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AEC RESEARCH AND
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MASTER

MCR Preliminary Design Report

Shield (U)

United States Atomic Energy Commission

Contract AT(30-1)-3078

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For The Atomic Energy Commission

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Chief, Declassification Branch

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MCR Preliminary Design Report

Shield (U)

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31 July 1964

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- Volume I—Plant Description
- Volume II—Shield
- Volume III—Power Generation
- Volume IV—Power Conversion Equipment
- Volume V—Plant Control
- Volume VI—Safety
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FOREWORD

This report presents the preliminary design of the Military Compact Reactor (MCR). This system is being designed and developed by the Allison Division of General Motors Corporation under Contract AT(30-1)-3078 for the U.S. Atomic Energy Commission. The goal of this project is to produce a piece of military field equipment which develops a given amount of electric power and meets certain limitations in size, weight, and performance.

The United Nuclear Corporation is principal subcontractor for the design and development of the reactor, shield, and primary loop.

The report covers the preliminary design period from 1 March 1963 to 30 June 1964.

The report is classified U.S. AEC Confidential—Restricted Data in accordance with CG-RAR-1, "AEC-DOD Classification Guide for the Army Nuclear Power Program," dated 18 December 1961.

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ABSTRACT

A detail physical description of the preliminary design of a Military Compact Reactor (MCR) powerplant is presented. The MCR is a mobile, nuclear powerplant with an electrical power capability of 3 Mw_e. The power source is a 15-Mw_t, UO₂-fueled, unmoderated reactor. The power conversion equipment consists of two simple open Brayton cycle gas turbines with each power section driving an 1875-kva alternator. Terminal voltage and frequency are 4160/2400 v and 60 cps, respectively, available at the edge of a 450-ft exclusion radius. The plant control system is fully automatic with manual override.

High mobility is obtained by dividing the plant into five packages. The size and weight of each package has been held to within limitations of transportation by aircraft, semitrailer, ship, and rail. Each package is shipped as an individual unit and assembled with the other packages at the operational site.

Package identification and content are:

- Package I (Shield) contains removable shield used for reactor operation
- Package II (Power Generation) contains the reactor and shutdown shielding, the primary coolant loop, and a self-contained afterheat removal system
- Package III (Power Conversion Equipment) contains the engines and main alternators
- Package IV (Power Conversion Electrical System and Auxiliaries) contains the switchgear and electrical protective equipment
- Package V (Control Console) contains the control console panel and associated computer equipment

Within 1.5 hr after arrival at the operating site, on four M-172A1 trailers and one M-35 truck, the plant can be ready for power generation. Packages I, II, III, and IV are assembled within a 50 X 150-ft area with Package V located 450 ft from the reactor.

The plant can be disassembled and ready for transport to a new site within 1.5 hr after shut-down. Assembly and disassembly of the plant is accomplished with an operational crew of seven and the five truck drivers.

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I. INTRODUCTION

This volume is one of seven presenting the preliminary design of the MCR. Included herein is the detail technical description of the shield (Package I).

In the initial MCR study conducted in the 1960-1961 period, Contract AT(30-1)-2302(XI), shield materials of all types were evaluated. Optimized unit shields, designed to minimize total weight and size, were studied. However, a shaped split shield concept was adopted to reduce individual package weights to meet transportability objectives. This concept provided a minimum weight fixed shutdown shield on the reactor skid. The removable shield on a separate package was designed as two clamshell-type sections.

Starting with Contract AT(30-1)-3078 in the fall of 1962, the entire MCR concept was reevaluated. The review confirmed the basic shield concept and effort was applied to validate nuclear and physical properties of the shielding materials, upgrade shielding codes, and conduct a preliminary design of the shield.

During this design phase, various configurations for the removable shield were investigated. Final preliminary design was conducted on a removable shield, consisting of a fixed half-section and two hinged quarter-sections designed to close about the reactor and fixed shield on the power generation package. The support skid is designed to function as an integral structure with the removable shield assembly and to form a rigid beam assembly with the power generation package.

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II. PACKAGE I PRELIMINARY DESIGN (SHIELD)

The shield concept for the MCR plant as defined during the MCR concept review,¹ * was based on dividing the shield into two parts: a minimum weight fixed shield on power generation Package II; and a removable shield which could be separated from the reactor for transportation. This volume describes the Package I removable shield design. Details of the fixed shield are presented in Volume III.

At the completion of the concept review, the recommended removable shield design consisted of two clam shell-type sections each containing a layer of lead gamma shielding material sandwiched between inner and outer layers of lithium hydride neutron shielding material. Heat deposited in the inner layers of the shield by nuclear interactions was removed by a cooling system which utilized a liquid organic as the coolant. All of the required casing and structure was fabricated of aluminum.

Subsequent detailed studies confirmed the choices of lead and lithium hydride as the materials for the removable shield and also confirmed the choice of monoisopropylbiphenyl as the shield coolant.

The same studies indicated that further reduction in the weight of the fixed shield could be obtained by using a high-density reflector followed by a lead fixed shield layer. Accordingly, the thicknesses and locations of the lead and lithium hydride layers were revised toward optimization.²

With the original clam shell concept, the interior of the shield was exposed during transport. The removable shield now consists of two quadrants rotated from hinges attached to the sides of a permanently mounted half-section. With this arrangement, the shield sections may be closed to avoid exposing nearby personnel to the most radioactive sections during transport. It also permits replacement of the shield inner layer of aluminum cladding with stronger, though more highly activating, stainless steel.

DESIGN CRITERIA

The design criteria were established to guide the design of each package. These design criteria were divided into three categories: Functional Requirements; Philosophy; and Design Requirements. The functional requirements list the main roles assigned to this package. Philosophy

*Superscripts refer to references in Section III.

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establishes the ground rules for direction and guidance, and design requirements define the main detail design values. Following are the design criteria established for Package I.

Functional Requirements

Functional requirements for Package I are:

- Will provide the radiation shielding around the reactor (in addition to that on Package II) required to reduce radiation levels during operation
- Will provide means for the assembly and disassembly of the removable shield about the reactor and fixed shield
- Will provide all necessary couplings for mating with Package II
- Will incorporate the neutron sensors used in reactor control
- Will incorporate necessary design features to meet transport requirement
- Will incorporate equipment to limit the interior temperatures of the fixed and removable shields to acceptable values, as specified in the appendix of this volume

Philosophy

- State-of-art in technology and equipment will be used where possible to achieve a shielding package concept which can be used with a highly mobile nuclear powerplant.
- Radiation exposure limits will be consistent with military combat application of the plant. Reduction of radiation exposures will be made at some sacrifice in mobility to meet Title 10, Section 20 of Code of Federal Regulations.
- New parts not associated with nuclear technology but specifically required for this application will be designed for minimum weight consistent with the reliability goals and the applicable design objectives presented in Volume I, Section II.
- Final development of Package I will be conducted during NRTS operation.

Design Requirements

To proceed with the design of the shield package, the following basic design requirements were imposed on each of the principle subsystems.

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General

- The package will be designed to meet the applicable design objectives, structural design criteria, and duty cycle presented in Volume I, Section II, and safety design criteria presented in Volume VI.
- The package will also meet the requirements specified in the Nuclear Materials Design Criteria presented in the appendix of this volume.
- Instrumentation for monitoring, control, and safety will be designed into all major subsystems of the package.
- The package will provide cooling for the fixed and removable shields.

Removable Shield

- The removable shield, in conjunction with the fixed shield in Package II, will provide radiation attenuation such that the biological dose rate will not exceed 10 mrem/hr at a distance of 450 ft from the reactor centerline in the horizontal plane when the reactor is producing 15 Mw of thermal energy.
- Passages will be provided for the circulation of coolant in the removable shield for absorbing 402,700 BTU/hr.

Shield Coolant System

- The shield coolant system will be designed to remove 28,000 BTU/hr of thermal heat, maintaining a maximum coolant temperature below 325°F at maximum ambient temperatures specified in Volume I, Section II.
- Coolant will be provided for the instrument thimbles to keep neutron detector temperatures below 300°F.
- A preheat system will be provided to increase coolant temperatures from -65 to 0°F in 30 min. The preheat system will operate on 400 cps electrical power.
- The complete system will be drainable from readily accessible connections.

Support Structure

- The structure, in combination with the structure of Package II, will be designed to form a rigid beam assembly. The assembly will be capable of supporting Package III from the interface of Packages II and III should the Package III trailer settle.
- The package structure will be sufficiently rigid to maintain component arrangement integrity during operation and transport.

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SCOPE

The nuclear analysis and mechanical design efforts established by the design criteria were concentrated on the following items:

- Designing the removable shield assembly to minimize system weight and to account for changes in the reactor and fixed shield design
- Integration of the structures required for canning and internal support of the shield materials with the supporting structure of the entire Package I assembly
- Investigation of shield coolant system designs and cooling media—air and organic
- Incorporation of the shield cooling system components and nuclear instrumentation thimbles into the overall design
- Development of calculational techniques for the computation of secondary gamma ray production, activation, nuclear heating, neutron penetration, and air and ground scattering

Implementation of the design criteria also required initiation of the following support investigations.

- The compatibility at design temperature of lead, aluminum, and alternate cladding materials with lithium hydride was investigated and confirmed.
- Small source shielding experiments were performed to compare measured and calculated secondary gamma ray dose rates from materials utilized in the MCR design.
- An experimental program, using the MCR critical assembly, was initiated to determine (for subsequent comparison with calculated values) the neutron spectrum, secondary gamma production, and gamma heating rates in the vicinity of the pressure vessel and shield.

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Package Description

The isometric view of the Package I assembly is shown in Figure 2-1. The drawing shows the large removable shield assembly which consists of two rotatable quadrants and a permanently mounted half section. This shield supplements the fixed shield on Package II, and serves to reduce the operational dose rate to 10 mrem/hr at 450 ft from the reactor centerline. Also shown are the major external components of the shield coolant system and the skid and associated structure which support both the removable shield and the shield coolant system.

The cutaway view in Figure 2-1 shows the three layers of shielding provided in all three sections: an inner LiH neutron shield layer, a thin lead layer for attenuation of secondary gamma radiation, and an LiH neutron shield layer. The LiH is fabricated in the form of blocks. These blocks are not individually canned but are fastened to support shelves located within hermetically sealed can housings. These can housings are designed to withstand pressure differentials consistent with the operation of the MCR from below sea level to 8000-ft altitudes. The can housing for the inner LiH layer is contoured to close about the reactor, fixed shield, and the shield segment located between the primary coolant lines on Package II. This inner housing is fabricated of stainless steel. The outer LiH layer can housing is aluminum. The lead gamma shield layer is bonded to it cladding—stainless steel on the inner face and aluminum on the outer face.

Four instrument thimbles, each containing two neutron sensors, penetrate the fixed half section of the removable shield.

The shield cooling system, using monoisopropylbiphenyl as the organic coolant, is located on the aft end of the removable shield and is shown in Figure 2-2. Cooling tubes are located within the inner LiH and lead layers to ensure that the maximum LiH temperature does not exceed 544°F and that the lead temperature does not exceed 305°F. The maximum temperature of the outer LiH is kept below 303°F. The small amount of heat generated in the outer layer is dissipated through the outer housing wall by natural convection of ambient air.

The organic-to-air heat exchanger and associated air blowers and ducting extend outward from the upper rear portion of the removable shield assembly. Beneath these components and mounted directly on the skid are the air dryer for purging the expansion tank and the two organic pumps, as well as the small additional pump used only during shutdown. The vertical cylindrical shield coolant expansion tank is installed in a recess in the half section of the removable shield. The organic in the tank provides approximately the same fast neutron attenuation as the LiH which it displaces. The shield coolant system is designed to limit the effects of radiolytic damage to the organic coolant. The formation of high boiler residue concentration is within acceptable limits, and dissolved gases are never at maximum solubility levels.

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Figure 2-1. Package I assembly isometric.

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Figure 2-2. Shield cooling system. (Sheet 1 of 2)

TOP VIEW

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Figure 2-2. (Sheet 2 of 2)

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The Package I skid is designed to function as an integral structural system with the removable shield assembly. The lead layer cladding is used as a principal structural column. The LiH can housings, support shelves, end plates, and vertical support plates stiffen the assembly and distribute static and dynamic loads to the Package I skid and truss members.

The half section of the removable shield is welded to hinge columns. This assembly is bolted to the shock-mounted skid underbody. The quarter sections are attached to the forward truss assembly through the hinge and turnbuckle columns. The forward truss assembly permits the rotation of the quarter sections for assembly and disassembly of Packages I and II. Turnbuckles and other subassemblies are provided for alignment and coupling to form a rigid beam of Packages I and II.

Two skis, located beneath the underbody, serve as foundation for the entire assembly and permit sliding the package. Sixteen shock mounts between the skis and underbody reduce any shock and vibration loads transmitted to the package. Provisions are made for attaching tiedowns to the shield and truss members to secure Package I during transport.

The skid assembly is shaped to receive the reactor support section of the Package II skid. Figure 2-3 shows the quarter sections opened to receive Package II. As the packages are drawn together, the guide rail on the Package II skid controls the closure of the quarter sections about the reactor and fixed shield.

Tables 2-I and 2-II present a breakdown of Package I weights and characteristics.

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Table 2-I.
Package I weight summary.

<u>Component</u>	<u>Weight (lb)</u>
Removable shield half section	
Inner neutron shielding	850
Outer neutron shielding	4,570
Gamma shielding	6,930
Aluminum canning and structure	860
Stainless steel canning and structure	420
Hardware	<u>120</u>
Subtotal	13,750
Removable shield quarter sections	
Inner neutron shielding	760
Outer neutron shielding	4,660
Gamma shielding	7,030
Aluminum canning and structure	760
Stainless steel canning and structure	360
Hardware	<u>120</u>
Subtotal	13,690
Shield patches	120
Shield coolant system	
Equipment	530
Pipe and fittings	220
Organic inventory	500
Heaters and insulation	<u>70</u>
Subtotal	1,320
Instrumentation (including thimbles)	300
Support structure	
Skis and suspension system	410
Underbody	520
Superstructure	750
Plates, rail, and gussets	220
Miscellaneous	<u>200</u>
Subtotal	<u>2,100</u>
Total	31,280

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Figure 2-3. Composite shield assembly.

Table 2-II.
Package I characteristics.

Overall assembled package	
Height	89 in.
Length	122.0 in.
Width (max)	102.75 in.
Total weight	31,280 lb.
Removable shield	
Performance	
Full power operating dose rate—at 450 ft from core centerline in reactor horizontal midplane	
Gamma rays	4.5 mrem/hr
Neutrons	5.5 mrem/hr
Total	10.0 mrem/hr
Shutdown dose rate from reactor—12 hr after shutdown (removable shield in place)- 10 ft from core centerline	
	6.2 mrem/hr
Dimensions in horizontal midplane	
Height	89 in.
Length (max)	101.375 in.
Transverse width (max)	102.50 in.
Inner diameter	37.66 in.
Weight	31,280 lb.
Inner neutron shield including liners	
Material	LiH with 304 SS canning
Thickness	8.41 in.
Max. operating temp.	544°F
Gamma shield	
Material	Pb
Thickness	3.37 in.
Max. operating temp.	305°F
Outer neutron shield (including liners)	
Material	LiH with A1-5652-0 canning
Thickness	20.72 in.
Max. operating temp.	303°F
Line of separation	At 1.5° to transverse axis of skid; half of shield toward engine also split along longitudinal axis
Shield coolant system	
Heat removal	
Pumping power required	184 kw
Operating	10.8 kw
Shutdown	1.0 kw
Coolant	Monoisopropylbiphenyl
Flow rate	12.79 lb/sec
Pressure drop	35 psi
Pressure	0 psig
Temperature at inlet	235°F
Temperature at outlet	260°F
Coolant inventory	500 lb
Makeup requirements for	
5000 fph	(included in inventory)
Expansion volume (70 to 270°F)	0.8 ft ³
Operating "hbr" equilibrium	30 w/o max
Skid and support structure	
Type construction	Welded and bolted truss assembly
Material	Aluminum
Shock mounts	
Number	16
Type	ML-1
Compliant medium	GE Elastomer SE565U

Shield Radiation Performance

The design dose rate for the operating shield is 10 mrem/hr at 450 ft from the reactor center-line. This dose rate was used as the radiation exposure criteria for many of the military mobile reactor applications considered in previous studies.^{1,3} It has been accepted as a suitable compromise between low shield weight and low radiation exposure.

Further analyses of permissible radiation exposures for operation of the MCR under military conditions were performed, considering exposure during operation, maintenance, and transport. The recommended maximum exposures for plant applications requiring highest mobility are:

- Maximum dose of 25 rem/crew member/yr for operation and maintenance, based on a 5000-hr full power operation, no expedient shielding, and maintenance shutdown periods not to exceed 24 hr
- Maximum dose of 5 rem/person participating in a transport operation

For a 10 mrem/hr dose rate at the control cab, the average dose per man to a seven man crew for 5000-hr full power operation is 14.3 rem/yr, if two operators are exposed at all times—this is well within the recommended maximum exposure.

DOSE RATES DURING OPERATION

Dose Rates at the Control Cab

The total calculated operating dose rate at 450 ft from the reactor center line for an operating power of 15 Mw is 10 mrem/hr. The neutron and gamma ray dose rate contributions to the total operating dose rate are summarized in Table 2-III. As pointed out in Volume III, the dose rate contribution at the control cab from the primary coolant loop activation sources is negligible.

A one-dimensional multilayer spherical geometry model was used for the analysis of the operating shield. Separate calculations were made for the radial shield, axial upward shield, and axial downward shield. The dimensions and compositions used in the model for each of the calculations performed in these directions are given in Tables 2-IV, 2-V, and 2-VI. The composition of the reactor core used in the calculations is presented in Table 2-VII.

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Table 2-III.
Dose rate at the control cab. *

	<u>mrem/hr</u>
Neutron dose rate from main shield	3.5
Neutron dose rate from ground scatter of neutrons from the bottom shield plug	<u>2.0</u>
Total neutron dose rate	5.5
Total gamma ray dose rate	<u>4.5</u>
Total dose rate	10.0

*Dose point 450 ft from reactor core center line and 4 ft above the ground level. These dose rates include the effect of air and ground scatter on attenuation and buildup of neutrons and gamma rays. Air density is 0.00129 gm/cm^3 at 32°F and sea level elevation.

Neutron penetration calculations for these models were made with the SANE Monte Carlo program which solves the neutron transport equation in spherical geometry.⁵ The spatial and energy distribution of neutrons in all shield regions of interest was calculated using cross-sectional data at 80 energy points. The program treated isotropic and anisotropic elastic scattering, discrete and continuum inelastic scattering, scattering by hydrogen, and the n,2n reaction in beryllium. A 32-energy group compilation of neutron fluxes for each spatial position of interest was used to calculate, in turn, those neutron interactions resulting in gamma ray formation (n, γ ; n, n'), formation of radioactive nuclides (n, γ ; n, p ; n, γ ; $n, 2n$), and direct heat deposition (n, γ ; n, n). Shield secondary gamma ray sources, activated nuclides, and neutron heat deposition were calculated in this manner. The leakage neutron dose was also calculated by the program.

Gamma ray penetration calculations were made using a similar model with the SAGE⁵ Monte Carlo program. Six monoenergetic source groups from 1 to 6 Mev were compiled from the results of the SANE calculations. The spatial and energy distribution of gamma ray photons was then calculated within all shield regions of interest. Compton scattering of photons and absorption processes owing to the photoelectric effect and pair production were considered. An 8-energy group compilation of photon fluxes for each spatial position of interest was used to calculate photon interactions of interest such as heat deposition.

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Table 2-IV.
Radial shielding at reactor core midplane.

<u>Shield layer</u>	<u>Thickness (in.)</u>	<u>Material</u>	<u>Volume fraction</u>	<u>Element</u>	<u>Atom density (atoms/cm³ × 10²⁴)</u>
Shroud	0.1875	SS	0.596	K	4.27×10^{-3}
		K	0.404	Fe	4.93×10^{-2}
Reflector I	1.50	BeO	0.421	Be	2.84×10^{-2}
		W	0.318	O	2.84×10^{-2}
		K	0.128	K	1.35×10^{-3}
		SS	0.133	Fe	1.10×10^{-2}
				W	1.94×10^{-2}
Reflector II	2.00	W	0.852	K	1.35×10^{-3}
		K	0.128	Fe	1.65×10^{-3}
		SS	0.020	W	5.20×10^{-2}
Reflector III	1.50	B ₄ C	0.269	B-10	2.86×10^{-2}
		K	0.140	C	1.02×10^{-2}
		B-SS	0.591	K	1.48×10^{-3}
				Fe	4.77×10^{-2}
Coolant annulus	0.300	K	1.00	K	1.06×10^{-2}
Pressure vessel	0.625	SS	1.00	Fe	8.27×10^{-2}
Insulation	0.260	Min-K	1.00	O	1.20×10^{-2}
Pressure vessel support skirt	0.250	SS	1.00	Fe	8.27×10^{-2}
Insulation	0.500	Min-K	1.00	O	1.20×10^{-2}
Gap	0.135	Void			
Inner lead*	3.785	Pb	0.940	H	1.20×10^{-3}
		Al	0.033	C	1.13×10^{-3}
		Organic	0.027	Al	1.99×10^{-3}
				Pb	3.086×10^{-2}
Inner LiH†	8.410	LiH	0.965	H	5.386×10^{-2}
		SS	0.025	Li	5.341×10^{-2}
		Organic	0.010	C	4.20×10^{-4}
				Fe	2.11×10^{-3}
Outer lead	3.370	Pb	0.98	H	4.5×10^{-4}
		SS	0.01	C	4.2×10^{-4}
		Organic	0.01	Fe	8.46×10^{-4}
				Pb	3.217×10^{-2}
Outer LiH‡	20.767	LiH	0.978	H	5.41×10^{-2}
		Al	0.018	Li	5.41×10^{-2}
		SS	0.01	Fe	8.46×10^{-4}
				Al	1.08×10^{-3}

*Includes inner and outer Al canning with 0.0625-in. thickness each.

†Includes inner and outer SS can with 0.0625-in. thickness each.

‡Includes inner and outer Al can with 0.125-in. and 0.250-in. thickness respectively.

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Table 2-V.
Axial upward shielding.

<u>Shield layer</u>	<u>Thickness (in.)</u>	<u>Material</u>	<u>Volume fraction</u>	<u>Element</u>	<u>Atom density (atoms/cm³ × 10²⁴)</u>
Top reflector	1.494	W	0.478	W	2.98 × 10 ⁻²
		Cb	0.178	K	2.85 × 10 ⁻³
		K	0.277	Fe	1.35 × 10 ⁻²
		SS	0.067		
Fission gas space	2.642	Void	0.478	K	2.85 × 10 ⁻³
		Cb	0.178	Fe	1.35 × 10 ⁻²
		K	0.277		
		SS	0.067		
End fittings	1.910	K	0.750	K	7.52 × 10 ⁻³
		SS	0.250	Fe	2.04 × 10 ⁻²
Grid	0.813	K	0.270	K	2.71 × 10 ⁻³
		SS	0.730	Fe	5.97 × 10 ⁻²
Outlet plenum	7.350	K	0.633	K	6.35 × 10 ⁻³
		SS	0.356	Fe	2.91 × 10 ⁻²
		B	0.011	B-10	1.65 × 10 ⁻³
Inner head	0.313	SS	1.000	Fe	8.274 × 10 ⁻³
Internal shielding	9.122	K	0.100	K	1.00 × 10 ⁻³
		SS	0.873	Fe	7.14 × 10 ⁻²
		B	0.027	B-10	4.05 × 10 ⁻³
Pressure vessel cover	0.875	SS	1.000	Fe	8.274 × 10 ⁻³
Insulation	0.750	Min-K	1.000	O	1.2 × 10 ⁻²
Inner LiH*	4.000	LiH	0.901	Li	4.99 × 10 ⁻²
		SS	0.047	H	5.22 × 10 ⁻²
		Organic	0.052	Fe	3.97 × 10 ⁻³
				C	2.18 × 10 ⁻³
Lead**	2.623	Pb	0.898	Pb	2.95 × 10 ⁻²
		SS	0.024	Fe	2.03 × 10 ⁻³
		Organic	0.078	C	3.28 × 10 ⁻³
				H	3.51 × 10 ⁻³
Outer LiH†	13.650	LiH	0.968	Li	5.36 × 10 ⁻²
		SS	0.032	H	5.36 × 10 ⁻²
				Fe	2.71 × 10 ⁻³

*Includes inner and outer SS cans with 0.0625-in. thickness each plus coolant ducting
0.0625-in. thick.

**Includes coolant ducting 0.0625-in. thick

†Includes inner and outer stainless steel cans with 0.219-in. thickness each.

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Table 2-VI.
Axial downward shielding.

<u>Shield layer</u>	<u>Thickness (in.)</u>	<u>Material</u>	<u>Volume fraction</u>	<u>Element</u>	<u>Atom density (atoms/cm³ × 10²⁴)</u>
Tungsten reflector	2.965	W	0.478	K	2.85×10^{-3}
		Cb	0.178	Fe	1.35×10^{-2}
		K	0.277	W	2.975×10^{-2}
		SS	0.067		
End fitting	1.910	K	0.50	K	5.285×10^{-3}
		SS	0.50	Fe	4.137×10^{-2}
Grid plate	1.125	K	0.27	K	2.854×10^{-3}
		SS	0.73	Fe	6.04×10^{-2}
Lower plenum	5.25	K	0.70	B-10	1.418×10^{-3}
		B-SS	0.30	K	7.40×10^{-3}
				Fe	2.482×10^{-2}
Tungsten bowl	0.250	W	1.00	W	6.224×10^{-2}
Pressure vessel	0.625	SS	1.00	Fe	8.274×10^{-2}
Insulation	0.50	Min-K	1.00	O	1.20×10^{-2}
Titanium hydride* (+1 w/o B ¹⁰)	14.0	Boronated Ti H ₂	0.98	H	8.792×10^{-2}
				B-10	2.194×10^{-3}
				Ti	4.396×10^{-2}
		SS	0.02	Fe	1.692×10^{-3}

*Includes inner and outer stainless steel cans 0.0625-in. thick.

Table 2-VII.
Reactor core composition.

<u>Material</u>	<u>Volume fraction</u>	<u>Element</u>	<u>Atom density (atoms/cm³ × 10²⁴)</u>
Potassium	0.274	O	2.176×10^{-2}
Stainless steel	0.041	K	2.923×10^{-2}
Columbium*	0.187	Fe	1.352×10^{-2}
Uranium dioxide (82.7% enriched)	0.498	U-235	9.004×10^{-3}
		U-238	1.877×10^{-3}

⁵⁶Fe of equivalent atom density was used in place of Cb.

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Two-dimensional Monte Carlo methods were used to calculate dose rates at the control cab from air- and ground-scattered radiation.

Secondary Gamma Ray Dose

In high performance compact shields most of the gamma ray leakage dose is from secondary gamma ray sources. In the MCR, core gammas are largely attenuated by the reflector and fixed shield; essentially all of the external gamma ray dose is due to secondary gamma rays produced within the shield by both neutron inelastic scattering and neutron capture.

The reflector regions are not important sources of secondary gamma rays as they are not exposed to low energy neutrons to any great degree and are well shielded by the two lead layers. The inner lead region and the thin stainless steel can, used at the inner face of the inner LiH region, contribute a significant portion of the secondary gamma ray dose rate due to the relatively high flux of neutrons of epithermal and intermediate energies in these regions.

The attenuation and subsequent absorption of the intermediate energy neutrons by the LiH in the inner LiH layer is such that the stainless steel members used within the LiH layer and as its outer canning material are not significant sources of secondary gamma rays. Similarly, the aluminum canning of the outer LiH layer is not a significant source of secondary gamma rays.

A breakdown of the fractional gamma ray dose rate from each shield layer is presented in Table 2-VIII. An approximate breakdown of these doses as they derive from neutron inelastic scattering and neutron capture processes is presented in Table 2-IX.

These calculations were performed by using one-dimensional Monte Carlo neutron penetration calculations to determine the gamma ray sources and one-dimensional Monte Carlo gamma ray penetration calculations to determine the dose outside of the shield.

Anisotropic Effects

The thicknesses of the various shield layers in the removable shield were determined by compromises between the desirable goals of minimum weight and minimum size. The weight of the removable shield is slightly greater than minimum in order to provide a significantly smaller shield diameter.

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Table 2-VIII.
Breakdown of operating gamma ray dose rate.

<u>Source region</u>	<u>Fraction of total gamma ray dose rate at the shield surface from each source region</u>
Core and shroud	nil
Tungsten reflector	0.048
Stainless steel reflector	0.007
Pressure vessel	0.004
Inner lead	0.275
Stainless steel can for LiH*	0.392
Inner LiH	0.059
Outer Pb	0.169
Outer LiH	<u>0.046</u>
Total	1.000

*Significant source is 1/16-in. thick stainless steel can at the inner face of the inner LiH layer.

Table 2-IX.
Breakdown of gamma ray doses from neutron inelastic scattering and neutron capture.

<u>Region</u>	<u>Fraction of gamma ray dose rate from each shield region</u>	
	<u>From neutron capture</u>	<u>From neutron inelastic scatter</u>
Core and shroud	—	—
Tungsten reflector	0.97	0.03
Stainless steel reflector	0.41	0.59
Pressure vessel	0.69	0.31
Inner lead	0.61	0.39
Stainless steel can for LiH	0.91	0.09
Inner LiH	1.00	—
Outer Pb	0.18	0.82
Outer LiH	1.00	—

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The radial geometry of the shield is essentially symmetric with some minor local variations at the two hinge points between the quarter sections and the half sections of the removable shield, and at the main coolant line penetration. The variations at hinge points lead to a local increase in the neutron and gamma ray doses. The effect of these variations is insignificant at the control cab. The variations at the coolant line penetration result from a somewhat thinner neutron shield, secondary gamma ray production in the stainless steel coolant lines, and some fast neutron leakage through the lines. A rather elaborate mechanical design minimizes the local effect of the pipe penetration. This effect is further reduced by the presence of closely packed primary coolant system equipment in the direction of the pipe penetration.

The performance of the shield is anisotropic in both the upward and downward directions. Space and material restrictions in these directions resulted from mechanical design considerations which dictated the height of the core, overall height of the skid, and dimensions of the vessel, and strongly influenced the choice of materials to be used inside the reactor vessel.

The anisotropic radiation leakage characteristics of the shield are summarized in Table 2-X. Greater attenuation is provided in the axial upward than downward direction. This is primarily due to the fact that the space available for top shielding above the reactor core is much greater than the distance axially downward from the bottom of the core to the edge of the package envelope. The elevation of the core is determined by several mechanical design considerations. The overall height of the package is limited to 92 in. The coolant nozzles on the vessel are required to be above the surface level of the core grid plate and the control rod drives are located outside and on top of the vessel.

The neutron dose rate at the upper surface of the shield is 1.5 times the neutron dose rate at the radial surface of the shield, as indicated in Table 2-X. However, the contribution of neutrons leaving the shield in the axial upward direction to the dose rate at the control cab via air and ground scatter is insignificant. The thickness of the outer lead layer enveloping the top of the reactor vessel is reduced to save weight, since the contribution of this component of the gamma ray leakage to the dose rate at the control cab will also be insignificant (<0.1 mrem/hr).

Because of the relatively limited space available for shielding in the axially downward direction, a material with a very high neutron attenuation per unit thickness (TiH_2) was used in the bottom shield plug. Nevertheless, the bottom shield surface neutron dose rate as indicated in Table 2-X is still very much higher than that for the radial or the top shield. Since the lower surface

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Table 2-X.
Anisotropy of shield performance.

	<u>Dose rate at shield surface</u>	
	<u>Near dose*</u>	<u>Far dose†</u>
	<u>(rem/hr)</u>	<u>(rem/hr)</u>
At top of shield on reactor axis		
Neutron dose rate	61	41
Gamma ray dose rate	850	740
Adjacent to shield at reactor core midplane		
Neutron dose rate	39	28
Gamma ray dose rate	110	98
At bottom of shield on reactor axis		
Neutron dose rate	10 000	7,000
Gamma ray dose rate	63,000	54,000

*The near dose is the dose at the surface of the shield. It is the neutron flux times the dose conversion factor summed over energy, calculated by dividing the far dose contribution of every neutron by the cosine of the angle the neutron makes with the normal to the outer shield boundary to account for angular distribution effects.

†The far dose is the dose applicable at distances far from the shield surface. It is evaluated by multiplying each emerging neutron by the dose conversion factor of the proper energy and summing over all neutrons.

of the bottom shield plug must be 3 in. above the supporting surface (ground or trailer bed) to provide clearance during transport, neutrons can be scattered outward from the supporting surface. For an MCR positioned on the ground, scattering from the ground occurs outward through a narrow 3-in. slot between the ground and the bottom of the skid. For this geometry, the neutron dose rate from this source at the control cab is 2.0 mrem/hr, as indicated in Table 2-III. When the MCR is operated on a trailer, the scattering contribution will increase because the distance between the shield surface and ground is increased. This analysis was performed using neutron albedo values for the ground determined by Monte Carlo methods.⁴

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Air and Ground Radiation Scattering Effects

To reduce the required amount of shielding, the control cab is physically separated by a distance of 450 ft from the shielded reactor.

Since both air and ground are scattering media, the actual dose rate at the control cab depends upon both the attenuation of the radiation by air and the buildup due to air and ground scattering. The former effect acts to attenuate the dose, while the latter effect tends to increase the particle flux and consequently the dose. Two-dimensional Monte Carlo calculations were used to calculate the dose at the control cab from the shielded reactor situated on the ground. As indicated in previous sections, the dose rates at the control cab from anisotropic portions of the shield were calculated separately and do not contribute significantly to the dose at the control cab.

The neutron leakage spectrum for the radial shield is presented in Figure 2-4. The U-235 fission spectrum is given on the same plot for comparison. The shield leakage spectrum is seen to be significantly harder than that of a pure fission spectrum above an energy of about 6 Mev. The gamma ray leakage spectrum for the radial shield is shown in Figure 2-5.

The dose rates calculated at 450 ft are presented. A plot of neutron dose rate versus distance at points 4 ft above the ground for the MCR situated on the ground is presented in Figure 2-6. The figure gives the neutron dose rate from the isotropic portion of the shield as well as that from ground scatter of the neutrons from the bottom shield. Figure 2-7 presents the gamma ray dose rate versus distance. Also plotted is the total neutron dose rate and the total dose rate from gamma rays and neutrons.

DOSE RATE AFTER SHUTDOWN

The dose rates from the reactor after shutdown, with the removable shield in place, are significantly lower than those with only the fixed shield present. Table 2-XI presents the gamma ray dose rate after reactor shutdown with the full shield in place.

The contribution to the dose rates after shutdown from the unshielded portion of the primary coolant system (as given by the isodose plots and correction factors of Figures 2-60 and 2-61 in Volume III) must also be considered. In those regions, in the vicinity of Packages I, II, and III, where maintenance operations are performed, the contributions of the coolant system to the total dose rate predominate over those from the reactor.

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Figure 2-4.
Shield neutron leakage
spectrum.

Figure 2-5.
Shield gamma ray leakage
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Figure 2-6. Neutron dose rates vs distance from MCR.

Figure 2-7. Gamma ray dose rates vs distance from MCR.

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Table 2-XI.
Shutdown gamma dose rate from reactor
with full shield in place.

Time after shutdown—hr	Dose rate* (mrem/hr)				
	0.5	1	6	12	24
Distance from center of core—ft					
10	28	21	9.4	6.2	3.9
20	7.0	5.4	2.4	1.5	0.98
30	3.1	2.4	1.1	0.69	0.44

*For full-power reactor operation of 1000 hr or more.

INTERNAL HEAT GENERATION

Internal heat generation rates in the several layers of the removable shield are listed in Table 2-XII for full power operating conditions. The contributions from neutron (n, α) absorption, neutron slowing down, and gamma absorption within each region are itemized. As seen in Table 2-XII, most of the heat generation in the removable shield occurs in the inner LiH layer.

Table 2-XII.
Internal heat generation summary—removable shield.*

Shield layer	Removable shield plus primary piping shield segment (PPSS)			
	Neutron n, α heating (kw)	Neutron slowing down (kw)	Gamma ray heating (kw)	Total heating (kw)
Inner LiH	108.0	17.6	0.327	126.0
Outer lead	—	—	0.297	0.297
Outer LiH	0.45	0.12	0.005	0.58
Total removable shield plus PPSS				126.8
Less PPSS				9.6
Net total removable shield				117.2

*For reactor operation at 15 Mw.

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SHIELD RADIATION ENVIRONMENT

The radiation exposure of materials within the radial shield at the reactor midplane is depicted graphically in Figures 2-8 and 2-9. Figure 2-8 gives the time-integrated fast neutron exposure ($nvt > 0.897$ Mev for 25,000 full power hours) versus radial position in the shield from the pressure vessel outward. Fast neutron exposure for points within the vessel is presented in Table 2-VI of Volume III. Figure 2-9 gives the time-integrated gamma ray exposure (ergs/gm in carbon for 25,000 full power hours) versus radial position in the shield from the pressure vessel outward. The units chosen for both neutron and gamma ray exposure are in accordance with those recommended by the Radiation Effects Information Center.⁶

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Figure 2-8. Fast neutron exposure (nvt 70.891 Mev) in radial shield at reactor case midplane.

Figure 2-9. Gamma ray exposure in radial shield in reactor core midplane.

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Removable Shield

The removable shield is that portion of the total shielding for the MCR powerplant which is separable from the reactor (and Package II) and is transported as a part of Package I. It is designed to supplement the fixed shield assembly of Package II so that the dose rate during full power operation is limited to 10 mrem/hr at 450 ft from the reactor centerline.

DESCRIPTION

The removable shield assembly consists of a fixed half section and two hinged quarter sections, as shown on Figure 2-10. The inner surface of the removable shield is contoured to close about the reactor and fixed shield, located on Package II, and the shield segment installed between the primary coolant lines. All mating end plate surfaces of the shield sections are stepped to minimize gamma and neutron radiation streaming.

The fixed half section is rigidly fastened to the Package I skid through the hinge columns, the vertical support plate, and tie shelf gussets. The quarter sections are attached to the skid forward truss assemblies at hinge columns and through the vertical support plates. The quarter sections swing out through an angle of 31° for assembly and disassembly of Packages I and II. Rollers, attached to the quarter sections, contact a contoured guide rail on the Package II skid to control the closure of the quarter sections about the reactor and fixed shield. Piping is provided external to the shield can housings to route shield coolant from internal cooling tubes and headers aft to the shield coolant system. The vertical coolant expansion tank is recessed into the outer housing of the fixed half shield section. Four instrument thimbles for neutron detectors are inserted in the fixed half section.

The removable shield diameter at the core midplane is 102.75 in. However, it is flattened in the direction of the primary loop to take advantage of the shielding afforded by the system components located in the forward direction, thus reducing the weight and overall length of Package I. The height of the removable shield is 80.75 in.

A summary of materials used is presented in Table 2-XIII. The composition and physical properties of the LiH and lead are presented and discussed in the appendix of this volume. The type 304 stainless steel is in accordance with specification ASTM A167, with a maximum cobalt impurity concentration of 0.03 w/o. The type 5652-0 aluminum is the same as type 5052-0 aluminum, except for a manganese content of 0.01 w/o as compared to 0.10 w/o. Physical properties and fabricability are identical.

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Table 2-XIII.
Removable shield materials.

<u>Component</u>	<u>Material</u>
Inner and outer neutron shield layers	Lithium hydride
Gamma shield layer	Corroding lead
Inner neutron shield canning and shelves	Type 304 stainless steel
Gamma shield inner cladding	Type 304 stainless steel
Gamma shield outer cladding	Type 5652-0 aluminum
Outer neutron shield canning and shelves	Type 5652-0 aluminum

SHIELD INTERNALS

The internal design of the fixed half section and the hinged quarter sections are the same and consistent with the concept of a spherical assembly around the reactor. The internal design for the fixed half section is shown in Figure 2-11. Figure 2-12 shows the internal design for the hinged quarter sections. Three layers of shielding are provided in all three sections. They are, measuring radially outward at the reactor core midplane, as follows:

- An inner LiH neutron shield layer—37.66-in. ID and 54.48-OD
- A lead secondary gamma shield layer—54.48-in. ID and 61.22-OD
- An outer LiH neutron shield layer—61.22-in. ID and 102.75-OD

The thicknesses of the metal can housings are included in the dimensions given for the LiH layers.

Differences in the internal design of the half section and quarter sections are:

- The end plates connecting the inner and outer faces of each section
- Thickness of the can housings, to account for the different static and dynamic loading conditions to which each section is subjected
- Local penetrations such as those for the coolant piping and instrument thimbles

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Figure 2-10. Removable shield assembly.

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Figure 2-11. Removable shield half section internals.

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Neutron Shielding

LiH is used as the neutron shielding in both the inner and outer layers of the shield sections. It is fabricated in the form of blocks isostatically pressed on a 1.00-in. grid $\times$ 0.001-in. thick stainless steel honeycomb matrix. The physical properties and specifications for the LiH are presented in the appendix.

The blocks of both the inner and outer LiH layers are supported on horizontal support shelves which bridge the inner and outer can housings.

The inner layer of LiH forms a right cylinder at the bottom of the shield. It has an ID of 37.78 in. and an OD of 54.35 in., as measured from the inside of the canning faces. The blocks, pressed initially as straight cylindrical sections, are machined to fit within these radii. The largest finished blocks for this layer are 30 in. long with an end cross section of 10.5×12 in.

The inside face of the LiH outer layer is contoured to match the lead gamma shield, and the outside face is contoured to match the overall spherical shield shape. At the core midplane, the outer LiH layer has a 61.47-in. ID and a 102.25-in. OD, as measured from the inside of the canning faces. Due to the thickness of this outer layer, two horizontal rows of blocks are required. The rows of blocks are offset and their support shelves are stepped vertically to overlap joints and minimize radiation streaming. The largest finished blocks are 39 in. long with an end cross section of 12×14 in. Both the inner face of the inner row of blocks and the outer face of the outer row of blocks are machined to match the contour of the canning surfaces.

The blocks are fastened to the support shelves to maintain the block position during transport to resist lateral and vertical shock loadings, and to permit thermal expansion of the LiH from the cold shutdown condition to the hot operating condition. Each block is bolted to the shelf on which it is supported, as shown in Detail 5 of Figure 2-11. Each block is held in compression by disk springs, located at the top of the block under the nut of the bolt. The compression in the spring is set to counteract a net upward 2-g shock load. The bolts are located at the center of gravity of each block to prevent any twisting action due to lateral shock loads.

Space is provided around each block, both between the blocks and canning as well as between the blocks themselves, to permit free thermal expansion. The disk springs are also designed to take the extra compression due to vertical expansion of blocks.

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Block sizes were determined on the basis of existing fabrication facilities. It was assumed that the maximum size LiH piece that can be pressed is 44-in. dia $\times$ 48-in. long, and that the maximum size piece that can be sintered is 24-in. dia $\times$ 48-in. long, establishing limiting dimensions. The fabrication procedure is as follows.

- Crushed LiH is loaded into polyvinylchloride containers and pressed onto a 300 series stainless steel matrix in a dry atmosphere (10% relative humidity).
- After pressing, the compacts are sintered at 1100°F.
- The sintered compact is machined in a dry atmosphere or, if size permits, in a dry nitrogen-filled glove box; machining tolerances on the flat faces of the blocks will be maintained to ± 0.03 in.

All machining of the blocks is performed prior to installing them on the shelves. Where required, the surfaces are milled to provide clearance for coolant tubes. Similarly, through-holes are bored in the blocks at the required radial dimensions and vertical angle for penetrations such as the instrument thimbles.

After fabricating the block to the correct outside dimensions, a 0.406-in. dia hole is drilled through at the block center of gravity. It terminates in a 1.50-in. dia $\times$ 1-in. deep countersunk hole at the top and bottom. A stainless steel bearing cup having 0.125-in. stainless steel wall and a center bolt hole, is inserted in the top hole to provide a recess for the bolt disk springs and hold-down nut. A stainless steel cylindrical block, drilled and tapped, is inserted in the bottom hole. A 0.375-in. dia bolt is passed through the hole in the LiH block, threaded into the top of the bottom cylinder, and preloaded by the disk springs and nut at the top. During assembly, the block is fastened to the support shelf by a special flat head 0.375-in. dia screw which is threaded into the bottom of the block cylinder through the shelf. The flat head of the screw is countersunk flush into the shelf. The screw is tack-welded for positive fastening on internal shelves and seal welded on exterior can surfaces.

Gamma Shielding

The lead shield layer located between the two LiH neutron shield layers of each removable shield section is provided to attenuate gamma radiation. Both the location and thickness of the lead have been determined on the basis of providing maximum shielding effectiveness consistent with minimum weight and size of the removable shield. The lead thickness is shaped to match the secondary gamma source strengths in interior regions. Geometrical shaping has been established to provide an approximately uniform thickness of inner LiH neutron shielding. At the bottom, the right circular cylinder geometry has been preserved to permit the lead to act as a structural column.

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housings. Each inner LiH can housing of the half and quarter sections is connected by 0.50-in. OD $\times$ 0.022-in. thick wall tubing through the lead column to its respective outer LiH can. The outer can is vented to atmosphere by a spring-loaded pressure relief valve.

At the reactor core midplane, the fixed half section can housing circumscribes an arc of 177° . It has an inside diameter of 37.66 in. and an outside diameter of 102.75 in. The inner and outer faces are connected by flat end plates, at an angle of 1.5° with respect to station line 500, intersecting the inner edge of the quarter section hinge column. These end plates are stepped to provide a minimum offset equal to twice the thickness of the radiation streaming path as formed by the plates plus thermal expansion voids. At the outer edge, the plates are stepped radially inward to form a chase for the hinge column and hinges of the Package I structure. This permits opening the quarter sections through an angle of 31° , without interference at the outer corners of the adjacent sections.

Housings for the two quarter sections are mirror images of each other for left and right side installation. Each circumscribes an arc of 91.5° . The inner and outer faces are connected by flat end plates along the longitudinal axis of the skid at buttock line 00.0, and along the lateral axis at an angle of 1.5° with respect to station line 500. The buttock line 00.0 end plates match the contour of the primary piping shield segment described in Volume III and the main primary coolant lines extending outside of this segment. An axial and horizontal chase is also provided directly on buttock line 00.0 for the forced convection afterheat coolant lines. The station line 500 plates are stepped to mate with the end plates of the fixed half section. They are also stepped inward to form a chase for the hinge column of the Package I structure.

The outer can surfaces for all three sections are tapered conically at the bottom from an OD of 102.75 to 83.43 in. The taper starts at an elevation of WL 124.75 in. A flat plate is used to seal the bottom of the can housings. A portion of the bottom plate of the fixed half section is raised 0.25 in. along buttock line 00.0 to provide clearance for the Package II skid structure when the packages are assembled. The quarter section bottom closure plates are located 0.25 in. above the Packages I and II skid platforms to provide clearance for movement of these sections as they open and close. Tapped bearing plates welded to the can housing of the quarter section are provided for bolting the guide rollers in place.

The can housing for the inner LiH shield layer is low cobalt-type 304 stainless steel while that for the outer layer is type 5652-0 aluminum. Stainless steel is used in the inner layer due to the relatively high LiH operating temperature of 544°F , while aluminum is used to can the lower

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temperature outer region to reduce the contribution to the operating dose of secondary gamma rays produced in the structural material. Minimum thickness materials have been used, to be consistent with the Nuclear Materials Design Criteria presented in the appendix. All penetrations into the outer surfaces of the can housing are seal welded. The material of the penetrating members is the same as that of the can housing at the points of penetration.

The shelves on which the LiH blocks are supported are welded to the cladding of the lead on one edge and supported from the shield can housing on the other edge by means of tabs. The tabs penetrate machined slots in the can housing and are seal welded. The slots on the inner face of the shield housing, adjacent to the fixed shield, are recessed to be flush with the shield face.

The shelves in the outer LiH layer have right angle steps at the junction point of the two horizontal rows of LiH blocks. These steps are 0.62-in. thick, twice as deep as the sum of the thickness of the 0.18-in. type 5652-0 aluminum shelf plus the maximum 0.125-in. clearance gap between the LiH and the adjacent shelf. No step is provided in the inner LiH neutron shield shelves, but the shelves in the inner layer are staggered in elevation with respect to the location of the shelves in the outer shield layer. Holes are provided in the shelves in areas of low stress to save weight.

Vertical support plates of 0.19-in. 5652-0 aluminum are used in conjunction with the end plates to tie the shelves and cans into an integral structural unit. This unit then supports the shielding materials and transmits the loads to the Package I structure.

The support plate in the fixed half section is located on buttock line 00.0 and those in the quarter sections are at an angle of 61° with respect to buttock line 00.0. The inner edges of the plates are welded to the cladding of the lead. Where they penetrate the outer can housings, they are seal welded. The fixed half section vertical support plate extends out and is bolted to the underbody of the skid structure. The quarter section plates are joined to the end of the Package I structure at the turnbuckle housing columns.

Attachment of the fixed half section to the Package I structure is made by welding the outer can housing to the truss hinge columns and bolting the vertical support plate to the underbody. Transport tiedowns are made to an external shelf, which is welded to the skin of the fixed half section at elevation WL 144, 44 in. above the bottom of the Package I skis, and bolted to the skid through gussets. This height corresponds to the elevation of the third horizontal shelf (counting from the lower plate), located approximately in line with the center of gravity of the removable shield assembly.

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The quarter section tie downs are made to tie plate attachments within the shield canning straddling buttock line 00.0. These 5652-0 aluminum plates are an integral part of the outer can housings. They are 1.00-in. thick, 12-in. long, 12-in. high, and are welded to the vertical buttock end plates. The tie plates are located between the aluminum shelves at the approximate elevations of WL 132 and 144 in. These two shelves and a third intermediate shelf are 0.38-in. thick between the vertical end plates and the vertical support plates. The tiedown bracket support plates are drilled and tapped from the outside of the can housing to permit attachment of a tiedown bracket for fastening the tiedown ropes and chains during transport without disturbing the hermetic seal of the LiH can housings.

Twenty 0.25-in. dia stainless steel coolant tubes piped in parallel from headers at the bottom and top of the inner LiH shield layer are installed inside the inner can housing to remove the heat generated in the inner LiH shield of the fixed half section. Each quarter section contains eight of these tubes. The faces of the inner LiH blocks are milled with slots for these tubes. The coolant piping external to the shield assembly is routed through vertical and horizontal chases in the can housings back to the coolant system installed aft of the fixed half section. A recess is provided in the outer housing of the fixed half section for installation of the 18-in. dia coolant expansion tank. The organic coolant in this tank provides fast neutron shielding approximately equivalent to that of the LiH which it replaces.

SHIELD ASSEMBLY

The removable shield is fabricated as three separate sections. After assembly of the individual sections, they are installed on the Package I structure (also fabricated separately) and are welded and bolted in place. The internal assembly of the fixed half section is shown in Figure 2-11 and that of the quarter sections in Figure 2-12.

All structural parts of the removable shield sections are prefabricated and machined prior to assembly. The lead cladding cylinders including the coolant tubes and headers, vertical support plates, segments of the two end plates (including all of the stainless steel on one side of the riveted joint and 2.5 in. of the aluminum on the other side as shown in Detail 1 of Figure 2-11), and all the LiH block support shelves are preassembled as a single welded assembly on the bottom plates. A ± 0.03 -in. tolerance will be held on all surfaces. The lead is then cast into its clad housing after preparation of the surface to ensure a metallurgical bond. Special jigs and fixtures will be used in conjunction with the welded shelves to hold a ± 0.03 -in. radial tolerance. The loading of the LiH is then performed in a controlled dry atmosphere. Machined inner and outer LiH blocks, compressively preloaded through the tiedown bolts, are located and bolted to support shelves. Bolting is through the support shelves; therefore, the sequence of

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loading will start from the top shelf. LiH blocks in the inner layer are loaded radially. The inner row of LiH blocks in the outer layer is loaded circumferentially from either end to the vertical support plate due to the stepping of the shelf to minimize radiation streaming. With the inner row installed, the outer row is loaded radially. After all LiH blocks are in place, the inner stainless steel can housing, with the attached coolant tubes and headers, is carefully fitted to the blocks which have been slotted for the tubes. This face is then hermetically seal welded to the end and bottom plates. Similarly, the outer aluminum end plates are completed by butt welding the end pieces to the segments initially welded to the lead cladding. The outer can housing is then positioned and seal welded to the end, bottom, and vertical support plates. Typical housing closure welds are shown in detail in Figure 2-11.

Each shelf has four 4-in. wide extension tabs that protrude through machined slots in the outer can faces. These tabs are used to support the outer edges of the shelves on the can housing. The canning face at these slots is recessed to permit 5.5-in. long stainless steel, oblong washers to fit over the tabs flush with the face. The washers are then seal welded both to the face and to the tabs. After welding, the tabs are ground flush with the face.

With the fixed half section can housing welded and assembled, the four aluminum instrument thimbles are inserted into the shield; these thimbles are guided by sleeves in the lead column and holes through the support shelves. The thimbles are supported from the outer can housing and seal welded at the point of penetration. The cans are then filled with a dry inert cover gas at 1-atm pressure.

Appendages to the quarter sections external to the can housing, such as the clamps straddling buttock line 00.0 and the guide rollers at the bottom, are bolted in place after the internal assembly is complete.

TEMPERATURE DISTRIBUTION

During reactor operation at 15 Mw_{th}, the total heat generation in the removable shield is 117.2 kw, or 400,200 BTU/hr. The volumetric heat deposition rate versus radial position in the lead layer of the fixed shield and the inner lithium hydride layer of the removable shield is presented in Figure 2-13. Essentially all of the heating takes place in the inner LiH neutron shield layer with only 1000 BTU/hr in the lead layer and 1940 BTU/hr in the outer LiH layer. In addition, there is a relatively small addition of 1000 BTU/hr at the inner faces of the quarter sections due to heat conduction from the primary coolant pipes.

Figure 2-13. Radial internal heat generation of reactor core midplane—inner shield layers—full power operation.

The total heat load of 401,200 BTU/hr is transferred from the removable shield by the organic shield coolant system. On a standard day with 59°F temperature, at sea level, the organic liquid enters the shield coolant headers at 235°F; it exits from the inner LiH layer at 265°F and from the lead layer at 255°F. Coolant flow in each of the 36 parallel coolant tubes of the inner LiH layer is 0.116 lb/sec flowing at a velocity of 8.7 ft/sec with a total header-to-header pressure drop of 6.8 psi. Coolant flow in each of the 25 parallel coolant tubes of the lead layer is 0.17 lb/sec flowing at a velocity of 5.5 ft/sec with a total pressure drop of 2.4 psi from header to header. The maximum temperature in the LiH is 544°F, peaking at 3 in. from the inner face closest to the reactor. The maximum temperature in the lead is 305°F. The temperature distribution across the removable shield assembly is shown in Figure 2-14.

STRESS ANALYSIS

The shield assembly structure is designed integral with that of Package I. The lead shield cladding is used as a principal structural column. The LiH can housings, support shelves, end plates, and vertical support plates are used to stiffen and distribute loads to the skid truss members. In addition to the static and dynamic loads, the LiH housings are designed to withstand pressure differentials with respect to ambient that will occur during operation of the MCR from below sea level to 8000-ft altitudes. All structural members were designed on the basis of the procedures and allowable material physical property limitations specified in the MCR Structural Design Criteria. A summary of the component member sizes, loading conditions for which they were analyzed, calculated maximum stress, and allowable maximum stress is presented in Table 2-XIV. Shock loadings to be encountered in all modes of transport were considered and the design of each component was based on the condition resulting in a maximum stress.

Pressure Differential

During operation the gas pressure within the LiH can housings will vary as a function of the gas generation due to:

- The $\text{Li}^6 (n, \alpha)$ reaction resulting in the formation of He and H_3 plus the release of H_2
- The operating temperature
- The change in physical volume as a result of the differential thermal expansion between the LiH and the aluminum and steel canning materials.

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Figure 2-14. Radial temperature distribution at reactor core midplane—fixed and removable shield—full power operation.

Table 2-XIV.

Removable shield structural analysis, half section and quarter section.

Structural member	Loading condition	Design thickness (in.)	Calculated maximum primary stress (psi)	Allowable stress	
				Value (psi)	Basis
SS inner can housing	Pressure (± 7 psi)	1/16	2,100	12,000	$0.66\sigma_{\text{yield}}$ at 500°F
SS inner bottom plate	Pressure (± 7 psi)	5/32	11,450	12,000	$0.66\sigma_{\text{yield}}$ at 500°F
SS inner bottom plate	Internal pressure plus vertical shock loading (5.5 g)	5/32	14,570	16,000	$(0.66\sigma_{\text{yield}}$ at 500°F) 1.33
Al outer bottom plate	Pressure (± 7 psi)	3/8	4,500	5,400	$0.66\sigma_{\text{yield}}$ at 300°F
Al outer bottom plate	Internal pressure plus vertical shock loading (5.5 g)	3/8	5,700	7,200	$(0.66\sigma_{\text{yield}}$ at 300°F) 1.33
SS end plate	Pressure (± 7 psi)	3/16	8,000	12,000	$0.66\sigma_{\text{yield}}$ at 500°F
Al end plate	Pressure (± 7 psi)	5/16	5,100	5,400	$0.66\sigma_{\text{yield}}$ at 300°F
SS LiH support shelf	Vertical shock loading (5.5 g)	1/8	4,700	44,500	$0.66\sigma_{\text{ultimate}}$ at 500°F
Al LiH support shelf	Vertical shock loading (5.5 g)	3/16	13,600	14,200	$0.66\sigma_{\text{ultimate}}$ at 300°F
Outer Al can housing	Pressure (± 7 psi)	1/4	1,300	5,400	$0.66\sigma_{\text{yield}}$ at 300°F
Al shelves at forward tie down	Aft shock (4.0 g)	3/8	3,550	3,600	$\frac{1.33}{2} (0.66\sigma_{\text{yield}}$ at 300°F)
Al facing plate for forward tie down	Aft shock (4.0 g)	1.0	7,200	7,200	$(0.66\sigma_{\text{yield}}$ at 300°F) 1.33
Vertical support plate aft tie down	Forward shock (4.0 g)	3/16	7,200	7,200	$(0.66\sigma_{\text{yield}}$ at 300°F) 1.33
Al cladding of lead	Differential expansion, thermal stress	1/8	3,520	16,300	$2(\sigma_{\text{yield}}$ at 300°F)
SS cladding of lead	Differential expansion, thermal stress	1/16	37,800	44,000	$2(\sigma_{\text{yield}}$ at 300°F)
Lead	Differential expansion, thermal stress	3.37	743	750	$2(\sigma_{\text{yield}}$ at 300°F)

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In addition, the ambient pressure over the environmental range in which the MCR is expected to operate will vary between 10.56 psia, at an altitude of 8000 ft, to 15.4 psia below sea level. Design of the can housings to meet the maximum pressure differential range that would be encountered would result in excessively thick walls, causing increased structural weight plus a dose rate penalty due to increased secondary gamma production. To alleviate this problem all compartments of the removable shield are interconnected to a spring-loaded pressure relief system set to bleed the gas at a pressure in excess of 7 psi with respect to ambient. This maximum pressure setting also ensures a maximum negative differential pressure of 7 psi over the ambient temperature range as discussed in the following paragraphs.

The average gas temperature in the LiH housings will range from -65°F at shutdown to approximately 225°F during full power operation on a 125°F day. This change in gas temperature for a constant volume system results in a pressure swing of 73%. However, the temperature change is also accompanied by a change in gas volume due to the difference in the coefficient of thermal expansion of the LiH, 11.2×10^{-6} in./in. °F, as compared to that of aluminum housing material, 13.2×10^{-6} in./in. °F. At the maximum temperature variation of 290°F, the change in volume is approximately 20% based on an assumed average tolerance gap between adjacent surfaces of one-half the maximum tolerance stack-up possible. Therefore, with the removable shield fabricated and assembled at an ambient temperature of 70°F, a rise in temperature on the first cycle would result in a gas bleed to maintain a maximum positive pressure differential of 7 psi with respect to ambient. On shutdown the internal gas pressure would fall to 48% of the maximum resulting in a negative pressure with respect to ambient. The lowest positive pressure will exist at 8000-ft altitude, 10.56 psia ambient pressure, plus 7 psi. The lowest negative pressure, 8.5 psia, will also exist at this altitude. It has been assumed that the MCR could then be transported at its lowest temperature to below sea level, ambient pressure 15.4 psia. Since the system is hermetically sealed the internal housing pressure will remain constant resulting in the maximum negative pressure differential of 7 psi. The range of pressures with respect to ambient, at all altitudes, for both operating and shutdown shield temperatures, is summarized in Table 2-XV.

The maximum source of gas generation is the inner LiH layer of the removable shield. Over a period of 25,000 full power hours of operation, 8.4 ft³ of tritium (H₃), 16.7 ft³ of helium (He), and 8.4 ft³ of hydrogen (H₂) will be generated. If released from the LiH matrix, this gas will be bled to the atmosphere through the pressure relief system should the housing pressure exceed 7 psi with respect to ambient.

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Table 2-XV.

Removable shield can housing pressure differentials.

Housing internal pressure (psia)		Ambient pressure and altitude	Maximum positive pressure differential	Maximum negative pressure differential
Operating	Shutdown		(psi)	(psi)
17.65	8.5	10.56 psia at 8000 ft	7	2.15
21.7	8.5	14.7 psia at sea level	7	6.2
22.5	8.5	15.4 psia below sea level	7	7.0

Internal Structure

The removable shield internal structure is designed to:

- Resist horizontal and vertical shock loads
- Resist loads due to tiedown during transport
- Provide attachment to the Package I skid structural members

The fixed half section is supported on Package I and its load is transmitted to the skid at the two end plates and the vertical support plate welded to the outer cladding of the lead shield layer. The end plates each carry about one-third of the shield load to the skid truss hinge columns located directly over the line of the skid elastomer shock mounts. The vertical support plate transfers the balance of the loading to the skid structure. Both the end plates and the support plate are fastened to the Package I skid structure.

Each quarter section is supported on the Package I skid. The loads are transmitted to the skid at the end plate attached to the hinge column and the vertical triangulated support plate welded to the outer cladding of the lead shield layer. About one-half of the quarter section shield load is carried by the end plate to the hinge column. The remainder of the shield load is carried by the vertical support plate to the turnbuckle column end of the Package I skid truss. During operation and transport with the shield fully assembled, this column end is bolted to the skid structure directly over the line of the skid elastomer shock mounts. When the quarter sections are rotated during assembly and disassembly of Packages I and II, the quadrants are cantilevered from the hinge column. A bearing plate on the skid underbody limits the vertical deflection of the quarter sections to 30 mils during rotation and when locked together.

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The limiting design stresses result from the horizontal 4-g shock loading during transport, as shown in Table 2-XIV, rather than the static support loadings. Some of the tiedown ropes anchoring the shield to the transport vehicle are attached to the fixed half section at the projecting tie shelf, located approximately in line with the shield center of gravity. This location permits a direct reaction to the inertial forces of the shield due to horizontal shock loads, without introducing additional eccentric loadings. Maximum stress in the vertical support plate as a result of the tensile force under the 4-g forward shock load is 7200 psi, approximately 87% of the aluminum yield strength at 300°F.

The tiedown ropes for the quarter sections are attached to a tiedown bracket straddling buttock line 00.0 which is bolted to matching tie plates in both the quarter sections. The tie plates bridge the second and third LiH support shelves and are further braced by an intermediate shelf located mid way between the first shelves. When Packages I and II are separated and the quarter sections are closed for transport, the tiedown bracket is attached to the shield. Inertial forces of the shield are transmitted directly to the tiedowns through the internal shelves and tie plates which are located approximately in line with the shield center of gravity. The maximum tensile stress in the tie plate is 7200 psi under the 4-g aft shock load, which is approximately 87% of the aluminum yield strength at 300°F.

Maximum stress in the shelves is a shear stress occurring at the opening in the quarter sections to accommodate the support column for the primary piping shield segment. The shelves in this area were thickened from 1/8 to 3/8 in. to limit the stress to 3500 psi, approximately 43.5% of the aluminum yield strength.

The support shelves for the LiH blocks were designed to withstand a 5.5-g vertical shock load. Deflection in the shelves is limited to the clearances between the bottom of the shelf and the top of the LiH block below. Since the shelves are stacked vertically, it was assumed that this deflection could be additive with the maximum deflection and bending stress occurring in the top shelves. This stress is calculated to be 4700 psi for the 1/8-in. stainless steel shelves and 13,600 psi for the 3/16-in. aluminum shelves, both below 66% of the ultimate material strength at 500 and 300°F, respectively.

The total shelf load due to bottoming of the loaded shelves is taken on the bottom plates of the housing. The combined stress in these plates due to the shelf load plus the maximum differential gas pressure is 22,800 psi in the 5/32-in. stainless steel bottom plate of the inner LiH shield layer and 5700 psi in the 3/8-in. aluminum plate of the outer LiH shield layer. Both values are less than 87% of the material yield strength.

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The shield housings including the end plates were designed for an internal and external differential pressure of 7 psi at operating temperatures. Thicknesses as shown in Table 2-XIV were selected to maintain the calculated stress (hoop or buckling) below 66% of the material yield strength.

The lead shield layer is clad in two different materials: stainless steel at the inner face, and aluminum at the outer face, joined by rivets. The lead is metallurgically bonded to the cladding to permit composite action of the lead and clad materials in resisting the various forces acting in the shield. Stresses resulting from static and dynamic shock loads are relatively small: 150 psi in the stainless clad, 50 psi in the lead, and 200 psi in the aluminum. These are all well below 87% of the material yield strength. Thermal stresses in the stainless steel and aluminum as a result of the differential thermal expansions between the cladding and lead are 37,800 psi and 3520 psi, respectively. For each material, thermal stresses are less than twice yield strength. These stress values will permit repetitive cycling without failure since, after the first few cycles with plastic strain of the aluminum, the stresses will be within the elastic envelope during subsequent cycles. Compressive stress in the lead is 743 psi, which is also below twice its yield strength at 300°F.

INSTRUMENTATION

Four instrument thimbles, each containing two neutron detectors mounted on a preassembled fixture, penetrate the fixed half section of the removable shield. In addition, a thermowell is installed in the lead layer of each of the shield segments. Both the instrument thimbles and thermowells are seal welded to the can housing at the point of penetration. They are designed as integral parts of the shield assembly as shown on the drawing of the removable shield half section internals, Figure 2-11. However, the instruments within these penetrations are readily accessible for maintenance or replacement as may be required. Two additional detectors are located on Package II just outside the removable shield to monitor shutdown level.

Instrument Thimbles and Neutron Detectors

The four instrument thimbles are spaced 30° apart where they penetrate the fixed half section at the top of the outer can housing. They extend through the shield at an 18° angle with respect to vertical and terminate at the inner face of the inner LiH shield layer housing at an elevation of 7 in. below the core midplane. The thimbles are fabricated of 0.06 and 0.12-in. type 5652-0 aluminum, 3.75-in. OD at the inner end and stepped to 5.25-in. OD at the outer end. They are supported and seal welded at the outer can housing of the shield and guided through the shield layers by sleeves through the lead layer and holes machined in the LiH blocks and support shelves.

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The voids in the instrument thimbles are filled with organic coolant which replaces the displaced LiH neutron shielding. The organic is circulated to remove the heat generation due to neutron and gamma attenuation in the coolant, in the detectors, and in the gamma shield plugs located within the thimbles. The total heat generation in each of the four instrument thimbles is 1075 BTU/hr which is removed by a flow of 0.122 lb/sec of coolant through each thimble.

Coolant for the thimbles is bypassed from the exit line of the fixed half of the removable shield to a common header at 260°F. The four thimbles are piped in parallel for first in-last out coolant flow. Inlet to each thimble is through a tube penetrating the top closure plate and extending the full thimble length to the bottom of the thimble. Coolant from this tube flows up through the thimble, exiting at the top at 266°F to the return header.

Neutron Detector Assembly

Each instrument thimble is provided with a neutron detector assembly as shown in detail 6 of Figure 2-11, which locates the source/power range detector and the intermediate range detector within the thimble. The assembly permits the replacement of a malfunctioned detector.

The neutron detector assembly is a rigid structure which consists of the cover plate, intermediate range detector support structure, lead shield plug, and the source/power range detector support cylinder. The cover plate is bolted to the thimble flange. A metal O-ring is provided for hermetic sealing.

The intermediate range detector support structure consists of three tubular rods which fix the shield plug to the cover plate and two disk clamps. The detector is held between the two disks which are mounted on the tubular rods. The disks can be moved along the rods so that the detector position can be varied by approximately 9 in. to achieve the designed flux level. Once the proper location has been determined the disks can be pinned to the support rods.

The source/power range detector is contained in a perforated cylindrical can which is bolted to the shield plug. To permit flux level adjustment this detector can be moved approximately 5 in. within the cylinder, in 1/2-in. increments, using spacer rings. The detector is compression loaded by a steel spring to maintain its position under the design shock loads.

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Neutron Detectors

Estimated neutron detector MTBF values.

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The outline specifications for the neutron detectors are summarized in Table 2-XVII.

Table 2-XVII.
Neutron detector outline specification.

Function	To monitor power level and start-up rate for control and protective functions
Type	Dual range, uranium-coated (~ 90% U-235) fission counter/chamber
Quantity	8
Operating temperature	-65 to 300°F
Pressure range	Essentially atmospheric
Coolant fluid	Monoisopropylbiphenyl
Power level range	See Detector Application entry in this table
Materials	
Body	Aluminum (2s)
Insulators	Mica and alumina
Coating	U-238 enriched to ~ 90% U-235
Filling gas	Argon and nitrogen (1 atm)
Operation characteristics	
Insulation resistance	$>10^{12}$ ohm at 70°F
Voltage	800
Output, pulse	100 μ v with $<0.2 \mu$ sec rise time
Counter sensitivity	0.7 cps/thermal nv
Chamber sensitivity	1.4×10^{-13} amp/nv
Gamma sensitivity	2.2×10^{-11} amp/R/hr
Cables	
Within thimble	Rigid mineral-insulated cables
Outside thimble	Flexible mineral-insulated cables

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Table 2-XVII. (cont)

Installation	Four neutron detector thimbles are installed in the removable shield structure. Each thimble houses two detectors (one intermediate range and one source/power range detector) which are mounted in a neutron detector assembly
Size	Detector 3-1/16-in. OD $\times$ 13-1/2-in. long
Weight	
Detector	5 lb each—total, 40 lb
Rigid mineral-insulated cable	3 lb/assembly—total, 12 lb
Flexible mineral insulated cable	10 lb/assembly—total, 40 lb
Assembly	35 lb/assembly—total 140 lb
Design life	75,000 thermal megawatt hours or 8000 operational hours, whichever is less

<u>Detector application</u>	<u>Power level range (%)</u>	<u>Output range</u>
Source range	10^{-8} to 5×10^{-3}	1 to 5×10^5 cps
Intermediate range	5×10^{-5} to 25	1 to 5×10^5 cps
Power range	0.1 to 150	6.3×10^{-7} to 9.5×10^{-4} amp
Shutdown (shield in place)	10^{-2} to 200	1 to 2×10^4 cps
Range (shield removed)	10^{-9} to 2×10^{-5}	0.1 to 2×10^3 cps

Temperature Measurement

A 1/4-in. OD $\times$ 0.031-in. wall aluminum thermowell is installed in the lead layer of each of the shield segments. The thermowells are cast into and metallurgically bonded to the lead. The thermowells enter the shield layer through the end plates along station line 500 and are seal-welded to the end plate. The end external to the shield housing is threaded to permit installation and securing of the thermocouples by means of a compression fitting. The outline specifications for the thermocouples are given in Table 2-XVIII.

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Table 2-XVIII.

Shield structure thermocouples outline specifications.

Function	To monitor shield structure lead region temperatures for indication and alarm functions
Type	Thermowell inserted, chromel-alumel thermocouples with swaged stainless steel sheathing
Quantity	7
Operating temperature	-65 to 600°F
Operating pressure	Atmospheric
Fluid	Air
Sheath material	Type 316 stainless steel
Sheath OD	0.125 in.
Sheath thickness	0.012 in.
Thermocouple material	Type K, chromel-alumel
Thermocouple junction	Grounded
Thermocouple wire size	22 gage, (0.025-in. dia)
Thermocouple length	See Table 2-XIX
Wire termination	See Table 2-XIX for type
Type A	Bare thermocouple leads 6-in. long. Open end of insulation sealed with epoxy cement.
Type B	Thermocouple connected to flexible chromel-alumel lead wire in stainless steel adapter housing. Adapter housing welded to thermocouple sheath. Connection secured by strain harness and encapsulated in moisture-proof potting compound. Adapter spring connected to lead wire. Lead wire insulated with silicone impregnated glass braid with overall jacket of flexible stainless steel braid. Lead wire termination shall be bare leads 6-in. long. Open end of insulation sealed with epoxy cement

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Table 2-XVIII. (cont)

Insulation	Magnesium oxide. Purity greater than 99.4% with boron plus cadmium content less than 30 ppm; sulphur content less than 50 ppm; carbon content less than 30 ppm.
Insulation resistance* (wire-to-wire, sheath-to-wire)	
At room temperature	$>10^{11}$ ohm-ft at 500 v dc
At 1000°C	$>5 \times 10^4$ ohm-ft at 50 v dc
Installation	Thermocouples are inserted into thermowells and secured with a compression fitting. Type "B" wire termination will be provided at the compression fitting for the removable shield quarter section thermocouples. Banding at intermediate points will be required for support.
Thermowell construction	Closed type
Thermowell material	Aluminum
Thermowell OD	0.250 in.
Thermowell wall thickness	0.031 in.
Thermowell length	See Table 2-XVII
Thermowell connection	1/4-in. NPT—female
Weight	2.1 lb total (does not include banding or thermowells)
Design life	25,000 hr

*Prior to fabrication of junction.

Pressure Relief and Measurement

Control of the pressure within the can housings of the LiH shield layers is maintained by means of a pressure relief valve with a set pressure of 7 psig. The relief valves are shown in Figure 2-3. The outline specifications for the valve are summarized in Table 2-XX.

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Table 2-XIX.
Shield structure thermocouple tabulation.

<u>Parameter</u>	<u>Number installed</u>	<u>Wire termination</u>	<u>Sheath (ft)</u>	<u>Well (in.)</u>	<u>Flexible leads (ft)</u>	<u>Weight (lb)</u>
Radial shield Pb temp	2	A	12	6	—	0.4
Pipe penetration shield Pb temp	1	A	12	6	—	0.4
Top plug shield Pb temp	1	A	12	12	—	0.4
Removable shield half section Pb temp	1	B	4	4	8	0.3
Removable shield quarter section No. 1 Pb temp	1	B	4	4	8	0.3
Removable shield quarter section No. 2 Pb temp	1	B	4	4	8	0.3

Table 2-XX.
Shield LiH container relief valve outline specifications.

Function	To prevent overpressurization of the shield LiH containers in both the fixed top plug and the removable shield
Type	Mechanically operated, balanced, self-actuated, and self-contained
Quantity	2
Fluid	Gas mixture (A, He, H ₂ , H ₃)
Operating temperature	-65 to 200°F
Design temperature	500°F
Operating pressure	-7 to 7 psi
Design pressure	125 psig
Set pressure	7 psi

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Table 2-XX. (cont)

Set pressure tolerance	$\pm 3\%$
Back pressure	Atmospheric
Seat leakage	Maximum of 1×10^{-6} atm cc/sec helium to 95% of set pressure
Envelope leakage	Maximum of 1×10^{-8} atm cc/sec helium
Line size	1/4 in.
End connections	1/4-in. OD prepared for butt welding
Body materials	Stainless steel
Dimensions	1-in. OD $\times$ 1-3/4-in. long
Weight	0.5 lb
Relieving rate	1 SCFH

Pressure gages and transducers are also provided to measure the pressure and monitor the integrity of the hermetically sealed LiH can housings. The outline specifications for the pressure gages and pressure transducers are given in Tables 2-XXI and 2-XXII.

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Table 2-XXI.

Shield LiH container pressure gages outline specifications

Function	To monitor shield lithium hydride container pressure
Type	Bourdon tube gage with safety back
Quantity	2
Operating temperature	-65 to 300°F
Pressure range	-7 to 7 psig
Fluid	Gas mixture (A, He, H ₂ , H ₃)
Gage size	2-1/2 in. nominal
Pressure element	Type 316 stainless steel Bourdon tube socket welded to 316 stainless steel socket
Gage case and dial	Drawn steel case, silver dial with black numbers
Connection	1/4 in. OD pipe stub prepared for butt welding
Installation	Gages are welded to container vent line upstream of relief valve
Overall size	2.8-in. OD × 1.25-in. deep
Weight	0.5 lb each, 2 total
Design life	25,000 hr
Service	Fixed shield LiH container vent line Removable shield LiH container vent line

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Table 2-XXII.

Shield LiH container pressure transducer outline specifications.

Function	To monitor shield LiH container pressures in both the fixed and removable shields.
Type	Diaphragm—linear voltage differential transformer pressure transducer
Quantity	2
Operating temperature	-65 to 200°F
Pressure range	± 7 psig
Fluid	Gas mixture (A, He, H ₂ , H ₃)
Materials in contact with fluid	Stainless steel
Proof pressure	150% of full scale
Burst pressure	300% of full scale
Accuracy	~2% of full scale over operating temperature range
Signal output	100 mv dc full-scale from translator
Excitation frequency	10 kc
Installation	Transducers are welded to container vent line upstream of relief valve
Size	1-1/2-in. OD × 3-in. long (excluding cables)
Weight	2 lb per transducer (includes 12 ft of cable)—10 lb total
Design life	25,000 hr

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Shield Coolant System

The shield coolant system maintains the temperature of all the shield components below the design temperature limits, both during operation and after reactor shutdown, before Packages I and II are separated. Heat generated in the shield as a result of neutron and gamma radiation attenuation as well as that conducted across the insulation from the reactor and primary system piping is removed by the shield coolant system and dissipated to the ambient air by a heat exchanger. In addition, the organic coolant serves the dual purpose of cooling and providing fast neutron shielding in the voids of the instrument thimbles.

DESCRIPTION

The coolant system is a forced flow loop rated at 628,000 BTU/hr for a coolant flow rate of 12.79 lb/sec. The coolant fluid is monoisopropylbiphenyl, an organic liquid. Its chemical composition and physical properties are summarized in the organic shield coolant design criteria presented in the appendix. The heat loads on the shield coolant system are summarized in Table 2-XXIII.

Table 2-XXIII
Shield coolant system heat loads.

<u>Component</u>	<u>Neutron and gamma attenuation (BTU/hr)</u>	<u>Conduction (BTU/hr)</u>	<u>Total (BTU/hr)</u>
Fixed shield			
Radial shield	16,700	17,100	33,800
Top shield plug	57,400	2,700	60,100
Bottom shield plug	89,000	2,700	91,700
Primary piping shield segment	32,000	3,200	35,200
Control drum drives	---	6,000	6,000
Removable shield			
Half shield	211,500	---	211,500
Quarter sections—(2)	184,400	1,000	185,400
Instrument thimbles—(4)	4,300	---	4,300
Total	595,300	32,700	628,000

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The coolant system, as shown schematically on Figure 2-15, is subdivided into a number of parallel-series flow paths. The legend used in this diagram is given in Figure 2-16. Coolant routing was determined on the basis of minimizing coolant flow rate requirements, pressure drops, and pumping power; maintaining a maximum coolant temperature below 325°F; and the physical arrangement of the shield sections to be cooled. From the discharge of the main coolant pump, the coolant enters the shield at a flow rate of 46,044 lb/hr and at a maximum temperature of 274°F for an ambient temperature of 96°F at an 8000-ft altitude. At sea level on a standard 59°F ambient temperature day with the MCR at 15 Mw_{th} full power operation, the coolant inlet temperature is 235°F. Flow rates, heat loads, and temperatures for each of the flow paths shown on Figure 2-15 are based on the latter standard day operating conditions, and are presented in Table 2-XXIV.

The total flow through the various shield sections exits into a common return header at 265°F. It is then cooled in a cross flow, forced air, finned tube heat exchanger, exiting at 235°F on a standard day (274°F maximum on a 96°F ambient day at 8000 ft). The cooled organic flows through a large storage capacity expansion tank. This tank provides a large surface-to-gas ratio and permits the gases dissolved in the liquid to reach equilibrium with the partial pressure of the gases in the air space above. Degassed coolant is then routed from the bottom of the expansion tank to the coolant pump inlet. System pressure drop at maximum flow is 41 psi.

Each of the main coolant pumps and heat exchanger fans is paralleled with 100% capacity standby units for system reliability. On failure of either operating unit, the standby unit will be automatically started by the control system.

After shutdown, the removable shield does not require any cooling. Cooling, however, is required for the fixed shield if Packages I and II are not decoupled immediately after shutdown. This cooling must be maintained until the skids are decoupled when natural convection can provide adequate cooling of the radial portion of the fixed shield, or until the reactor vessel temperature falls below 500°F. If reactor shutdown was caused by a shield coolant system malfunction, damage to the fixed shield can be prevented by the prompt decoupling of Package I. With Package I decoupled, the combination of thermal heat capacity and natural air convection cooling is sufficient to prevent overheating of the fixed shield lead (due to heat conduction from the reactor vessel) throughout the afterheat removal period.

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Table 2-XXIV.
Shield coolant system flow data.

<u>Line number</u>	<u>Medium</u>	<u>Flow (lb/sec)</u>	<u>Temperature (°F)</u>
2 in. -P-701-1-AA	Organic	12.79	235
2 in. -P-701-2-BB	Organic	12.79	235
3/4 in. -P-701-3-BB	Organic	2.06	235
3/4 in. -P-701-4-CC	Organic	2.06	235
3/4 in. -P-701-5-BB	Organic	2.06	235
3/4 in. -P-701-6-BB	Organic	1.00	235
3/4 in. -P-701-7-BB	Organic	1.06	235
2 in. -P-701-8-BB	Organic	10.73	235
1 in. -P-701-9-BB	Organic	3.82	235
1 in. -P-701-10-EE	Organic	1.90	235
1 in. -P-701-11-EE	Organic	1.92	235
1 in. -P-701-12-DD	Organic	1.92	235
3/4 in. -P-701-13-DD	Organic	0.96	235
3/4 in. -P-701-14-DD	Organic	0.96	235
2 in. -P-701-15-BB	Organic	6.91	235
1 in. -P-701-16-BB	Organic	4.85	235
1 in. -P-701-17-BB	Organic	2.31	235
1 in. -P-701-18-BB	Organic	2.54	235
3/4 in. -P-701-20-BB	Organic	2.06	235
3/4 in. -P-701-21-CC	Organic	2.06	235
3/4 in. -P-701-22-BB	Organic	2.06	235
3/4 in. -P-701-23-BB	Organic	1.06	235
3/4 in. -P-701-24-BB	Organic	1.00	235
2 in. -P-702-1-AA	Organic	12.79	235
1 in. -P-703-1-BB	Organic	3.05	112
3/8 in. -P-704-1-EE through 15-EE	Organic	0.169	235-255
1 in. -P-704-16-BB	Organic	2.54	255
1/4 in. -P-704-17-EE through 36-EE	Organic	0.116	235-265
1 in. -P-704-37-BB	Organic	2.31	265
1 in. -P-704-38-BB	Organic	4.85	260
3/8 in. -P-704-39-BB	Organic	0.49	260
3/8 in. -P-704-40-AA	Organic	0.49	260

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Table 2-XXIV. (cont)

<u>Line number</u>	<u>Medium</u>	<u>Flow (lb/sec)</u>	<u>Temperature (°F)</u>
1/4 in. -P-704-41-DD through 44-DD	Organic	0.123	260
1 in. -P-704-45-BB	Organic	4.36	260
1-1/2 in. -P-704-46-BB	Organic	6.42	260
1-1/2 in. -P-704-47-BB	Organic	10.24	265
2 in. -P-704-48-BB	Organic	10.24	265
2 in. -P-704-49-BB	Organic	12.30	264
2 in. -P-704-50-AA	Organic	12.30	264
2 in. -P-704-51-AA	Organic	12.79	265
1/4 in. -P-705-1-EE through 8-EE	Organic	0.125	235-265
3/4 in. -P-705-9-BB	Organic	1.00	265
3/8 in. -P-705-10-EE through 14-EE	Organic	0.212	235-256
3/4 in. -P-705-15-BB	Organic	1.06	256
3/4 in. -P-705-16-BB	Organic	2.06	260
3/4 in. -P-705-17-CC	Organic	2.06	260
3/4 in. -P-705-18-BB	Organic	2.06	260
1-1/2 in. -P-705-19-BB	Organic	2.06	260
1/4 in. -P-706-1-EE through 8-EE	Organic	0.125	235-265
3/4 in. -P-706-9-BB	Organic	1.000	265
3/8 in. -P-706-10-EE through 14-EE	Organic	0.212	235-256
3/4 in. -P-706-15-BB	Organic	1.06	256
3/4 in. -P-706-16-BB	Organic	2.06	260
3/4 in. -P-706-17-CC	Organic	2.06	260
3/4 in. -P-706-18-BB	Organic	2.06	260
1/4 in. -P-707-1-EE	Air	0.02 scfm	40° dew point
1/4 in. -P-707-2-DD	Air	0.02 scfm	40° dew point
1 in. -P-708-1-EE	Organic	1.90	263
3/4 in. -P-709-1-DD	Organic	0.95	263
1/2 in. -P-709-2-DD through 4-DD	Organic	0.317	266
3/4 in. -P-709-5-DD	Organic	0.95	266
1/2 in. -P-709-6-DD through 8-DD	Organic	0.317	267
3/4 in. -P-709-9-DD	Organic	0.95	267
1/2 in. -P-709-10-DD and 11-DD	Organic	0.475	270
3/4 in. -P-709-12-DD	Organic	0.95	270
1/2 in. -P-709-13-DD through 15-DD	Organic	0.317	271

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Table 2-XXIV. (cont)

<u>Line number</u>	<u>Medium</u>	<u>Flow (lb/sec)</u>	<u>Temperature (°F)</u>
3/4 in. -P-709-16-DD	Organic	0.95	271
1/2 in. -P-709-17-DD through 19-DD	Organic	0.317	294
3/4 in. -P-709-20-DD	Organic	0.95	274
1 in. -P-709-21-EE	Organic	1.90	274
3/4 in. -P-709-22-DD	Organic	0.95	263
1/2 in. -P-709-23-DD through 25-DD	Organic	0.317	266
3/4 in. -P-709-26-DD	Organic	0.95	266
1/2 in. -P-709-27-DD through 29-DD	Organic	0.317	266
3/4 in. -P-709-30-DD	Organic	0.95	267
1/2 in. -P-709-31-DD and 32-DD	Organic	0.475	267
3/4 in. -P-709-33-DD	Organic	0.95	270
1/2 in. -P-709-34-DD through 36-DD	Organic	0.317	270
3/4 in. -P-709-37-DD	Organic	0.95	271
1/2 in. -P-709-38-DD through 40-DD	Organic	0.317	271
3/4 in. -P-709-41-DD	Organic	0.95	274
1/4 in. -P-710-1-DD through 11-DD	Organic	0.096	235-245
1/2 in. -P-710-12-AA	Organic	0.96	245
1 in. -P-710-13-DD	Organic	1.92	245
1 in. -P-710-14-EE	Organic	1.92	245
1/4 in. -P-711-1-DD through 11-DD	Organic	0.096	235-245
1/2 in. -P-711-12-AA	Organic	0.96	245
1 in. -P-712-1-EE	Organic	1.92	264
1 in. -P-712-2-EE	Organic	1.74	264
1/4 in. -P-712-3-EE	Organic	0.18	264
5/32 in. -P-712-4-EE through 13-EE	Organic	0.018	264-283
1/4 in. -P-712-14-EE	Organic	0.18	283
1 in. -P-712-15-EE	Organic	1.92	266
1 in. -P-712-16-BB	Organic	3.82	270
1/4 in. -P-713-1-DD	Organic	0.122	266
3/8 in. -P-713-2-DD	Organic	0.490	266
1/4 in. -P-714-1-DD	Organic	0.122	266

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Table 2-XXIV. (cont)

<u>Line number</u>	<u>Medium</u>	<u>Flow (lb/sec)</u>	<u>Temperature (°F)</u>
1/4 in. -P-715-1-DD	Organic	0.122	266
1/4 in. -P-716-1-DD	Organic	0.122	266
2 in. -P-717-1-AA	Organic	12.79	235
1/4 in. -P-717-2-DD	Air	0.02 scfm	Ambient
1/4 in. -P-717-3-EE	Air	0.02 scfm	Ambient
2 in. -P-718-1-AA	Organic	12.79	235
2 in. -P-718-2-AA	Organic	12.79	235
1 in. -P-718-3-AA	Organic	3.05	112
1 in. -P-718-4-AA	Air	—	—
1/8 in. -P-718-5-DD	Organic	0.001	265

To reduce the shield coolant system load on the APUs during shutdown with skids coupled, a small shutdown pump and fan are provided in parallel with the main units. A check valve isolates the fixed shield cooling channels from the removable shield cooling channels when the shutdown pump is energized. The shutdown cooling flow in the fixed shield is 3.05 lb/sec (~80% of the normal fixed shield coolant flow or 24% of the total shield coolant flow). While approximately 14% of the normal fixed shield coolant flow is required to satisfy the fixed shield heat conduction load (32,700 BTU/hr) the higher flow rate is provided to satisfy the organic coolant velocity design criterion. The power requirements for the shutdown pump (0.9 kw) and fan (0.15 kw) total 1.05 kw as compared to 10.8 kw for operation of the main unit (9 kw for the pump and 1.8 kw for the fan).

System Coolant Charge

Adequate system charge volume is incorporated into the system so that maximum high boiler residue concentration (hbr), resulting from radiolytic damage to the coolant during 5000 hr of full power operation, will not exceed 30 w/o. Coolant volumes exposed to radiation were minimized to the extent possible by use of relatively high velocity coolant passages located at the points of minimum energy deposition. Energy deposition in the coolant due to neutron slowing down and gamma ray attenuation was determined from a one-dimensional Monte Carlo calculation, and the molecules of hbr formed for 5000 hr of full power operation between reactor refuelings were computed. Based on a total hbr formation of 150 lb, the system is designed for a charge of 500 lb. During refueling, at the end of an operational cycle the coolant will be drained, the system flushed, and recharged with purified coolant. A summary of coolant volumes in each shield segment, energy deposited, and hbr formed per 5000 hr of full power operation is presented in Table 2-XXV.

HAND OPERATED VALVE		VAPOR TRAP		PRESSURE REGULATING VALVE (SELF-CONTAINED, SELF ACTUATED)
MOTOR OPERATED VALVE		LOCAL INSTRUMENT		AUTOMATIC BLOCK VALVE
STEPPER MOTOR OPERATED VALVE		CONTROL CONSOLE INSTRUMENT		RELIEF VALVE
SOLENOID VALVE		QUICK DISCONNECT		CHECK VALVE
RELIEF VALVE		FLAME ARRESTOR		HAND OPERATED VALVE
CHECK VALVE		FLEXIBLE HOSE		CONTROL VALVE
CHECK VALVE WITH FLOW ORIFICE		HEAT TRANSFER SURFACE		FLOW ELEMENT
SELF-ACTUATED REGULATOR		TEMPERATURE ELEMENT		FLOW CONTROLLER
RESTRICTION ORIFICE		TEMPERATURE CONTROLLER		RESTRICTION ORIFICE
CAP		TEMPERATURE ALARM		LEVEL ELEMENT
DAMPER		THERMOWELL		LIMIT SWITCH
SOLENOID OPERATOR		PRESSURE ELEMENT		MANUAL CONTROL
MOTOR OPERATED BLOWER		PRESSURE INDICATING CONTROLLER		VOLTAGE CONTROLLER
ELECTROMAGNETIC FLOWMETER		PRESSURE INDICATOR		HEATER
MECHANICAL JOINT		PRESSURE CONTROL VALVE
REDUCER				

Figure 2-16. Legends used on shield coolant system composite flow diagram.

Table 2-XXV.
Organic coolant hbr formation in 5000 hr of full power operation.

<u>Shield segment</u>	<u>Coolant volume (in. ³)</u>	<u>Energy deposition (mev $\times 10^{-21}$)</u>	<u>hbr (lb)</u>
Radial fixed shield	33.2	17.66	37.2
Top plug	120.0	9.12	17.6
Bottom plug	117.6	12.82	27.0
Removable shield	111.0	23.76	50.0
Total hbr formation			131.8

Degasification

In conjunction with the hbr formation, hydrogen is released as a function of energy absorption. Gas bubble formation must be avoided at points of highest temperature or at the point of lowest pressure (pump suction) to eliminate the possibility of vapor locks or pump cavitation which could be caused by entrained gases. Accordingly, the system is designed so that the dissolved gas in the liquid never exceeds the maximum solubility.

The hydrogen concentration in the air space of the expansion tank is maintained at 3 v/o by means of a dry air purge, -40°F dew point. Coolant from the heat exchanger flows through the expansion tank, establishing equilibrium of dissolved gases with the H₂ partial pressure of 23 mm Hg in the expansion tank gas space. The mole fraction of dissolved hydrogen leaving the expansion tank is 16.5×10^{-5} mole H₂/mole monoisopropylbiphenyl. Flowing through the shield, a total of 2.17 cc/min of gas is generated, which, when dissolved in the coolant, will increase the mole fraction to 16.7×10^{-5} mole H₂/mole monoisopropylbiphenyl. Compared to the maximum solubility at the maximum temperature, the dissolved gas mole fraction is still a factor of 20 below the maximum solubility which would lead to gas bubble formation.

The purge gas flow required to achieve the conditions mentioned is 70 cc/min. This flow is taken as a bypass from the discharge of the main heat exchanger coolant fans, passed through a molecular sieve air drier, and then through the expansion tank.

ARRANGEMENT

The organic shield coolant system components are designed in accordance with applicable commercial or military specifications. The arrangement of the equipment is shown on Figure 2-17.

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Equipment

The heat exchanger is located aft of the removable shield half section over the right rear corner of the Package I skids, overhanging the rear of the skid by 18.5 in. Ducting from the heat exchanger is horizontal and shaped to match the face of the shield. The duct is 16.25-in. long and is reduced from an area of 6.5 ft² at the heat exchanger to an area of 4.0 ft² at the blower inlet face. An assembly of three blowers is mounted horizontally to this face. The blowers and duct are arranged to provide good flow distribution with any one blower operating. Air inlet to each blower housing is through a damper attached to the housing.

The two main shield coolant pumps are located on the aft part of the Package I floor, approximately under the expansion tank to provide maximum net positive suction head. Suction line centers are at an elevation of 5.5 in. above the skid floor. The shutdown pump is located beneath the heat exchanger duct at the same elevation as the main pumps.

The vertical expansion tank is located partly in the outer layer of the neutron shield in the removable shield half section and partly outside the shield boundary. The tank is elevated to provide space for the two main pumps and to permit coolant outlet from the bottom of the tank.

The air dryer tank requires vertical installation and is located directly beneath the heat exchanger.

The interpiping between the heat exchanger, pumps, and expansion tank is arranged at the rear of the skid. All equipment is anchored; line expansions and stresses are absorbed in the piping. Three of the pipes penetrate the vertical support plate of the removable shield half section. The four control valves are readily accessible, mounted with their control stems horizontal and facing the rear of Package I. The highest elevation for any control valve is 15 in. above the bottom of the skid.

Piping

The shield coolant system is connected with both type 304 stainless steel and type 5652-0 aluminum pipe, tubing, valves, and fittings. Five piping codes, summarized in Table 2-XXVI and designated on the shield coolant system flow diagram of Figure 2-15, were used in designing the system. The code designations are:

- AA—aluminum pipe
- BB—stainless steel pipe
- CC—stainless steel flexible tubing
- DD—aluminum tubing
- EE—stainless steel tubing

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Figure 2-17. Shield coolant system piping and equipment arrangement.

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Table 2-XXVI.
Shield coolant system piping codes.

Piping code AA	Aluminum pipe
Design pressure—psi	100
Design temperature—°F	300
Pipe material	Type 5652-0 aluminum
Pipe sizes	1/4 to 2 in. schedule 10
Fittings	Formed welding fittings
Mechanical connectors	Conoseal joints as made by Marman Division of Aeroquip Corp.
Valves	
Isolation	Dynaseal ball, type 136, modified, as made by W-K-M Division of ACF Industries or equal. Material—aluminum
Check	Swing type as made by the Wm. Powell Co or equal. Material—aluminum
Piping code BB	Stainless steel pipe
Design pressure—psi	100
Design temperature—° F	300
Pipe material	Type 304 stainless steel
Pipe sizes	3/8 to 2 in. schedule 10
Fittings	Formed welding fittings
Mechanical connectors	Conoseal joints as made by Marman Division of Aeroquip Corp.
Valves	
Isolation	Dynaseal ball, type B 316 modified, as made by W-K-M Division of ACF Industries or equal. Material—stainless steel
Check	Swing type as made by the Wm. Powell Co. or equal. Material—stainless steel
Piping code CC	Stainless steel flexible tubing
Type	Corrugated, close pitch, one-wire braid
Design pressure—psi	100
Design temperature—°F	300
Material	Type 304 stainless steel
Size—in.	3/4

Table 2-XXVI. (cont)

Fittings	Welding fittings
Piping code DD	Aluminum tubing
Design pressure—psi	100
Design temperature—°F	300
Tube material	Type 5652-0 aluminum
Tube sizes	1/8 × 0.022-in. wall to 1 × 0.062-in. wall
Fittings	Formed welding fittings and sleeves for brazed connections
Piping code EE	Stainless steel tubing
Design pressure—psi	100
Design temperature—°F	500
Pipe material	Type 304 stainless steel
Pipe sizes	1/4 × 0.022-in. wall to 1 × 0.062-in. wall
Fittings	Formed welding fittings and sleeves for brazed connections

Aluminum was used wherever possible to minimize weight. However, where penetrations of the stainless steel housing cans of the shield are required, a transition to stainless steel piping was made. The flexible tube provides the connections to the removable shield quarter sections permitting them to rotate through the full 31° angular rotation. Tubing was used for all small lines, 3/8-in. dia and smaller. Quick acting make-break Conoseal joints, as manufactured by the Marman Division of the Aeroquip Corp, were used for mechanical connections to major equipment which may be subject to replacement. These same type joints, using a metal Belleville spring seal were used to effect the transition between the stainless and aluminum piping.

Connections of the coolant system between Packages I and II is accomplished by self-sealing, quick disconnect couplings similar to those manufactured by the Bruning Company. The couplings, attached to the skids, will be locked by the skid structures when assembled and the extensions will compensate for skid misalignment and tolerance stack-ups to ensure engagement.

Isolation valves for each of the main parallel flow streams were provided in the system, accessible from the aft end of Package I. These valves will also balance the system pressure drops.

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For those parallel streams within the shield sections such as the inner LiH and lead of the removable shield, balancing will be provided by orifices. Orifice unions seal welded in the line are used for this purpose.

Space limitations did not permit sloping all lines to the expansion tank for venting. Therefore, all high points are vented by bypass lines to the expansion tank. To control the bypass and still permit venting, restriction orifices have been installed in these lines.

All piping and equipment external to the shield are traced with electrical resistance heaters and insulated to ensure operation of the organic coolant above 0°F.

COMPONENT DESCRIPTION

Expansion Tank

The expansion tank is an upright cylindrical vessel with ASME code flanged and dished heads, fabricated of 5652-0 aluminum. The upper 12 in. of the tank contain horizontal baffling plates to provide a high contact surface area of the fluid with the purge air. The tank is supported by means of straps anchored to the shield can housing. All connections to the vessel are welded. The pertinent design data for the expansion tank are given in Table 2-XXVII.

Heat Exchanger

The heat exchanger is a cross flow, forced air, fin and tube extended surface exchanger, similar to the type 205-35 as manufactured by the Trane Company, with plate fins mechanically bonded to round tubes. For creating additional turbulence and increasing the film coefficient on the tube or organic side of the heat exchanger, turbulators are used inside the tubes. The turbulator is a smooth, spiral strip of metal inserted in the full length of each tube. Material of construction is aluminum. The heat exchanger has been sized in conjunction with the blowers, discussed in the subsection titled Blowers, to satisfy all MCR operating conditions at ambient temperatures from -65°F to +125°F and from below sea level to 8000-ft altitude. The pertinent data for the heat exchanger are listed in Table 2-XXVIII.

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Table 2-XXVII.
Expansion tank data.

Function	Provide storage capacity and expansion volume for shield coolant system
Fluid	Monoisopropylbiphenyl shield coolant
Operations conditions	
Working pressure—psig	0
Design pressure—psig	15
Working temperature—°F	255
Design temperature—°F	300
Life expectancy—hr	40,000
Size	
Capacity—ft ³	8
Diameter—in.	18
Wall thickness—in.	0.125
Length, tangent to tangent—ft	4.25
Maximum operating level—ft	4
Design	
Materials	5652-0 aluminum
Fabrication	All welded construction
Nozzles	
Coolant	2-in. butt weld ends (2)
Vent	1-in. butt weld end (1)
Purge	1/4 in. NPT (1)
Heads	ASME flanged and dished top and bottom
Supports	Horizontal straps

Pumps

The two main pumps and the shutdown pump are single-stage, centrifugal, canned pumps similar to those manufactured by Chempump Division of Fostoria Corporation. This type of pump eliminates the servicing of seals and stuffing boxes. The pump has only one rotating part, the combined rotor and impeller assembly, which is driven by the rotating magnetic field of the motor. Both rotor and stator are hermetically sealed. The suction and discharge ends of the pumps have welded fittings sealed to the piping with a Conoseal joint. Material of construction of the pumps is aluminum wherever possible to minimize weight. Pertinent data for the pumps are given in Table 2-XXIX.

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Table 2-XXVIII.
Heat exchanger data.

Function	Dissipate to atmosphere the heat generated in and conducted to the shield		
Type	Air cooled finned tube, cross flow, compact heat exchanger		
Service conditions	Shutdown operation	Standard operation	Heat exchanger limiting duty operation
Rating—BTU/hr	34 130	628 000	456 000
Air inlet temperature—°F	59	59	96
Ambient pressure—in Hg	29 92	29 92	21 5
Air flow—cfm	825	4 400	4 000
Air exit temperature—°F	197	204	240
Air ΔP maximum—in H ₂ O	0 02	1 34	1 75
Organic inlet temperature—°F	112	265	296
Organic flow—lb/hr	11 000	46 000	46 000
Organic outlet temperature—°F	105	235	274
Organic ΔP maximum—psi	2	10	10
Range of operating conditions (not including shutdown)	Sea level	8000-ft altitude	
Rating—BTU/hr	685 400 to 529 400	603 400 to 455 400	
Air inlet temperature—°F	-65 to +125	-65 to +96	
Air flow—cfm	2900 to 3400	2900 to 4000	
Organic inlet temperature—°F	155 to 285	150 to 295	
Organic flow—lb/hr	46 000	46,000	
Design	5652-0 aluminum (tube fins, headers and frame)		
Materials	All surfaces in contact with organic will be welded		
Fabrication	Fins mechanically bonded to tubes		
No of organic passes	10		
No of air passes	1		
Tube size	5/8-in OD with turbulators		
Header size	2-in pipe		
Header arrangement	Vertical		
Header-to-tube arrangement	First in—last out		
Fin size—in	1 25 OD		
Fin spacing	85/ft		
Frame dimensions—in			
Height	37-3/8		
Width	27-1/2		
Depth	22		
Maintenance			
Allowable frequency			
Minimum	75,000 Mw _{th} -hr or 8,000 operating hours, whichever is less (except for air movers)		
Preferred	25 000 operating hours or 5 years whichever is less		

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Table 2-XXIX.

Pump data.

	<u>Main coolant pump</u>	<u>Shutdown coolant pump</u>
Function	Provide forced circulation of shield coolant for fixed and removable shields	Provide forced circulation of shield coolant for fixed shield after reactor shutdown
Type	Canned rotor, single-stage centrifugal	Canned rotor, single-stage centrifugal
Quantity	2	1
Liquid characteristics		
Line fluid	Monoisopropylbiphenyl shield coolant	Monoisopropylbiphenyl shield coolant
Flow rate—lb/hr	46,000	11,000
Flow temperature—°F max	295	125
Suction pressure—psia	17	17
Differential pressure—psi	50	21
NPSH—ft	39	39
Operation		
Efficiency at rating	0.25	0.25
Maximum bhp	12	1.2
Rotation rpm	5600	5600
Direction of rotation (facing pump)	Counterclockwise	Counterclockwise
Number of stages	1	1
Motor		
Volts	208, 3-phase	208, 3-phase
Type	400-cps ac	400-cps ac
Enclosure	Canned rotor	Canned rotor
Duty	Continuous	Continuous
Materials of construction	Aluminum and stainless steel	Aluminum and stainless steel
Connections		
Suction	2 in. horizontal	1 in. horizontal
Discharge	1-1/2 in. vertical	3/4 in. vertical
End preparation	Butt weld	Butt weld
Design life—hr	2500 minimum	2500 minimum

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The two main blowers and the shutdown blower are lightweight, compact, 400-cps, direct drive axial fans capable of high volume flows with high pressure, similar to those manufactured by Joy Manufacturing Company. The motor is placed inside the fan housing for compactness. Lightweight aluminum, one-piece housing castings are designed to withstand shock and vibration requirements. Pertinent data for the blowers are listed in Table 2-XXX.

Main blowers

Shutdown blower

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Air Dryer

The air dryer consists of a packed bed of an adsorptive desiccant called a molecular sieve as manufactured by Linde Company. Molecular sieves, in contrast to other adsorbents, have pores which are precisely uniform in size and are of molecular dimensions. This combination of properties enables this type of dryer to provide a high level of efficiency in gas-drying operations. The packed bed is contained in a stainless steel vessel with a 1/4-in. tube inlet at the bottom and outlet at the top of the vessel. Pertinent data for the air dryer are given in Table 2-XXXI.

Table 2-XXXI.
Air dryer data.

Function	Dry shield coolant system purge air
Type	Molecular sieve dessicant
Quantity	1
Vessel dimensions	
Diameter—in.	12
Height—in.	24
Support	Vertical legs
Materials of construction	300 series stainless steel
Design pressure—psig	15
Design temperature—°F	125
Connections (2)	1/4-in. NPT
Operating conditions	
Air flow—cc/min	70
Inlet air temperature—°F	-65 to +125
Inlet air pressure—in. H ₂ O	2
Exit dew point—°F	-40
Pressure drop—psi/ft of bed	<0.001
Dessicant	
Charge—lb	50
Pellet size—in.	1/8
Break through capacity—w/o H ₂ O	12

Shield Coolant Preheat Subsystem

The preheat subsystem elementary diagram, Figure 2-18, shows the four zones supplied for preheating the shield coolant subsystem. The zones will be energized simultaneously with on-off temperature control. Each zone is provided with an installed unconnected spare heater.

The outline specifications enumerated under Preheat and Antifreeze Subsystem in Volume III are applicable to the Shield Coolant Preheat Subsystem.

The heaters will be installed on shield coolant lines and equipment in a manner similar to that described in the Preheat and Antifreeze Subsystem for the primary loop in Volume III.

The details of shield coolant preheat subsystem control are presented in Volume V, Plant Control. Each zone will be controlled in an on-off manner with heaters sized to raise the organic coolant from -65 to 0°F in 30 min. Since the organic coolant is liquid at -65°F, no provision is necessary for permissive sequence interlocks as is the case with the primary loop preheat system.

The subsystem performance characteristics are summarized in Table 2-XXXII.

Table 2-XXXII.
Shield coolant preheat subsystem performance summary.

Time to preheat shield coolant subsystem—hr	0.5
Design ambient temperature—°F	350
Design cycles	-65°F to 0°F, 60 times
Energized design life—hr	25,000
Power consumption—kw-hr	6
Peak power—kwh	12
Max power input capability—kw	12
Redundancy	100% installed but not connected
Power	208 v, 400 cps, 3 phase

INSTRUMENTATION

The instrumentation and control system for the shield and its cooling is described in Volume V, Section III, Control and Instrumentation.

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Instrumentation is provided for the shield coolant system to monitor coolant system temperatures, coolant pump discharge pressure, and expansion tank level. The principal functions of this instrumentation are:

- To monitor the overall coolant system performance
- To maintain system operation in the event of coolant pump or heat exchanger blower malfunctions by initiating operation of the backup units
- To prevent excessive shield temperatures by initiating a controlled shutdown in the event of abnormal deviations in heat exchanger outlet temperature, pump discharge pressure, or expansion tank level

Direct control of the coolant system temperatures is not required because the coolant system design permits the system temperatures to vary with ambient temperature over the design range (-65°F to +125°F).

Additional instrumentation is provided to control the pumps and blowers when the control console has been secured.

The outline specifications for the instrument sensors required for the shield coolant system instrumentation are given in Tables 2-XXXIII through 2-XXXVI. Specifications for the actuators required for the shield coolant system instrumentation are presented in Tables 2-XXXVII through 2-XLI.

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Table 2-XXXIII.
Shield coolant thermocouples.

Function	To monitor shield coolant loop temperatures for indication, control, and protective functions.
Type	Surface mounted Chromel-Alumel thermocouples with swaged stainless steel sheathing.
Quantity	19
Operating temperature—°F	-65 to +300
Operating pressure	Atmospheric
Fluid	Air
Sheath material	316 stainless steel
Sheath OD—in.	0.125
Sheath thickness—in.	0.012
Thermocouple material	Type K, Chromel-Alumel
Thermocouple junction	Grounded
Thermocouple wire size	22 gage (0.025 in.)
Thermocouple length	(see Table 2-XXXIV)
Wire termination	(see Table 2-XXXIV)
Type A	Bare thermocouple leads 6-in. long. Open end of insulation sealed with epoxy cement
Type B	Thermocouple connected to flexible Chromel-Alumel lead wire in stainless steel adapter housing. Adapter housing welded to thermocouple sheath. Connection secured by strain harness and encapsulated in moisture proof potting compound. Adapter spring connected to lead wire. Lead wire insulated with silicone impregnated glass braid with overall jacket of flexible stainless steel braid. Lead wire termination shall be bare leads, 6-in. long. Open end of insulation sealed with epoxy cement.
Insulation	Magnesium oxide. Purity greater than 99.4% with boron plus cadmium content less than 30 ppm sulphur content less than 50 ppm carbon content less than 30 ppm
Insulation resistance* (wire-to-wire, sheath-to-wire)	
At room temperature	$>10^{11}$ ohm-ft at 500 v-dc
At 1000°C	$>5 \times 10^4$ ohm-ft at 50 v-dc
Installation	Thermocouples are welded to piping or component surfaces at junction and thermally insulated. Banding at intermediate points will be required for support. Type "B" wire termination will be provided for thermocouples installed on removable shield quarter section piping.
Weight—lb	7.6 total, (less banding and insulation)
Design life—hr	25,000

*Prior to fabrication of junction

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Table 2-XXXIV.
Shield coolant thermocouple data.

<u>Parameter</u>	<u>Number installed</u>	<u>Wire termination</u>	<u>Sheath</u>	<u>Length (ft) Flexible leads</u>	<u>Weight (lb)</u>
Radial and top plug shield cooling header outlet temperature	1	A	12	--	0.4
Bottom plug and pipe penetration shield plug cooling header outlet temperature	1	A	12	--	0.4
Removable shield, half section LiH region cooling header outlet temperature	1	A	12	--	0.4
Removable shield, half section Pb region cooling header outlet temperature	1	A	12	--	0.4
Removable shield, quarter section No. 1 LiH region cooling header outlet temperature	1	B	4	8	0.3
Removable shield, quarter section No. 2 LiH region cooling header outlet temperature	1	B	4	8	0.3
Removable shield, quarter section No. 1 Pb region cooling header outlet temperature	1	B	4	8	0.3
Removable shield, quarter section No. 2 Pb region cooling header outlet temperature	1	B	4	8	0.3
Heat exchanger inlet coolant temperature	1	A	12	--	0.4
Heat exchanger outlet coolant temperature	3	A	12	--	0.4
Main coolant pump No. 1 discharge temperature	1	A	12	--	0.4
Main coolant pump No. 2 discharge temperature	1	A	12	--	0.4
Shutdown coolant pump discharge temperature	1	A	12	--	0.4
Expansion tank temperature	1	A	12	--	0.4
Expansion tank outlet temperature	1	A	12	--	0.4
Control drum drive outlet header	1	A	12	--	0.4
Instrument thimble outlet header	1	A	12	--	0.4

Table 2-XXXV.
Main coolant pump discharge pressure transducers.

Function	To monitor main coolant pump discharge pressures for indication, control, and protective functions
Type	Diaphragm type—linear voltage differential transformer pressure transducer
Quantity	3
Operating temperature—°F	-65 to +200
Pressure range—psig	0 to 35
Fluid	Monoisopropylbiphenyl
Materials in contact with fluid	Stainless steel
Proof pressure	150% of full scale
Burst pressure	300% of full scale
Accuracy	~2% of full scale over operating temperature range
Signal output	100 mv dc full scale from translator
Excitation frequency	10 kc
Installation	Transducers are welded to system piping with 1/2-in. OD pipe stubs
Size	1-1/2 in OD × 3 in long (excluding cables)
Weight—lb	2 per transducer (includes 12 ft of cable), 10 total
Design life—hr	25,000

Table 2-XXXVI.
Shutdown shield coolant pump discharge pressure transducer.

Function	To monitor the shutdown coolant pump discharge pressure for pump control and protective functions
Type	Diaphragm type—snap action pressure switch
Quantity	1
Operating temperature—°F	-65 to +300
Pressure range—psig	0 to 50
Fluid	Monoisopropylbiphenyl
Materials in contact with fluid	Stainless steel
Proof pressure	150% of full scale
Burst pressure	300% of full scale
Accuracy	2% of full scale over operating temperature range
Signal output	DPDT switch contacts to reverse position on decreasing pressure below setpoint
Setpoint adjustment range	Screw adjustable over ~100% full scale
Installation	Transducer is welded to system piping with 1/2-in OD pipe stub
Size—in.	3-1/2 w × 3-1/2 d × 4 h
Weight—lb	2
Design life—hr	25,000

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Table 2-XXXVII.
Expansion tank level transducer (proportional type).

Function	To monitor shield coolant expansion tank level during power operation and after shutdown, prior to separation of the plant packages for indication, control, and protective functions
Type	Diaphragm type—linear voltage differential transformer, differential pressure transducer
Quantity	3
Operating temperature—°F	-65 to +200
Differential pressure range—psi	0 to 3
Fluid	Monoisopropylbiphenyl
Materials in contact with fluid	Stainless steel
Proof pressure	150% of full scale
Burst pressure	300% of full scale
Accuracy	~2% of full scale over operating temperature range
Signal output	100 mv dc full scale from translator
Excitation frequency	10 kc
Installation	Transducer high pressure port is welded to tank at minimum level with 1/2-in. OD pipe stub. Low pressure port is connected to tank above maximum fluid level
Size—in.	1.5 OD by 3 long (excluding cables)
Weight—lb	2 per transducer (includes 12 ft of cable), 6 total
Design life—hr	25,000

Table 2-XXXVIII.
Heat exchanger air blower damper.

Function	To prevent bypassing of air through nonoperating leg of air supply system
Type	Butterfly type, solenoid-operated
Quantity	3 (see Table 2-XXXIX)
Operating fluid	Air
Operating temperature—°F	-65 to +200
Size	(see Table 2-XXXIX)
End connections	Suitable for flange mounting
Design flow	(see Table 2-XXXIX)
Design pressure drop	(see Table 2-XXXIX)
Materials of construction	Aluminum
Trim materials	Suitable for specified service
Weight—lb	40 (total of 3 dampers and operator)
Operator	Solenoid
Operator power supply	115 v, single-phase 400-cps

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Table 2-XXXIX.
Heat exchanger air blower damper data.

<u>Service</u>	<u>Damper size diameter (in.)</u>	<u>Design flow (cfm)</u>	<u>Pressure drop (in. H₂O)</u>	<u>Weight (lb)*</u>
Main cooling air blower No. 1	14	4400	< 0.2	15
Main cooling air blower No. 2	14	4400	< 0.2	15
Shutdown cooling air blower	9	600	< 0.1	10

*Includes operator and drive linkage.

Table 2-XL.
Motor contactors.

Function	To provide remote starting of the shield coolant system motors
Type	Full voltage, nonreversing type electromagnetic starter
Quantity	6 (see Table 2-XLI)
Load service	208 v, 3 phase, 4 wire, 400 cps
Load current	(see Table 2-XLI)
Operating coil rating	115 v, 1 phase, 400 cps
Overload protection	Thermal type, automatic reset
Installation	Motor contactors will be mounted on the removable shield package
Operating temperature—°F	-65 to +200
Size	(see Table 2-XLI)
Weight—lb	40.5 total (see Table 2-XLI)
Design life—hr	25,000

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Table 2-XLI.
Motor contactor tabulation.

<u>Service</u>	<u>Load current (amp)</u>	<u>NEMA size</u>	<u>Size (in.)</u>	<u>Weight (lb)</u>
Main coolant pump No. 1	50	2	7-5/8 w × 12 h × 4-1/2 d	10
Main coolant pump No. 2	50	2	7-5/8 w × 12 h × 4-1/2 d	10
Shutdown coolant pump	5	00	4-7/8 w × 7-11/16 h × 4-13/32 d	4-1/2
Heat exchanger main cooling air blower No. 1	7.24	0	6-5/16 w × 9-3/16 h × 4-1/2 d	5-3/4
Heat exchanger main cooling air blower No. 2	7.24	0	6-5/16 w × 9-3/16 h × 4-1/2 d	5-3/4
Heat exchanger shutdown cooling air blower	5.55	00	4-7/8 w × 7-11/16 h × 4-13/32 d	4-1/2

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Support Structure

The Package I support structure, shown in Figure 2-19, functions as an integral structural system with the removable shield assembly. It retains the individual and arrangement integrity of the Package I components during all conditions of operation and transport. This structure assembles with Package II so that during operation, the removable shield is maintained concentric with the fixed shield and reactor of Package II.

The Package I skid underbody is designed to receive the reactor support section of the Package II skid underbody. Dowels, turnbuckles, and pressure pads align and couple Packages I and II. When coupled, the Package I and Package II skids form a rigid beam assembly. The most stringent requirement is that of supporting Package III from the interface of Packages II and III, in the event that the trailer supporting Package III should settle.

DESCRIPTION

The principal subassemblies of the Package I skid structure are the skis, suspension system, underbody, and superstructure. Two skis, one on each side of the package, serve as a foundation for the entire assembly and permit sliding of the package. The underbody and superstructures which support the removable shield and shield cooling system components, are suspended on 16 rubber shock mounts positioned on the skis. The suspension system serves to reduce shock and vibration loads transmitted to the package.

The removable shield is joined to the superstructure, an axially loaded truss assembly, through hinge and turnbuckle columns. Additional support is furnished to the fixed half section of the shield by the underbody. The package weight is reduced by using the lead layer cladding of the removable shield as the principal structural column. The LiH can housings, support shelves, end plates, and vertical support plates of the removable shield are also used as structure and to stiffen the complete assembly as well as to distribute static and dynamic loads.

Turnbuckles and pressure pads are provided for coupling Packages I and II. The coupling loads are isolated from the skid structure proper in that all the coupling loads are reacted in and around the turnbuckle housings.

Two sets of dowels ensure proper alignment between the packages. Otherwise, interference between the removable shield and the fixed shield around the reactor could occur, resulting in loads being applied to the reactor, primary loop piping, and other components. System failures, particularly at operating temperatures, would then be of concern.

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SKIS

The two skis are extruded 6061-T6 aluminum channels, reinforced with plates, gussets, and by the shock mount housings. They provide a contact surface pressure of 16.5 psi, and position the suspension system shock mounts.

The two skis, 11.00 in. wide, extend for the full 104.00-in. length of the lower part of Package I. The 4.00-in. vertical portions of the channel are spaced 6.50 in. apart to accommodate the ML-1 type mounts, shown in Figure 2-20. The thickness of the vertical web sections is increased from 0.375 to 0.750-in. at the top to increase the section strength. The base plate is 0.50 in. thick.

The shock mounts are positioned with their center line along buttock line 42.38, both sides, as shown in Figure 2-19. The mounting bracket for the shock mount is bolted to the vertical walls of the channel, with a 0.06-in. allowance for shimming on each side, as shown in Figure 2-21. The end of each ski is cut at an angle and covered with an aluminum plate welded to the channel. The tapered end provides a leading edge for sliding the package over small projections extending from the ground or other contact surface.

SUSPENSION SYSTEM

The suspension system reduces the shock and vibration loads, imposed during operation and transport, to acceptable levels for the package components. The overall package shock and vibration environments are discussed in Volume I.

Sixteen rubber mounts support the underbody structure and the package, using the skis as a foundation. The mounts are spaced on the basis of a static and dynamic load analysis, to meet roll and pitch requirements while providing a maximum damping effect. The design assumes the use of an ML-1 type shock mount, as shown in Figure 2-20. This mount uses a General Electric elastomer, SE 565U, as the ~~compliant~~ ^{compliant} medium, and has a limiting deflection of about 2.00 in.

The mounting bracket for the shock mount is a forged aluminum cylinder attached to the vertical walls of the ski. The elastomer fits into this cylinder. A tapered plug, which fits into the elastomer, is welded to a top plate bolted to the underbody support beams, as shown in Figure 2-21.

Figure 2-19. Package I support structure.

- ① X-83601 OPERATION OF TURNBUCKLE
- ② X-83809 PACKAGE I QUADRANT MECHANISM
- ③ X-83811 PACKAGE I & II DOWEL & PRESSURE PAD ASSEMBLY
- ④ X-83992 SUSPENSION SYSTEM
- ⑤ X-83808 PACKAGE I HINGES
- ⑥ X-83803 OPERATION OF PKG I QUADRANT MECHANISM

Figure 2-20. ML-1 type shock mount.

The shock mounts function to reduce the input shocks through shear and compressive loads on the elastomers. The initial vertical loading of the elastomer is shear, changing to compression as the load is increased. The rubber elastomer expands to fill the mounting bracket and then extends over the cylindrical column. Lateral loads are absorbed as compression in the elastomer, bearing against the tapered plug and the side of the mounting bracket.

The vertical deflection rate for this shock mount is shown for a static load application in Figure 2-22. The lateral deflection is shown for a static load application in Figure 2-23. The dynamic characteristics are shown in Figure 2-24.

These mounts perform satisfactorily from the standpoint of shock and vibration inputs from most common carriers. The shock mounts will be locked out during air transport to avoid shock magnifications under emergency landing conditions. The mounts also limit drop shocks (from handling drops of slightly more than 1 in.) on Package I and its components to the design value of 5.5-g.

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UNDERBODY

The underbody is an aluminum structural assembly upon which the skid superstructure, shield, and various components are mounted. The underbody distributes the Package I weight to the shock mounts and acts as the lower horizontal truss member for the rear truss assembly of the superstructure. The principal components of the underbody are two support beams, a connecting structure for the support beams, and a floor plate. Two dowel and pressure pad assemblies are provided for aligning Packages I and II for assembly.

The two underbody support beams, above the skis and shock mounts, are built up of formed 0.250-in. thick aluminum, as shown in Figure 2-19. Their function is to support and distribute to the shock mounts the loads from the superstructure and the vertical support plate of the fixed half section of the removable shield, and those additional loads transmitted by Package II. Plate and gusset reinforcements are provided within the underbody support beams for mounting the fixed half section hinge columns and the tiedown shelf support gussets, the shield coolant system, turnbuckle columns, and lower pressure pad assemblies. Top plates of the shock mounts are bolted to the support beams, thereby locating the reaction points of the underbody and skis.

The underbody support beams extend for the length and width of the skis. They are connected across the rear with a beam structure built up of 0.250-in. aluminum. The connecting structural section is 24.75 in. wide and 5.00 in. deep. This section is reinforced with plates and gussets. This crossmember section, in addition to joining and spacing the support beams, partially supports the removable shield fixed half section at the vertical support plate, located at buttock line 00.

The underbody support beams widen toward the rear to form, with the rear crossmember structure, a tapered mating with the reactor support section of the Package II skid underbody. The complete underbody structure is covered with a 0.250-in. thick aluminum floor plate.

Packages I and II are aligned at assembly with two sets of dowels, located on Package II, and mating receptacles, located on Package I. Two forward dowel receptacles are located on the front of the Package I skid underbody assembly, with the center line at water line 105.5 and buttock line 42.38, as shown in Figure 2-25. The left dowel receptacle mates with the truncated cone-shaped dowel on the Package II skid, and the right dowel receptacle mates with the V-shaped dowel on the Package II skid. The structure connecting the underbody support beams contains the aft dowel receptacles which mate with double tapered dowels located on the Package II skid.

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Figure 2-21. Detail layout of suspension system.

Figure 2-22. Effect of static load on vertical deflection of ML-1 shock mounts.

Figure 2-23. Effect of static load on lateral deflections of ML-1 shock mounts.

Figure 2-24. Dynamic characteristics of ML-1 shock mounts.

The dowel receptacle locations are adjustable. Therefore, the clearance between the dowels and dowel receptacle, and their location tolerance, does not increase the clearance required between the removable shield and the fixed shield.

Contact between Packages I and II is through pressure pads. The lower pressure pads for Package I are part of the forward dowel receptacle forging as shown in Figure 2-25. The assembly is attached to the underbody structure through oversize holes and shimmed to permit adjustment in the vertical, lateral, and fore and aft directions. This arrangement also helps to maintain the clearance required between the removable shield, and the fixed shield.

Figure 2-25. Dowel and pressure pad assembly—Packages I and II.

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Aluminum bearing plates, as shown on Figure 2-19, are located on the skid underbody beneath the quarter sections to limit the maximum deflection of the fixed half section hinge columns during opening and closing of the shield. Thus, any possible interference between the quarter sections and the reactor support section of the Package II skid underbody, during opening or closing of the shield, is avoided. The bearing plates are 36.00 in. long, 6.00 in. wide, and 0.220 in. thick.

Four restraining links, one at each corner of the package, connect the underbody directly to the skis, as shown in Figure 2-25. They do not affect the downward movement of the underbody relative to the skis, but they restrict the upward movement. Their function is to prevent separation of the shock mounts during handling or in the event excessive negative g-loads are applied to Package I during transport.

SUPERSTRUCTURE

The superstructure, shown on Figure 2-19, is a truss-type aluminum structure for positioning the removable shield and shield cooling system during operation and transport, and for joining Package I to Package II. It is comprised of the following major subassemblies: two hinge column truss sections mounted to and supporting the fixed half section of the removable shield; and two front truss sections for supporting the two removable shield quarter sections and joining the Package I skid to the Package II skid.

The can housings of the three removable shield sections are welded to the four 3 X 4-in. I-beam hinge columns making them an integral part of the overall Package I structure. The fixed half section hinge columns are bolted to the skid underbody assembly. The rear diagonal members are riveted to the fixed half section hinge column at the top and bolted to the underbody at the floor line. The vertical hinge columns are the principal load members in these truss assemblies. The diagonal members provide fore and aft stability. The underbody support beams function as the lower horizontal members for the truss.

To form the two front truss assemblies, each upper turnbuckle housing is welded to a 3-in. tubular turnbuckle column and to an upper horizontal member, thereby coupling these two members. Each lower turnbuckle housing is welded to the turnbuckle column, lower horizontal member, and to the front diagonal member. The turnbuckles are mounted to brackets that are riveted to these housings. The front truss assemblies are then riveted to the quarter section hinge columns and to the quarter section vertical support plates. The horizontal and diagonal members of these truss assemblies are 3 X 5-in. I-beams.

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The quarter section hinge columns are attached to the fixed half section hinge columns through the hinges shown in Figure 2-26. Top and bottom thrust bearings are located in both the upper and lower hinges to support the bearing loads during normal operation, and in a negative g direction during handling and transport.

The upper pressure pad is mounted to the upper turnbuckle housing, as shown in Figure 2-25; the lower pressure pad is part of the dowel assembly located in the underbody structure. Therefore, the tension load applied to the upper turnbuckle in attaching the Package I skid to the Package II skid, and the compression load applied to the pressure pad in reacting the turnbuckle, are both contained within the turnbuckle housing. The same loads, in the lower turnbuckles and pressure pads, are reacted in the turnbuckle housings and portions of the underbody structure.

Loads are applied to the superstructure under three different conditions:

- During operation, with Package I attached to Package II
- During transport of Package I
- During assembly of Package I and II, with the quarter sections in an open or partially open position

The load usually applied during normal operation will be that due to the weight of the shield and related components. The turnbuckle and pressure pad attachment loads to the Package II skid will be reacted within and around the turnbuckle housings. In the event that the Package III trailer settles, Package III will be supported from the interface of Packages II and III. A portion of Package III will remain on the Packages I and II trailer, as shown schematically in Figure 2-27, with support from the turnbuckles and pressure pads which couple Packages II and III. The deflections which this condition will impose on the structure of the Packages I and II skids are shown in Figure 2-28. These deflections would not affect the operation of the plant, and would actually be reduced somewhat by the rigidity furnished by component mounts and the components themselves, especially the removable shield.

The turnbuckle columns are bolted to the package underbody when the quarter sections are closed for operation or transport. An aluminum channel tie bar is bolted to the underbody support beams across the front opening of the underbody to stiffen the front truss and quarter section assembly during transport.

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Figure 2-26. Removable shield quarter section hinges.

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Figure 2-27. Package III cantilevered from the Packages I and II trailer and supported from the interface of Packages II and III.

Figure 2-28. Deflections of Package I structure with Package III cantilevered.

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When the shield quarter section is open, during assembly and disassembly of Packages I and II, the quarter section is cantilevered from the hinge column, presenting an eccentric loading on the fixed section hinge column at the hinges. For the condition where the center of gravity of the quarter section is in line with the center line of the shock mounts, the deflection of the hinge column would be 0.0815 in. forward and 0.198 in. downward. This analysis treated only the superstructure; the deflection would actually be less due to the increased rigidity afforded by the fixed half section shield structure. The vertical deflection of the quarter sections is limited to a maximum of 0.030 in. at any position by a bearing plate on the Package I skid floor.

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APPENDIX

Nuclear Materials Design Criteria

In the preparation of the MCR reference design described herein, design criteria were prepared for each of the major reactor and shield materials used. These criteria established a set of limiting values for the major design parameters associated with the application of each material and presented a compilation of the material properties. The reference design has been based on these criteria and is consistent with the values contained therein. These criteria will be continuously updated to reflect the latest results of the MCR development program as well as to reflect data which may become available from investigations being conducted at other facilities. In addition, during the detailed design phase of the MCR program, they will be supplemented by material procurement, design, and fabrication specifications.

Individual design criteria were prepared for the following:

- Ceramic fuel material
- B₄C poison material
- BeO reflector material
- Tungsten reflector material
- Borated stainless steel shield material
- Lead gamma shield material
- LiH neutron shield material
- TiH₂ neutron and gamma shield material
- Organic shield coolant material
- Primary system coolant material
- Primary system corrosion, mass transfer, and activity transfer

The pertinent features of each are summarized in this appendix.

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Ceramic Fuel

DESIGN LIMITATIONS

Material Specifications

The design limitations and materials properties data presented in these criteria are based on the UO₂ materials specifications summarized in Table A-I.

Table A-I.
UO₂ tentative material specifications.

Composition	O/U atom ratio of 2.00 to 2.02. (Ratios higher than 2.02 would reduce the thermal conductivity of the fuel and also increase the amount of fission gas released.) Impurity levels shall be maintained within acceptable commercial grade specifications. In addition, nitrogen, carbon, and fluorine contents will have to be specified consistent with fuel clad compatibility. Limits will be established in the material procurement specifications.
Fabrication method	Pellets cold pressed and sintered in hydrogen at 1750°C
Density ^{4*}	10.4 gm/cm ³ (95% of theoretical density)
Grain size	20 microns or less

*Superscript numbers refer to references at the end of this appendix.

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Assembly Configuration

The ceramic fuel to be used within the MCR shall be hermetically sealed within Cb-1% Zr clad housing tubes. Axial reflectors, both top and bottom, may also be contained within the clad housing. The clad shall be designed to accommodate release of fission gas from the fuel and may also be required to restrain swelling of the UO_2 as a result of irradiation. Heat generated in the fuel shall be dissipated by conduction to the reactor coolant through a helium-fission gas gap.

Lifetime

Lifetime requirements are defined in terms of the MCR reactor thermal output. The system design must account for all steady-state and transient operating conditions as well as start-up, shutdown, and transportability cyclical requirements. The fuel shall be designed for lifetime of 75,000 $\text{Mw}_t\text{-hr}$ or 8000 operational hours, whichever is less.

Design Stress

Stress categories and limits as defined in the MCR Structural Design Criteria in Volume I shall be considered in the design and evaluation of the fuel pin cladding. The cladding shall be designed, consistent with the limits for a ductile material, to contain the volatile fission products released from the UO_2 .

The clad shall be designed to be free standing and capable of withstanding external coolant pressure without collapsing against and depending on the UO_2 for support.

In addition, if the design is to be based on restraint of UO_2 growth, the additional stress imposed on the clad due to this restraint (based on the creep properties of the UO_2) shall not exceed the allowable stress limitations imposed herein.

UO_2 Temperature

As discussed in the preceding paragraph, the design of the clad is particularly sensitive to fission gas release and creep properties of the UO_2 , both of which depend on and increase with temperature. Since the effect of the latter can be compensated for in the design by establishing the gas gap clearance between the UO_2 and the clad wall, the temperature limitations are based on the former consideration. The nominal design center temperature limit, including the effects of both the radial and axial maximum-to-average power distribution, shall be

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2900°F. The maximum hot spot temperature limit, accounting for physical tolerance ranges, hot channel factors, and confidence limits in the material physical properties, shall be 4000°F. This hot spot temperature has been selected with respect to UO₂ melting, allowing a reasonable factor of safety.

Gas Gap Conductance

The conductance across the gas gap is a required design parameter in determining the UO₂ center temperature. The assembled radial clearance between the UO₂ and clad will be such as to avoid an interference fit, due to differential thermal expansion, during steady-state operation. However, the gap can vary, depending on whether the design of the fuel pin is based on intimate contact between the UO₂ and cladding as a result of restraint of UO₂ radiation swelling, or whether a minimum gas gap clearance is maintained throughout the operating lifetime. The conductance across an intimate contact interface can be evaluated, within limits, if contact pressure and surface conditions are known. The methods of computation are noted in the following paragraphs and a maximum limiting value based on extrapolated experimental data is specified. For the design where a minimum gas gap is maintained, the conductance shall be analytically determined as a function of the gap thickness and thermal conductivity of the helium and fission gas constituents.

The heat transfer coefficient across the UO₂ clad interface shall be determined as follows with a value of 1000 BTU/hr-ft²-°F representing a limiting maximum coefficient for end of life conditions.

For the case where a small, finite, radial gap exists between the UO₂ and the clad,

$$h = K_f / \Delta r$$

where

h $\equiv$ heat transfer coefficient—BTU/hr-ft²-°F

Δr $\equiv$ hot radial gap—ft

K_f $\equiv$ thermal conductivity of gas mixture (fill gas + fission gases)—BTU/hr-ft-°F.

Thermal conductivity of the gas shall be computed at that point in the reactor operating lifetime which will give a maximum fuel temperature in any pin constituting the reactor core. An average gas temperature shall be used, computed as the temperature of the fuel pin clad wall temperature plus 1/2 of the differential temperature across the gas gap.

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When the UO_2 is in contact* with the clad,¹⁷

$$h = \frac{K_f}{\delta + (g_1 + g_2)} + \frac{K_m}{aH}$$

where

- h $\equiv$ heat transfer coefficient—BTU/hr-ft²-°F
- K_f $\equiv$ gas mixture thermal conductivity—BTU/hr-ft-°F
- K_m $\equiv 2 K_{\text{UO}_2} \cdot K_{\text{clad}} / (K_{\text{UO}_2} + K_{\text{clad}})$
- δ $\equiv$ weighted-mean thickness of the fluid film—ft (see the subsection titled Heat Transfer Coefficient Evaluation)
- $(g_1 + g_2)$ $\equiv$ temperature jump distance due to accommodation effect—ft (see the subsection titled Heat Transfer Coefficient Evaluation)
- P $\equiv$ interfacial pressure—psf
- a mean radius of solid contacts—ft
- H $\equiv$ Meyer microhardness of the softer material (in general, this will be the clad material)

Gas Generation and Release

The fission gas generated is a function of the fissionable fuel and neutron environment. Some of the gas formed is contained within the UO_2 and the remainder is released to the environment of the clad tube. The release rate is generally believed to be a volume diffusion process between UO_2 temperatures of 1800 to 2900°F. However, existing data, with respect to diffusion coefficients and actual diffusion surface versus geometric surface, have too great a scatter to permit assignment of any reasonable confidence limits. Therefore, fission gas release limits are based on an extrapolation of irradiation experiment data most nearly approaching the MCR conditions. For UO_2 having a center temperature limit of 2900°F or lower, fuel pin design shall be based on a gas release of 30% of all gas generated.

At UO_2 temperatures in excess of 2900°F, experiments indicate a sharp increase in fission gas release over that predictable by volume diffusion.¹⁶ This increase, apparently attributable to the structural changes in the material at the high temperature, does not permit a reasonable

*While, in general, radiation heat transfer will not be appreciable, it should be checked.

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basis for determining the amount of volatile fissionable products retained in the UO_2 . Therefore, the fuel pin design shall also allow for a 100% gas release of the gas generated in the region of the UO_2 fuel above 2900°F .

The initial gas gap between the UO_2 and the cladding shall be helium at an initial pressure of 1 atm at room temperature.

Burnup

In general, the physical and mechanical properties, fission gas release, and dimensional stability of the UO_2 can be adversely affected by the atom percent burnup. Experimental data^{8,18} have indicated relatively small effects up to 30,000 Mwd/tonne U. Significant increases in fission gas release and degradation of dimensional stability have been noted in the range of 30,000 to 60,000 Mwd/tonne U burnup, with most of the experiments indicating a step change at the upper limit.¹⁸ Therefore, the maximum burnup limit shall be limited to a maximum of 40,000 Mwd/tonne U (4.2 a/o of U equivalent) set near the lower end of the marginal range.

Dimensional Stability

Fuel pin design shall be based on an irradiation swelling of the UO_2 of 1 v/o per 10,000 Mwd/tonne U. *

MATERIALS DATA

Physical and mechanical properties data are presented in Tables A-II and A-III. In addition, detailed explanatory data to be used with the analytical procedures specified and to permit interpretation of the experimental data compiled from prior work at other facilities have been included.

Additional Data for UO_2 Design Application

- Production of volatile fission products in UO_2 —see Figure A-7
- Vapor pressure of fission products
 - Cesium—see Figure A-8
 - Rubidium—see Figure A-9

*Estimated from irradiation of annular shaped pellets¹⁴ to 30,000 Mwd/tonne U. See the subsection entitled Irradiation Swelling of UO_2 .

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Table A-II.
Ceramic fuel physical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Thermal conductivity*	See Figure A-1	1
Linear thermal expansion	See Figure A-2	2
Coefficient of linear thermal expansion		2
RT to 750°F	5.0×10^{-6} in./in./°F	
750 to 1500°F	6.0×10^{-6} in./in./°F	
1500 to 2300°F	7.2×10^{-6} in./in./°F	
Melting point, unirradiated †	$5072 \pm 36^\circ\text{F}$	3
Melting point, irradiated	See Figure A-3	3
Theoretical density ‡ (room temperature)	10.96 ± 0.01 gm/cm ³	4
Theoretical density of fully enriched UO ₂ (room temperature)	10.85 gm/cm ³	4
Vapor pressure	See Figure A-4	5
Specific heat	See Figure A-5	6
Heat of fusion** (melting point)	22 BTU/lb	7
Heat of vaporization	915 BTU/lb	6

* See subsection entitled Irradiated Thermal Conductivity of UO₂ for discussion of effect of irradiation on thermal conductivity.

† In helium.

‡ For natural UO₂—for enriched UO₂, density should be corrected by ratioing atomic weights.

**Based on 9.65% change in volume of UO₂ upon melting.

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Table A-III.
Ceramic fuel mechanical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Modulus of rupture	See Figure A-6	8
Compressive strength* (room temperature)		2
0 to 5 grain size	140,000 psi	
10 to 15 grain size	70,000 psi	
15 to 20 grain size	60,000 psi	
Young's modulus (E)		8
RT	$25.4 \times 10^6 \dagger$ psi	
1500°F	23.0×10^6 psi	
Creep rate‡ at 5×10^3 psi		9
1800°F	5.7×10^{-10} in./in./hr	
3000°F	1.9×10^{-4} in./in./hr	
Hardness, KHN (room temperature)	666 ± 14	10

*From results of fused UO_2 specimens with length/diameter ratio of 2:1.

†Averaged from five specimens reported in Reference 8.

‡Based on unirradiated specimens. Evaluated from

$$\epsilon = 500 \exp \left(-\frac{8.25 \times 10^4}{T} \right) \sigma^{1.3} \text{ in./in./hr}$$

where T = temperature in °R

σ = stress in psi

- Thermal conductivity of mixture of helium and fission gases—see Figure A-10*

*For calculation to determine a/o He, see the subsection entitled Helium a/o in Mixture of Helium and Fission Product Gases.

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Figure A-1. Effect of temperature on thermal conductivity of sintered UO_2 (corrected for 95% density).¹

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Figure A-2. Effect of temperature on correlated linear thermal expansion of UO_2 .²

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Figure A-3. Effect of burnup on melting temperature of irradiated UO_2 .³

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Figure A-4. Effect of temperature on correlated vapor pressure of UO_2 .⁵

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Figure A-5. Effect of temperature on correlated specific heat of UO_2 .⁶

Figure A-6. Effect of porosity and grain size on modulus of rupture of UO_2 at room temperature and at 1000°C.⁸

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Figure A-7. Fission gas production in a fast spectrum reactor—5 kw/cm³.¹¹

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Figure A-8. Effect of temperature on correlated vapor pressure of cesium.¹²

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Figure A-9. Effect of temperature on correlated vapor pressure of rubidium.¹²

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Heat Transfer Coefficient Evaluation

The following information should be used in evaluating the heat transfer coefficient between the UO_2/clad contact surface as mentioned previously and based on experimental results.¹⁵

$$\delta = C (R_{\text{UO}_2} + R_{\text{clad}})$$

where R $\equiv$ arithmetic-mean roughness height for each surface—ft

C $\equiv$ dimensionless constant = 2.5
(for interfacial pressure below 5000 psi)

- At standard temperature and pressure

$$(g_1 + g_2)_{\text{He}} = 20 \times 10^{-6} \text{ ft}$$

$$(g_1 + g_2)_{\text{A}} = 10 \times 10^{-6} \text{ ft}$$

$$(g_1 + g_2)_{\text{Kr}} = 2 \times 10^{-6} \text{ ft}$$

$$(g_1 + g_2)_{\text{Xe}} = 2 \times 10^{-6} \text{ ft}$$

and $(g_1 + g_2)$ increases directly with the absolute temperature and inversely with the gas pressure.

$$a = a_0 \sqrt{\bar{R}}$$

where $a_0 = 0.181 \text{ ft}^{1/2}$

$$\bar{R} = \sqrt{1/2 (R_{\text{UO}_2}^2 + R_{\text{clad}}^2)} \text{ ft}$$

Figure A-10. Effect of temperature on thermal conductivity of mixtures of fission product gases and helium for fission product gases of 15% Kr-85% Xe.¹³

Irradiated Thermal Conductivity of UO₂

Low Burnups (<10,000 Mwd/tonne U)

- <1000°F—Reduction in the thermal conductivity of UO₂ with the damage reaching a saturation at 0.5 Mwd/tonne U. The reduction in thermal conductivity appears to be UO₂ lattice damage.
- 1000 to 1800°F—Some reduction in thermal conductivity (approximately 10 to 20% maximum) but markedly less than for temperatures below 1000°F.
- >1800°F—No measurable reduction in the thermal conductivity of UO₂ due to irradiation.

High Burnups (10,000 to 40,000 Mwd/tonne U)

- <1800°F—At an average fuel temperature of 980°F, the effective thermal conductivity of UO₂ had decreased 24% for a burnup¹⁵ of 40,000 Mwd/tonne U. While it is not apparent as to what effect the time of irradiation had on the reduction in thermal conductivity, an appreciable part of this loss is likely to have occurred in the early stages of irradiation, as discussed previously.
- <1800°F—While little information of thermal conductivity at high temperatures and high burnup is available, there is no evidence to indicate an appreciable reduction in the UO₂ thermal conductivity at burnups to 40,000 Mwd/tonne U.

Helium a/o in Mixture of Helium and Fission Product Gases

To determine the thermal conductivity of a mixture of helium and fission product gases in a fuel element from Figure A-10, the helium a/o can be calculated using the equation

$$a/o \text{ He} = 100 \left[1 + \frac{0.036 A \times fr}{E} \left(\frac{T_F}{P_F} \right) \right]^{-1}$$

where

- A ≡ volume of fission gases generated at STP/vol of UO₂
fr ≡ fraction release of fission gases
E ≡ fuel pin void volume per UO₂ volume
T_F ≡ helium fill temperature—°R
P_F ≡ helium fill pressure—psia

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For the case where

$$\begin{aligned} T_F &\equiv 530^\circ\text{R} \\ P_F &\equiv 14.7 \text{ psia} \\ \rho_{\text{UO}_2} &\equiv 10.0 \text{ gm/cm}^3 \text{ at operating temperature} \end{aligned}$$

assuming 5000 hr operation and using Figure A-7 (assuming 95% of fission gases are Xe and Kr)

$$a/o \text{ He} = 100 \left[1 + 2.3 \times 10^{-4} \left(\frac{B \times fr}{E} \right) \right]^{-1}$$

where $B \equiv$ fuel burnup—Mwd/tonne U.

Irradiation Swelling of UO₂

Below 2000°F

For highly restrained UO₂ (>2000 psi), it is estimated that the swelling rate is about 0.4 v/o per 10⁴ Mwd/tonne U initially and that the rate increases to about 1.25 to 1.75 v/o per 10⁴ Mwd/tonne U at higher burnups (depending on restraint and fuel porosity).¹⁸ For unrestrained UO₂ it is estimated that the swelling rate is 1.25 to 1.75 v/o per 10⁴ Mwd/tonne U.* It appears that the swelling of UO₂ below 2000°F is due mainly to lattice distortion and accommodation of fission fragments.

Above 2000°F

At temperatures above 2000°F, the contribution to the swelling rate by lattice strain is apparently small.† Solid growth is estimated to be <1/3 v/o per 10⁴ Mwd/tonne U. Based on the irradiation of annular-shaped UO₂ pellets irradiated to a maximum of 30,000 Mwd/tonne U, it is estimated that the overall swelling rate of UO₂ within this range of burnups is around 1 v/o per 10⁴ Mwd/tonne U.

*This is based on irradiation of plate type fuel elements where it was postulated that the true swelling rate of UO₂ is between 1.25 and 1.75 v/o per 10⁴ Mwd/tonne U but that for highly restrained elements the apparent rate of swelling is lower (~0.4 v/o per 10⁴ Mwd/tonne U) until the as-fabricated internal porosity of the UO₂ is eliminated.

†UO₂ irradiated at low temperatures and annealed out-of-pile at above 1800°F has demonstrated the recovery of lattice structure.¹⁷

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Boron Carbide

DESIGN LIMITATIONS

Material Specifications

The design limitations and materials property data presented in these criteria are based on the B₄C materials specifications summarized in Table A-IV.

Table A-IV.
B₄C tentative material specifications.

Composition	B ₄ C, 92% enriched in B-10 72.4 w/o B-10
Fabrication method	Hot pressing ¹⁹
Density	
Theoretical density (natural) ²⁰	2.51 gm/cm ³
Theoretical density (92% enrichment in B-10)	2.38 gm/cm ³ (calculated)
Attainable ¹⁹	99% TD

Assembly Configuration

All B₄C to be used within the MCR pressure vessel shall be separated from the reactor coolant by hermetically sealed encapsulating tubes. Heat generated in the B₄C shall be dissipated to the reactor coolant through a helium gas gap between the B₄C and the encapsulating tube. The tube shall be made of type 316 stainless steel and shall be designed to accommodate release of helium gas generated in the B₄C under irradiation.

Lifetime

Lifetime requirements are defined in terms of the MCR reactor thermal output. The system design must account for all steady-state and transient operating conditions as well as start-up, shutdown, and transportability cyclical requirements. The poison material within the control drums shall have a minimum lifetime of 375,000 Mw_t-hr or 40,000 operational hours, whichever is less.

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Design Stress

Stress categories and limits as defined in the MCR Structural Design Criteria in Volume I shall be considered in the design and evaluation of the stainless steel tubing. The tubing shall be designed, consistent with the limits for a ductile material, to contain the helium gas release from the B₄C but not to restrain the thermal expansion or swelling of the B₄C. The B₄C is not a load-bearing material in the assembly configuration. The tubing shall be designed to be free-standing and capable of withstanding external coolant pressure without collapsing against and depending on the B₄C for support.

Geometry

The configuration of the B₄C shall be determined in conformance with the preceding design limitations to achieve the following.

- A copper barrier shall be provided to prevent contact between the B₄C and the stainless steel tubing.
- Physical dimensional tolerances shall permit B₄C expansion and swelling, helium gas release, and internal pressure increase due to temperature rise, without exceeding allowable stress limits.

Gas Generation and Release

Gas release limits are based on extrapolation of experimental data.

For the B₄C at MCR conditions, the design shall be based on a gas release rate of 30% of the total gas generated.²³

Burnup

The maximum burnup of B-10 atoms shall be limited to 15%.

Dimensional Stability

The B₄C tube design shall be based on an irradiation swelling of the B₄C of 7 v/o for burnup of 15% of the B-10 atoms.

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MATERIALS DATA

Physical and mechanical property data are presented in Tables A-V and A-VI.

Table A-V.
B₄C physical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Thermal conductivity	See Figure A-11	21
Thermal expansion (200 to 800°C)	$4.5 \times 10^{-6}/^{\circ}\text{C}$	22
Electrical resistivity (25°C)	$3.8 \times 10^5 \mu \text{ ohm-cm}$	22
Heat capacity (20°C)	0.233 cal/gm-°C	22
Melting point	2460°C	22
Crystal structure*		20, 22
a ₀	5.60Å	
c ₀	12.12Å	

*B₄C has an open lattice structure in which there are several positions sufficiently large to accommodate fission atoms.

Figure A-11. Effect of temperature on thermal conductivity of boron carbide.²¹

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Table A-VI.
B₄C mechanical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Compression strength (25°C)	420,000 psi	19, 22
Young's modulus	65.3×10^6 psi	22
Tensile strength (980°C)	22,500 psi	22
Modulus of rupture		19, 22
70°F	50,000 psi	
1200°F	42,000 psi	
2000°F	35,000 psi	
Modulus of elasticity (70°F)	65×10^6	19
Knoop hardness (100 gm)	2800	19
Impact resistance	Low	22

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BeO Reflector Material

DESIGN LIMITATIONS

Material Specifications

The design limitations and materials properties data presented in these criteria are based on the BeO materials specifications summarized in Table A-VII. The chemical composition of UOX grade BeO is given in Table A-VIII.

Table A-VII.
BeO tentative material specifications.

Composition	≤ 1 w/o MgO or Bentonite* in UOX grade BeO (Brush Beryllium Co. designation)
Fabrication method	Cold pressed, sintered, and outgassed during canning to remove volatile impurities
Density	2.85 gm/cm ³ (95% of theoretical density)
Grain size	20 microns or less

*Hydrous (MgCa) aluminum silicate.

Table A-VIII.
UOX grade BeO impurity content.

<u>Element</u>	<u>Impurity (ppm)</u>	<u>Element</u>	<u>Impurity (ppm)</u>	<u>Element</u>	<u>Impurity (ppm)</u>
Al	30	V	10	Mo	<3
As	< 30	Zn	< 20	Na	7
B	< 0.5	Cr	< 3	Ni	5
Ba	< 3	Cu	3	P	<100
Bi	< 2	Fe	20	Pb	<1
Ca	20	K	< 5	Sb	<10
Cd	< 3	Li	2	Si	100
Co	< 5	Mg	20	Sn	<3
Ti	< 10	Mn	1	Sr	<1

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Assembly Configuration

All BeO to be used within the MCR pressure vessel shall be separated from the reactor coolant by a hermetically sealed encapsulating structural can housing. Heat generated in the BeO shall be dissipated to the reactor coolant through a helium gas gap between the BeO and the encapsulating can. The can shall be made of type 316 stainless steel for the radial reflector in the rotating control drums. It shall be designed to accommodate release of helium gas generated in the BeO under irradiation.

Lifetime

Lifetime requirements are defined in terms of MCR operational hours. The system design must account for all steady-state and transient operating conditions as well as start-up, shut-down, and transportability cyclical requirements. The material in the control drums shall have a minimum lifetime of 25,000 operational hours and a preferred life of 40,000 operational hours or 5 yr, whichever is less.

Design Stress

Stress categories and limits as defined in the MCR Structural Design Criteria in Volume I shall be considered in the design and evaluation of both the structural can housing and the BeO. The housing shall be designed, consistent with the limits for a ductile material, to contain the helium gas released from the BeO but not restrain the thermal expansion or swelling of the BeO. The housing shall be designed to be freestanding and capable of withstanding external coolant pressure without collapsing against and depending on the BeO for support. The BeO, consistent with the limits for a brittle material, is not a load-bearing material in the assembly configuration but should be designed to maintain its integrity under thermal stress cycling.

Geometry

The configuration of the BeO shall be determined in conformance with the preceding design limitations to achieve the following goals.

- A thermal barrier shall be achieved to maintain temperatures above that region in which intergranular separation occurs.
- Physical dimensional tolerances shall permit BeO expansion and swelling, helium gas release, and structural can internal pressure increase, due to temperature rise, without exceeding allowable stress limits.

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- Thermal stress as a result of a temperature gradient will conform to the stress limitations for a brittle material.
- Thickness of the BeO will be determined to minimize differential growth between the inner and outer faces as a result of neutron flux attenuation and spectrum change.
- The helium generation and release, controlling BeO swelling, shall be set by the physical and stress limitations of the design.

Gas Generation and Release

The helium gas generated in the BeO is a function of the neutron environment. Some of the gas generated is contained by the BeO and the remainder is released to the gas environment of the structural can housing. It has been postulated that helium loss from the BeO occurs by volume diffusion and, therefore, the fraction of gas generated remaining in the BeO can be estimated on the basis of the BeO component size and geometry.

The fraction, f_r , of helium formed that remains in a solid cylinder having a large length in comparison to the diameter is given by⁴⁹

$$f_r = \frac{4r^2}{Dt} \sum_{n=1}^{\infty} \left(\frac{1 - e^{-Da_n^2 t / r^2}}{a_n^4} \right)$$

where

- r = radius of the cylinder—cm
- D = diffusion coefficient—cm²/sec (see Reference 49 for experimental values)
- t = time—sec
- a_n = roots of the J_0 Bessel function

This formulation is based on a correlation with experimental data.⁴⁹ However, since there is considerable uncertainty as to the confidence limits which may be placed on the diffusion coefficients and the effects of actual diffusion surface versus geometric surface, the limits for gas release specified herein have been set at a minimum value based on an extrapolation from experimental data most closely approaching MCR conditions. The design gas release shall be 50% of that generated in the BeO during irradiation.

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The initial gas gap between the BeO and the cladding shall contain helium at an initial pressure of 1 atm at room temperature. If the release computed by the volume diffusion correlation exceeds this minimum, it should be used as the controlling design value.

Temperature Limitations

Irradiation damage due to displaced atoms as a function of time is evidenced by swelling of the lattice, which, if uncontrolled, could lead to grain boundary separation and resultant cracking and possible powdering of the BeO. Since the neutron environment is to be based on reactor nuclear considerations, the irradiation damage shall be limited by thermal annealing wherein the atoms return to their normal lattice sites. The rate of thermal annealing is a function of the operating BeO temperature.

Swelling due to irradiation can be expressed as³⁰

$$\left(\frac{\Delta V}{V}\right)_L = \frac{K}{A} (1 - e^{-At})$$

where

K = defect production rate
A = defect annealing rate
t = time of irradiation—sec

$$K = 3.3 \times 10^{-23} \phi$$

$$A = 1.9 \times 10^{-4} e^{-10,400/RT}$$

where

K and A are defined in terms of $(\Delta V/V)_L$ /sec
 ϕ = the neutron flux, $n_v \geq 1$ Mev
R = molar gas constant = 1.987 cal/°K-mole
T = absolute temperature—°K

Dimensional Stability

The BeO minimum operating temperature shall be that required to limit the $(\Delta V/V)_L$ to 0.3. This value is approximately 25% below that believed to be the limiting value for grain boundary separation.

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MATERIALS DATA

Physical and mechanical properties data are presented in Tables A-IX and A-X. Data for un-irradiated material and the effects of irradiation are included.

Table A-IX.
BeO physical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
General physical properties	See Table A-XI.	As listed
Theoretical versus measured density	See Figure A-12.	Calculated
Thermal expansion	See Table A-XII.	39
Elastic modulus, temperature effects	See Figure A-13.	34, 39
Elastic modulus, density effects	See Figure A-14.	38
Rigidity modulus	See Figure A-15.	42
Internal friction	See Figure A-16.	43
Electrical resistivity	See Figure A-17.	33
Dielectric constant	See Figure A-18.	Information supplied by National Beryllia Corpo- ration
Emissivity	See Figure A-19.	35
Thermal conductivity, temperature effects	See Figure A-20.	34, 39, 44
Specific heat	See Figure A-21.	43
Enthalpy change	See Figure A-22.	35
Standard enthalpy change	See Figure A-23.	35
Standard free energy change	See Figure A-24.	35
Entropy change	See Figure A-25.	35
$G^\circ-H^\circ/T$ values (free energy function)	See Figure A-26.	26
Thermal conductivity and nvt effects	See Figure A-27.	25 to 32
Effect of irradiation temperature on length expansion	See Figure A-28.	31
Volume increase versus nvt, experimental	See Figure A-29.	32
Volume expansion computed versus nvt at 2×10^{13} nv	See Figure A-30.	30
Volume expansion computed versus nvt at 2×10^{14} nv	See Figure A-31.	30

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Table A-X.
BeO mechanical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Ultimate tensile strength	See Figure A-32.	35, 38
Compressive strength	See Figure A-33.	35
Tensile creep at 95 psi	See Figure A-34.	38
Tensile creep—various stress and temperatures	See Figure A-35.	42
Compressive creep at 100 psi	See Figure A-36.	45
Compressive creep at 1200 and 1500°C	See Table A-XIII.	46, 47
Modulus of rupture	See Table A-XIV.	34, 38
Stress to rupture at 1400°C	See Figure A-37.	48
Ratio of irradiated to unirradiated modulus of rupture	See Figure A-38.	30

Table A-XI.
BeO general physical properties.^{33,41}

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Crystal lattice	Hexagonal	33
Structure	Wurtzite	33
a_0	2.6980 Å	34
C_0	4.3780 Å	34
C_0/a_0	1.623	34
Bonding	Ionic	35
Allotropy	Possible cubic form above 2050°C	36
Molecular weight	25.01	
Density*	3.008 gm/cm ³	33
Melting point	2570°C	35
Boiling point	4300°C	33
Specific heat, * C_p (25 to 925°C)	$8.45 + 4.00 \times 10^{-3} T_{(K)} - 3.17 \times 10^{-5} T_{(K)}^2$	35
Heat of fusion	15,440 cal/mole	37
Entropy of fusion	5475 cal/mole-°C	37
Heat of vaporization	117,000 cal/mole	35
Entropy of vaporization	25.6 cal/mole-°C	35
Heat of sublimation (600 to 3000°C)	152,000 cal/mole	35

*Further information in graphs or tables.

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Table A-XI. (cont)

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Vapor pressure (1977 to 2140°C)	$\text{Log}_{10} P_{\text{mm}} = 18.50 - 34,230/T_{(\text{C})}$ $-2 \log_{10} T_{(\text{C})}$	35
Dielectric constant* (93% TD)	6.3	35
Diamagnetic susceptibility	-11.93×10^{-6} emu	35
Index of refraction	1.726	38
Work function	3.30 ev	35
	3745 Å photoelectric threshold	
Coefficient of linear expansion* (0 to 1500°C)	10.15×10^{-6} in./in.-°C	39
Modulus of elasticity* (20°C)	55×10^6 psi (100% TD)	39
Shear modulus (20°C)	20×10^6 psi (96.5% TD)	40
Poisson's ratio (20 to 1000°C)	0.204 (dynamic, 100% TD)	39
	0.34 (static, 93% TD)	39
Critical temperatures		
1000°C	BeO deforms plastically	35
2000°C	Extensive grain growth	41
2050°C	Possible disintegration of BeO	41
2050°C	Possible transformation to a cubic structure	36

*Further information in graphs or tables.

Table A-XII.
BeO thermal expansion.³⁹

<u>Temperature range (°C)</u>	<u>Coefficient of thermal expansion (in./in.-°C)</u>	<u>Temperature range (°C)</u>	<u>Coefficient of thermal expansion (in./in.-°C)</u>
0 to 200	5.60×10^{-6}	0 to 500	7.24×10^{-6}
200 to 400	7.95	500 to 1000	10.32
400 to 600	9.30	1000 to 1500	12.84
600 to 800	10.15		
800 to 1000	10.90	0 to 500	7.24×10^{-6}
1000 to 1200	12.60	0 to 1000	8.78
1200 to 1400	13.25	0 to 1500	10.15
1400 to 1600	12.75		
1600 to 1800	12.25		

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Figure A-12. A comparison of theoretical with measured density of BeO.

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Figure A-13. Effect of temperature on elastic modulus of BeO.^{33,39}

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Figure A-14. Effect of density on dynamic elastic modulus of BeO at room temperature.³⁸

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Figure A-15. Effect of temperature on modulus of rigidity of BeO.⁴²

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Figure A-16. Effect of temperature on internal friction of BeO.⁴³

Figure A-17. Effect of temperature on electrical resistivity of 96.5% theoretical density BeO.³³

Figure A-18. Effect of temperature on dielectric constant of 100% theoretical density BeO.

Figure A-19. Effect of temperature on emissivity of BeO.³⁵

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Figure A-20. Effect of temperature on thermal conductivity of BeO.^{34,37,44}

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Figure A-21. Effect of temperature on specific heat of BeO.⁴³

Table A-XIII.
BeO compressive creep.

<u>Relative purity</u>	<u>Grain size (microns)</u>	<u>Percent of theoretical density</u>	<u>Load (psi)</u>	<u>Creep (%)</u>
<u>At 1200°C in 500 hr</u> ^{46,47}				
Low (commercial)	16	95.6	1000	0.18
	15	95.2	3000	0.62
	46	98.6	2000	0.03
	43	98.6	3000	0.03
	43	96.5	6000	0.09
High (reactor)	22	96.4	3000	0.09
Very high	20	96.1	6000	0.22
	15	96.3	3000	0.18
	15	94.0	3000	0.68
<u>At 1600°C</u> ⁴⁷				
-	-	99.7	10,000	0.0

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Figure A-22. Effect of temperature on enthalpy change of BeO.³⁵

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Figure A-23. Effect of temperature on standard enthalpy change of BeO.³⁵

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Figure A-24. Effect of temperature on standard free energy change of BeO.³⁵

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Figure A-25. Effect of temperature on entropy change of BeO.³⁵

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Figure A-26. Effect of Temperature on free energy function ($G^\circ-H^\circ/T$ values) of BeO .²⁶

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Figure A-27. Suggested values of thermal conductivity at 1500°F of BeO irradiated at 1500°F, as a function of integrated neutron flux.²⁵⁻³²

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Figure A-28. Effect of irradiation temperature on percentage of length expansion for four microstructures of UOX-MgO.³¹

Figure A-29. Effect of irradiation temperature and integrated neutron flux on volume expansion of UOX-grade BeO containing 0.5% MgO.³²

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Figure A-30. Effect of temperature and integrated neutron flux on expansion behavior of randomly oriented BeO of 20-micron grain size and 2.9 gm/cm³ in neutron flux of 2×10^{13} nv (≥ 1 Mev).³⁰

Figure A-31. Effect of temperature and integrated neutron flux on expansion behavior of randomly oriented BeO of 20-micron grain size and 2.9 gm/cm³ in neutron flux of 2×10^{14} nv (≥ 1 Mev).³⁰

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Figure A-32. Effect of temperature on ultimate tensile strength of BeO.^{35,38}

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Figure A-33. Effect of temperature on compressive strength of 94% theoretical density BeO .³⁵

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Figure A-34. Creep of BeO at 95 psi.³⁸

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Figure A-35. Creep of BeO.⁴²

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Figure A-36. Effect of temperature on compressive creep of BeO for a 100-psi load, approximately 10-micron grain size, and 96% theoretical density.⁴⁵

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Table A-XIV.
BeO modulus of rupture.^{34,37}

Relative purity	Grain diameter (microns)	Density (gm/cm ³)	Modulus of rupture × 10 ³ (psi)						Reference
			20°C	300°C	500°C	800°C	1000°C	1200°C	
Commercial grade (low)	5	2.60 (86.5% TD)	26.9	27.1	29.0	24.5	21.4	16.6	34
	10		28.4	30.1	33.7	30.3	24.9	18.5	
	20		25.1	23.8	24.1	23.8	20.4	17.0	
	50		18.1	16.7	18.5	19.9	18.6	20.4	
	5	2.75 (91.5% TD)	26.0	31.7	37.3	32.1	21.8	19.5	
	10		34.1	35.7	38.8	33.6	27.4	22.3	
	20		27.1	29.2	30.1	28.9	27.2	21.4	
	50		20.2	21.7	27.4	28.2	28.3	17.8	
	80	2.90 (96.5% TD)	14.4	12.8	19.8	15.6	20.8	19.7	
	10		33.3	37.7	34.1	30.7	25.2	19.8	
	20		35.0	35.1	34.9	33.8	25.3	20.3	
	50		19.4	20.7	20.1	25.1	24.5	22.9	
	80		15.4	22.3	20.9	23.1	22.8	22.4	
	100		12.1	15.0	13.8	19.1	18.2	18.4	
Reactor grade (high)	20	2.90	30.3	35.1	37.3	40.4	35.6	31.1	34
	5	2.75	26.7	25.4	25.5	34.9	32.4	19.0	
	20	2.90	23.5	23.5	25.8	31.6	34.2	26.6	
	50		17.0	15.4	15.2	24.7	26.9	18.2	
	80		14.3	14.2	11.0	20.0	26.7	30.6	
	100		15.0	-	-	-	-	-	
-	-	99.7% TD	21.5	20.0	19.0	17.5	16.5	15.5	47

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Figure A-37. Maximum stress to rupture in bending BeO.⁴⁸

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Figure A-38. Ratio of postirradiation to preirradiation modulus of rupture strength as a function of percent length expansion for 20-micron grain size 2.9 gm/cm^3 AOX and UOX-MgO.³⁰

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Tungsten

DESIGN LIMITATIONS

Material Specifications

The design limitations and materials property data presented in these criteria are based on tungsten and tungsten composite having the following compositions:

- For use in reflector—commercial tungsten of 99.95% purity
- For use in shield—tungsten composite having a composition such as 95% W, 4% Ni, and 1% Cu

Assembly Configuration

The tungsten reflector material within the MCR pressure vessel shall be unclad. Heat generated within the tungsten shall be dissipated by conduction to the reactor coolant.

The tungsten composite shield material within the reactor coolant stream shall be encased in a type 316 SS can. Heat generated in the composite shall be dissipated to the reactor coolant through a helium gas gap between the composite and the can.

The tungsten composite material located outside the liquid metal system shall be plated to prevent oxidation.

Lifetime

Lifetime requirements are defined in terms of MCR operational hours. The design must account for all steady-state and transient operating conditions as well as start-up, shutdown, and transportability cyclical requirements. The tungsten material shall have a minimum lifetime of 25,000 operational hours with a preferred life of 40,000 operational hours or 5 yr, whichever is less.

Design Stress

Stress categories and limits as defined in the MCR Structural Design Criteria in Volume I shall be considered in the design and evaluation of both the structural can, the tungsten, and tungsten composite. The housing shall be designed, consistent with the limits for a ductile material, to

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be freestanding and capable of withstanding external coolant pressure without collapsing against and depending on the composite for support, but not to restrain the thermal expansion or swelling of the composite. The tungsten and the composite, consistent with the limits for a brittle material, are not load-bearing materials in the assembly configuration but should be designed to maintain their integrity under thermal stress cycling, thermal shock, and mechanical shock conditions.

Geometry

The configuration of the tungsten and tungsten composite shall be determined in conformance with the preceding design limitations to achieve the following.

- Physical dimensional tolerances shall permit tungsten and composite expansion and swelling and structural can internal pressure increase, due to temperature rise, without exceeding allowable stress limits.
- Thermal stress as a result of a temperature gradient will conform to the stress limitations for a brittle material.
- Tungsten shapes are to be designed so that they can be pressed and sintered close to final dimensions (tungsten composite shapes can be machined).
- Supports for the tungsten and tungsten composite shall be designed to minimize impact due to a shock load.

Dimensional Stability

Provision shall be made in the design for an irradiation swelling of 2 v/o for both the tungsten and the composite for the lifetime specified.

MATERIALS DATA

Physical and mechanical property data are presented in Tables A-XV and A-XVI.

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Table A-XV.
Tungsten physical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Density*		50
Tungsten		
75°F, 93% TD	18 gm/cm ³	
1300°F	17.8 gm/cm ³	
Composite (75°F)	17.8 gm/cm ³	
Thermal expansion*		51
Tungsten (70 to 1500°F)	$2.63 \times 10^{-6}/^{\circ}\text{F}$	
Composite (70 to 1500°F)	$2.8 \times 10^{-6}/^{\circ}\text{F}$	
Thermal conductivity*		51
Tungsten		
75°F	72.6 BTU/hr-ft ² /°F	
1300°F	67.5 BTU/hr-ft ² /°F	
Composite (75°F)	79 BTU/hr-ft ² /°F	
Melting point		51, 52
Tungsten	6170°F	

*Information also supplied by Mallory Metallurgical Corporation.

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Table A-XVI.
Tungsten mechanical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Modulus of elasticity*		51
Tungsten		
75°F	55×10^6 psi	
1300°F	50×10^6 psi	
Composite (75°F)	40×10^6 psi	
Ultimate tensile strength		53, 54
Tungsten		
75°F	59,000 psi	
1300°F	50,000 psi	
Composite		
75°F	85,000 psi	
1300°F	30,000 psi	
Yield strength (0.2% offset)		53, 54
Tungsten		
75°F	59,000 psi	
1300°F	18,000 psi	
Composite (75°F)	82,000 psi	
Poisson's ratio		Information supplied by Fansteel Metallurgical Corporation
Tungsten	0.284	
Impact strength (Charpy V-notch)*†		55, 56
Tungsten	See Figure A-39	
Composite	2 ft-lb	

*Additional information supplied by Mallory Metallurgical Corporation.

†Additional information supplied by General Electric Company.

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Table A-XVI. (cont)

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Elongation		Information supplied by
Composite		Mallory Metallurgical
75°F	1.5%	Corporation
1300°F	2%	
Hardness (R _A)		Information supplied by
Composite		Mallory Metallurgical
70°F	65	Corporation
1300°F	45	
Ductile-to-brittle transition		54
Tungsten	See Figures A-40, A-41, and A-42.	
Effects of irradiation on pure tungsten	See Table A-XVII.	As listed

Figure A-39. Effect of test temperature on impact properties of tungsten.^{55,56}

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Figure A-40. Effect of purity on ductile-to-brittle transition of tungsten.⁵⁴

Figure A-41. Effect of crystal structure on ductile-to-brittle transition of tungsten.⁵⁴

Figure A-42. Effect of strain rate on ductile-to-brittle transition of tungsten.⁵⁴

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Table A-XVII.
Effects of irradiation on pure tungsten.^{57,61}

<u>nvt</u>	<u>T_{irr}</u> (°F)	<u>T_{test}</u> (°F)	<u>Property</u>	<u>Δproperty</u> (%)	<u>Remarks</u>	<u>Reference</u>
$\sim 5 \times 10^{19}$ (fast) (2 specimens)	212	400	Ultimate tensile strength	+11	99.9% pure W wire Slow bend D-B transition increased from 244 to 262°F	57
			Ultimate tensile strength	0		
			Yield strength	+11		
			Yield strength	-11.5		
			% elongation	(0-0)		
			% elongation	(2.4-4.2)		
6×10^{19}			Density	0	99.9% pure W	58
			Dimensions	0		
5×10^{19} (fast) (estimate) (2 specimens)			Ultimate tensile strength	-9		59
			Ultimate tensile strength	-34		
			% elongation	(0-0)		
			% elongation	(0-0)		
4.9×10^{19} >1 Mev	120	75	Density	-0.10	99.99 a/o pure W	60
5×10^{19} (fast)	100		Transition temperature	(+8°C)	Subsize tension and impact specimens	61

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Borated Stainless Steel

DESIGN LIMITATIONS

Material Specifications

The design limitations and materials property data presented in these criteria are based on borated stainless steel alloy having 1 w/o boron (92% enriched in B-10) in type 304 stainless steel.

Assembly Configuration

All internal shielding material within the MCR pressure vessel shall consist of unclad borated stainless steel. Heat generated within the borated stainless steel shall be dissipated by conduction to the reactor coolant.

Lifetime

Lifetime requirements are defined in terms of the MCR reactor thermal output. The design must account for all steady-state and transient operating conditions as well as start-up, shut-down, and transportability cyclical requirements. The material shall have a minimum lifetime of 375,000 Mw_t -hr or 40,000 operational hours, whichever is less.

Design Stress

Stress categories and limits as defined in the MCR Structural Design Criteria in Volume I shall be considered in the design and evaluation of the borated stainless steel shielding.

Geometry

The configuration of the borated stainless steel shall be determined in conformance with the preceding design limitations to achieve the following.

- Physical dimensions shall permit expansion and swelling due to irradiation without exceeding allowable stress limits.
- Thermal stress as a result of a temperature gradient shall conform to the allowable stress limits for a brittle material.
- Configuration of the borated stainless steel shall be designed to avoid welded joints.

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Burnup

The maximum burnup of B-10 atoms shall be limited to 25%.

Dimensional Stability

The supports and surrounding structure for the borated stainless steel shall be designed to allow for an irradiation swelling of 2% in any direction.

MATERIALS DATA

Physical and mechanical property data are presented in Tables A-XVIII and A-XIX.

Table A-XVIII.
Borated stainless steel physical properties.

<u>Property*</u>	<u>Value</u>	<u>Reference</u>
Density	See Figure A-43.	54
Thermal expansion	See Figure A-44.	54

*For other required physical property data use those of type 304 stainless steel.

Figure A-43. Variation of mean density of type 304 stainless steel plus 1.0 w/o B-n with temperature.⁵⁴

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Figure A-44. Effect of temperature on the mean coefficient of linear thermal expansion of type 304 stainless steel plus 1.0 w/o B-n.⁵⁴

Table A-XIX.
Borated stainless steel mechanical properties.

Property	Value	Reference
Percent elongation	See Figures A-45 and A-46.	54, 69
Charpy impact strength	See Figure A-45.	69
Ultimate tensile strength	See Figures A-45 and A-47.	54, 69
Rockwell hardness	See Figure A-45 and Table A-XX.	54, 69
Yield strength	See Figures A-45 and A-47.	54, 69
Fatigue behavior	See Figure A-48.	69
Stress to produce rupture	See Figure A-49.	54
Stress to produce 0.2% creep	See Figure A-50.	54
Modulus of elasticity	See Figure A-51.	54
Irradiated tensile properties	See Figure A-52 and Table A-XXI.	54, 69
Irradiated impact properties	See Table A-XXII.	69

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Figure A-45. Effect of boron content on mechanical properties of 18 w/o Cr, 10 w/o Ni, boron-stainless steels.⁶⁹

Figure A-46. Effect of temperature on elongation of type 304 stainless steel plus 1.0 w/o B-n in short-time tensile failure.⁵⁴

Figure A-47. Effect of temperature on short-time tensile properties of type 304 stainless steel plus 1.0 w/o B-n.⁵⁴

Table A-XX.

Preirradiation and postirradiation hardness* of type 304 stainless steel plus 1.0 w/o B-n and type 304 stainless steel plus 0.2 w/o B-10.⁵⁴

10¹⁹ nvt at 1200°F

Type 304 stainless steel and 0.2 w/o B-10 Type 304 stainless steel and 1.0 w/o B-n

	Preirradiation	Postirradiation	Preirradiation	Postirradiation
Range	23 to 30	22 to 40	32 to 43	35 to 49
Average	27	31	37	42

*Rockwell 30-N.

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Figure A-48. Fatigue behavior of B-10 stainless steel—model burnable poison elements.⁶⁹

Figure A-49. Larson-Miller parameter for stress to produce rupture in type 304 stainless steel plus 1.0 w/o B-n.⁵⁴

Figure A-50. Larson-Miller parameter for stress to produce 0.2% creep in type 304 stainless steel plus 1.0 w/o B-n.⁵⁴

Figure A-51. Effect of temperature on modulus of elasticity (dynamic) of type 304 stainless steel plus 1.0 w/o B-n.⁵⁴

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Figure A-52. Effects of radiation environment on tensile properties of type 304 stainless steel boron.⁵⁴

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Table A-XXI.

Irradiated tensile properties of 1.0 w/o B-10 stainless steel.*⁶⁹

Test temperature (°F)	Thermal flux (nvt)	Boron depletion (% B-10)	Ultimate tensile strength (psi)	Percent increase from non-irradiated	0.2% yield strength (psi)	Percent increase from non-irradiated	Percent elongation	Percent decrease from non-irradiated
RT	2.6×10^{20}	15	153,500	26.0	149,000	60	3.4	78
RT	4.4×10^{20}	25	137,100	13.4	-	-	1.6	90
RT	7.8×10^{20}	40	59,350	-51.2	-	-	-	-
RT	30.5×10^{20}	86	24,800	-79.5	-	-	-	-

*1.0 w/o B-10, 18.0 w/o Cr, 8.0 w/o Ni

Table A-XXII.

Irradiated impact properties of 1.18 w/o boron stainless steel.*⁶⁹Boron depletion

Test temperature (°F)	Thermal flux (nvt)	Percent B-10	Percent of total atoms	Impact strength (ft-lb)	Percent decrease from nonirradiated
RT	4.35×10^{20}	37.7	0.44	0.61	73.5
600	4.35×10^{20}	37.7	0.44	0.66	63.0

*1.18 w/o B, 18 w/o Cr, 12 w/o Ni

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Lead Gamma Shield Material

DESIGN LIMITATIONS

Material Specifications

The design limitations and materials property data presented in these criteria are based on corroding lead proposed for use as a gamma shield. "Doe Run Lead," manufactured by St. Joseph Lead Co. (or an approved equivalent), is a good quality commercial lead with a small impurity content. The chemical composition of this type of lead is given in Table A-XXIII.

Table A-XXIII.
Chemical composition of corroding lead.⁷²

<u>Element</u>	<u>Maximum content (ppm)</u>
Silver	4
Cadmium	2
Copper	1
Cobalt-nickel	1
Arsenic, antimony, and tin together	1
Zinc	1
Iron	1
Bismuth	0

Assembly Configuration

Both the fixed and removable shields shall use lead as a gamma shield material. Lead deformation as a result of temperature, steady-state structural loadings, and transportability shock loadings will be restrained by a suitable aluminum or stainless steel canning. The lead and canning material shall be metallurgically bonded to provide common structural action between the two materials at all times.

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Lifetime

Lifetime requirements are defined in terms of MCR operational hours. The design must account for all steady-state and transient operating conditions as well as start-up, shutdown, and transportability cyclical requirements. The lead gamma shield material shall have a minimum lifetime of 25,000 operational hours with a preferred life of 40,000 operational hours or 5 yr, whichever is less.

Design Stress

Stress categories and limits as defined in the MCR Structural Design Criteria in Volume I shall be considered in the design and evaluation of lead gamma shield segments. Loads shall be distributed proportionately between the can material and the lead in accordance with their moduli of elasticity and cross-sectional areas.

Lead Temperature

The maximum lead temperature shall not exceed 500°F, providing a margin of 120°F below the melting point. Maintaining lead in the solid form eliminates the need of designing the can housing for the large volume increase of lead which occurs with a phase change. In addition, the mechanical properties of the lead can significantly contribute to the shield structural design if the lead is maintained at a lower temperature.

Radiation Streaming

Clearance gaps in the shield assembly to account for assembly tolerances and shield segment thermal expansion shall be either staggered or offset to eliminate direct radiation streaming. The offset shall be equivalent to a minimum of one step at right angles to the gap, equal in length to at least two times the gap thickness, where the gap thickness includes the thickness of any structural material adjacent to the gap.

MATERIALS DATA

Physical and mechanical properties data are presented in Tables A-XXIV and A-XXV. The data are for corroding lead conforming to ASTM B29-55 and are assumed to be applicable also to high purity lead.

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Table A-XXIV.
Lead gamma shielding physical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Density (68°F)	0.409 lb/in. ³	71
Density and temperature effects	See Figure A-53.	71
Melting point	621°F	71
Linear coefficient of thermal expansion		71
63 to 212°F	16.3×10^{-6} in./in.-°F	
-310 to 66°F	14.7×10^{-6} in./in.-°F	
Specific heat (200°F)	0.031 BTU/lb-°F	71
Specific heat and temperature effects	See Figure A-54.	71
Thermal conductivity (200°F)	19.4 BTU/hr-ft-°F	71
Thermal conductivity and temperature effects	See Figure A-55.	71
Latent heat of fusion	11.3 BTU/lb	72
[REDACTED] in volume on fusion	4.01%	72

Decrease

Figure A-53. Effect of temperature on density of corroding lead.⁷¹

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Figure A-54. Effect of temperature on specific heat of corroding lead.⁷¹

Figure A-55. Effect of temperature on thermal conductivity of corroding lead.⁷¹

Table A-XXV.
Lead gamma shielding mechanical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Tensile strength (68°F)	1920 psi	72
Tensile strength and temperature effects	See Figure A-56.	72
Yield strength (68°F)	800 psi	71
Modulus of elasticity (68°F)	2×10^6 psi	71
Larson-Miller parameter for creep of lead versus stress	See Figure A-57.	71, 72

Figure A-56. Effect of temperature on tensile strength of lead.⁷²

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Figure A-57. Larson-Miller parameter for creep of lead.^{71,72}

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Lithium Hydride

DESIGN LIMITATIONS

Material Specifications

The design requirements, limitations, and materials properties data presented in these design criteria are applicable to lithium hydride blocks fabricated in the manner (and having the chemical composition) specified herein. Material meeting these specifications has been fabricated and has demonstrated resistance to excessive cracking and separation of the hydride when used as a shield material.

The lithium hydride is to be isostatically pressed with 30,000 psi on a stainless steel matrix.⁵⁴ The matrix shall be a honeycomb of 0.001-in. thick series 300 stainless steel members welded into a square cell array, 1 in. across flats. To permit bonding of the hydride to the steel, 1/2-in. holes will be drilled or punched on 3/4-in. centers across the length of the matrix members. Total metal content of the compact will not exceed 2.5 w/o.

Compacted blocks will be sintered at approximately 1100°F in an inert atmosphere to drive off water and liberate H₂ formed by the reduction of LiOH and Li₂CO₃. As a result of this sintering, degradation of the LiH due to chemical interaction with impurities shall be negligible.

The isotopic composition of the lithium hydride shall be that of natural lithium: Li-6—7.5 w/o and Li-7—92.5 w/o. Chemical composition of the bulk material used for the cold pressed compact will be consistent with the minimum and maximum limits listed in Table A-XXVI.

Assembly Configuration

The lithium hydride compacts described in the preceding subsection are to be used for neutron shielding of the MCR. The compacts in the form of blocks shall be retained in hermetically sealed stainless steel and aluminum shield housings. Clearance shall be provided between the housing and the blocks to permit unrestrained thermal expansion of the blocks. The environment of the housing shall be a dried inert gas. Gas released from the lithium hydride shall be either contained within the housing or released at a controlled rate, depending on system pressure and location of the compacts.

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Table A-XXVI.
Lithium hydride chemical composition.⁸⁰

<u>Constituent</u>	<u>Unit</u>	<u>Typical</u>	<u>Minimum</u>	<u>Maximum</u>
Lithium (Li)	w/o	86.6	85.5	
Hydrogen (H)	w/o	12.4	12.0	
Hydroxide (OH)	w/o	1.0		2.5
Carbonate (CO ₃)	w/o	0.75		1.5
Chloride (Cl)	w/o	0.05		0.1
Na	ppm	100		300
Ba	ppm	30		80
Ca	ppm	40		200
Cr	ppm	6		25
Co	ppm	40		60
Fe	ppm	500		1500
K	ppm	100		400

Lifetime

Lifetime requirements are defined in terms of MCR operational hours. The design must account for all steady-state and transient operating conditions as well as start-up, shutdown, and transportability cyclical requirements. The LiH neutron shield shall have a minimum life of 25,000 operational hours, with a preferred life of 40,000 operational hours or 5 yr, whichever is less.

Design Stress

Stress categories and limits as defined in the MCR Structural Design Criteria in Volume I shall be considered in the design and evaluation of both the structural canning and the LiH blocks. The canning shall be designed consistent with the limits for a ductile material. The LiH shall be designed consistent with the limits of a brittle material.

Gas Generation and Release

Dissociation of the lithium hydride due to chemical impurities and operating temperatures and pressures resulting in release of free hydrogen will be minimal. The sintering of the pre-machined lithium hydride blocks as specified in the material specifications will be of sufficient duration to complete the reduction of any LiOH and Li₂CO₃ present in the compacts. This will

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virtually prevent any further evolution of gas due to chemical reaction. The dissociation pressure of lithium hydride is quite low, approximately 20 mm Hg at its melting point of 1267°F. Vapor pressure in the housings will be well in excess of this pressure, with temperatures maintained considerably below the melting point. Therefore, pyrolytic dissociation will be negligible.

Major gas release will be from the Li-6 (n, α) reaction resulting in the formation of helium, tritium, and the release of hydrogen originally bound by the mutated Li. It is possible and even probable that some of the tritium and hydrogen might combine with free lithium present in the compact. In addition, some of the gas formed may be retained in the pores of the compact. However, there are no experimental data available at MCR conditions; it is therefore assumed that all gas formed or released from the molecular structure will be released from the compact to the housing environment. The gas generated shall be either hermetically sealed within the housing or released at a controlled rate to the atmosphere, depending on pressure.

Radiation Stability

Available irradiation data of isostatically pressed pure lithium hydride compacts, in a stainless steel honeycomb, exposed to an nvt of 2×10^{19} and temperatures up to 1000°F have shown no measurable effects with regard to either gas evolution or dimensional changes.⁵⁴ Based on the stability indicated by these data (possibly attributable to the restraint of the stainless steel matrix and the much lower MCR temperatures), no allowance will be made for swelling of the compact as a result of the higher MCR integrated neutron dose.

Temperature

The limiting temperature for the lithium hydride is based only on maintenance of the material integrity resulting in a maximum allowable temperature approaching the melting point. Neither shielding effectiveness nor pyrolytic dissociation will be affected at these temperatures. The number of hydrogen atoms per cubic centimeter of material (N_H) is a measure of the shield effectiveness. In solid materials, the largest cause of N_H decrease is the evolution of H_2 at the higher temperatures. However, LiH is stable to above its melting point. Therefore, its N_H/ρ value of 7.53×10^{22} H atoms/gm is fairly consistent. Pyrolytic damage is also negligible as indicated by the dissociation pressure of 20 mm Hg at the melting point.

Since LiH is plastic above 1100°F, the maximum allowable temperature in the LiH shall not exceed 900°F, which is 367°F below the melting point.

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Geometry

The configuration of the lithium hydride compacts shall be determined in conformance with the preceding design limitations. They shall further be limited in size and shape by the limits of the isostatic pressing equipment, the sintering furnaces, and the machining facilities.

Gaps must be provided between the hydride compacts and the housing to accommodate differential expansion of the housing and the hydride.

The offset radiation streaming, all gaps in the LiH shielding shall have a minimum of one step at right angles to the gap, equal in length to at least two times the gap thickness. The gap thickness shall include the thickness of any metal at the gap.

MATERIALS DATA

Physical and mechanical property data of LiH are presented in Tables A-XXVII and A-XXVIII.

Table A-XXVII.
Lithium hydride physical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Melting point	1267°F	54
Density and temperature effects	See Figure A-58.	74
Thermal expansion	See Figure A-59.	75
Heat capacity	See Figure A-60.	76
Thermal conductivity	See Figure A-61.	77
Dissociation pressure	See Figure A-62.	74
N _H and density effects	See Figure A-63.	75

Table A-XXVIII.
Lithium hydride mechanical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Modulus of rupture	1800 to 2570 psi	54
Compressive strength	See Figure A-64.	78

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Figure A-58. Effect of temperature on density of lithium hydride.⁷⁴

Figure A-59. Effect of temperature on linear thermal expansion of lithium hydride.⁷⁵

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Figure A-60. Effect of temperature on heat capacity of lithium hydride.⁷⁶

Figure A-61. Effect of temperature on thermal conductivity of pressed lithium hydride.⁷⁷

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Figure A-62. Effect of temperature on dissociation pressure of lithium hydride.⁷⁴

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Figure A-63. Variation of the hydrogen atom concentration of pure lithium hydride with density.⁷⁵

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Figure A-64. Effect of temperature on ultimate compressive strength of isostatically pressed compacts of lithium hydride.⁷⁸

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Titanium Hydride

DESIGN LIMITATIONS

Material Specifications

The design requirements, limitations, and materials properties data presented in these criteria are applicable to titanium hydride blocks fabricated in the manner (and having the chemical composition) specified herein. The titanium hydride is fabricated by either cold pressing TiH_2 powder or by the direct hydriding of massive titanium metal. Such additives as TiB_2 will be used to incorporate boron and to keep grain size small and thus improve fabricability.

Material having a hydrogen atom concentration (N_H) of 8.0 has been produced by the cold pressing method.* Material having an N_H of 8.7 has been produced by the direct hydriding method.⁸⁵ Chemical composition of the material used for cold-pressed compacts will be approximately as given in Table A-XXIX.

Table A-XXIX.

Approximate chemical composition of cold-pressed titanium hydride compacts.

<u>Element</u>	<u>Composition (w/o)</u>
Ti	94.2
H	3.93
O	0.52
N	0.015
Z	0.05
Al	0.05
Ca	0.05
Fe	0.05
Hf	0.005
Mg	0.05
Si	0.05
B	1.00 (92% enriched in B-10)

*Results of United Nuclear Corporation development program.

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Assembly Configuration

The titanium hydride compacts described in the preceding section are to be used for neutron and gamma shielding of the MCR. The compacts in the form of blocks shall be retained in a stainless steel housing. Clearance shall be provided between the stainless steel housing and the blocks to permit unrestrained thermal expansion of the blocks. The environment of the housing shall be dry hydrogen. Any gas released from the titanium hydride shall be contained within the housing.

Lifetime

Lifetime requirements are defined in terms of MCR operational hours. The design must account for all steady-state and transient operating conditions as well as start-up, shutdown, and transportability cyclical requirements. The TiH_2 neutron shield shall have a minimum lifetime of 25,000 operational hours, with a preferred life of 40,000 operational hours or 5 yr, whichever is less.

Design Stress

Stress categories and limits as defined in the MCR Structural Design Criteria in Volume I shall be considered in the design and evaluation of both the structural canning and the TiH_2 blocks. The canning shall be designed consistent with the limits for a ductile material. The TiH_2 shall be designed consistent with the limits of a brittle material.

Geometry

The configuration of the titanium hydride compacts shall be determined in conformance with the preceding design limitations. The compacts shall further be limited in size and shape by the limits of the processing equipment, furnaces, and machining facilities.

Gaps must be provided between the hydride compacts and the housing to accommodate differential expansion of the housing and the hydride.

To offset radiation streaming, all gaps in the TiH_2 shielding shall have a minimum of one step at right angles to the gap, equal in length to at least two times the gap thickness. The gap thickness shall include the thickness of any metal at the gap.

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MATERIALS DATA

Physical and mechanical property data are presented in Tables A-XXX and A-XXXI.

Table A-XXX.
Titanium hydride physical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Density		81
Ti + 3.93 w/o H ($N_H = 8$), cold pressed	3.41 gm/cm ³	
Ti + ($N_H = 8.7$), hydrided	3.82 gm/cm ³	
Effect of hydrogen content on density	See Figure A-65.	82
Thermal expansion		88
Ti + 3.13 w/o H ($N_H = 7.3$), 3.9 gm/cm ³		
Room temperature	$5 \times 10^{-6}/^{\circ}\text{C}$	
500°C	$13 \times 10^{-6}/^{\circ}\text{C}$	
Specific heat	See Figure A-66.	83

Figure A-65. Effect of hydrogen content on density of titanium hydride.⁸²

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Figure A-66. Effect of temperature on mean specific heat of hydrided titanium alloy.⁸³

Table A-XXXI.
Titanium hydride mechanical properties.

Property	Value	Reference
Modulus of rupture	See Table A-XXXII.	88
Dynamic modulus of elasticity	See Table A-XXXIII.	83

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Table A-XXXII.

Modulus of rupture* or maximum fiber stress at yield point of titanium hydride. † ‡⁸⁸

Test temperature (°C)	Hours at 540°C	Cross section dimensions		Load (kg)	Modulus rupture (maximum fiber stress) (kg/mm ²)	Hydrogen analysis after test	
		Height (mm)	Width (mm)			(w/o)	Nature of fracture
20	456	6.53	8.02	199	24.8	1.93	Brittle
20	456	6.35	8.22	283	35.3	1.93	Brittle
20	456	6.22	7.90	358	44.6	1.92	Brittle
343	1072	8.25	6.02	658	34.4	-	Brittle
357	1072	6.26	6.90	406	49.9	-	Green stick-type fracture (some evidence of ductility)
385	1072	7.15	5.96	621	65.0**	-	None (ductile bend)
427	1072	8.10	6.20	544	47.5**	-	None (ductile)
540	456	6.14	7.77	182	21.2**	1.91	None (ductile)
540	456	8.12	5.98	250	21.6**	1.91	None (ductile)
540	456	6.42	7.66	204	22.1**	1.92	None (ductile)

*3-point suspension (2.3 cm span).

† Nominal hydrogen content 1.93 ± 0.02 w/o; specimen cut from 14.0-kg ingot; specimens tested after oxidation testing.

$$\ddagger MR = \frac{MC}{1} = \frac{3}{2} \times \frac{Pl}{W(H)^2}$$

**Ductile bend obtained in these samples, therefore not a true modulus of rupture—data shown for comparative purposes only.

Table A-XXXIII.

Preliminary dynamic modulus of elasticity values for titanium composites.⁸³

Sample composition (w/o)	Hydrogen content (w/o)	Density (gm/cm ³)	Dynamic modulus of elasticity × 10 ⁻⁶ (psi)					
			20°C	100°C	200°C	315°C	425°C	540°C
Ti-3B ₄ C	3.14	3.89	22.8	22.6	22.7	22.7	22.8	22.7
Ti-5TiB ₂	3.13	3.89	23.5	23.1	22.9	-	22.3	22.1
Ti	3.46	3.83	20.1	-	20.0	19.9	19.8	19.8

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Organic Shield Coolant Material

DESIGN LIMITATIONS

Material Specifications

In general, the design requirements presented in these criteria are applicable to the use of any organic coolant. The limitations and physical properties specified are based on the use in the MCR of a commercially available monoisopropylbiphenyl (MIPB) having the chemical formula $C_{15}H_{16}$ and typically consisting of a mixture of 62% meta- and 38% para isomers.

Usage

The organic coolant for the MCR will be used to cool the fixed and removable shields, the instrument thimbles, and the control drum drive mechanisms. The coolant system will consist of a continuously forced circulation pumped loop to remove heat from components being cooled and to dissipate this heat to ambient air through a heat exchanger. All fluid contact surfaces are to be either stainless steel or aluminum.

Lifetime

Lifetime requirements as applied to the coolant charge are defined in terms of the MCR reactor thermal output. The system design must account for all steady-state and transient operating conditions as well as start-up, shutdown, and transportability cyclical requirements. The initial coolant charge shall have a minimum lifetime of 75,000 Mw_t -hr or 8000 operational hours, whichever is less.

Decomposition Products

The chemical bonds between the molecules of an organic compound are disrupted by radiation energy absorption and thermal pyrolysis. This disruption results both in formation of gas and of large complex molecules having a higher boiling point than the coolant and known as high boiler residues (HBR). The gas released is mainly hydrogen with smaller quantities of methane, propane, ethylene, etc.

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The concentration of HBR on the coolant will be controlled by minimizing HBR formation where possible, and by dilution with fresh coolant. Both radiolytic decomposition and thermal pyrolysis will be determined by the reactor and shield design; the coolant system will be designed to accommodate the HBR formed. The coolant physical properties depend on the HBR concentration. An increase in HBR content results in an increase in the coolant specific gravity and viscosity and a decrease in specific heat and thermal conductivity, all of which affect the heat transfer capabilities of the fluid. These effects as a function of HBR concentration are summarized in the materials data paragraphs herein. The coolant heat transfer capability shall be based on HBR concentrations at a maximum HBR concentration of 30 w/o in the coolant charge at end of operating lifetime.

The gas formed as a result of the coolant decomposition, if not removed from the system, will saturate the coolant, resulting in excessive pressure buildup and/or gas bubble formation. Therefore, the system shall be designed either to degas the organic coolant (periodically or continuously) so that gas bubbles will not form within the shield or piping, or to cope with bubble formation by positive sweeping of gas bubbles from internal piping, by venting gas accumulation from the system, and by taking steps to prevent cavitation damage to the pumps. In any case, compositions of confined gases shall be held outside explosive limits.

Heat Transfer Correlation

Heat transfer correlations have been developed for organic coolants on the basis of experimental data. The correlation to be used is⁹¹

$$\frac{hD}{k} = 0.0117 \left(\frac{DV\rho}{\mu} \right)^{0.84} \left(\frac{C_p\mu}{k} \right)^{0.6}$$

The design shall be based on a coefficient of heat transfer determined from the physical properties of the coolant with maximum HBR concentration. A value of 80% of the analytically computed coefficient from the preceding correlation shall be used.

Heat Transfer Surface Fouling

Both inorganic and organic fouling of organically cooled heat transfer surfaces have been noted experimentally. Inorganic fouling has been attributed to the mechanism of mass transfer where an organic complex, in a steel system, extracts Fe from the colder surface and deposits it on the hot surface. The rate of deposition depends on the temperature differential of the metal

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surfaces, the temperature of the hottest surface, the coolant velocity, and coolant impurities. An increase in any of these parameters tends to increase the rate of deposition of the film.

Organic fouling has been attributed to the deposition of particulates of micron and submicron size from the coolant onto the heat transfer surface. The rate of deposition depends on the temperature of the heat transfer surface, radiation environment, coolant impurities, and coolant velocity. The fouling film is increased by increases in the first three parameters and decreased by an increase in velocity.

Inorganic fouling on heat transfer surfaces below 750°F is generally insignificant. However, the coolant system design shall account for expected levels of organic fouling. A fouling resistance of 0.003 hr-ft²-°F/BTU shall be used to reflect the effect of the organic fouling of the heat transfer surface based on the following coolant system design limitations.

- Maximum heat transfer surface temperatures shall not exceed 700°F.
- Coolant velocity past heat transfer surfaces shall not be less than 5 ft/sec.
- Impurity levels at initial charge shall not exceed the following limits: Fe less than 5 ppm, H₂O less than 50 ppm. Particulate contamination shall be controlled in the micron size by bypass filtration.

Temperature Limitations

Temperature limits for the organic coolant shall be established with respect to both operating and safety considerations including the following.

- The maximum temperature shall be such as to minimize pyrolytic damage as discussed in the Decomposition Products paragraphs and shall not exceed the coolant flash point of 315°F.
- The minimum temperature permitting operation of the shield cooling system is the lowest temperature at which the system coolant can be pumped and shall not be less than 0°F.

MATERIALS DATA

Physical properties data (before and after irradiation) applicable to monoisopropylbiphenyl (MIPB) consisting of 62% meta- and 38% para isomers are presented in Table A-XXXIV.

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Table A-XXXIV.
Monoisopropylbiphenyl physical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
Melting point	-65°F	91
Boiling point	563 to 572°F	91
Density and temperature effects	See Figure A-67.	89
Viscosity and temperature effects	See Figure A-68.	89
Specific heat and temperature effects	See Figure A-69.	89
Thermal conductivity and temperature effects	See Figure A-70.	89
Vapor pressure and temperature effects	See Figure A-71.	89
Flash point*	315°F	
Fire point*	340°F	
N _H (hydrogen atoms/cc) and temperature effects	See Figure A-72.	89
Gas solubility and temperature effects	See Figure A-73.	90
Effect of radiolytic tar on density	See Figure A-74.	89
Effect of radiolytic tar on viscosity	See Figure A-75.	89
Effect of radiolytic tar on specific heat	See Figure A-76.	89
Effect of radiolytic tar on N _H	See Figure A-72.	89
Neutron dosage effects on polymer formation	See Figure A-77.	89
Effect of gamma dosage on density	See Figure A-78.	91
Effect of gamma dosage on viscosity	See Figure A-79.	91
Effect of gamma dosage on pour point	See Figure A-80.	91
Effect of gamma dosage on flash, fire, and autoignition temperature	See Figure A-81.	91
Effect of gamma dosage on decomposition gas generation	See Figure A-82.	91

*Information supplied by Monsanto Chemical Co., St. Louis, Mo.

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Figure A-67. Effect of temperature on density of monoisopropylbiphenyl.⁸⁹

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Figure A-68. Effect of temperature on viscosity of monoisopropylbiphenyl.⁸⁹

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Figure A-69. Effect of temperature on specific heat of monoisopropylbiphenyl.⁸⁹

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Figure A-70. Effect of temperature on thermal conductivity of monoisopropylbiphenyl.⁸⁹

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Figure A-71. Effect of temperature on vapor pressure of monoisopropylbiphenyl.⁸⁹

Figure A-72. Effect of temperature and radiolytic tar content on hydrogen atom concentration of monoisopropylbiphenyl.⁸⁹

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Figure A-73. Effect of temperature on gas solubilities in monoisopropylbiphenyl at 760 mm Hg.⁹⁰

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Figure A-74. Effect of temperature and radiolytic tar content on density of monoisopropylbiphenyl.⁸⁹

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Figure A-75. Effect of temperature and radiolytic tar content on viscosity of monoisopropylbiphenyl.⁸⁹

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Figure A-76. Effect of temperature and radiolytic tar content on specific heat of monoisopropylbiphenyl.⁸⁹

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*Fast flux = 2×10^{11} nv; Thermal flux = 2×10^{12} nv

Figure A-77. Effect of integrated neutron flux on polymer formation for monoisopropylbiphenyl.⁸⁹

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Figure A-78. Effect of gamma dosage on specific gravity, 68/68°F, of monoisopropylbiphenyl.⁹¹

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Figure A-79. Effect of gamma dosage on viscosity of monoisopropylbiphenyl.⁹¹

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Figure A-80. Effect of gamma dosage on the pour point of monoisopropylbiphenyl.⁹¹

Figure A-81. Effect of gamma dosage on flash, fire, and autoignition temperature of monoisopropylbiphenyl.⁹¹

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Figure A-82. Effect of gamma dosage on decomposition gas generation of monoisopropylbiphenyl.⁹¹

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Primary System Coolant

DESIGN LIMITATIONS

Material Specifications

The coolant design limitations and material properties data presented in these criteria are based on the use of either natural potassium (93.1% K-39—6.9% K-41) or isotopically separated potassium in which 99% of the active K-41 isotope has been removed. It is assumed that both materials possess the same physical, thermodynamic, and transport properties and have the same effect on corrosion and mass transfer of structural materials when maintained at comparable impurity levels.

Coolant Quality

Potassium procured for use in the MCR primary system shall have an impurity level equivalent to or lower than that shown in Table A-XXXV. Coolant meeting these specifications is commercially available. Before introduction into the MCR system, material will be purified by aging at 160 to 180°F for 100 hr, filtered through a 5-micron stainless steel filter, and hot gettered over zirconium foil at 1500°F for a minimum of 100 hr. The purity shall be maintained for the plant lifetime by means of a hot getter purification system appended to the primary loop.

Chemical Analyses

The level of chemical impurities specified in Table A-XXXV is predicated on analyses by the following methods.

- Metallic impurities other than sodium shall be determined by standard spectrographic analysis.
- Sodium shall be determined by the flame photometric method developed under this contract.
- Oxygen shall be determined by the mercury amalgamation technique as modified by methods developed under this contract.
- Carbon shall be determined by the technique developed under this contract involving dissolution in water and oxidation by Van Slyke fluid.
- Nitrogen shall be determined by the micro-Kjeldahl technique as modified by methods developed under this contract.

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Table A-XXXV.
Potassium coolant procurement specifications.

<u>Element</u>	<u>Maximum content permissible (ppm)</u>	<u>Element</u>	<u>Maximum content permissible (ppm)</u>
Boron	10	Lead	4
Silicon	10	Iron	1
Calcium	1	Chromium	3
Manganese	1	Aluminum	2
Magnesium	5	Beryllium	1
Molybdenum	1	Nickel	2
Tin	1	Sodium	50
Vanadium	2	Oxygen	45
Copper	3	Carbon	45
Silver	1	Nitrogen	3
Titanium	10	Particulate	5 microns
Cobalt	1	matter	

The specified maximum oxygen and carbon levels of 45 ppm are based on a statistical average. Use of the analysis techniques requires that a minimum of five samples from a given batch of potassium averages 45 ppm or less and that no sample exceeds 50 ppm.

Coolant Containment

The primary coolant shall be contained under pressure in an all-welded system fabricated of type 316 stainless steel. Other welded structural components in the system shall be fabricated of Cb-1% Zr and tungsten. Purity specifications for the coolant have been established consistent with the mass transfer and corrosion limits of the structural components as detailed in the design criteria paragraphs dealing with primary system corrosion, mass transfer, and activity transfer.

Lifetime

The lifetime requirements for the coolant are defined in terms of the MCR reactor thermal output. The system design must account for all steady-state and transient operating conditions as well as start-up, shutdown, and transportability cyclical and handling requirements. An initial

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coolant charge shall have a minimum lifetime of 75,000 Mw_t -hr or 8000 operational hours, whichever is less. If possible, it shall be capable of being used for the full plant lifetime without reprocessing.

Temperature and Pressure

The coolant temperature shall be limited by the design criteria limitations, structural design, mass transfer, and corrosion of the welded structural members. Similarly, the coolant pressure shall be limited by the reactor safety design criteria in that no bulk or subcooled boiling shall be permitted under any steady-state or transient conditions. Pressurization shall be maintained by a high-purity argon cover gas above the coolant.

MATERIALS DATA

Physical properties data are presented in Table A-XXXVI.

Table A-XXXVI.
Potassium physical properties.

<u>Property</u>	<u>Value</u>	<u>Reference</u>
General physical properties	See Table A-XXXVII.	92, 93, 102
Thermodynamic properties of potassium saturated phases	See Table A-XXXVIII.	93
Density	See Figure A-83.	92, 93
Vapor pressure	See Figure A-84.	92, 93
Viscosity	See Figure A-85.	92, 96
Thermal conductivity	See Figure A-86.	92, 97
Heat capacity	See Figure A-87.	92
Latent heat of vaporization	See Figure A-88.	93
Electrical resistivity	See Figure A-89.	92, 97, 99

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Table A-XXXVII.

Natural potassium general physical properties.^{92,93,102}

<u>Property</u>	<u>Value</u>
Atomic weight	39.096
Atomic number	19
Melting point	145.8°F
Boiling point	1395°F
Density of solid (at 68°F)	53.690 lb/ft ³
Density of liquid (at BP)	41.45 lb/ft ³
Density of vapor (at BP)	0.0314 lb/ft ³
Critical data	
Critical pressure	2500 ± 735 psia
Critical temperature	3095 ± 540°F
Surface tension	
At melting point	0.0059 lb/ft
At 212 to 302°F	0.0059 lb/ft
At melting point to 392°F	0.0059 to 0.0055 lb/ft
Volume change on fusion	2.41% of solid volume
Volume bulk modulus (20°C, 99 to 493 atm)	32.1 × 10 ⁻⁶ bars ⁻¹
Latent heat of fusion	25.5 BTU/lb

Table A-XXXVIII.

Thermodynamic properties of potassium saturated phases.⁹³

<u>Temperature</u>		<u>Enthalpy</u> <u>of liquid—</u>	<u>Enthalpy</u> <u>of vapor—</u>	<u>Entropy</u> <u>of liquid—</u>	<u>Entropy</u> <u>of vapor—</u>
<u>(°F)</u>	<u>(°R)</u>	<u>(H-H₀)_L</u> <u>(BTU/lb)</u>	<u>(H-H₀)_V</u> <u>(BTU/lb)</u>	<u>S_L</u> <u>(BTU/lb-°R)</u>	<u>S_V</u> <u>(BTU/lb-°R)</u>
840	1300	246.5	1152.3	0.5988	1.2956
940	1400	264.7	1161.6	0.6123	1.2530
1040	1500	283.0	1170.4	0.6249	1.2166
1140	1600	301.2	1178.7	0.6367	1.1851
1240	1700	319.6	1186.6	0.6478	1.1580

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Table A-XXXVIII. (cont)

<u>Temperature</u>		Enthalpy of liquid— ($H-H_0$) _L (BTU/lb)	Enthalpy of vapor— ($H-H_0$) _V (BTU/lb)	Entropy of liquid— S_L (BTU/lb-°R)	Entropy of vapor— S_V (BTU/lb-°R)
<u>(°F)</u>	<u>(°R)</u>				
1340	1800	338.0	1194.8	0.6584	1.1344
1440	1900	356.7	1202.7	0.6685	1.1137
1540	2000	375.6	1210.5	0.7682	1.0956
1640	2100	394.8	1218.4	0.6875	1.0797
1740	2200	414.3	1226.5	0.6966	1.0658
1840	2300	434.2	1234.9	0.7054	1.0536
1940	2400	454.4	1243.4	0.7141	1.0428
2040	2500	475.2	1252.0	0.7225	1.0333
2140	2600	496.4	1260.9	0.7308	1.0249
2240	2700	518.2	1270.4	0.7391	1.0177

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Figure A-83. Effect of temperature on density of potassium.^{92,93}

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Figure A-84. Effect of temperature on vapor pressure of potassium.^{92, 93}

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Figure A-85. Effect of temperature on viscosity of potassium.^{92,96}

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Figure A-86. Effect of temperature on thermal conductivity of liquid potassium.^{92,97}

Figure A-87. Effect of temperature on heat capacity of potassium.⁹²

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Figure A-88. Effect of temperature on latent heat of vaporization of potassium.⁹³

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Figure A-89. Effect of temperature on the electrical resistivity of potassium.^{92,97,99}

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Primary System Corrosion, Mass Transfer, and Activity Transfer

DESIGN LIMITATIONS

Corrosion and Mass Transfer

The corrosion and mass transfer rates presented herein are based on experimental work performed in thermal convection loops designed, where possible, to approach the operating characteristics of the MCR system. These thermal convection loops, however, operate at inherently low velocities—about 0.5 ft/sec as opposed to 20 to 35 ft/sec in the MCR. In addition, the thermal convection loops lack means of purity control. These differences between thermal convection loops and the MCR could significantly affect the corrosion and mass transfer rates and result in significant changes in the values specified.

The following corrosion and mass transfer rates shall be applied to the potassium-cooled bimetallic MCR system:

- Corrosion of Cb-1% Zr—0.3 mg/cm²-mo weight loss or 0.18 mil/yr calculated uniform surface removal
- Mass transfer of type 316 stainless steel—0.55 mg/cm²-mo weight loss or 0.33 mil/yr calculated uniform surface removal

The thickness of all structural components shall be designed to reflect material loss based on the corrosion and mass transfer rates specified.

Activity Transfer

The rates of the preceding paragraphs are based on an assumption of uniform surface removal although preferential removal of metallic elements (for example, nickel and manganese) is known to occur. This assumption of uniform surface removal in design calculations is adequate for structural determinations. With regard to activity transfer, however, considerable care must be exercised as transfer of minor quantities of highly active isotopes may result in deposition of excessive quantities of radioactinants outside the reactor core area. Because specific activity transfer rate data for MCR conditions are lacking, the mass transfer rate will be used as a first approximation to calculate activity transfer rates.

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The activity transfer rates shall be applied to $1/2$ of the total surface within the core and to all surfaces above the core. Material removed shall be considered to be deposited in the primary loop heat exchangers. Both weight loss and deposition shall be considered to be uniform.

Coolant Purity

The potassium coolant shall be gettered and of high purity conforming to the quality specified in the subsection dealing with Primary Coolant. If impurities in excess of these limits are permitted—in particular oxygen—corrosion and mass transfer rates higher than those specified herein will be applied to the system.

Structural Components

Structural components of both type 316 stainless steel and Cb-1% Zr in contact with flowing potassium shall be designed in accordance with the MCR Structural Design Criteria in Volume I. The surface removal rates shall be considered in all stress calculations to ensure structural integrity over the life of the components.

Mass Transfer Deposits

Movement of metallic elements from the hotter to the cooler portions of the primary system will be controlled by the temperature profile, geometry, and velocity of the loop. The gross transfer in thermal convection loops to date is insufficient to measure the distribution of deposits through the loop. It is quite probable that nonuniform deposition will occur in the MCR, based on significant differences in the controlling parameters. The overall weight loss of type 316 stainless steel at 1600°F after 5000 hr in thermal convection loops was determined to be 4.8 mg/cm². That for type 316 stainless steel at 1500°F was found¹⁰³ to be 2.2 mg/cm². Even assuming nonuniform deposition in MCR, the relatively small quantity of material transferring will not create a problem with regard to plugging of channels and orifices.

Lifetime

The effect of corrosion and mass transfer on both the structural integrity of the wetted components as well as the activity transfer limits for the system are dependent upon the lifetime of each of the components. Lifetime requirements are defined in terms of the MCR reactor thermal output. The system design must account for all steady-state and transient operating conditions as well as start-up, shutdown, and transportability cyclical requirements.

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The design lifetime of the Cb-1% Zr components will be a minimum of 75,000 Mw_t -hr of operation or 8000 operational hours, whichever is less. The type 316 stainless steel within the core associated with the fuel, such as the hexagonal fuel element housing can, shall also have a minimum design lifetime of 75,000 Mw_t -hr or 8000 operational hours, whichever is less. All other type 316 stainless steel components shall be designed for a lifetime of 25,000 operational hours with a preferred life of 40,000 operational hours or 5 yr, whichever is less.

Temperature and Pressure

The corrosion, mass transfer, and activity rates and limits are based on a maximum metal surface temperature of 1600°F. In addition, based on the requirements of the safety design criteria, no bulk boiling shall be permitted under any steady-state or transient conditions. Pressurization shall be maintained by a high purity argon cover gas above the coolant.

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References cited within the preceding sections are listed here. Additional references of interest which are applicable to particular subsections are shown in Table A-XXXIX.

Table A-XXXIX.
Additional references.

<u>Subsection</u>	<u>Reference</u>
Ceramic fuel	14
Tungsten	62, 63, 64, 65, 66, 67, 68
Borated stainless steel	64, 70
Lithium hydride	73, 79
Titanium hydride	84, 85, 86, 87
Primary system coolant	94, 95, 98, 100, 101

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