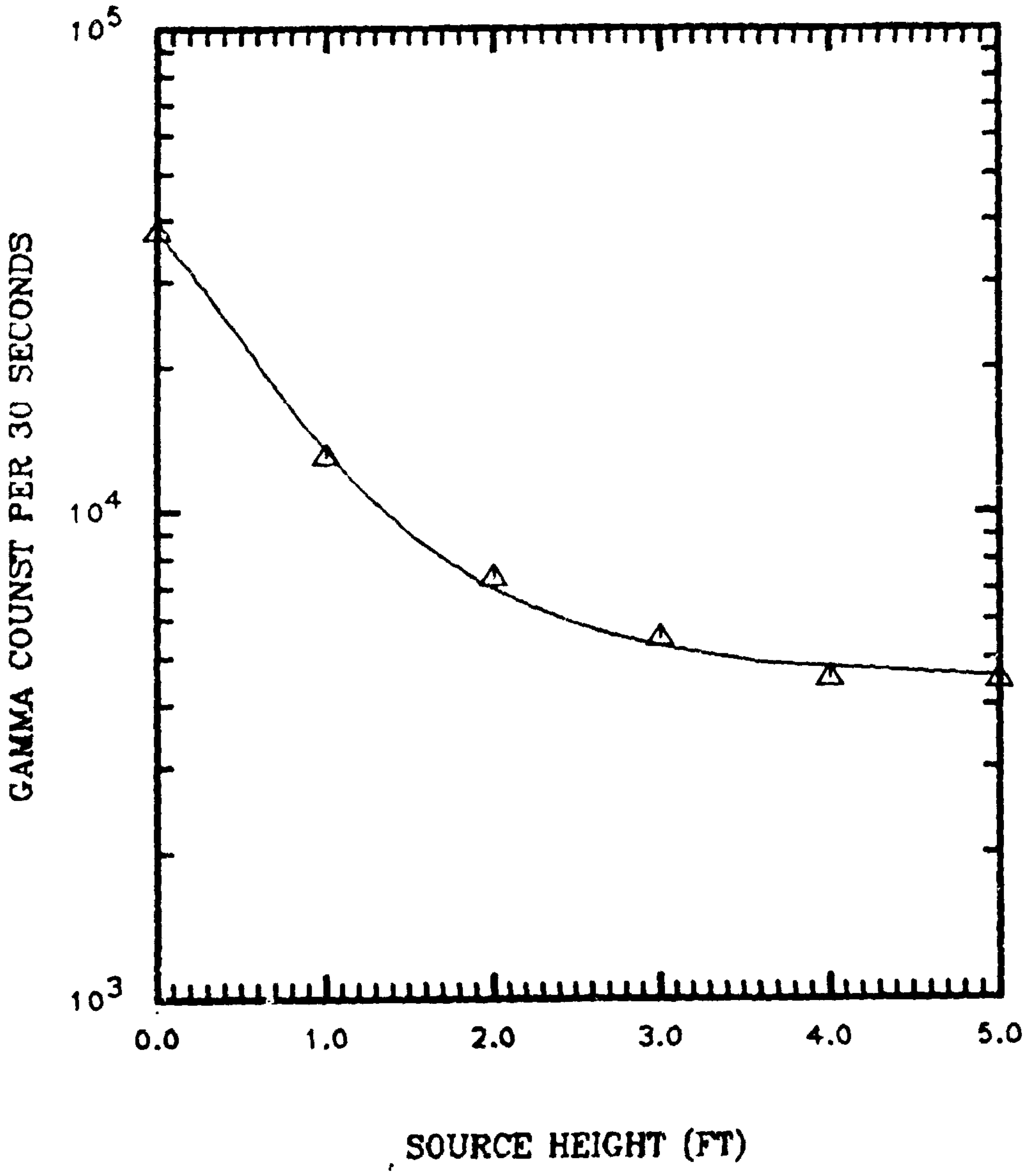

Figure B.10. Gamma count rates measured as a function of height of source above ground. Base of detector was located one foot from base of source.

Curve fit: $\ln y = 8.40 + 2.35 \exp(-x) - 1.36 \exp(-2x)$

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