TRIGA Reactor Facility

Nuclear Engineering Teaching Laboratory

The University of Texas at Austin

SAFETY ANALYSIS REPORT

Submitted May 1991

Revision 1.01

Revision Dates

Chapter 1	5/91	Chapter 7	5/91
Chapter 2	5/91	Chapter 8	5/91
Chapter 3	5/91	Chapter 9	5/91
Chapter 4	5/91	Chapter 10	5/91
Chapter 5	5/91	Chapter 11	5/91
Chapter 6	5/91		

Page Replacements - October 1991

2-25,	7-5, 22, 23, 27, 28,
4-69,	8-1, 7, 10, 11, 16, 18, 22,
5-12, 14,	9-11, 9-15
6-13, 15,	10-2, 6, 9, 10, 31

Chapter 4

TRIGA REACTOR

The reactor design bases are predicted on the maximum operational capability for the fuel elements and configuration described in this report. The TRIGA reactor system has three major areas which are used to define the reactor design bases:

a. Fuel temperature,

b. Prompt negative temperature coefficient,

c. Reactor power.

Of these three only one, fuel temperature, is a real limitation. A summary is presented below of the conclusions obtained from the reactor design bases described in this section.

4.1. DESIGN BASES

The fuel temperature is a limit in both steady-state and pulse mode operation. This limit stems from the out-gassing of hydrogen from U-ZrH (H/Zr ; x) fuel and the subsequent stress produced in the fuel element clad material. The strength of the clad as a function of temperature can set the upper limit on the fuel temperature. Fuel temperature limits of 1150°C (with clad $\leq$ 500°C) and 970°C (with clad $\geq$ 500°C) for U-ZrH (H/Zr ; 1.65) have been set to preclude the loss of clad integrity. Simnad [34] summarizes the properties of U-ZrH_x fuel materials for TRIGA reactors, including the limiting design bases and parameters.

The basic parameter which provides the TRIGA system with a large safety factor in steady-state operation and under transient conditions is the prompt negative temperature coefficient which is rather constant with temperature (~0.01% $\delta k/k$°C), as described later. This coefficient is a function of the fuel composition and core geometry.

Fuel and clad temperature limit the operation of the reactor. However, it is more convenient to set a power level limit which is based on temperature. The design bases analysis indicates that operation at up to 1900 kW (with an 85 element core and 120°F inlet water temperature) with natural convective flow will not allow film boiling, and therefore high fuel and clad temperatures which could cause loss of clad integrity could not occur.

4.1.1 Reactor Fuel Temperature

The basic safety limit for the TRIGA reactor system is the fuel temperature; this applies for both the steady-state and pulse mode of operation.

Two limiting temperatures are of interest, depending on the type of TRIGA fuel used. The TRIGA fuel which is considered low hydride, that with an H/Zr ratio of less than 1.5, has a lower temperature limit than fuel with a higher H/Zr ratio. Figure 4-1 indicates that the higher hydride compositions are single phase and are not subject to the large volume changes associated with the phase transformations at approximately 530°C in the lower hydrides. Also, it has been noted [1] that the higher hydrides lack any significant thermal diffusion of hydrogen. These two facts preclude concomitant volume changes. The important properties of delta phase U-ZrH are given in Table 4-1.

Table 4-1

PHYSICAL PROPERTIES OF DELTA PHASE U-ZrH

Thermal conductivity (93°C - 650°C)	13 Btu/hr-ft^2-°F
Elastic modulus: 20°C	9.1 x 10^6 psi
650°C	6.0 x 10^6 psi
Ultimate tensile strength (to 650°C)	24,000 psi
Compressive strength (20°C)	60,000 psi
Compressive yield (20°C)	35,000 psi
Heat of formation (δH_f^o 298°C)	37.72 kcal/g-mole

Among the chemical properties of U-ZrH and ZrH, the reaction rate of the hydride with water is of particular interest. Since the hydriding reaction is exothermic, water will react more readily with zirconium than with zirconium hydride systems. Zirconium is frequently used in contact with water in reactors, and the zirconium-water reaction is not a safety hazard. Experiments carried out at GA Technologies show that the zirconium hydride systems have a relatively low chemical reactivity with respect to water and air. These tests have involved the quenching with water of both powders and solid specimens of U-ZrH after heating to as high as 850°C, and of solid U-Zr alloy after heating to as high as 1200°C. Tests have also been made to determine the extent to which fission products are removed from the surfaces of the fuel elements at room temperature. Results prove that, because of the high resistance to leaching, a large fraction of the fission products is retained in even completely unclad U-ZrH fuel.

4.2. NUCLEAR DESIGN AND EVALUATION

The characteristics and operating parameters of this reactor have been calculated and extrapolated using experience and data obtained from existing TRIGA reactors as bench marks in evaluating the calculated data. There are several TRIGA systems with essentially the same core and reflector relationship as this TRIGA so the values presented here are felt to be accurate to within 5% but, of course, are influenced by specific core configuration details as well as operational details.

An operational core of 86 fuel elements, 3 fuel followed control rods, and one air followed control rod is to be arranged in 5 rings with a central, water filled hole. Dimension of the active fueled core, a cylinder, is 15 inches in height with an average radius of 8.6 inches. The cylinder radius is calculated as the average radius of a hexagonal fuel array with 91 unit cells (6 filled rings including the center hole) and a unit cell area of 2.55 square inches.

Table 4-3 summarizes the typical Mark II TRIGA reactor parameters for a core containing high-hydride, stainless steel clad fuel elements.

Table 4-3

TYPICAL TRIGA CORE NUCLEAR PARAMETERS

Fuel elements	SS-clad U-$ZrH_{1.6}$
Cold clean critical loading	~64 elements
	~2.5 kg U-235
Operational loading	~90 elements
	~3.4 kg U-235
ℓ, Prompt neutron lifetime	41 μsec
ß, Effective delayed neutron fraction	0.0070
α, Prompt negative temperature coefficient	~1.0 x 10^{-4} $\delta k/k$°C
T_f Average fuel temperature (1.1 MW)	265°C
T_w Average water temperature (1.1 MW)	65°C
Water coolant volume to cell volume ratio	~1/3

4.2.1. Reactivity Effects

The reactivity associated with the control rod is of interest both in the shutdown margin and in calculations of possible abnormal conditions related to reactivity accidents. Table 4-4 gives approximate reactivity values associated with a total control rod travel of 15 in. (38.1 cm), the full travel in the core.

Table 4-4

ESTIMATED CONTROL ROD NET WORTH

Control Rod	diameter in. (cm)	δk/k %
C ring - transient	1.25 (3.18)	2.1
C ring - regulating	1.35 (3.43)	2.6
D ring - shim 1	1.35 (3.43)	2.0
D ring - shim 2	1.35 (3.43)	2.0

The maximum reactivity insertion rate is that associated with the transient rod which can be fully removed from the core in 0.1 sec producing an average reactivity insertion rate of 21% δk/k-sec.

The total reactivity worth of the control system is about 8.7%. With a core excess reactivity of 4.9%, the shutdown margin with all rods down is about 3.8% and with the most reactive rod stuck out is about 1%.

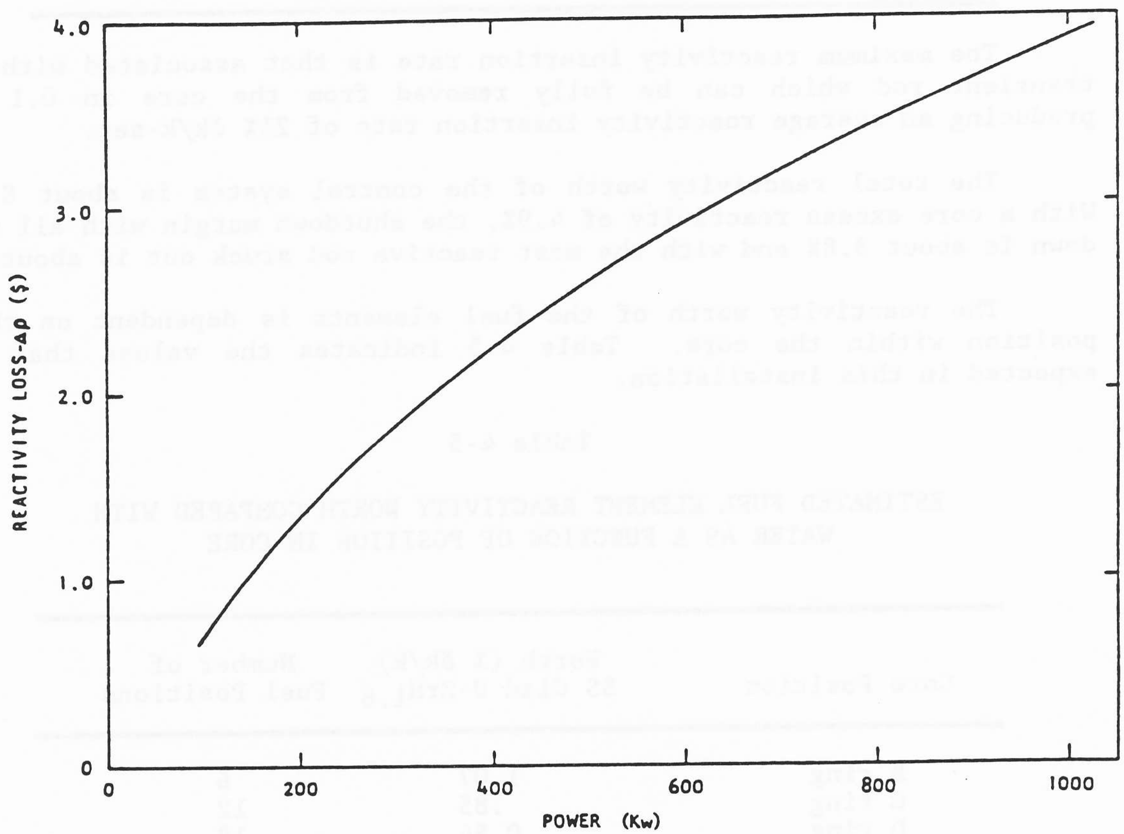
The reactivity worth of the fuel elements is dependent on their position within the core. Table 4-5 indicates the values that are expected in this installation.

Table 4-5

ESTIMATED FUEL ELEMENT REACTIVITY WORTH COMPARED WITH WATER AS A FUNCTION OF POSITION IN CORE

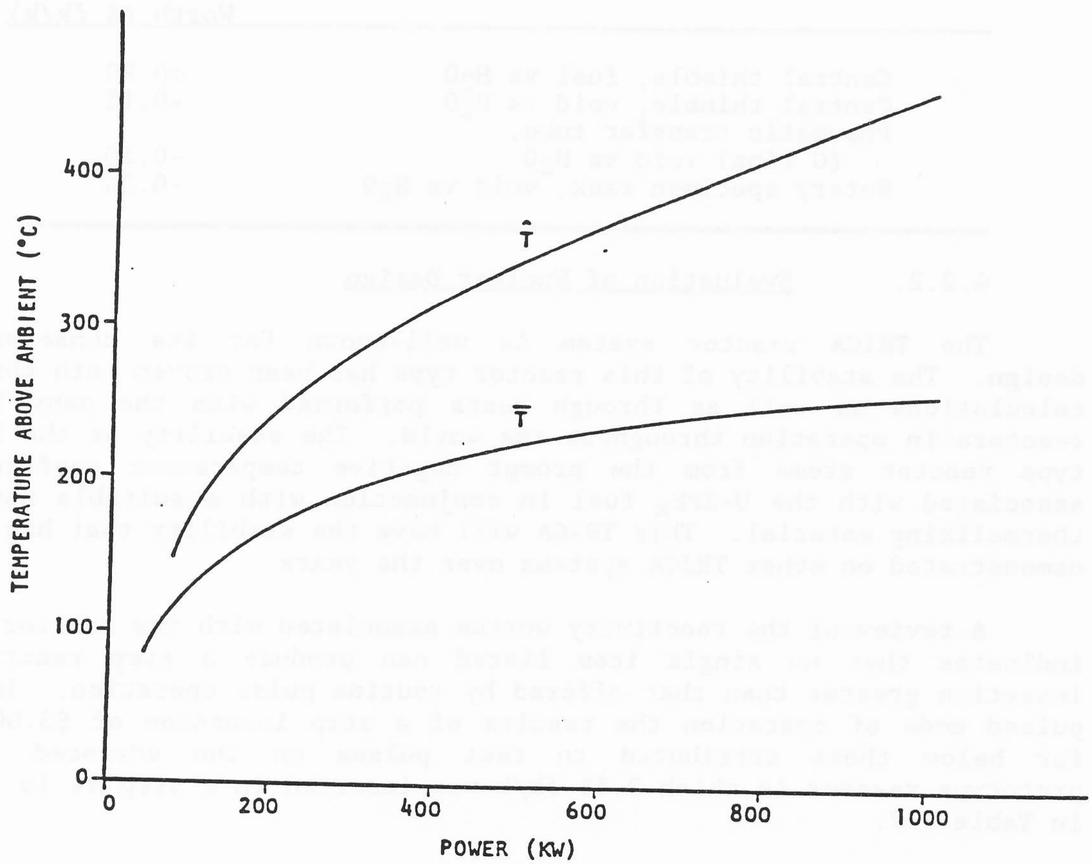
Core Position	Worth (% δk/k) SS Clad $U\text{-}ZrH_{1.6}$	Number of Fuel Positions
B ring	1.07	6
C ring	.85	12
D ring	0.54	18
E ring	0.36	24
F ring	0.25	30
G ring	0.19	36

Because of the prompt negative temperature coefficient a significant amount of reactivity is needed to overcome temperature and allow the reactor to operate at the higher power levels in steady-state operation. Figure 4-23 shows the relationship of reactor power level and associated reactivity loss to achieve a given power level. Figure 4-24 relates fuel temperature to a given steady-state reactor power level.



ESTIMATED REACTIVITY LOSS VERSUS POWER

Figure 4-23



ESTIMATED MAXIMUM B RING AND
AVERAGE CORE TEMPERATURE VERSUS POWER

Figure 4-24

The reactivity effects associated with the insertion and removal of experiments in or around the core are difficult to predict; however, Table 4-6 is supplied to provide a guide to the magnitude of the reactivity effects associated with the introduction of experiments in the reactor core.

Table 4-6

EXPECTED REACTIVITY EFFECTS ASSOCIATED WITH EXPERIMENTAL FACILITIES

	Worth (% $\delta k/k$)
Central thimble, fuel vs H_2O	+0.90
Central thimble, void vs H_2O	-0.15
Pneumatic transfer tube, (G ring) void vs H_2O	-0.10
Rotary specimen rack, void vs H_2O	-0.20

4.2.2. Evaluation of Nuclear Design

The TRIGA reactor system is well-known for its conservative design. The stability of this reactor type has been proven both through calculations as well as through tests performed with the many TRIGA reactors in operation throughout the world. The stability of the TRIGA type reactor stems from the prompt negative temperature coefficient associated with the U-ZrH_x fuel in conjunction with a suitable neutron thermalizing material. This TRIGA will have the stability that has been demonstrated on other TRIGA systems over the years.

A review of the reactivity worths associated with the reactor core indicates that no single item listed can produce a step reactivity insertion greater than that offered by routine pulse operation. In the pulsed mode of operation the results of a step insertion of $3.00 are far below those attributed to test pulses on the advanced TRIGA prototype reactor in which 3.5% $\delta k/k$ was inserted in a step as is shown in Table 4-7.

A total reactivity limit for experiments is set at $3.00. This limit constrains the worst case transient accident to less than the design pulse insertion.

The possibility of a reactivity accident which could produce reactor powers and fuel temperatures attributed to a $4.00 step insertion has been considered and evaluated in the accident analysis section of this report. It is concluded from this analysis that the peak and average fuel temperatures resulting from this accident are well below the temperatures indicated as safety limits described in the reactor design bases of this document. It is further concluded that the integrity of the fuel containment will not be jeopardized and no adverse effects to the reactor system or personnel will arise from the advent of such an accident.

Table 4-7

COMPARISON OF REACTIVITY INSERTION EFFECTS

	Pulse Resulting from Insertion of Maximum Excess Reactivity in This TRIGA	Max Pulse Tested on SS-Clad, High Hydride Fueled TRIGA types
Reactivity insertion, $	3.00	5.00
Steady-State power before pulse, kW	< 1	< 1
Peak power, MW	~1400	~8400
Total energy release, MW-sec	~18	~54
Period, msec	~3.1	~1.4
Maximum fuel temperature, °C	~540	~1050
Pulse width, msec	~11	~5.5

4.3 THERMAL AND HYDRAULIC DESIGN

This TRIGA reactor will be operated with natural convective cooling by reactor pool water. This method of heat dissipation is more than adequate for the power level of the reactor; i.e. 1100 kW(t). The thermal and hydraulic design of the reactor is well within the safety limits required to assure fuel integrity.

4.3.1. Design Bases

The thermal and hydraulic design for this TRIGA is based on assuring that fuel integrity is maintained during steady-state and pulsed mode operation as well as during those abnormal conditions which might be postulated for reactor operation. During steady-state operation fuel integrity is maintained by limiting reactor powers to values which assure that the fuel cladding can transfer heat from the fuel to the reactor coolant without reaching fuel-clad temperatures that could result in clad rupture. If these temperature conditions were exceeded, the maximum local heat flux in the core would be greater than the heat flux at which there is a departure from the nucleate boiling regime and consequently film blanketing of the fuel. This heat flux safety limit is a function of the inlet coolant temperature.

Figure 4-22 summarizes the results of the thermal and hydraulic analysis for steady-state operation of the TRIGA. In the figure critical heat flux for departure from nucleate boiling is plotted as a function of the coolant inlet temperature. The maximum power density in a TRIGA core is found by multiplying the average power density by a radial peak-to-average power generation ratio of 1.6 and an axial value of 1.25.

The correlation used to determine the heat flux at which there is a departure from nucleate boiling is from Bernath [33]. This correlation encompasses a wider range of experimental data than the usual correlations, e.g., the correlation due to McAdams, and, generally gives a lower value for the DNB ratio than the other correlations.

Table 4-8

1000 kW(t) TRIGA HEAT TRANSFER AND HYDRAULIC PARAMETERS

Number of fuel elements	90
Diameter	1.475 in.
Length (heated)	15.0 in.
Flow area	0.522 ft^2
Wetted perimeter	34.75 ft
Hydraulic diameter	0.0601 ft
Heat transfer surface	43.44 ft^2
Inlet coolant temperature	120°F (48.9°C)
Exit coolant temperature (average)	174°F (78.9°C)
Coolant mass flow	63,700 lb/hr
Average flow velocity	0.55 ft/sec
Average fuel temperature	500°F (260°C)
Maximum wall temperature	280°F (138°C)
Maximum fuel temperature	842°F (450°C)
Average heat flux	78,600 Btu/hr-ft^2
Maximum heat flux	157,100 Btu/hr-ft^2
Minimum DNB ratio	2.0

Table 4-8 lists the pertinent heat transfer and hydraulic parameters for the TRIGA operating at a nominal power level of 1000 kW. These data were taken from the results of calculations described in Section 4.1.

During pulsing operation the limiting thermal-hydraulic condition is the fuel temperature and the corresponding H_2 excess pressure beyond which clad rupture may occur. As indicated in Section 4.1, coolant temperature is not a limiting condition in pulsing since heating conditions are essentially adiabatic and significant transfer of heat energy to the coolant does not occur until after peak fuel-clad temperatures occur.

The safety limit on fuel temperature occurring in the pulse mode of operation is 1150°C. This temperature will give an internal equilibrium hydrogen pressure (U-ZrH fuel H/Zr; 1.6) less than that which would produce a stress equivalent to the ultimate strength of the clad at a temperature of 680°C. This clad temperature is higher than would actually occur and therefore conservative even in the case of a pulse producing a peak adiabatic fuel temperature of 1150°C.

4.3.2. Thermal and Hydraulic Design Evaluation

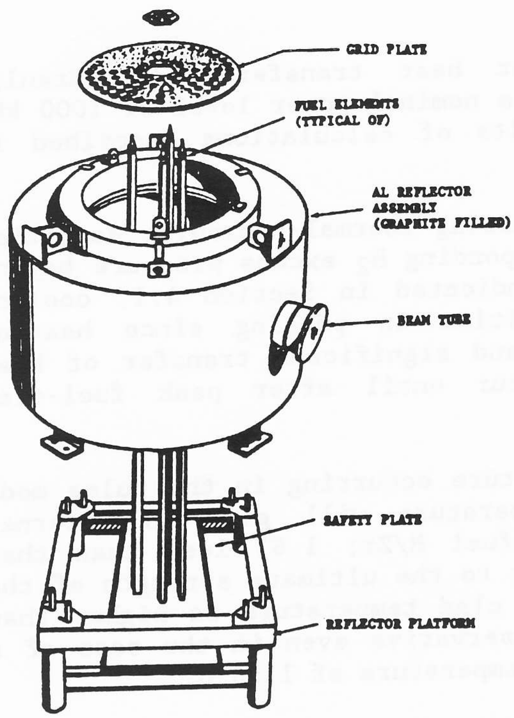
The validity and safety of the TRIGA thermal-hydraulic design is established in Section 4.1. In that section it is shown that design-basis conditions evaluated for TRIGA reactors using stainless steel clad U-ZrH (H/Zr; 1.6) fuel elements provide a generous safety margin for this TRIGA. These general evaluations are supported by extensive experience in operation of TRIGA cores at equivalent fuel temperatures and reactor power levels. No adverse results are reported from other similar TRIGA reactors with comparable fuel temperatures and power levels.

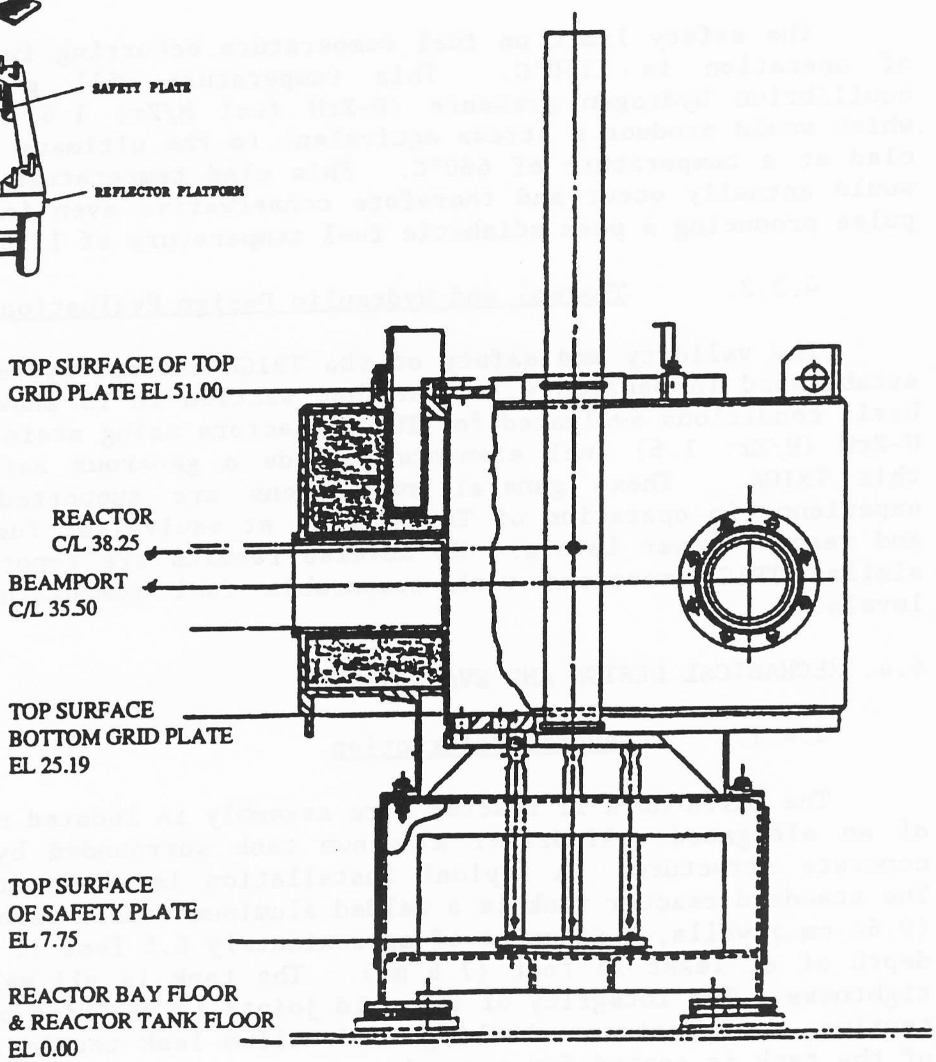
4.4. MECHANICAL DESIGN AND EVALUATION

4.4.1. General Description

The TRIGA Mark II reactor core assembly is located near the bottom of an elongated cylindrical aluminum tank surrounded by a reinforced concrete structure. A typical installation is shown in Figure 4-25. The standard reactor tank is a welded aluminum vessel with 1/4 in. thick (0.64 cm.) walls, a diameter of approximately 6.5 feet (2 meters), and a depth of at least 25 feet (7.6 m.). The tank is all-welded for water tightness. The integrity of the weld joints is verified by radiographic testing, dye penetrant checking, and helium leak testing. The outside of the tank is coated for corrosion protection.

An aluminum angle used for mounting the ion chambers, fuel storage racks, underwater lights, and other equipment, is located around the top of the tank. Demineralized water in the tank is provided such that at least 21 feet (6.4 m.) of shielding water is above the core. The core is shielded radially by a minimum of 7.97 feet (2.43 m) of concrete with a density of 2.88 gm/cc, 1.5 feet (~45 cm.) of water, and 10.2 inches (25.9 cm.) of graphite reflector (see Figure 4-26).

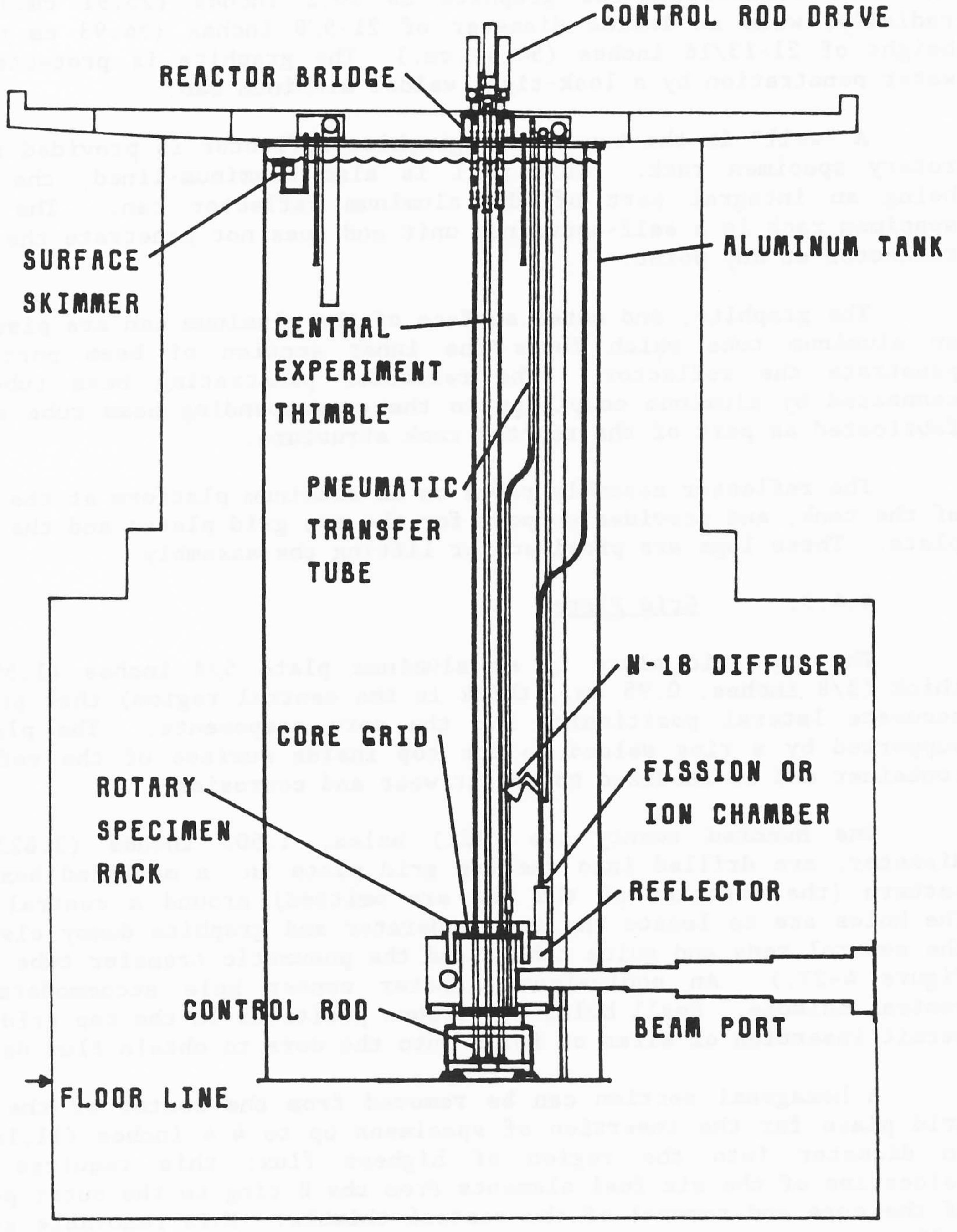




TRIGA reactor - elevation view

REACTOR, REFLECTOR, AND SHIELDING

Figure 4-25



TRIGA MARK II REACTOR

Figure 4-26

4.4.2. Reflector Assembly

The reflector is a ring-shaped block of graphite that surrounds the core radially. The graphite is 10.2 inches (25.91 cm.) thick radially, with an inside diameter of 21-5/8 inches (54.93 cm.) and a height of 21-13/16 inches (54.40 cm.) The graphite is protected from water penetration by a leak-tight welded aluminum can.

A "well" in the top of the graphite reflector is provided for the rotary specimen rack. This well is also aluminum-lined, the lining being an integral part of the aluminum reflector can. The rotary specimen rack is a self-contained unit and does not penetrate the sealed reflector at any point.

The graphite, and outer surface of the aluminum can are pierced by an aluminum tube which forms the inner section of beam ports that penetrate the reflector. The reflector penetrating beam tubes are connected by aluminum couplings to the corresponding beam tube section fabricated as part of the reactor tank structure.

The reflector assembly rests on an aluminum platform at the bottom of the tank, and provides support for the two grid plates and the safety plate. Three lugs are provided for lifting the assembly.

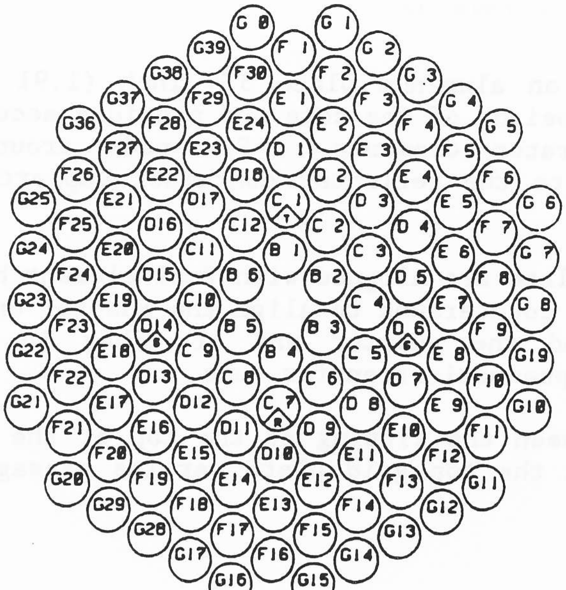
4.4.3. Grid Plates

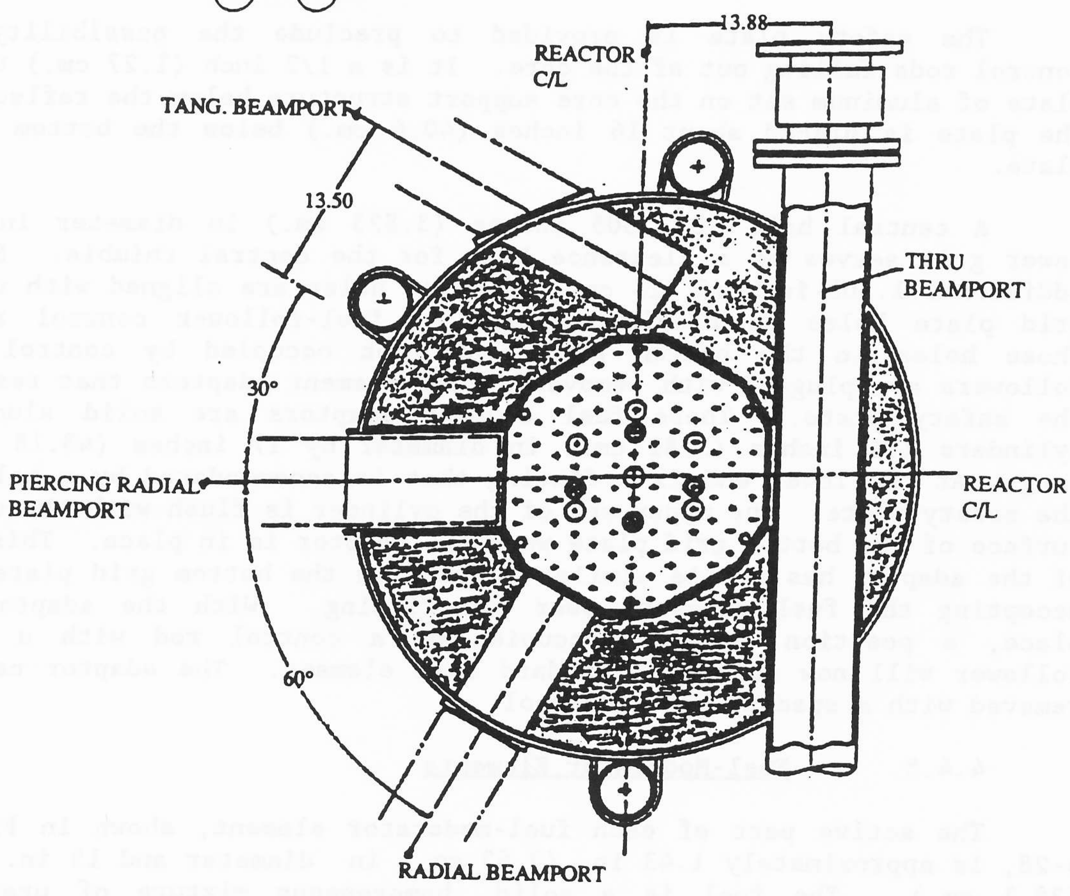
The top grid plate is an aluminum plate 5/8 inches (1.59 cm.) thick (3/8 inches, 0.95 cm., thick in the central region) that provides accurate lateral positioning for the core components. The plate is supported by a ring welded to the top inside surface of the reflector container and is anodized to resist wear and corrosion.

One hundred twenty one (121) holes, 1.505 inches (3.823 cm.) diameter, are drilled into the top grid plate in a modified hexagonal pattern (the vertexes of the hex are omitted) around a central hole. The holes are to locate the fuel-moderator and graphite dummy elements, the control rods and guide tubes, and the pneumatic transfer tube. (See Figure 4-27.) An equivalent diameter center hole accommodates the central thimble. Small holes at various positions in the top grid plate permit insertion of wires or foils into the core to obtain flux data.

A hexagonal section can be removed from the center of the upper grid plate for the insertion of specimens up to 4.4 inches (11.18 cm.) in diameter into the region of highest flux; this requires prior relocation of the six fuel elements from the B ring to the outer portion of the core and removal of the central thimble. This removable section will not be used initially; a license amendment will be obtained prior to its use.

Two generally triangular-shaped sections are cut out of the upper grid plate. Each cut out encompasses two E and one D ring holes. Fuel elements placed in these locations, require lateral support by a special fixture. When the fuel elements and support are removed, there is room for inserting specimens up to 2.4 inches (6.1 cm.) in diameter.





TRIGA reactor - cross section through beamports

CORE ARRANGEMENT

Figure 4-27

The bottom grid plate is an aluminum plate 3/4 inch (1.91 cm.) thick which supports the entire weight of the core and provides accurate spacing between the fuel-moderator elements. Six pads around a hexagonal ring which is welded to the reflector container support the bottom grid plate.

Holes in the bottom grid plate are aligned with fuel element holes in the top grid plate. They are countersunk to align the adaptor end of the fuel-moderator elements and the adaptor end of other in core experiment systems, such as the pneumatic transfer tube.

The differential area between the fitting at the top of the fuel elements and the round holes in the top grid plate permits passage of cooling water through the plate.

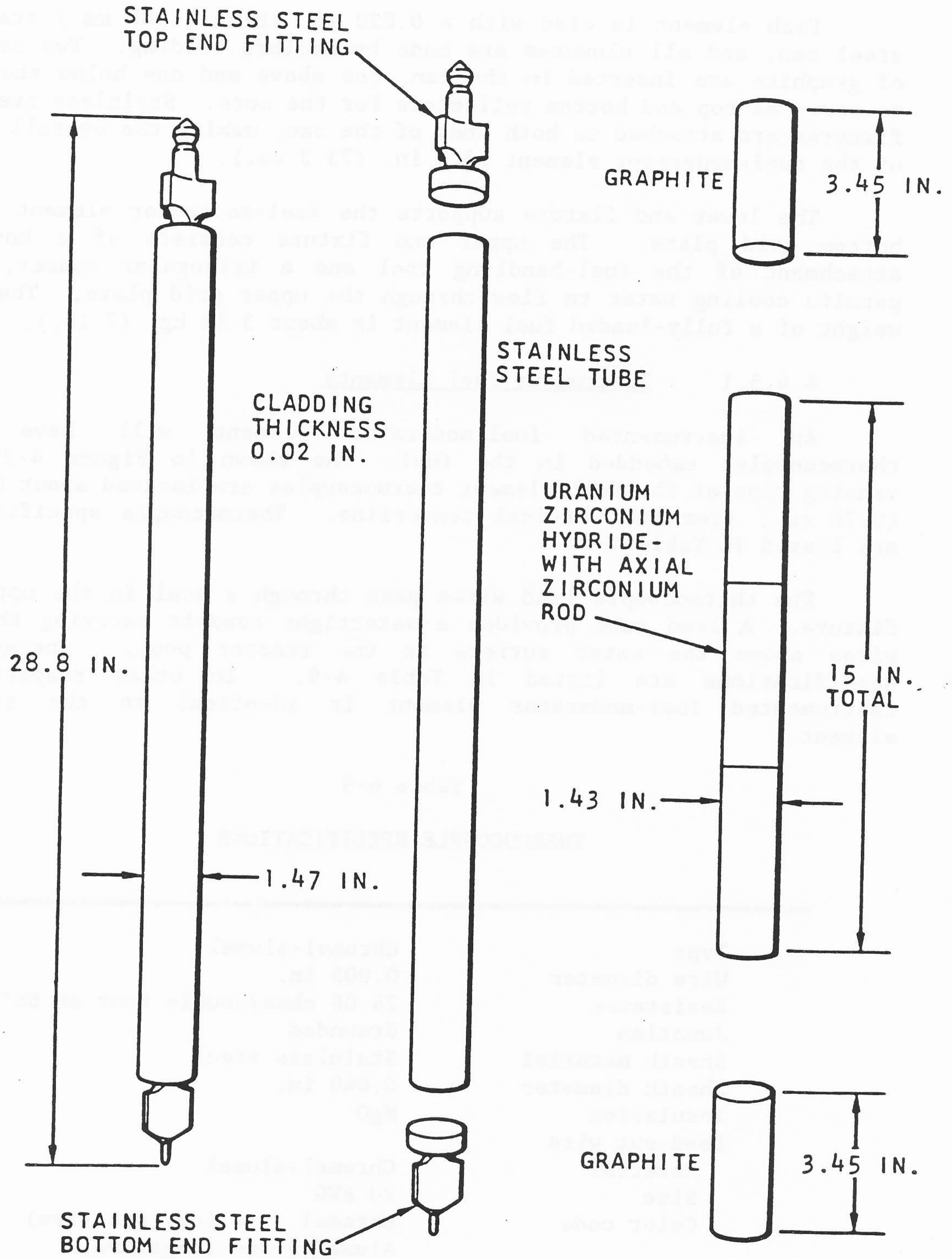
4.4.4. Safety Plate

The safety plate is provided to preclude the possibility of control rods falling out of the core. It is a 1/2 inch (1.27 cm.) thick plate of aluminum set on the core support structure below the reflector. The plate is placed about 16 inches (40.6 cm.) below the bottom grid plate.

A central hole of 1.505 inches (3.823 cm.) in diameter in the lower grid serves as a clearance hole for the central thimble. Eight additional 1.505-inch (3.823 cm.) diameter holes are aligned with upper grid plate holes to provide passage of fuel-follower control rods. Those holes in the bottom grid plate not occupied by control rod followers are plugged with removable fuel element adaptors that rest on the safety plate. These fuel element adaptors are solid aluminum cylinders 1.5 inches (3.81 cm.) in diameter by 17 inches (43.18 cm.) long. At the lower end is a fitting that is accommodated by a hole in the safety plate. The upper end of the cylinder is flush with the upper surface of the bottom grid plate when the adaptor is in place. This end of the adaptor has a hole similar to that in the bottom grid plate for accepting the fuel element lower end fitting. With the adaptor in place, a position formerly occupied by a control rod with a fuel follower will now accept a standard fuel element. The adaptor can be removed with a special handling tool.

4.4.5. Fuel-Moderator Elements

The active part of each fuel-moderator element, shown in Figure 4-28, is approximately 1.43 in. (3.63 cm.) in diameter and 15 in. long (38.1 cm.). The fuel is a solid, homogeneous mixture of uranium-zirconium hydride alloy containing about 8.5% by weight of uranium enriched to 20% U-235. The hydrogen-to-zirconium atom ratio is about 1.6. To facilitate hydriding, a small hole is drilled through the center of the active fuel section and a zirconium rod is inserted in this hole after hydriding is complete. The hydriding hole and zirconium rod are not shown in Figure 4-28. Several types of end fittings exist, therefore, those shown are typical.



TRIGA STAINLESS STEEL CLAD
FUEL ELEMENT WITH END FITTINGS

Figure 4-28

Each element is clad with a 0.020 in. thick (.508 mm.) stainless steel can, and all closures are made by heliarc welding. Two sections of graphite are inserted in the can, one above and one below the fuel, to serve as top and bottom reflectors for the core. Stainless steel end fixtures are attached to both ends of the can, making the overall length of the fuel-moderator element 28.8 in. (73.2 cm.).

The lower end fixture supports the fuel-moderator element on the bottom grid plate. The upper end fixture consists of a knob for attachment of the fuel-handling tool and a triangular spacer, which permits cooling water to flow through the upper grid plate. The total weight of a fully-loaded fuel element is about 3.18 kg. (7 lb.).

4.4.5.1 Instrument Fuel Elements

An instrumented fuel-moderator element will have three thermocouples embedded in the fuel. As shown in Figure 4-29, the sensing tips of the fuel element thermocouples are located about 0.3 in. (0.76 cm.) from the vertical centerline. Thermocouple specifications are listed in Table 4-9.

The thermocouple lead wires pass through a seal in the upper end fixture. A lead tube provides a watertight conduit carrying the lead wires above the water surface in the reactor pool. Thermocouple specifications are listed in Table 4-9. In other respects the instrumented fuel-moderator element is identical to the standard element.

Table 4-9

THERMOCOUPLE SPECIFICATIONS

Type	Chromel-alumel
Wire diameter	0.005 in.
Resistance	24.08 ohms/double foot at 68°F
Junction	Grounded
Sheath material	Stainless steel
Sheath diameter	0.040 in.
Insulation	MgO
Lead-out wire	
Material	Chromel-alumel
Size	20 AWG
Color code	Chromel - yellow (positive) Alumel - red (negative)
Resistance	0.59 ohms/double foot at 75°F

4.4.5.2. Evaluation of Fuel Element Design.

General Atomic has acquired extensive experience in the fabrication and operation of high hydride, stainless steel clad fuel elements. As shown in other sections of this report, the stresses associated with the fuel and cladding temperatures in all modes of operation, normal and abnormal, are within the safety limits described in the Reactor Design Bases.

Dimensional stability of the overall fuel element has been excellent in the TRIGA reactors in operation. Analysis of the heat removal from elements that touch owing to transverse bending shows that the contact will not result in hot spots that damage the fuel.

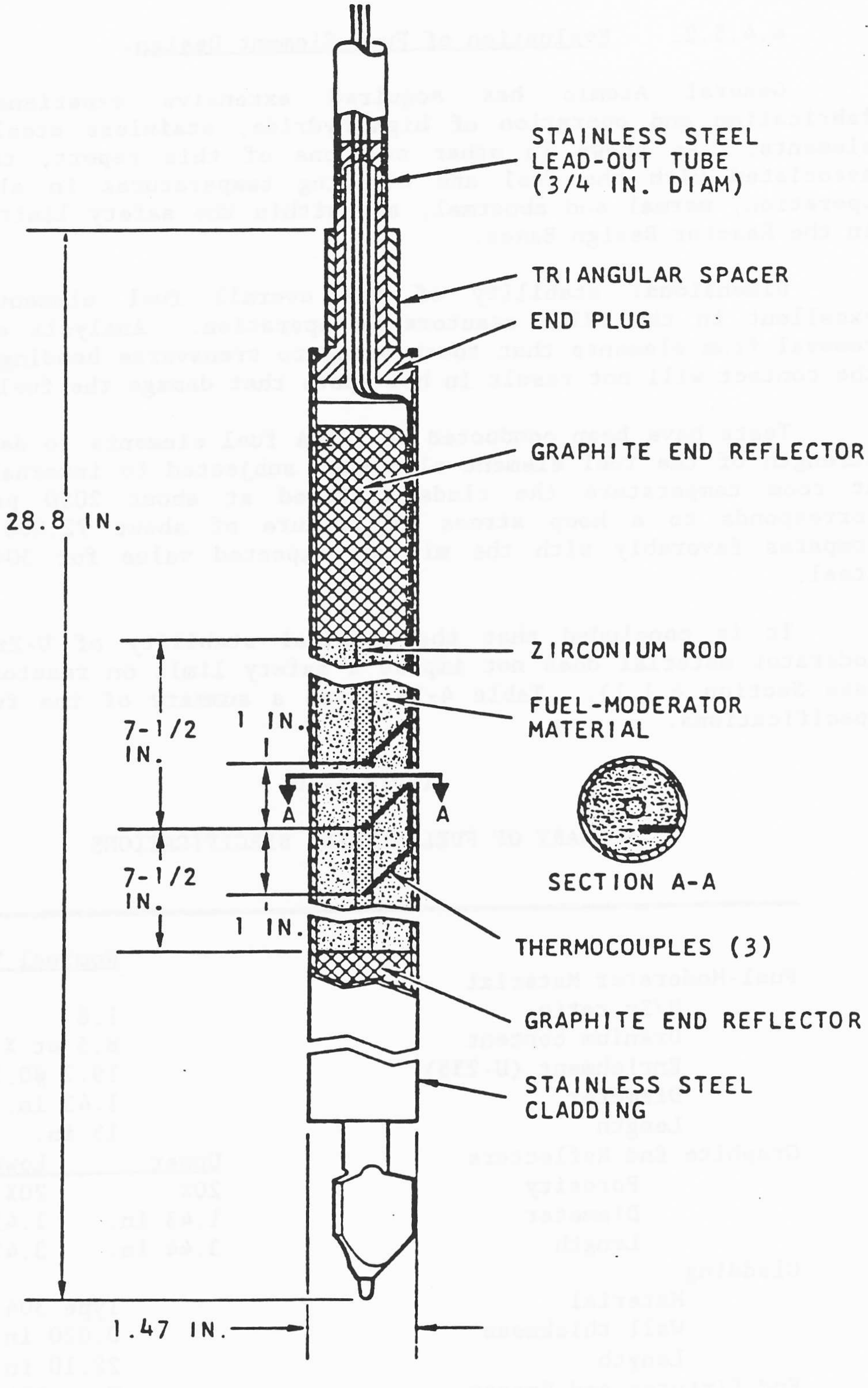
Tests have been conducted on TRIGA fuel elements to determine the strength of the fuel element clad when subjected to internal pressure. At room temperature the clads ruptured at about 2050 psig. This corresponds to a hoop stress at rupture of about 72,000 psi which compares favorably with the minimum expected value for 304 stainless steel.

It is concluded that the chemical stability of U-$ZrH_{1.6}$ fuel-moderator material does not impose a safety limit on reactor operation (see Section 4.1.1). Table 4-10 gives a summary of the fuel element specifications.

Table 4-10

SUMMARY OF FUEL ELEMENT SPECIFICATIONS

	Nominal Value	
Fuel-Moderator Material		
H/Zr ratio	1.6	
Uranium content	8.5 wt %	
Enrichment (U-235)	19.7 #0.2	
Diameter	1.43 in.	
Length	15 in.	
Graphite End Reflectors	Upper	Lower
Porosity	20%	20%
Diameter	1.43 in.	1.43 in.
Length	3.44 in.	3.47 in.
Cladding		
Material	Type 304 SS	
Wall thickness	0.020 in.	
Length	22.10 in.	
End Fixtures and Spacer	Type 304 SS	
Overall Element		
Outside diameter	1.47 in.	(3.73 cm)
Length	28.37 in.	(72.06 cm)
Weight	7 lb.	(3.18 kg)



INSTRUMENTED FUEL ELEMENT

Figure 4-29

Most of the fuel for the initial core loading will consist of elements with burnups of a fraction of a MW-day to several MW-days. It is anticipated that an initial core loading of about 94 fuel elements, including instrumented elements, and fuel followed control rods, will produce a cold, clean excess reactivity of ~4.9% $\delta k/k$. The operational core configuration will contain two instrumented fuel elements with at least one located in the inner most reactor ring.

4.4.6. Neutron Source and Holder

A 2 or 3 curie americium beryllium neutron source will be used for startup. The neutron source holder is made of aluminum, is cylindrical in shape, and has a cavity to hold the source. The source holder can be installed in a vacant fuel or graphite element location. A shoulder at the upper end of the holder supports the assembly on the upper grid plate, the rod itself, which contains the source, extending down into the core region. The neutron source is contained in a cavity in the lower portion of the rod assembly at the horizontal centerline of the core. This cylindrical cavity is 0.981 in. (2.492 cm.) in diameter and approximately 3 in. (7.62 cm.) deep. The upper and lower portions are screwed together. A soft aluminum ring provides sealing against water leakage into the cavity. Since the upper end fixture of the source holder is similar to that of the fuel element, the source holder can be installed or removed with the fuel handling tool. In addition, the upper end fixture has a small hole through which one end of a stainless steel wire may be inserted to facilitate handling operation from the top of the tank.

4.4.7. Graphite Dummy Elements

Graphite dummy elements may be used to fill grid positions not filled by the fuel-moderator elements or other core compounds. They are of the same general dimensions and construction as the fuel-moderator elements, but are filled entirely with graphite and are clad with aluminum.

4.4.8. Control System Design

The reactor uses four control rods:

a. Shim rod 1

b. Shim rod 2

c. A transient rod

d. A regulatory rod

The regulating and shim rods are sealed 304 stainless steel tubes approximately 43 in. (109 cm) long by 1.35 in. (3.43 cm) in diameter in which the uppermost 6.5 in. (16.5 cm) section is an air void and the next 15 in. (38.1 cm) is the neutron absorber (boron carbide in solid form). Immediately below the neutron absorber is a fuel follower section consisting of 15 in. (38.1 cm) of $U\text{-}ZrH_{1.6}$ fuel. The bottom section of the rod is 6.5 in. (16.5 cm) air void.

The regulating and shim rods pass through and are guided by 1.5 in. (3.81 cm) diameter holes in the top and bottom grid plates. A typical control rod with fuel follower is shown in the withdrawn and inserted positions in Figure 4-30.

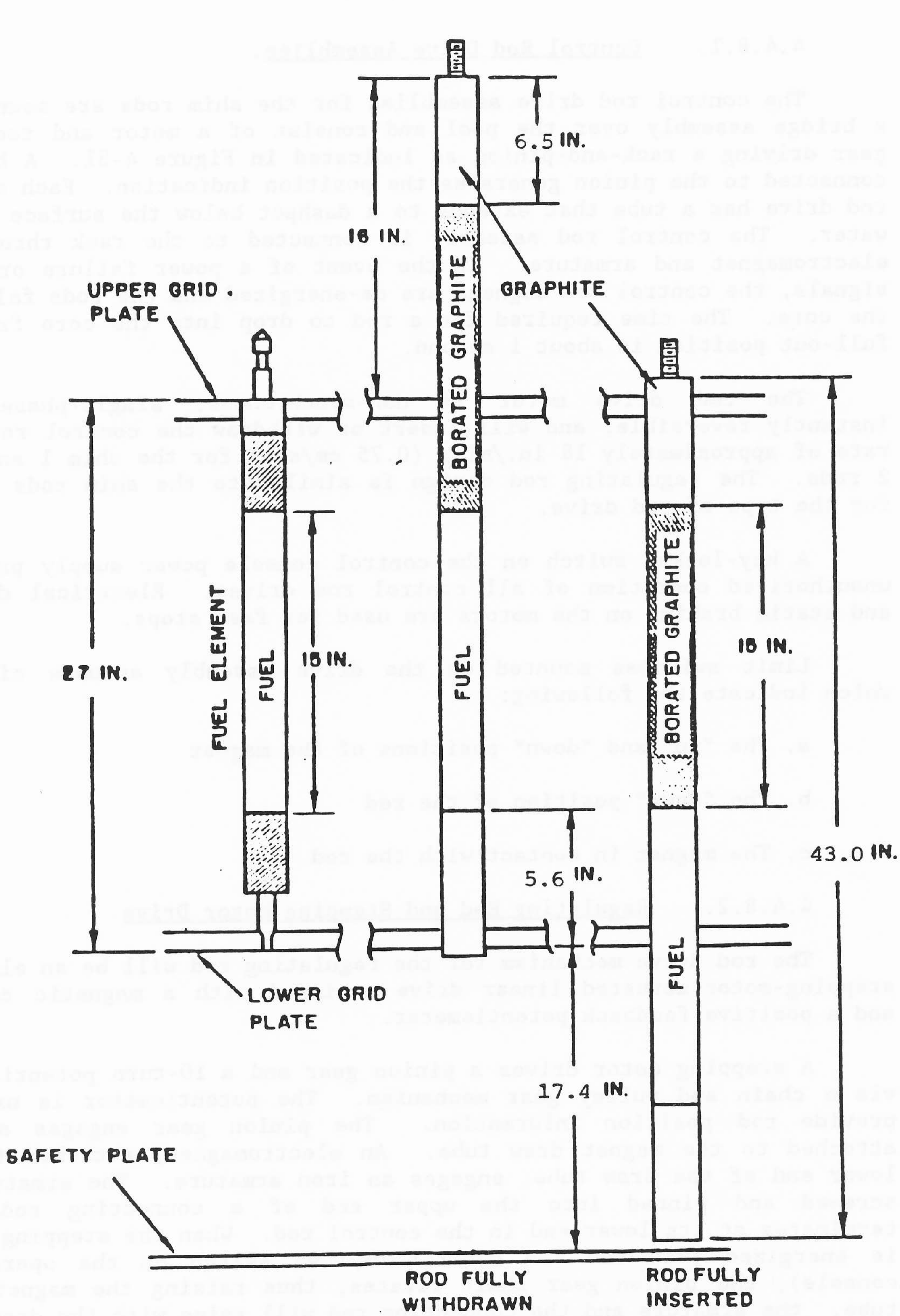
The safety-transient rod is a sealed, 36.75 in. (93.35 cm) long by 1.25 in. (3.18 cm) diameter tube containing solid boron carbide as a neutron absorber. Below the absorber is an air filled follower section. The absorber section is 15 in. (38.1 cm) long and the follower is 20.88 in. (53.02 cm) long. The transient rod passes through the core in a perforated aluminum guide tube. The tube receives its support from the safety plate and its lateral positioning from both grid plates. It extends approximately 10 in. (25.4 cm) above the top grid plate. Water passage through the tube is provided by a large number of holes distributed evenly over its length. A locking device is built into the lower end of the assembly.

The control rods are connected to their individual drive units by screwing the upper end of the rod into a control rod drive assembly connecting rod. Vertical travel of each rod is approximately 15 in. (38.1 cm). Reactivity worths and core positions for each rod are summarized in the section on nuclear design. A summary of other control rod design parameters is given in Table 4-11.

Table 4-11

SUMMARY OF CONTROL ROD DESIGN PARAMETERS

	Transient	Shim and Regulating
<u>Cladding</u>		
Material	Al	Type 304 SS
OD	1.25 in. (3.18 cm)	1.35 in. (3.43 cm)
Length	36.75 in. (93.35 cm)	43.13 in. (109.5 cm)
Wall thickness	0.028 in. (0.071 cm)	0.020 in. (0.051 cm)
<u>Absorber</u>		
Material	Boron Carbide (solid form)	
OD	1.19 in. (3.02 cm)	1.31 in. (3.32 cm)
Length	15 in. (38.1 cm)	14.25 in. (36.20 cm)
<u>Follower</u>		
Material	Air	$U\text{-}ZrH_{1.6}$
OD	1.25 in. (3.18 cm)	1.31 in. (3.34 cm)
Length	20.88 in. (53.02 cm)	15 in. (38.1 cm)



FUEL FOLLOWED CONTROL ROD

Figure 4-30

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