CHAPTER II

REACTOR DESIGN

The purpose of this thesis is to investigate the ability of the existing NSCR reactor to operate safely at a power level of 1.49 MW. Since this power upgrade will not involve any major core changes, a detailed description of the existing reactor systems is given in the rest of this chapter. In general, the NSCR operates with a core composed of 86 General Atomic FLIP fuel elements, four shim safety control rods with fueled followers, one regulating control rod, and one transient control rod. These elements attach to a reactor grid plate along with graphite reflecting elements, experimental notches and instrumentation. The entire core is covered by 26 feet of water. Detailed descriptions of these components are presented below.

Mechanical Design

The reactor core, control and instrumentation systems are supported by a bridge that spans the reactor pool. Mounted on four wheels, the bridge travels on rails at the sides of the pool. This allows the reactor to be moved from one operating position to another. Electrical power, control-circuit wiring, and compressed air are supplied to the core through the bridge.

The reactor grid plate is welded to an aluminum suspension frame which is a welded structure of 3/8" x 2" x 2" aluminum angle. The west side of the frame is open toward the large section of the pool. The angle construction allows unrestricted flow of the cooling water. An aluminum stabilizer frame is bolted to the bottom of the grid plate for vertical support. Stainless steel guides on the bottom of the stabilizer fit between tracks on the pool floor. This allows accurate repositioning of the reactor core which is essential for numerous experiments. The stabilizer also allows the core to be lowered to the bottom of the pool to prevent sway.

Fuel elements and control rods are contained in bundle assemblies which are positioned and supported by the grid plate in a 9 x 6 array of 54 holes. A top view of the grid plate is shown in Figure 1, The reactor core can be arranged in a number of ways on the grid plate. A typical core loading containing 90 fuel elements and graphite reflectors is shown in Figure 2. In this configuration the A row of the grid plate is available for placing experiments. A 3/4" diameter clearance hole through the grid plate is used to allow passage of the fueled section of the control rods as shown in Figure 3.

The NSCR currently utilizes General Atomic TRIGA FLIP type fuel moderator elements in which a zirconium hydride moderator is homogeneously combined with highly enriched uranium fuel. The expected fuel life of FLIP fuel has been stated to be 3000 MWD[4], although calculations support burnup as high as 4600 MWD. TRIGA FLIP fuel elements have a 15 inch long active fuel section. These elements contain approximately 8.5 weight-% uranium enriched to 70% in ^{235}U that is homogeneously mixed with ZrH and with approximately 1.5 weight-% erbium as a burnable poison.

To facilitate hydriding, an 0.18 inch diameter hole is drilled through the center of the active section, and a zirconium rod is inserted in this hole after hydriding is complete. As shown in Figure 4, 3.5 inch long graphite slugs, act as top and bottom reflectors. The active fuel section and top and bottom graphite slugs are contained in a 0.020-inch thick stainless steel clad. The stainless steel clad is welded to the top and bottom end fittings. The approximate overall weight of the rod is 7 pounds with an average ^{235}U content of about 123 grams. Serial numbers on the bottom end fittings are used to identify individual fuel rods. The principal design parameters are shown below in Table 1.

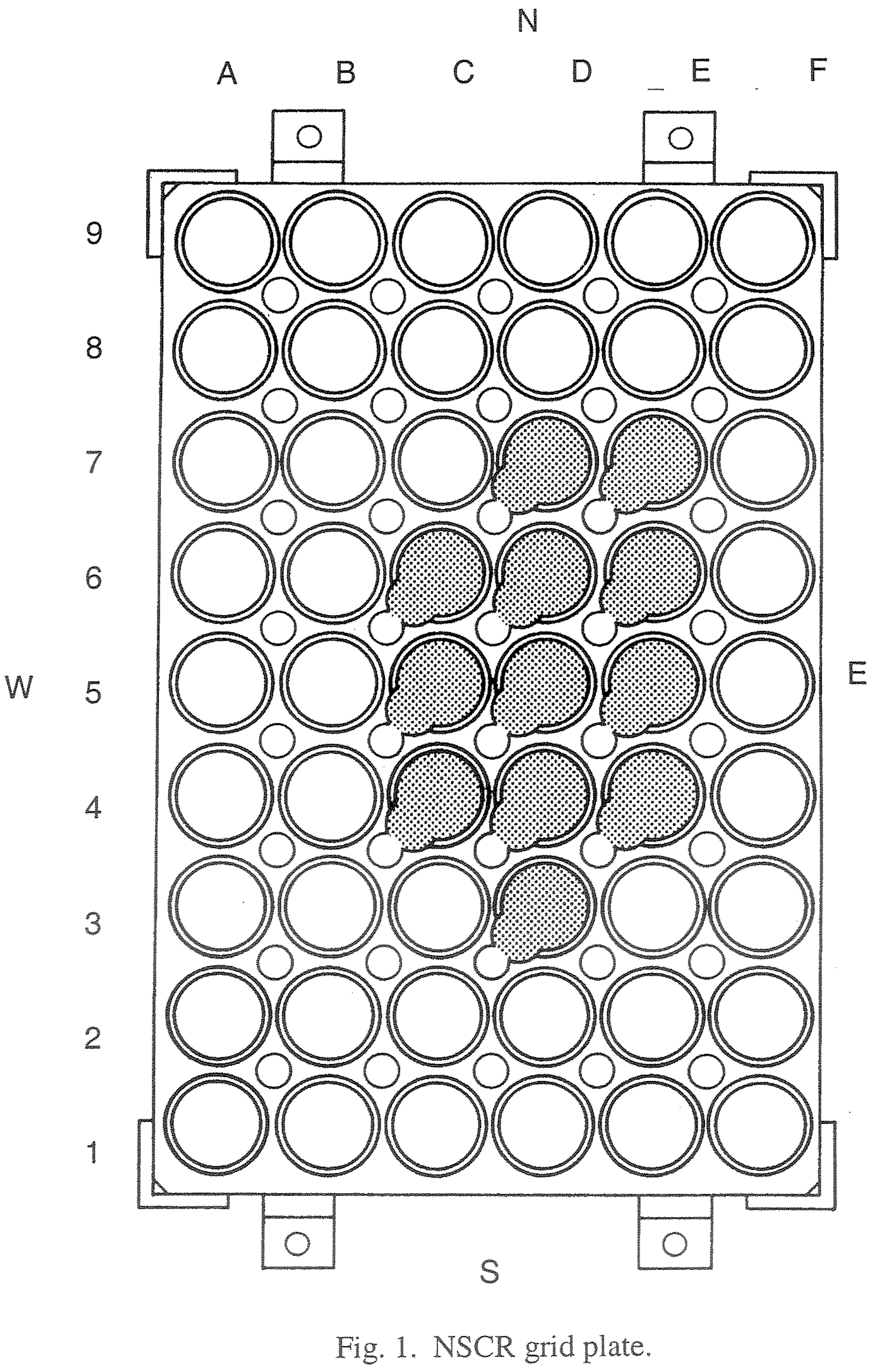

Fig. 1. NSCR grid plate.

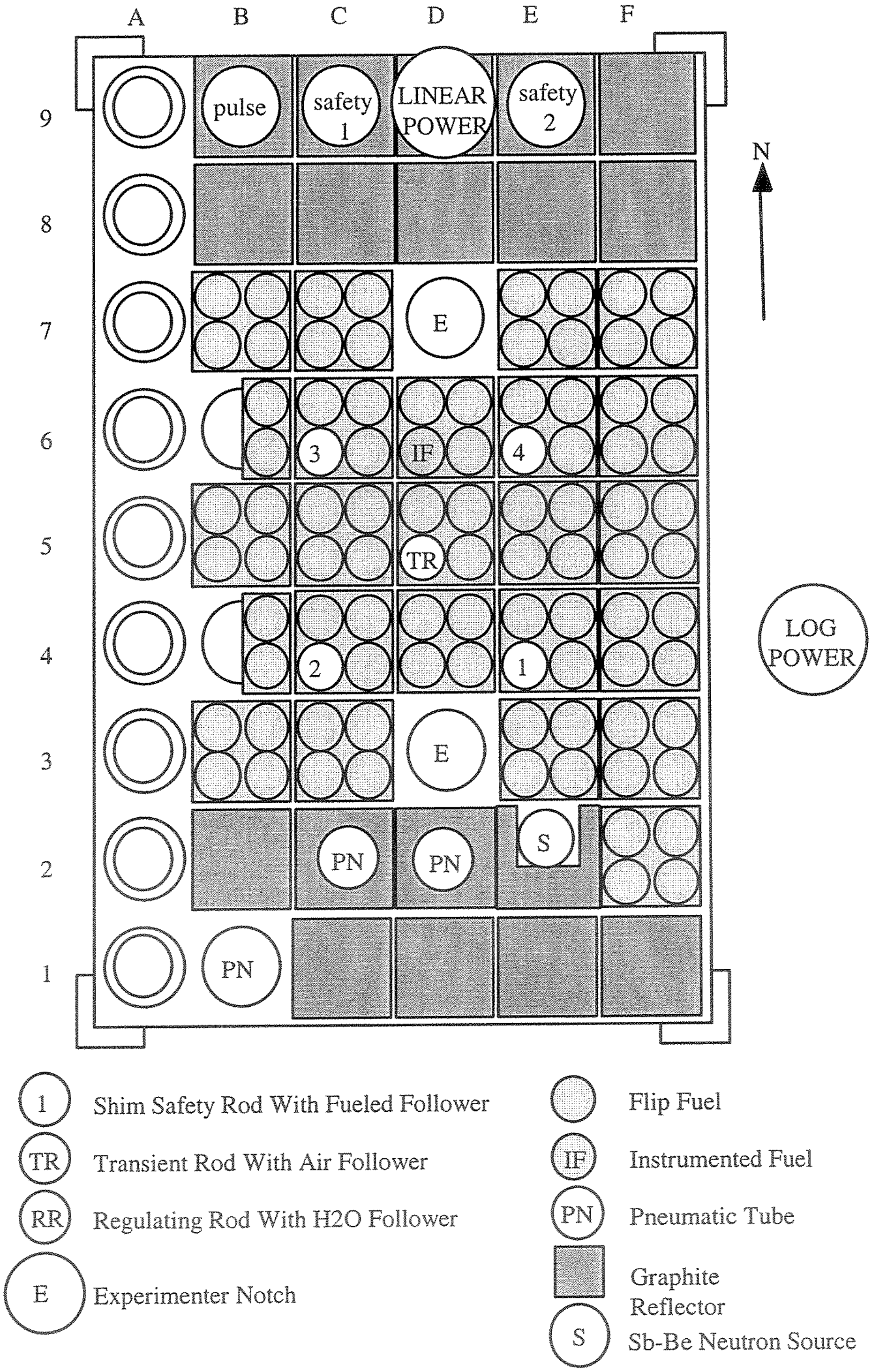

Fig. 2. FLIP core configuration.

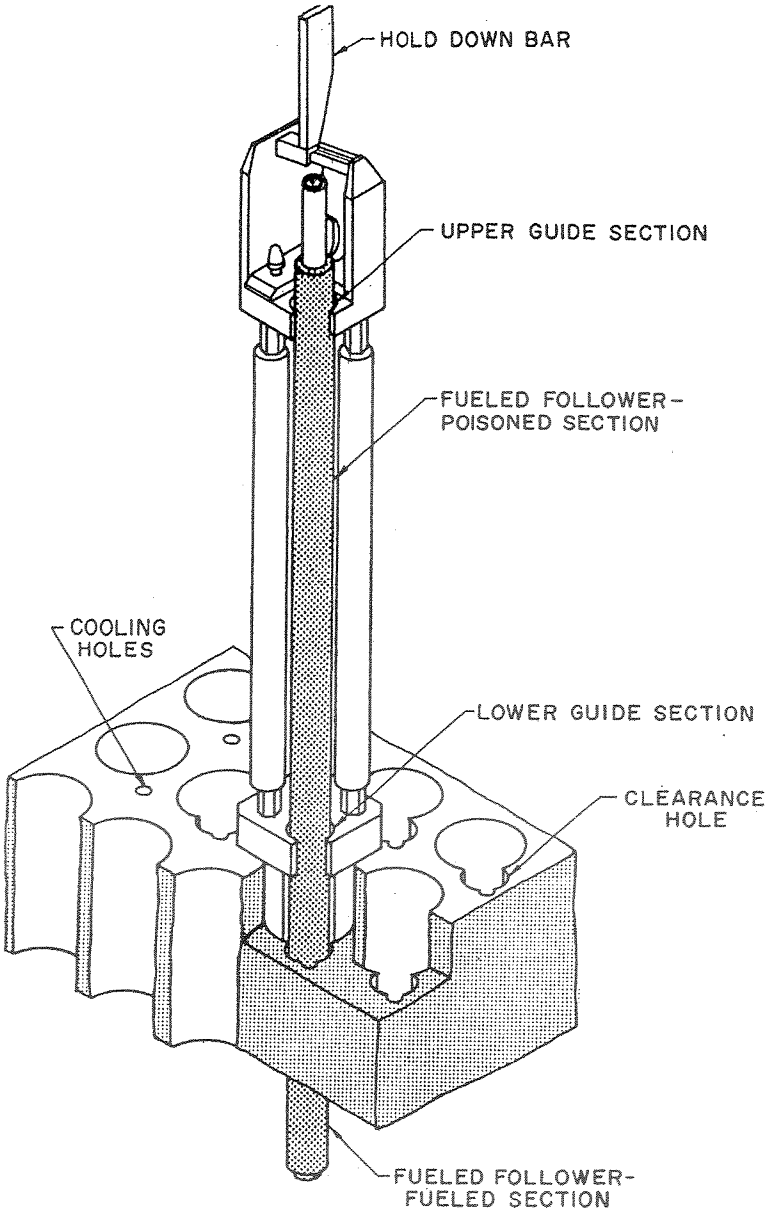

Fig. 3. Fueled follower installation.

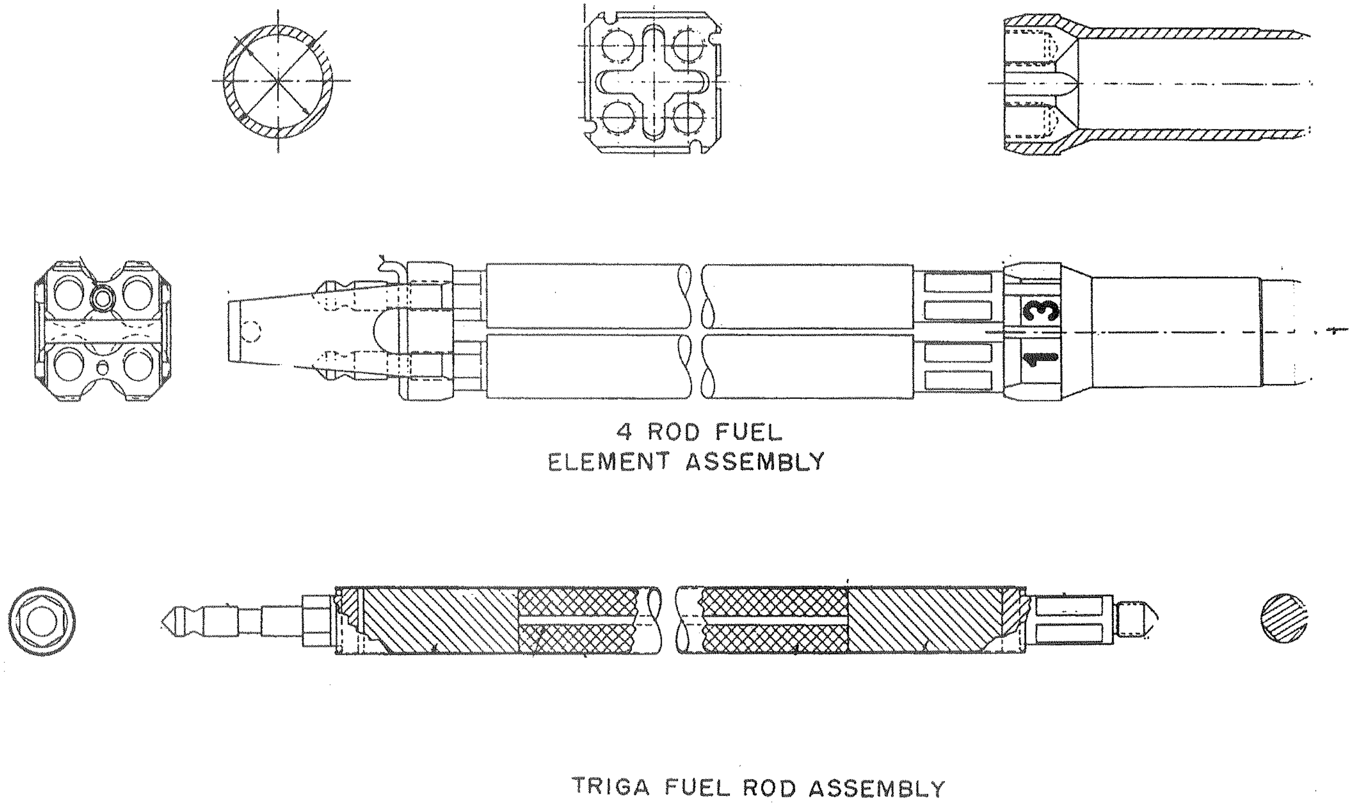

Fig. 4. Four rod fuel element assembly for the NSCR.

TABLE 1

Principal Fuel Element Design Parameters for TRIGA FLIP Fuel

Fuel-moderator material	U-ZrH
Uranium content	8.5 Wt-%
U-235 enrichment	70%
U-235 content (avg.) per element	123 g
Burnable poison	natural erbium
Erbium content	1.5 wt-%
Shape	cylindrical
Length of fuel meat	15 in
Diameter of fuel meat	1.371 in
Cladding material	Type 304 SS
Cladding thickness	0.020 in

A specially fabricated instrumented fuel element containing three thermocouples embedded in the fuel is used to measure fuel temperature during reactor operation. As shown in Figure 5, the sensing tips of the instrumented fuel rod's thermocouples are located halfway from the radial center line at the axial center of the fuel section and one inch above and below the axial center. The thermocouple leadout wires pass through a seal contained in a stainless steel tube welded to the upper end fixture. This tube projects about three inches above the upper end of the element. A watertight conduit, composed of tubing connected by swagelock unions, guides the leadout wire above the water surface in the reactor pool.

The NSCR fuel elements are arranged in two, three or four rod assemblies. The four rod assembly consists of an aluminum bottom adapter, four stainless steel clad TRIGA fuel rods, and an aluminum top fitting which serves as a handle. The bottom adapter fits into

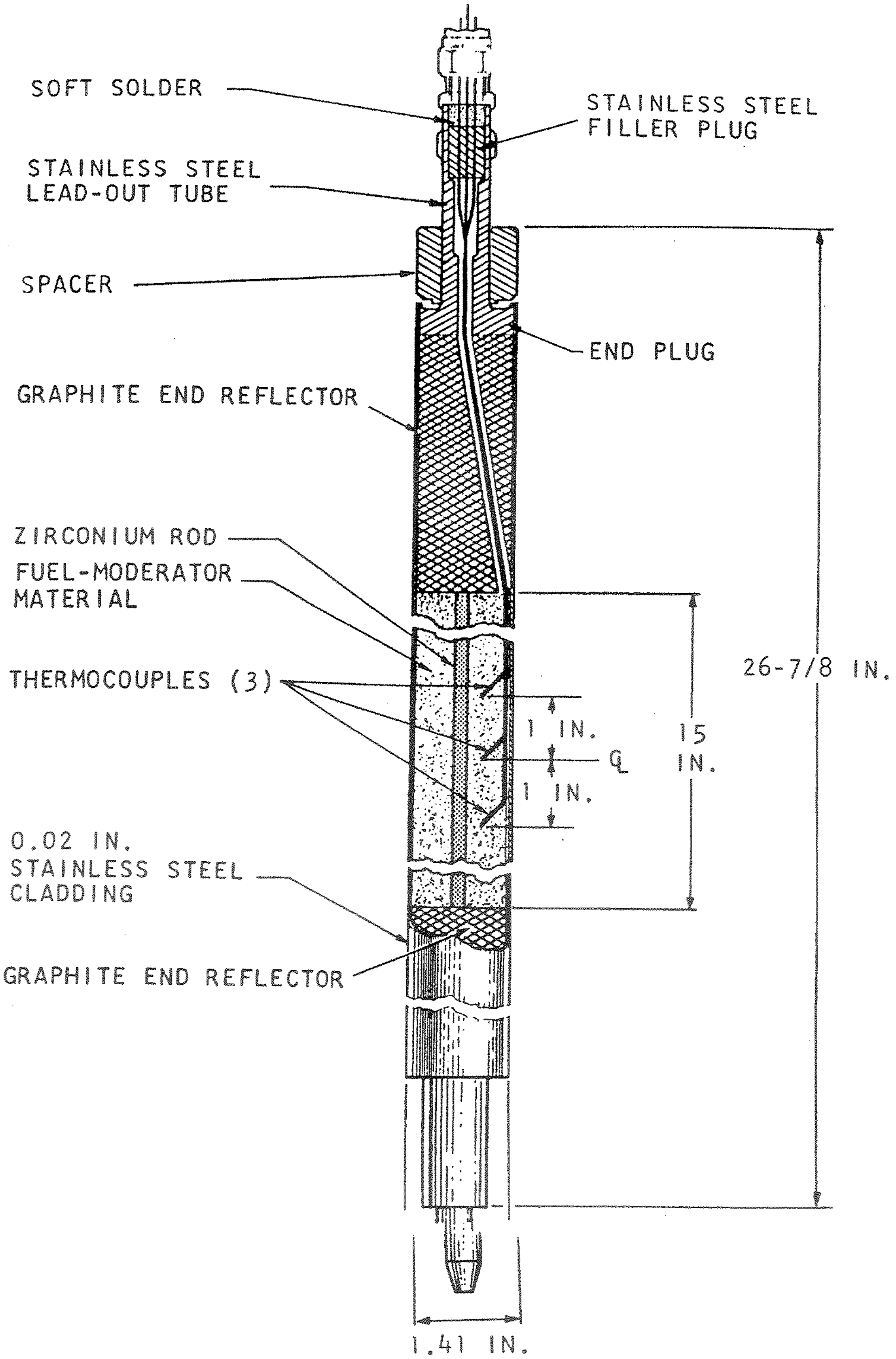

Fig. 5. The instrumented fuel rod.

the NSCR grid plate, and the top adapter contains four tapped holes into which the fuel rods are threaded. The bottom fitting on the fuel rod has a flange at the base of the threads so that the fuel rod seats firmly on the adapter and is rigidly supported. The details of the four rod assembly are shown in Figure 4.

A three rod fuel assembly may accommodate a control rod, an instrumented fuel element, or an experiment. The NSCR utilizes two separate types of three rod fuel assemblies for housing control rods. The first permits one fuel rod in an assembly to be replaced by a control rod guide tube which has an outside diameter of 1.5 inches. The handles on control rod elements are modified to accommodate the guide tube. A regulating rod and a transient rod without a follower will utilize this type of assembly. The second type, shown in Figure 6, is designed for use with shim safety control rods which are fuel followed. The transient rod which has a follower uses a specially designed control rod guide tube and must also have a base assembly as shown in Figure 6. The instrumented fuel rod fits into the bottom adapter. Not being an integral part of the bundle, the instrumented fuel rod is positioned into the bundle after it is in the grid plate.

Two rod assemblies are identical to four rod assemblies except that they contain only two fuel rods. These assemblies are used to produce thermal neutron flux traps by replacing fuel with water. Two rod bundles are positioned along the core's periphery in order to enhance the neutron flux available at certain irradiation locations. The nonfuel section of a two rod assembly may also be used to contain an experiment.

Six motor-driven control rods (four shim-safety rods, a regulating rod, and a transient rod control the reactor during steady-state operation. Typical control rod locations are shown in Figure 2. The shim-safety control rods have scram capability and contain borated graphite powder as a poison in a stainless steel cladding. The shim safety control rods consist of a 35.56 cm (14 in.) long poison section with a diameter of 1.7 cm on top of a 38.10 cm (15 in.) fueled section with a composition identical to the fuel rods, but with a fuel diameter of only 1.7 cm instead of the 1.74 cm fuel rod diameter. These are capped

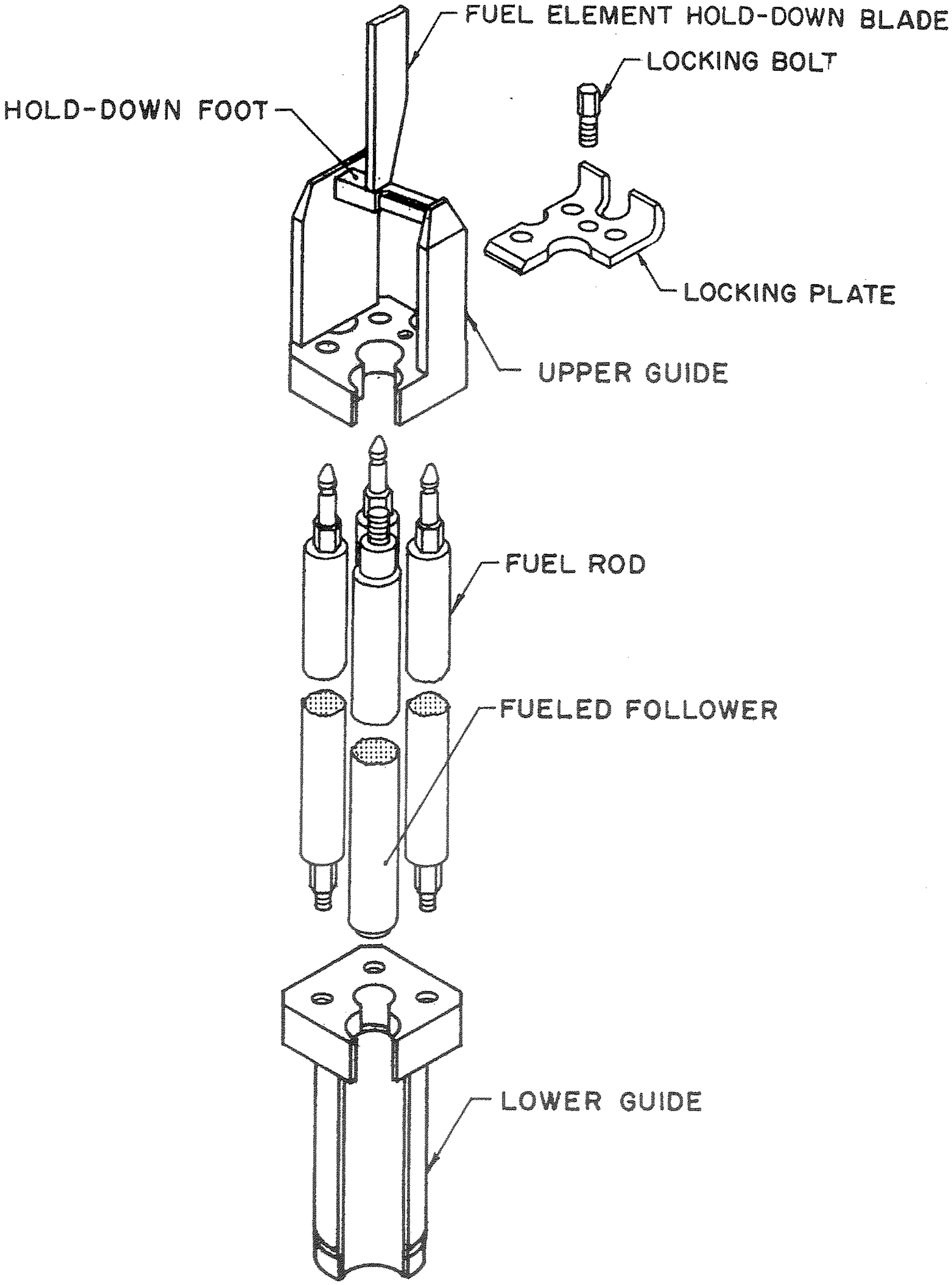

Fig. 6. Fueled follower fuel bundle assembly.

on both ends by void regions as shown in Figure 7. The regulating rod consists of a 38.10 cm (15 in.) poison section with a diameter of 1.52 cm. The transient rod has a 38.10 cm (15 in.) poison region on top of a 50.80 cm (20 in.) void section. Both of these sections have diameters of 1.52 cm. The shim safety rods and the transient rod have scram capability, but the regulating rod does not.

The shim safety and regulating control rods are moved axially throughout the core with electromechanical drive mechanisms. The shim safety rod drives are controlled manually, and can be moved individually or in gang. Their maximum withdrawal speed is 11.4 cm/min. The regulating rod can be controlled manually, or operated in automatic mode, during which the rod position is varied to maintain a constant power level. Its maximum withdrawal rate is 24.4 cm/min. The transient rod is held in position by high pressure air, and is capable of rapid ejection from the core for pulsing.

Nuclear Design

The design and operating characteristics of standard TRIGA cores are well known as is the inherent safety characteristics of this class of reactors.[5] TRIGA fuel is designed with physical parameters to insure safety under a wide range of operating conditions. Pulsing is one of this reactor's most notable capabilities. When the transient rod is ejected, the reactor can reach powers as high as 1000 MW for millisecond time intervals; as heat begins to build up in the fuel, the power automatically decreases due to the prompt negative temperature coefficient of TRIGA fuel.

The current reactivity limit for pulsing the NSCR is $2.35 which results in a safe, licensable condition. It is worth noting that earlier operational NSCR cores were regularly pulsed with $3.00 insertions. The pulsing characteristics for an operational NSCR TRIGA-FLIP core are shown in Figure 8 for pulses as high as $1.80. This data was recorded during an experiment performed in 1993.

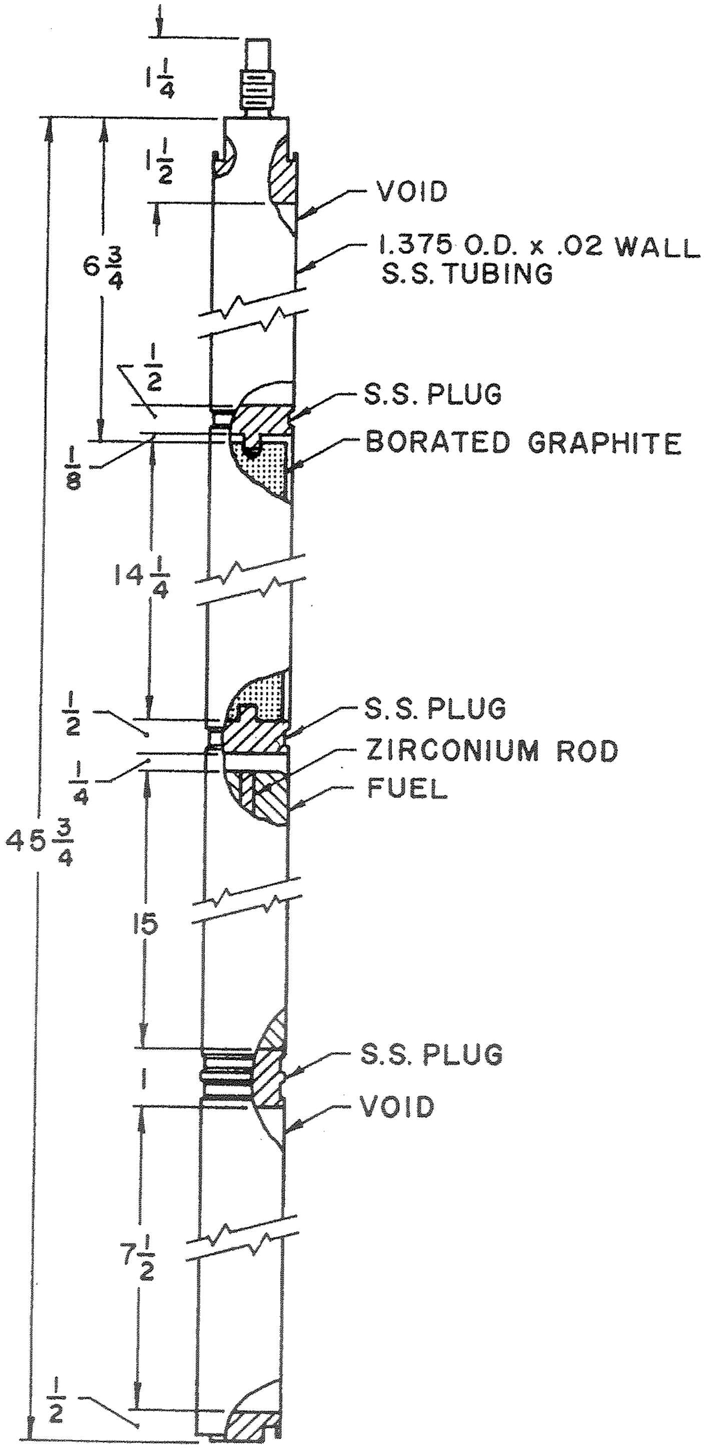

Fig. 7. NSCR fueled follower control rod.

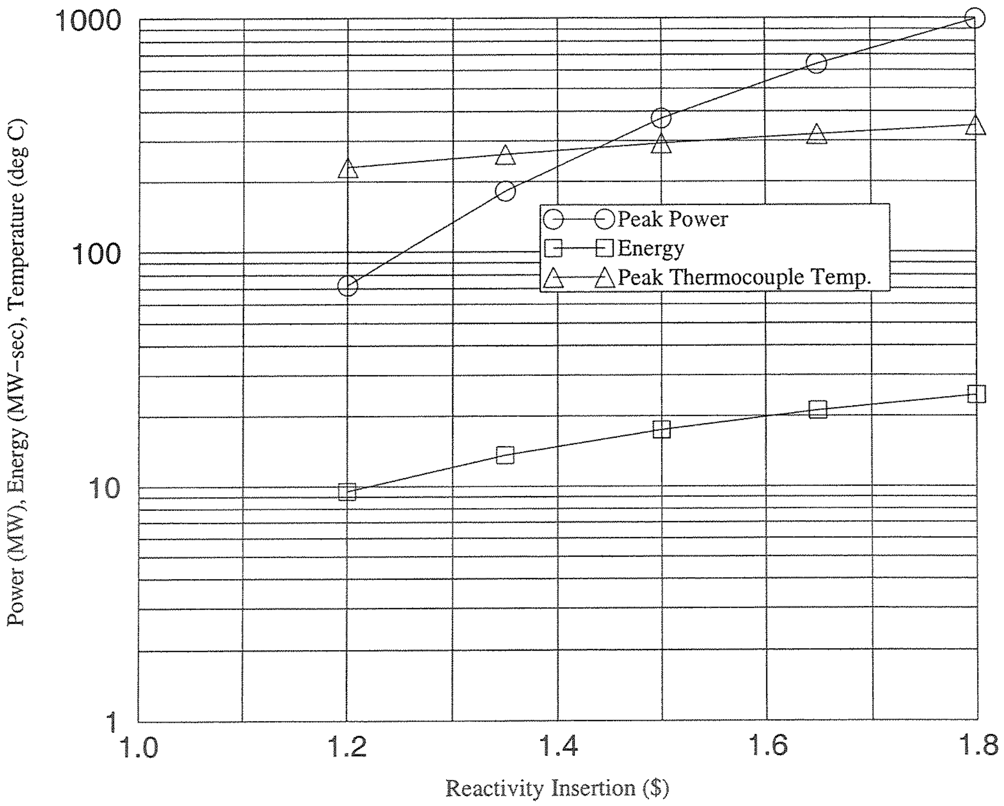

Fig. 8. FLIP pulsing characteristics measured from an experiment in 1993.

TRIGA FLIP fuel contains two important constituents that allow pulsing to occur safely. One of these is erbium with natural isotopics which is loaded to 1.5 weight % as a burnable absorber. ^{167}Er has a large resonance cross section at ~0.5 eV. As the neutron spectrum is hardened by fuel and moderator temperature increases during the pulse, more neutrons reach the energy range of the ^{167}Er resonance and are absorbed. TRIGA FLIP fuel also contains ZrH as a moderator in the fuel structure which allows fission neutrons to be thermalized in the fuel rod where they are produced. As the fuel temperature increases, the ZrH heats immediately and moderates the neutrons to a higher average energy, placing even more neutrons in the ^{167}Er resonance and resulting in fewer fissions. The ZrH and ^{167}Er together enhance the negative temperature feedback.

The calculated temperature coefficients for FLIP fuel are shown in Figure 9. The temperature dependent variation of the temperature coefficient of a TRIGA FLIP core is advantageous in that an acceptable reactivity loss is incurred in reaching normal operating temperatures, but any further increases in the average core temperature result in a sizably increased prompt negative temperature coefficient to act as a shutdown mechanism. Burnup calculations indicate that after 3000 MWD of operation with FLIP fuel, the ^{235}U concentration averaged over the core is ~67% and the ^{167}Er concentration is ~33% of the beginning-of-life values. The temperature coefficient of reactivity at end-of-life is less temperature dependent than the beginning-of-life temperature coefficient of reactivity because of the sizable loss of ^{167}Er and the resulting loss of the ~0.5 eV resonance absorption.

The transient behavior during pulses of $1.80 are shown in Figure 10 for both beginning of life and end of life conditions. The effects of the decrease in the erbium concentration can be seen since the same insertion results in a higher power when the pulse occurs at the end of life. The peak fuel temperatures for these pulses are shown in Figure 11. As expected, the peak temperature at end of life is higher than that at the beginning-of-life.

Fuel Description and Safety Limits

The most restrictive limit on the operation of a TRIGA core results from the dissociation of hydrogen from the uranium-zirconium hydride fuel. As the hydrogen is dissociated from the fuel matrix, pressure increases inside the fuel rod and can eventually cause a cladding failure. Another concern is the migration of hydrogen from the hot radial center of the fuel to the pellet edge under prolonged irradiation. Hydrogen to zirconium ratios near the edge of the fuel can increase by over 15% from their initial values. During a pulse, the temperature is momentarily peaked at the edge of the fuel, and even greater

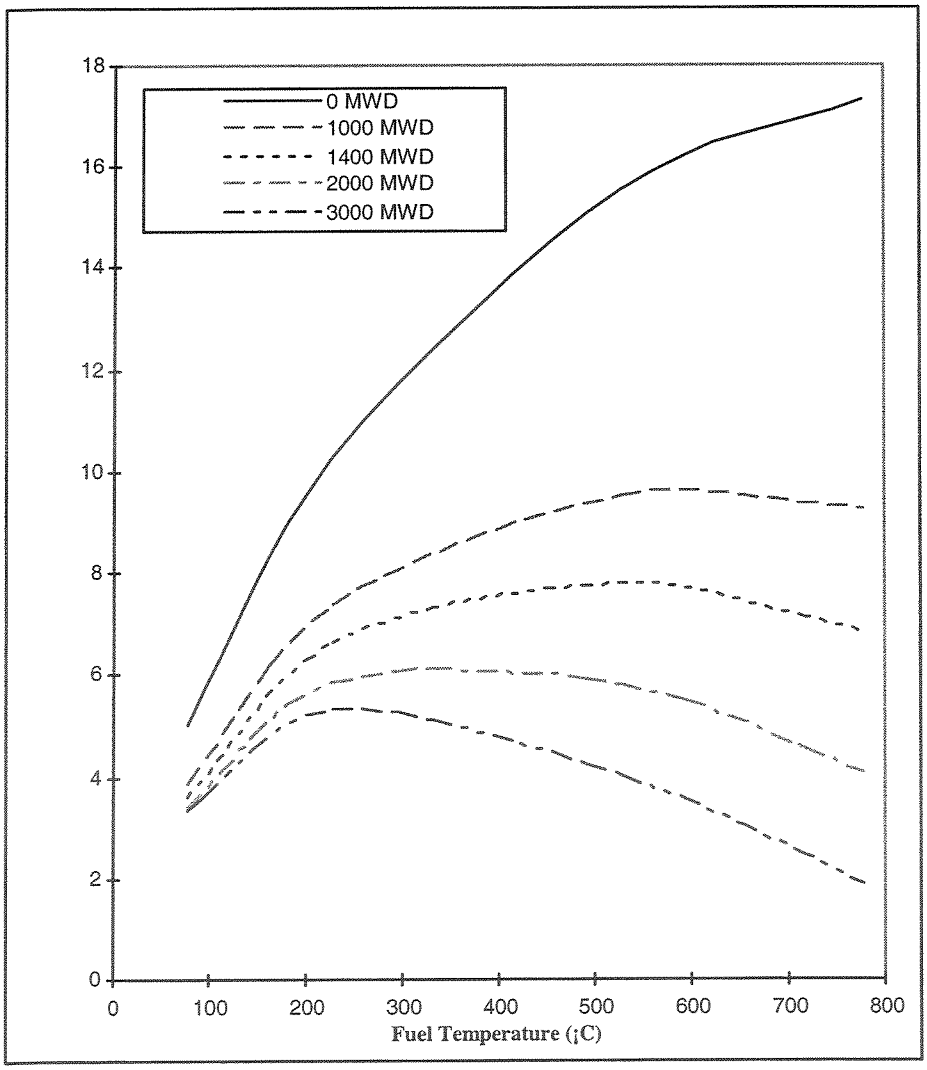

Fig. 9. Prompt negative temperature coefficient for FLIP fuel.

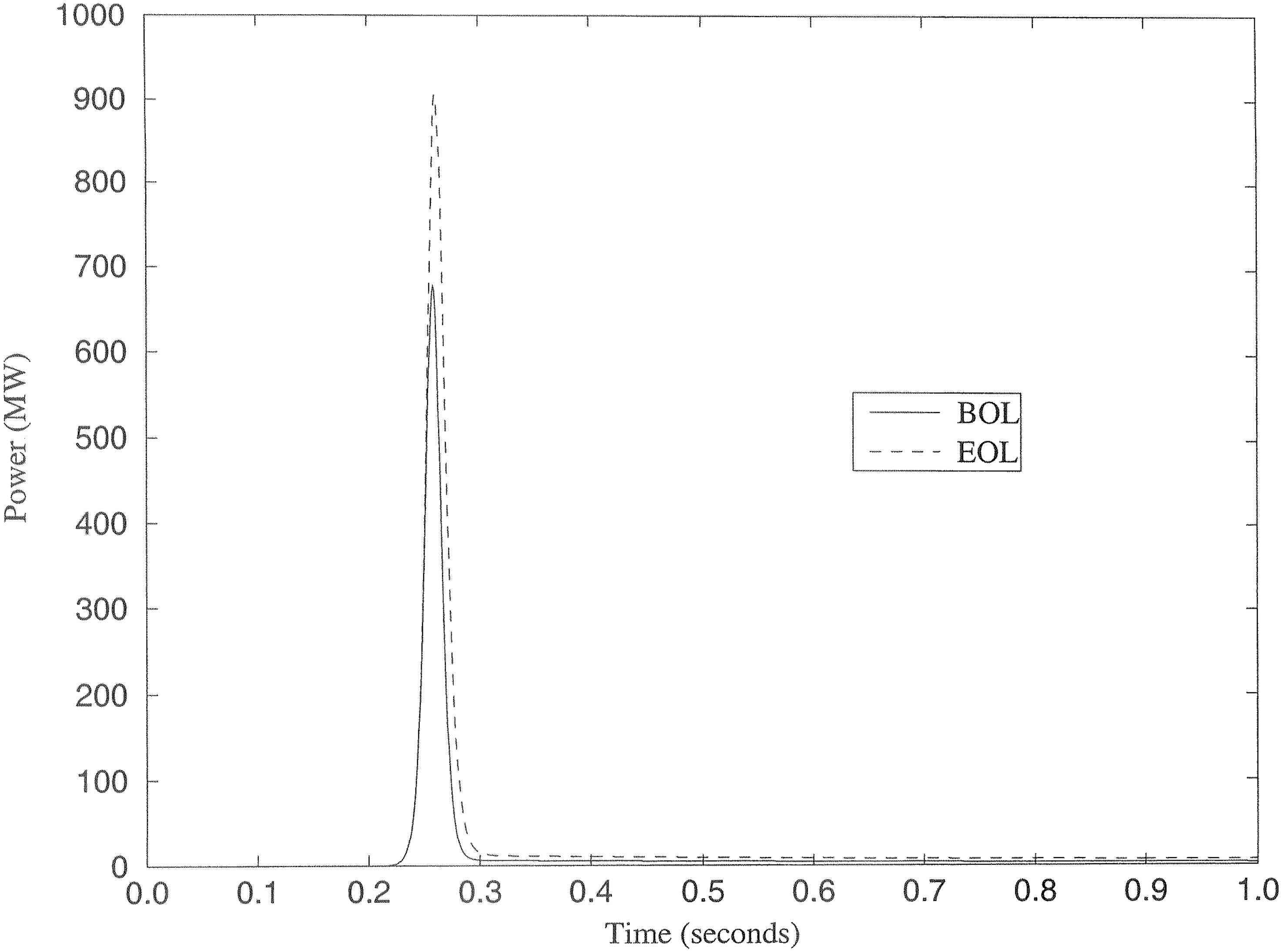

Fig. 10. Comparison of core powers from BOL and EOL $1.80 pulses modeled in **PARET**.

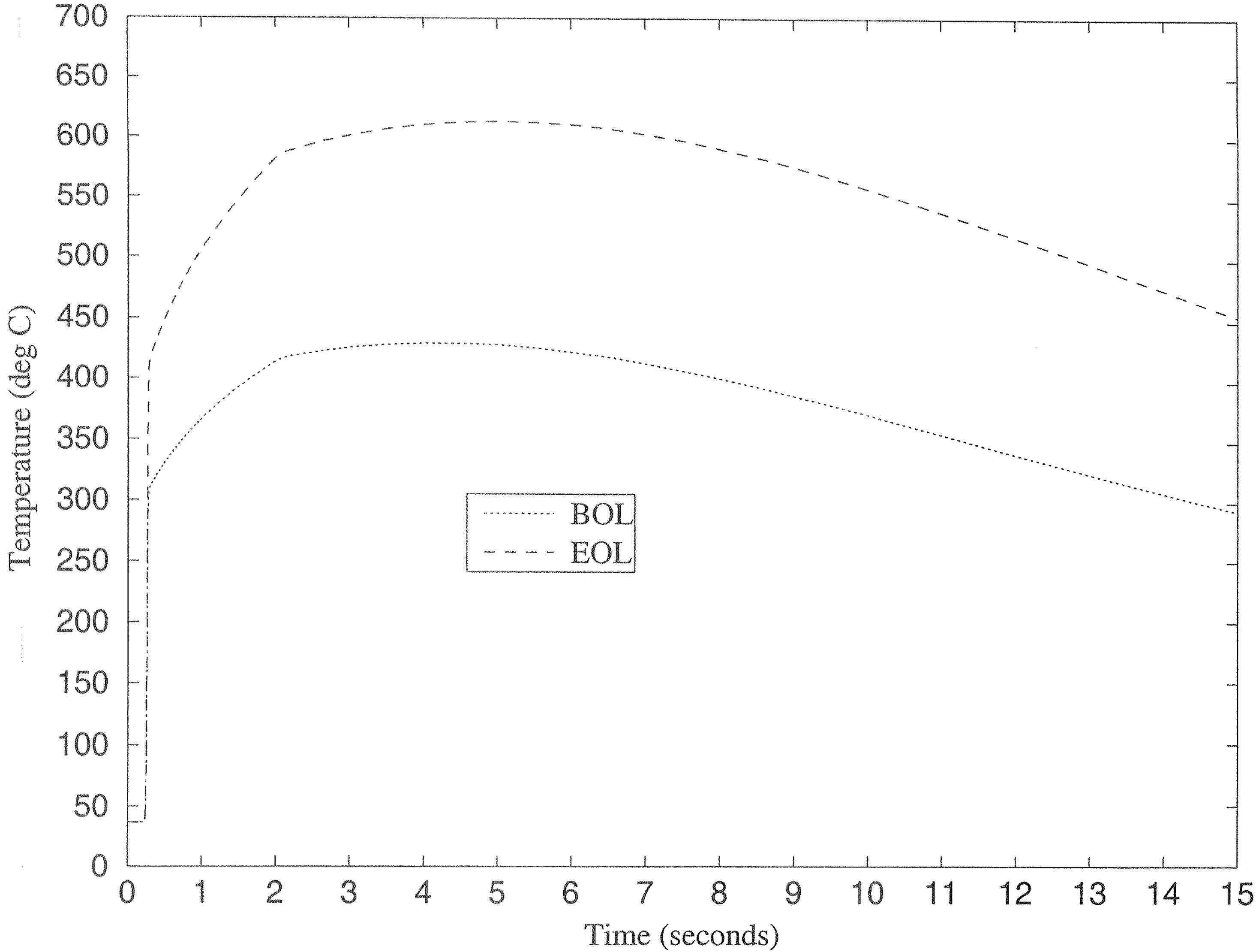

Fig. 11. Comparison of fuel centerline temperatures from BOL and EOL $1.80 pulses modeled in PARET.

hydrogen dissociation can occur. The resulting pressure can cause swelling and fuel element deformation. Pulse insertion limits may have to be adjusted at higher burnups to prevent this deformation. Studies show that hydrogen pressures resulting from a fuel temperature of up to 1150°C would not produce a stress in the clad in excess of its ultimate strength as long as the cladding temperature does not exceed 500°C.[6] In order to reduce the risk of fuel deformation, all operations must be such that the peak temperature limit in any fuel rod, under all conditions of operation, will not to exceed 950°C.

Thermal Design

The NSCR is cooled by natural convection and can be operated at any position along the pool center line except near the gateway between the stall and large pool section. The reactor core is constantly surrounded by pool water which is drawn in freely from the bottom and sides of the core during the convective cooling process.

Figure 4 shows that the four rod assembly has been designed to provide easy passage of cooling water through the element. Water is drawn into the assembly by natural convection through the 2" diameter hole in the grid plate adapter. It passes through the large cruciform opening and then over the entire element until it leaves the core through the numerous openings in the aluminum handle. In addition to the coolant passages through the grid plate adapters, the NSCR grid plate has additional 1/2 inch diameter coolant holes located at the corner of each four rod element.

Mark III standard fuel elements and FLIP elements have been successfully operated in TRIGA cores by General Atomic at steady state power levels of up to 1.5 MW. The arrangement of fuel in the NSCR has been designed so that the minimum nominal spacing between the fuel rods provides adequate convective cooling for core powers up to 2.0 MW. The spacing of the fuel rods in the NSCR core is shown in Figure 12. Core cooling should be enhanced by the rod to rod spacing and by the extra cooling holes at the corners of the bundle. Cooling of the NSCR is also improved due to the increased depth of pool. The NSCR core is normally covered by 26 feet of water which places it at a depth greater than that of most TRIGA installations. The increase in hydrostatic pressure created by this greater depth reduces nucleate bubble formation and improves the margin to departure to nucleate boiling (DNB).

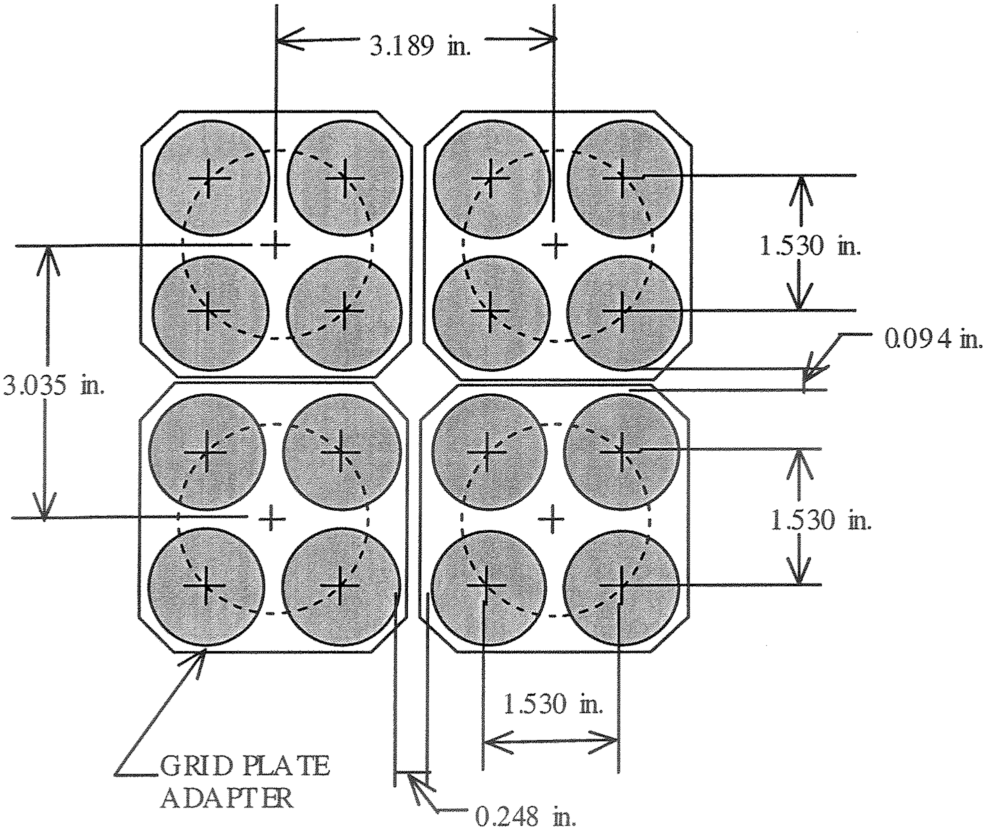

Fig. 12. Nominal fuel rod spacing in the NSCR core.