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LMFBR SPENT FUEL TRANSPORT: CONCEPTUAL DESIGN AND PARTIAL SAFETY ANALYSIS OF A SODIUM-COOLED CASK

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CHEMICAL TECHNOLOGY DIVISION
GENERAL ENGINEERING DIVISION
METALS AND CERAMICS DIVISION

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ABSTRACT

Conceptual designs for 6- and 18-subassembly casks are presented. The casks are intended for transport of LMFBR spent fuel which has decayed a minimum of 30 days. These casks use sodium as the primary coolant, an auxiliary shield coolant system in normal operation, heavy steel members as both gamma shield and structure, and a eutectic mixture of LiOH and NaOH as a neutron shield. The analysis indicates that there will be no leakage of coolant or fission products under normal or hypothetical accident conditions.

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1. INTRODUCTION

The development of a safe and economic method of shipping spent LMFBR fuels has been actively pursued for a number of years. This effort has yielded information and ideas which can now be translated into a conceptual design of a fuel shipping cask that we believe will constitute a safe means for shipment of highly active short-decayed (30-day) fuel. This conceptual design, in our opinion, exceeds the requirements of the federal regulations by a considerable margin, and in many respects provides as safe a container as is practicable for rail transport. The development work is not complete. Although the development work is incomplete, the analyses are made on the basis that the development effort will be completed with positive results. The areas which we believe require additional development will be identified and the range of alternatives and general magnitude of the problem made known.

This report describes the principal features of a cask suitable for shipment of LMFBR spent fuel decayed for a period of 30 days or longer. Cask operation and that of related loading facilities are discussed. The safety of these features is examined under normal operating conditions and under hypothetical accident conditions. We have not included designs or analyses of peripheral items such as trunnions, tie-downs, and external coolant systems.

Conceptual designs and partial analyses for two versions of the cask, an 18-subassembly unit and a 6-subassembly unit, are presented in this report. The design for the large unit typifies the size of cask that will probably be used over the long term. The smaller unit is one that could be used in the near future for shipment of FTR and demonstration reactor fuels.

The cask described in this report is intended to have the capability of carrying a variety of fuel subassemblies. These include those from the Fast Test Reactor (FTR), as well as those of Atomics International (AI), General Electric (GE), and Westinghouse follow-on reactor designs. The cask openings and cask magazines are sized to accept any of these fuels in a somewhat bowed condition. Shielding and heat dissipation requirements are based on 30-day-cooled AI follow-on reactor fuel irradiated to 100,000 MWd/ton.

The features of the cask are markedly different from those employed in current practice for the reason that the physiological hazard of the releasable activity and the decay heat generation of LMFBR fuel shipped at short-decay time are orders of magnitude greater than are found in LWR fuel shipped at the decay times presently used. Because this cask is new in concept and the cargo will contain unprecedented amounts of mobile radioactivity, we are presenting this conceptual design and partial safety analysis for careful, critical scrutiny before either development work or design is completed.

2. SUMMARY

The most outstanding of the novel features of this conceptual cask design are: (1) sodium primary coolant, (2) steel gamma shielding, and (3) lithium hydroxide – sodium hydroxide neutron shielding. The sole reason for employing these innovations is their contribution to improved performance, and thereby safety.

A brief discussion of those features contributing to cask safety follows.

Total Containment. The cask is designed such that, when sealed and tested in accordance with operating instructions, no leakage of fission products or cask primary coolant will occur either under normal conditions or as a result of the design basis accident. This is accomplished by use of (1) very thick (9 in. or greater) monolithic walls of steel, (2) dual containment barriers with an integral leak detection system where a relatively thin barrier is a practical necessity, and (3) triplicate leak-tested seals with pressurized gas pockets between pairs of seals where mechanical (gasketed) closures are employed. The use of pressurized gas pockets between pairs of seals assures zero leakage of fission products and coolant even though each of the flanges is leaking at a measurable rate. The permissible leakage rate is sufficiently high that high-quality commercial seals should suffice. In numerous impact tests made with model casks employing a seal similar to the proposed design, no damage to the seal has been observed. The same type of seal has been found by other investigators to leak no sodium at temperatures and pressures to 1100°F and 1100 psi. The helium leak rate was less than 10^{-7} atm cm^3 helium per second at 250 psi differential pressure.

Dissipation of Heat. Sodium as the primary coolant yields more effective heat transport within the fuel cavity than does any other applicable material. Because sodium has excellent heat transport characteristics, the maximum fuel rod temperature and maximum coolant temperature will probably be less than 200°F hotter than the cask interior surface. Also, owing to its very low vapor pressure, this coolant can be contained at high temperature without difficulty. In addition, it is unaffected by gamma radiation. Tests have been made with a mockup of a fuel subassembly containing two hundred seventeen 0.25-in.-diam rods wrapped with 0.090-in. wire. The temperature variation from the center of this subassembly to the shroud was only 40°F when 10 kW was being liberated in the 4-ft-long core section. Other tests with a mockup of a 37-subassembly cask demonstrated low temperature variations outside the fuel subassembly. Although the system proposed for this cask is not completely analogous to either of these two situations, sufficient evidence is available to support a confident prediction of low temperature variations, even in the absence of correlations to accurately estimate performance.

The chemical affinity of sodium for anions does not constitute a significant drawback to its use as a coolant in a fuel shipping cask, provided the conditions of total containment can be met. Common steel is satisfactory as a long-term container material for sodium at modest temperatures. It will suffice for a substantial period (i.e., several weeks) at elevated temperatures (800°F). Stainless steel, Inconel, and similar materials are essentially fully resistant at even higher temperatures in relatively pure sodium. The cask body is made of carbon steel. Most of the fuel cavity surface is weld-overlayed with stainless steel; the remaining portion of the surface is lined with Inconel 600.

This design is predicated on the ability to maintain relatively pure sodium, to establish systems and conditions which will preclude loss of any fission products or sodium from the fuel cavity into a space occupied by oxygen-containing gas, to maintain normal temperatures at levels where chemical attack by oxides of sodium (if such were present) would be negligible, and to maintain close surveillance of all facets of cask use and condition. We believe that all these requirements can be met without undue difficulty. The first three of these are more or less inherent in the design. Surveillance of cask use and condition can be neglected only at great peril with a cask of any design.

Gamma Shield. The gamma shield, which also serves as the cask structure, is fabricated of steel. This material provides excellent strength and ductility, as well as a high maximum allowable temperature and slow thermal response to heat inputs. The shield is graded in thickness along the length of the cask in accordance with the shielding requirement for normal conditions. Axial shifting of 50% of the fuel charge is calculated to increase the radiation dose rate to values somewhat less than the maximum permitted by the regulations. The possibility and degree of fuel shifting should be more fully assessed. With the casks as designed, any hazard resulting from fuel shifting would be of a strictly local nature. If shifting were found to be a reasonable possibility and to result in an unacceptably high radiation dose, additional shielding could be provided with little difficulty.

Neutron Shield. The proposed neutron shield, which uses a eutectic mixture of LiOH and NaOH with about 1% borax added, is a solid at normal operating temperatures and melts at 428°F. It is hermetically sealed in steel containers welded to the gamma shield. In the solid state it has very poor heat transmittance. However, since heat is removed from the gamma shield under normal circumstances by means of an auxiliary cooling system, the insulating property of the neutron shield during normal circumstances is not a disadvantage. In the event of a fire or loss of auxiliary shield cooling, a substantial amount of sensible and latent heat would be absorbed by the hydroxide. After melting, heat can be transported effectively between the gamma shield and the exterior shell by thermal convection. Some experimental work has been done to support this concept, but the development is not yet complete.

Fire Tolerance. Calculations indicate that a cask of this general design would be essentially unaffected by the 30-min-duration fire stipulated by the regulations, and could survive a 3-hr-duration fire. This tolerance stems from the low vapor pressure of the sodium primary coolant, the high heat capacity of the steel gamma shield, and both the sensible and latent heat capacities of the neutron shield.

Although the analyses presented herein are incomplete and, in many cases, approximate, they indicate to us that such a cask, with no more than minor refinements in design, can meet the requirements of the regulations. Additional development work producing positive results is assumed for the following areas: (1) seals — impact, life, and thermal cycle tests; (2) seal installation and testing; (3) fuel subassembly support and magazine design; and (4) neutron shields. None of the above appears to be an intractable or long-duration problem.

3. CASK DESCRIPTIONS

Both casks are similar except for the number of fuel subassemblies to be accommodated and the resulting differences in construction and performance requirements (see Figs. 3-1 and 3-2). The heat transfer medium used inside the fuel cavity is sodium; the seals are all metal units capable of withstanding the effects of high temperatures, impact, and gamma radiation. The cask walls are made of solid steel instead of steel-clad heavy metal (usually lead), which is commonly used in the United States at present. The features of these casks are described below. No attempt is made to describe the details of the entire system; that is, the parts having no bearing on general function or safety are intentionally deleted.

3.1 Structure and Gamma Shielding

The cask structure itself and the gamma shielding are comprised of a low-carbon alloy steel coated inside and out with corrosion-resistant materials that will be applied by a welding process. The interior of the cask is coated with type 304 stainless steel, and the outside is coated with Inconel 600. The structure varies in thickness from about 18 in. at the midsection to about 9 in. at points removed from the highly radioactive fuel core section. The structure is fabricated from thick plates or forgings and assembled entirely by welding except for a joint located between the cask body and a plug which forms the top. A mechanical joint is provided in this area because substantial shrinkage can be anticipated from a weld of this size, and distortion of the cask internals would likely occur as a result of a stress relief procedure that is considered desirable, if not mandatory, for such a weld. The plug is retained in position by a series of studs, which are threaded into holes that are drilled with half of the diameter in one piece and half in the other. (This type of joint is described in ref. 1.) Beneath the cask end plug is an Inconel 600 liner, which is welded to the body of the cask. The attachment between the cask and the liner is such that minor radial shifts can be tolerated without overstressing the liner. The liner will also be formed so that it can expand

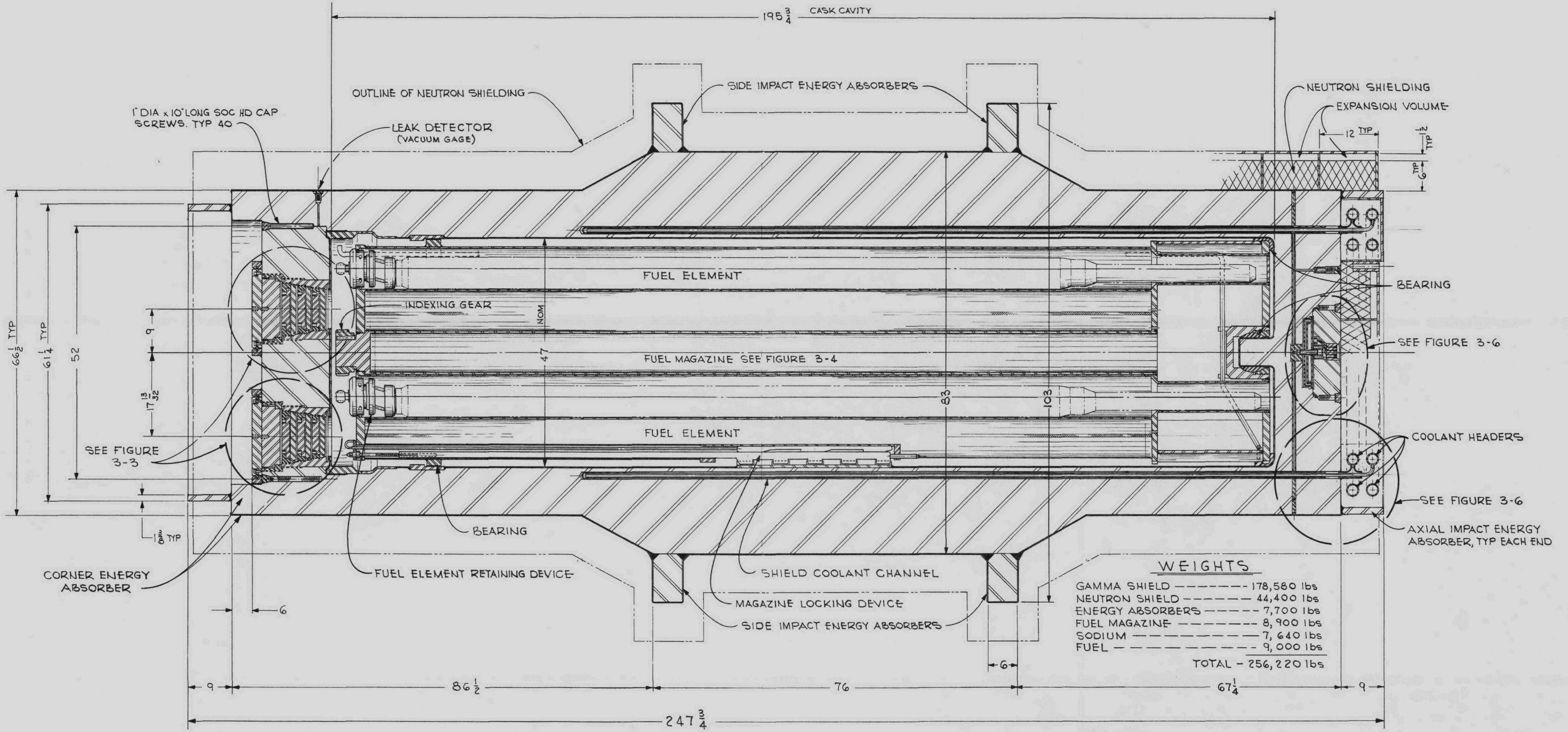

Fig. 3-1. 18-Subassembly Cask Sectional Elevation.

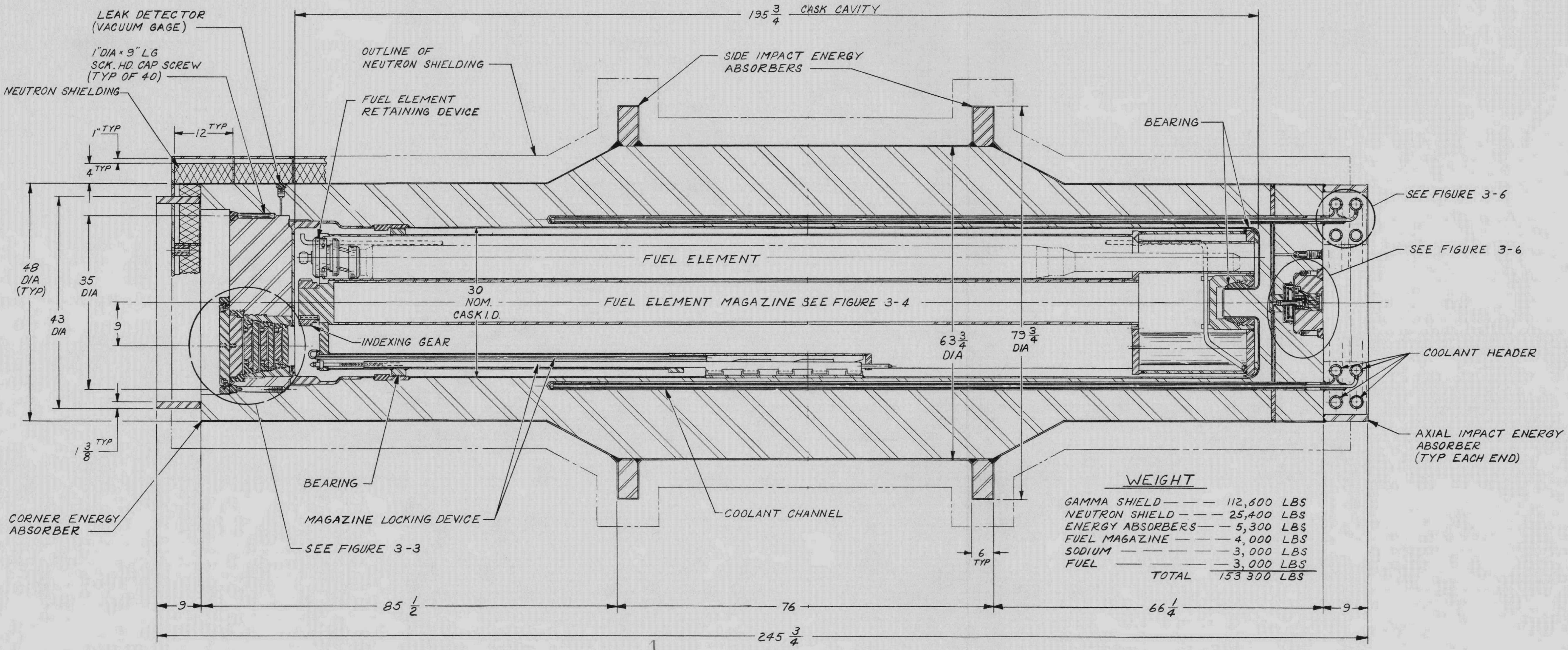

Fig. 3-2. 6-Subassembly Cask Sectional Elevation.

or contract axially without being overstressed in any area. Thinner portions of the liner will be fully supported by the cask structure. The juncture of the end plug and cask body is seal welded. A thick plate is welded over the seal weld area to protect it from puncture. The fuel access port housing is made separately from the end plug, and the two are mechanically joined. In addition, they are also seal-welded together. The small cavity bounded by the walls of the plug, cask body, and end plug liner is connected to a thermal conductivity vacuum gage. It is evacuated to a high vacuum and sealed by welding at the time of construction.

3.2 Mechanical Seals

The fuel access ports are the only openings leading into the fuel cavity. There are two of these in the 18-subassembly cask and one in the 6-subassembly cask. These openings are provided with three all-metal seals that are capable of being tested prior to each usage (see Fig. 3-3). The space between the two pairs of seals (three seals total) is filled with helium gas under pressure, which will assure integrity of the cask contents even if one of the three seals fails in transit. As indicated above, each of the seals can be leak-tested prior to shipment after the seal has been assembled. This manner of testing will eliminate concern over errors in assembly or damage to sealing surfaces during assembly as an undetected cause of seal failure.

The seal that is proposed for use is a modified version of the Grayloc connector made by the Gray Tool Company in Houston, Texas. The sealing plate is held in place by a nut having interrupted threads to minimize the amount of nut rotation. The retaining nut is maintained in a fixed position during shipment by a latch that is a part of the seal plate assembly (or shielding cover plate) located above the seal-plate assembly in question. (The latch is not shown in Fig. 3-3.)

3.3 Fuel Support

The fuel is supported in a rotatable magazine made up of a number of tubes (Figs. 3-4 and 3-5). The purpose of this magazine is to retain the fuel subassemblies

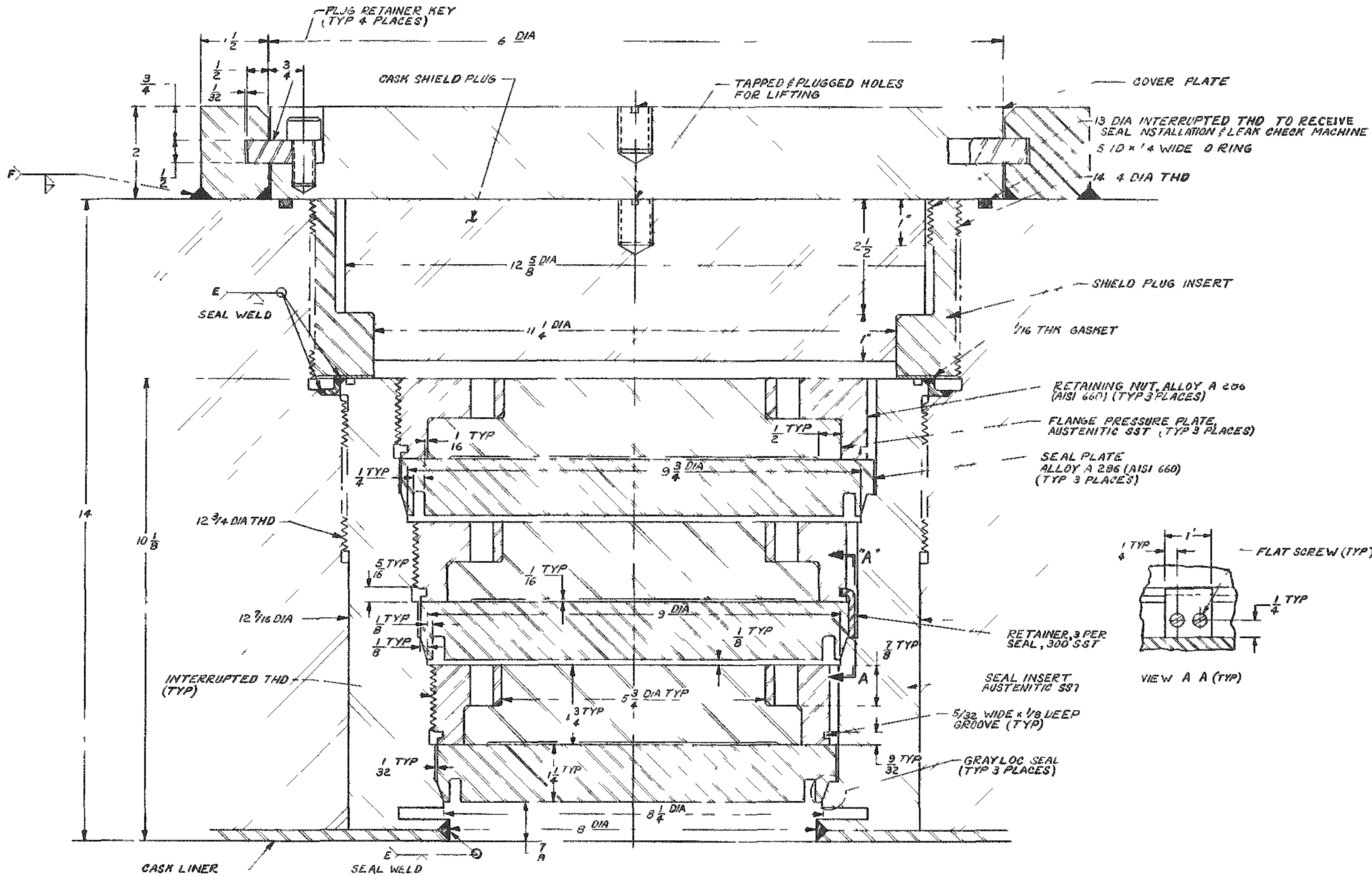

Fig. 3-3. Fuel Access Port Seal Assembly.

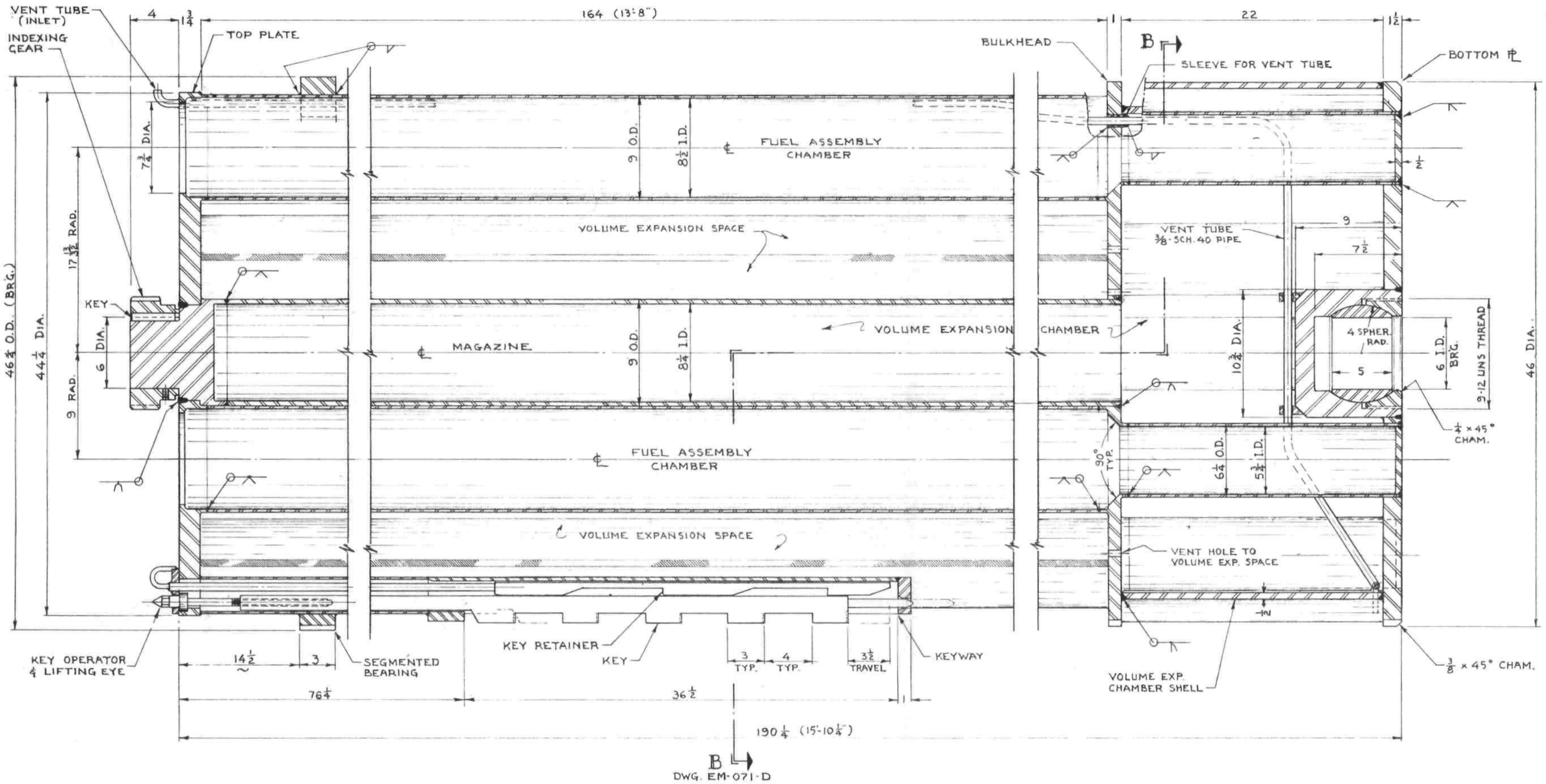

Fig. 3-4. Fuel Support Magazine Longitudinal Section.

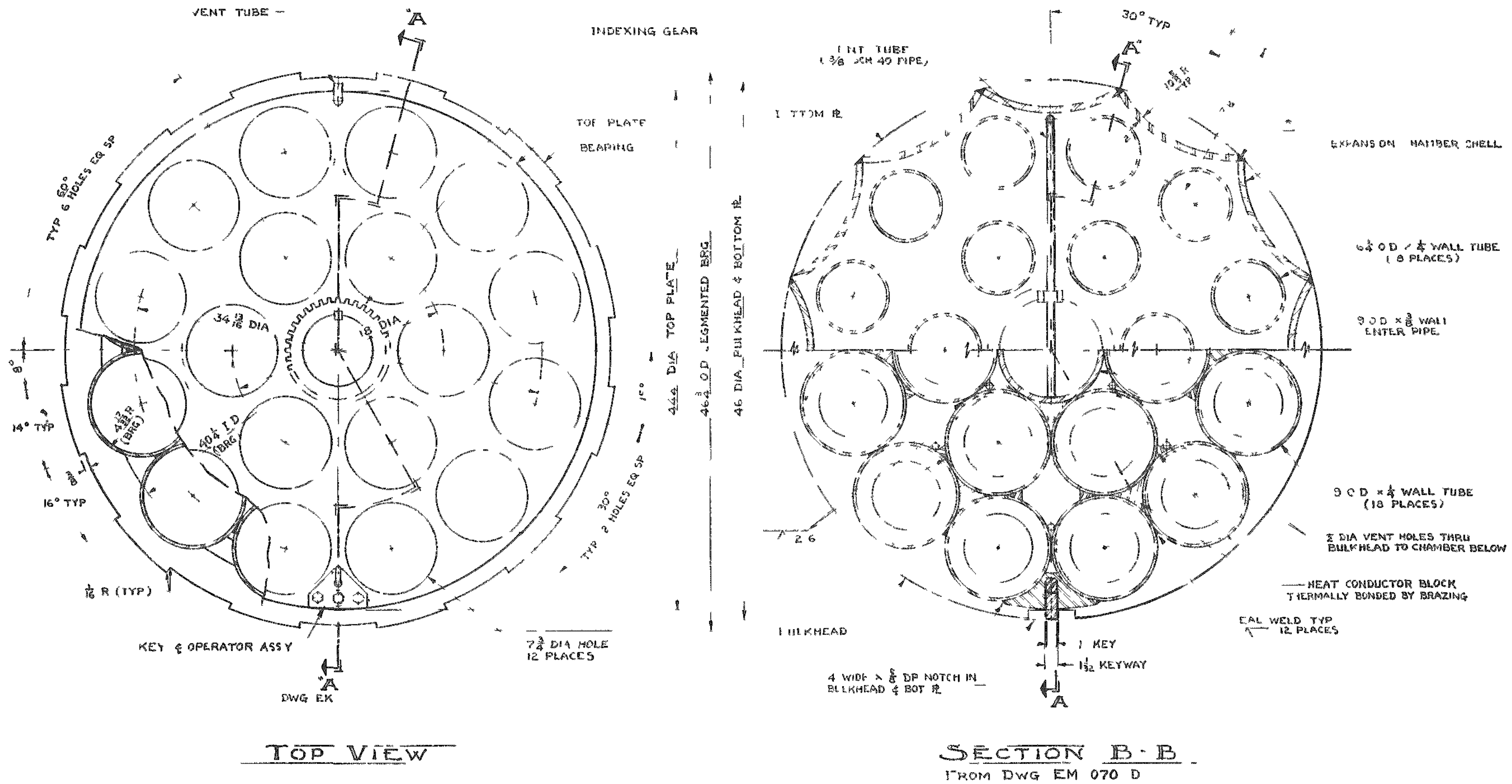

Fig. 3-5. Fuel Support Magazine Cross Sections.

in a fixed array in such a way that damage under normal conditions, as well as uncontrolled variation in fissile material spacing in the event of highly abnormal circumstances (namely, accidental impact), is precluded. The magazine can be rotated by means of a machine located within the service cell to which it is attached for loading and for discharge of its cargo. It can be precisely positioned so that the openings in the fuel magazine are positioned (each in turn) under an access port. During shipment the magazine will be locked in position by a device that is operable by means of a tool inserted into the fuel cavity through one of the fuel access ports. The locking device is removable through the loading port.

The openings in the magazine are sufficiently large to accept bowed fuel. The fuel is to be inserted into the cask while attached to a fitting through which gas can be passed for cooling of the subassembly prior to placement in the cask. This fitting locks into the opening of an individual fuel support tube. The available openings in the fitting (top plate) are small enough to prevent escape of substantial amounts of fuel particles in the event of fuel subassembly rupture during accidental impact. The fuel support magazine is held in place by simple bearings and restraints. The bearings are of the common journal type, in which metal contacts metal, but at very low speed and under low unit pressure.

3.4 Heat Removal Systems

Heat produced by radioactive decay of fission products in the spent fuel being carried in the fuel cavity will generate about 10 kW per fuel subassembly at 30 days decay (see Sect 7). Liquid sodium is used in the fuel cavity to aid the transport of heat from the fuel pins to the cask interior wall. This practice will introduce no new materials to the LMFBR fuels. Sodium will serve to minimize temperature variations within the fuel cavity.

Under normal conditions, heat will be removed from the cask shielding by means of coolant flowing through passageways located near the interior wall of the cask (see Fig. 3-6). These passageways contain mercury as a heat removal agent. In each passageway is a series of tubes mounted concentrically such that entering

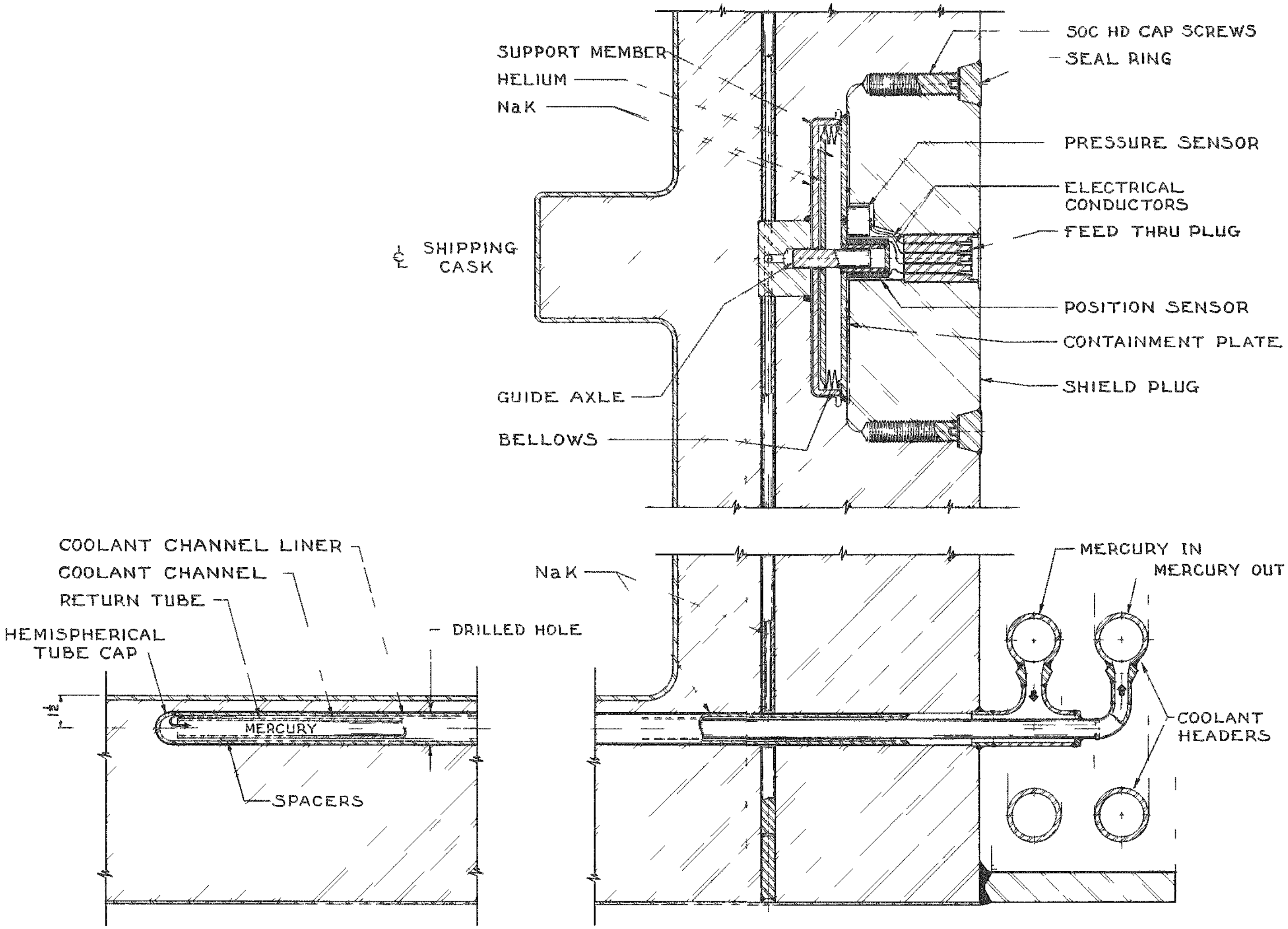

Fig. 3-6. Auxiliary Shield Cooling System.

and exiting coolant occupy the two centermost spaces. Two metal walls separated by a eutectic mixture of sodium and potassium (NaK) under pressure isolate the mercury coolant from the fuel cavity. The NaK serves as a thermal bond (between the two metal walls) and as a leak detection fluid. Inasmuch as NaK is under pressure, NaK will flow out of the annular gap if a leakage path should develop from the annular space (between the mercury coolant passageway and the fuel cavity) either into the mercury coolant passage or into the fuel cavity. The annular gaps are connected to a common cavity fitted with a bellows. On one side of the bellows is NaK, while gas under pressure is on the other. A position indicator is provided to indicate the amount of NaK present, and a pressure indicator is installed to show the gas pressure on the bellows. With this arrangement, the existence of two intact barriers to the escape of cask contents via the coolant channels can be established before each cask usage. Failure of one of these barriers can occur (although calculations indicate that neither of them will fail under normal or accident conditions) without causing loss of cask contents to the environment.

The mercury coolant is pumped into the coolant channels and thence passes to an air-cooled heat exchanger. Two separate systems are employed, each of which is capable of removing the entire heat load without attaining excessive temperatures in the fuel cavity. Drives for the pumps, fans, etc., are powered by electrical battery, which is normally charged by movement of the rail car but is charged if movement is inadequate by a diesel-driven generator.

In the event of failure of the auxiliary cooling system, the temperature of the cask will rise slowly to the level required to effect discharge of the heat through the cask walls and the neutron shield to the environment via the external cask surface.

3.5 Coolant Volume Expansion Device

As the temperature of the coolant (sodium) varies, the volume of the coolant also varies. This phenomenon is responsible for the excellent heat transport afforded by thermal convection of liquids. However, this characteristic does require that sufficient free space be provided for expansion of the liquid over the largest expected variation in temperature. The volume expansion device is integral with the fuel support magazine. The equipment is illustrated in Fig. 3-4. Under normal circumstances, the fuel magazine (and volume expansion device) will be positioned either vertically or horizontally. When in the horizontal position a predetermined portion of the magazine will be at the top. The volume expansion device consists of a series of cavities connected to the fuel cavity by means of a pipe having two loop sections, one in a horizontal and the other in a vertical plane. This system provides a gas trap to prevent liquid from flowing into the cask, regardless of position, unless a differential pressure exists. Under a differential pressure, as would be created by expanding liquid, flow can readily occur through the entry pipe and loop seals. Since the temperature of the cask will normally be essentially constant, no substantial amount of coolant will enter the volume expansion space. In an accident in which the temperature increases substantially, there will be no significant cycling of temperature; instead, a steady rise will be experienced until the steady-state value is reached. If the temperature of the cask were reduced and the fuel magazine were placed in an orientation different from that in which it was shipped, gas, rather than liquid sodium, would be expelled from the volume expansion space into the fuel cavity. This might leave a portion of one or more fuel subassemblies above the sodium level. However, the worst conceivable result would be failure of a portion of the fuel rods. No fission gas would escape the cask. We believe that it is reasonable to assume that emergency crews could be directed to place the cask in the desired orientation prior to reducing the cask temperature.

The availability of space in the volume expansion device can be proved prior to each usage by observing the change in liquid level in the fuel cavity as the overpressure is changed.

Although other methods of volume expansion accommodation could be employed, we believe that this method will be satisfactory; it is simpler, by far, than any other method that has been proposed.

3.6 Neutron Shield

The neutron shield consists of a thick layer of a eutectic mixture of about 20 wt % LiOH in NaOH, with 1 wt % borax added. This mixture has a melting point of about 428°F and negligible vapor pressure at temperatures in excess of the temperature of the hypothetical fire stipulated in the regulations (1475°F). The thicknesses of the hydroxide salt used in the cask designs under consideration are 4 in. and 6 in. for the 6- and 18-subassembly casks, respectively. The hydroxide is housed in numerous small containers (boxes) that are welded to the gamma shield. These boxes are about 12 x 12 in., with 0.25-in.-thick steel walls and a 0.5-in.-thick steel top. The inside height is about 25% greater than the thickness of the hydroxide layer to allow for expansion of the material during and after melting.

3.7 Instrumentation

There is no fixed instrumentation which penetrates into the fuel cavity. A minimum of fixed instrumentation is provided on the basis that very little information is needed except during the loading and closing procedure. The only instrumentation that is directly connected to the cask or its immediate attachments is for measurement of: (1) the temperature of the cask gamma shield, (2) inlet and outlet temperatures of the auxiliary shield coolant, (3) auxiliary shield coolant flow, (4) pressure and quantity of the auxiliary shield coolant leak detector fluid, and (5) a vacuum indicator (for leak detection purposes) between redundant seals at the top of the cask. The readout mechanisms for the three sensing devices indicated in (4) and (5) will not be attached to the sensors while in transit but will be carried with the rail car for use at both the loading and unloading stations.

In addition to the instrumentation closely associated with the cask, other controls and instruments are provided to guarantee a continuous supply of auxiliary shield coolant except under severe accident conditions. The controls include alarms to signal failure of a component of the auxiliary shield cooling system. Because the shield cooling system is redundant, failure of a single component or system will not disable the entire system.

The following information will be determined by instruments located in the loading and unloading facilities:

1. Sodium liquid level as a function of sodium overpressure.
2. Position of the fuel support magazine.
3. Helium leak rate of all mechanical seals used in closing the fuel cavity.
4. Various other data related to position of seal plate, force applied to seal plate, position of locking nut, and gas pressure sealed in the cavity between sequential closure plates.

References for Section 3

1. S. M. Jorgensen, "Closures and Shell Joints for Large High-Pressure Cylinders," ASME Publication 68-PVP-9, American Society of Mechanical Engineers, New York, 1968.

4. CHARACTERISTICS OF FUEL LOAD

A concise description of the various fuel subassemblies proposed for use in LMFBRs was presented by engineers at the Aerojet General Corporation in the report LMFBR Fuel Shipping Study, NDS-23, dated July 15, 1970. The following is quoted from this document:

> Figure 4-1 illustrates the various LMFBR fuel assembly configurations with the fuel, blanket and fission gas plena or vent regions identified. Table 4-1 presents further pertinent data on dimensions, weight, fissile and fertile material masses, burnup expectations, refueling cycle numbers and parameters useful for thermal analysis. It should be emphasized that these data are taken from reports published in 1970. Continuing work by the respective study groups can be expected to change the data. As given, though, it is representative of the variations in fuel assembly design which must be considered in the design of the LMFBR shipping cask.

The bulk of all fission products will be located in the relatively short "fuel" section indicated in Fig. 4-1. Consequently, the fission product decay heat will be produced in this same short area.

The basis for calculations of shielding and criticality for the conceptual designs is the AI follow-on reactor fuel subassembly irradiated to 100,000 MWd/ton and decayed for 30 days. The fictitious irradiation was used to provide a degree of conservatism. Fission product concentrations and decay heat were calculated by use of the ORIGEN code.[1] The calculated elemental radioactivities and decay heats are displayed in Tables 4-2 and 4-3.

The fuel subassemblies as charged to the reactor will be essentially straight and will have substantial ductility. After irradiation to $> 10^{22}$ neutrons/cm^2 (>0.1 MeV), the ductility will have decreased markedly,[2] probably to $< 1\%$.[3] In addition, nonuniform swelling will have occurred in the various sections of the subassembly wrapper as a result of variation in neutron flux. Compounding the problem are thermal gradients resulting from variations in neutron flux. Swelling, bending stresses, and metal creep will result.[4] Where the fuel subassemblies are removed from the reactor, some of them may be bowed significantly. Distortion of the

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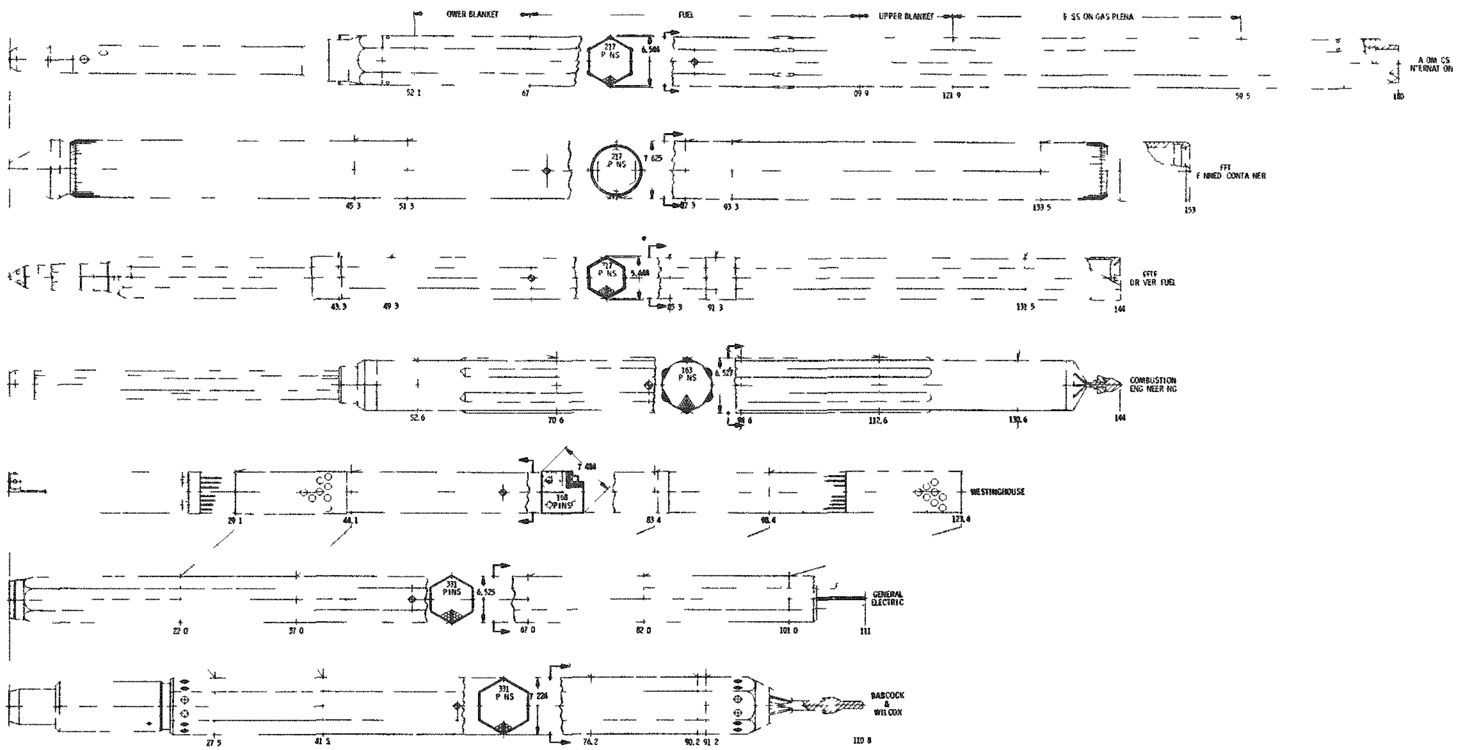

Fig. 4-1. LMFBR Fuel Subassembly Configurations.

Table 4-1. Fuel Subassembly Properties

Reactor Designer	Fuel Assembly: Dwg. No. and Ref.	Fuel Assembly: Max. Length (in.)	Fuel Assembly: Max. Diameter (in.)	Fuel Assembly: Weight (lb)	Pin Geometry: Number / Assembly	Pin Geometry: Diameter (in.)	Spacing (in.)	(U + Pu) Kg / Power MWt / Burnup MWd / Kg: Lower Blanket	Core	Upper Blanket	Inner Blanket	Outer Blanket	Refueling Cycle: # Assys./Cycle Time: Core	Blanket
Atomics International	NO9624006	180	6.544	750	217 Hex	0.300	0.3592	26.6/.14/3.1	69.7/8.0/67.4 2 Cycles	21.3 .3/3.6	127/1.3 14 5 Cycles	102 .51 10 7 Cycles	137 Year	23 5 Year
Babcock and Wilcox	A31073E	111	7.448	--	331 Hex	0.280	0.337	33.1/.59 19	82.3/7.7/100 3 Cycles	33.1/.59 19	116/.64/5.9 3 Cycles	116/.29/4.5 5 Cycles	96 Year	34 Year
Combustion Engineering	Figure 1-2	144	7.224	~750	163 Round	0.400	0.451	58/.60 8.6	78/9.4/100 3 Cycles	58/.60/8.6	116, 2.3/49 9 Cycles	--	73 344 Days	7/344 Days
General Electric	174F140	111	6.525	--	331 Hex	0.250	0.300	29.7/.72 15	53.2/8.4/100 2 Cycles	29.7/.72/15	132, 1.2/8.6 3 Cycles	132/.6/5.8 4 Cycles	133- Year	18+ Year
Westinghouse	ED/SK 334577J	123+	7.486	--	168 ~Square	0.302	0.3745	19/.67 18	49.8 9.8 100 2 Cycles	19/.67/18	135/-/-	135/-/-	122 400 Days	65 400 Days 130 800 Days
FFTF		144	5.444	430	217 Hex	0.230	0.286	--	37.5 4.9 45 3 Cycles	--	--	--	25/136 Days	--

Table 4-2. Radioactivity of Irradiated LMFBR Fuel

A I FOLLOW-ON LMFBR - POSTIRRADIATION DECAY OF CORE FUEL

POWER= 50.91MW, BURNUP= 100000.MWD, FLUX= 3.78E 15N/CM**2-SEC

ELEMENTAL ACTIVITY, CURIES
BASIS = METRIC TON OF (U+PU) AS CHARGED TO CORE

	CHARGE	DISCHARGE	10. D	30. D	60. D	100. D	150. D	210. D	280. D	360. D	450. D	550. D
H	0.0	2.84E 03	2.84E 03	2.83E 03	2.82E 03	2.80E 03	2.78E 03	2.75E 03	2.72E 03	2.69E 03	2.65E 03	2.61E 03
ZN	0.0	9.35E-01	2.61E-02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GA	0.0	3.07E 02	3.75E-02	2.93E-05	1.24E-20	3.98E-41	0.0	0.0	0.0	0.0	0.0	0.0
GE	0.0	4.38E 04	1.70E-03	2.78E-16	1.84E-35	4.90E-61	0.0	0.0	0.0	0.0	0.0	0.0
AS	0.0	2.96E 05	2.04E 02	3.76E-02	9.43E-08	3.21E-15	1.49E-24	9.37E-36	8.02E-49	9.32E-64	0.0	0.0
SE	0.0	1.42E 06	2.22E 00	1.61E 00	1.61E 00	1.61E 00	1.61E 00	1.61E 00	1.61E 00	1.61E 00	1.61E 00	1.61E 00
BR	0.0	1.27E 06	8.19E 01	6.61E-03	4.79E-09	3.11E-17	1.82E-27	9.55E-40	4.50E-54	0.0	0.0	0.0
KR	0.0	7.97E 06	2.25E 04	2.24E 04	2.23E 04	2.22E 04	2.20E 04	2.17E 04	2.15E 04	2.12E 04	2.08E 04	2.05E 04
RB	0.0	1.21E 07	8.40E 03	4.00E 03	1.32E 03	2.99E 02	4.09E 01	5.07E 00	3.78E-01	1.95E-02	7.33E-04	5.63E-05
SR	0.0	1.51E 07	1.47E 06	1.15E 06	8.14E 05	5.28E 05	3.31E 05	2.16E 05	1.59E 05	1.34E 05	1.25E 05	1.21E 05
Y	0.0	2.34E 07	2.09E 06	1.67E 06	1.21E 06	8.03E 05	5.00E 05	3.09E 05	2.04E 05	1.53E 05	1.32E 05	1.24E 05
ZR	0.0	1.22E 07	3.71E 06	3.00E 06	2.18E 06	1.42E 06	8.34E 05	4.40E 05	2.09E 05	8.89E 04	3.40E 04	1.17E 04
NB	0.0	2.95E 07	4.15E 06	3.89E 06	3.29E 06	2.44E 06	1.58E 06	8.87E 05	4.37E 05	1.91E 05	7.38E 04	2.55E 04
MO	0.0	2.47E 07	3.86E 05	2.70E 03	1.57E 00	7.63E-05	3.10E-10	1.05E-16	2.97E-24	7.02E-33	1.39E-42	7.28E-53
TC	0.0	2.95E 07	3.69E 05	2.62E 03	4.54E 01	4.39E 01	4.39E 01	4.39E 01	4.39E 01	4.39E 01	4.39E 01	4.39E 01
RU	0.0	1.61E 07	6.84E 06	5.57E 06	4.29E 06	3.28E 06	2.58E 06	2.12E 06	1.79E 06	1.52E 06	1.27E 06	1.05E 06
RH	0.0	2.17E 07	6.88E 06	5.57E 06	4.29E 06	3.28E 06	2.58E 06	2.12E 06	1.79E 06	1.52E 06	1.27E 06	1.05E 06
PD	0.0	2.49E 06	6.06E 00	7.30E-01	7.30E-01	7.30E-01	7.30E-01	7.30E-01	7.30E-01	7.30E-01	7.30E-01	7.30E-01
AG	0.0	2.37E 06	1.18E 05	2.16E 04	4.46E 03	3.01E 03	2.60E 03	2.21E 03	1.82E 03	1.46E 03	1.14E 03	8.70E 02
CD	0.0	3.71E 05	7.42E 03	3.37E 03	2.23E 03	1.[illegible]7E 03	8.37E 02	5.70E 02	4.56E 02	4.14E 02	3.98E 02	3.90E 02
IN	0.0	4.87E 05	3.22E 03	2.29E 01	1.09E 01	6.27E 00	3.13E 00	1.36E 00	5.17E-01	1.70E-01	4.90E-02	1.22E-02
SN	0.0	2.49E 06	8.92E 04	4.31E 04	2.73E 04	2.09E 04	1.58E 04	1.14E 04	7.78E 03	5.04E 03	3.10E 03	1.91E 03
SB	0.0	8.37E 06	1.25E 05	6.97E 04	6.44E 04	6.16E 04	5.89E 04	5.61E 04	5.32E 04	5.02E 04	4.71E 04	4.39E 04
TE	0.0	1.58E 07	9.23E 05	4.08E 05	2.61E 05	1.59E 05	9.87E 04	6.52E 04	4.63E 04	3.48E 04	2.73E 04	2.23E 04
I	0.0	1.95E 07	1.45E 06	2.04E 05	1.51E 04	4.81E 02	6.59E 00	1.43E-01	1.06E-01	1.06E-01	1.06E-01	1.06E-01
XE	0.0	2.46E 07	1.47E 06	1.12E 05	3.64E 03	1.82E 02	9.42E 00	2.80E-01	4.59E-03	4.18E-05	2.11E-07	6.01E-10
CS	0.0	1.76E 07	6.35E 05	5.11E 05	4.57E 05	4.41E 05	4.34E 05	4.27E 05	4.20E 05	4.13E 05	4.05E 05	3.96E 05
BA	0.0	1.80E 07	2.64E 06	1.11E 06	4.74E 05	3.36E 05	3.19E 05	3.16E 05	3.15E 05	3.13E 05	3.12E 05	3.10E 05
LA	0.0	1.74E 07	2.66E 06	9.05E 05	1.78E 05	2.04E 04	1.36E 03	5.29E 01	1.19E 00	1.57E-02	1.20E-04	5.34E-07
CE	0.0	1.62E 07	5.27E 06	4.18E 06	3.17E 06	2.42E 06	1.93E 06	1.58E 06	1.31E 06	1.07E 06	8.61E 05	6.74E 05
PR	0.0	1.35E 07	4.88E 06	3.26E 06	2.42E 06	2.05E 06	1.79E 06	1.55E 06	1.30E 06	1.07E 06	8.60E 05	6.74E 05
ND	0.0	3.61E 06	9.15E 05	2.62E 05	4.03E 04	3.31E 03	1.46E 02	3.45E 00	4.35E-02	2.94E-04	1.07E-06	2.10E-09
PM	0.0	3.82E 06	1.03E 06	9.00E 05	8.47E 05	7.97E 05	7.54E 05	7.14E 05	6.76E 05	6.37E 05	5.97E 05	5.55E 05
SM	0.0	7.78E 05	2.62E 04	1.48E 04	1.47E 04	1.47E 04	1.47E 04	1.47E 04	1.47E 04	1.46E 04	1.46E 04	1.46E 04
EU	0.0	4.72E 05	2.45E 05	1.80E 05	1.45E 05	1.32E 05	1.24E 05	1.16E 05	1.08E 05	1.00E 05	9.14E 04	8.28E 04
GD	0.0	4.59E 04	1.02E 01	6.28E 00	5.76E 00	5.14E 00	4.45E 00	3.75E 00	3.07E 00	2.44E 00	1.89E 00	1.42E 00
TB	0.0	2.02E 04	1.19E 04	6.87E 03	4.74E 03	3.21E 03	1.98E 03	1.11E 03	5.69E 02	2.64E 02	1.11E 02	4.24E 01
DY	0.0	1.93E-02	1.83E-08	3.08E-10	6.71E-13	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HO	0.0	1.01E-03	2.14E-06	4.69E-10	1.01E-12	2.85E-16	1.06E-29	8.16E-46	1.29E-64	0.0	0.0	0.0
TOTALS	0.0	3.63E 08	4.84E 07	3.31E 07	2.42E 07	1.82E 07	1.40E 07	1.10E 07	8.87E 06	7.34E 06	6.16E 06	5.19E 06

Table 4-3. Heat Generation of Irradiated LMFBR Fuel

A I FOLLOW-ON LMFBR - POSTIRRADIATION DECAY OF CORE FUEL

POWER= 90.91MW, BURNUP= 100000.MWD, FLUX= 3.78E 15N/CM**2-SEC

ELEMENT THERMAL POWER, WATTS
BASIS = METRIC TON OF (U+PU) AS CHARGED TO CORE

	CHARGE	DISCHARGE	10. D	30. D	60. D	100. D	150. D	210. D	280. D	360. D	450. D	550. D
H	0.0	1.01E-01	1.01E-01	1.01E-01	1.00E-01	9.96E-02	9.89E-02	9.80E-02	9.69E-02	9.57E-02	9.44E-02	9.29E-02
ZN	0.0	1.36E-03	3.81E-05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GA	0.0	5.27E 00	7.69E-04	6.01E-07	2.55E-22	8.15E-43	0.0	0.0	0.0	0.0	0.0	0.0
GE	0.0	2.07E 02	1.79E-05	2.92E-18	1.93E-37	5.14E-63	0.0	0.0	0.0	0.0	0.0	0.0
AS	0.0	3.03E 03	2.84E-01	5.24E-05	1.31E-10	4.48E-18	2.07E-27	1.31E-38	1.12E-51	1.30E-66	0.0	0.0
SE	0.0	1.63E 04	1.19E-03	6.10E-04	6.10E-04	6.10E-04	6.10E-04	6.10E-04	6.10E-04	6.10E-04	6.10E-04	6.10E-04
BR	0.0	1.16E 04	1.35E 00	1.09E-04	7.91E-11	5.14E-19	3.01E-29	1.58E-41	7.44E-56	0.0	0.0	0.0
KR	0.0	1.06E 05	3.62E 01	3.61E 01	3.59E 01	3.56E 01	3.53E 01	3.49E 01	3.45E 01	3.40E 01	3.35E 01	3.29E 01
RB	0.0	2.42E 05	3.95E 01	1.88E 01	6.19E 00	1.41E 00	2.20E-01	2.38E-02	1.78E-03	9.18E-05	3.29E-06	1.06E-07
SR	0.0	1.87E 05	4.99E 03	3.86E 03	2.64E 03	1.62E 03	9.08E 02	4.96E 02	2.92E 02	2.04E 02	1.72E 02	1.60E 02
Y	0.0	3.20E 05	8.18E 03	6.61E 03	4.85E 03	3.29E 03	2.14E 03	1.41E 03	1.01E 03	8.17E 02	7.34E 02	7.01E 02
ZR	0.0	5.50E 04	1.94E 04	1.57E 04	1.14E 04	7.44E 03	4.37E 03	2.30E 03	1.09E 03	4.65E 02	1.78E 02	6.13E 01
NB	0.0	2.56E 05	1.96E 04	1.84E 04	1.56E 04	1.16E 04	7.50E 03	4.22E 03	2.08E 03	9.07E 02	3.52E 02	1.22E 02
MO	0.0	1.99E 05	1.74E 03	1.21E 01	7.05E-03	3.43E-07	1.39E-12	4.72E-19	1.33E-26	3.15E-35	6.23E-45	1.03E-55
TC	0.0	3.18E 05	3.13E 02	2.21E 00	3.09E-02	2.97E-02	2.97E-02	2.97E-02	2.97E-02	2.97E-02	2.97E-02	2.97E-02
RU	0.0	7.07E 04	1.30E 04	9.17E 03	5.49E 03	2.79E 03	1.24E 03	5.04E 02	2.17E 02	1.17E 02	8.12E 01	6.35E 01
RH	0.0	9.23E 04	2.92E 04	2.78E 04	2.61E 04	2.40E 04	2.18E 04	1.94E 04	1.70E 04	1.46E 04	1.23E 04	1.02E 04
PD	0.0	7.02E 03	1.31E-02	6.06E-05	6.06E-05	6.06E-05	6.06E-05	6.06E-05	6.06E-05	6.06E-05	6.06E-05	6.06E-05
AG	0.0	7.90E 03	3.32E 02	9.77E 01	5.30E 01	4.51E 01	3.93E 01	3.33E 01	2.75E 01	2.21E 01	1.73E 01	1.31E 01
CD	0.0	2.64E 03	2.69E 01	1.26E 01	7.95E 00	4.43E 00	2.28E 00	1.20E 00	7.47E-01	5.87E-01	5.36E-01	5.18E-01
IN	0.0	4.84E 03	6.42E 00	6.29E-02	3.31E-02	1.90E-02	9.51E-03	4.14E-03	1.57E-03	5.17E-04	1.49E-04	3.71E-05
SN	0.0	1.87E 04	4.47E 02	1.79E 02	9.53E 01	7.01E 01	5.28E 01	3.79E 01	2.57E 01	1.65E 01	1.01E 01	5.80E 00
SB	0.0	1.31E 05	6.19E 02	2.83E 02	2.40E 02	2.20E 02	2.05E 02	1.92E 02	1.80E 02	1.69E 02	1.58E 02	1.47E 02
TE	0.0	1.56E 05	1.74E 03	8.48E 02	5.00E 02	2.66E 02	1.37E 02	7.61E 01	4.79E 01	3.36E 01	2.53E 01	2.01E 01
I	0.0	2.44E 05	1.00E 04	8.95E 02	6.20E 01	1.98E 00	2.67E-02	1.98E-04	4.61E-05	4.57E-05	4.57E-05	4.57E-05
XE	0.0	1.76E 05	1.58E 03	1.20E 02	3.75E 00	1.78E-01	9.15E-03	2.72E-04	4.46E-06	4.06E-08	2.05E-10	5.84E-13
CS	0.0	3.05E 05	4.55E 03	2.64E 03	1.82E 03	1.61E 03	1.54E 03	1.48E 03	1.42E 03	1.35E 03	1.29E 03	1.22E 03
BA	0.0	1.13E 05	9.09E 03	3.91E 03	1.78E 03	1.31E 03	1.25E 03	1.24E 03	1.24E 03	1.23E 03	1.22E 03	1.22E 03
LA	0.0	2.39E 05	4.42E 04	1.50E 04	2.96E 03	3.39E 02	2.26E 01	8.78E-01	1.98E-02	2.61E-04	1.99E-06	8.86E-09
CE	0.0	7.33E 04	7.69E 03	5.61E 03	3.80E 03	2.56E 03	1.84E 03	1.43E 03	1.16E 03	9.43E 02	7.55E 02	5.91E 02
PR	0.0	9.63E 04	2.39E 04	1.97E 04	1.70E 04	1.51E 04	1.33E 04	1.15E 04	9.69E 03	7.97E 03	6.40E 03	5.01E 03
ND	0.0	1.60E 04	2.56E 03	7.34E 02	1.13E 02	9.27E 00	4.09E-01	9.64E-03	1.22E-04	8.24E-07	2.99E-09	5.88E-12
PM	0.0	1.77E 04	2.46E 03	1.57E 03	1.10E 03	7.53E 02	5.38E 02	4.24E 02	3.66E 02	3.33E 02	3.09E 02	2.86E 02
SM	0.0	2.23E 03	5.11E 01	2.57E 01	2.57E 01	2.57E 01	2.56E 01	2.56E 01	2.56E 01	2.55E 01	2.55E 01	2.54E 01
EU	0.0	3.09E 03	1.24E 03	5.91E 02	2.66E 02	1.71E 02	1.50E 02	1.42E 02	1.35E 02	1.28E 02	1.20E 02	1.12E 02
GD	0.0	1.46E 02	1.83E-02	9.05E-03	8.31E-03	7.41E-03	6.42E-03	5.41E-03	4.43E-03	3.52E-03	2.72E-03	2.04E-03
TB	0.0	9.00E 01	7.12E 01	5.39E 01	3.97E 01	2.70E 01	1.67E 01	9.38E 00	4.79E 00	2.22E 00	9.34E-01	3.57E-01
DY	0.0	6.04E-05	1.55E-11	2.61E-13	5.69E-16	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HO	0.0	4.44E-06	9.36E-09	2.06E-12	4.42E-15	1.25E-18	4.65E-32	3.57E-48	5.66E-67	0.0	0.0	0.0
TOTALS	0.0	3.49E 06	2.07E 05	1.34E 05	9.60E 04	7.33E 04	5.71E 04	4.49E 04	3.60E 04	2.94E 04	2.42E 04	2.00E 04

subassemblies is a problem of great concern to the reactor designer, and several methods are being considered to minimize or accommodate the distortion. No reliable estimate of the amount of bowing to expect seems possible at this time. The safe assumption seems to be that a portion of the assemblies will be bowed. We are assuming that the bowing may be as great as 1 in.

References for Section 4

1. M. J. Bell, personal communication, December 3, 1971.
2. P. Patriarca, Fuels and Materials Quarterly Progress Report for Period Ending September 30, 1971, ORNL-TM-3550 (Dec. 1971).
3. E. E. Bloom, personal communication, January 1972.
4. P. R. Huebotter et al., Design, Research, and Development Implications of Metal Swelling in Fast Reactors, ANL-7786 (April 1971).

5. CASK LOADING AND OPERATION

The methods for loading and operating the 6- and 18-subassembly casks are similar. A brief description of the procedures is given below.

The shipping cask is to be transported horizontally on a special rail car. At the loading (or unloading) site, the neutron shield attached to the top end will be removed. The cask will then be raised to a vertical attitude without moving the bottom end of the cask any significant distance from its original position. The auxiliary shield coolant lines will remain attached, and cooling (or heating) will continue. The cask will have a pliable cover over the top end (during shipment). This cover serves to prevent the spread of any contamination that may be present on this surface of the cask. One end of a plastic sleeve having a diameter equal to, or slightly greater than, the diameter of the cask will be attached to the end of the cask (and over the pliable cover) by means of bagging techniques such as those used with alpha glove boxes. Teeing off from one side of this sleeve is a pocket and a gloved armhole. When the cask is in the upright position and near to the mating portion of the bottom of the cell, the free end of the large plastic sleeve will be attached to the ring on the bottom of the cell in the same glove-box fashion as previously mentioned. The space inside the plastic sleeve will be purged prior to final attachment, using an inert gas (either argon or nitrogen). Subsequent to the purging, the pliable cover that protects the end of the shipping cask and the similar one that covers the opening into the cell will be removed and placed in the pocket on the side of the plastic sleeve. The protective covers for the fuel access port will be removed and stored in the sleeve. The cask can then be raised until its top is mated to a shielding member on the floor of the cell above. By this action, a seal is made between a bellows section that is secured to the bottom of a removable plug located in the floor of the cell and the similar openings that are located in the top of the cask. After this is accomplished, all personnel will be evacuated from the room occupied by the cask, and the doors will be closed.

A machine(s) located in the shielded space (cell) above the receiving room will perform the remaining operations. First, each shielding plug will be removed by rotation through an angle of about 60° followed by lifting. (The plug will be stored for later reinsertion.) Then the three seal plates will be removed by pressing downward on the center portion of each seal-plate assembly with sufficient force to unload the retaining nut. The retaining nut will be rotated about 60°, the force on the assembly will be released, and the seal-plate assembly will be retracted into the loading cell. The three assemblies will be transferred to a place in the loading cell where they can be inspected, and the gaskets will be replaced if necessary. Subsequently, a metal sleeve will be inserted into the entry port to protect the seats from mechanical damage and from contact with sodium coolant in the event of splashing. The fuel magazine will be unlocked by using a tool to reach down into the cask through the fuel entry port and rotate a nut that moves the locking mechanism. Another device will be used to engage a gear that is part of the fuel magazine assembly and rotate it until the first magazine opening is positioned under the entry port. If the cask has two entry ports, this device will remain in place. If only one entry port is available, as in the 6-subassembly cask, the device must be retracted after each repositioning operation.

The fuel subassemblies will be attached to fittings which can be fixed into the end of the fuel support tube and through which gas can be forced for cooling. Each subassembly will be slowly lowered into the sodium coolant. (Simple calculations indicate that fairly rapid changes in fuel rod temperature should have no adverse effect on the cladding.) The opening in the fuel support tube is sufficiently large to accept bowed fuel subassemblies. The subassembly will be fixed in its support tube by a locking device on the fitting. (This fitting closes the fuel support tube to everything except fluids and very small particles.)

The magazine positioning and fuel loading operation will be repeated until the cask is filled. The magazine will be locked by a procedure similar to the one used for unlocking. All the other procedures are similar to the corresponding opening operation except for testing of coolant level, checking the available volume expansion space, and the installation of fuel entry port seals.

The level of coolant and the existence of adequate volume expansion space must be determined prior to each shipment. Liquid level can be adequately determined by means of a gas-purged dip tube that is attached to a differential pressure indicator. The liquid level will be observed as the gas pressure over the sodium is slowly varied from 1 to 2 atm. The increase in pressure will force sodium into the volume expansion chamber and will, in turn, cause a reduction in the level in the cask. The reduction in level will be a highly predictable function of system pressure as long as the expansion chamber is not occupied by sodium. This test will confirm that the volume expansion space has not developed a leak and that the anticipated space is available for coolant expansion. If the level of sodium in the cask is found to be inappropriate, changes can be made either by admitting more sodium via a tube inserted through the fuel entry port or by withdrawing sodium by vacuum via the same port.

Prior to installation of the seals, the seating surfaces and surrounding areas will be visually inspected (by remote means) for damage and presence of foreign material, including sodium above the first seal line. If any foreign matter is found, it will be removed.

The fuel entry port seals are to be installed in such a manner that the leak rate of each seal plate is found to be satisfactory and a pressurized inert gas pocket exists between each pair of seals. To meet these requirements, the seal-plate installation machine will be fitted with devices to permit pressurization of the space around the seal with helium gas prior to final positioning and fastening of the seal. The gas under the first seal will be at atmospheric pressure; the remaining two columns will contain helium gas at about 300 psi. At the time a seal plate is fastened into position, the gas pressure (whether 15 or 300 psia) on both sides of the plate will be the same. After the plate is fastened, the gas above the fastened seal plate will be discharged into an evacuated volume. If no gross leak is present, the pressure in the previously evacuated volume will increase to a predetermined value. The volume above the seal will be closed off to the previously evacuated volume and then evacuated through a helium mass spectrometer leak detector. A leak rate on the order of 10^{-7} (atmospheric) cm^3 of helium per second will be acceptable.

6. OUTLINE SPECIFICATIONS

Design and fabrication of all components having a bearing on containment of cask contents shall be in accordance with the ASME Boiler and Pressure Vessel Code, Section III, Class 1, with the following exceptions:

1. Methods of fabrication not recognized by the Code may be used if engineering calculations or scale-model tests establish that the particular method will satisfy the intent of the design.
2. Materials of construction that are not recognized by the Code may be used, provided test data are available to establish the adequacy of performance for the intended use and that standards used in the Code for other materials are not exceeded in determining the maximum design stress.
3. Destructive tests of scale models may be used to establish adequacy of design in lieu of stress analyses in cases where analytical methods are insufficient or unavailable.
4. The Code stamp is not required.

The materials used in construction shall be in accordance with appropriate ASTM specifications. The principal materials of construction are as follows:

Cask body - A508, Class I, carbon steel
Top head liner - Inconel 600
Seal Insert - type 304 stainless steel
Seal plate and retainer nut - AISI 660 alloy

The cask fuel cavity shall be pneumatically tested at 2000 psi prior to making seal welds between the cask body and the top plug, and between the top plug and the seal insert. The leak rate of the liner shall be determined with a helium mass spectrometer having a sensitivity of not less than 1×10^{-10} atm cm^3 of helium per second. Any detectable leakage will be cause for rejection. The top plug shall be removed after the test, and the visible portions of the liner examined for defects. Any indication of a defect will be studied, the source of the problem identified, and the difficulty remedied. The test shall be repeated after repairs are made.

The coolant channels shall be hydrostatically tested prior to installing the fuel support magazine at 1.25 times the maximum pressure that could develop as a result of a 200-g acceleration. The areas over the coolant channels inside the fuel cavity shall be examined visually and by means of dye penetrant for cracks, bulges, and any other signs of incipient failure.

7. ANALYSIS OF CASK PERFORMANCE UNDER NORMAL OPERATING CONDITIONS

The capacity of the casks to perform their functions safely under normal conditions are examined in this section. Nuclear safety, radiolytic decay heat dissipation, radiation shielding, materials compatibility, and thermal effects are examined. The analyses accomplished in this and the subsequent section are generally quite unsophisticated. In spite of the elementary approach, the bases assumed for determinations are intended to be very conservative, thereby providing a degree of assurance that a precise analysis that includes all factors will yield a result indicating that the margin of safety is at least as great as indicated by the first approximation.

7.1 Nuclear Safety

The effective neutron multiplication of the fuel in the cask, k_{eff}, has been estimated from the equation below. This formula was derived[1] to describe the results of criticality calculations of fresh LMFBR fuel in sodium and other coolants[2] using the ANISN and KENO codes.

$$k_{eff} = \frac{k_{\infty} (dc/di)(N)^{1/2}}{1 + M_B \left[\left(\frac{2.405}{R_i + \delta} \right)^2 + \left(\frac{\pi}{H_c + \delta} \right)^2 \right]} ,$$

where

k_{eff} = effective multiplication factor of the cask;

k_{∞} = infinite-system multiplication factor for a system filled with sodium;

N = number of elements in the cask;

dc = effective cell diameter used in determining k_{∞} (20.3 cm);

di = inside diameter of cask (cm);

M_B = effective migration area (~ 145 cm^2);

R_i = inside radius of the cask (cm);

H_c = length of the core section of the element (107 cm);

δ = reflector savings (~ 7 cm).

The values of k_{eff} are given in Table 7-1.

Table 7-1. Calculated k_{eff} for the 6- and 18-Subassembly Casks

Cask Capacity (Subassemblies)	Cask Diameter (in.)	k_{eff}
6	30.5	0.536
18	47	0.699

We expect these values to be conservative, since the original calculations were based upon a subassembly in the center of the cylindrical array (which does not exist in these two casks) and the fissile content of the core material has been depleted by irradiation.

A recent ANISN calculation indicated that a decrease of about 25% in k_{eff} could be expected when fuel is irradiated.

7.2 Removal of Fission Product Decay Heat

The fission product decay heat generated in the fuel subassemblies is calculated to be 9.34 kW per unit at 30 days after reactor shutdown. In order to maximize the margin of safety during shipping and promote operating convenience at the receiving site, the operating temperature of the fuel during shipment is to be maintained near the minimum level that we feel is consistent with maintaining the sodium coolant above its melting point of 208°F. For design purposes the inner wall temperature has been set at about 250°F.

Most of the decay heat will be liberated in the individual fuel rods. Heat transport data have been collected at Oak Ridge National Laboratory from an electrically heated mockup of a subassembly quite similar to that of the AI follow-on reactor.[3] The observed temperature differential from central rod to the bottom of the cluster with the fuel assembly in the horizontal position and about the same power input as used for the design basis was 40°F. Outside the subassembly, but within the 10-in.-diam vessel housing the subassembly and sodium, the greatest additional temperature variation was 13°F.

A mockup of a possible shipping configuration of 37 half-length fuel subassemblies mounted horizontally in a cask was also operated with sodium coolant.[3] This mockup simulated the subassembly externals only. In this unit with a heat input of 182 kW, which roughly corresponds to 364 kW for a full-length system, the maximum temperature variation was 70°F.

On the basis of the above observations, the maximum temperature differential within the fuel cavity of the 6-subassembly cask is conservatively estimated to be 75°F. Because the 18-subassembly cask has more fuel units and is constructed differently from the large test system, its maximum fuel cavity variation can be expected to be larger. In this case, an estimate of the resistance to radial heat flow from the inner row of six subassemblies will be added to the other temperature drops. In passing through the walls from the inner row to the outer row (see Fig. 3-4), the available surface area per subassembly will be about 4 ft^2 and the average thickness of stainless steel is of the order of 1 in. With a heat flux of 8000 Btu/hr · ft^2, the Δt across the stainless steel between the inner and outer tubes will be approximately

$$\Delta t = \frac{q\,A^{-1}}{k\,l^{-1}} = \frac{8000 \text{ Btu/ft}^2}{(108 \text{ Btu/hr} \cdot \text{ft}^2 \cdot {}^\circ\text{F} \cdot \text{in.}) \;/\; (1 \text{ in.})} = \sim 75^\circ\text{F}.$$

The maximum total variation in temperature within the 18-subassembly fuel cavity is conservatively estimated to be 40 + 75 + 50°F = 165°F.

To maintain the sodium coolant at the desired temperature, both with and without fuel assemblies in the cavity, an auxiliary shield cooling system is required. The shield temperature control system has been designed to maintain the sodium temperature at the wall at 250°F under ambient temperature conditions of 130°F when the casks have a full load of 30-day-decayed fuel. The system can also be used to supply heat to the cask when the heat load in the cavity is too low to maintain temperature. The portion of auxiliary shield temperature control system that is part of the cask has been sized; the portions that are separate from the cask have not. Their design can be of a conventional nature, and are therefore not considered further.

The devices used to remove, or add, heat from the shield are described in Sect. 3 and are depicted schematically in Fig. 3-6.

The heat transfer calculations were accomplished by use of conventional formulae and utilizing some very conservative simplifying assumptions. The results are presented in Table 7-2. The indicated number of coolant channels per cask represents only half of the total present. The remainder are part of a separate system which is on standby, should the first system fail. Under completely normal conditions, both systems would operate with the coolant temperature controlled at a sufficiently high level to maintain the inside wall temperature at greater than 208°F.

Table 7-2. Summary of Operating Conditions for Heat Removal Systems

	18 Subassemblies	6 Subassemblies
Heat produced in cavity, Btu/hr	575,000	191,300
Heat rejected at the cask surface, Btu/hr	75,000	55,300
Heat removed by heat exchange system, Btu/hr	500,000	136,000
Number of parallel coolant channels	12	5
Heat removed by each channel, Btu/hr	41,700	27,200
OD of the outer/inner tube, in.	1.5/1.0	1.5/1.0
Mass of flowing mercury in each channel, lb/hr	42,080	27,500
Velocity in annulus, ft/sec	3.96	2.58
Velocity in return inner tube, ft/sec	3.89	2.53
Inlet temperature, °F	140	140
Outlet temperature, °F	170	170
Inside end temperature, °F	194	194
Length of channel, ft	13.25	13.25
Sodium temperature at wall, °F	250	250
Ambient temperature, °F	130	130

7.3 Radiation Dose Rate

Shielding calculations for primary gammas, neutrons, and secondary gammas were made by utilizing the ANISN code,[4] which is a one-dimensional, discrete ordinates, transport code with anisotropic scattering. The source terms, as a function of energy groups, were determined from ORIGEN code runs involving AI follow-on fuel assemblies irradiated to 100,000 MWd/metric ton (see Sect. 4). The buildup of ^{242}Cm and ^{244}Cm constitutes the primary source of neutrons. The quantities of these actinides per ton of (U + Pu) charged to the reactor are given in Table 7-3.

Table 7-3. ^{242}Cm and ^{244}Cm Concentrations per Ton of (U + Pu)

Nuclide	Cooling Time (days)	
	0	30
^{242}Cm, g	63.7	56.4
^{244}Cm, g	64.8	64.6

The fuel is treated as a multiplying source by the code since the neutrons from curium cause fission in the fissionable isotopes. Because of the high neutron flux produced, a neutron shield is required to reduce the dose rate from this source to acceptable levels.

Figures 7-1 and 7-2 show the dose rate as it varies through the outer portions of the central section of the 6- and 18-subassembly casks. Due to the relative unimportance of the exact shielding thicknesses to the design concept, no attempt has been made to optimize the shielding thicknesses based on dose rates from the primary and secondary gammas and the neutrons. Table 7-4 lists the dose rates at the outer surface of the cask. It also specifies the approximate surface dose rate to be expected on failure of the neutron shield as the result of an accident. (This possibility is discussed in more detail in Sect. 8.1.6.) These casks will be shipped "exclusive use" and, consequently, will be governed by a 10-mrem/hr dose rate 6 ft from

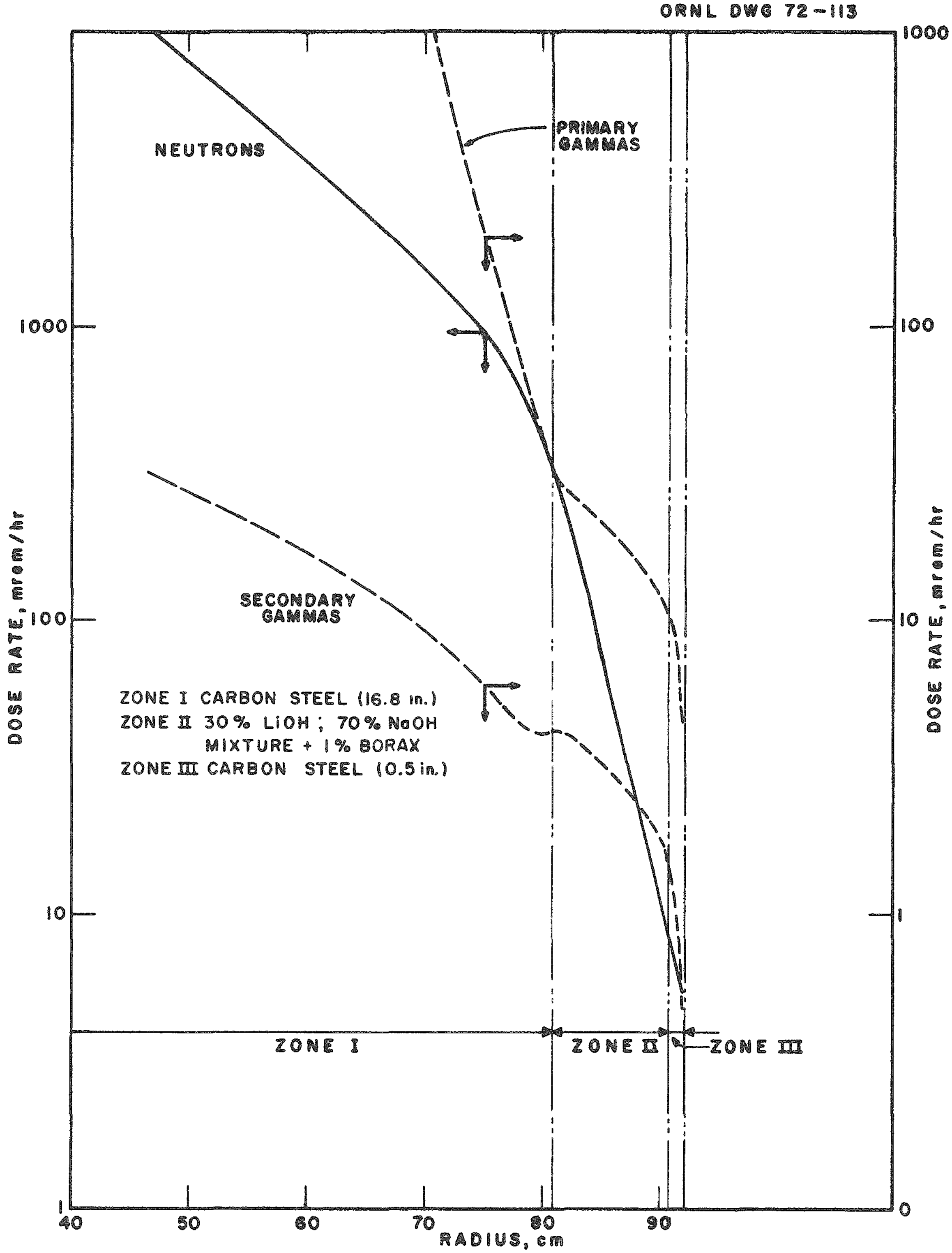

Fig. 7-1. Dose Rates Through the 6-Subassembly Cask Shield.

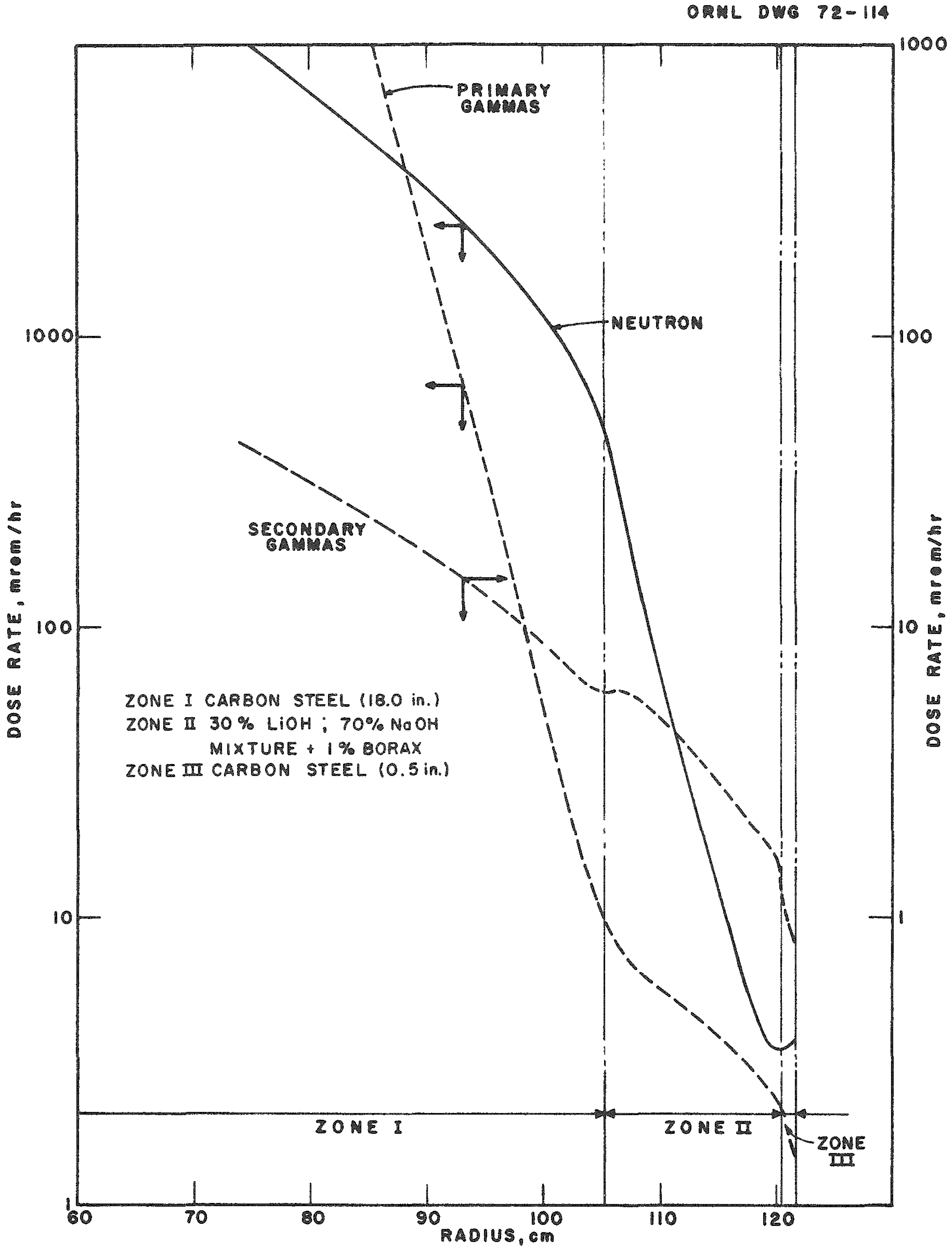

Fig. 7-2. Dose Rates Through the 18-Subassembly Cask Shield.

Table 7-4. Radiation Dose Rate from 6- and 18-Subassembly Casks

Radiation	Dose Rate (mrem/hr) at a Specified Distance from:					
	6-Subassembly Casks			18-Subassembly Casks		
	0 ft	3 ft	6 ft	0 ft	3 ft	6 ft
Normal:						
Primary gamma	4.78			1.44		
Secondary gamma	0.49			9.83		
Neutrons	5.66			3.65		
Total	10.93	4.14	2.46	5.92	2.66	1.66
Loss of neutron shield:						
Primary gamma	14			4		
Secondary gamma	2			2		
Neutrons	535			854		
Total	551	208	124	860	386	241

the surface. Following an accident, the dose rate is permitted by regulations to increase to 1000 mrem/hr at 3 ft from the cask surface.

7.4 Materials Compatibility

Sodium, NaK, mercury, and solid LiOH and NaOH are employed at various places in the cask. Their effect on the proposed materials will be discussed below.

Sodium will occupy the fuel cavity and will be in normal contact with the innermost seal of the fuel access port. The materials in contact with the sodium are type 304 stainless steel, Inconel 600, and AISI 660 alloy (Carpenter A-286). The normal operating temperature for the components exposed to sodium is about 250°F, as stated elsewhere in this report. The maximum calculated temperature of the fuel cavity surface of the 18-subassembly cask is only 670°F if fire conditions are no more stringent than those specified by the federal regulations (see Sect. 8). If the fire should continue for 3 hr, as opposed to 30 min, the maximum calculated surface temperature is 850°F. Alloys of this type have good resistance to sodium at temperatures in excess of 1100°F.[5]

NaK will be used under the same temperature conditions as indicated for sodium. The least resistant of the wetted parts to attack by NaK is the carbon steel. However, carbon steel is recommended for long-term use in NaK at temperatures well above the normal operating temperature of the cask and will be entirely satisfactory in the intended service for the relatively short period of exposure that might be expected in the event of a 3-hr fire.[6]

Mercury will be contained by carbon steel components. Carbon steel is reported to have good resistance, at temperatures up to 1100°F, to mercury containing small amounts of titanium and magnesium.[7] Under normal conditions, the temperature will be less than 250°F. The maximum abnormal temperature is the same as that for sodium and NaK.

LiOH-NaOH eutectic will normally be present as a solid at temperatures less than 250°F. It is planned that the caustic will be poured and cast in place, the space above the caustic will be evacuated, and the container will be sealed by welding. The gamma shield (and cask structure) surface is to be overlaid with Inconel 600 (an alloy containing about 75% nickel plus cobalt), and the other five sides of the container are to be made of carbon steel. This system should be satisfactory since manufacturers of anhydrous caustic soda commonly allow the product to "solidify in single-trip steel drums . . . ."[8] The material of construction for the evaporators for anhydrous caustic is "low carbon nickel, or Inconel."[8] These evaporators operate at temperatures in excess of 716°F. It is also reported that objectionable rates of attack (for long-term use) of caustic soda on various metals and nickel alloys occur at temperatures above 1000°F and that hydroxides of other metals, including lithium, exhibit a corrosive behavior not significantly different from NaOH.[9]

7.5 Structures

Under the hypothetical accident condition, most of the structures will be subjected to conditions much more stringent than those that exist during normal operation. Thermal stress and vibration are the only two parameters requiring examination for acceptable performance during normal operation.

Thermal stress can develop in stress-relieved materials of uniform composition only if a temperature gradient exists. Except in the zones around the coolant channels, the temperature gradients will be far less under normal operating conditions than under accident conditions. As a first approximation, the ligament will be assumed to be 0.4 in. thick and made of steel having a thermal conductivity of 300 Btu/hr · ft^2 · in. · °F. The heat flux through the ligament will be less than that obtained by dividing the heat transmitted per channel by the projected area of the channel, or

$$\frac{q}{A} = \frac{41{,}700 \text{ Btu/hr}}{1.38 \text{ ft}^2} = 30{,}212 \text{ Btu/hr} \cdot \text{ft}^2 .$$

The temperature drop across the 0.4-in.-thick ligament is 40°F. The maximum thermal stress in a totally restrained member as a result of temperature change is equal to the temperature change multiplied by the product of the coefficient of thermal expansion and the modulus of elasticity.

$$\sigma = (40)\,(7 \times 10^{-6})\,(3 \times 10^{7}) = 8400 \text{ psi.}$$

This calculated value is much higher than would actually exist. Therefore, the thermal stress in the area of the coolant channels under normal conditions is negligible.

Vibration in a cask could conceivably cause difficulty by causing repeated stressing of a structural member to values that are a substantial fraction of the yield point, or by gradually opening a closure that is held in place by friction.

We will consider first those parts which comprise the containment system. The cask body and the seals have heavy cross sections and conformations that would cause their natural frequency to be very high. The vibration frequencies encountered in rail shipment of loads weighing more than 60 tons are not in the range that would be expected to correspond to the natural frequency of the heavy members of the cask. The coolant channel liners, which are relatively light, would not be expected to be affected by vibration because of the large amount of surface area involved, the small clearance available, and the presence of fluid between the adjacent surfaces. The bellows in the NaK expansion space could cause difficulty if previous attention is not given to the problem; however, means are available to resolve such problems. A mechanical stop can be used to prevent a closure retainer from backing off.

The fuel support magazine conceivably could also be a source of difficulty. Analysis of the final design could reveal any problems, and likewise suggest alternative designs which would circumvent the area of difficulty.

[Note: The above is the understanding the author obtained in discussions (of January 1972) concerning vibration problems as related to this cask design with T. G. Carley (University of Tennessee) and H. C. Nelms (ORNL), who are knowledgeable of vibration theory and practice.]

References for Section 7

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8. SAFETY ANALYSIS UNDER HYPOTHETICAL ACCIDENT CONDITIONS

The portions of the regulatory hypothetical accident sequence with which this section is concerned are: (1) 30-ft free-fall impact against a plane, unyielding surface; (2) puncture by a 6-in. steel piston after a 40-in. free fall; and (3) exposure to a 1475°F fire for 30 min, during and after which all "artificial" heat removal systems are considered inactive. Immersion in water is not considered a hazard to the two casks discussed here because they are designed to preclude either entry or exit of materials from the fuel cavity. Also, the neutron shield provided around them is essentially black to neutrons. Hence, full reflection of the very small number of neutrons passing through the neutron shield will have an entirely negligible effect on the k_{eff} of the system.

At this point, we wish to reiterate that the calculations and proofs presented in this report are recognized to be less than exhaustive. They are simply intended to demonstrate by the simplest, most direct means at hand that a cask of the general design we have described either is, or can be designed to be, capable of surviving the hypothetical accident sequence.

8.1 Impact

This section examines the effects produced on various parts of the cask by a 30-ft free-fall impact of the cask onto an unyielding surface in various attitudes. The design of the cask is intended to be such that no part of the containment system will fail or will be materially impaired as a result of impact, even though certain portions of the containment system are provided in duplicate and one system (the seal closures) is provided in triplicate.

Both the 6-subassembly cask and the 18-subassembly cask employ similar design features. Although the larger cask will have a wall thickness only slightly greater than that of the smaller one, its weight will be about 60% greater. Therefore, the stresses imposed upon certain parts of the larger unit will be more severe than those imposed on the corresponding parts of the smaller unit. Hence, we will confine our examination of the effects of impact to the larger cask on the basis that satisfactory performance by the larger unit will assure more than satisfactory performance by the smaller one.

8.1.1 Energy Absorbers

Energy absorbers are provided to limit the rate of deceleration to 200 g regardless of the attitude assumed by the cask when it strikes a plane, unyielding surface at a speed of 30 mph (the speed attained in a 30-ft free fall). The energy absorbers are simple in design, consisting of relatively massive rings of steel that are deformed plastically on impact. Fairly extensive testing of lead specimens has been done to determine the amount of energy absorbed per volume of metal displaced.[1] Fewer tests have been made with steel; however, the results have been similar. The major difference between the two metals (as energy absorbers) is that steel absorbs much more energy per volume of metal displaced than does lead, i.e., 4000 to 6000 in.-lb/in.^{3} of lead as compared with 100,000 in.-lb/in.^{3} of steel.[2]

Each of the two ends of the cask is equipped with a relatively thin ring of steel (see Fig. 3-1), whose dimensions were calculated by means of an IBM-360 computer program similar to the one described in ref. 3. This ring is provided to absorb the energy of the cask in the event of a perpendicular end impact against an unyielding surface. In such a case, the entire ring would contact the surface and would flow under the pressure created in the area of contact. A thicker, relatively heavy section ring of steel, also included at the top of the cask, is intended to absorb the energy of a top end edge impact in which the cask center of gravity is directly above the point of contact. In the absence of this ring, metal displacements and deformations might extend into the seal area. The heavy type of ring is not provided at the bottom because the rate of deceleration will be acceptable without the additional rings and the expected amount of metal displacement and deformation in that area will not cause a hazard. In an edge impact, the thinner ring will absorb only a small portion of the total energy. Both the thicker ring at the top end and the bottom end of the cask are of sufficient size to absorb the remaining energy while producing a maximum deceleration of less than 200 g. Tests of scale-model casks indicate that the top ring or bottom corner would deform plastically about 3.5 in.

Two heavy rings of steel (see Fig. 3-1) are located at the ends of the thickest portion of the gamma shield. These rings extend 5-3/4 in. beyond the neutron shield located around the body of the cask, but will be covered with a neutron shield that will be partially destroyed in the hypothetical accident condition. These rings will be deformed a maximum of 3.6 in. in the event of a side impact and will produce a deceleration rate of 200 g or less in the cask.

If the cask strikes a plane surface in an attitude intermediate between any of the three just mentioned, a fraction of the potential energy will be transformed into rotational energy and the cask will tend to spin. This motion will involve more than one of the energy absorbers, and a larger volume of metal will be affected; consequently, the deceleration will be lower.

Results of tests performed on scale-model casks and/or their parts by (or under the direction of) the authors have indicated that metal deformations extend only a very short distance below the surface of the displaced metal. The model casks (hollow cylindrical steel shapes) used in these tests were not fitted with energy absorbers. In the case of the 6- and 18-subassembly casks, the metal to be deformed (i.e., the energy absorber) has a much smaller cross section than does the supporting cask structure; the energy absorbers are designed and located to ensure that deformations and displacements will not extend into any vital part of the cask structure.

8.1.2 Cask Body

The side walls and bottom of the cask are made up of heavy steel members that are welded into an essentially monolithic structure. A mechanical joint (provided for final assembly reasons) and an access port(s) for fuel subassemblies (see Fig. 3-1) are used at the top of the cask. The steel members comprising the cask body are quite ductile at the anticipated operating temperature (about 250°F).

If the cask were subjected to an end or edge drop onto an unyielding surface, the energy absorbers would limit the deceleration force to 200 g or less. A hydraulic pressure peak would develop within the fuel cavity for a short period (~ 0.1 sec).

At a peak deceleration rate corresponding to 200 g in an end impact, the peak pressure at the lower end of the cavity would approach 1500 psi. This pressure would create a uniformly distributed load on the end plug of about 2,600,000 lb for that same time period. The mass of the end plug would have the effect of increasing the uniformly distributed load by about 50%. The studs holding this plug in place would be placed in shear along the plane between the edge of the plug and the edge of the cylindrical section. The stress in the studs from such a load is 12,500 psi. The shear stresses in the threads on the studs will be less than the stress at the center plane of the studs since the area of shear is larger by a factor of $\pi/2$. The maximum stress in the plug is due to bending. By conservatively assuming the plug is supported and unrestrained at the edges, the stress is calculated to be 20,700 psi. The calculated maximum deflection is 0.10 in. The yield stress of the cask structure is 31,500 psi at 250°F. The stresses and deflections were calculated by the use of flat plate equations suggested by Timoshenko.[4] A stress intensification factor of 2, as suggested by the ASME Boiler and Pressure Vessel Code,[5] was used to compensate for the increase in stress brought about by the fuel access port openings.

The stresses in the bottom end structure were calculated as if the structure were a circular plate with a 16-in.-diam hole in the center and restrained at the outer edge. A uniform load equal to the sum of the hydrostatic pressure and the inertial force of the metal, plus a concentrated load at the 16-in. diameter, were used as the bases for the calculation. The maximum resultant stress was calculated to be 6600 psi. The calculation was made using published formulas.[11]

The thin unsupported section of the containment barrier at the top of the cask is 47 in. in diameter and 1-1/2 in. thick (see Fig 3-1). The peak pressure of 1500 psi will create a momentary stress of 24,000 psi. The material of construction, Inconel 600, has a yield stress of 40,000 psi at 300°F (slightly higher than the operating temperature).

If the cask should strike an unyielding surface in a horizontal attitude, a bending moment would be produced about the two circumferential energy absorbers.

The shear stress will be no more than about 8000 psi; the maximum stress produced as a result of bending will be about 17,000 psi.

The possibility of brittle fracture of the cask body has been considered. Such an occurrence in these casks is deemed incredible. A discussion of brittle fracture and of the factors leading to the selection of the cask body materials is found in Appendix A.

8.1.3 The Shield Coolant System

The shield coolant system, which consists of a number of channels in the cask wall near the fuel cavity, must withstand hydraulic pressures created by the working fluid in the heat exchangers (mercury) and the thermal bonding material (NaK) when subjected to deceleration forces produced by an impact. The design of the coolant system is described in Sect. 3 and is shown schematically in Fig. 3-6.

The pressure, P_h, developed in the mercury at the extreme end of the 13.25-ft-long coolant channel in the 18-subassembly cask under a 200-g decelerating force is:

$$
\begin{aligned}
P_h &= (13.25)\,(13.6)\,(200\ \underline{g})\,/\,30 \text{ in. Hg per atm} \\
&= 1201 \text{ atm} \\
&= 17{,}659 \text{ psi.}
\end{aligned}
$$

The pressure developed at a corresponding point in the NaK-filled annular space between the mercury-filled tube and the cask body as a result of the head of liquid will be about 1300 psi. The coolant channel liner will have been hydraulically expanded to the dimensions of the channel, less elastic shrinkage during the fabrication process. Thus the liner will be backed up by the channel and, under high internal pressure, will be supported by it. The entire channel will be treated, for purposes of a first approximation analysis, as though it were a tube having a wall thickness approximately equal to the minimum metal thickness from the fuel cavity to the mercury coolant. As shown in Fig. 3-6, the thinnest part of the wall consists of 3/8-in. carbon steel with a 3/32-in.-thick stainless steel weld overlay. The tube has a 1/8-in. wall. The calculated stress using an effective metal thickness of 0.50 in. is calculated as follows:

$$S = \frac{P\,(R + 0.6t)}{Et} = 32{,}000 \text{ psi} ,$$

where

- P = differential pressure, 16000 psi;
- S = tensile stress, psi;
- E = joint efficiency, 1;
- t = minimum wall thickness, 0.50 in.;
- R = radius of channel, 0.69 in.

The yield stress of the carbon steel material used in the wall is 31,500 psi; its ultimate stress is about 60,000 psi. Owing to the conservative nature of the assumption that the structure be considered as a tube, this value is probably safe. If a thorough analysis should reveal potential overstressing, the channel diameter could be reduced and the number of channels could be increased.

The pressure in the annular space between the coolant channel wall and the liner is 1300 psi (as indicated above). In the event of a bottom end impact, the absence of pressure inside the liner tube can be postulated on the basis of complete failure of the mercury supply and return lines. In this case, a 1300-psi external pressure would be placed upon the liner. Using the charts and instructions in Section VIII of the ASME Code,[5] the allowable external pressure for an unsupported 1.5-in.-OD by 0.12-in.-wall carbon steel tube having a yield strength of 35,000 psi is 1360 psi. In actuality, the allowable external pressure is probably much higher because the tube is surrounded by a wall, which will at least tend to prevent instability.

Each of the connecting passageways between the annular space of the coolant channel and the NaK expansion bellows will be restricted to a sufficiently small dimension that rapid flow of liquid between the expansion chamber and the annular spaces cannot occur. Hence, impacting on the bottom end of the cask will not result in the transfer of a significant amount of additional NaK into the expansion chamber. Prior to impact (normal conditions), the quantity of NaK in the expansion chamber will be near the minimum, with substantial room left for expansion in the event of a large increase in temperature. Thus, there will be very little rise in pressure in the expansion chamber as a result of impact. The expansion bellows will be made of relatively thin metal and will probably rupture due to impact forces. However, rupture of the bellows will not harm the containment capability of the system since containment is provided by the expansion chamber housing, which is surrounded and supported by the cask structure.

8.1.4 Seal Assembly

The seal assembly must resist hydraulic pressures produced by rapid deceleration as well as the forces resulting from deceleration of the movable parts of the assembly. Tests have been made which have clearly demonstrated that deformations in the metal structure of a steel cask head do not extend any significant distance beyond the area of the displaced metal. Eight model steel casks having wall thicknesses proportional to their size and fitted with nominal 1-in. Grayloc seals have been subjected to a 30-ft free-fall impact on an unyielding surface without benefit of any energy absorber, and no change in leak rate that could be construed as indicative of materials deformation or failure has been noted in any of the tests. The most stringent of these tests was an end drop of an unprotected 1/6-scale model in which a pipe was welded to the cask body around the seal opening. This pipe was filled to a height of 11 in. with mercury. The impact produced a deceleration of about 2000 g, which is equivalent to a pressure of about 10,000 psi. The seal did not fail; and there was no detectable change in helium leak rate as measured by a mass spectrometer. The leak rate, both before and after the test, was less than the limit of detection ($< 10^{-10}$ cm^3/sec). A fuller description of the tests and results can be found in refs. 6 and 7.

The seals that are proposed for this cask are of the same general design and construction as those used in the 1/6-scale model casks. As the seal nearest the outside is largest in diameter and identical metal thicknesses are to be used in all seal assemblies, the stresses produced in this unit will be greater than in any of the other units for the same pressure loading. In actuality, the only one of the three sequential seals that would be exposed to a pressure excursion is the one that is located the greatest distance from the outside. However, all three of the seals are designed similarly, and each of them is intended to be capable of surviving the peak pressure that would result from a 200-g deceleration.

The seal in question is 9.75 in. in diameter. The peak pressure would create a total force of 112,000 lb. The metal is removed from the area immediately behind the sealing lips of the seal plate to allow some flexing of these lips (see Fig. 8-1). The retaining nut will extend slightly beyond (toward the center) the relieved area behind the seal lips. The internal load imposed on the thick central section of the seal plate can then be transmitted to the retaining nut without imposing a shear load on the thinner section joining the central section with the outer portion of the seal plate.

The strength of the central portion of the seal plate was calculated by assuming it to be supported at the edges by the retaining nut. A uniform load was used over the surface. The maximum stress and deflection (at the center) were calculated to be 23,635 psi and 0.009 in., respectively. The material of construction is AISI 660 steel, which has a yield stress of 90,000 to 100,000 psi at the temperature in question. The angle of the outer edge of this central section, when supported as indicated above, was calculated to be 0.0015 radian.

The thin section between the lips and the central section can be placed under load from axial forces only by the force applied from the outside to move the seal plate down, and by flexing of the central portion of the plate. The amount of flexure indicated above will be experienced only under exceedingly abnormal circumstances. Under such circumstances, the thinner member will be strained to 0.0045 in./in., which is well below its ductility limit.

The retaining nut has a maximum design load resulting from an estimated differential pressure across the seal plate of 1500 psi. This nut will be restrained at the outer edges by interrupted threads. For analytical purposes it was assumed that the entire load is placed on the inner diameter of the nut. Under this condition, the maximum calculated shearing stress is 16,600 psi and the maximum deflection is 0.001 in. The material of construction is AISI 660 steel. The maximum shearing stress in the interrupted threads is 16,700 psi.

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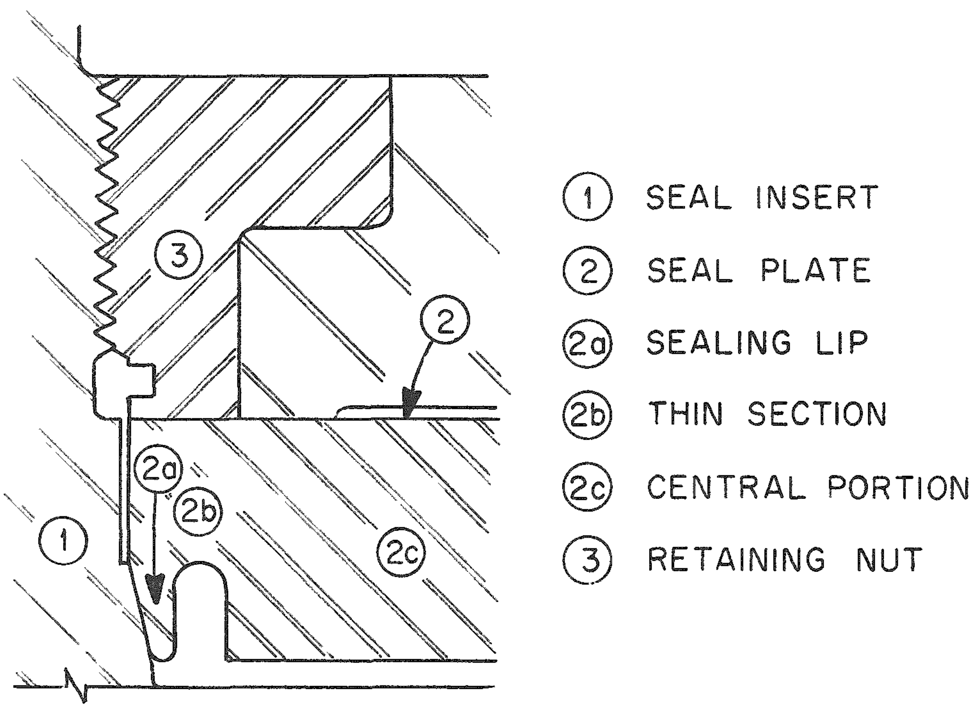

Fig. 8-1. Seal Assembly Details.

Side thrusts will be produced by inertial forces on the various parts. The retaining nut is to be fitted with V-shaped, interrupted threads. Any loaded bolt having V-threads will automatically center itself. In order to displace the bolt from the center of the nut (assuming that some clearance exists), the minimum side force required to achieve motion, assuming 90° V-threads and no friction, must be equal to the load on the bolt. In this case the load will be at least 25,000 lb, as indicated by manufacturers' literature and confirmed by tests we have made. Also, the retaining nut and the seal plate press against each other with the same force of 25,000 lb. Thus there can be no relative motion between the two members unless the friction between them is overcome. Assuming the coefficient of static friction to be the accepted value for dry steel on steel (i.e., 0.3), the available restraining force between the two parts is 7500 lb. The largest seal plate will weigh approximately 26 lb. Therefore, the side deceleration of 200 g would not effect motion between the seal plate and nut; consequently, no side load could be placed on the sealing lips without sidewise motion of the retaining nut. And sidewise motion of the nut in the threads cannot occur (when loaded to 25,000 lb) in a seal plate—retainer nut complex having a combined weight (of all parts) of 60 lb or less when the maximum deceleration rate is less than 200 g.

The seal seats are machined into the seal insert. This insert is secured to the cask end plug by means of threads. (The insert is also seal-welded to the end plug for containment purposes.) An end impact would load the threads in shear as a result of hydrostatic force plus the inertial force attributable to the mass (~ 360 lb) of the seal assembly. The total shearing stress in the threads would be less than 2500 psi in the event of a 200-g axial deceleration.

The shield plug and cover plate located above the seal plates are secured to the cask by shear keys. They have a combined weight of 230 lb. A 200-g axial deceleration would produce a shearing stress of 1830 psi on the keys.

8.1.5 Fuel Magazine and Volume Expansion Chamber (See Figs. 3-4 and 3-5)

If the cask were to impact on the top, a fuel subassembly would apply a load to its retaining device. (The concept of linkage between the subassembly and retaining device is not adequately developed and cannot be analysed.) The shearing stress applied to the pins securing the retaining device in the magazine would be 40,000 psi. Hence, the element would remain in the element channel after the impact. Because the fuel subassemblies will be linked to the retaining device, a bottom impact will produce the same shearing stress in its pins as indicated above.

If the cask impacts on its side (perpendicular to the axis of the cask), the fuel magazine is placed in bending. The maximum bending moment of 46.36×10^6 in.-lb is located 86.3 in. from the top of the magazine. The resulting bending stress of 65,000 psi is somewhat above the yield stress but is of little consequence since the corresponding maximum deflection of 0.7 in. would not render the magazine inoperable.

If the cask were subjected to an end impact normal to its bottom surface, the members forming the gas-filled volume (provided for thermal expansion of sodium) would be loaded by pressure and by the inertial forces attributable to the mass of the magazine and fuel elements. The curved ligaments forming the outer shell would be in a biaxial state of stress consisting of a hoop stress of 31,900 psi and a longitudinal compressive stress of 28,600 psi. The shearing stress resulting from this condition would be 30,400 psi. At the junction of the curved ligaments and the bulkheads, the hoop stress diminishes, but a localized bending stress of 55,800 psi is present in addition to the compressive stress. The tube sections forming the lower portion of the fuel element channels will be similarly stressed, but to a significantly lower level. The hoop stress will be 17,625 psi; the compressive stress will be 28,000 psi. The resultant shearing stress is 23,100 psi, and the localized bending stress is 31,900 psi. Stresses of this magnitude will not result in significant deformations or changes in the internal volume available for expansion of sodium. Whatever changes do occur in the expansion device will not decrease the total available expansion volume.

An end impact would load the bottom magazine thrust bearing to 3,660,000 lb, which is below its static load capacity.

8.1.6 Neutron Shield

An impact in any orientation would cause stressing of the neutron shield housing. An acceleration of 200 g in a direction normal to the 12 x 12 x 1/2-in.-thick cover plate is calculated to produce a maximum bending stress of 20,200 psi and a maximum deflection of 0.009 in. at the center of the plate. With the direction of impact parallel to the face of the cover plate, stress and deflection in the plate are calculated to be 11,800 psi and 0.005 in., respectively. This same loading is calculated to produce a maximum stress of 28,900 psi and a deflection of 0.008 in. in the 1/4-in.-thick members of the box structure. Such stresses are quite acceptable since absence of deformation is not a requirement for the neutron shield housing.

8.1.7 Fuel Subassembly and Criticality

An axial impact would place the fuel subassembly either in tension or in compression. If the fuel subassembly is considered as a column and the impact is assumed to occur directly on the top end of the cask, the maximum compressive load placed on the wrapper tube is estimated to be about 100,000 lb. Loading of this intermediate length column is certain to be non-ideal, and failure by buckling is expected. Buckling would proceed until side support was gained from the support tube. The manner of failure of the fuel subassembly is in doubt, because the wrapper metal and the cladding would have lost much of their ductility due to neutron irradiation. There is also reason to question the fate of the intrasubassembly fuel restraints when they are placed under load by impact. If the fuel were in the original condition (in which the rods could move with relative freedom within the wrapper), the load imposed upon the restraint would almost surely cause failure. However, swelling may be sufficient to fix the position of the fuel tubes relative to the wrapper.

The spectrum of possibilities that exists cannot be fully resolved with the available evidence. However, the worst conceivable situation involves a failure of fuel rods and cladding that results in the position of the fuel charge being shifted axially to the upper end of the cask where the shielding is thinner. The fuel position and configuration in this case would be restricted to that which is attainable within the fuel support tubes, since both ends of the fuel support tube are closed to everything except fluids and very small particles.

Another probable result of a 200-g impact of the cask against an unyielding surface is rupture of the tubes due to external pressure. This would occur even if the subassembly structure did not break down. The calculated maximum permissible external pressure is 640 psi greater than the internal pressure. Since the internal pressure will be no greater than 450 psi at 250°C, a peak external pressure of 1500 psi would cause collapse of the plenums. With ductile tubing, a momentary collapse would probably not result in rupture, but irradiated tubing is expected to be relatively brittle (about 1% elongation) and consequently would be expected to rupture.

The minimum critical masses have been calculated for spheres of mixed stainless steel and urania-plutonia interspersed with varying fractions of sodium.[8] The ratios of stainless steel, urania, and plutonia used were those specified for the core section of an AI follow-on subassembly. The calculated masses, and their equivalent in terms of number of AI follow-on subassemblies, are indicated in the following table:

Volume Fraction of Sodium	Critical Mass of Sphere (kg Pu)	Equivalent Number of Fuel Assemblies
0	123.0	14.5
0.2	175.5	20.8
0.4	377.6	44.8

The sodium volume fraction in an AI follow-on fuel subassembly in its virgin condition is 0.33. The probability of achieving a sodium fraction in the mixture less than 0.33 is regarded as extremely remote. As the fuel will be contained within the fuel magazine support tubes, the urania-plutonia-stainless steel mixture can occupy a fraction of the total volume which is no greater than the inside cross-sectional area of the support tubes divided by the cross-sectional area of the magazine. This fraction is 0.67. Therefore, the minimum attainable effective sodium (non-fuel-containing) volume in the fuel magazine is 0.57. Hence it is concluded that attainment of criticality is incredible in the 6- and 18-subassembly casks loaded with AI follow-on fuel.

8.1.8 Gamma Shielding

Impact accidents will decrease the thickness of the gamma shielding to a very small degree and, therefore, will not result directly in significant increases in the gamma radiation level outside the cask. However, if a shift in fuel location should occur (as described in the previous subsection) in which the core section is relocated within the zone surrounded by only about 9 in. of steel, the gamma radiation level would be markedly changed. Dose rates resulting from relocation of 50% of the core material have been estimated from the data used in the normal condition shielding analysis (see Figs. 7-1 and 7-2 pertaining to dose rate vs distance from cask center). These estimates are summarized in Table 8-1.

The regulations permit a postaccident dose rate of 1000 mrem/hr at 3 ft from the cask surface. A shift of 100% of the core material would produce dose rates somewhat greater than 1000 mrem/hr at 3 ft.

Table 8-1. Dose Rates Resulting from a Shift of 50% of the Core

No. of Assemblies in Cask Load	Gamma Shield Thickness (in.)	Neutron Shield Thickness (in.)	Expected Dose Rates (mrem/hr)	
			At Surface	At 3 ft
6	9	4	1865	587
18	9.5	6	1660	654

8.2 Puncture

The 1/2-in.-thick outer steel shell, which forms the outer envelope of the cask and contains the neutron shielding material, is vulnerable to puncture when the cask is subjected to a 40-in. free fall onto a 6-in.-diam piston. Although the neutron shield could be penetrated by a projectile or other means by which extreme local forces are applied, the loss of shielding would occur only in a localized area since the shield is compartmentalized. The dose rates resulting from a local loss of neutron shield will be less than those specified in Table 7-4 since the dose rates given in the table are for a complete loss of the neutron shield. In turn, the calculated dose rates for a complete loss of neutron shield are less than the rate permitted following the hypothetical accident.

The portion of the cask surface with the greatest potential for damage from puncture is that of the fuel access port (see Fig. 3-3). An impact with a 6-in. piston would result in an acceleration of 10.4 g and apply a maximum force of 2,700,000 lb to the access port cover plate. In the area of contact, the peak compressive stress would be 95,000 psi and the metal would be locally displaced to a depth of 0.2 in. Load would be placed on the shield plug, which would deflect about 0.035 in. Because the distance between the shield plug and the top seal plate assembly is much greater than 0.035 in., no load would be transmitted to that plate. The shearing stress on the threads of the shield plug insert (which supports the shield plug) would be 14,500 psi; hence, no significant load would transfer to the removable seal insert. Therefore, the seals would be exposed only to acceleration-induced loads by puncture loads in that area. No significant damage to shielding would result.

8.3 Fire

8.3.1 Temperature Transients

An accident sequence is presumed to start when a cask is operating normally. The cask body will be at approximately 250°F, as controlled by the auxiliary shield cooling system. The temperature distribution throughout the cask resulting from simultaneous loss of auxiliary shield cooling and the start of a hypothetical 1475°F fire was calculated by the computer code HEATING.[9]

The calculations were made on the basis of an unfinned cask without a neutron shield. The results are conservative as to the effects of a fire, because a fusible shield will absorb a great quantity of heat during melting. The results of the calculations for 30-min-duration and for 3-hr-duration fires are displayed in Figs. 8-2 and 8-3 for the 6- and 18-subassembly casks, respectively. The 30-min fire can be seen to have little effect on the cask inside temperature. A fire of this duration will only reduce the time required for the cask to reach steady-state temperature for unaided discharge of heat to the atmosphere. The calculated values under the above condition for the 6- and 18-subassembly casks were 362°F and 505°F at the outside and 430°F and 645°F on the inside surface. The peak fuel rod temperature for the two cases would be 70°F and 165°F (for the 6- and 18-subassembly casks, respectively) greater than the above estimated inside surface temperatures, due to temperature variations in the fuel cavity as described in Sect. 7.2. A 3-hr-duration fire for either of the casks (with no neutron shield) raises the outside temperature to about 1150°F and on the inside to about 850°F.

The effect of the LiOH-NaOH neutron shield on the response of a cask to fire can be surmised in part from the following. The latent heat of fusion of a 6-in. layer of the eutectic mixture (m.p. 428°F) is about 7300 Btu/ft^2. The maximum heat input by the fire is about 1700 Btu/hr · ft^2. Hence, the maximum heat input from a 30-min fire could do very little more than melt the LiOH-NaOH. However, the suggested construction of the neutron shield will reduce the fire heat input by a substantial amount because there is no contact between the outside shell (which is

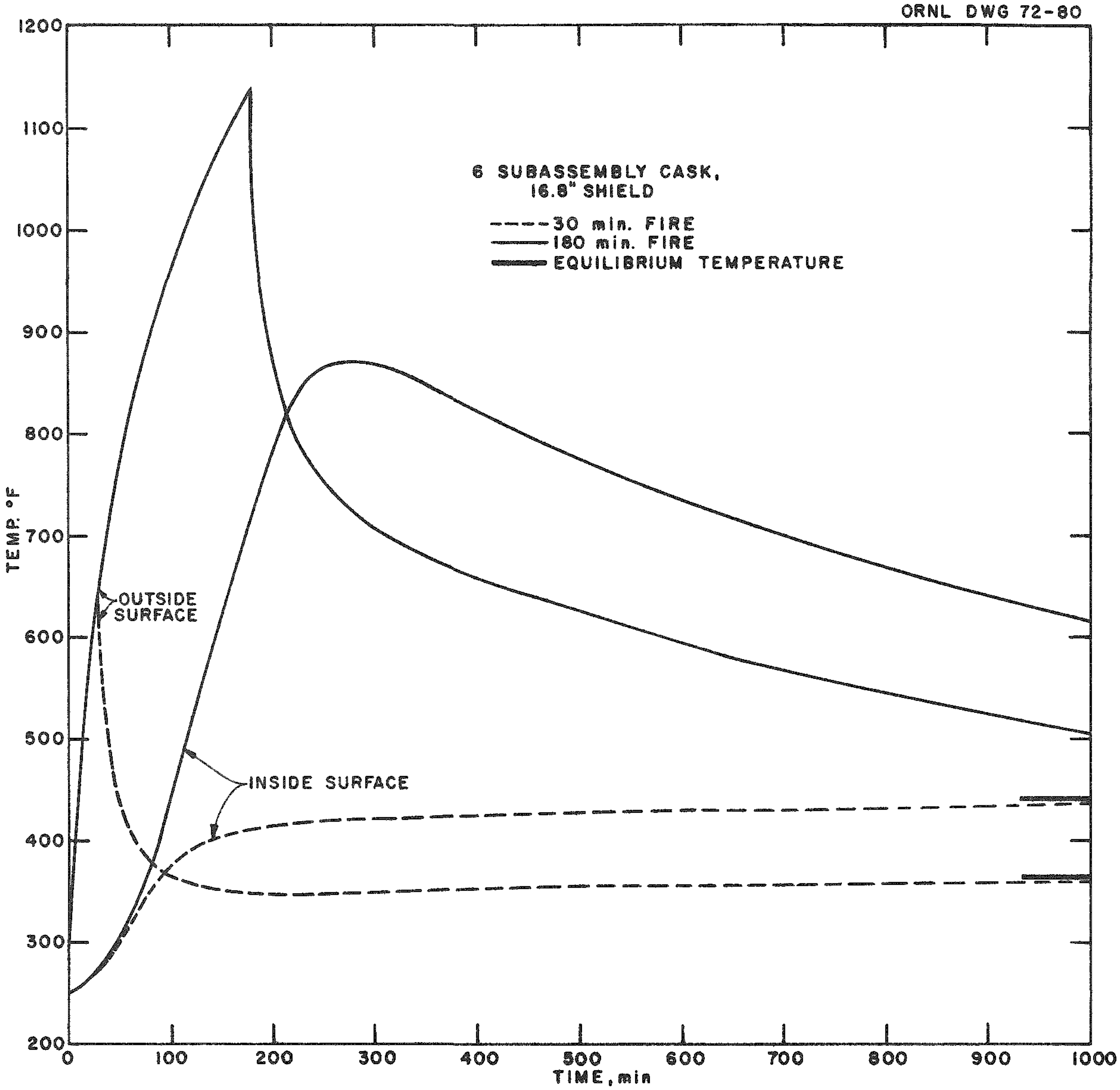

Fig. 8-2. Effect of 30-min and 3-hr Fires on 6-Subassembly Cask Temperatures.

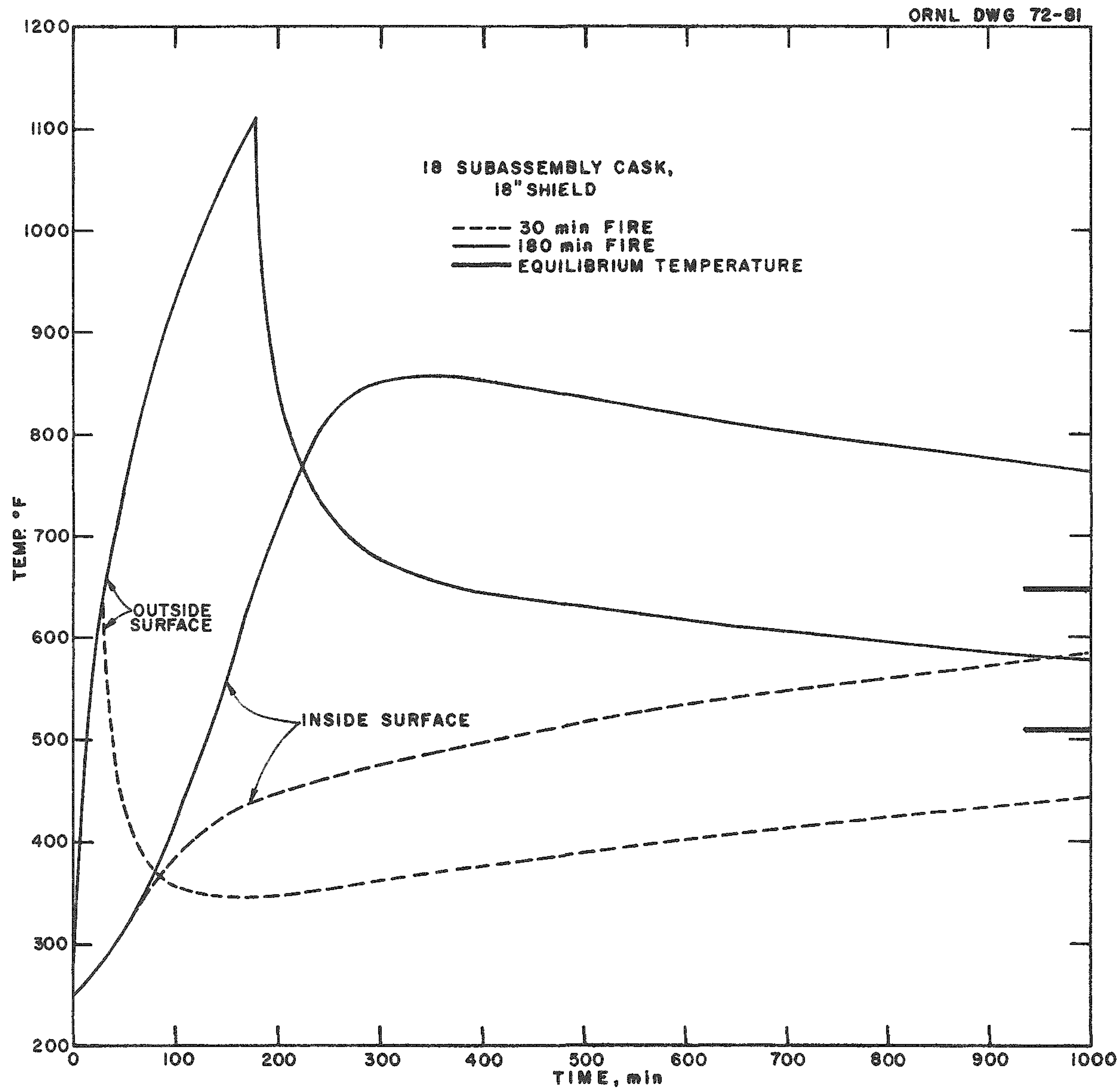

Fig. 8-3. Effect of 30-min and 3-hr Fires on 18-Subassembly Cask Temperatures.

heated by the fire) and the LiOH-NaOH. Initially, the only paths available for entry of externally supplied heat are radiation, and conduction along the walls of the neutron shield containers. The effect of this construction on rate of heat input has not been determined, but it is expected to be pronounced.

Another effect of the LiOH-NaOH neutron shield is expected to be a minimum steady-state shield temperature for the loss-of-auxiliary-shield-cooling condition. While the hydroxide mixture is melted, thermal convection will cause its effective thermal conductivity to be high; therefore, heat will pass through the neutron shield with very little drop in temperature as long as the cask surface temperature is 428°F or more. However, the thermal conductivity of the solid is relatively low (probably approximately 1 Btu/hr · ft · °F). Hence, the neutron shield will behave as a gamma shield minimum temperature controller, with a 428°F set point.

8.3.2 Temperature Effect on Sodium Volume and Cask Pressure

Under normal operating conditions of 250°F and atmospheric pressure, a gas-filled volume equal to 15% of the sodium volume will exist in the volume expansion device and above the sodium level in the fuel cavity. Expansion of the sodium with temperature will increase the pressure in the cask according to the curve shown in Fig. 8-4. The pressure expected to be attained at steady state with loss of auxiliary shield cooling in the 18-subassembly cask (temperature about 720°F) is 48 psi. The maximum pressure attained in the cavity of this cask during exposure to a 3-hr fire (sodium temperature, about 935°F) is estimated to be 105 psi. The ability of the components to perform under these conditions is discussed in subsequent subsections.

8.3.3 Cask Body and Other Structural Members

The maximum pressure calculated as achievable as the result of sodium expansion under hypothetical accident conditions, with defective fuel rods (the worst case) releasing fission gas into the fuel cavity, is 400 psi. The design pressure for the cask body, seals, etc., is 1500 psi at 250°F. The changes in allowable stresses as a function of temperature of the materials used in the containment structure are shown in Fig. 8-5. The maximum stresses on essentially all parts of the system are

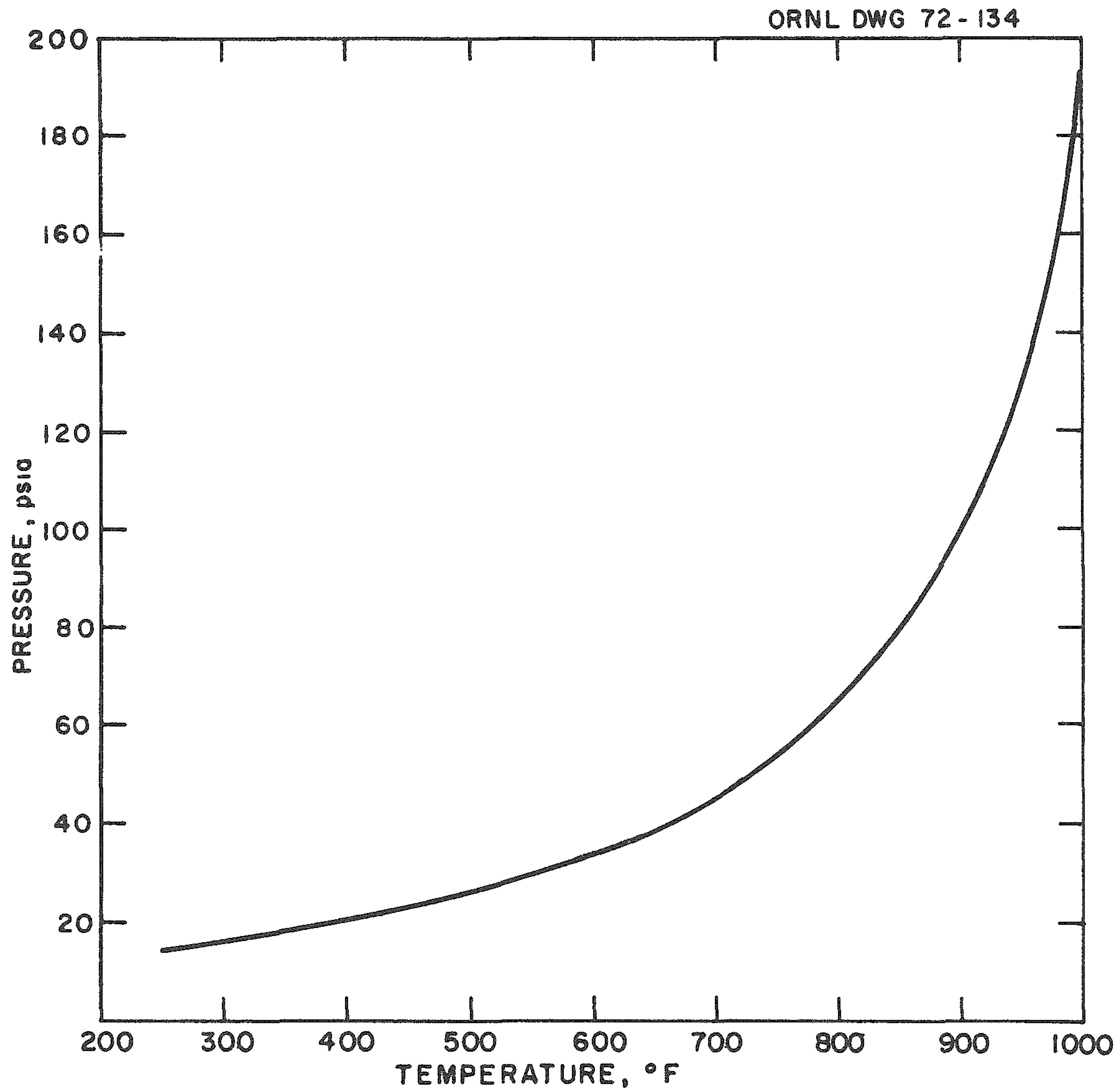

Fig. 8-4. Effect of Temperature on Pressure in a Sodium-Filled Vessel Having 13% Free Volume at 250°F.

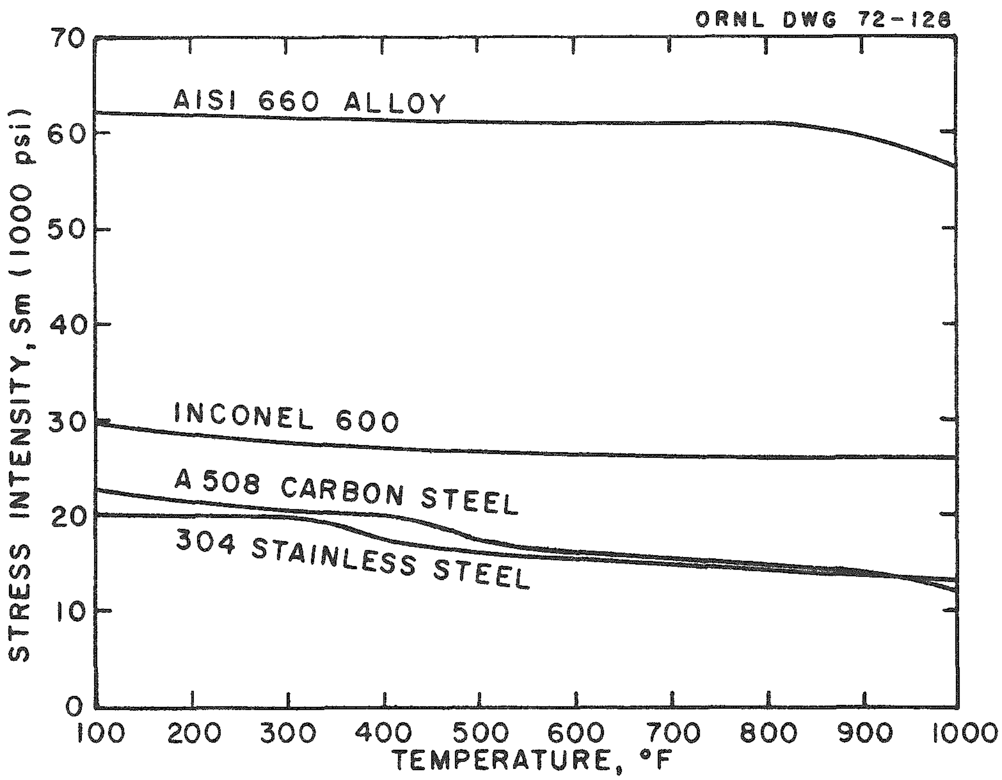

Fig. 8-5. Effect of Temperature on Allowable Working Stress of Various Alloys. Allowable stress for Inconel 600 and AISI 660 alloy based on two-thirds of yield stress.

reduced to about 27% of those which would occur at the calculated peak pressure of 400 psi as opposed to the peak impact pressure of 1500 psi. It can be seen in Fig. 8-5 that the properties of the construction materials are reduced relatively little by increasing the metal temperature from 250 to 665°F. Hence, the structure is adequate to withstand the pressures that will result from a 30-min fire and loss of cooling. A 3-hr fire can also be tolerated if sufficient space is available for expansion of the fission product gas that leaks from the ruptured fuel rods.

Thermal stresses present an additional problem. An accident involving loss of auxiliary shield cooling and/or a fire will be extremely rare in the life of a cask. In a practical sense, thermal stresses can cause failure of equipment only if the materials of construction are nonductile, if the thermal stresses are applied repeatedly, or if a mechanism for concentration of the stresses exists. All the materials proposed for use in these casks possess substantial ductility (more than 15% elongation in 2 in.). Even 100 thermal cycles would be considered a small number for most thermal stresses to present a serious problem, whereas no cycles are probable in this case; and 10 cycles is a very conservative maximum estimate. A final cask design would be carefully analyzed and checked to assure that mechanisms which would concentrate thermal stresses were not built into the system.

8.3.4 Fuel Access Port Seals

Test information is not available to establish that the seal concept described in this report will perform satisfactorily during a thermal transient. Exhaustive calculational approaches have not been made, and would be extremely suspect in the absence of experimental proof. Although no supporting evidence is needed to establish that a thermal transient can cause leakage of a gasket seal, the negative results obtained with a model fuel access port will be described. The model fuel access port was subjected to a much more rapid thermal transient than would occur in practice,and relatively gross leakage occurred. This test unit employed a massive, one-piece plug that had very little contact with the surrounding massive metal housing. The material for both the housing and plug was 17-4 PH, while the Conoseal gasket extending between the two pieces was made of Inconel X-750.

The coefficient of thermal expansion of 17-4 PH is less than that of Inconel X-750 by about 1×10^{-6} in./in.-°F. The sequence of events is surmised as follows: (1) The temperature of the metal housing led the temperature of the plug by a rather large margin. (2) The gasket was probably at essentially the same temperature as the housing; as the temperature increased the interference between the housing and the gasket OD increased slightly. (3) The temperature of the inner plug may have lagged the gasket temperature by 200°F or more. This could cause a change in gasket-plug interference of minus 0.010 in. When the assembly returned to room temperature, leak-tight sealing was restored.

In the proposed design, the gasket is in direct contact with the mating part, and its temperature will be almost the same as that of the surrounding metal. The coefficient of thermal expansion of the gasket (AISI 660) is very slightly greater than that of the seats (type 304 stainless steel). Increases in temperature will tighten the gasket in its mating part. However, if the thermal cycle causes substantial deformation in the seal lips owing to (in effect) additional stressing, a leak could occur on reduction in temperature.

A gasketed closure employing this general design and these materials has performed satisfactorily under test at Hanford.[10] The test unit was a modified Grayloc connector made with type 316 stainless steel flanges and AISI 660 seal ring. It has been operated with liquid sodium at temperatures and static pressures up to 1100°F and 300 psi, respectively. This unit was subjected to a pressure pulse from 300 psi to 1100 psi in 0.1 sec. No leakage of sodium occurred, as determined by visual examination after disassembly. A thermal transient test was run in which the temperature was increased from 400°F to 1200°F in a period of 4 hr, and then reduced to 400°F in a second 4-hr period. Helium gas at 250 psi was outside the joint, and a vacuum was inside. The leak rate was less than 10^{-7} atm cm^3/sec at all times.

A modified Conoseal connector has also contained sodium at 1100°F and 300 psi without leakage in tests performed at Hanford.[10] The test unit used flanges made of type 316 stainless steel, with the seating surface overlaid with a Stellite. The seal ring was made of Inconel X-750. Only static pressure sodium runs have been made to date.

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9. DESIGN ALTERNATIVES AND DEVELOPMENT PROGRAM

The overall cask design described in the previous sections of this report has used only one of several options that could have been selected for seals, fuel support, volume expansion, neutron shield, energy absorbers, auxiliary heat removal, emergency heat dissipation, and cask body construction. Tests of seals, cask body construction, neutron shield, energy absorbers, and convective heat transport are currently in progress or are planned for the near future. These items will be discussed in some detail below.

Seals. Alternative seal designs include at least three different commercial seals: Grayloc, Conoseal, and Gamah. Retention, installation, and leak detection methods have yet to be fully tested. A spring between the retaining nut and the seal plate may be desirable.

We are in the process of conducting life expectancy tests for the seal seats of Grayloc and Conoseal gasketed joints, and we will soon perform some thermal transient tests. Other tests to be carried out in the near future will determine the need for spring loading the seal plate. Construction of two or more seal assembly models, followed by static, thermal, and acceleration tests, is planned. A sufficient number of tests can be made by the end of 1972 to assure that the design objectives stated in this report can be met.

Cask Body. The construction problem involved in making the final cask closure was forcibly brought to our attention by Combustion Engineering personnel in Chattanooga, Tennessee (G. A. Rutledge et al.), in early December 1971. A possible solution to the problem was devised and translated into a design for a nominal 1/6-scale model of the principal parts. Two units, as shown in Fig. 9-1, are being constructed and will be tested during the month of February 1972 with mercury in the fuel cavity, and with the expectation that the general method of liner installation in a mechanically retained head will be proved acceptable.

Neutron Shield. A neutron shield segment that will employ the eutectic mixture of NaOH and LiOH is being constructed. This work will establish the

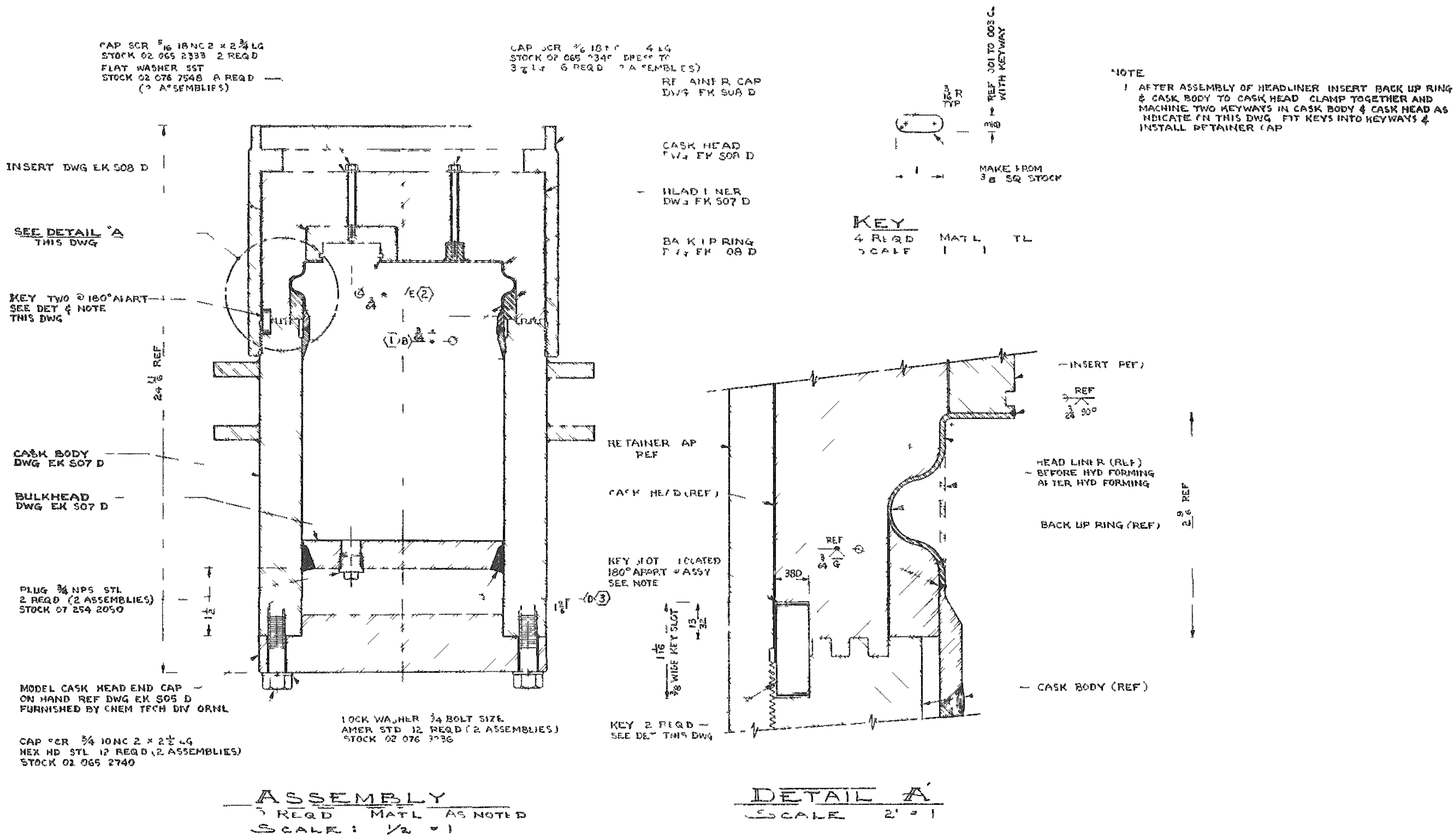

Fig. 9-1. Top Head Liner Test Assembly

maximum fire resistance that can be achieved by any known practical method of construction. Further investigations of materials of construction and the potential for using hydrated hydroxides can be completed by July 1972. The required effort is small.

Convective Heat Transport. Convective heat transport tests are continuing with the two mockups mentioned in Sect. 7. The work with these mockups will be completed during this fiscal year. Other development work in this area would be desirable, but necessary only for making close predictions of performance.

Energy Absorber. Energy absorber tests involving simple steel cylinders and perforated steel bars will be accomplished in February. The holes in the bars will be filled with polyethylene. Such a system might possibly serve as a combination energy absorber and neutron shield. The required effort is small.

Fuel Support. Additional understanding of the characteristics of irradiated LMFBR fuel is needed to arrive at an optimal fuel support system. Additional study of the problem and liaison with those involved in the LMFBR fuels and materials program would be beneficial. The exact nature of the fuel support system can be changed, even after the cask is constructed. Hence, a late determination of the need to employ a different method of fuel support would not cancel the utility of the cask.

The bearings for the rotor are a matter of some concern. The use of roller bearings would reduce friction drastically, but would be more subject to damage in transit than are the metal-on-metal bearings specified earlier. A suitable method of unloading the roller type bearings could conceivably permit the attainment of both ruggedness and near-frictionless operation.

A study involving less than 6 man-months is estimated for more adequate definition of the fuel support complex.

10. ACKNOWLEDGMENTS

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G. A. Rutledge, Combustion Engineering
E. A. Stephenson, Combustion Engineering
C. T. Ward, Combustion Engineering

APPENDIX A: CASK MATERIAL SELECTION
(D. A. Canonico)

The choice of steel for fabrication of a cask has one primary requirement: that this material serve its purpose with unquestionable safety. Subordinate to this requirement are ease of fabrication and cost. The internal dimensions and wall thicknesses of the cask are dictated by the intended service application and the necessary biological shielding. Hence, the advantage obtained with high-strength materials (nominally decreased wall thickness) is not a consideration.

It has been determined that the biological shielding will be provided by a steel shell about 18 in. thick. Design stresses are sufficiently low that a plain carbon steel with yield and ultimate strengths of 35,000 psi and 70,000 psi, respectively, is adequate. Therefore, the safety requirement from a strength viewpoint can be easily satisfied. The point of concern then becomes one of adequate toughness during service to assure safe behavior. The choice of material, therefore, is based on this requirement alone. From the standpoint of safety, the cask must serve adequately only when transporting spent fuel. At that time, the cask will be at a temperature of 200 to 250°F.

In regard to catastrophic failure, leak-before-failure is a desirable feature for the usual containment vessel. However, such a feature is of questionable value in this service application; in addition, simple calculations will show that this criterion cannot be met. If an expected and reasonable fracture toughness value for K_{Ic} at 200°F of 200,000 psi $\sqrt{\text{in.}}$ is assumed, then the flaw size required for frangible behavior at stresses of yield point magnitude (35,000 psi in this example) is about 10 in. This flaw size will decrease for more highly stressed materials and for materials of poorer fracture toughness. Therefore, a leak-before-failure requirement is unobtainable.

The selection of a material with a higher strength is justified only if it results in a bonus insofar as toughness is concerned. An assessment of this possibility can be made through the use of the Ratio Analysis Diagram (RAD) developed by the Naval Research Laboratory personnel.[1] The RAD allows one to assume a level of safety based on a flaw size prediction that may cause failure. At low K_{I_c}/σ_{ys} ratios (<0.5), the flaw size that can cause a catastrophic failure is quite small and presumed to be below the limits detectable by nondestructive examination techniques. K_{I_c}/σ_{ys} ratios greater than 3 indicate a need for huge flaws, and these should be easily detected; therefore, their presence can be considered incredible. Three toughness criteria are used in the RAD: Charpy V notch (C_V) upper shelf values, Dynamic Tear Test upper shelf values, and K_{I_c} values. The C_V values are easily obtained and are most often employed in assessing toughness behavior. The use of fracture mechanics values of K_{I_c} is being extended to practical temperatures for structural steels; however, the specimen sizes necessary to obtain valid data are large, and the data are, therefore, unobtainable in many instances, or else expensive.

A RAD analysis is included as Fig. A-1. The assessment of the toughness for the steels applicable to the cask will be based on C_V upper shelf energy values because they have been the basis of material selection in the past and considerable data are available. We can narrow the steel selection to the Forging Grade ASTM A508, Classes 1, 2, 4 and 4a, and 5 and 5a. These steels exhibit minimum yield strength values of 35,000, 50,000, 85,000, and 100,000 psi, respectively. Classes 1, 2, and 4 obtain their strength values through alloy content. Table A-1 contains their analyses. Classes 4, 5, 4a, and 5a are essentially identical steels, and the differences in their strength levels are obtained through heat treatment. If conservative C_V upper shelf values are assumed for the four classes, they will probably range from 80 ft-lb for Class 1 to 120 ft-lb for Class 2. Classes 4, 4a, 5, and 5a should fall conservatively between these two values.

As previously mentioned, the service application is at temperatures in excess of 200°F. At these temperatures, the steel selected, regardless of class, will be on the upper shelf of the C_V curves. The advantage of a low transition temperature, which is usually associated with the more alloyed steels, is not beneficial in this application. Therefore, the only toughness criterion of consequence is the upper shelf C_V value.

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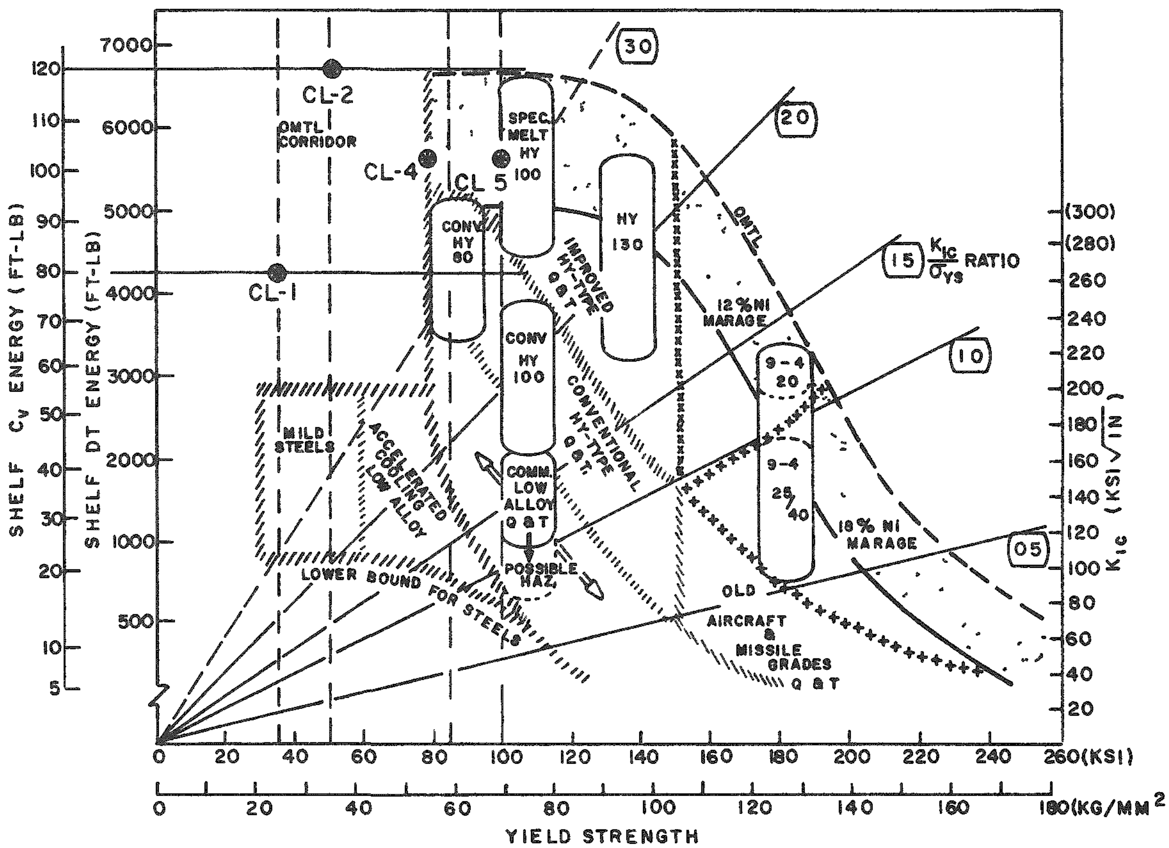

Fig. A-1. Compendium RAD Indexing for Generic Classes of Steels.

Table A-1. Chemical Requirements for ASTM A508 Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forging for Pressure Vessels

Element	Class				
	1	2	3	4 and 4a	5 and 5a
C, %	0.35 max	0.27 max	0.15 to 0.25	0.23 max	0.23 max
Mn, %	0.40 to 0.90	0.50 to 0.90	1.20 to 1.50	0.20 to 0.40	0.20 to 0.40
P, %	0.025 max	0.025 max	0.025	0.02 max	0.02 max
S, %	0.025 max	0.025 max	0.025	0.02 max	0.02 max
Si, %	0.15 to 0.35	0.15 to 0.35	0.15 to 0.35	0.30 max	0.30 max
Ni, %	-	0.5 to 0.9	0.40 to 0.80	2.75 to 3.90	2.75 to 3.90
Cr, %	-	0.25 to 0.45	-	1.50 to 2.00	1.50 to 2.00
Mo, %	-	0.55 to 0.70	0.45 to 0.60	0.04 to 0.06	0.40 to 0.60
V, %	0.05 max	0.05 max	0.05 max	0.03 max	0.08 max

The assessment of the toughness of the four steels is shown in Fig. A-1. Vertical dashed lines have been drawn on the diagram to represent the four yield strength values. It is assumed that steel made to the ASTM A508, Class 1 specification will be a high-quality product. The expectation of an 80 ft-lb C_V upper shelf is not unreasonable. The intersection of the 80 ft-lb C_V value and the 35,000 psi yield value lies in the region above the K_{I_c}/σ_{ys} ratio of 3. Therefore, it is expected that huge flaws will be necessary to cause failure, and it can be predicted that failure will only occur due to plastic instability. Hence, brittle fracture is an incredible accident condition. The other three steels, based on reasonable upper shelf C_V values provide equal freedom from brittle fracture, but no advantage over Class 1 steel in this respect.

As further support for the choice of a high-quality plain carbon steel, we can now cite cost and fabrication advantages. The fabrication of the plain carbon steels, particularly welding, is much simpler than fabrication of low alloy steels. The cost of material and fabrication should provide a savings of nearly 50% over the Class 2 alloy.

The only other factor to be considered prior to final material selection is performance under an accident condition involving a fire. In such an event, it is conceivable (although extremely improbable) that the cask could reach a temperature of 1200°F. The difference in the strengths of these steels at elevated temperatures is negligible, and no advantage of one over another is expected.

In view of the preceding discussion, the cask material selected is ASTM A508, Class 1, or its equivalent.

<u>References for Appendix A</u>

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