TRIGA research reactors: A pathway to the peaceful applications of nuclear energy

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LESS THAN FIVE years from the date of President Dwight D. Eisenhower's December 1953 "Atoms for Peace" proposal to the United Nations General Assembly, TRIGA—a new kind of inherently safe training, research, and isotope-production nuclear research reactor—was conceived, built, and operating at the General Atomic Division of General Dynamics Corporation in San Diego, Calif. Over the years, TRIGA (Training, Research, Isotope production, General Atomic) has evolved into the most widely used research reactor in the world, with operating power levels up to 14 000 kW, designs up to 25 000 kW, and with an installed base of 65 reactors in 24 countries on five continents (Fig. 1). (A complete list of TRIGA reactors around the world can be found at <triga.ga.com>).

In a time frame virtually unknown by today's standards, the first three TRIGA reactors were placed in operation in 1958, just two years after the idea for such a reactor was originally conceived. These three reactors were the prototype TRIGA reactor, at General Atomic (GA) in San Diego (May 3); another TRIGA, which operated at the Second Geneva Conference for the Peaceful Uses of Atomic Energy (September 1–13); and a third TRIGA, which started up at the University of Arizona (December 7).

Because of its simplicity and safety, the reactor was chosen by the U.S. Atomic Energy Commission (AEC) to produce short-lived radioisotopes for the U.S. government's Life Sciences Exhibit at Geneva. Delegates and other visitors to the conference were able to view the below-ground TRIGA (Fig. 2) in operation down through a protective water shield and watch the radioisotope production process and a working neutron spectrometer continuously measuring the neutron cross-sections for several typical materials.

Two more TRIGA sales were announced directly at the Geneva Conference. In a public ceremony at the Palais des Nations, the Italian National Committee for Nuclear Research (CNRN) formally signed a contract for the installation of an aboveground TRIGA at CNRN's new research center in Rome. Three days later, the Republic of Vietnam announced its selection of an aboveground TRIGA. And finally, the University of Lovanium in the Congo made arrangements to acquire the actual TRIGA that operated in Geneva, which subsequently was shipped from Geneva to Leopoldville and became the first nuclear reactor to be installed and operated on the African continent. As a result of the reactor demonstrations carried out at the Geneva Conference, coupled with the work of Frederic de Hoffmann, then president of GA (now General Atomics), several additional, later sales of TRIGA reactors were also initiated during the conference.

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Fig. 1. World map showing TRIGA installations to date

Fig. 2. TRIGA reactor in operation at the Second Geneva Conference (1958)

Still another TRIGA operated at the World Agriculture Fair in New Delhi, India, beginning in late 1959 as part of the U.S. government's Life Sciences Exhibit. President Eisenhower himself pushed the button to place the TRIGA in operation as the climax to the formal opening of the United States exhibit (Fig. 3). Accompanied by India's President Rajendra Prasad and other notables, including noted Indian scientist Homi J. Bhaba, President Eisenhower termed the reactor startup "a really beautiful sight" as he and Prasad witnessed the reactor's blue glow upon attaining its steady-state operating level of 100 kW. Some 3 million visitors saw that reactor in operation as it produced radioisotopes used in demonstrations of the use of atomic energy in agricultural research.

With word of the new reactor spreading internationally, no fewer than 20 more TRIGA orders were announced from 1958 through 1961. In the United States, the University of Illinois, Cornell University, Kansas State University, the University of Texas, and the Veterans Administration Hospital in Omaha were among those making plans to install the reactor. Overseas, TRIGA research reactors were ordered for national research centers or universities in Austria, Brazil, Finland, Germany, Indonesia, Korea, Japan, and Yugoslavia, and a second reactor in Italy, at the University of Pavia.

Many of these early TRIGAs were acquired with the help of grants from the AEC or National Science Foundation. In many cases, the International Atomic Energy Agency assisted with the supply of U.S.-origin fissile material for the reactor fuel, from the pool of special fissionable material placed at the agency's disposal by the United Kingdom, the United States, and the USSR.

Four of the TRIGAs were installed under the Atoms for Peace program itself (Korea, Vietnam, Indonesia, and Yugoslavia, all Third World countries at the time). The reactor for Japan's Rikkyo (St. Paul) University was purchased with the help of a fundraising drive led by the Episcopal Church of the United States.

The birth of TRIGA

The original TRIGA patent, "Reactor with Prompt Negative Temperature Coefficient and Fuel Element Therefor," was filed on May 9, 1958, by Theodore Taylor, Andrew McReynolds, and Freeman Dyson and assigned to General Atomic on March 31, 1964 (Fig. 4).

The idea for such an inherently safe research reactor dates back to the summer of 1956, when a team of distinguished scientists was assembled in San Diego by GA (then General Atomic Division of General Dynamics) to help the new company define its first products. The story of that summer has been described by Freeman Dyson in his 1979 book, *Disturbing the Universe*.[1] The mandate to this group, working under Edward Teller, was to design a reactor so safe that if it were started from its shutdown condition and all of its control rods instantaneously removed, it would settle down to a steady level of operation without melting any of its fuel or releasing fission products.

In other words, "engineered safety," or the prevention of accidents by engineering the reactor control and safety system, was not good enough, and the challenge was, therefore, to design a reactor with "inherent safety" guaranteed by the laws of nature. This way, the safety of the reactor

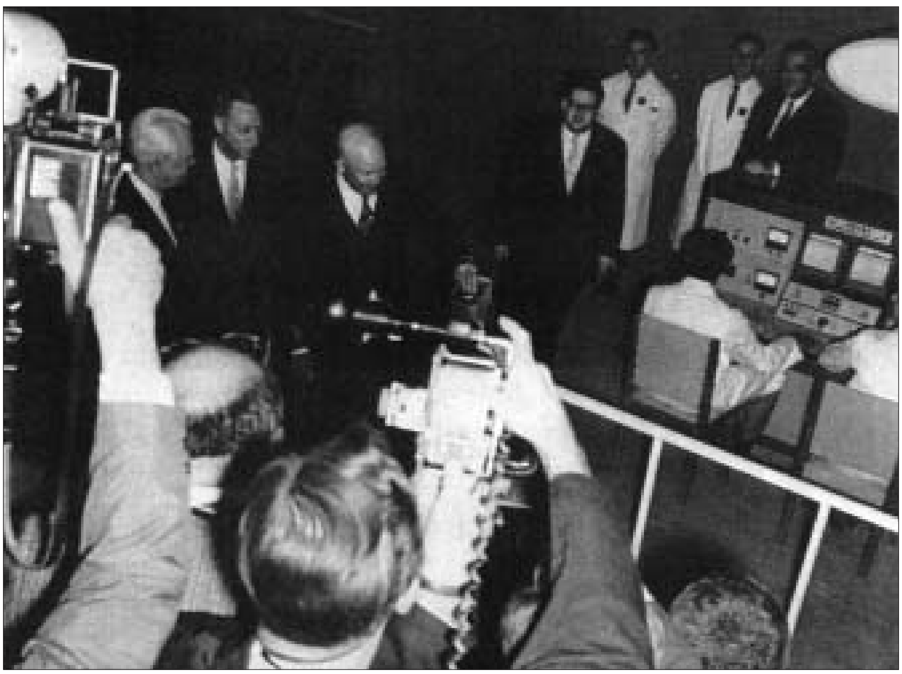

Fig. 3. President Eisenhower placing the TRIGA in operation at the New Delhi World Agricultural Fair (1959)

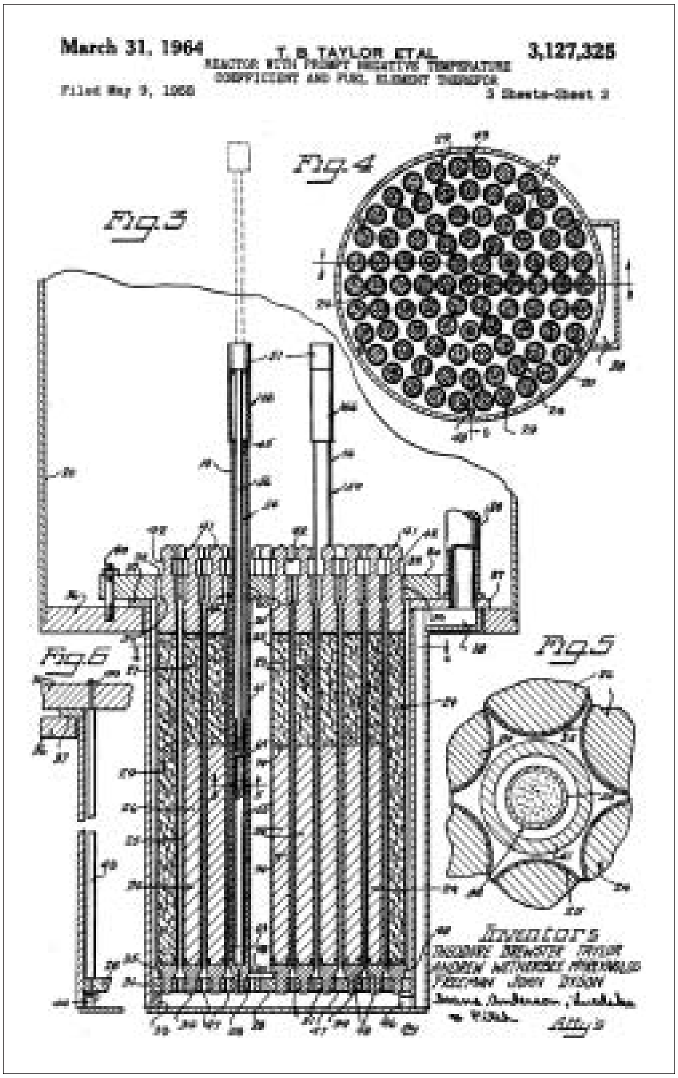

Fig. 4. U.S. Patent No. 3,127,325, filed May 9, 1958

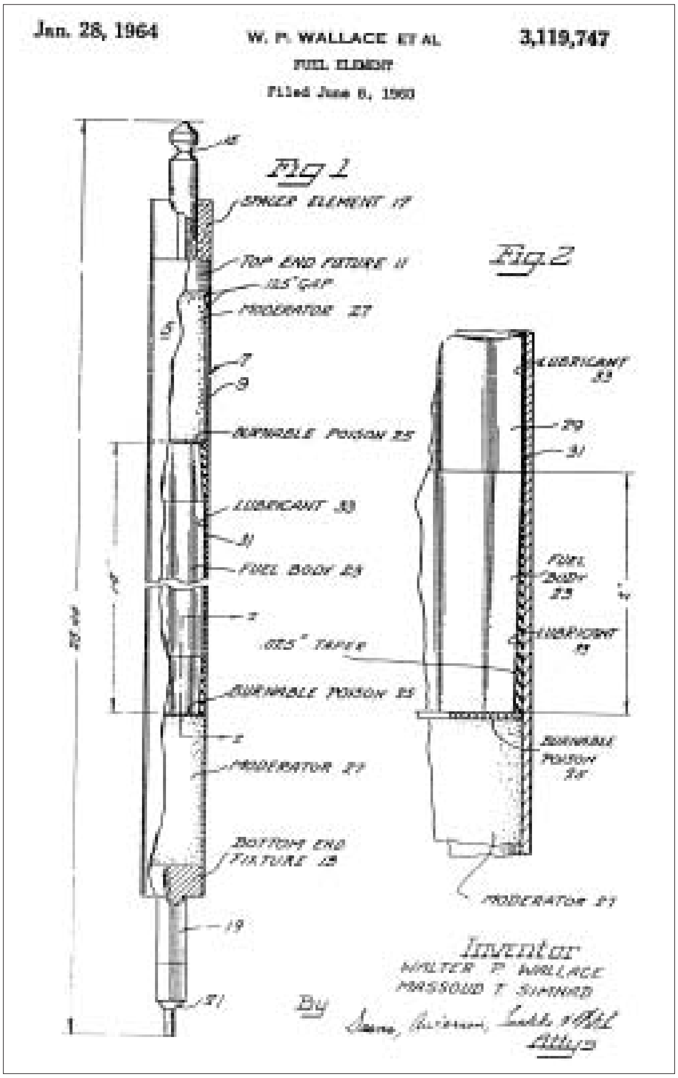

Fig. 5. U.S. Patent No. 3,119,747, filed June 8, 1960

would be guaranteed even if the engineered features were bypassed and the control rods were rapidly removed.

In meeting this challenge, the idea of the "warm neutron principle" was introduced as a first step toward the design of an inherently safe reactor. Generally, in water-cooled reactors, the result from suddenly removing the control rods is a catastrophic accident, leading to a melting of the fuel. This is because the neutrons from the fission reaction remain "cold" from interacting with the water around the fuel and maintain their ability to cause further fissioning of uranium atoms in the fuel. This in turn results in the temperature of the fuel continuing to increase rapidly until the fuel finally melts.

TRIGA, however, is no ordinary water-cooled reactor, because much of its "moderation" of neutrons is due to the hydrogen that is mixed in with the fuel itself. There-

Fig. 6. Standard TRIGA fuel element

fore, as the fuel temperature increases when the control rods are suddenly removed, the neutrons inside the hydrogen-containing fuel rod become warmer (i.e., gain energy) than the neutrons outside in the water. These warmer neutrons inside the fuel cause less fissioning in the fuel and escape from the fuel, where they are cooled in the water with some of them then disappearing by absorption in the fuel cladding material.

The end result is that the reactor automatically reduces power within a few thousandths of a second, faster than any engineered device can operate. In other words, the fuel rods themselves act as an automatic power regulator, shutting the reactor down without engineered devices.

The initial patent for TRIGA fuel, "Fuel Element," was filed on June 8, 1960, by Walter Wallace and Massoud Simnad, and assigned to General Atomic on January 28, 1964 (Fig. 5). By the early 1960s, GA had extended the development of hydrogen-containing uranium-zirconium fuel rods to higher contents of hydrogen, increasing the hydrogen-to-zirconium atomic ratio from 1.0 to 1.7, and replacing the aluminum cladding previously used with stainless steel (Fig. 6). All this further enhanced the TRIGA's safety features. The resulting metal alloy was as robust and as corrosion-resistant as stainless steel. While safety-related incidents are rare at research reactors, the UZrH-containing fuel element made such potential incidents of no consequence at a TRIGA reactor, based on the simple physical principles of this fuel.

Fig. 7. Looking down into the pool of the original 10-kW TRIGA Mark I reactor at San Diego, Calif.

Temperature coefficient

The warm neutron principle used in UZrH fuel gives TRIGA a "prompt negative temperature coefficient of reactivity,"

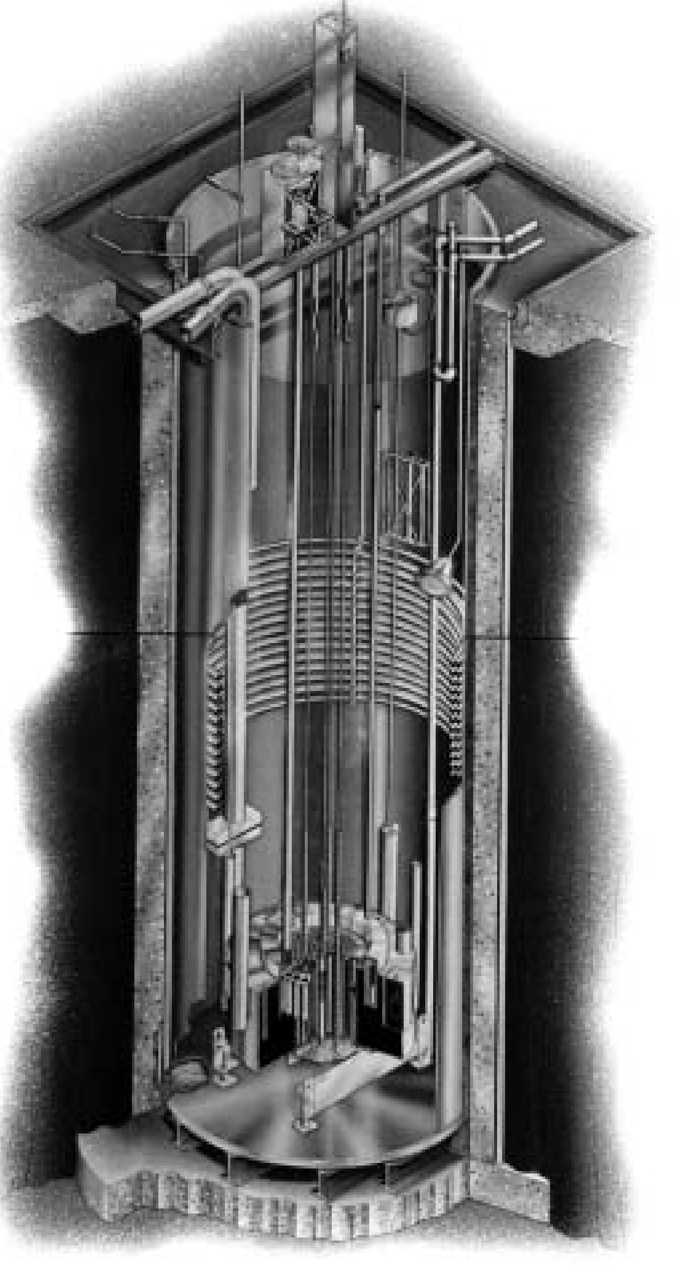

Fig. 8. Cutaway showing the internals of the original 10-kW TRIGA Mark I reactor at San Diego, Calif.

as compared to a delayed coefficient for other types of research reactors using aluminum-clad plate-type fuel. This allows TRIGA to withstand events that would destroy plate-fueled reactor cores. Such an unparalleled degree of safety made the reactor well-suited for use in universities and research institutions, even in developing countries. It also permitted TRIGAs to be installed directly at medical institutions such as the Veterans Administration Hospital in Omaha and other medical centers in Hannover and Heidelberg, Germany.

The UZrH fuel provides several other advantages. UZrH is chemically stable; it can be quenched at 1200 °C with no interactions in water. The high-temperature strength and ductility of the stainless steel or Alloy 800 fuel cladding provides total clad integrity at fuel temperatures as high as 1150 °C in an operating reactor (or up to 950 °C with air cooling). The UZrH fuel offers far superior retention of radioactive fission products compared with aluminum-clad plate-type fuel. It could retain more than 99 percent of its volatile fission product inventory even if all the cladding were removed.

The prototype TRIGA at GA of the Mark I type (Figs. 7, 8), was originally licensed to operate at a power level of 10 kW, but was soon upgraded to 250 kW, with brief licensed tests conducted at power levels approaching 1000 kW. Because of its inherent safety features, this reactor could be "pulsed" to power levels of over 1000 MW, after which (and without any outside intervention) it returned in a few thousandths of a second to a safe low power as a result of the ubiquitous warm neutrons. This pulsing feature of UZrH-fueled reactors, first demonstrated at the prototype TRIGA at GA, is now a standard feature among many TRIGA reactors (Fig. 9).

A second TRIGA was built at GA in 1960, known as the Mark F, expressly to utilize these pulsing features and especially to demonstrate the behavior of UZrH fuels when pulsed to power levels even above 5000 MW. This reactor was designed to provide controlled, instantaneous pulses of intense neutron and gamma radiation for use in radiation-effects testing, biomedical investigations, basic neutron physics research, and many other research studies where high neutron flux and narrow pulse widths were required.

The startup of the Mark F reactor freed the original prototype Mark I reactor at GA for other types of radiation services, both for GA and outside customers. The Mark I became particularly useful in developing and demonstrating neutron activation analysis as an extremely sensitive technique for the detection of trace amounts of impurities in a variety of sample materials. GA operated a mail-order analysis service for customers sending in samples of biological materials, agricultural products, chemical and petroleum products, semiconductors, and metals. A forensic activation analysis service was also offered to law enforcement agencies.

A third TRIGA reactor was built at GA in the mid-1960s, known as the Mark III. This 2-MW reactor was installed as a below-ground facility, but served as a prototype of the later, Mark III-type TRIGA reactors installed aboveground. In San Diego, this reactor was designed to operate as a steady-state reactor, and served for several years as a test bed for thermionic fuel cell development.

Standard TRIGA designs

The basic TRIGA reactor has been developed and offered to users in several standard designs. The below-ground TRIGA Mark I reactor (Figs. 10, 11) is extremely simple in physical construction. It has a graphite-reflected core installed near the bottom of an aluminum tank and typically operates at power levels up to 1 MW with

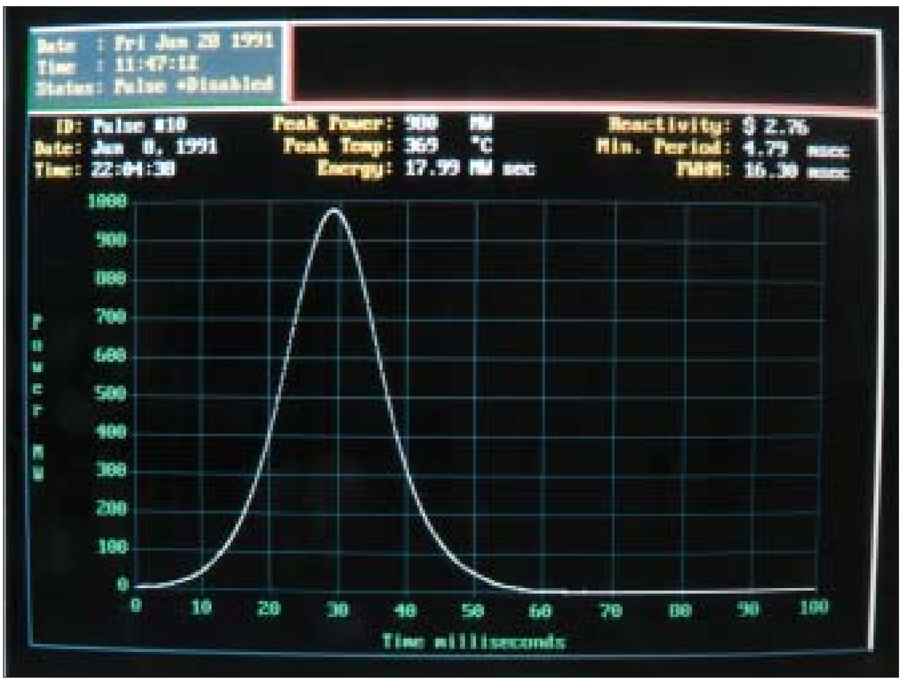

Fig. 9. Graphical representation of pulsing feature of TRIGA reactors

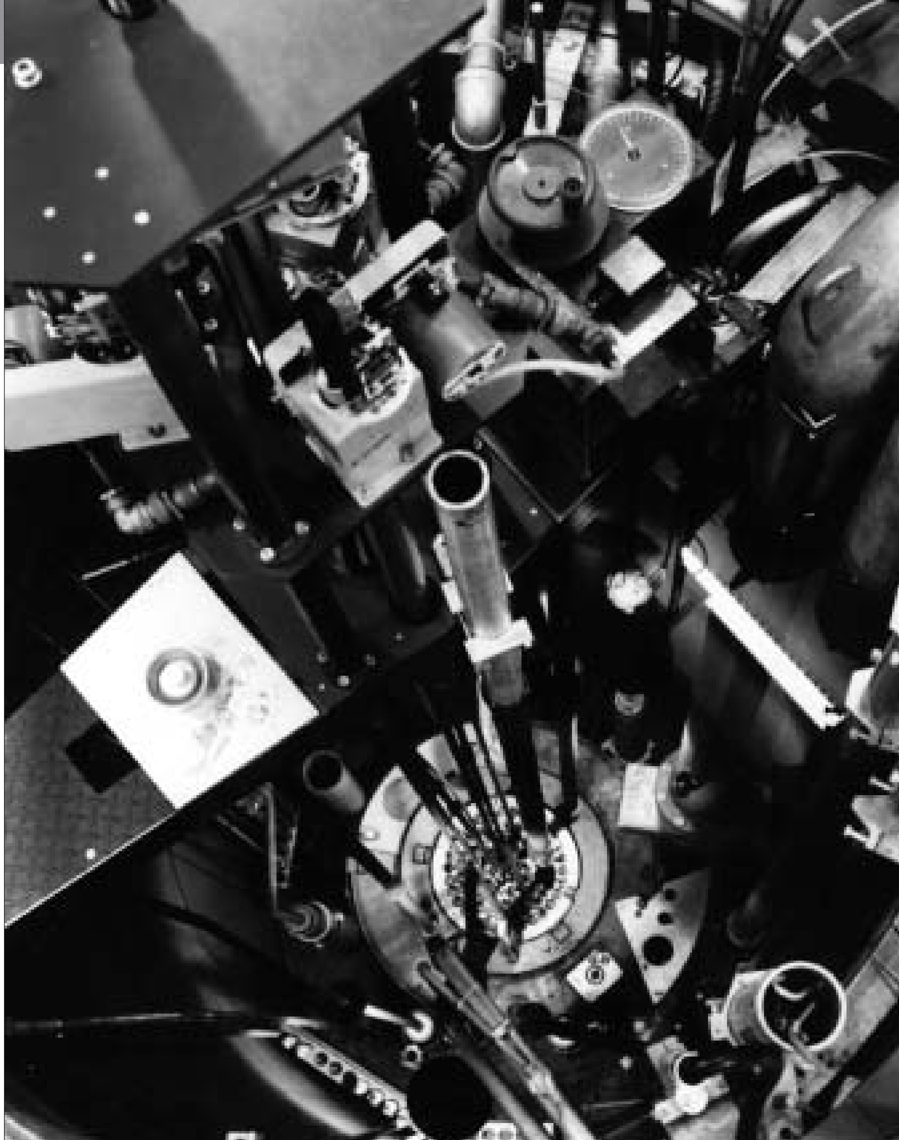

Fig. 10. TRIGA Mark I reactor at General Atomics, in California

pulsing capability. Surrounding earth and demineralized water provide most of the required radial and vertical shielding. No special containment or confinement building is necessary, and installation in an existing building has often been feasible. Core cooling is achieved through natural convection. Each Mark I reactor is equipped with various irradiation facilities (Fig. 4), including a central thimble for high-flux irradiation, pneumatic rabbit with in-core terminus, and a rotary specimen rack for uniform irradiations of up to 80 sample containers.

The aboveground TRIGA Mark II reactor (Fig. 12) has a core that is identical to that of the Mark I but is located in a pool surrounded by a concrete biological shield that is above the reactor room floor. The pool water provides natural convection cooling for operation up to 2 MW, with operation at 3 MW possible with forced cooling provisions. In addition to the Mark I's irradiation facilities, the Mark II includes four horizontal beam ports extending through the concrete shield to the faces of the reflector, and a graphite thermal column providing a source of well-thermalized neutrons suitable for physical research or biological irradiations. In the early TRIGA Mark II reactors, a separate thermalizing column was included together with an associated water-filled pool for shielding studies. In recent times, users have converted these for other applications, such as dry neutron radiography facilities with built-in shielding.

A later design option, TRIGA Mark III (Fig. 13), provided a movable reactor core, supporting both steady-state (up to 2 MW) and pulsing operations, but with greatly increased operational flexibility. The core can be moved to one end of the pool for experiments in an adjacent dry, walk-in exposure room, or to the opposite end for experiments involving the thermal columns and beam ports, or used in the center of the pool for isotope production and other applications.

Instrumentation and control (I&C) systems for all new TRIGA reactors has now evolved into compact, microprocessor-driven systems. As with previous generations of the I&C systems, they are designed to enable inexperienced students and nontechnical personnel to operate the reactor with a minimum of training, with simplicity afforded as a result of the inherently safe characteristics derived from the physical properties of the UZrH fuel. Four operating modes are typically available: manual, automatic, pulsing, and "square wave," the

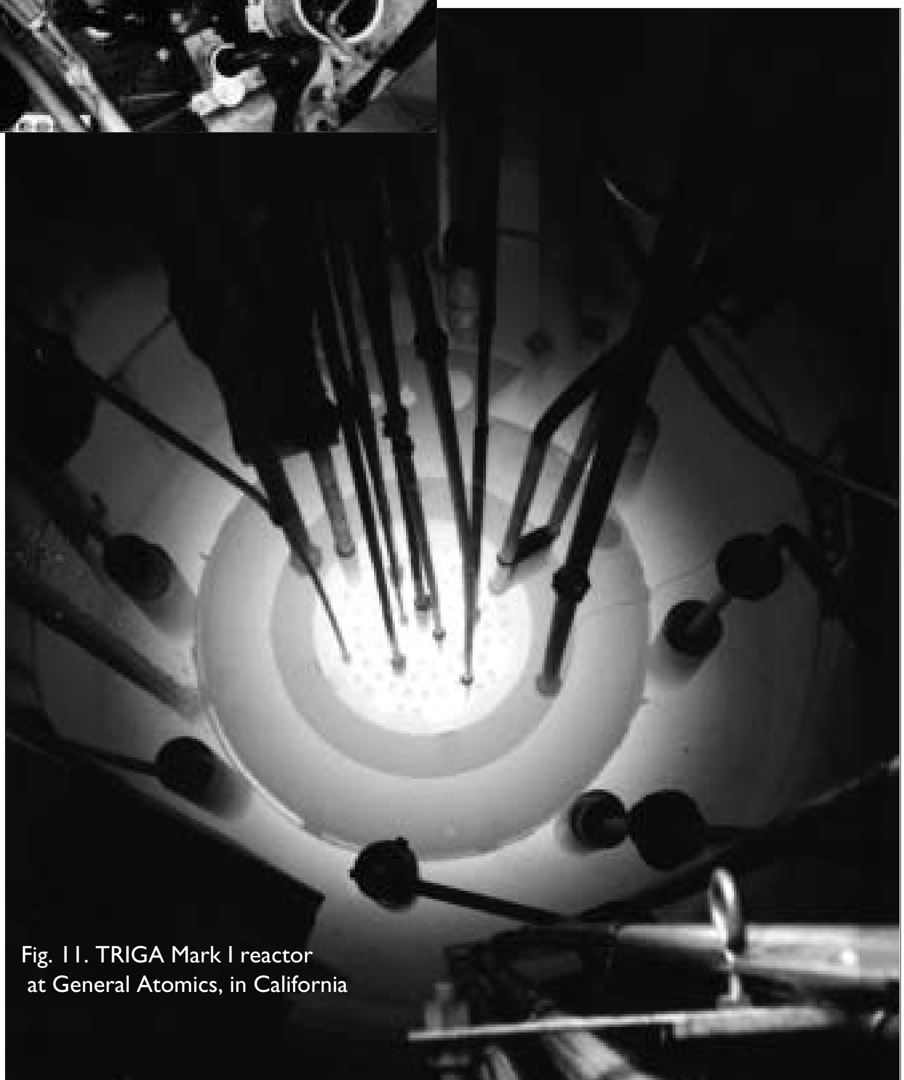

Fig. 11. TRIGA Mark I reactor at General Atomics, in California

Fig. 12. TRIGA Mark II reactor at Mainz, Germany

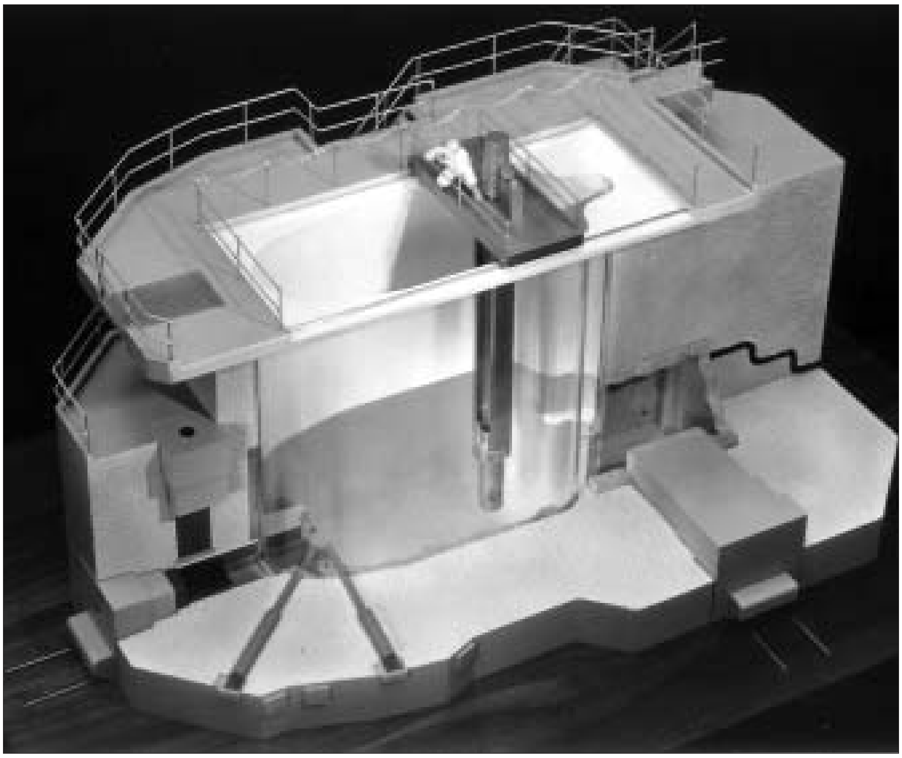

Fig. 13. TRIGA Mark III movable core reactor cutaway

latter being a one-button startup sequence for bringing the reactor up quickly (a few seconds) to its operating steady-state power level. TRIGA reactors have also been licensed to operate in unattended mode, again as a result of the protection afforded by the safety characteristics of the UZrH fuel.

TRIGA reactors evolve

The 1960s, 1970s, and 1980s saw a number of low- and medium-power, as well as higher-power, TRIGA installations built and operated, often making use of the reactor's pulsing capability. A TRIGA reactor with a movable core arrangement at the Armed Forces Radiobiology Research Institute at Bethesda, Md., was built for research on the biological effects of radiation, including studying biomedical effects of intense nuclear radiation to which military and civilian populations might be exposed in the event of nuclear attack. The Army's Harry Diamond Laboratories in Maryland have operated a movable core reactor for radiation-effects testing of electronic components, as has Northrop Corporation in California (Fig. 14). TRIGA Mark III reactors were built at the University of California's Berkeley campus (Fig. 15—that reactor is now decommissioned), and at the Institute of Nuclear Research in Mexico City.

An early TRIGA Mark II, at Musashi Institute of Technology in Japan, was adapted for pioneering research and therapeutic treatment for malignant, inoperable brain tumors and melanoma, using the Neutron Capture Therapy (NCT) technique. About 125 brain tumor patients have been treated at the Musashi facility.

Annular Core Pulsed TRIGA Reactors were designed and built for use at Sandia National Laboratories, the Institute for Nuclear Technologies in Romania, and the Japan Atomic Energy Research Institute (Fig. 16). These have routinely achieved pulsed power levels up to 22 000 MW for testing power reactor fuels. These reactors have a large (25-cm diameter), dry central test cavity (Fig. 17) that can accommodate samples in the central core regions. They employ specially designed cladding for the UZrH fuel elements, permitting higher peak fuel temperatures in standard UZrH material, while retaining the inherent safety and simplicity of natural convection cooling.

A special-purpose TRIGA was designed and commissioned for the U.S. Air Force at McClellan Air Force Base, in California, for real-time neutron radiography inspection of large aircraft components. Known as the Stationary Neutron Radiography System (SNRS), this is a modified Mark II reactor that has provided high-volume, real-time inspection of large parts such as complete aircraft wings and subassemblies. A custom-designed TRIGA reactor with four neutron beam ports transmits neutrons to special component inspection bays where parts are robotically positioned and imaged in real time using digital imaging techniques, as well as the traditional film technique. The reactor was transferred in place to the University of California–Davis (the air force base itself was closed in 2001). The reactor facility, now known as the McClellan Nuclear Radiation Center, offers services in nondestructive inspection, irradiation, radioisotope production, and other areas.

The use of TRIGA fuels was extended in the 1980s in cooperation with the Department of Energy's Reduced Enrichment for Research and Test Reactors program, by designing and qualifying proliferation-resistant (low-enriched) uranium UZrH fuels. These fuels were developed with higher uranium densities for use in higher power regimes where newer TRIGAs were being designed to operate. This fuel design continues to provide the highest degree of safety against nuclear incidents, regardless of power level.

One other major development, which started as early as the late 1960s, was the conversion of existing non-TRIGA research reactors that used plate-type fuel to TRIGA-

Fig. 14. TRIGA movable core reactor at Northrop Corp., in California

Fig. 15. TRIGA Mark III reactor (now decommissioned) at University of California–Berkeley campus

Fig. 16. Annular core pulsing reactor, in Tokaimura, Japan

type fuel. In most cases, the converted reactors have retained their existing core grid structure, and, in some cases, their existing reactor control systems. The conversion to a complete TRIGA-type reactor is accomplished using TRIGA four-rod clusters, and can be added a few clusters at a time to an operating plate-type core. The resulting conversion provides a dual steady-state/pulsing capability in a range of designs rated from less than 1 MW to 3 MW.

Research reactors with plate-type fuel that have converted to TRIGA-type fuel include installations at the University of Maryland (Fig. 18), Penn State, Texas A&M, Washington State, and the University of Wisconsin, as well as locations in Taiwan, Thailand, Philippines, and (most recently) Colombia.

General Atomics also began incorporating modifications to accommodate higher-power TRIGA operations (5 to 25 MW). A smaller-diameter (13-mm) UZrH fuel rod with a high-strength and -ductility Inconel alloy cladding (Fig. 19) and forced cooling to replace natural convection cooling were included in the 14-MW TRIGA reactor commissioned in Romania in 1980 (Fig. 20). Designs using the smaller-diameter fuel rods have been extended to steady-state power levels up to 25 MW.

Two newest projects

Today, two new TRIGA construction projects are under way. The first involves a 10-MW multipurpose TRIGA reactor that will be the center of a Nuclear Research Center being built for Thailand's Office of Atoms for Peace near Bangkok (Fig. 21). It will use the same high-density small-diameter fuel type that has been successfully demonstrated to very high burnups in the Romanian TRIGA reactor, and will include a radiation treatment facility for neutron cancer therapy (NCT), production of medical and industrial radioisotopes and high-purity semiconductor materials for the electronics industry, and neutron-beam research facilities to meet Thailand's science and education needs.

The second project involves a 2-MW TRIGA Mark II research reactor, with provisions to be upgraded to 3 MW, under construction at the Kingdom of Morocco's National Cen-

Fig. 17. Dry central cavity in annular core pulsing reactor

ter for Nuclear Science, Energy and Technology (CNESTEN) near Rabat (Fig. 22). The center, whose remaining infrastructure has recently been completed, will provide broad capabilities for performing basic research and training in such areas as isotope production, metallurgy, and chemistry. The TRIGA reactor and associated laboratories form the centerpiece of this new facility, which is expected to evolve into a regional center of excellence.

Throughout their 45 years of operating history, TRIGA reactors have demonstrated several common features that have made them so widely used in supporting the peaceful applications of atomic energy. Their simple design, ease of operation, versatility, and safety have made them unique—whether for basic student-type training and isotope production or for advanced scientific research involving sophisticated beam experiments, and also for medical uses such as NCT.

Applications

In the steady-state mode of operation, TRIGA reactors provide much the same research and training capabilities as other types of research reactors. These include neutron activation analysis, radioisotope production, neutron transmutation doping of silicon, and a variety of neutron-beam applications, including neutron radiography and NCT.

Fig. 18. TRIGA conversion reactor at University of Maryland

In addition, however, TRIGA reactors offer the unique and added capabilities to produce pulsed bursts of neutrons. This capability has provided scientists and researchers a wide variety of additional areas of research applications. These have included: studies of biomedical effects in pulsed radiation fields, transient radiation effects in electronic com-

Fig. 19. High-power TRIGA fuel element

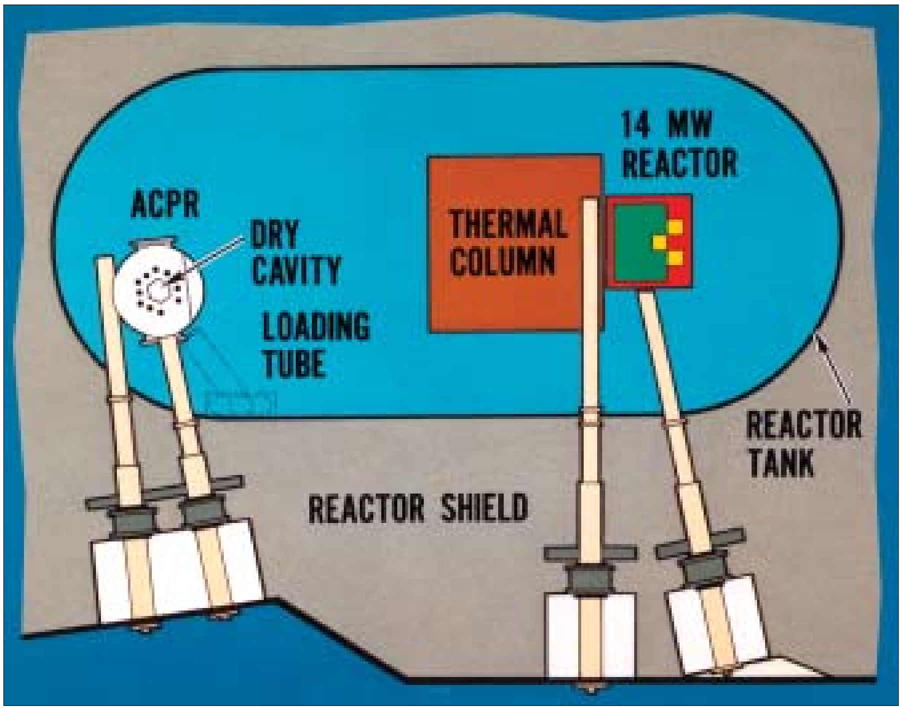

Fig. 20. Reactor pool arrangement showing the 14-MW steady-state and ACPR (annular core pulsing reactor) cores in Romania

Fig. 21. TRIGA multipurpose reactor at Nuclear Research Center, in Thailand

ponents, tests of power reactor fuel under simulated accident conditions, and the production of very short-lived radionuclides for radiochemistry and nuclear physics studies using 500- to 2000-MW pulses.

More recently, the precision in reactor control afforded through the use of digital electronics has allowed pulsing TRIGA reactor designs to offer "continuous pulsing" at power levels reaching 50 MW. The latter would serve in lieu of a pulsed spallation accelerator system as a neutron source for neutron beam applications.

Fig. 22. TRIGA Mark II reactor at National Center for Nuclear Science, Energy and Technology, in Morocco

And what about that original prototype TRIGA reactor at General Atomics in San Diego? In 1997 it was shut down permanently because of its age, but not before it had been designated by the American Nuclear Society in 1986 as a Nuclear Historic Landmark. The citation highlighted its role in pioneering the use of unique, inherently safe capabilities in nuclear reactors.

References

1. Freeman Dyson, "Little Red Schoolhouse" in *Disturbing the Universe*, Basic Books, 1979. NN