Design of a 10-kw Reactor for Isotope Production, Research and Training Purposes

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The object of this paper is to describe the TRIGA, a new 10-kw training, research and isotope production reactor developed at this laboratory during the past year. The work described represents contributions from many members of General Atomic whose names do not appear as authors. The guiding principles in the design of this reactor were the following:

Safety. Of the design criteria, the greatest importance was given to the requirement that the insertion of all of the available excess reactivity in the most dangerous possible way would not raise the power to a dangerous level. This requirement was fulfilled by: (*a*) designing a system that has a large, prompt negative coefficient, (*b*) limiting the available excess reactivity to a value less than that required to achieve prompt criticality, and (*c*) employing a geometrical arrangement of the fuel elements approximating that required for maximum criticality. A further degree of safety is assured by the use of fuel elements which can be heated to a relatively high temperature without chemical or physical change.

Simplicity of design and operation. The rapid growth of areas of utility of nuclear reactors has led to a need for a system requiring no appreciable maintenance over long periods and requiring a minimum of special skills for its operation.

Utility. The increasingly important role which is being played by radioisotopes in research, medical treatment and diagnosis, and in industry, has generated a demand for a reactor which is a convenient source of isotopes, particularly those having short half-lives. For this reason a great deal of emphasis was placed on the TRIGA's isotope production facility. The power level chosen was high enough to allow the production of useful specific activities for a large number of isotopes.

Cost. The cost was kept as low as was compatible with the above considerations.

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Including work by R. G. Fischer, M. Frankel, R. B. Minogue and H. A. Thomas.

DESCRIPTION OF REACTOR

General Arrangement

The reflector and core of the TRIGA reactor are located at the bottom of a water-filled tank 6 ft in diameter and approximately 20 ft deep, as shown in Fig. 1. Approximately 16 ft of water above the core provides neutron and gamma shielding for the reactor. Water can be withdrawn from the tank either continuously or intermittently and circulated through a filtration and demineralization system. Except for minor differences in the mechanical arrangement, the TRIGA reactor exhibited at the 1958 Geneva Conference is essentially identical to the prototype of the TRIGA reactor which is located at the John Jay Hopkins Laboratory for Pure and Applied Science near San Diego, California.

Core and Reflector Assembly

The core and reflector assembly for the TRIGA reactor is shown in Fig. 2. The reflector consists of a cylinder of graphite approximately 42 in. in diameter and 22 in. high. The reflector is pierced vertically by a 17-in.-diameter hole in which the core is located. This arrangement provides a 1-ft-thick graphite reflector surrounding the sides of the cylindrical core. The graphite is completely encased in a welded aluminum can to ensure water-tightness. In the upper section of the reflector is an aluminum-lined well for the rotary specimen rack. Grid plates used to position the fuel elements in the core are supported by the top and bottom of the reflector assembly.

Fuel Elements

Approximately 65 fuel elements are required to achieve criticality in the TRIGA reactor. Twenty of the spaces in the grid plates are filled with dummy fuel elements which contain graphite instead of active core material. The remaining 6 spaces in the grid plates are filled with 3 control rod guide tubes, a central thimble, a pneumatic transfer tube and a neutron source. Approximately 67% of the active core volume is occupied by fuel elements and 33% by cooling water.

The active part of the fuel element consists of a cylindrical rod of uranium–zirconium hydride containing 8 wt % uranium enriched to 20% in U^{235}. This fuel-moderator material contains approximately one hydrogen atom per zirconium atom and has a density nearly equal to that of zirconium metal. This uranium–zirconium hydride fuel element has been developed at the General Atomic Laboratory.[1]

The dimensions of this uranium–zirconium hydride rod are 14 in. in length and 1.417 in. in diameter.

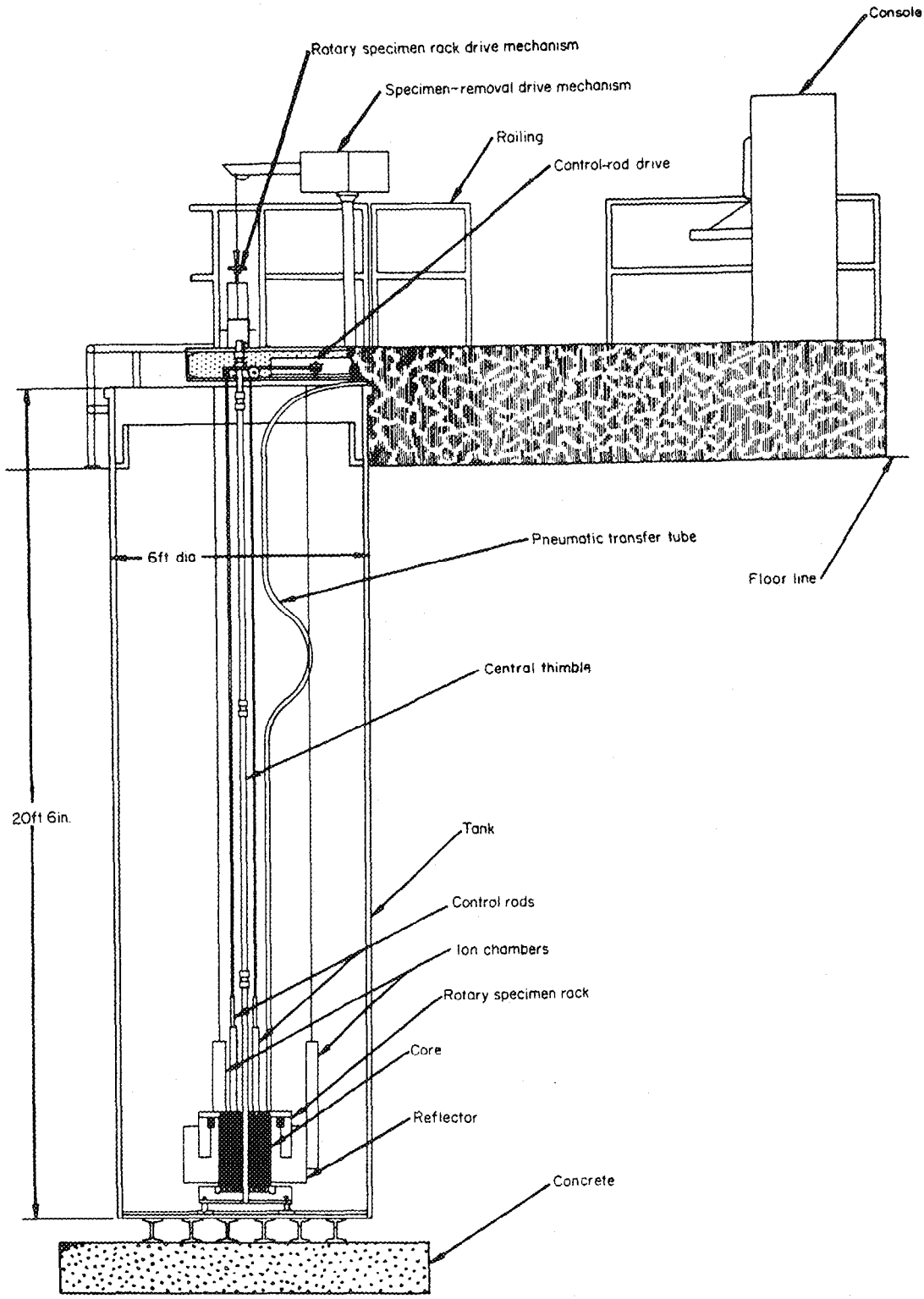

Figure 1. Elevation view of the TRIGA reactor

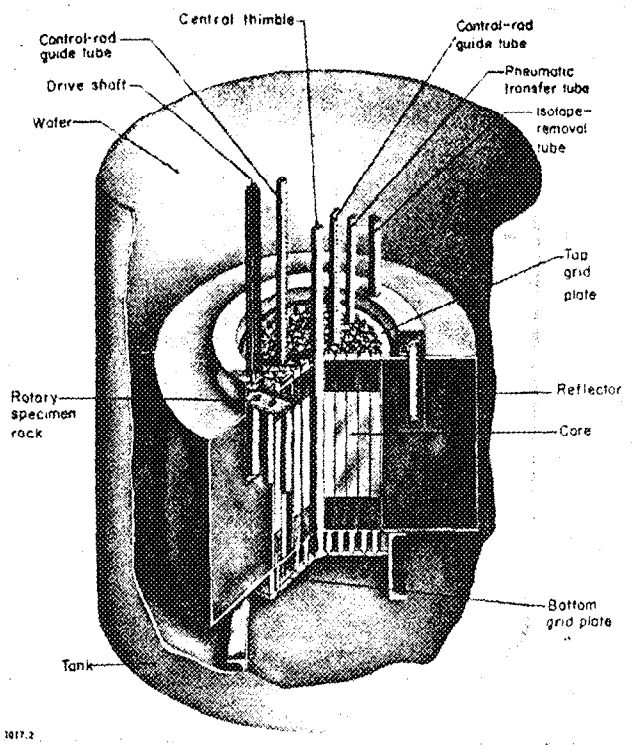

Figure 2. Core and reflector assembly

Graphite slugs 4 in. in length are located above and below the uranium–zirconium hydride rod to provide top and bottom reflectors. The uranium–zirconium hydride rod and the two graphite slugs are encased in an unbonded 30-mil-thick aluminum can with aluminum end fittings. Each fuel element is approximately 29 in. in over-all length and has a maximum diameter of approximately 1.5 in.

In order to decrease the amount of excess reactivity required in the reactor, burnable poison is included in each fuel element. This burnable poison is in the form of samarium oxide–aluminum wafers approximately 0.05 in. thick. Wafers are located immediately above and immediately below the rod, between the rod and the graphite reflector slugs. These wafers contain approximately 1 wt % samarium oxide.

Irradiation and Research Facilities

The primary facility of the TRIGA reactor for the production of radioisotopes is the rotary specimen rack. This rack is located in a welded aluminum box which fits into a well in the reflector assembly. The rotary specimen rack consists of an aluminum ring which is supported by a large deep-groove bearing. Aluminum cups, evenly spaced around the ring, are hung from the ring and serve as irradiation specimen holders. There are two aluminum tubes extending upward from the rotary specimen rack to positions above the surface of the water. Through one of these tubes passes a drive shaft which rotates the aluminum ring to any desired position. Through the other tube, specimens are loaded into, or removed from, any of the 40 specimen containers. An indexing and keying device is provided on the top of the reactor to ensure positive positioning of the cups.

A pneumatic transfer tube is provided in the TRIGA reactor for the rapid introduction and removal of samples. By means of a vacuum system, specimens are transferred into and out of the reactor. The lower end of the transfer tube is positioned at a fuel element location near the outer edge of the core. Loading and unloading of the samples from the pneumatic transfer tube is accomplished at a terminal point above floor level.

A central thimble is provided on the TRIGA reactor. This thimble has an inside diameter of approximately 1 in. and extends from floor level down into the center of the core. The portion of the thimble below the top grid plate is always filled with water. The portion of the thimble above the top grid plate can be emptied by displacing the water with compressed air.

Objects which are too large to fit into the above facilities can be irradiated in the water surrounding the reflector.

Control System

There are three control rods on the TRIGA reactor. The drives for these rods are located near floor level above the reactor and are winch-type drives having a speed of approximately 6 in. per minute. The control rods are coupled to the drives by means of holding magnets attached to the lower ends of the drive cables. The magnets and the control rods operate in vertical aluminum guide tubes which extend from the bottom grid plate to a point approximately 3 ft above the core.

The rods themselves are boron carbide-filled aluminum tubes. One of the rods is used as a safety rod, one as a shim safety rod, and a third as a regulating rod. The safety rod and the shim safety rod each have reactivity worth of approximately 1.2% and the regulating rod has a worth of approximately 0.3%. Position indication for the shim safety rod and the regulating rod is obtained by a rotary potentiometer.

Instrumentation

Four detection channels are provided on the TRIGA reactor. These are a count-rate channel, a log n and period channel, and two linear power level channels. Signals from two of these channels may be selected for display on strip chart recorders. Scram signals can be initiated by excessive power on either of the two linear power level channels, by too short a positive period on the log n and period channel, or by an off-scale reading on the linear recorder.

Most of the circuits used in these detection channels employ transistors rather than vacuum tubes.† This, of course, results in longer life and higher reliability than can be realized with vacuum tube circuits, and

† These circuits were developed by H. A. Thomas, John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California.

it also makes the electronic instrumentation quite compact. All of the electronic circuitry is housed in a control console 60 in. × 22 in. × 51 in.

PHYSICS OF THE CORE–REFLECTOR SYSTEM

A summary of the important parameters of the system is given in Table 1. Additional comments about some of these quantities are given in this section.

Critical Mass

For reasons of both safety and economy, the ratio of water to fuel element volume was chosen to yield close to a minimum critical mass. The resulting system is somewhat undermoderated, and therefore still possesses a negative void coefficient. The present reactor loading consists of 2 kg of U^{235} in the form of 20% enriched material.

Temperature Coefficient

A very great effort has gone into designing the reactor so that an increase in temperature of the fuel elements will immediately result in a relatively large decrease in reactivity. This negative fuel-temperature coefficient results from the following effects:

(1) Doppler broadening of the capture resonances in U^{238} gives a contribution to the temperature coefficient of approximately -2×10^{-5}/°C.

(2) When the fuel elements are heated, they expand and force a small amount of cooling water out of the core. This effect adds about -2×10^{-5}/°C to the temperature coefficient.

(3) When the fuel temperature increases, the zirconium hydride temperature follows it essentially instantaneously. This causes an increase in the neutron temperature because of the increase in the probability that neutrons will gain energy from the excited hydrogen atoms in the zirconium hydride lattice.[2] This increased fraction of speeded-up neutrons results in an increase in thermal leakage from the core and in the relative number of neutrons captured in the water. The temperature coefficient due to this effect is approximately -2×10^{5}/°C at 20°C and increases strongly with temperature.

Excess Reactivity

Access to neutrons from the reactor is provided primarily in regions in the reflector where the thermal neutron flux is relatively high but the adjoint thermal flux is low. This leads to a requirement of approximately 0.1% excess reactivity for experiments and activations. At 10 kw, the reactivity required to override xenon poisoning is about 0.1%. The requirement for excess reactivity to override the build-up of samarium in the reactor has been removed by including samarium in the fuel element during fabrication. The samarium contained in the fuel elements is slightly greater than that which corresponds to equilibrium samarium poisoning in the reactor. This excess of poison burns out at such a rate as to compensate for the depletion of U^{235}. In principle, the

Table 1. Summary of Technical Data

Core	
Fuel-moderator elements:	
Material	Uranium–zirconium hydride (8 wt% uranium, 91 wt% zirconium, 1 wt% hydrogen)
Uranium enrichment	20% U^{235}
Fuel element dimensions	1.47 in. (3.73 cm) diam × 28.7 in. (72.8 cm) long
Cladding	0.030 in. (0.076 cm) thick, 1100 aluminum
Dimensions (active lattice)	17 in. (43.2 cm) diam × 14 in. (35.6 cm) high
Reflector	
Material	Graphite, 6061 aluminum clad
Peripheral thickness	12 in. (30.5 cm)
Top and bottom thickness	4 in. (10.2 cm)
Nuclear Characteristics	
Thermal neutron flux at 10 kw:	
Average in core	$\sim 10^{11}$ neutrons/cm² sec
At rotary specimen rack	$\sim 0.7\times10^{11}$ neutrons/cm² sec
At central irradiation thimble	$\sim 1.5\times10^{11}$ neutrons/cm² sec
Excess reactivity allowance:	
Fuel burn-up and samarium poison	0.2%
Xenon poison	0.1%
Isotope production	0.1%
Startup	0.1%
	Total 0.5%
Core loading	2 kg U^{235}
Reactivity value in control system (minimum)	2.5%
Prompt temperature coefficient of reactivity at 50°C	$\sim -5\times10^{-5}$/°C
Void coefficient of reactivity	-0.001, $\Delta k/k$ per 1% void
Prompt neutron lifetime	$\sim 1.5\times10^{-4}$ sec
Thermal Characteristics	
Power	10 kw
Cooling method	Light water, natural convection
Coolant flow rate	13 gpm (49.2 liters/min)
Coolant average velocity in core	0.05 ft/sec (1.5 cm/sec)
Control System	
Boron carbide control rods	3 (safety, shim safety, and regulating)
Maximum rod withdrawal rates	6 in./min (15.2 cm/min)
Drives for rods	Winch type
Instrumentation	
Linear and log count-rate circuit, driven by fission counter	1
Log n and period circuit, driven by compensated ion chamber	1
Linear power-level channels, driven by uncompensated ion chambers	2
Experimental and Irradiation Facilities	
Rotary specimen rack	40-position rotary specimen rack located in aluminum-clad graphite reflector, 3 in. (7.6 cm) from core
Specimen containers	Capacity 50 cm³, 1 in. (2.54 cm) diam × 4 in. long
Pneumatic transfer tube	1.0 in. (2.54 cm) id, located in core near outside edge
Central thimble	1 in. (2.54 cm) diam

excess reactivity required for a core life of 5 years at a steady power of 10 kw is less than 0.05%. Small errors in the initial samarium loading, however, may introduce up to $\pm$ 0.2% excess reactivity during a 5-year period.

REACTOR OPERATING CHARACTERISTICS

The TRIGA reactor has undergone an extensive test program ‡ designed to investigate experimentally its operating characteristics. Two distinct series of experiments were performed.

The first series consisted of a number of "quasi-equilibrium" experiments in which the reactor power level was slowly increased from one power level to the next in increments of approximately a factor of three. System reactivity loss was measured at each new power level. This measurement was made as soon as possible after attaining a new power to minimize the reactivity effects associated with changes in inlet water temperature. The result of these experiments is shown in Fig. 3. This figure shows that there is a decrease of approximately 1 cent in system reactivity for each kilowatt increase in reactor power level (100 cents equal 0.79% $\Delta k/k$). Auxiliary experiments have shown that changes in average core temperature have a small effect on system reactivity. Hence, one concludes that the observed reactivity loss is due primarily to changes in reactor fuel temperature and that the effect is therefore prompt. The fuel temperature coefficient measured in this way is equal to approximately -1 cent/°C over the range from 20 to 120°C.

‡ This test program was carried out under the direction of R. S. Stone.

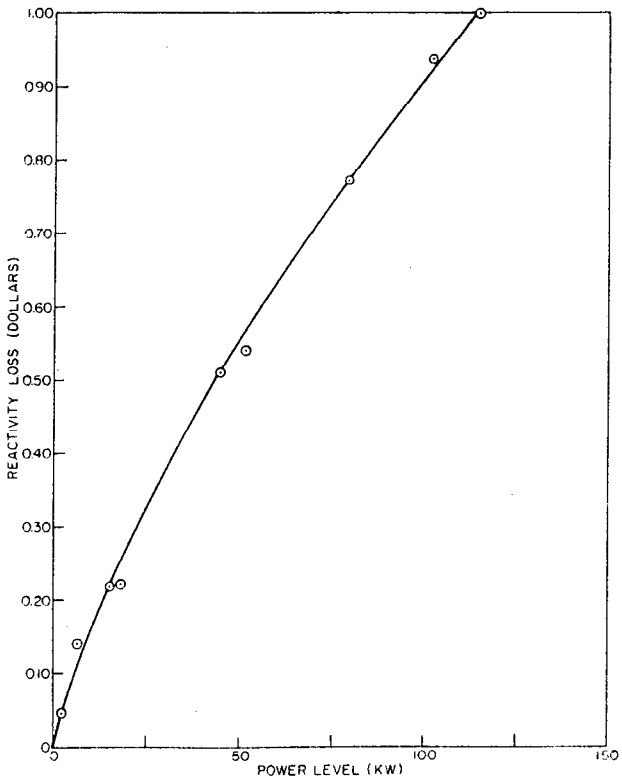

Figure 3. Reactivity loss as a function of power level in quasi-equilibrium experiments

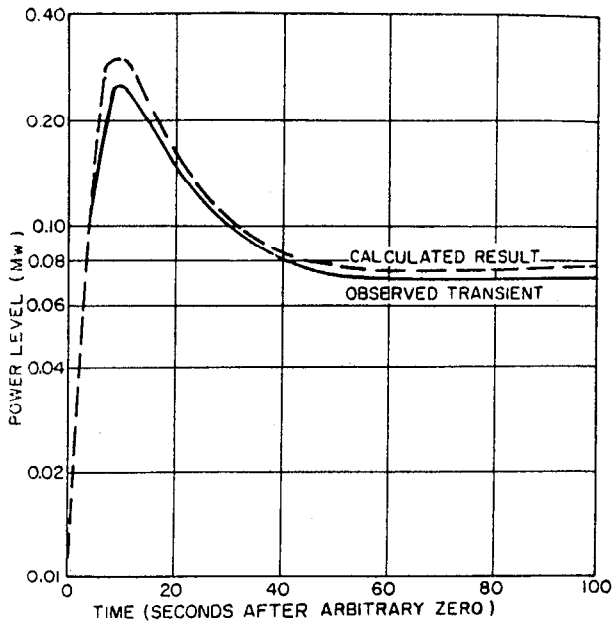

Figure 4. Comparison of predicted and observed TRIGA power-level transients with 75 cents reactivity insertion. IBM-704 input data for predicted results obtained from quasi-equilibrium experiments

The effectiveness of this prompt temperature coefficient in limiting the magnitude of a reactor transient was investigated in the second series of experiments. In these experiments, the reactor power level was initially maintained constant at between 1 and 10 w. A series of reactor transients were then performed, each succeeding transient involving progressively larger amounts of excess reactivity. As of 2 July 1958, the maximum excess reactivity insertion has been 75 cents. A plot of power level as a function of time for this transient is shown in Fig. 4. The peak power was limited to 0.25 Mw and the asymptotic power level was equal to that obtained in the quasi-equilibrium experiments for this reactivity insertion. The dashed curve gives the predicted transient behavior of the reactor based on temperature coefficient data obtained from the quasi-equilibrium experiments. The highest measured temperature rise in a fuel element was only 90°C. No evidence of boiling was expected or observed.

REFERENCES

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2. M. Nelkin, A. McReynolds, M. Rosenbluth and W. Whittemore, *Neutron Thermalization by Chemically Bound Hydrogen*, P/1540, Vol. 16, these Proceedings.