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RSV TAPIRO and TRIGA RC-1 research reactors activities☆

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ABSTRACT

Neutrons produced by research reactors have an important role in the development of nuclear science and technology and also in education and training on these applications.

These facilities, originally constructed during the '60 s and '70 s decades, were initially used for the national nuclear program, then their original mission was converted to host the activities correlated with the neutrons and gamma radiations.

The increasing interest in neutron radiation damage analysis, due to the very qualified energy spectrum of these types of reactors, allowed the ENEA research reactors, RC SV TAPIRO and TRIGA RC-1, to be used for different R&D areas.

In this paper, the main characteristics and the most relevant applications of these two reactors carried out during their life operations have been fully described.

1. Introduction

Research reactors produce neutrons for use in industry, medicine, agriculture and forensics, among others. They play an important role in the development of nuclear science and technology. They are also important tools of advanced education and training on nuclear technology for energy and other applications.

They were originally used for basic research, radioisotope production, neutron scattering and radiography, and material characterization and testing.

The original mission of these facilities, in many cases constructed in the 60 s and 70 s decades, has been abandoned, as in the case of Italy because the nuclear program was dismissed. Nevertheless, such research reactors represent a unique occasion for young generation scientists to appreciate the wide possibilities of utilization of reactors by-product, which is neutrons and gamma radiation.

Furthermore, research reactors have been always considered as a powerful tool to investigate the effects of neutron radiation damage on a wide class of structural components of interest for both research and industrial applications. Depending on the damage level demanded after irradiation, high power or low power research reactors are usually selected as radiation fields.

There is an increasing attention also towards low power research reactors for neutron radiation damage analyses, essentially because they can provide very qualified, in terms of both intensity and energy spectrum, neutron radiation fields, being such characteristics very useful for irradiation of electronic components and/or innovative neutron detectors.

The ENEA low power fast spectrum TAPIRO research reactor and thermal pool TRIGA RC-1 reactor, located in the Casaccia Research Centre near Rome, are very unique facilities and also the two of the three research reactors in operation in Italy.

Despite their low nominal power characteristics, TRIGA RC-1 and RSV TAPIRO have been used in many of the activities mentioned above during the last decade, thanks to their neutron spectral features and the diversity of their experimental irradiation channels, as described in the paper.

RSV TAPIRO is a unique facility completely designed by ENEA staff and represents a reference reactor for the IV generation fast reactor design also because it is the last fast reactor in operation in Western Europe.

This paper describes the main characteristics of the RSV TAPIRO and TRIGA RC-1 ENEA research reactors and their utilization during their life operations, focusing on the most relevant applications and research programs carried out during this time period.

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2. The TAPIRO reactor

TAPIRO (TAratura PIla Rapida a Potenza 0) is a fast neutron source reactor licensed in 1971 for a maximum thermal power of 5 kW (Musso et al., 1969).

The project, entirely developed by ENEA's staff, was based on the general concept of AFSR (Argonne Fast Source Reactor – Idaho Falls). Since 1971, it has been used for fast reactor shielding experiments, biological effects of fast neutrons, electronic component neutron damage, etc.

The reactor core is made of several disks of high enriched uranium–molybdenum alloy (98.5 % U, 1.5 % Mo in weight). As well know, the addition of molybdenum stabilizes the gamma phase of uranium and increase the melting point of the fuel. The disks are assembled in three parts each one with a 0.5 mm thickness stainless-steel clad. The complete assembly has a cylindrical shape with about 6 cm of radius and 11 cm of height. Two core parts constitute two-thirds of the fuel mass and are fixed to the upper part of the reflector by a stainless-steel cage, whereas the remaining part is movable and is 1.5 m below the fixed parts at the shutdown. The movable part is placed inside a stainless-steel cage on a copper cylinder, forming the so-called "safety plug". An electrical motor and a rack pinion system move the safety plug inside a vertical guide tube from the shutdown position up to the bottom surface of the fixed core assembly to reach the criticality mass. Furthermore, the safety plug can lead the reactor to a very low subcritical level when two pistons powered by compressed air push it down.

The reflector is made of copper and is divided into two concentric blocks: a 10 cm thick inner block is contained inside the primary cooling system, and an outer block is about 20 cm thick. In the design phase, the choice of material to be used for the reflector was made based on the Los Alamos report LA-1958. In this report, the neutron reflection efficiency of Aluminium, Iron, Nickel, Copper, and natural Uranium reflectors coupled with a spherical core of 90 % enriched uranium were compared, and copper was the best choice in terms of activation, cost, procurement, etc.

Finally, a borate concrete shielding about 170 cm thick surrounds the reflector and guarantees a dose rate in the reactor hall below 10 μSv/h at the maximum power.

For a thermal power greater than 50 W, the core is cooled using forced helium circulation with a flow rate of 100 g/s at a pressure of 6.5 ata. At the maximum power of 5 kW, the cooling system can maintain the difference between the inlet and outlet helium temperatures below 10 °C.

The reactor is controlled by five copper control rods of 15 mm length positioned in as many vertical cylindrical cavities inside the inner reflector. The control rods can be moved in those cavities, modifying the amount of copper reflectors and, consequently, the fission rate inside the core. In fact, inserting a control rod increases the number of neutrons reflected to the core and reduces the neutron leakage through the empty portion of the reflector cavity; the opposite occurs when the rods are withdrawn. Two safety rods and the safety plug can singularly make the reactor subcritical and bring the reactor into safe condition. The criticality is reached by the regulating rod that controls the power level with the amount of rod insertion. Finally, two shim rods compensate for the lack or excess of neutrons caused by the dimensions, compositions, and position of the samples inserted in the irradiation channels.

The reactor state is constantly monitored during the operation, measuring several operational variables, some of which are connected to the reactor safety system. The most important are the neutron production rate, the core and helium temperature, the helium flow rate and pressure, and the radiological conditions in the reactor hall, like the gamma dose rate, radioactive particulate, and ^{131}I concentration in the air. Some of those measurement systems are redundant; for example, the neutron production rate measurement is constituted of two start-up and power channels.

The reactor is equipped with 6 main experimental channels (4 horizontal and 2 vertical channels) and a large cavity, labelled thermal column (parallelepiped 110 × 110 × 160 cm^3), see Figs. 1 and 2. One mid-plane channel crosses the core allowing irradiations of small samples (∼ 1 cm) in an almost pure ^{235}U fission spectrum. In the thermal column a more energetic neutron spectrum is realized removing a 60° sector from the outer reflector.

The irradiation channels (see Fig. 2) allow to insert devices also in high flux regions. They are enclosed in a metallic jacket and have a reducing section toward the core to limit the dose rate in the reactor hall. Each channel plug is constituted by a casing filled with shielding material and a copper extension placed in the reflector zone. The samples are placed in a holder, generally made of aluminium, and fixed to the channel plug using a modified copper extension.

At the maximum thermal power of 5 kW, the total core integrated neutron source strength is of ≈ 3 × 10^{14}n/s that is equivalent to a total neutron flux of ≈ 4 × 10^{12}n/cm2/s at the core center and a total neutron flux of about 1.3 × 10^{10}n/cm2/s at the entrance of the thermal column. A list of some neutron characteristics and the maximum size of different channels are reported in Table 1.

The dimension of the channels constitutes a limitation for the maximum sample size and, together with the neutron flux intensity and neutron energy distribution, represent the three main constraints in the feasibility of neutron irradiation. The low thermal and epithermal component in the neutron energy distribution is present in almost all the channels, see Table 2, and constitutes a strength of the TAPIRO reactor that makes its use suitable for all those applications with fast neutrons. Furthermore, utilizing material with the properties of reducing the neutron energy makes available a wide range of neutron spectra, even if the flux intensity is expensive.

3. The TRIGA reactor

TRIGA RC-1, located at ENEA Casaccia Research Center, is a 1 MW thermal pool reactor based on the General Atomic TRIGA Mark II reactor design, built-in 1960 (Di Palo et al., 1966). It is a light water reactor cooled by water natural convection. The core consists of an annular structure (Fig. 3) arranged in a honeycomb-like array, forming an annulus with six coaxial cylindrical rings of fuel elements. The core, surrounded by the graphite reflector, is contained in an aluminium vessel (190.5 cm diameter), seven meters deep, filled with demineralized water. The core and the reflector assemblies are located at the bottom of this vessel; the core is shielded by about 6 m of water above, and the cylindrical graphite structure around the core is the lateral reflector of the reactor. The core consists of a lattice of fuel elements, graphite dummy elements, and control and regulating rods. There are 127 channels divided into seven concentric rings (from 1 to 36 channels per ring; see Fig. 3). The channels are loaded with fuel rods, graphite dummies, and control or regulating rods depending on the experimental campaign and the power level required. One channel generally houses the Am-Be start-up source, while two fixed channels (the central vertical channel and another one) are available for irradiations or other experiments. The central position of the core (position A) usually is not used for a fuel element but as an irradiation channel filled with water or air. So, the first ring loaded with fuel is the second one (ring B). Reactor control rods in the current configuration are located in the third ring (positions C4, C7, and C10 (see Figs. 3, 4). The fine regulation rod is a peripheral one and is located at F1. The amount of reactivity controlled is concentrated in the three shim rods. Table 3 shows the integral reactivity associated with each rod.

The pitch of the core elements is 4.05 cm, and the mean ratio fuel/water is 0.635/0.365. The actual configuration is composed by 111 standard TRIGA fuel elements.

Changes in the reactivity due to the movement of control rods are limited by specific functions of the reactor safety system. The reactor period must be less than 50 s and to ensure this limit the protection system is equipped with an alarm corresponding to the 90 % of the scale

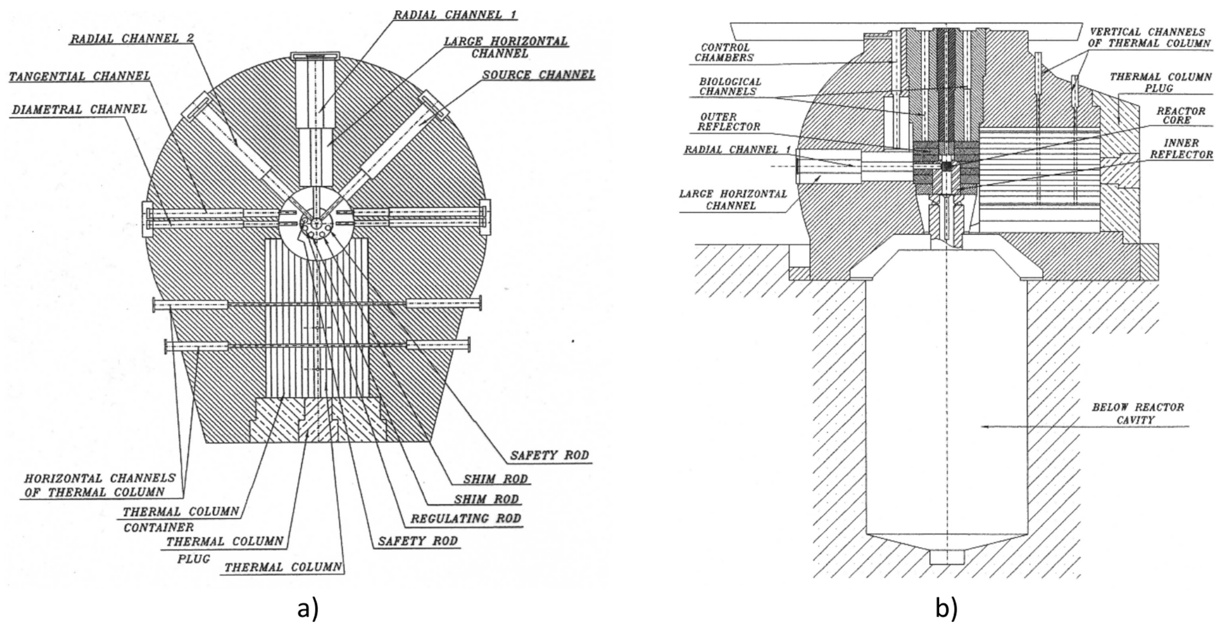


Fig. 1. Horizontal a) and vertical b) drawing sections of the TAPIRO research reactor with the indication of the irradiation channels (Musso et al., 1969).

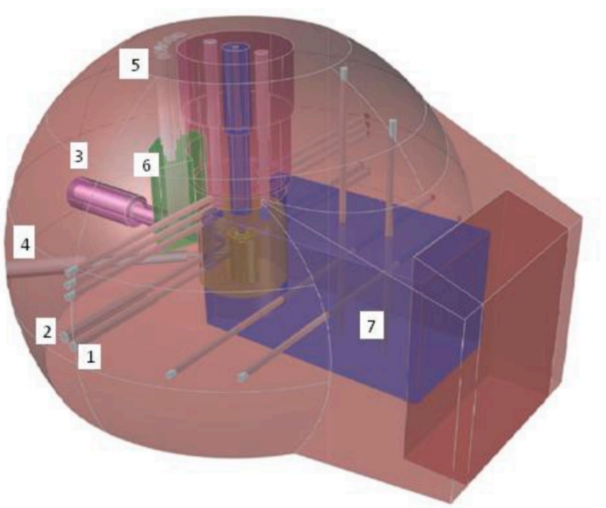


Fig. 2. Irradiation facilities of TAPIRO (Musso et al., 1969): 1) diametral channel; 2) tangential channel; 3) radial channel 1; 4) radial channel 2; 5) detector channels; 6) paraffin; 7) thermal column.

Table 1
Some neutron characteristics of the main irradiation positions.

Irradiation position	Maximum diameter (cm)	Neutron flux (1/cm^2/s)	Average neutron energy (MeV)
Diametral (central position)	1	$2.9 \cdot 10^{12}$	1.25
Tangential (central position)	3	$9.1 \cdot 10^{11}$	0.54
Radial channel 1 (innermost position)	5.6	$8.2 \cdot 10^{11}$	0.55
Radial channel 2 (innermost position)	8	$1.5 \cdot 10^{11}$	0.18
Thermal column (maximum flux position)	Volume of about 2 m^3	$1.3 \cdot 10^{10}$	0.08

Table 2
Percentage fraction of the neutron energy distribution in the classical four energy subdivisions for the main irradiation channels.

Irradiation position	% of total neutron flux			
	Thermal 0 – 0.1 eV	Epithermal 0.1 eV – 1 keV	Fast 1 keV – 1 MeV	High 1 MeV –10 MeV
Diametral (central position)	0	0.018	59.6	40.4
Tangential (central position)	0	0.57	86.2	13.3
Radial channel 1 (innermost position)	$1.2 \cdot 10^{-6}$	0.64	85.8	13.6
Radial channel 2 (innermost position)	$2.2 \cdot 10^{-4}$	3.7	94.6	1.7

of the instrumentation measuring the thermal power. The start-up channel and the linear channels operates having this safety protection. From the point of view of the safety, the reactivity for an operating core configuration is also limited by some prescriptions. The parameter measured in this case are: the shut-down margin, the reactivity excess, the maximum value of the total reactivity available with control rods and the rate of change of reactivity associated with each control rod. Table 4 summarize this operation limits and show the current value for the operating core configuration.

These limits must be verified periodically as a function of the core changes due to core reconfiguration, refuelling for example, or due to fuel burn-up.

The biological shield is provided by concrete with an average thickness of 2.2 m. The water inside the vessel provides first biological shield, neutron moderator and cooling mean.

TRIGA RC1 cooling system is composed of two thermohydraulic loops: a primary loop circulates the water from the pool to two heat exchangers, and a secondary loop circulates the water from the heat exchangers to two cooling towers. The primary loop is complemented by a purification loop, derived from the primary loop, containing the instrumentation devoted to the measure of the water. Temperature, conductibility, activation, and flow rate are the four parameters measured to define the working point of the cooling system and ensure the safe operation of the reactor itself. The purification loop is equipped with a component working by means of purification resins. The heat is

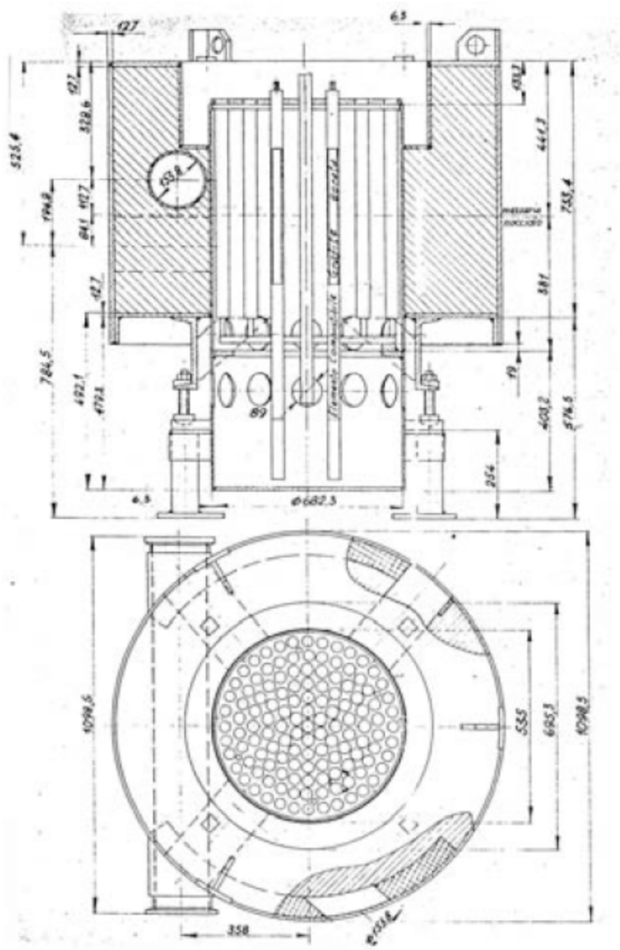


Fig. 3. Schematic view of the reactor assembly (from (Di Palo et al., 1966).

removed from the core by natural circulation.

The cooling system is operated by three pumps on the primary and secondary loop and two on purification. For each section of the cooling system, one of three pumps is a backup, so the total flow is ensured by two pumps on the primary and secondary loops and one on the purification one. The value that corresponds to an acceptable, by prescription, working condition is $Q = 86\ m^3/h$ on the primary with a corresponding $Q = 2.6\ m^3/h$ on the purification (subsection of the primary) and $Q = 180\ m^3/h$ of the secondary loop.

Fixed the flowing conditions above described the temperature gradient along the vertical axis of the core, due to the spatial distribution flux, causes a flow from bottom to top of the fuel element, generating a core output water flow, by design, of about 67 °C at 1 MW. The mean temperature of the pool water at the maximum power must be less than 50 °C. This limit is imposed by the maximum temperature of the ion resin exchangers of the purification loop. Temperature is also measured at six points of the entire cooling circuit: pool. Inlet and outlet of the first heat exchanger (primary and secondary section), Inlet and outlet of the second heat exchange (secondary and primary section), purification loop, cooling towers. The heat exchangers have been designed in order to remove 1 MW of thermal power, and at a stable operation power level of 1 MWth, the system has a $\Delta T = 10$ °C.

The safety system of the reactor relates to warnings and alarms generated by the cooling system. Considering the water level in the pool as the first parameter monitored by the control room, a two-levels alarm is implemented using an instrumentation in console that measures the water level in term of the percentage of the full tank, corresponding to the 100 % of the instrumentation scale. The warning signal is generated if the water level is less than 60 % whereas the "MINIMUM LEVEL" alarm is caused by a water level less- equal to 30 %. The warning doesn't cause a trip of the reactor system, but just a signal for the operator. The alarm, on the contrary, causes a SCRAM signal for the prompt reactor

Table 3
Integral values of the control rods reactivity (¢).

Safety	Shim 1	Shim 2	Regulation
421	368	348	78

Table 4
Safety operation limit for TRIGA RC-1.

	Shutdown margin (¢)	Excess of reactivity (¢)	Max reactivity velocity insertion (¢/s)	Regulation rod reactivity (¢)
Prescribed value	> 71	< 643	< 10	< 92
Value measured	284	512	4.91	78

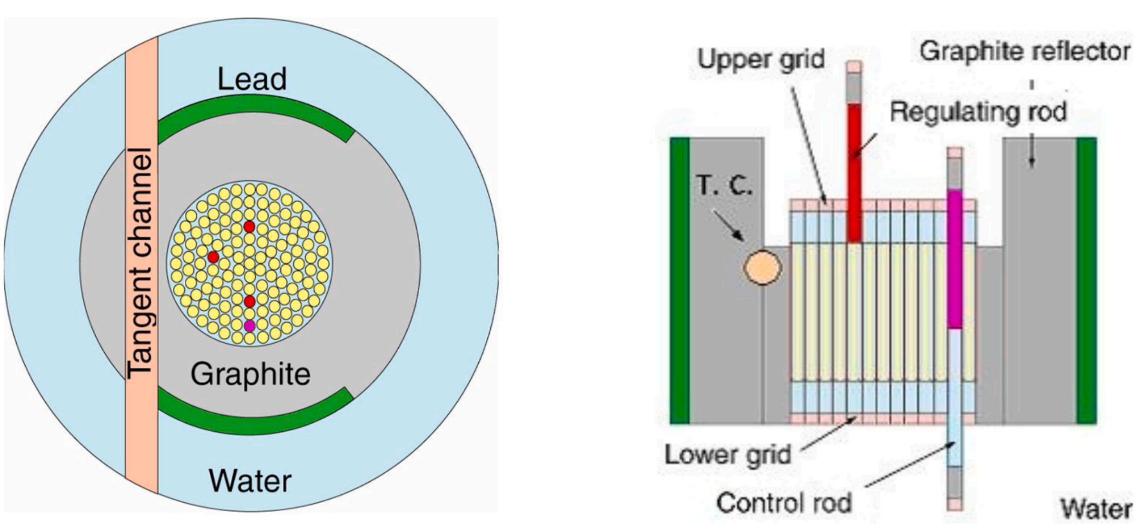


Fig. 4. Vertical section of the core and standard configuration.

shutdown. A “MINIMUM LEVEL2 is associated with a LOCA and can be caused by the damage to the tank or to a tube of the cooling system. The warning, if related to a stable water level is not classified as a safety event but can be related to a heavy evaporation of the water. Due to the design of the TRIGA RC1 a normal operation of the reactor at 1 MW can cause the lowering of the water that must be refilled. This operation is a routine procedure for the staff. With the aims of re-filling the reactor pool in any condition, TRIGA RC1 is served by two circuit the first working in normal conditions and the other in emergency conditions (LOCA).

During the last year the pumping system of the primary and purification loop have been substituted due to obsolesce and ageing of the installed components.

The horizontal section of the core with graphite surrounding the core, a detail of the core with fuel elements, control rods and graphite dummies elements are shown in Fig. 4. In Fig. 5 the horizontal and vertical section of the reactor are shown, together with 3D section of the reactor with neutron channels.

The diameter of the core is about 56.5 cm while the height is 72 cm. Neutron reflection is provided by graphite contained in an aluminium container which is surrounded by 5 cm of lead acting as a thermal shield. An empty aluminium tube (15 cm diameter and 0.6 cm thick) traverses the graphite reflector tangentially to the reactor core for thermal flux irradiations.

The reactor is controlled by four boron carbide rods: three, stainless steel cladded, are fuel follower type (two shims and the safety rods) whereas the last, aluminium cladded, is the regulation rod.

The reactor is monitored by a starting channel, two wide range linear channels, and one safety channel. One logarithmic channel operates between 10 W and 10 MW. Three X, γ monitors, two monitors for α and β contamination, and one for gaseous contamination of the air extracted from the reactor hall and radiochemical lab ensure complete information about the radiological situation in the plant and relative laboratories.

In Fig. 5 it is possible to identify the experimental channels used for neutron extraction. Other irradiation facilities are the Lazy Susan, the pneumatic transfer system and the central thimble.

The TRIGA fuel elements, cylindrically shaped and stainless-steel cladding (AISI 304 – thickness 0.5 mm), are characterized by an external diameter of 3.73 cm and a total height of 72 cm end cap included (Fig. 6). The fuel is a cylinder (38.11 cm high, 3.63 cm external diameter, 5.9 g/cm^3 theoretical density) of a ternary alloy of H-Zr-U with a metallic zirconium rod inside (38.11 cm high, 0.5 cm in diameter, 6.49 g/cm^3 of density. The alloy contains 8.5 % by weight uranium 20 % enriched in ^{235}U. The average weight of a fuel element is approximately 3.4 kg with an average content of 38 g of ^{235}U. The metallurgic alloy's stability is related to a variation of the total number of atoms less than 1 %: the ternary mixture ensures that also in case of total burn up, in

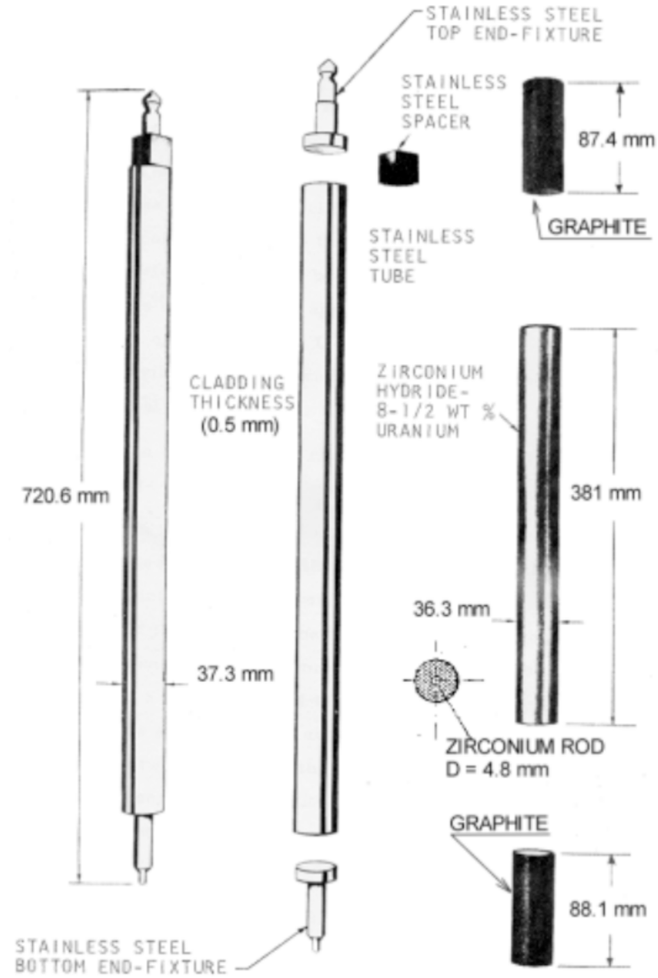


Fig. 6. Fuel element details.

theory, of the whole ^{235}U present in the fuel element (about 38 g for element) the total atom variation in the alloy should be less than 0.7 %. Another feature regards the prescription that forces the removal of elements from the core if their burn up is higher than 35 %: this is a condition linked to the U-ZR-H lattice properties.

Two graphite cylinders (8.7 cm high, 3.63 cm in diameter, 2.25 g/cm^3 of density) at the top and the bottom of the fuel rod ensure the upper and lower neutron reflection. The fuel element is provided externally with two fittings to allow remote movements and the correct placement of the grid plates. Fig. 6 shows the fuel elements details.

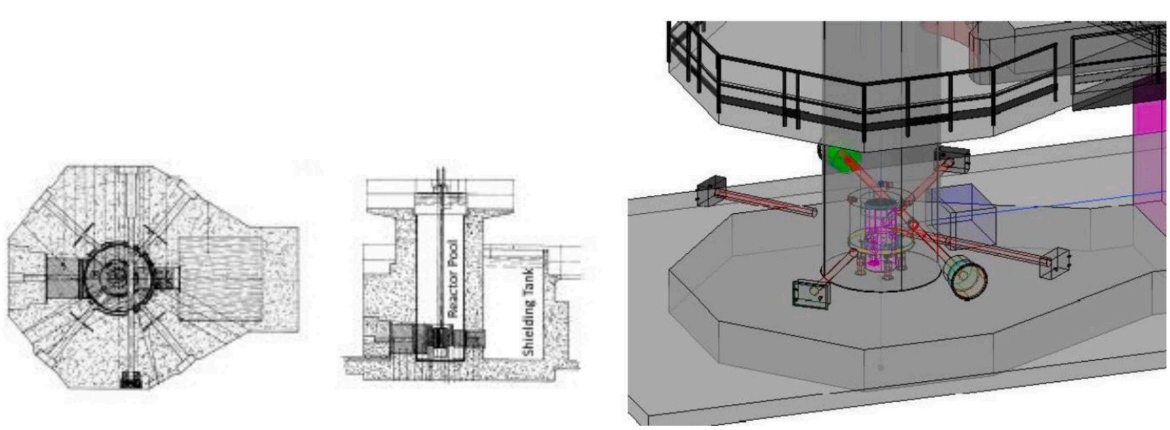


Fig. 5. Horizontal and vertical section of RC-1 research reactor and neutron channels.

In Table 5 the main characteristics of the TRIGA RC-1 elements are given.

The regulation rod has the same morphological aspect as the fuel rod: the only difference is that instead of the mixture of the ternary alloy uranium–zirconium-hydrogen there is the absorber (graphite with powdered boron carbide); naturally the inner Zr cylinder is not present. The control rods are "fuel followed": the geometry is like that of the regulation rod with the bottom graphite cylinder replaced with fuel. The graphite dummies are like the regulation rod but without boron inside the central volume.

From the point of view of the utilization, the reactor is mainly utilized for training, flux measurement and irradiation of neutron detectors, radioisotope studies and damage study for aerospace.

RC1 is equipped with various irradiation facilities, many of which very common for a low power TRIGA reactor, that can be classified in "in-core" and "ex-core" positions providing a wide range of neutron and gamma spectra and intensities. Different irradiation positions influence also the volume available for the sample, being true that "in-core" positions set a limitation on the sample dimension (less 3 cm of diameter), but ensure a higher neutron intensity and a harder neutron spectrum. On the other hand, "ex-core" positions, out of the biological shield, as an example, allow less limitation on sample dimensions, but have a heavier contribution to the non-collimation of the neutron beam and an energy degradation of the neutron energy.

TRIGA RC-1 irradiation facilities, show in Fig. 5, are characterized by a shape, a geometrical dimension and a neutron flux. This last parameter, in the present work, correspond directly to the maximum thermal power of RC1, that is 1 MW. A synthesis of the irradiation capability is shown in Table 6. The green items represent the "ex-core" capability, while the yellow items represent the "in-core".

Neutron flux values correspond to a specific position for each facility. For the "ex-core" the value is referred to the closest position, respect to the core. The values for the "in-core" position are otherwise associated with the middle plane of the specific facility of irradiation. Measurements have been performed by means of metallic foils and the specific position are better highlighted in Fig. 7.

Channel of the "ex-core" group have also been evaluated by means of a MCNP simulation with the aims of trying to characterize them from the point of view of:

ü the neutron flux in a different position respect to the core
ü The neutron energy spectrum

The complete MCNP model of the TRIGA RC1 (L.Falconi et al. 2016) research reactor has been implemented with a detailed view of the irradiation channels. The model with the reference points for the evaluations is shown in Fig. 8.

The points, shown in Fig. 8, have been selected with the aims of:

ü have a comparison between experimental and evaluated data
ü have a provision for the outermost points, having not yet a corresponding experimental measurement.

Table 5
Main characteristics of the TRIGA RC-1 elements.

Nominal fuel density (g/cm^3)	5.8
U weight	8.50 %
Enrichment ^{235}U	20.00 %
Atomic ratio H/Zr	1.7
Internal Zr rod diameter (cm)	0.5
Fuel diameter (cm)	3.63
Clad thickness (cm)	0.05
Element active length (cm)	38.11
Elements pitch (cm)	4.054
Water associated to each element (cm^2) (*)	6.28

(*) For the central element the associated water is 1.98 cm^2.

Table 6
TRIGA RC1 irradiation facilities.

Facility	Neutron flux (ncm^{-2}s^{-1})	Cd (*) ratio	Shape	Dimension (mm)
A-Radial Channel	4.8 10^{12}	≈ 2.2	Cylindrical	$\varphi_{int} = 152$
B-Radial Channel	4.3 10^{10}	≈ 3	Cylindrical	$\varphi_{int} = 152$
C-Radial Channel	4.3 10^{10}	≈ 3	Cylindrical	$\varphi_{int} = 152$
D-Tangential Channel	5.4 10^{10}	≈ 10.4	Cylindrical	$\varphi_{int} = 152$
Tangential Piercing (TPC)	2.2 10^6	≈ 1	Cylindrical	$\varphi_{int} = 180$
Thermal Column Horizontal Channel	2.2 10^6	≈ 3.2	Cylindrical	$\varphi_{int} = 40$
Central Thimble	2.68 10^{13}	≈ 1.8	Cylindrical	$\varphi_{int} = 34$
Rotary Specimen Rack	2.0 10^{12}	≈ 2.7	Cylindrical- 40 positions	$\varphi_{int} = 32$
Rabbit (pneumatic transfer tube)	5.1 10^{12}	≈ 2	Cylindrical	$\varphi_{int} = 14$

(*) Cd is the Cadmium ratio.

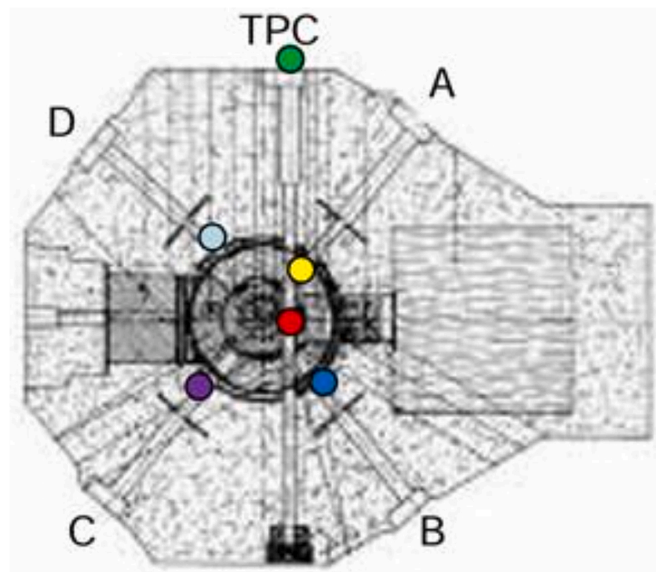


Fig. 7. Irradiation channels measure points.

Results of the MCNP simulation are shown in Table 7- 10.

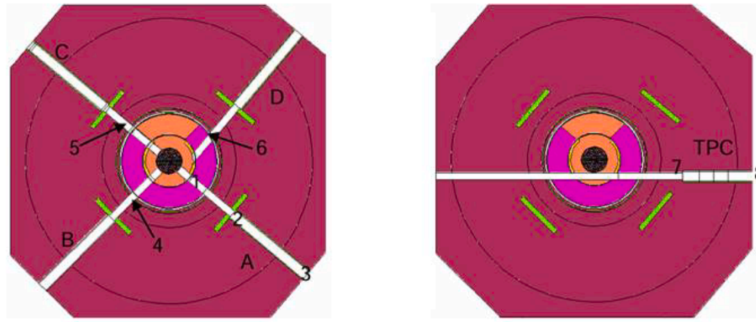
The disagreement between experimental to calculated value can be addressed by means of different causes, but mainly the uncertainty on the available experimental data is an important one. Data are referred to measurements performed in the 80 s and with a fully different core configuration. The innermost position depends on the core configuration and core burn-up.

As a further information, Table 11 represents the percentage of the neutron population for each of the energy intervals chosen to describe the neutron flux.

During the last year, some upgrades have been scheduled and will be installed during 2025 regarding:

ü The environmental monitoring system
ü The nuclear instrumentation devoted to the power monitoring
ü The main console used to operate the reactor

The new monitoring system has been designed in order to integrate all the detectors monitoring the environmental X and gamma field, the gaseous contamination of the air and the water radioactivity. The system allows to increase the HMI into the Control Room giving an immediate information of the reactor status to the operator. The system is also



(*) TPC – Tangential Piercing Channel

Fig. 8. MCNP tally evaluation points.

Table 7
TRIGA RC1 Radial channel A evaluated fluxes.

Channel A Thermal neutron flux (n cm^{-2} s^{-1})			
Type of estimator	Point 1		
Tally F5	(1.61 ± 0.02) 10^{12}	(9.13 ± 0.07) 10^{9}	(1.44 ± 0.03) 10^{7}

Table 8
TRIGA RC1 Irradiation channels B, C, D evaluated fluxes.

Thermal neutron flux (n cm^{-2} s^{-1})			
Type of estimator	**Channel B**	**Channel C**	**Channel D**
	Point 4	**Point 5**	**Point 6**
Tally F5	(5.56 ± 0.01) 10^{10}	(3.65 ± 0.07) 10^{10}	(1.96 ± 0.07) 10^{10}

Table 9
TRIGA RC1 Tangential Piercing channel evaluated fluxes.

Channel TPC Thermal Neutron Flux (n cm^{-2} s^{-1})		
Type of estimator	**Point 7**	**Point 8**
Tally F5	(2.33 ± 0.13)10^{9}	(9.03 ± 0.25)10^{7}

Table 10
TRIGA RC1 Experimental channels E/C fluxes.

Experimental channel	**Experimental measure (E)**	**Evaluated Data (C)**	**Ratio E/C**
Channel A	4.8 10^{12}	1.61 10^{12}	2.98
Channel B	4.3 10^{10}	5.56 10^{10}	0.78
Channel C	4.3 10^{10}	3.65 10^{10}	1.18
Channel D	5.4 10^{10}	1.96 10^{10}	2.76
Channel TPC	2.0 10^{8}	9.03 10^{7}	2.21

Table 11
Evaluated neutron flux energy spectrum in different energy ranges.

Energy Interval	% of population	
	Channel A	**Channel TPC**
Thermal (up to 1 eV)	59.95	32.80
Epithermal (0.1 eV < E_n < 1 keV)	23.72	32.64
Fast (1 keV < E_n < 1 MeV)	14	25.38
High (1 MeV < E_n < 20 MeV)	5.34	5.59

equipped with interfaces dedicated to the remote communication with external and independent instrumentation able to store and analyse the reactor behaviour. The signals from every equipment are received every second and stored in the Control Room.

Furthermore, all the nuclear instrumentation devoted to the nuclear power monitoring will be substituted. The new instrumentation is provided with more efficient interaction with the operator. Also, in this case the remote connection and the storage of data is ensured.

To complete the renewal of the Control Room also the main console will be changed. In particular the joystick for the control rods movement and the indicator of the control rods position will be substituted.

Finally, it can be stated that the whole reactor monitoring and control of the reactor will be enhanced giving more reliability and stability.

4. The TRIGA RC-1 and RSV TAPIRO reactors activities

4.1. RSV TAPIRO activities

The zero-power fast research reactor TAPIRO was conceived in the early 60 s by the researchers of the Italian National Committee for Nuclear Energy (CNEN) to assist the Italian program on fast nuclear reactors (Farinelli et al., December 1963). Since 1971, when the reactor reached its first criticality, the TAPIRO nuclear research reactor has been used as a source of fast neutrons for several research activities in the fields of aerospace, nuclear fusion, burning of minor actinides, particle accelerators, neutron cross-sections measurement, biological damage ….

The neutron field produced by the reactor was characterized during a very important experimental campaign performed from 1980 to 1985 in collaboration with the SCK-CEN center in Mol, Belgium. In this characterization campaign, it was demonstrated that the TAPIRO can provide neutron fluxes with extremely variable energy spectra starting from that close to the fission spectrum that occurs at the center of the core (Fabry, 1989). This characteristic, together with the excellent spherical symmetry of the spatial distribution of the flow, makes the TAPIRO a unique facility for notable metrological and experimental applications.

In 2012, the TAPIRO reactor became part of the Mediterranean Research Reactor Network (MRRN) promoted by the IAEA, and in 2016, it was included in the neutron training program organized by the National Institute of Metrology of Ionizing Radiations (INMRI) of AENEAS.

The life of TAPIRO was characterized by a few significant operational stops. One occurred in 1978 when a fire event was initiated in a component of the console in the control room and involved several electrical cables and electronic devices. The event was characterized by slow combustion with the absence of flames; more precisely, we can classify this event as a smoldering event. The reactivation of the reactor required about two years. From 2012 to 2020, there was a second plant shutdown to restore its nominal configuration and reconfigure the irradiation channels and reflector.

Although not exhaustive, the following provides a list of activities, subdivided by type of application.

4.1.1. Neutron cross-section validation and reactor physics

The first meaningful activities at TAPIRO began in 1973 and concerned integral experiments, reactor physics and cross-section validations. In the context of international collaborations with the CEA (Commissariat à ĺEnergie Atomique et aux Energies Alternatives), TAPIRO was involved in the measure of fast neutron propagation in a mixture of sodium and steel used as shielding materials for fast reactors such as Super Phénix (J.C. Estiot et al. April, 1977; D. Calamand et al. April, 1977; Antonini et al., 1978; J.C. Estiot et al. October, 1979). With its geometrical simplicity, TAPIRO was used for defining calculation models suitable to test methods and cross-sections (D'Angelo et al., 1973) and the measure of the importance function using the ^{252}Cf neutron source in the core and reflector of TAPIRO (L. Bozzi et al. May 1974).

TAPIRO was identified as a candidate benchmark neutron spectrum in the first IAEA Consultants' Meeting on detector cross sections (1974). Irradiation of activation detectors were performed in the core and reflector for improving the knowledge of their cross sections (Belli et al., 1974).

In the 80 s, some experimental activities of the TAPIRO plant concerned neutron propagation properties of different blanket configurations usable in fast power reactors (NEFERTITI experience – NEutronics of FERTILE materials Tapiro- Interface) (Angelone et al., October 1982; Carta et al., 1982), experiments on delayed neutrons.

In 2017, in the frame of the NEA Expert Group on Integral Experiments for Minor Actinide Management (M. CARTA et al. 2015) a joint collaboration between ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) and CEA (French Alternative Energies and Atomic Energy Commission) was established with the aim to study the feasibility of a Minor Actinides (MA) irradiation campaign in the TAPIRO fast neutron source research reactor located at the ENEA Casaccia center.

4.1.2. Medical applications

The applications of TAPIRO reactor in medical field are connected to the biological effects of fast neutrons both for studies on neutron damage and their use in cancer therapy.

Since the beginning, several irradiations were made by inserting organic material into one of the biological channels such as rice, potato powder, hair, human blood, and even mice (Russo et al., 1983; Pacchierotti et al., 1987).

In the 90 s, activities on biological samples continued with the measurement of the neoplastic transformation of C3H 10 T1/2 cells to determine neutron radiation quality RBE values (Coppola, 1993) and on biological effectiveness of multifractionated low doses of high-LET radiation using BC3F1 male mice (Di Majo et al., 1994).

In the early 2000, the plant was used extensively in activities related to the BNCT (Boron Neutron Capture Therapy) that also involved the modification of some plant components and the design, construction, and installation in the thermal column of several facilities like the neutron epithermal facility EPIMED (Agosteo et al., 1999) and the thermal facility HYTOR (HYbrid Thermal spectrum shifter TapirO Reactor) (Esposito et al., 2008).

In 2010, the EPIMED facility and the related experimental room made of concrete blocks and borated polyethylene sheets were dismantled, restoring the original door of the TAPIRO's thermal column.

4.1.3. Radiation damage studies

The activities on the studies on damage effects of fast neutrons on detectors, electronic components or circuits, etc… constituent the one of the most frequent application of TAPIRO.

In the 90 s, a collaboration began with the INFN (National Institute of Nuclear Physics) to investigate the radiation resistance of photon sensors used in the ECAL calorimeter of the CMS (Compact Muon Solenoid) of the LHC (Large Hadron Collider) of CERN (Puill, 1999). Specifically, this activity involved the irradiation of lead tungstate scintillator single crystals, APD (Avalanche Photo Diode), and optical plates with yttrium oxide coating for the verification of neutron damage and coating studies (Baccaro et al., 1998). Furthermore, other activities were carried out regarding the measurement of the neutron effects on Signal-to-noise ratio, spatial resolution, charge collection, and overall efficiency of silicon microstrip detectors at different temperatures (Angarano et al., 2000); irradiations for the study of the characteristics and efficiency of meters containing ^{16}N (SILENA project) to be used in nuclear power plants in Eastern Europe.

In 2006, a collaboration started with the University of Rome 3 and the University of Calabria for the study of the resistance to neutron radiation and the tracking in a high neutron-gamma background environment of a precision chamber of the muon spectrometer of the ATLAS experiment at CERN's LHC (Branchini et al., 2007).

In a collaboration with the University of Padua, GaAs and InAs samples were irradiated in the tangential channel of TAPIRO. This experimental campaign was dedicated to the development of a Terahertz (THz) radiation source based on new materials and solid-state laser technologies.

In 2013 a piezoceramic motor, identified as the potential apparatus for carrying out the rotation of the scanning head of a laser radar system used for viewing the first wall of the ITER vessel, was tested in the fast neutron field of TAPIRO (Pillon et al., 2015).

Since 2019, TAPIRO has been included in the group of facilities used by the Italian Spatial Agency (ASI) for the irradiation of fast neutrons of electronic components to be installed in devices to be used in space missions.

In 2021, commercial low-dropout (LDO) voltage regulators were tested under fast neutron damage in the TAPIRO (Abovyan et al., May 2022). Those types of regulators were considered a practical solution for powering on-detector electronics in the ATLAS Muon System.

Currently, the TAPIRO reactor is involved in neutron irradiation of a piezo actuator of the Equatorial Visible/Infrared Wide Angle Viewing System (WAVS) for ITER in collaboration with the CIEMAT as well as irradiation of KAPTON samples for the solar sail satellite propulsion and test of RadFET radiation dosimeters in the epithermal neutron field of TAPIRO thermal column.

4.1.4. Education and training

The RSV TAPIRO reactor is involved in Educational and Training activities: thesis, hands-on educational experiences, technical visits, and workshops are performed, in some cases, in collaboration with the University Sapienza of Rome for national and international students or specialists.

4.2. TRIGA RC-1 activities

TRIGA (Training, Research, Isotopes, General Atomics) reactors, designed and manufactured by General Atomics, are the most widely used non-power nuclear reactors in the world. These nuclear research reactors are used in many diverse applications, including production of radioisotopes for medicine and industry, treatment of tumors, nondestructive testing, basic research on the properties of matter, and for education and training.

TRIGA RC-1, of ENEA's Casaccia research Center, reached its first criticality in 1960 and, after an upgrade completed in 1967, its power was increased till 1 MW. This reactor is mainly utilized for training of reactor's operators and students from the university, neutron activation analysis, non-destructive techniques, tests on new type of neutron detectors and as a reference facility for safety-security emergency drills.

During these 50 years of operation, many experiments took place also in the field of radiochemistry for medicine and industry.

4.2.1. Medical applications

In the 90 s the TRIGA RC-1 reactor has been involved in the radioisotope production (^{90}Y, ^{166}Ho, ^{186}Re and ^{188}Re isotopes) for medical purpose in collaboration with Nuclear Medicine Department of S. Eugenio Hospital in Rome for different medical applications on solid tumors (A. Tata et al. 1997; F. Sedda et al. 2011).

Recently, TRIGA RC1 research reactor has been involved in the SECURE EU funded project (Strengthening the European Chain of sUpply for next generation medical RadionuclidEs) (L. Spagnuolo et al. 2024). The project aims to make a major contribution to the sustainability of medical isotope production and its safe application in Europe. It is focusing on promising developments on the design of irradiation targets, production routes for existing and new isotopes in nuclear therapy and diagnostics. The ENEA is involved in the target development and yield determination of a promise beta emitter (terbium-161) with the TRIGA RC-1 reactor. The ENEA investigation in SECURE focused on the possibility to produce 161 Tb by neutron activation of gadolinium target (highly enriched in 160Gd). After appropriate chemical processes, ^{161}Tb (precursor of the radiopharmaceuticals for cancer therapy) and ^{160}Gd oxide (to start new cycles) are extracted. As to study the production capabilities of the TRIGA RC-1, simulations are performed by MCNP and FISPACT-II codes, along with irradiation experiments for validation.

4.2.2. Radiation damage studies

Utilization of neutrons for irradiation of materials has been improved during these last years to investigate the radiation hardness effect on electronics (Falconi et al., 2021; M.Carta et al. 2018).

During 2017 an agreement was signed between ENEA, INFN and the Italian Spatial Agency to cooperate in the field of neutron/gamma radiation damage analysis on electronic components to be used in future space-crafts. This agreement provides for use TRIGA RC-1 research reactor as a facility to perform neutron/gamma irradiation on such electronic devices. This agreement has been endorsed by the European Space Agency through the creation of the ASI Supported Irradiation Facilities (ASIF) coordination and by including ENEA TRIGA RC-1 and TAPIRO research reactors into ASIF.

The neutronic characterization is the first and necessary step to use the reactor as a reference for the utilization in radiation damage studies (M.Carta et al. 2018) so, in the ASIF frame, an experimental characterization of the neutron flux spectrum has been performed (April 2018) in the Central Channel and in the Lazy Susan irradiation facility of the TRIGA RC-1 reactor (Chiesa et al., 2019; Falconi et al. 2021). The ASIF project has been prolonged and an ASIF 2 phase started in 2022 and ended at the beginning of 2025.

During the last year, a collaboration has been signed in the Rome area between two different ENEA laboratories, namely the nuclear research reactors laboratory (RNR) and the particle accelerators for medical applications laboratory (APAM). The aim is to profit of the full availability, in the same institution, of neutron beams from nuclear research reactors (a 1 MW TRIGA – RC1 nuclear reactor and a fast neutron source nuclear reactor, named RSV TAPIRO) managed by RNR at the ENEA Casaccia Research Centre and proton and electron beams (TOP-IMPLART, REX and TECHEA facilities linear accelerators) managed by APAM at the ENEA Frascati Research Centre. The collaboration may allow comparative experiments and tests in many fields of science: nuclear physics, accelerator physics, aerospace, science material, medicine, detectors, beam diagnostics. A "distributed neutron facility" could be set up, thermal neutron, pure fission spectrum neutron, monochromatic and high energy neutron fields might be made available for complementary ad synergic research and development activities over a wide spectral range (Croia et al., 2023).

4.2.3. ADS TRIGA-based facility

TRIGA reactor since 2001 was involved in the TRADE (TRiga Accelerator Driven Experiment) project (Monti, 2003; Rubbia et al., 2003). TRADE experiment, which consists in the coupling of an external proton accelerator to a target to be installed in the central channel of the TRIGA core scrammed to sub-criticality, was based on an original idea of Prof. Carlo Rubbia, presented at CEA in October 2000 and was aimed at a global demonstration of the ADS concept.

The TRADE program, which was foreseen in RC-1 TRIGA reactor located at ENEA-Casaccia research centre near Rome, was planned to investigate the static and dynamic behaviour of ADS at power in thermal neutron spectrum. Because problems in financial backing, the program was interrupted at the end of 2004. Despite these unlucky circumstances, a huge experimental data bank has been set up during the time period prior to the program interruption. In 2007 IAEA endorsed this experimental campaign, and an experimental benchmark was launched in the frame of the Coordinated Research Project "Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems (ADS)" coordinated by IAEA (2006–2010) (Carta et al., 2017).

4.2.4. TRIGA RC1 as a reference facility for safety and security scenarios

In 2015 ENEA participated to the EU funded project EDEN (END-USER DRIVEN DEMO FOR CBRNE), based on the principle that CBRNe should be supported by Research & Development actions. During the project, TRIGA RC1 reactor has been used for testing system and components developed by R&D during a security-safety event (De Dominicis et al. 2014; De Dominicis et al., 2021).

4.2.5. Education and training

TRIGA RC1 has been used since the beginning to support Universities for the courses regarding nuclear reactor theory and radioprotection. Moreover a great number of students worked on their thesis on the TRIGA RC1, performing basic experiments of reactor physics.

Italian laws don't allow students to operate a reactor or simply manage instrumentation working in the control room. An alternative has been implemented on the TRIGA RC-1 (Memmi et al., 2011) installing a digital console fully decoupled by the official one. The digital console, based on LabView code, includes all the radiological monitoring and control rods position instrumentation.

5. Conclusions

Neutrons are precious (and costly). They make possible a wide range of scientific investigations having anything to do with nuclear power, and in this frame, Research Reactors are sophisticated devices for basic and applied research in the fields of particle and nuclear physics, radiochemistry, activation analysis, materials sciences, and nuclear medicine.

TRIGA RC-1 and RSV TAPIRO research reactors are part of our domestic heritage for the future of the nuclear culture in Italy.

They offer a unique opportunity to the student community interested in this field to improve their knowledge by having such powerful particles at disposition that are able to disclose a hidden world when interacting with the matter. Currently, ENEA has many collaborations with Italian universities both in supporting academic activities, with the possibility for the students to perform simple measurements on basic reactor physics parameters, and in collaborating in research activities.

ENEA research reactor will continue to operate in the fields of aerospace and radiation damage, with a particular application in developing models for the representativity of neutron fields in reactors operating in a typical extraterrestrial environment.

A particular interest is going to start in the field of radiobiology, and in the future, the reactor will be investigated in the frame of a collaboration with other ENEA Casaccia laboratories.

The availability of a fast neutron source such as RSV TAPIRO allows to continue to work in the field of nuclear data uncertainty reduction, giving fundamental support to the development of IV-gen reactors. This field is also strongly supported by important international cooperation with other national agencies and universities. RSV TAPIRO will also be strategic for the irradiation of components for the fusion reactors due to its uniqueness in the neutron spectra.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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