History, development and future of TRIGA® Research Reactors

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Abstract. TRIGA® reactors (Training, Research, Isotopes, General Atomics) can be considered to constitute a 'World of their Own' among the large variety of research reactors. Originally conceived and demonstrated in the late1950s, they were constructed all around the world at a rapid pace in the 1960s and 1970s, and while this pace of construction slowed in later years, many of the early ones continue to operate successfully today. As both the front end (availability) and the back end (disposal) of TRIGA fuel became increasingly important to TRIGA reactors, the IAEA took the initiative to invite all TRIGA reactor operators to a dedicated Technical Meeting in Vienna/Austria in November 2013 to discuss important issues and challenges facing the operators, such as utilization, management, technical support, fresh fuel supply and spent fuel options. One of the outcomes of this meeting was the unanimous decision to compile a dedicated TECDOC, describing the history, technology, present status and future perspectives of TRIGA facilities worldwide. This paper aims to be an overview of this publication [1].

1. Historical Background

The TRIGA (Training, Research, Isotopes General Atomics) concept has its origins in August 1955, when a large international conference, sponsored by the United Nations on Peaceful Uses of Atomic Energy, was held in Geneva, Switzerland. One of the two US organizers of that meeting was F. de Hoffman, a nuclear physicist employed by General Dynamics Corporation in San Diego, California, USA. After the conference, de Hoffman persuaded General Dynamics that the time was ripe for commercial development of nuclear reactors and nuclear energy. General Dynamics responded by creating the General Atomic Division in 1956 (now known as General Atomics, GA), with de Hoffman as its first president.

In June of 1956, then General Atomic Division of General Dynamics convened a group of scientists, mostly veterans from the US Manhattan Project and others, to consider the commercialization of nuclear reactors. Three groups were formed, one of which was assigned the challenge of designing a 'safe reactor'. Notable British mathematician F. Dyson, Iranian metallurgist M. Simnad and US weapons specialist E. Teller joined this group. E. Teller was in charge of this group and insistent that a safe reactor must be one that "could be given to a bunch of high school children to play with, without any fear that they would get hurt." Further, that "engineered safety was not good enough" and the reactor fuel itself should have inherent safety characteristics for reactivity insertion events. Over the next two years, experiments with neutron moderation [2] and intense metallurgical work by M. Simnad [3] allowed the group to complete a reactor design, manufacture fuel [4], carry out subcritical measurements, and create a working reactor. The prototype, named TRIGA Mark I, was first taken critical on 3 May 1958 at the General Atomic division's new facilities in La Jolla,

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California, USA. In 1964 [5], full patents on the TRIGA reactor were granted to its early designers.

The idea that control rods could be rapidly removed safely was tested early on. The operator pulled a switch that "pulsed" the TRIGA Mark I reactor to about 1500 MW, returning safely to a modest 500 kW power level immediately thereafter without any human intervention. This special feature is enabled due to the large prompt negative temperature coefficient of reactivity of the $UZrH_n$ fuel, which has been measured on a 'just-critical' system giving results from -3 to -6 × 10^{-5} $1/k\ dk/dT$ over a temperature range from 20°C to 120°C.

Over the years, following the successful, initial demonstration and validation of the concept with the prototype, GA developed and provided larger and more complex reactor designs to accommodate increasingly complex irradiation experiments and requirements. Furthermore, the TRIGA fuel element design evolved simultaneously and with some independence from the TRIGA reactor design. All TRIGA type fuels are inherently safe for reactivity insertion events by virtue of the $UZrH_n$ matrix; however, there are several TRIGA fuel types that differ in cladding, enrichment, weight percent uranium, size, and burnable poisons. 66 TRIGA research reactors (RRs) have been constructed to date in 23 countries (Figure 1), and in 2015, 38 RRs were still in operation. In addition to complete reactors, GA also designed and contracted to supply $UZrH_n$ fuel assemblies to a number of existing reactors that had previously been using other fuel types. Most of these non-TRIGA reactors used fuel in the form of thin plates (which came to be known as Material Test Reactor or MTR fuel), and so the design of the new TRIGA type fuel assemblies had to be adjusted to fit into the existing reactor core structure as a one-for-one replacement, maintaining its inherently safe characteristics.

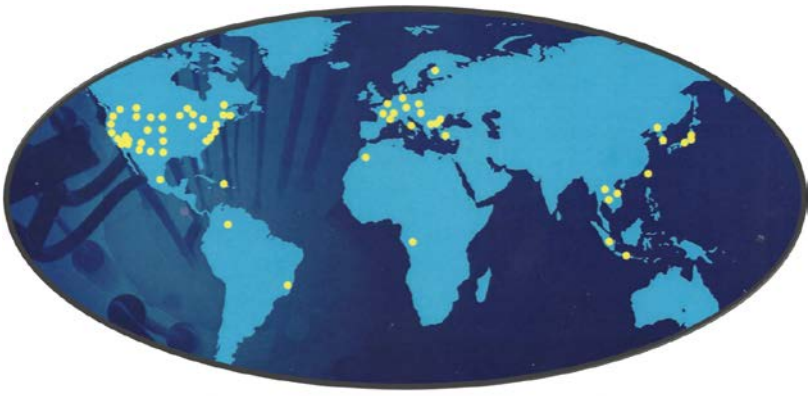

FIG.1. World map of TRIGA installations. Photo: courtesy of General Atomics.

2. Technical Characteristics

2.1. Reactor Designs

General Atomics has developed six research and test reactor designs; all based on the principle of inherent safety for reactivity insertion events utilizing $UZrH_n$ fuels, and all under the registered trademark TRIGA. All designs are open-pool, light-water moderated, using a homogenously mixed fuel moderator fuel element design. Boron carbide is as the neutron absorbing material in the control rods. The various control rod types with different reactivity worth allow the TRIGA reactor to be operated in diverse modes: steady state, square, and pulsed operations. An overview of the different TRIGA RR designs can be found in Table 1.

TABLE 1: TRIGA TYPE REACTORS

	TRIGA Mark I	TRIGA Mark II	TRIGA Mark III/F	TRIGA ACPR	TRIGA MPR*
pool characteristics	underground, aluminium tank, 6.35 m × 1.98 m diameter,	above ground tank surrounded by a concrete shell house, cylindrical dimensions	as TRIGA Mark II, dimensions are 10 × 17 × 8 m tall (outside)	10 × 5 × 9 m tall	10 × 5 × 9 m tall
cooling system	water, natural convection flow	water, natural convection flow	water, natural convection flow	water, natural convection cooling	water, forced convection cooling
core type	below ground, fixed, cylindrical geometry with the fuel elements arranged in a circular or hexagonal geometry	Above ground with same core geometry as Mark I	above or below ground, but moveable core in same geometry as Mark I and Mark II	Above ground, fixed	square shaped, compact, and uses square shaped fuel rod 4x4 or 5x5 assemblies inside the rectangular core structure
reflector	graphite, water	graphite, water	water	Graphite	beryllium
max. power steady-state	18 kW - 250 kW	100 kW - 2 MW	1-2 MW	500 kW	5 - 20 MW (14 MW)
max. power (pulse)	1 MW	6 400 MW	6400 MW	20 000 MW	none
max. accessible neutron flux ($cm^{-2} \cdot s^{-1}$)	thermal 1.6×10^{12}	thermal 8.0×10^{13}	fast and thermal 6.5×10^{13}	max. thermal during pulse 1.0×10^{17}	thermal 2.6×10^{14}
Irradiation facilities	various irradiation facilities in core and ex-core are possible e.g. central dry or wet cavity; other in-core irradiation facilities in fueled locations; and a rotary specimen rack in the graphite reflector	various irradiation facilities in-core and ex-core are possible as in the Mark I, as well as radial and tangential beam tubes and thermal column,	similar to Mark II, as well as large exposure rooms.	central dry cavity,	several experiment regions in-core and ex-core
				one tangential beam tube, one radial beam tube	tangential beam tube, radial beam tubes, silicon doping cavity, multiple experiment positions in reflector.

The TRIGA Mark II reactor is basically an aboveground version of the Mark I reactor with the addition of four horizontal irradiation ports for extended experimental capabilities [6]. A concrete shell houses the core tank and irradiation beam tubes providing both structural support and radial irradiation shielding. The ability to perform irradiation experiments had become the primary function and feature of TRIGA reactors, and GA wanted to enhance this capability. Mark F and III design concepts originated with the Advanced TRIGA Prototype Reactor (ATPR) programme [7]. This particular reactor concept takes elements from previous TRIGA reactor designs to maximize high-energy neutron and γ ray irradiation experimental capabilities [8].

The fixed core Annular Core Pulsed Reactor (ACPR) concept was designed to take maximum advantage of the pulsing characteristics of the TRIGA core. The function of the ACPR is to study the transient behavior of materials to intense radiation for short time durations. While delivering intense levels of radiation the ACPR is still cooled by natural convection from the demineralized reactor pool water. The Multipurpose Reactor (MPR) design is the highest power TRIGA reactor concept ($\geq$ 5 MW steady state power) and departs from many of the traditional core configurations from previous core designs. The configuration is more compact and thus has higher power densities to produce steady state power levels from 5 MW to as high as 20 MW for continuous irradiation experiments [9]. At this writing, the MPR-16 reactor in Romania is the only operating reactor in this class of TRIGA reactors. The MPR-16 and ACPR in Pitesti (Romania) have the unique characteristic of being operated in the same open pool (also known as a dual-core).

2.2. Fuel Element Designs and Variations

Early fuel elements used type 1100F aluminum cladding, which were later discontinued as the thermal power of the reactors increased, in favor of type 304 stainless steel and Incoloy-800 clad designs. During the 1970ties TRIGA HEU fuel with 70% enrichment (FLIP-Fuel Life Improvement Programme) were offered by GA to extend the core lifetime in higher power TRIGA reactors. Other fuel element variations were also developed to perform specific functions in the core. Starting with a basic single rod fuel moderator element (Figure 2a), the first variation added thermocouples within the metal fuel matrix to support fuel temperature monitoring reactor operation. Fueled follower control rods are also available. Other fuel variations, like fuel for annular core pulsing reactors (ACPR), TRIGA 4-fuel rod cluster designs for converting reactors with plate type fuel clusters without changing the core grid (Figure 2b), and smaller diameter 1.37 cm fuel rod clusters for higher power (> 5 MW(th)) TRIGA reactors were designed and marketed for specific reactor designs dictated by user needs. All fuels, regardless of dimensions and geometry, retain the basic inherent safety characteristics of UZrH fuels.

The early fuels had samarium burnable poison discs placed between the fuel rod and the graphite to minimize reactivity changes from ^{149}Sm, fission product build up and ^{235}U burnup. As reactor power was increased, later fuels abandoned the use of such a burnable poison disc in favor of the use of erbium mixed homogenously within the fuel matrix to minimize reactivity changes from ^{235}U burnup in the high density fuels. This also enhances the prompt negative temperature coefficient due to the ^{167}Er resonance peak. All fuels now also include a Mo disc, which is placed between the lower graphite reflector piece and the fuel meat to prevent bonding at higher temperatures between the fuel meat and the lower graphite reflector.

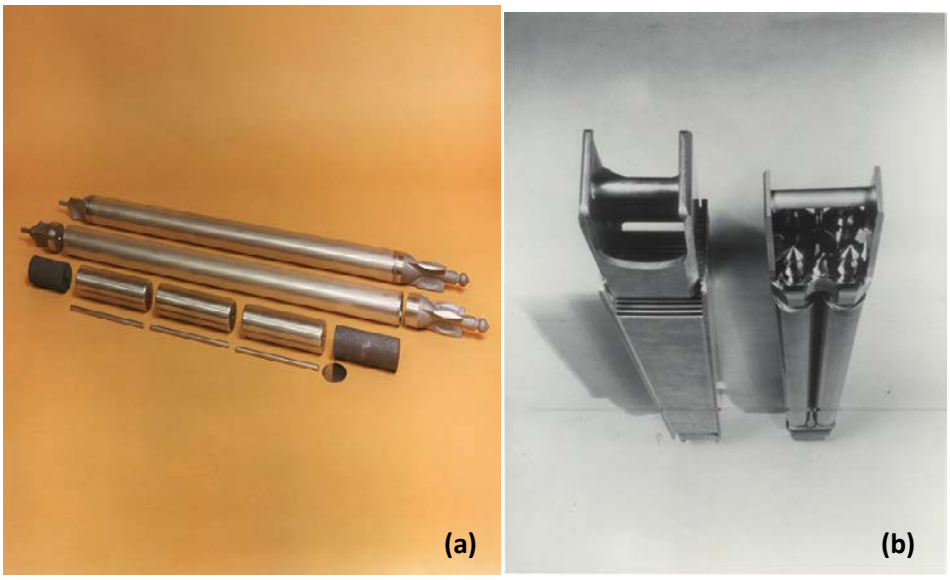

FIG.2. (a) photo, inside a TRIGA fuel element, (b) MTR to TRIGA Conversion Fuel Assembly. Photo: courtesy of General Atomics.

3. Applications

TRIGA reactors are versatile, multipurpose facilities covering diverse areas of utilization and applications [10].

Compared to higher power research reactors, TRIGA reactors with a power level below 2 MW usually have neutron flux densities around 10^{13} $cm^{-2}\cdot s^{-1}$ in the central irradiation position. They offer a number of distinct advantages to a variety of users and for these reasons would be generally described as user-friendly. Among these attractive features of TRIGA reactors one should mention:

- High degree of passive safety: the reactor will shut down on its own due to negative temperature coefficient, and this is of paramount importance for training related applications;
- Ease of operation: a minimum number of restrictions are imposed on the students and instructors (e.g. the control console can be operated safely by inexperienced students after a short instruction time under the supervision of a licensed operator);
- Ease of maintenance: equipment is arranged to provide easy access for maintenance, and components are selected for life and minimum maintenance;
- Ease of experiments for students and instructor: a wide variety of training and research experiments for students can be performed.

TABLE 2: OVERVIEW OF TRAINING FOR SCIENTISTS AND OPERATIONAL PERSONNEL UTILIZING TRIGA RR [10, 13]

Training of Physics Students	Training for Non-Physics Students and Researchers	Training of Reactor Operating Personnel
nuclear radiation measurements	archaeometry;	fuel loading and unloading;
reactor theory in neutron transport	biological applications;	approach to criticality;
reactor kinetics and reactor dynamics;	chemical applications;	effects of prompt and delayed neutrons;

Training of Physics Students	Training for Non-Physics Students and Researchers	Training of Reactor Operating Personnel
reactor operation and control, also by using associated computers;	earth sciences;	poisoning effects (xenon, samarium);
criticality and power increase of the reactor;	environmental sciences;	temperature effects;
relative and absolute flux measurements;	medical applications;	reactivity effects;
reactivity measurements;	metallurgy;	load variations;
control rod calibration;	industrial applications;	instrumentation and calibration;
temperature coefficient measurement;	forensic applications;	flux and power measurements;
poisoning effect measurement;	radiation detector.	reactor kinetics and dynamics;
neuron spectrum measurement;		radiation protection;
void coefficient determination;		radiochemistry.
radiation protection and shield measurement;		

Furthermore, there are mainly three RR based techniques in basic and applied research with growing significance neutron activation analysis, non-destructive testing by neutrons (as neutron radiography), and production of short-lived radioisotopes. Practically all fields of natural sciences and technology, especially medicine, biology, chemistry, geology and metallurgy, can be served by these procedures.

Applications of TRIGA RRs are varied and cover most of the products and services RRs can possibly provide [10-12]. Below some selected examples of using extracted neutron beam are explained in more detail. Cold, thermal, or epithermal neutron beams extracted through reactor beam tubes can efficiently be used to study:

- Neutron scattering (small-angle neutron scattering, diffraction, residual stress measurements, neutron interferometry, neutron reflectometry, neutron spin echo, etc.) [10, 13];
- Neutron radiography (or neutron imaging) [10, 14-15];
- Large sample neutron activation analysis; [10, 16]
- Prompt gamma neutron activation analysis [10, 17];
- Boron neutron capture therapy [10, 18-19].

4. HEU-LEU Conversion

This chapter deals with the HEU–LEU conversions of TRIGA type reactors, both of MTR reactors to UZrH fuel, as well as under the US Government's Global Threat Reduction Initiative (GTRI). In the United States, Title 10 of the Code of Federal Regulations, Section 50.64, requires non-power reactors to replace all highly enriched uranium (HEU) fuel (i.e. fuel with > 20% enrichment) with low enriched uranium (LEU) fuel (i.e. fuel with < 20% enrichment) acceptable to the US Nuclear Regulatory Commission (NRC). In addition to nine US-Reactors, nine non-US TRIGAs (and additional non-TRIGA research reactors) have been converted in the past years.

Different principal parties beside the reactor owner and the reactor vendor (GA) can be involved to provide significant technical support. As example the IAEA aided the conversion of the IAN-R1 in Bogota, Colombia, by international experts, including overall project management support, review and acceptance of the safety analysis report (SAR), inspection and acceptance of as-manufactured fuel assemblies, installation of auxiliary equipment, and fuel loading and commissioning operations by the reactor vendor. In other cases the conversion process was typically carried out by the host institutions with assistance from various US national laboratories, General Atomics, TRIGA International and the USNRC.

Consequently, for each step careful planning and rehearsal was needed especially for the shipment of spent nuclear fuel (SNF), which is not a routine occurrence for most research reactors. Therefore, experts who have experience in this procedure are invaluable for personal observation to compensate the lack of institutional knowledge.

5. Ageing Management

As the majority of operational TRIGA research reactors are more than 45 years old, ageing management of these facilities becomes crucial in order to continue their operation. This chapter describes the different challenges in ageing management and important tasks to address ageing related safety concerns [20-23]. An important task to determine ageing related effects is the periodic visual inspection of the reactor tank internals, the periodic inspection of the fuel elements in elongation and bowing (with specific requirements usually incorporated into the reactor license), and the regular cleaning of the primary water system.

Within the TRIGA community a continuous information exchange and mutual support exists to share both operation experience and development of new methods for maintenance and inspection. Together with a strong in-service inspection programme, TRIGA reactors around the world can be kept in an excellent operational state without any major ageing effects. It is hoped that with proper ageing management, many of the TRIGA reactors will safely and efficiently operate for many more years.

FIG.3. With the evolution of desktop computers, PC based I&C systems were introduced and various designs continue to be in use today. Photo: courtesy of General Atomics.

TRIGA reactors constructed during the 1950s and early 1960s were all equipped with vacuum tube type instrumentation & control (I&C) systems. Due to the fast development of transistor technology and increasing requirements by the nuclear regulatory institutions during the late 1960s and 1970s, I&C suppliers offered improved I&C system based on solid state technology. Many TRIGA reactors around the world then converted to this type of I&C

systems. Finally in the 1980s digital electronics also triggered a new generation of I&C reactor systems which were commercially offered by early 1990s and continued into the next decade (Figure 3). Some of the TRIGA reactors then converted their I&C system a third time as technology improvements in hardware and software offered greater operational flexibility, efficiency and data management features. These digital systems usually had a full hard-wired safety system as back up, as the regulatory authorities were wary of using a digital system to perform safety functions, as the software verification and validation was always in question. Even these digital &C systems installed in the 1990s have reached a point where, due to obsolescence of key components, operators have to consider upgrades to current digital technology.

6. Issues and Challenges

Challenges of research reactors, including TRIGA RRs, may change over time, but some generic issues will always be present. Besides individual challenges of facilities (e.g. ageing management, refurbishment projects, enhancement of utilization, etc.), there are three main issues which are faced by many TRIGA RRs:

- continued supply of TRIGA fuel in the long term due to lack of sufficient demand to justify the costs of operating a dedicated fabrication facility,
- back end options related to the spent nuclear fuel return to the country of origin programme (2016/2019 deadline for non-US located reactors),
- as demand for new research reactors continues to decrease and the workforce ages, there are valid concerns about continuing technical support at a high level from the original reactor designer/manufacturer.

To evaluate the present situation of operational TRIGA research reactors and estimating future needs of fuel in the next 5 years, the IAEA has prepared and sent out a specific questionnaire to the operational TRIGA RRs. Unfortunately, there are research reactors where the fuel is needed now, and they have been operating their facilities at reduced power/cycles. For supporting those countries, a future challenge might be to transfer fuel from one country to another. But it has to be taken into account that not all reactors use the same type of fuel as well as some countries might have restrictions to import the fuel from fuel non-originating countries. So the availability of unused fuel may not meet the needs of all facilities. Finally, the concern about lack of a fresh fuel supply can be alleviated as soon as there is sufficiently quantified demand, with clear commitment from TRIGA community, to make a clear business case for continued operation of a fuel fabrication factory. The US DOE has announced that its spent nuclear fuel programme to repatriate US origin fuel will cease in 2016/2019. All fuel to be returned must cease irradiation in May 2016 and all return shipments must be completed by May 2019. The non-US TRIGA community is thus facing the challenge to find a final storage for several thousands of spent fuel elements or cease operations by 2016. Since IAEA is fully aware of this situation, regional solutions, by mutual agreement, may be able to be accomplished. However, the available time is running short, and therefore requires coordination followed by immediate steps to be taken by all involved parties. One of these networks is the Global TRIGA RR Network (GTRRN) which has established their goals in order to:

- Strengthen regional and global cooperation among TRIGA facilities toward the development of solutions for common issues and challenges, including fuel front-end and back-end options;
- Enhance TRIGA reactor utilization through common and complementary products and services as well as exchange of experiences and practices;

- Increased viability and visibility of TRIGA reactor operation in the future through contacts and effective relationships with national and international stakeholders.

7. Conclusion

The basic incentive in undertaking the preparation and publication of this document was to collect in a single IAEA source, historical information on the legacy of TRIGA technology, its foundations, history and continued development of TRIGA reactors over the last half a century. In addition, information on specific topics such application and utilization, ageing management, core conversion and other fuel issues, present challenges and future perspectives of TRIGA research reactors worldwide is presented. It is expected that it is going to be a useful source of information for much broader stakeholder community than just representatives of TRIGA reactors themselves. Finally, to obtain a wider perspective on the operation of TRIGAs worldwide through individual facility examples and experiences, a number of individual country contributions were collected and have been included in the attached CD-ROM.

8. Acknowledgements

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