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PRELIMINARY DESIGNS OF SPACE POWER NUCLEAR REACTOR SHIELDS

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16. Abstract

Preliminary designs of two 4π shield configurations for a SNAP-8 mercury-Rankine cycle power system are presented. The shield materials are lithium hydride, tungsten alloy, and depleted uranium. The nuclear heat generated in the shields is discussed and methods of rejecting this heat are suggested. Layout drawings are included that show structural details. A detailed weight breakdown is given for both shields. The number and sizes of the shield penetrations are given. Several problem areas are identified.

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SUMMARY

The preliminary designs of two 4π nuclear reactor shield configurations for a SNAP-8 mercury-Rankine power system are presented. The reactor used is a SNAP-8 Development Reactor (S8DR) with minor modifications. These designs consider two gallery sizes. The gallery is the space inside the shield containing the primary loop components other than the reactor. Two dose levels that appear to be in the range of interest for manned systems are considered.

A shield with a gallery height of 60 inches (152.5 cm) (to accommodate the gallery components as currently designed) and a radiation dose level of 2 millirem per hour at 130 feet (39.6 m) in the crew direction and 1 rem per hour at 130 feet (39.6 m) elsewhere weighed 43 000 pounds (19 550 kg). A shield with the same dose level but a gallery height of 25 inches (63.5 cm) (this gallery would require the development of components for an additional loop) weighed 37 000 pounds (16 830 kg). A shield with a gallery height of 60 inches (152.5 cm) and a radiation dose level of 0.5 millirem per hour at 130 feet (39.6 m) in all directions weighed 137 000 pounds (62 300 kg). A shield with the same dose level but a gallery height of 25 inches (63.5 cm) weighs 105 000 pounds (47 700 kg).

The shielding materials selected for these designs are natural lithium hydride and depleted uranium, arranged in alternate layers. In one case a tungsten alloy replaced one of the uranium layers.

Thermal analyses were conducted to define the shield and the reactor reflector assembly cooling requirements. To avoid exceeding the temperature limit of the reflector assembly, an actively cooled wall must be placed around it. The innermost layer of lithium hydride must be actively cooled to limit its peak temperature.

Layout drawings are included which show the shield support structure. Shield penetrations, compatibility of system fluids with shield materials, and power system replaceability are discussed.

INTRODUCTION

NASA has proposed a manned orbiting Space Base to be constructed in the early 1980's. To supply electrical power to this Space Base, nuclear-reactor-type power systems are being considered. The SNAP-8 (Systems for Nuclear Auxiliary Power) mercury-Rankine power system is being developed for space use. The components of the SNAP-8 mercury-Rankine power conversion system have reached the stage of development where their integration into a space flight configured system is possible (ref. 1). A combined system test is planned that would couple this power conversion system (PCS) to a SNAP-8 Reactor. To attain a flight configured system, the Lewis Research Center is investigating space flight shield designs for use in the planned combined system test.

The type of shield being considered is a shield which completely surrounds the reactor (4π shield). The reactor for which the shields were designed is the SNAP 8 Development Reactor (S8DR) with minor modifications. These shields were designed when the S8DR was being considered for use in the combined system test. Currently the reference zirconium hydride reactor is contemplated for use in this test. Shield designs for the reference zirconium hydride reactor are being investigated; however, they are not included in this report.

The SNAP-8 mercury-Rankine PCS consists of four major loops (ref. 1). These loops are the primary NaK loop, the mercury power conversion loop (liquid and vapor), the NaK heat rejection loop, and the lubrication cooling loop containing polyphenyl ether. Because the primary loop NaK is activated by neutron absorption in the reactor, the primary loop is located inside the shield. All primary loop components except the reactor are grouped in a compact arrangement called the gallery. The gallery is shielded from the reactor to avoid activation of the fluids in the power conversion loops.

This report gives the preliminary results of the 4π shield design studies. Thermal analyses were conducted to define reactor reflector assembly and shield cooling requirements. Conceptual constructional details and weights are also discussed.

SHIELD DESCRIPTION

Shield configurations were considered for two radiation dose levels and two gallery heights.

These dose levels were:

(1) The higher of the two radiation dose levels was 2 millirem per hour at a distance of 130 feet (39.6 m) in the crew direction and 1 rem per hour at this same distance elsewhere (see fig. 1).

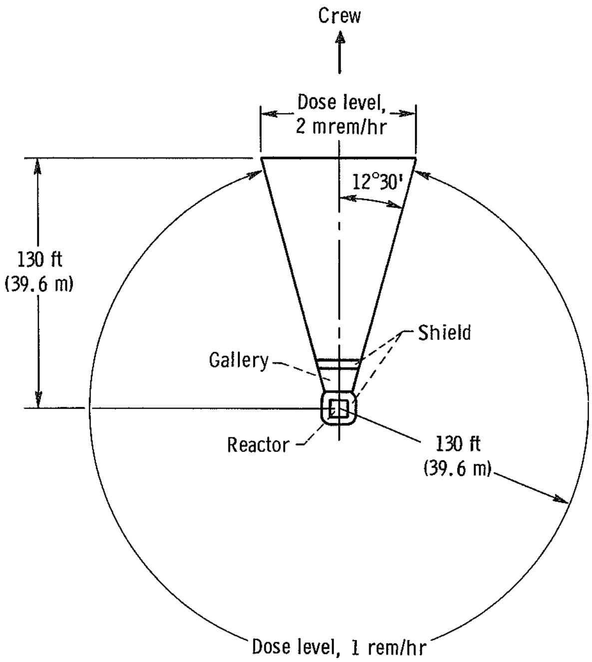


Figure 1. - Radiation dose levels for higher dose level shields.

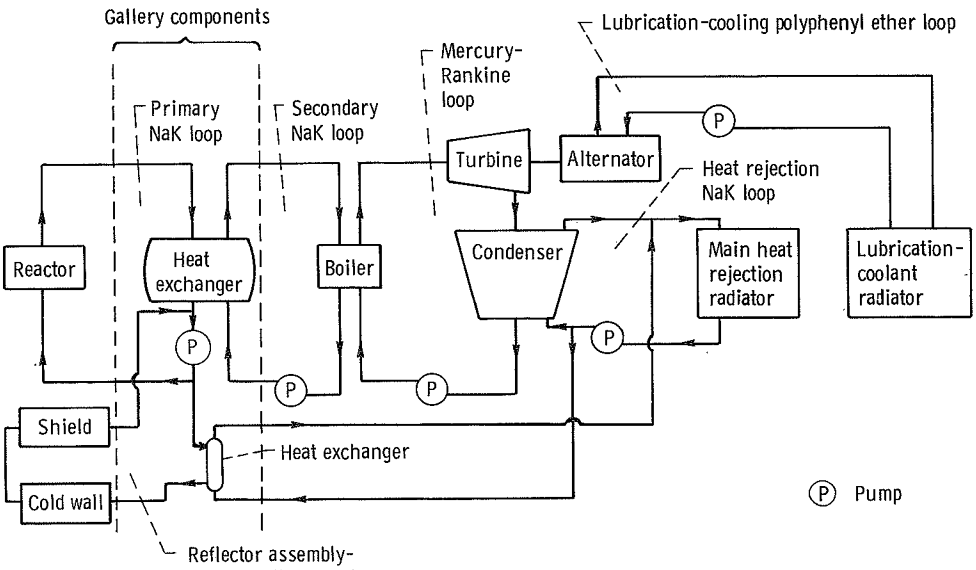


Figure 2. - SNAP-8 mercury-Rankine power system, modified to include intermediate heat exchanger in gallery and reflector assembly-shield cooling loop.

(2) The lower radiation dose level was 0.5 millirem per hour at a distance of 130 feet (39.6 m) in all directions.

These dose levels appear to be in the range of interest for manned space power nuclear reactor systems.

The gallery in all the shield configurations of this study was located between the reactor and the crew (see fig. 1). Galleries located at the other end of the reactor (away from the crew) are being studied but are not covered in this report.

Shield weights were determined for two gallery heights, 60 inches (152.5 cm) and 25 inches (63.5 cm). In the existing SNAP-8 PCS (ref. 1), the gallery is 60 inches (152.5 cm) high to accommodate the mercury boiler. Shield weight can be reduced if the gallery size is reduced. The large cost of launching payloads into orbit is the incentive to reduce the shield weight. To reduce shield weight, a modified SNAP-8 PCS may be used (see fig. 2) that has a small heat exchanger in a secondary NaK loop between the reactor primary loop and the mercury-Rankine loop. The gallery height may be only 25 inches (63.5 cm) high if the heat exchanger is used. For the design using a 25-inch (63.5-cm) gallery the mercury boiler is located outside of the shield.

The shields were designed to accommodate a S8DR reactor with minor modifications. The materials of these shields were selected as tungsten and depleted uranium for the high density gamma ray attenuating layers and natural lithium hydride for the neutron attenuating layers. The material location and layering of the shields were optimized for minimum weight. Shields with the higher radiation dose level will be referred to as three layer shields (one high density material layer and two lithium hydride layers in the radial direction - see fig. 3). Shields with the lower radiation dose level will be referred to as six layer shields (three high density layers and three lithium hydride layers - see fig. 4).

The reflector assembly of the S8DR was designed to radiate heat directly to space so that the temperature of the reflector assembly including the bearings does not exceed 1200° F (923 K). A shield that surrounds the reactor introduces a thermal barrier that would cause the reflector assembly to exceed 1200° F (923 K). To avoid this overtemperature condition, an actively cooled wall ("cold" wall) at a temperature of about 500° F (533 K) must be placed around the reflector assembly inside the shield. A thermal analysis of the shields shows that the innermost lithium hydride layer will also require cooling. One NaK loop can be used to cool the wall around the reflector assembly and to cool the shield as shown schematically in figure 2.

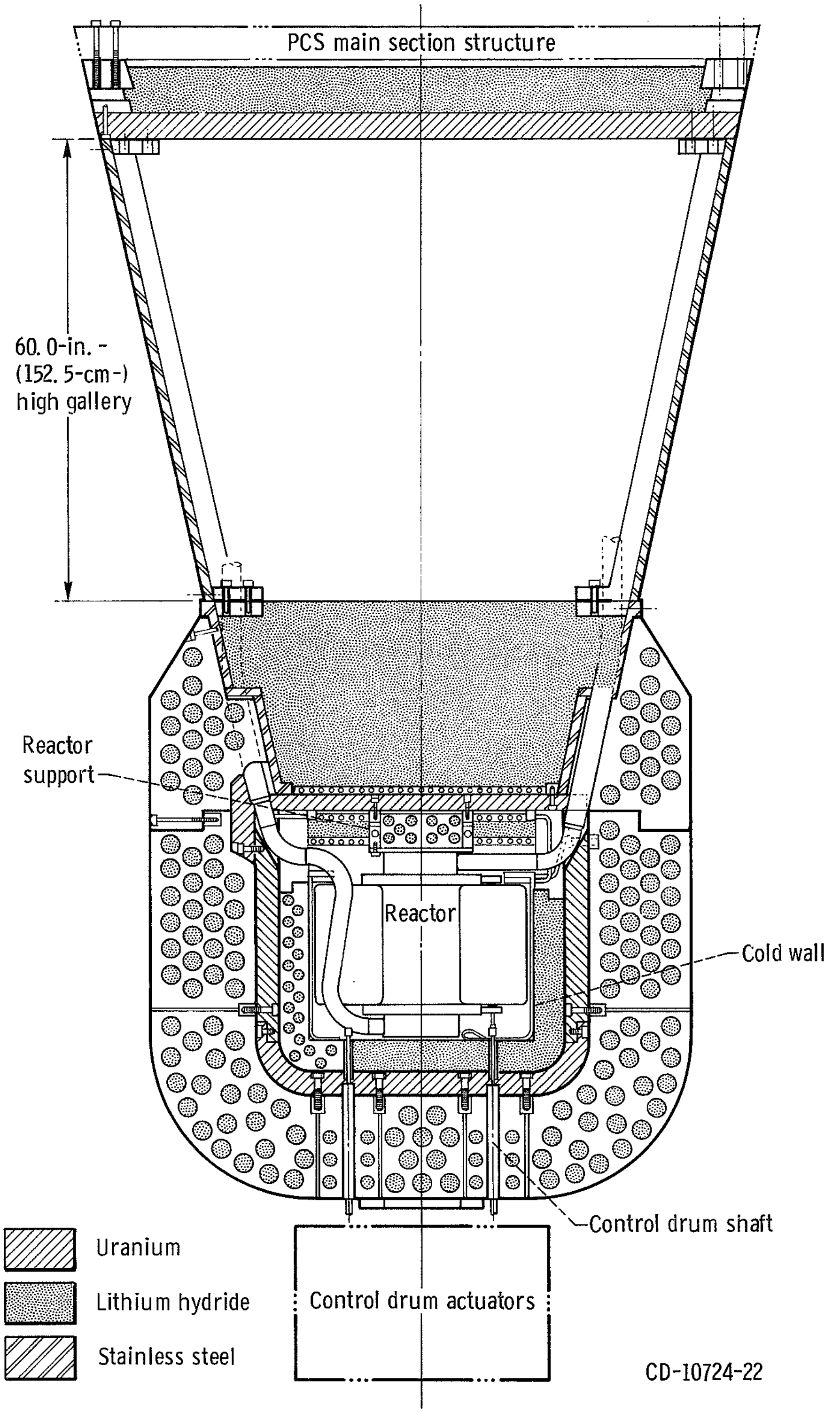


Figure 3. - Three layer S8DR shield for higher dose level and 60-inch- (152. 5-cm-) high gallery. Weight, 43 000 pounds (19 550 kg); dose level, 2 millirem per hour at 130 feet (39. 6 m) in crew direction and 1 rem per hour at 130 feet (39. 6 m) elsewhere.

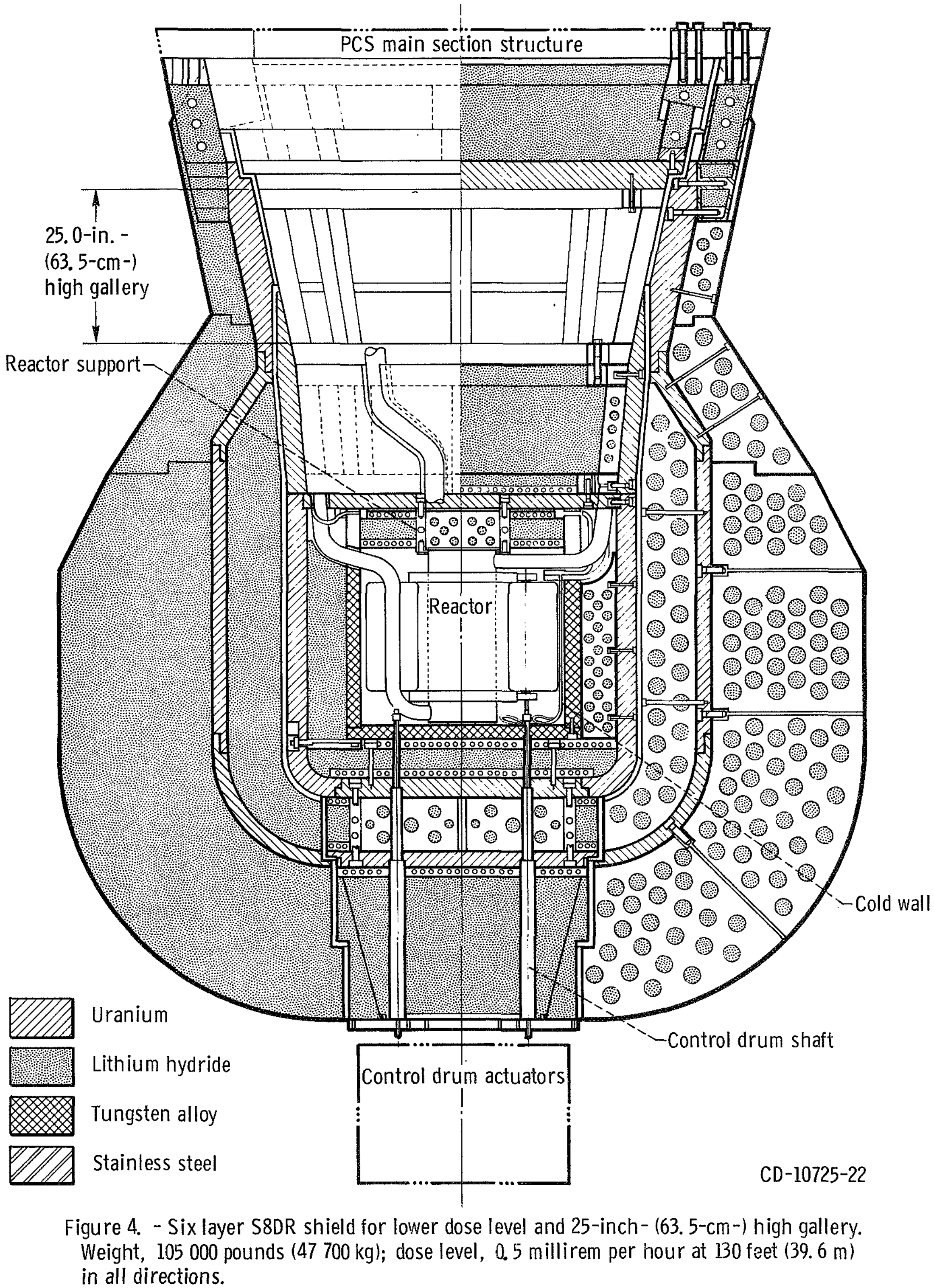


Figure 4. - Six layer S8DR shield for lower dose level and 25-inch- (63.5-cm-) high gallery. Weight, 105 000 pounds (47 700 kg); dose level, 0.5 millirem per hour at 130 feet (39.6 m) in all directions.

SHIELD MATERIALS AND GEOMETRY

Neutrons and gamma rays are the two types of radiation that must be considered in nuclear reactor shielding. Alpha and beta particles can contribute significantly to local heat generation but their limited range in the shield material does not make them a primary factor in shield design. Most neutrons are born within the reactor core and are emitted with the fission energy spectrum. Gamma rays are born in many locations in a nuclear space power system. Not only are primary gammas born in the reactor core as a direct result of fission but secondary gammas are born throughout the shield and in the primary coolant. The secondary gammas are the result of neutrons being absorbed or inelastically scattered by the shield and the reactor coolant. They strongly influence the shield design. The dense gamma ray attenuating material cannot all be located adjacent to the core to save weight. Secondary gammas born near the outside of the dense material would be insufficiently attenuated by the outer low density neutron shield. To optimize the shield weight required for the attenuation of all radiation sources, the shield is divided into alternate layers of gamma and neutron shield materials.

The following sections discuss shield materials and shield geometry.

Shield Materials

The guidelines for selecting materials for the preliminary shield design were:

(1) The material must be state-of-the-art; that is, sufficient research and development has been conducted on the material to establish its feasibility for use in a shield. As a minimum, material compatibility, irradiation resistance, and fabrication techniques must have been established.

(2) The lowest cost material was selected among equivalent material candidates.

Two types of materials are usually required to attenuate the neutron and gamma ray sources. The shield design developed during this study uses neutron and gamma shielding materials placed in discrete regions around the reactor and the primary cooling loop. An efficient neutron shield consists of low atomic number nuclei with a large number of nuclei per unit volume. These material characteristics are effective in slowing down (reducing neutron energy) the highly energetic neutrons released from the fission events in the reactor. During or after the slowing down process, the neutron shield material must capture the neutrons without producing excessive gamma radiation. This capture process must also sufficiently attenuate the neutrons to minimize the fission capture if depleted uranium is used for the gamma shield. Efficient gamma shielding consists of high atomic number materials of high density.

Neutron attenuating materials. - Hydrogen or hydrogenous materials are prime candidates for neutron shielding. Solids appear to be the practical shield material. The danger of leakage from the shield makes the use of gases or liquids questionable. Of the solid hydrogenous materials, lithium hydride was chosen as the neutron attenuating material for the shield. Lithium hydride has a high hydrogen density and better neutron attenuation properties than other possible materials. Lithium hydride has other advantages, including, low density, good thermal stability, high melting point, low dissociation pressure, and Li^6 (7.5 wt.% in natural lithium) absorbs neutrons without producing secondary gamma rays. The disadvantages of using LiH are: low thermal conductivity, high thermal expansion, low strength, and brittleness. The properties of lithium hydride and a discussion of fabrication techniques can be found in appendix A.

Gamma attenuating materials. - Gamma shields require a high specific density of electrons for efficient attenuation. This characteristic is found in dense high atomic number (Z) materials such as lead, uranium, and tungsten. A slight weight saving in the gamma shield may be possible with the use of lead instead of tungsten or uranium because lead produces fewer secondary gammas than tungsten or uranium. But lead has a low melting point and very poor engineering properties. Lead was not selected because its use would either require active cooling to prevent melting or using molten lead. In general, uranium was selected as the gamma attenuating material for this design study. It is cheaper and easier to fabricate. The uranium should be depleted since the uranium-235 in natural uranium (about 0.7 percent by weight) is easily fissioned. Even so, placing the depleted uranium too close to the reactor will cause (1) some fissioning in uranium-238 due to fast neutrons, and (2) fissioning of uranium-235 since the depletion of uranium-235 is not complete (about 0.2 wt.% of U^{235} remains in the depleted uranium). Both of these factors could double the heat generation in the shield if a depleted uranium layer immediately surrounds the reactor. Because the innermost layer of the six layer shield is a gamma attenuating material, tungsten rather than depleted uranium is used in this layer to avoid excessive heat generation.

In a space flight shield using the SNAP-8 reactor, the maximum temperature of the gamma shield will be about 1000° F (811 K). The high strength properties of unalloyed tungsten at elevated temperatures ($>2500^{\circ}$ F) (1645 K) are not required for this application. Since tungsten is difficult to machine and fabricate, a lower strength, more easily machinable alloy such as 90W-6Ni-4Cu can replace the unalloyed tungsten. However, larger thicknesses of this alloy will be required to attain the same gamma attenuating characteristics of the unalloyed tungsten. This will increase the weight of the shield.

Both shield designs use the uranium as the main internal support structure (see the SHIELD DESIGN section). The strength of unalloyed uranium at a temperature greater than 500° F (533 K) may not be suitable for this application. However, uranium may be alloyed with molybdenum or titanium to enhance its strength.

Another problem that has plagued the use of unalloyed uranium is its thermal instability when it is thermally cycled. Alloying uranium with molybdenum has eliminated this problem (ref. 2). Heat treatment methods (ref. 3) have also been effective in controlling the thermal instability of unalloyed uranium when thermally cycled from 70° to 700° F (30 to 644 K).

Compatibility of PCS Fluids with Shield Materials

If failures occur in the SNAP-8 mercury-Rankine PCS, the fluids contained in the PCS may contact the shield surrounding the reactor and gallery.

The PCS components contain three fluids. These fluids are NaK, mercury, and polyphenyl ether (the lubrication-coolant fluid). Only NaK is present in the reactor cavity. If the mercury boiler is in the gallery, both NaK and mercury are present in the gallery. The PCS main section (outside of the shield) contains all three fluids.

If any of the three PCS fluids should be released to a vacuum, they would vaporize quickly. In a relatively large volume such as that existing in the PCS main section, the vapors may disperse and exhaust to space rapidly. In the gallery and reactor cavity, however, the confined spaces may retain the released PCS fluids (NaK and mercury) for an appreciable time.

All shield materials selected (see the section Shield Materials) except uranium appear to be adequately resistant to attack by the PCS fluids. The most serious incompatibility exists between mercury and uranium. Mercury alloys with uranium at temperatures as low as -58° F (233 K). Although uranium and polyphenyl ether may be incompatible at high temperatures ($>700^\circ$ F or 644 K), the probability of polyphenyl ether contacting the uranium at such high temperatures is low. This is because the polyphenyl ether is in the PCS main section that is relatively far from the high temperature uranium.

The close proximity of the mercury and uranium around the gallery requires that a protective coating on the uranium be used. Uranium can be electroplated by using conventional plating methods if proper surface cleaning is accomplished. Chromium plating will protect the uranium from mercury attack. Nickel plating may also be used but it is less resistant to mercury attack than the chromium. The uranium may also be clad with stainless steel to form the protective coating.

Shield Geometry

The size and shape of the shield depends on three factors: (1) the physical size and location of the radiation sources, (2) the reactor thermal power and radiation spectrum, and (3) the allowable radiation dose levels. The two major radiation sources in the SNAP-8 power system are the reactor and the NaK coolant in the primary loop. The reactor considered in these designs has an overall height of 24.8 inches (63.0 cm). The overall diameter of the reactor (including the control drums in their outermost position) is 27.6 inches (70.0 cm).

To minimize shield weight, the shield is moved as close to the reactor as practical. The reactor cavity dimensions in the shield were chosen as 25.5 inches (64.7 cm) high and 29.25 inches (74.4 cm) in diameter (see fig. 5). Of the 0.7-inch (1.8-cm) axial clearance, 0.2 inch (0.5 cm) is allowed for thermal expansion, 0.25 inch (0.64 cm) for insulation at the coolant outlet end of the reactor, and 0.18 inch (0.46 cm) for insulation at the coolant inlet end of the reactor. The remaining 0.07 inch (0.18 cm) is allowed for dimensional tolerances. In the radial direction a clearance of 0.82 inch (2.10 cm) on the radius exists. The thermal expansion allowance is 0.25 inch (0.64 cm); 0.25 inch (0.64 cm) is allowed for a cold wall (see the SHIELD COOLING section) and 0.25 inch (0.64 cm) is allowed for insulation between the cold wall and the shield. The remaining 0.07 inch (0.18 cm) radial clearance is allowed for dimensional and location tolerances.

The control drum actuators were located outside of the shield (see fig. 5) because locating the actuators inside the reactor cavity would increase shield weight. The shafts connecting the actuators to the control drums were stepped to reduce radiation streaming.

Sufficient shielding material must be placed between the reactor and the gallery to limit activation of the fluids in the power conversion loops (see fig. 5). The gallery must also be surrounded with sufficient high Z material to attenuate the gammas emanating from the activated primary loop NaK and from fission products in the NaK. The shape and material placement for a three layer and a six layer shield is shown on figures 6 and 7, respectively. Both of these shields were designed for a S8DR operating at 600 kilowatts (thermal). The three layer shield has a conical gallery 60 inches (152.5 cm) high with a base diameter of 83.5 inches (212.2 cm) and a $12^{o}30'$ half angle. This gallery contains the large mercury boiler. The six layer shield has a conical gallery 25 inches (63.5 cm) high with a base diameter of 59 inches (149.9 cm) and a $12^{o}30'$ half angle. This smaller gallery contains an intermediate heat exchanger.

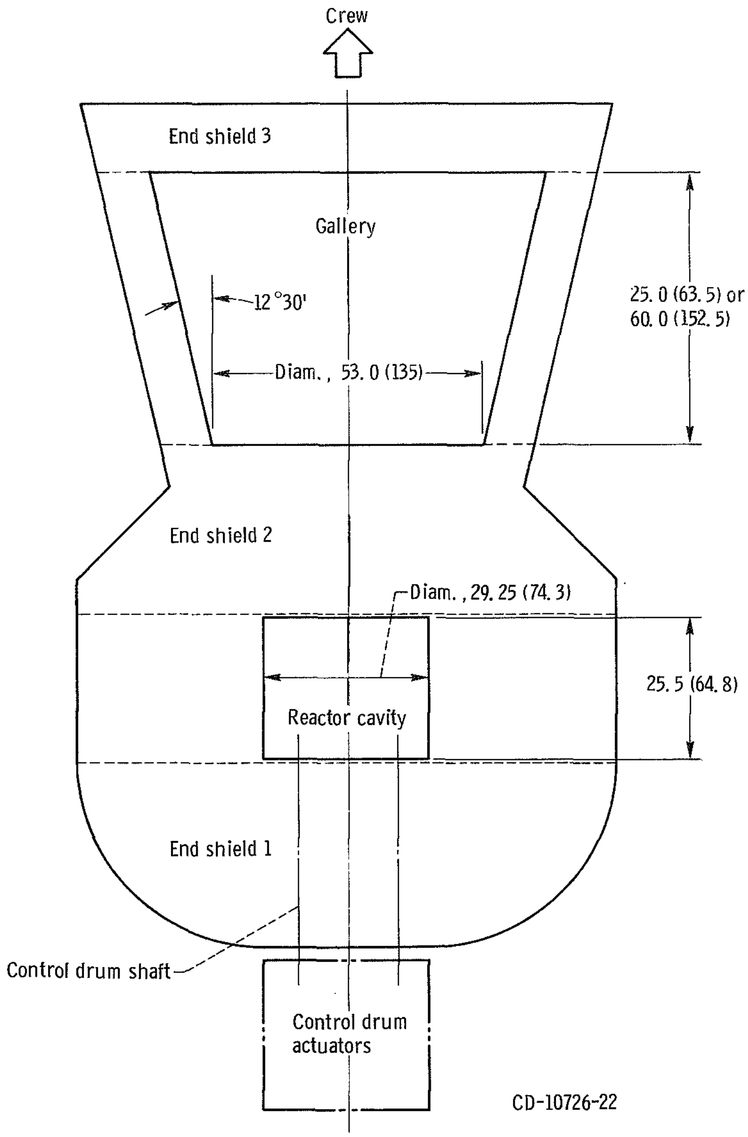


Figure 5. - General shape of 4π shield. (All dimensions in inches (cm) unless indicated otherwise.)

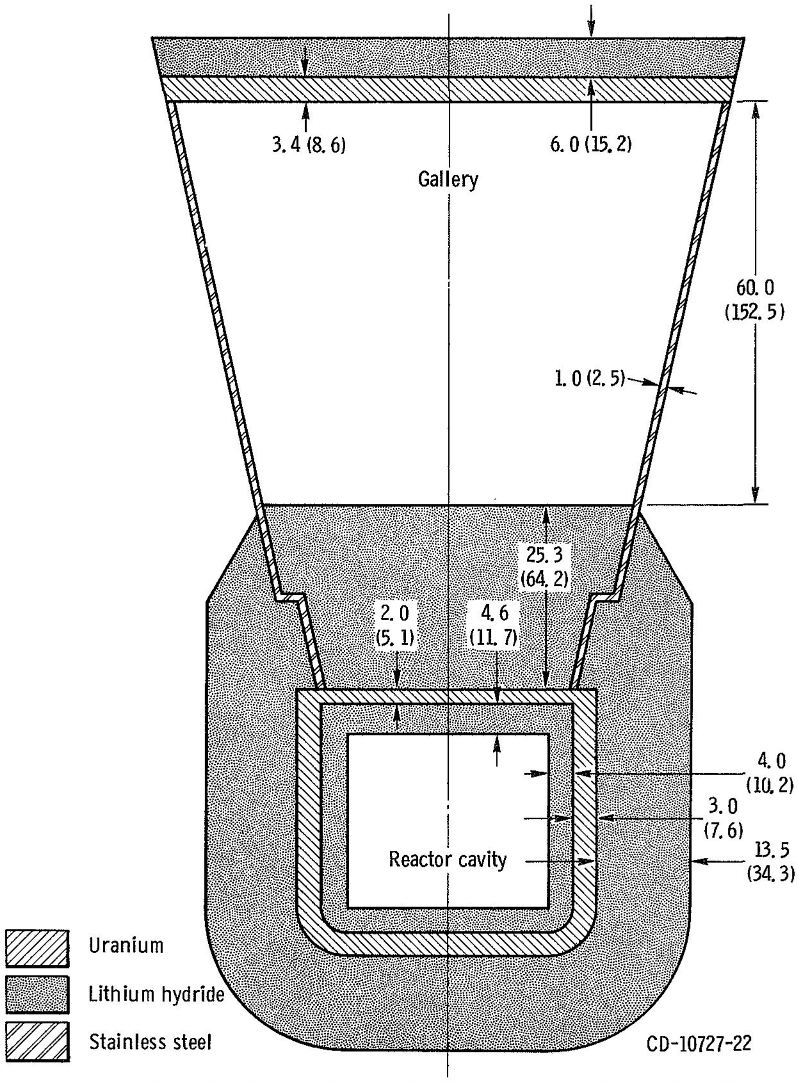


Figure 6. - Shape and material thicknesses for three layer shield with 60-inch- (152.5-cm-) high gallery. (All dimensions in inches (cm).)

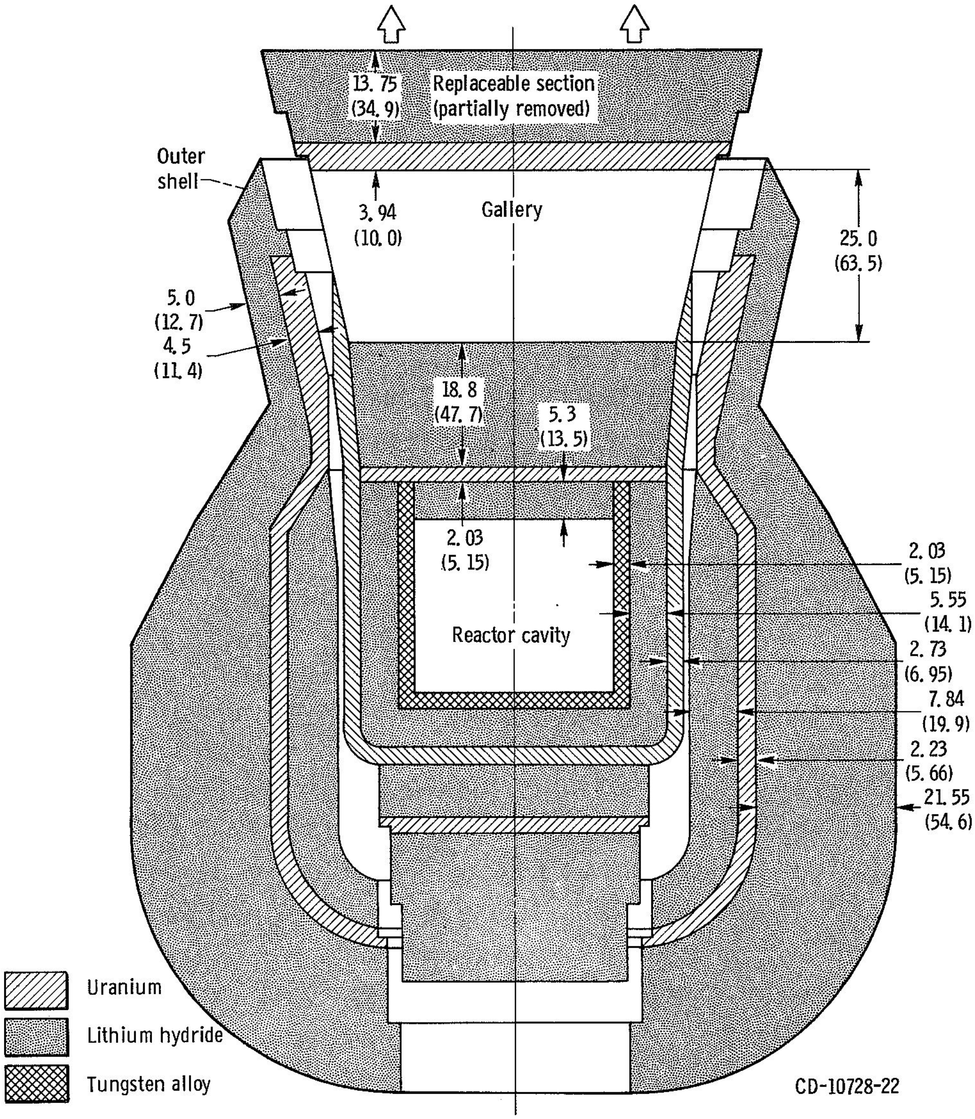


Figure 7. - Shape and material thicknesses for six layer shield with 25-inch- (63.5-cm-) high gallery. (All dimensions in inches (cm).)

SHIELD DESIGN

A preliminary design study was conducted on the two selected shields (see figs. 3 and 4) to produce engineering layouts and to perform preliminary analyses so that problem areas could be defined.

Nuclear Design

The thicknesses and placement of the shield materials were determined by digital computer programs using neutron transport theory. These programs optimized the material thicknesses for a minimum weight shield. The calculations were one-dimensional. That is, the sides and the one end between the actuators and reactor were analyzed on the basis of spherical geometry. Also the shield between the reactor and the gallery and the shield between the gallery and the PCS were analyzed on the basis of slab geometry. No attempt was made to calculate the effects of the cylindrical corners and the penetrations. These areas of the shield were estimated. Thus, the overall weight of the shield is uncertain from the standpoint of the simple one-dimensional modeling and from the estimated effects of penetrations and corners.

Structural Design

The major structural interfaces of the shield with the SNAP-8 mercury-Rankine power system are attachments to the reactor and the PCS structure. Launch acceleration and vibration loads may reach values as high as 5 g's. During launch, the power system will not be operating. Thus, the temperature levels will be low. In orbit, while the power system is operating, temperature levels in the shield may be as high as 1000° F (811 K) (see the SHIELD COOLING section). Although the highest loads occur during launch, the wide variation in temperature may cause certain components to be critically stressed in orbit.

Figures 3 and 4 are layouts of the two selected shield types. These designs use the gamma attenuating materials as structural materials wherever possible to minimize the shield weight. Figures 8 and 9 show the main structure of the two shield designs. Note that the six layer shield consists of two separable structures. The inner portion of the shield contains the reactor and gallery. This part of the shield is the replaceable section. If the PCS or reactor must be replaced in orbit, the outer part of the shield could be removed and temporarily stowed on the Space Base. The entire inner part of the shield could be discarded (see POWER SYSTEM REPLACEABILITY).

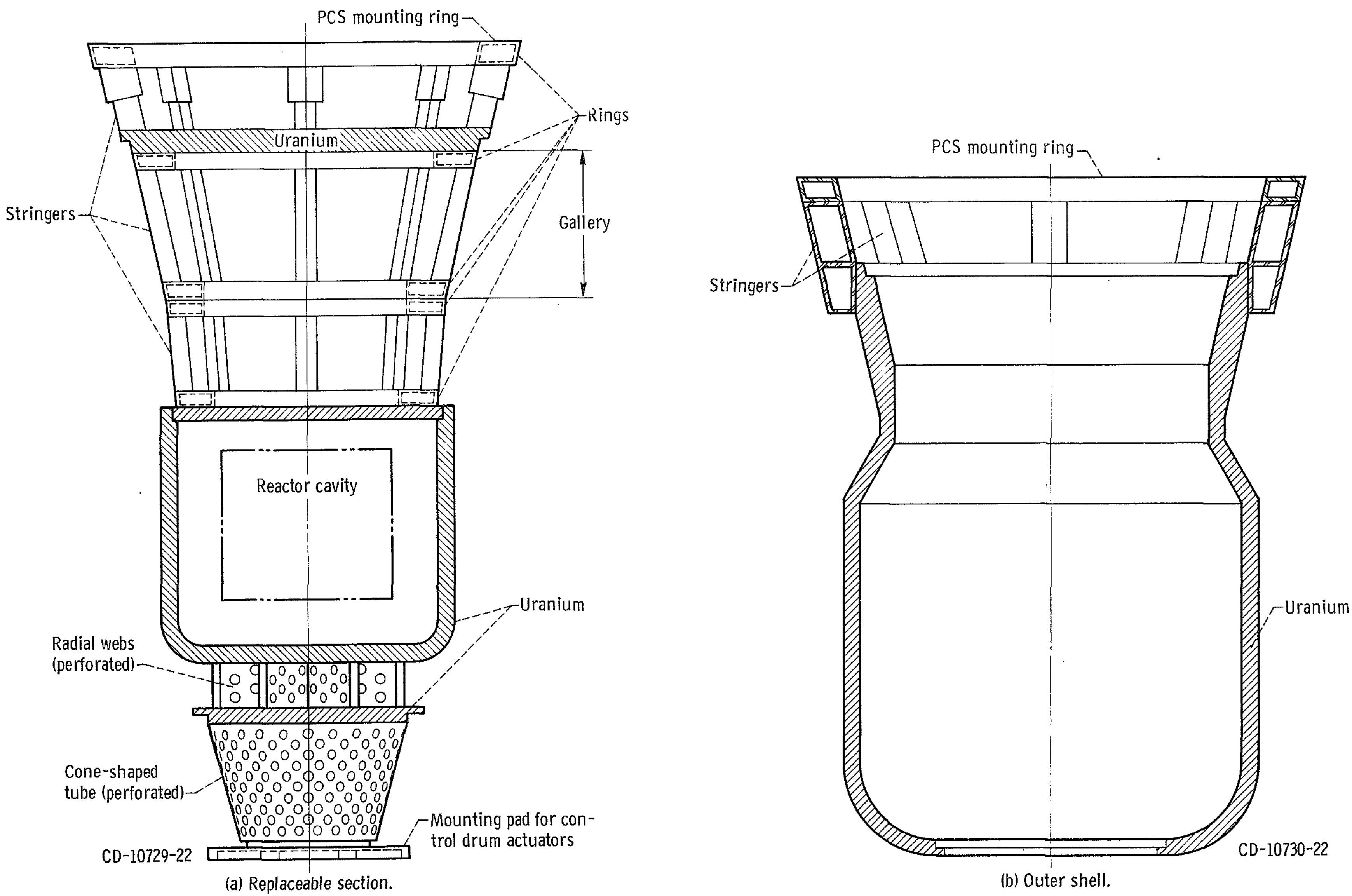


Figure 8. - Main structure of six layer shield.

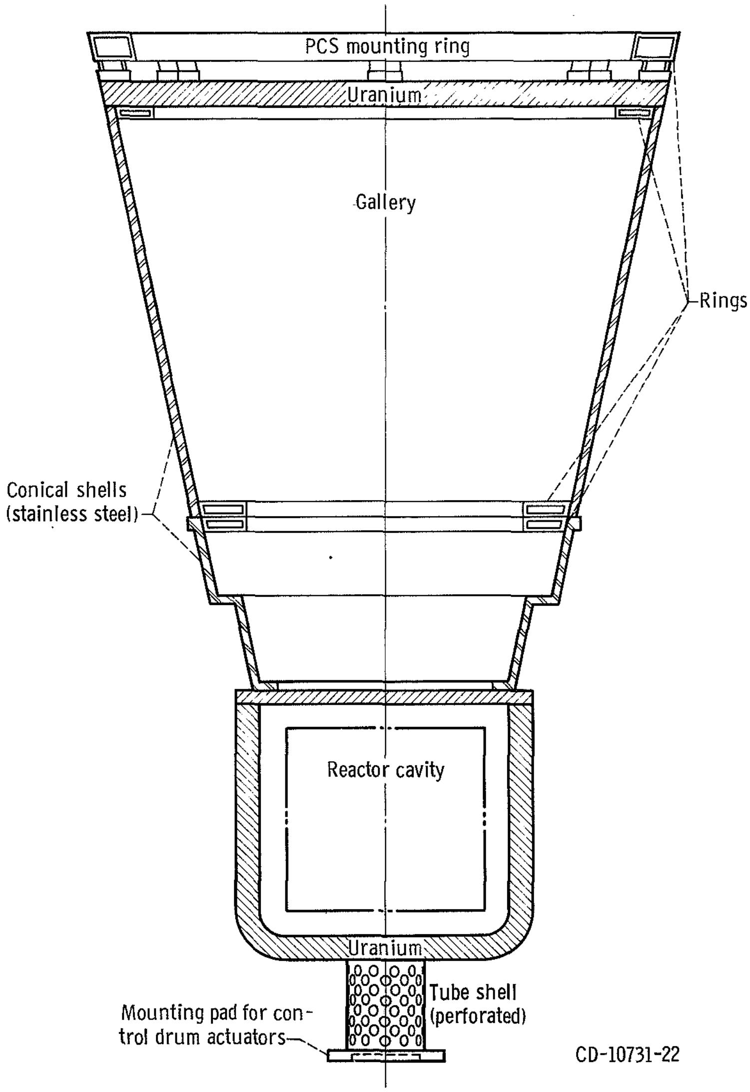


Figure 9. - Main structure of three layer shield.

Shield support structure. - The main structure of the replaceable section of the six layer shield consists of a closed cylinder of uranium around the reactor that is attached to the combination ring and stringer structures of the shield that contains the gallery (see fig. 8(a)). The ring and stringer structure in the two layers of lithium hydride between the reactor cavity and gallery have perforated walls so that lithium hydride can be cast into them. Filling the internal structures of the lithium hydride layers minimizes the neutron streaming caused by these structures. The attachment point is a ring at the shield-PCS interface. The structure in the three shield layers between the closed uranium cylinder and the control drum actuators is also shown in figure 8(a). This section contains the six stepped shafts that connect the control drums to their actuators. The actuators are mounted on a pad at the surface of the outer lithium hydride layer.

The innermost layer of gamma material in the six layer shield is the tungsten alloy. This layer is assumed to be self-supporting. It is attached to the main shield structure in two places (see fig. 4). The tungsten layer is secured to the uranium disk located between the reactor and the gallery. It is also secured (radially) with tension rods to the second gamma shield layer (uranium support structure). The cold wall (see the SHIELD COOLING section) is attached to the inner surface of this tungsten layer.

The reactor attachment is the same for both shields. One end of the reactor (the NaK outlet plenum) is secured to the uranium disk through internal structure (posts and radial bulkheads) provided inside the lithium hydride layer. No other attachment is used so that the reactor may freely expand thermally in the axial and radial directions.

The structure of the outer part of the six layer shield consists of the cylindrical third gamma layer (uranium), the side shield of the gallery (also uranium), and stringers connecting the gallery side shield to the mounting ring (see fig. 8(b)).

The main support structure of the three layer shield (see fig. 9) is similar to the replaceable section of the large shield except around the gallery. The structure around the gallery is a 1-inch- (2.54-cm-) thick plate of stainless steel with a conical shape. This plate is required to attenuate the gamma radiation (to limit the side dose level to 1 rem/hr at 130 ft (39.6 m)) from the activated NaK in the gallery components.

Lithium hydride containment. - The lithium hydride is fabricated by casting directly into its containment structure. Welch (ref. 4) has successfully cast lithium hydride in austenitic stainless steel containers for a SNAP-8 flight-type shield. Very thin container walls (<0.04 in. or 0.1 cm thick) are usually severely distorted in the casting process. Selection of the wall thickness also depends on the amount of micrometeroid penetration of the outer skin and the allowable rate of hydrogen diffusion through the container walls in the inner high temperature layers. The lithium hydride container wall thickness has been tentatively selected at 0.078 inch (0.198 cm) of an austenitic stainless steel. This thickness should limit container distortions to 0.10 inch (0.25 cm), the loss of hydrogen to less than 0.5 percent due to diffusion at 1000° F (811 K) for 10 000 hours, and the loss of hydrogen in the outer LiH layer to <1 percent from micrometeroid damage in near Earth orbits for 10 000 hours.

The general construction of the lithium hydride containers will be by welding. Brazing may be possible but most nickel base braze alloys are unsuitable since nickel is very reactive with molten LiH (ref. 5). Haynes Stellite 157 (a cobalt base alloy) was found compatible with molten LiH (ref. 6). The use of large amounts of cobalt, however, may make disposal of the spent shield difficult because of its activation.

Lithium hydride structural design. - Lithium hydride has very poor structural properties. Although some compressive loading is possible, lithium hydrides' tensile strength is nil. A honeycomb-type reinforcing structure can be used to control crack size and crack location in the brittle lithium hydride (ref. 7). Perforated bulkheads (longitudinal and radial) that are welded to the container walls, as shown in figures 3 and 4, can be used to support the lithium hydride. This type of structure also enhances the bulk thermal conductivity of the lithium hydride containers (ref. 4). Where bulkheads are not required, perforated ribs welded to the container walls (see figs. 3 and 4) may also be used to increase the thermal conductance of the lithium hydride layers. These perforated structures secure the lithium hydride to the container walls enabling the lithium hydride to withstand vibrations (ref. 4). Lack of such structure would allow the lithium hydride to rattle in its container when vibrated and cause excessive cracking. These cracks could then allow neutron streaming.

The lithium hydride containers are bolted to the main support structures of the shield (see figs. 3 and 4). Where possible, the lithium hydride containers have internal female-type bosses to accept the fasteners.

Shield Penetrations

Both preliminary shield designs require penetrations for process lines, electrical conduits, and control drum actuator shafts. A study was made to determine the size and number of penetrations required. In the case of the process lines, the number and the sizes are defined for the mercury-Rankine cycle PCS. Preliminary designs for the six actuator shafts are shown in figures 3 and 4.

The number of electrical leads and their location have not been defined for the combined system test. In this area, estimates were made based on the control system requirements of the S8DR test and on the number of process variables that appeared desirable to monitor.

The process lines will be insulated to prevent the melting of the lithium hydride. The thickness of the insulation required has not been determined and was, therefore, not considered in the sizing of penetrations. The insulation material, however, has to have the following characteristics:

(1) Low thermal conductivity at high temperatures

(2) Nuclear radiation resistance

One promising insulating material currently under investigation is the multifoil design.

The penetrations for the six layer shield are the same as those for the three layer shield, with one exception. The 25-inch- (63.5-cm-) high gallery shown in figure 4 cannot accommodate the two mercury boilers; hence, an intermediate heat exchanger would be required. In this case, the mercury lines between the gallery and main section would be replaced by NaK lines.

In the summary of the penetrations to follow, the shield sections containing the penetrations are identified numerically, as shown in figure 5, to facilitate their description.

The following list summarizes the required penetrations:

(1) Penetrations through end shield 1

(a) Six penetrations for control drum actuator shafts. The sizes of the penetrations vary from 0.5 to 2.0 inches (1.27 to 5.08 cm) in diameter.

(b) Vacuum exhaust duct, if necessary

(2) Penetrations through end shield 2

(a) Two 2.5-inch (6.35-cm) NaK coolant lines

(b) Two cold wall lines

(c) Two shield cooling lines

(d) One 2.5-inch (6.35-cm) conduit (17 nuclear instrumentation coaxial cables, 42 thermocouple (TC) leads)

(e) One 1.0-inch (2.54-cm) conduit (15 TC leads, 4 resistance temperature detectors (RTD) coaxial cables).

(3) Penetrations through end shield 3

(a) Two 2.0-inch (5.08-cm) mercury vapor lines

(b) Two 1.0-inch (2.54-cm) NaK coolant lines

(c) Two 0.75-inch (1.91-cm) mercury liquid lines

(d) Two 0.75-inch (1.91-cm) cold trap lines

(e) One 2.5-inch (6.35-cm) conduit (17 nuclear instrumentation coaxial cables, 42 TC leads)

(f) One 1.5-inch (3.81-cm) conduit (6 NaK pump motor power lines)

(g) One 1.0-inch (2.54-cm) conduit (15 TC leads, 4 RTD lines)

While the sizes and the number of penetrations have been determined, no attempt was made to design the actual layout of these penetrations. The physical configurations of the penetrations will have to be determined by nuclear calculations and experiments.

The size and the number of electrical conduits were the best estimates based on the study of the instruments that will be used for monitoring nuclear effects, temperature, pressure, and flow parameters during reactor operation.

The size of the conduits was determined solely on the basis of cross-sectional areas of the wires. The problems of signal interference among the wires in the same conduit or temperature restrictions were disregarded. A detailed description of the penetrations is given in appendix B.

Assembly Procedure

The assembly sequences for the six layer and three layer shields are shown in figures 10 and 11, respectively. The assembly procedure for both shields require that the reactor control drums be positively locked in their open positions at all times during the shield assembly. This locking device will be located in the reactor cavity. After the

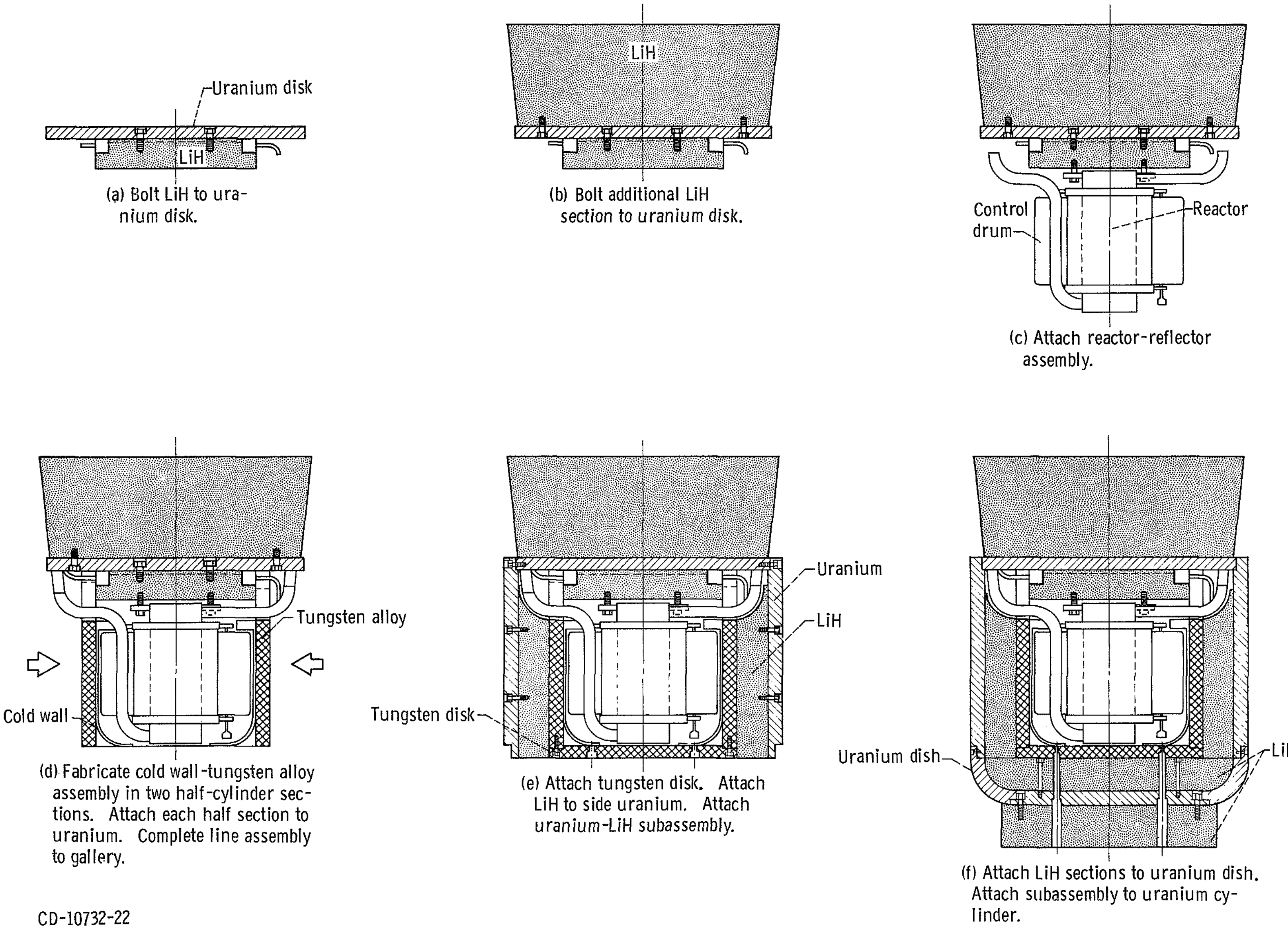
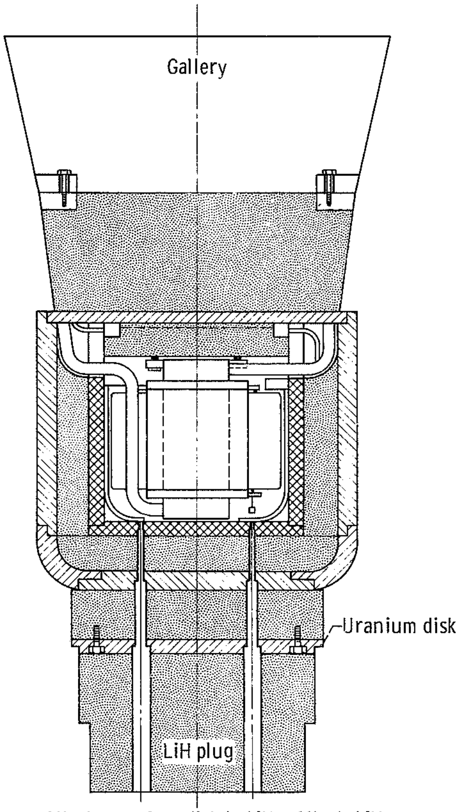
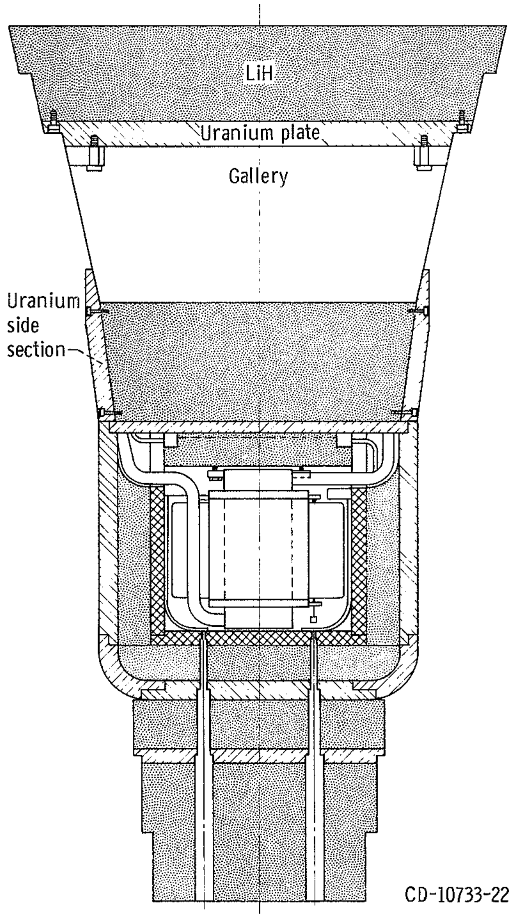


Figure 10. - Assembly sequence of replaceable section of six layer shield.

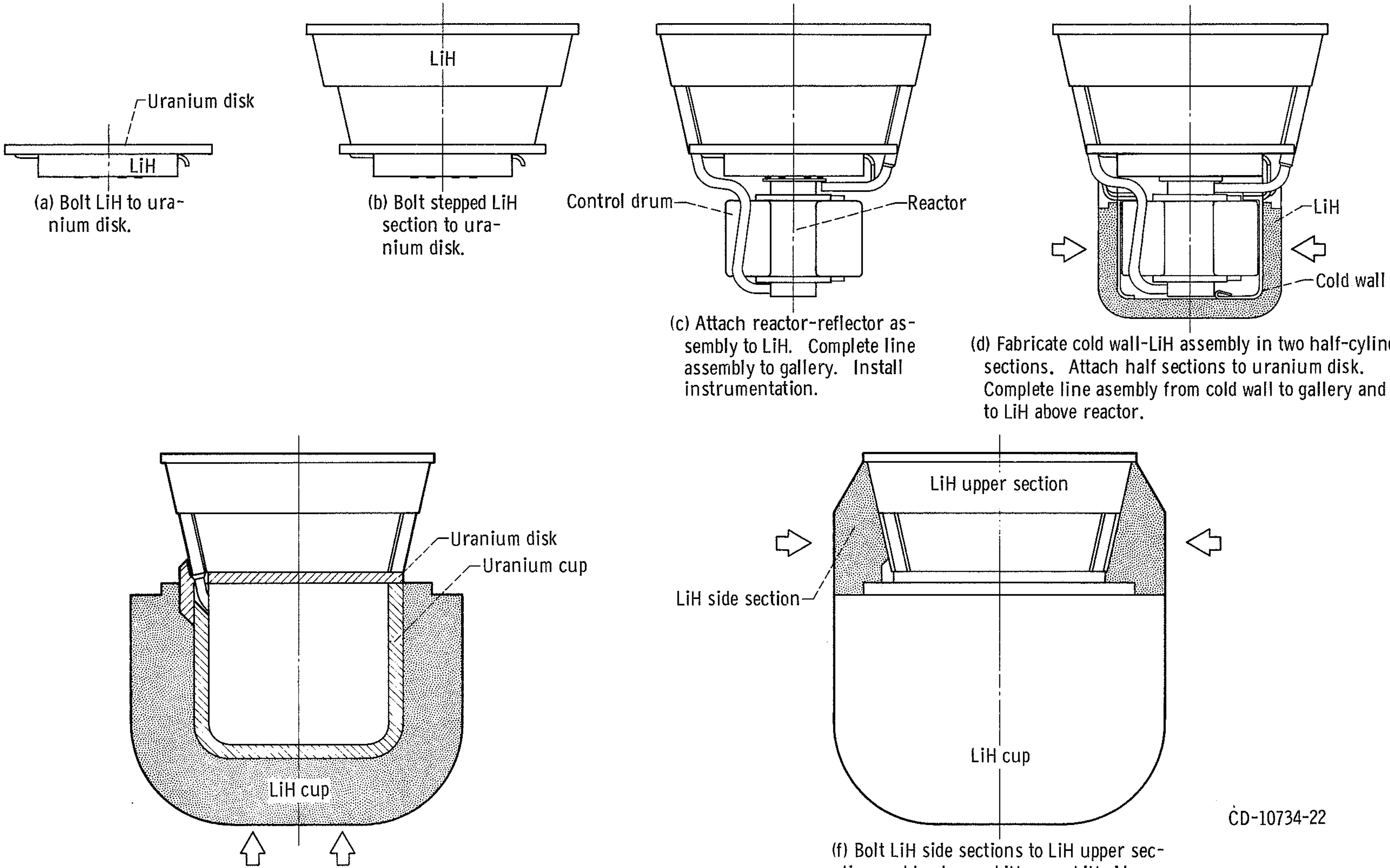


(g) Attach uranium disk to LiH. Attach LiH plug. Attach gallery. Connect lines.



(h) Attach uranium side sections. Attach LiH to uranium plate and attach to gallery.

Figure 10. - Concluded.



(a) Bolt LiH to uranium disk.

(b) Bolt stepped LiH section to uranium disk.

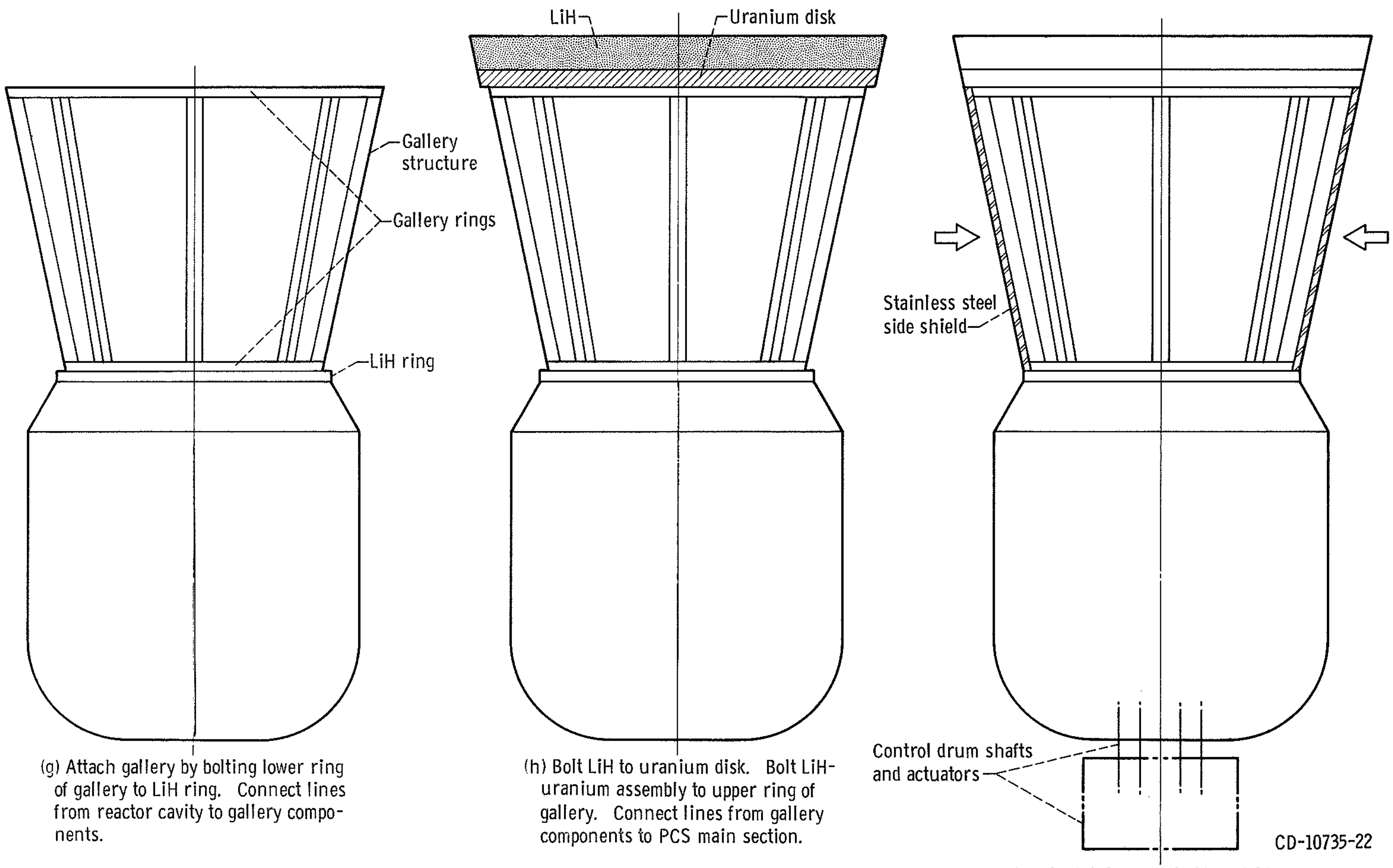
(c) Attach reactor-reflector assembly to LiH. Complete line assembly to gallery. Install instrumentation.

(d) Fabricate cold wall-LiH assembly in two half-cylinder sections. Attach half sections to uranium disk. Complete line asembly from cold wall to gallery and to LiH above reactor.

(e) Bolt uranium cup to LiH cup. Bolt uranium-LiH cup assembly to uranium disk.

(f) Bolt LiH side sections to LiH upper section and to step on LiH cup. LiH side sections are fabricated as two half cylinders.

Figure 11. - Assembly sequence of three layer shield.



(g) Attach gallery by bolting lower ring of gallery to LiH ring. Connect lines from reactor cavity to gallery components.

(h) Bolt LiH to uranium disk. Bolt LiH-uranium assembly to upper ring of gallery. Connect lines from gallery components to PCS main section.

(i) Bolt stainless steel side shields to both rings of gallery structure. Side shields are fabricated as two conical half shells. Install control drum shafts and actuactors.

Figure 11. - Concluded.

shield is assembled, the stepped control drum shafts will be inserted (one at a time) into the shield and engage the stub shaft on the control drums. The control drum locking device in the reactor cavity must be designed so that when engaging the stepped shaft to the stub shaft the locking device is released. After each shaft is inserted (one at a time), its actuating mechanism is installed. The control drum lockout device on the actuating mechanism is then engaged. This procedure is repeated until all six control drum actuators are installed. If one control drum is inadvertenly rotated all the way in, no hazard will result. The S8DR reactor will not go critical with one control drum in if the other five control drums are full out.

SHIELD COOLING

The shield will be a source of heat resulting from the attenuation of primary radiation from the reactor and secondary radiation generated in the shield and structural members. Heat must be removed from the shield to prevent the lithium hydride from exceeding the design value of 1000° F (811 K), 260° F (145 K) below the melting point of 1260° F (956 K). But the innermost layer of lithium hydride must not drop below 700° F (644 K) or excessive radiation damage will result (more than 5 percent volumetric swelling for 2×10^{20} nvt fast dose, ref. 6). This lower temperature constraint does not apply to the outer layers of lithium hydride which receive a lower dose.

As previously discussed (see the SHIELD DESCRIPTION section), a "cold" wall will be provided between the reflector assembly and the innermost surface of the shield. Figure 12 shows the calculated values of the maximum temperature in the reflectors

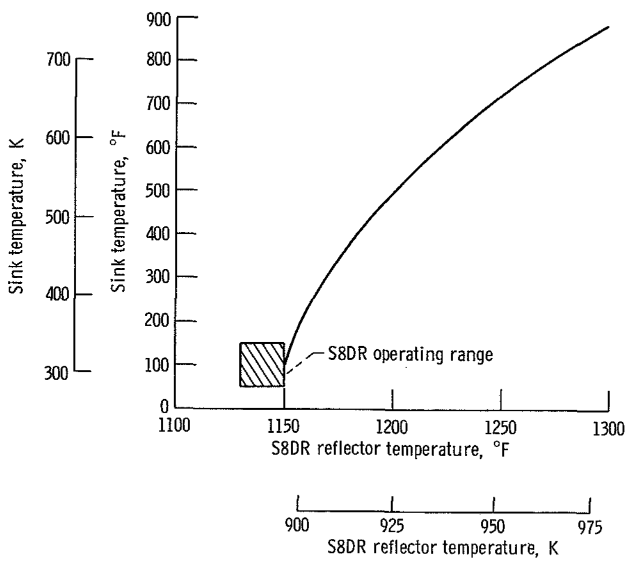
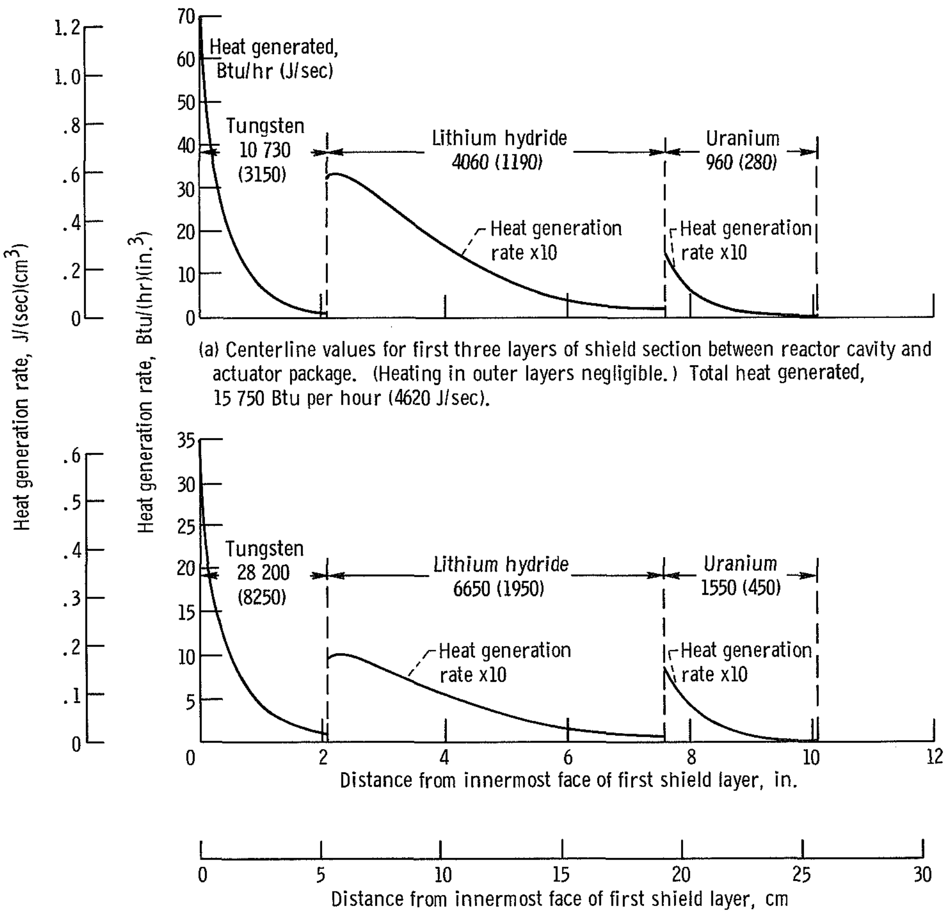


Figure 12. - Effect of heat sink (cold wall) temperature on S8DR reflector temperature.

as a function of this sink temperature. Operation of the reflector above 1200° F (921 K) in a high nuclear flux will result in excessive volumetric swelling of the beryllium reflectors and overheating of the control drum bearings. This dictates that a "cold" wall temperature of approximately 500° F (533 K) be maintained around the reactor. The "cold" wall temperature can be maintained by rejecting heat through the PCS heat rejection loop (HRL) (see fig. 2).

Three possible methods of removing the heat generated in the shield were investigated: (1) passive cooling - insulate the shield from the "cold" wall so that nearly all of the heat generated will be conducted through the shield to its exterior surface, where the heat is radiated to space; (2) use the existing "cold" wall as a sink to which the inner surface of the shield radiates heat; and (3) active cooling - using cooling coils in the shield to transfer some of the heat to a coolant fluid which in turn transfers this heat to the HRL of the PCS.

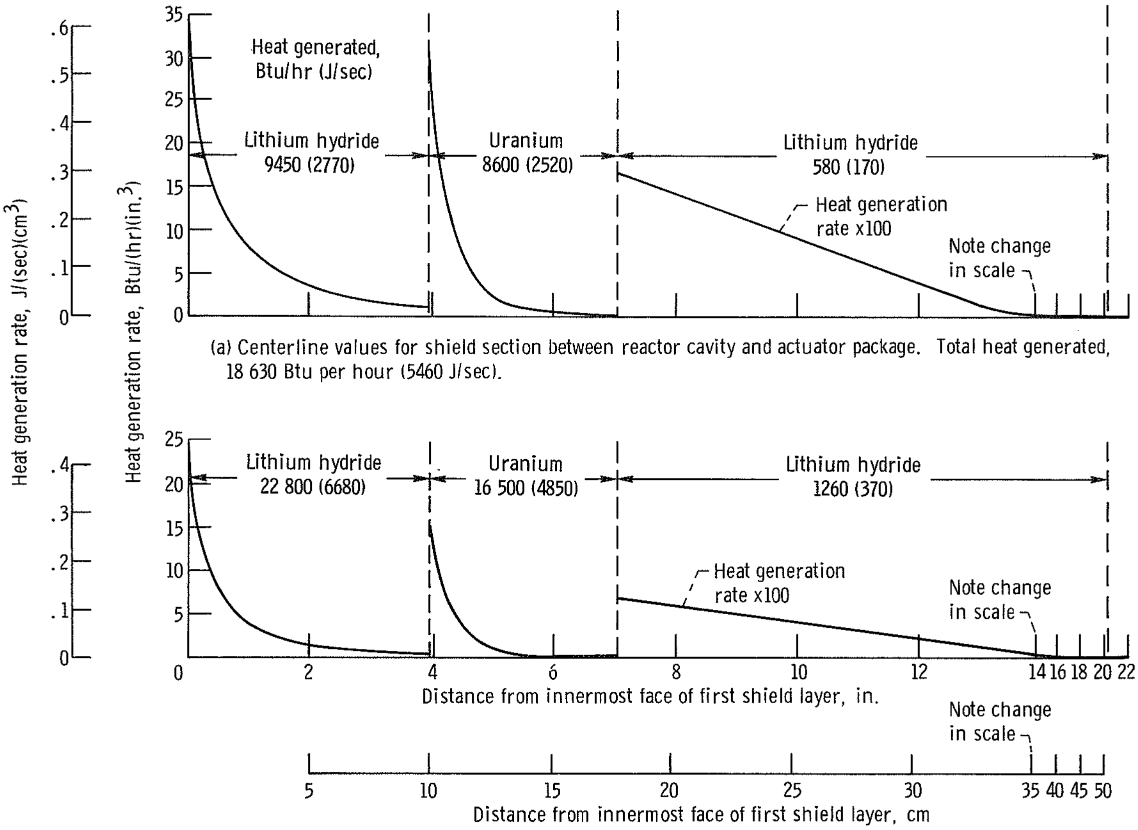
Figures 13 to 15 show the calculated heat generation rates and the total heat load



(a) Centerline values for first three layers of shield section between reactor cavity and actuator package. (Heating in outer layers negligible.) Total heat generated, 15 750 Btu per hour (4620 J/sec).

(b) Midplane values for first three layers of side shield. (Heating in outer layers negligible.) Total heat generated, 36 400 Btu per hour (10 650 J/sec).

Figure 13. - Heat generation rates for six layer shield with 29.25-inch (74.4-cm) inside diameter by 25.5-inch- (64.7-cm-) long reactor cavity. Dose level, 0.5 millirem per hour at 130 feet (39.6 m).



(a) Centerline values for shield section between reactor cavity and actuator package. Total heat generated, 18 630 Btu per hour (5460 J/sec).

(b) Midplane values for side shield. Total heat generated, 40 560 Btu per hour (11 900 J/sec).

Figure 14. - Heat generation rates for three layer shield with 29.25-inch (74.4-cm) inside diameter by 25.5-inch- (64.7-cm-) long reactor cavity. Dose level, 1 rem per hour at 130 feet (39.6 m).

used in this study in various sections of the two shields being investigated. These values are a result of a preliminary analysis. Significant deviation from these values would require a new evaluation of the shield cooling requirements. The conductivity values for LiH that were used to calculate the conduction through the shield are overall values for lithium hydride which is cast in a stainless steel container with interior ribs and honeycomb structure (ref. 4). Casting cracks and separation from the container walls result in lower thermal conductivity values than occur in cast lithium hydride without the container, ribs, and honeycomb.

The heat generated in the gallery shield is insignificant (approximately four orders of magnitude lower than the shield section between the reactor cavity and the gallery). There is no danger of the gallery shield exceeding allowable temperatures due to the generated heat. The thermal heat load from the hot NaK in the gallery is the only significant source of heat which could affect the gallery shield temperature. This heat load from the gallery interior may be reduced to negligible amounts by insulating the interior of the gallery shield. The gallery components were designed to operate in close proximity with the hot NaK and are not adversely affected by high temperature.

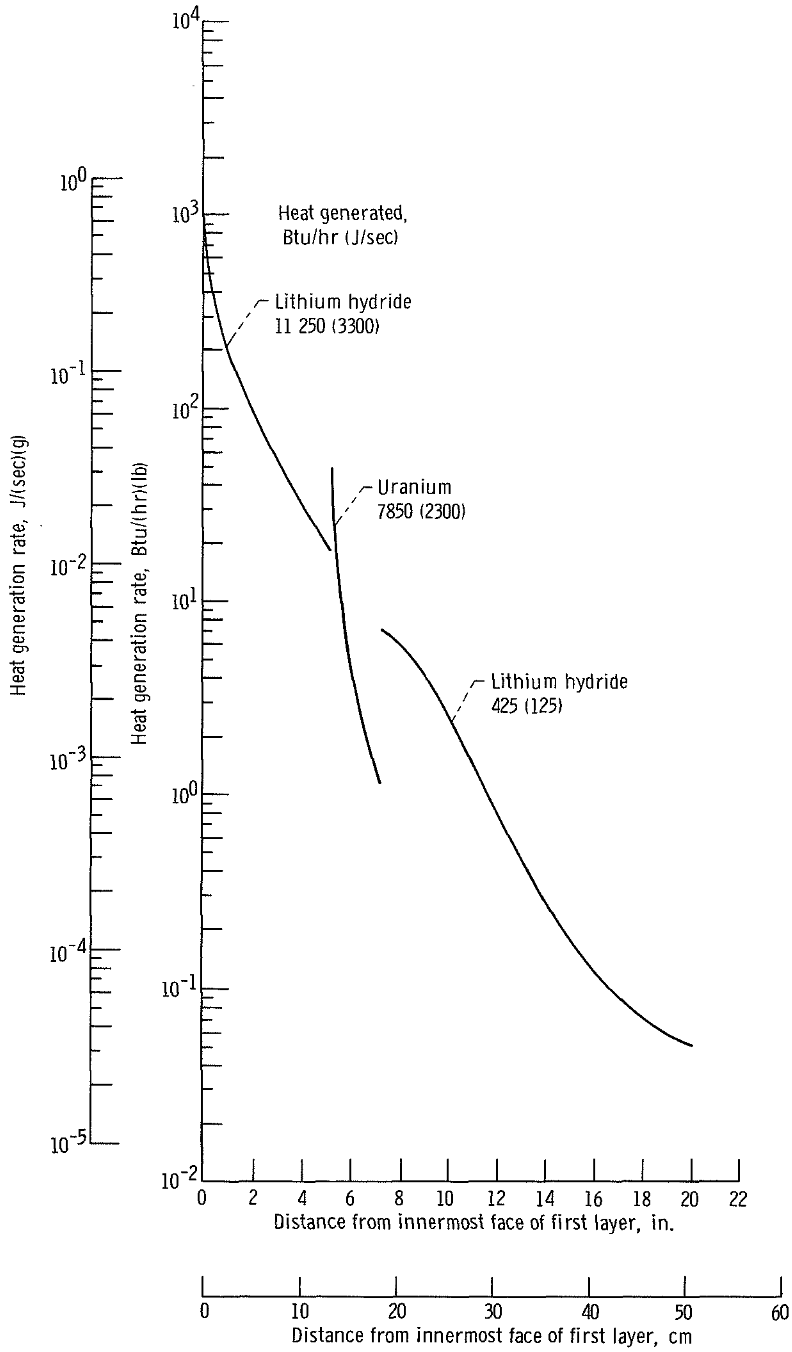


Figure 15. - Centerline heating rates for shield section between reactor cavity and gallery of six layer and three layer shields. Total heat generated, 19 525 Btu per hour (5725 J/sec).

The results of the heat transfer calculations for the two shield designs will be discussed in the following sections.

Six Layer Shield

Calculations using STHTP (ref. 8), a steady-state heat transfer digital computer program, have shown passive cooling of the six layer shield to be inadequate. Because the contact resistance between shield layers is unknown, an attempt was made to bracket the actual shield temperatures by assuming: (1) no thermal resistance between layers; and (2) no contact between layers (i. e., heat transfer by radiation only). For some cases a third condition was calculated. Two shield layer interfaces had no contact and the remaining interfaces had no thermal resistance. One gap is between the tungsten layer and the innermost lithium hydride layer (these faces are not bolted together in the six layer shield design); the other is the gap required for reactor replaceability.

The maximum lithium hydride temperature for the passively cooled shield in the section between the reactor cavity and the gallery was calculated to be 1065^{o} F (847 K) with no resistance, and 1345^{o} F (1003 K) with radiation only between layers. The side shield lithium hydride temperatures are 1420^{o} F (1044 K) without thermal contact resistance and 1700^{o} F (1200 K) with radiation only between layers. The shield section between the reactor cavity and the actuator package would have a maximum lithium hydride temperature of approximately 2500^{o} F (1643 K) with two radiation gaps and no thermal resistance between the other layers. If passive cooling is the only mode of heat transfer, the maximum allowable lithium hydride temperature of 1000^{o} F (831 K) will be exceeded in all three portions of the shield.

Allowing the inner surface of the shield to radiate directly to the "cold" wall should provide adequate cooling for the side shield. The side shield lithium hydride temperatures were calculated to be 710^{o} F (650 K) without thermal resistance and 760^{o} (678 K) with radiation only between layers. The third case with two radiation gaps and no thermal resistance between the other layers results in a maximum lithium hydride temperature of 680^{o} F (633 K). Although the third case has two radiation gaps, the temperature of the innermost lithium hydride layer is lower than in the case where no radiation gaps are present. Because a large amount of the shield heat is generated in the tungsten layer, the thermal resistance of the radiation gap between the tungsten and lithium hydride significantly reduces the outward flow of heat tending to lower the lithium hydride temperature. The second radiation gap located between two of the outer shield layers tends to raise the lithium hydride temperature. The net effect is a reduction of the temperature in the innermost lithium hydride layer.

The shield section between the reactor cavity and the actuator package when radiating to the "cold" wall approaches the limiting temperature of the lithium hydride. The resulting maximum lithium hydride temperature is 975° F (797 K). This temperature may be marginal as zero thermal resistance was assumed at all but two of the shield layer interfaces. Active cooling may be used in this section of the shield eliminating the need for the "cold" wall in this area. If cooling coils are used between the tungsten layer and the first lithium hydride layer, the effect of the NaK coolant temperature on the maximum lithium hydride temperature is shown in figure 16. This maximum lithium hydride temperature is about 25° F (13.9 K) above the coolant temperature.

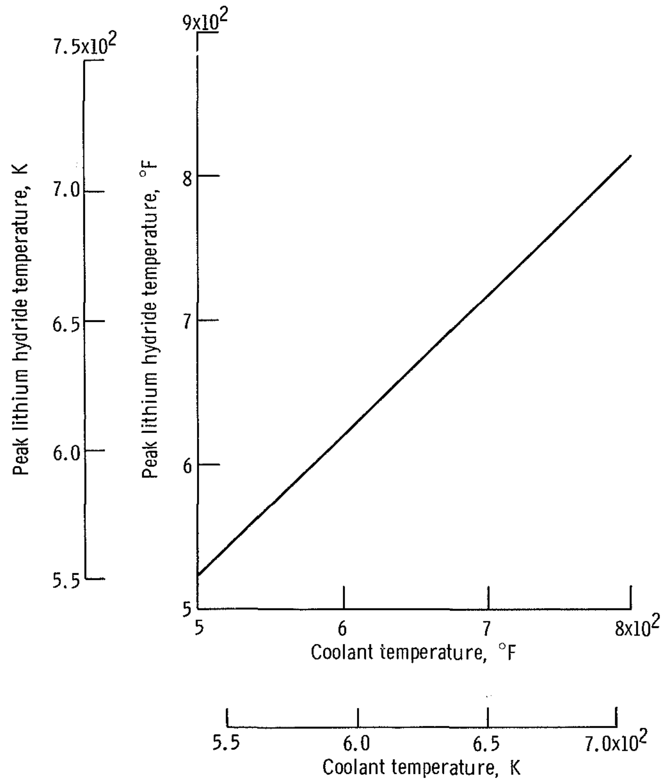


Figure 16. - Peak lithium hydride temperature in six layer shield section between reactor cavity and actuator package as function of coolant temperature.

The shield section between the reactor cavity and the gallery does not benefit from "cold" wall cooling. Active cooling of this portion of the shield using 700° F (644 K) NaK as the coolant between the inner (reactor cavity side) lithium hydride layer and the uranium layer results in a 975° F (797 K) maximum lithium hydride temperature; therefore, 700° F (644 K) is the maximum allowable coolant temperature in this region. Figure 17 shows the peak lithium hydride temperature in this section of the shield as a function of the coolant temperature.

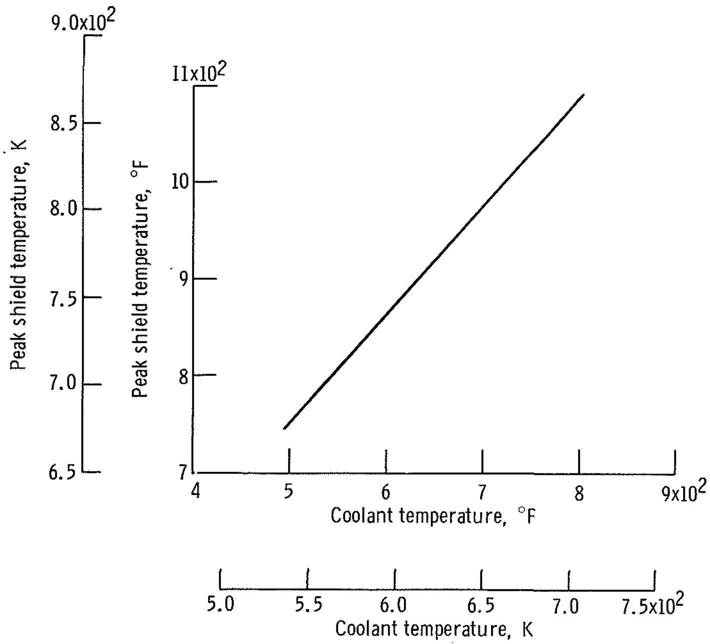


Figure 17. - Peak temperature in shield section between reactor cavity and gallery as function of coolant temperature.

TABLE I. - SIX LAYER SHIELD MAXIMUM LITHIUM HYDRIDE TEMPERATURES

Shield section	Temperature, °F (K)					
	No resistance between layers		Radiation only at two interfaces; no resistance at others		No contact between layers (radiation only)	
	With cooling	Without cooling	With cooling	Without cooling	With cooling	Without cooling
Side shield	[a]710 (650)	1420 (1043)	[a]680 (633)	----------	[a]760 (678)	1700 (1200)
Shield section between the reactor cavity and gallery	---------	1065 (847)	---------	----------	[b]975 (797)	1345 (1003)
Shield section between the reactor and the actuator package	---------	----------	[a]975 (797) [c]815 (708)	2500 (1643)	---------	----------

[a]Cooled by radiation to 500° F (533 K) "cold" wall.
[b]Cooled with 700° F (644 K) active cooling.
[c]Cooled with 800° F (700 K) active cooling.

Table I summarizes the maximum lithium hydride temperatures in the various sections of the six layer shield.

Three Layer Shield

Passive cooling of the side of the three layer shield would be marginal at the very best. The end shield cannot be adequately cooled by passive cooling. Figures 18 and 19 show the temperature distributions through the side and end both with radiation between layers and with no thermal resistance. The section of the shield between the reactor and gallery is essentially the same as the six layer shield and will require active cooling.

The "cold" wall may be used to cool the side and end of the three layer shield. The problem arises of overcooling of the inner lithium hydride layer (temperature, <700° F or 644 K) with direct radiation from the side shield wall to the "cold" wall. This can be avoided by installing insulation between the "cold" wall and side shield. The effect of the insulation on the amount of heat transferred to the "cold" wall is shown in fig-

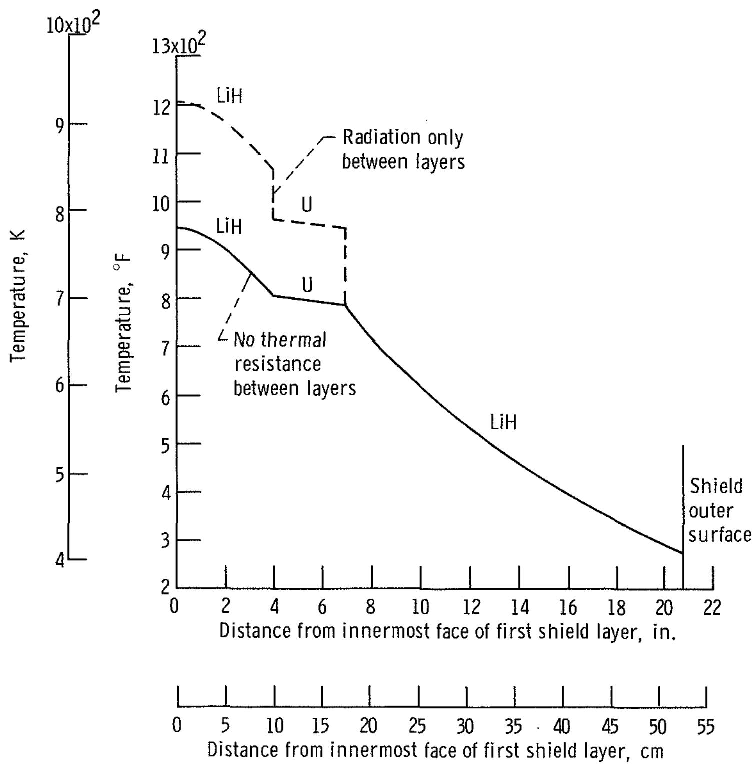


Figure 18. - Temperature distribution across side section of three layer shield.

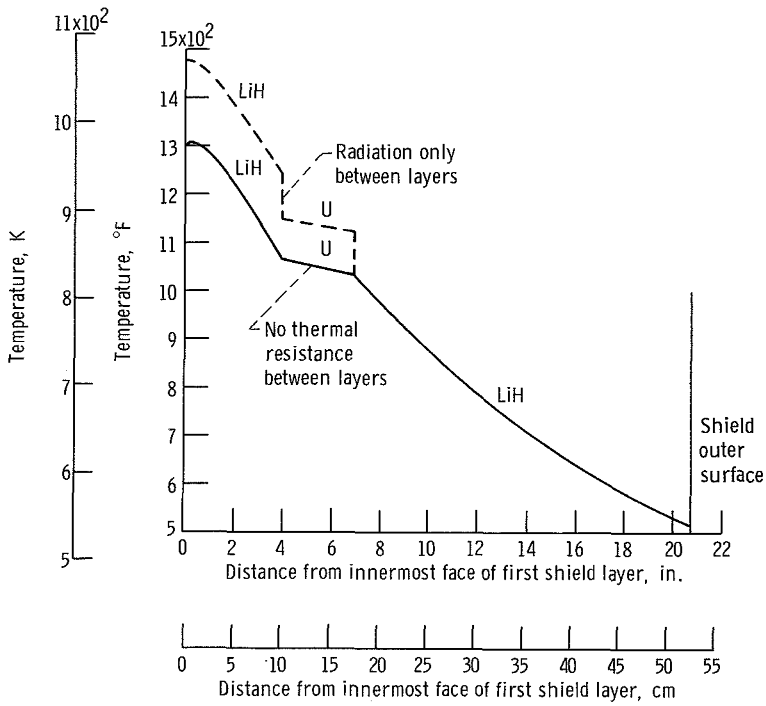


Figure 19. - Temperature distribution across end section of three layer shield.

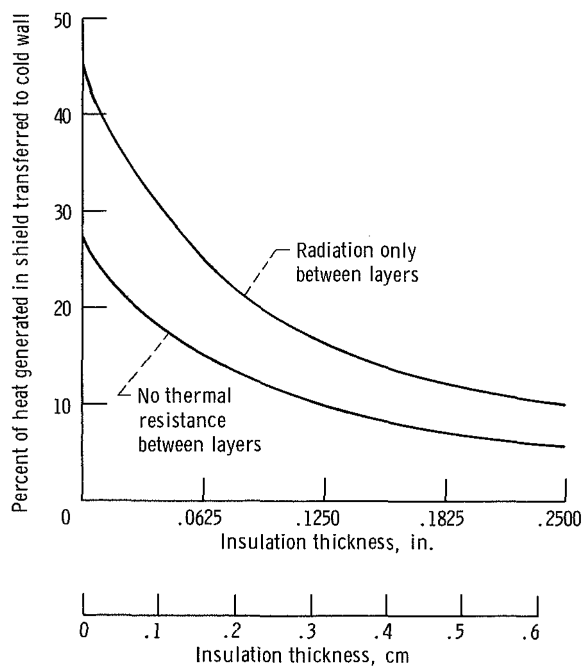


Figure 20. - Effect of insulation thickness on heat transfer to cold wall from three layer side shield. (Insulation has thermal conductivity of 0.1 Btu/(hr)(ft)(°F) or 1.73×10^{-4} J/(sec)(cm)(K) and does not fill space between cold wall and shield. A gap always exists across which heat is transferred by radiation.)

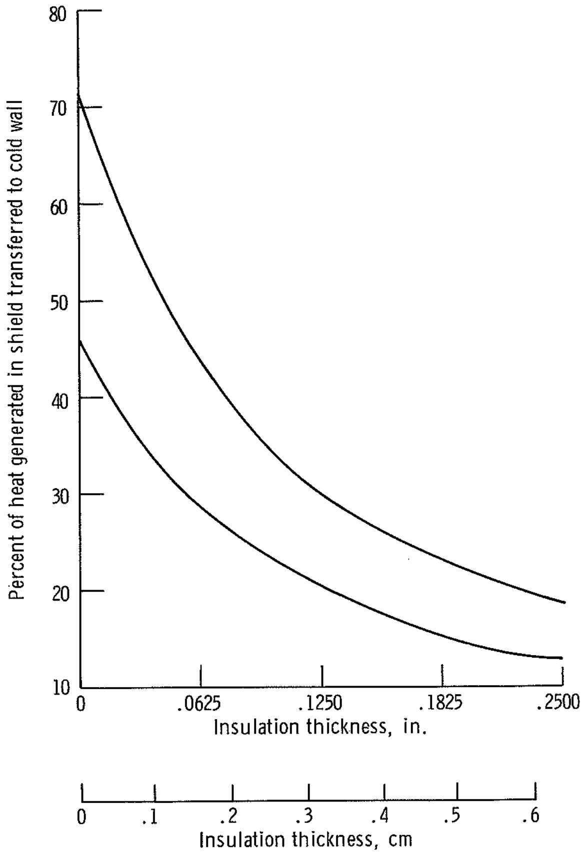


Figure 21. - Effect of insulation thickness on heat transfer to cold wall from six layer side shield. (Insulation has thermal conductivity of 0.1 Btu/(hr)(ft)(°F) or 1.73×10^{-4} J/(sec)(cm)(K) and does not fill space between cold wall and shield. A gap always exists across which heat is transferred by radiation.)

ure 20. Figure 21 is included to show the effect of using the insulation on the six layer shield.

"Cold" Wall and Shield Cooling Loop

The shield cooling fluid (NaK - 78) can be at a higher temperature than the "cold" wall fluid. This suggests placing them in series in a continuous coolant loop (see fig. 2). This arrangement will allow the NaK coolant to reach the maximum possible temperature before exchanging heat with the HRL fluid.

POWER SYSTEM REPLACEABILITY

The orbiting Space Base, having a desirable lifetime of 5 to 10 years, may require repair or replacement of its main electrical power generating system. Currently, components of the SNAP-8 mercury-Rankine power system have minimum lifetimes in the range of 1 to 2 years. Although further development may extend these lifetimes, it is unlikely that no failures will occur over the desired lifetime of the Space Base. For this reason the design of a nuclear-reactor-type power system must allow for replacement of components, subassemblies, or the whole power system.

For noncatastrophic failures it would be desirable to make the repairs or replacement on the component level. This may be feasible in such areas as the main section of the power conversion system (outside of the shield). All of the components are accessible and radiation dose levels are low when the reactor is shut down. For components inside the gallery and reactor cavity, however, the required compact design for a minimum weight shield severely limits their accessibility. Then too, radiation levels remain sufficiently high for long periods of time after the reactor is shut down. Close approach by personnel would be very hazardous.

The three layer shield has only one layer of gamma shielding 3 inches (7.62 cm) thick (see fig. 3) around its sides and one end. The shutdown dose level at 20 feet (6.1 m) from the reactor, 60 hours after reactor shutdown is 2.7 rem per hour. Therefore, the whole shield is discarded when the reactor-gallery assembly is replaced. No attempt is made to save the outer lithium hydride layer. Its weight (about 4600 lb (2090 kg)) is a relatively small saving.

For the six layer shield the amount of shield required around the spent reactor-gallery assembly during its replacement depends on the techniques that will be developed to accomplish this task. Tolerable dose levels during replacement are unknown at this time. For this preliminary design study the two inner gamma ray attenuating layers remain around the reactor on the replaceable section (see fig. 7). Most of the shielding is removed from the gallery sides. During replacement (when the outer shell has been removed), the side dose level is 2 rem per hour at 20 feet (6.1 m) from the reactor, 60 hours after reactor shutdown. The contribution of the gallery to this dose level is 1.8 rem per hour. The radiation sources that were considered in the gallery are the Na-24 gammas and an assumed release to the gallery of 1 percent of the volatile fission products produced in the core. The remaining 0.2 rem per hour is from core gammas and fission product gammas produced in the uranium of the replaceable section. Table II shows the effects on the dose level of the number of gamma attenuating layers on the replaceable section and time after reactor shutdown.

TABLE II. - DOSE LEVEL AFTER REACTOR

SHUTDOWN FOR THE SIX LAYER SHIELD

Number of high Z layers	Time after reactor shutdown, hr	
	60	120
	Dose level, rem/hr[a]	
0	1200	1150
1	25	13
2	2	0.4

[a]At 20 ft (6.1 m) from reactor.

SHIELD WEIGHTS

A weight analysis was made for the three layer and six layer shields shown in figures 3 and 4. Figures 6 and 7 show the material placement and dimensions for both of these shields.

The weight analysis disregarded all penetrations and tapped holes. The stainless steel stringers embedded in the lithium hydride structure as either support or heat transfer members were excluded from the weight calculations.

Three Layer Shield

The total weight of the three layer shield with a 25.0-inch (63.5-cm) gallery is approximately 37 000 pounds (16 800 kg). The increase in height of the gallery to 60.0 inches (152.5 cm) increases the weight by 6000 pounds (2720 kg). The following table shows the weight breakdown by materials:

Materials	Gallery height, in. (cm)			
	25.0 (63.5)		60.0 (152.5)	
	Weight			
	lb	kg	lb	kg
Depleted uranium	22 800	10 350	26 700	12 120
Lithium hydride	6 900	3 130	7 100	3 220
Stainless steel	7 300	3 320	9 200	4 180
Total weight	37 000	16 800	43 000	19 520

Six Layer Shield

The total weight of the six layer shield with the 25.0-inch (63.5-cm) gallery (as shown in fig. 7) is approximately 104 600 pounds (47 490 kg). If the gallery height is increased to 60.0 inches (152.5 cm), the shield weight increases by 32 400 pounds (14 750 kg) to a total of 137 000 pounds (62 240 kg). The weight breakdown by materials is as follows:

Materials	Gallery height, in. (cm)			
	25.0 (63.5)		60.0 (152.5)	
	Weight			
	lb	kg	lb	kg
Tungsten alloy	5 600	2 540	5 600	2 540
Depleted uranium	71 600	32 500	101 000	45 900
Lithium hydride	20 800	9 450	23 300	10 600
Stainless steel	[a]6 600	3 000	[a]7 100	3 200
Total weight	104 600	47 490	137 000	62 240

[a]The stainless steel weight includes steel containers for lithium hydride and steel structure in the gallery.

The following table presents the weight breakdown by materials of the replaceable section and the outer shell of the six layer shield with a 25-inch- (63.5-cm-) high gallery:

Materials	Weight of replaceable section		Weight of outer shell	
	lb	kg	lb	kg
Tungsten alloy	5 600	2 540	------	------
Depleted uranium	31 800	14 400	39 800	18 100
Lithium hydride	4 100	1 860	16 700	7 600
Stainless steel	3 200	1 440	3 400	1 550
Total weight	44 700	20 240	59 900	27 250

Weight Comparison

There is a wide range of shield weights from 37 000 to 137 000 pounds (16 800 to 62 240 kg) depending on the dose level and the gallery size. The major contribution to this weight difference is the dose level. For the 60-inch (152.5-cm) gallery height a weight reduction of 94 000 pounds (42 700 kg) is possible if the 0.5 millirem per hour dose level at 130 feet (39.6 m) everywhere is increased to the higher dose level. This same increase of dose level reduces the weight of the shield with the 25-inch- (63.5-cm-) high gallery by 68 000 pounds (30 900 kg).

A reduction of the gallery size can also significantly reduce the shield weight. If the gallery height is changed from 60 to 25 inches (152.5 to 63.5 cm), a 32 400-pound (14 750-kg) weight reduction is possible for the six layer shield. The weight of the three layer shield can be reduced by 6000 pounds (2720 kg) for the same reduction of gallery height.

The electrical power output of the SNAP-8 PCS is reduced if the small gallery is used. For the shields having a 25-inch- (63.5-cm-) high gallery, the mercury boiler is placed outside the shield. An intermediate heat exchanger is placed in the gallery (see fig. 2). Adding an intermediate loop may result in a reduction of 13.5 percent of net electrical output if flow rates, reactor outlet temperature, and turbine outlet pressure remain the same. The causes for this net reduction are the decrease of turbine inlet temperature and the increased pumping power required by the additional loop. For the three layer shield a weight reduction of about 14 percent occurs if the gallery height is reduced from 60 to 25 inches (152.5 to 63.5 cm). Thus there may be no reduction of specific weight (shield weight/net electrical output) for the three layer shield if the gallery height is reduced. The six layer shield, however, has a weight reduction of about 23 percent for the same gallery height reduction. This may result in a 10 percent reduction of specific weight.

PROBLEM AREAS

Several problem areas have been identified as a result of this preliminary design study. These problem areas include structural design, shield assembly, fabrication, and a power conversion system modification.

Structural Design

The major problem in the structural design of the six layer shield is the allowance for thermal expansion between tungsten and uranium. The inner tungsten layer is attached to the uranium structure. The large difference of thermal expansion between these materials will require special attention.

Shield Assembly

Several welding operations in the primary loop, secondary loop, and the shield cooling lines are required during assembly. Because of the compact design of the shield these weld joints have limited accessibility. Such a compact shield design may require the development of special welding methods.

A reliable control drum lockout mechanism in the reactor cavity must be provided. This mechanism shall be designed so that it is released when the stepped control drum shafts are assembled in the shield. If the stepped shaft is removed from the shield, the control drum must be locked in the full out position.

Fabrication

Large annular shapes of depleted uranium and the tungsten alloy are required for the shields. Some success has been shown (refs. 9 and 10) in the fabrication of these materials in large shapes. However, the shapes required for the shields are larger than those that have been fabricated thus far.

The fabrication of large annular sectors and thin disks of lithium hydride by casting is also a problem area. Although lithium hydride has been successfully cast in solid cylindrical shapes weighing up to 800 pounds (364 kg) (ref. 4), the larger sizes and different shapes required for the shields may necessitate further development of the casting process.

Power Conversion System Modification

Lower shield weights are obtainable by reducing the gallery size. A significant reduction of gallery size is possible by replacing the mercury boilers with an intermediate heat exchanger in the gallery. The mercury boilers would then be moved to the main section of the PCS. This modification would require the development of new components and possibly the modification of existing components.

CONCLUDING REMARKS

The preliminary designs of two 4π nuclear reactor shield configurations have been presented. These designs considered two gallery sizes and two dose levels that appear to be in the range of interest for manned nuclear reactor power systems. The reactor was a SNAP-8 Development Reactor (S8DR) with minor modifications. A shield with a gallery height of 60 inches (152.5 cm) and a radiation dose level of 2 millirem per hour at 130 feet (39.6 m) in the crew direction and 1 rem per hour at 130 feet (39.6 m) elsewhere weighs 43 000 pounds (19 550 kg). A shield with the same dose level but a gallery height of 25 inches (63.5 cm) would weigh 37 000 pounds (16 830 kg). A shield with a gallery height of 60 inches (152.5 cm) and a radiation dose level of 0.5 millirem per hour at 130 feet (39.6 m) in all directions would weigh 137 000 pounds (62 300 kg). A shield with the same dose level but a gallery height of 25 inches (63.5 cm) would weigh 105 000 pounds (47 700 kg).

A 60-inch (152.5-cm) gallery height accommodates the gallery components as currently designed in the SNAP-8 mercury-Rankine power system. A gallery height of 25 inches (63.5 cm) would require the development of components for an intermediate loop.

The shielding materials selected for these designs are natural lithium hydride and depleted uranium or a tungsten alloy for gamma ray attenuation. For minimum shield weights these materials are arranged in alternate layers to efficiently attenuate secondary gamma rays produced in the shield.

Thermal analyses were conducted to define the shield and the reflector assembly cooling requirements. To avoid exceeding the temperature limit of the reflector assembly, an actively cooled wall must be placed around the reflector assembly. This wall must be maintained at a temperature of about 500° F (533 K). The innermost layer of lithium hydride must also be actively cooled to limit peak temperatures in the lithium hydride to 1000° F (811 K).

Shield structure was shown on layouts of the two shield configurations. The depleted uranium layers are used as shield structure to minimize the shield weight.

The number and sizes of penetrations through the shield were determined. However, the shaping and routing of the penetrations were not designed.

Several problem areas have been defined as a result of this preliminary design study. These problem areas are: fabrication, structural design, shield assembly, design of a reliable control drum lockout mechanism, and the development of components for an intermediate loop.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 9, 1970,
120-27.

APPENDIX A

LITHIUM HYDRIDE PROPERTIES

Lithium hydride (LiH) is a unique compound of lithium and hydrogen possessing the following properties:

Crystal structure	Face centered cubic
Molecular weight, lbm/mole; g/mole	0.0175; 7.936
Density, lbm/ft^3; g/cc	38.3; 0.775
Hydrogen content (natural LiH), wt.%	12.68
Hydrogen density (natural LiH), H atoms/$in.^3$; H atoms/cc	9.3×10^{23}; 5.86×10^{22}
Melting point, ^{o}F; K	1267; 959
Plateau dissociation pressure at melting point, in. Hg; mm Hg	0.98; 25
Thermal conductivity at 1000^{o} F (813 K), Btu/(hr)(ft)(^{o}F); cal/(sec)(cm)(^{o}C)	2.9; 0.012
Thermal expansion in range of 70^{o} to 1000^{o} F (493 to 813 K), percent	2.62

The physical forms of LiH that have been considered for use in shielding range from vibration-packed powders (up to 70 percent density) to hot-pressing (99^{+} percent density). Cold-pressing and casting usually result in a density that is 93 to 95 percent of theoretical density. The advantage of using vibration-packed powders is low cost. The disadvantages are: low hydrogen densities (shields will be bulkier and heavier), very low thermal conductivity, and no strength. Hot-pressing is the most expensive method of fabrication. The high density that can be achieved with hot-pressing will result in a minimum weight shield. However, from the radiation damage standpoint, a very high density may be a disadvantage. It appears that a 3 to 5 percent void in the LiH is required (ref. 6) to accomodate the radiation-induced volume expansion. Thus it appears that cold-pressing and casting are the prime candidate methods of fabricating LiH for space flight shields.

Fabricating LiH by cold-pressing may be more costly than the casting method. Cold-pressed LiH requires expensive machining operations in a dry box to produce the geometry to match the container. The casting method permits the LiH to be cast directly in the container.

Regardless of the method of fabrication, LiH must be protected from water vapor at room temperature. At elevated temperatures, water vapor, oxygen, nitrogen, carbon dioxide, and many other elements and compounds must not contact LiH. Also, at elevated temperatures LiH must be protected by a slight hydrogen overpressure or by a sealed container to prevent the loss of hydrogen by decomposition. These special requirements for handling and fabrication are not unique to LiH. In general, all high melting point hydrogenous compounds would require similar treatment.

The development of LiH for use as a neutron shield was investigated in the early 1960's in connection with the Aircraft Nuclear Propulsion (ANP) project (ref. 7). In recent years it has been used for SNAP-2, SNAP-10A, and SNAP-8 shields (ref. 4) and is generally considered to be suitable for space application.

APPENDIX B

PENETRATION, INSTRUMENTATION, AND COAXIAL CABLE REQUIREMENTS

Penetrations

The following sections describe the six layer shield penetration requirements. For the identification of the shield sections to be discussed refer to figure 5.

Description of the penetrations. - The shield penetrations are required for process lines, electrical conduits, and drum actuator shafts.

Process lines carry the working fluid to and from the components located in the reactor cavity, gallery, and the main section. Electrical conduits protect the thermocouple lead-ins, control signal lines, and power lines. All process lines will be type-316 stainless steel welded tubing.

Penetrations through end shield 1. - The control drum actuators were located outside the shield; hence, end shield 1 will have six penetrations for the shafts connecting the control drums with the drum actuators (based on the S8DR control system). The actuator shafts for the six layer shield differ in design from those for the three layer shield. While the actuator shafts for the six layer shield have three steps reducing the shaft diameter from 2 to 1.25 inches (5.08 to 3.18 cm) and finally to 0.5 inch (1.27 cm), the shafts for the three layer shield have only two steps of 1.25 and 0.5 inches (3.18 and 1.27 cm). A clearance of 0.125 inch (0.318 cm) is maintained between the shaft and the shield penetration.

To prevent the oxidation damage to the graphite control drum bearings, the reactor cavity must be evacuated to a vacuum pressure of 10^{-5} torr before the startup of the reactor. It was assumed that the clearance around the actuator shafts will provide sufficient flow area for reactor cavity evacuation within the time needed to evacuate the test chamber of the space power facility for the combined system test. If the time lag is too large, an additional duct for the evacuation of the reactor cavity may be required. This duct will penetrate end shield 1.

Penetrations through end shield 2. - Two 2.50-inch (6.35-cm) outside diameter by 0.065-inch (0.165-cm) wall tubes will penetrate end shield 2. They will carry the NaK coolant from the pumps located in the gallery to the reactor and back to the pumps. The NaK coolant line will have to be insulated to prevent the lithium hydride from melting.

The cold wall and the active cooling sections of the shield may require a pair of process lines for each. The sizes of the lines are not determined at the present time.

Coaxial cables from measuring devices, the thermocouple lead-ins, and power lines will be installed inside electrical conduits. In estimating the number of conduits, several simplifying assumptions have been made:

(1) Signal interference between the lines in the same conduit does not exist.

(2) Temperature inside the conduits is not excessive.

(3) No thermal insulation is required.

The grouping of the lines into the conduits was based solely on the cross-sectional areas of the cables and the conduits with the objective of minimizing the number of penetrations.

The number and the size of the coaxial cables needed for the nuclear monitor instruments are based on the requirements for the S8DR test. Reference 11 lists the type of monitors and their general location. Redundant systems were assumed throughout. The total number and the size of the penetrations through end shield 2 are as follows:

(1) Two 2.5-inch (6.35-cm) NaK coolant lines

(2) One 2.5-inch (6.35-cm) conduit (17 nuclear instrumentation coaxial cables and 42 thermocouple (TC) leads)

(3) One 1.0-inch (2.54-cm) conduit (15 TC leads and four resistance temperature detector cables)

(4) Two shield cooling lines

(5) Two cold wall lines

A detailed description of the measuring devices and the coaxial cables needed for their operation is given in the Instrumentation section of this appendix.

Penetrations through end shield 3. - A pair of 2.0-inch (5.08-cm) mercury vapor lines, one of which is redundant, will connect the turbine in the main section with the boiler in the gallery.

Two 0.75-inch (1.91-cm) lines, one of which is redundant, will carry liquid mercury from the pumps in the main section to the boiler in the gallery.

From the temperature control valve (TCV) located in the main section, two 1.0-inch (2.54-cm) NaK coolant lines will run to the startup heat exchanger; two of the same size lines will return NaK coolant to the TCV.

Going to and from the cold trap, which removes the impurities from the NaK by precipitation, are two 0.75-inch (1.91-cm) NaK lines. If cold trap redundancy is desired, another pair of 0.75-inch (1.91-cm) lines will be installed.

Coaxial cables, thermocouple leads, and power lines will penetrate end shield 3. These lines will be protected by electrical conduits. The same assumptions as stated previously apply here.

The following are the lines that run between the gallery and the main section, penetrating end shield 3:

(1) Two 2.00-inch (5.08-cm) mercury vapor lines

(2) Two 0.75-inch (1.91-cm) mercury liquid lines

(3) Two 1.00-inch (2.54-cm) NaK coolant lines

(4) Two 0.75-inch (1.91-cm) cold trap lines

(5) One 1.5-inch (3.81-cm) conduit (12 transducer coaxial cables, two flowmeter coaxial cables, and six TC leads)

(6) One 1.0-inch (2.54-cm) conduit (motor power lines)

Two conduits, 2.5 and 1.0 inches (6.35 and 2.54 cm), coming from the reactor cavity will also penetrate end shield 3.

Instrumentation

Nuclear monitors. - The nuclear monitor requirements were based on the S8DR system. Reference 11 lists the following nuclear instruments required to monitor the levels of radiation:

(1) Intermediate Range Monitor (IRM), two channels required

(2) Power Range Monitor (PRM), three channels required

(3) Source Range Monitor (SRM), two channels required

(4) Extended Range Monitor (ERM), one channel required

The following table shows the total number and the size of the coaxial cables needed for nuclear instrumentation:

Device	Channels	Coaxial cables per channel	Number of cables (0.410 in. diam)
IRM, compensated ion chamber	2	3	6
PRM, uncompensated ion chamber	3	2	6
SRM, fission counter	2	1	2
ERM, compensated ion chamber	1	3	3
Total number of cables			17

Thermocouples. - A total of 57 thermocouples and four temperature resistance detectors are required. These include redundant systems.

A total of six thermocouples will be used on the reflector assembly; 27 thermocouples will measure the reactor core temperature and 18 the shield temperature.

The temperature of the NaK coolant in the primary loop will be measured by two thermocouples located at the inlet and outlet of the NaK-mercury boiler.

The NaK pump and pump motor coil temperature will be monitored by four thermocouples. Four resistance temperature detectors (RTD) will measure primary NaK reactor outlet temperatures. Each RTD requires one 0.25-inch (0.64-cm) coaxial cable.

Pressure transducers and flowmeters. - The pressure differential across the NaK pumps located in the gallery will be measured by six pressure transducers, which will require a total of twelve 0.25-inch (0.64-cm) coaxial cables.

Four electromagnetic flowmeters, two at the inlet and two at the outlet of the NaK pump located in the gallery, will require one 0.25-inch (0.64-cm) coaxial cable each.

Power lines. - Six 0.50-inch (1.27-cm) cables will provide necessary electrical power for operation of the NaK pump motors.

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