THE RESEARCH REACTOR IRT-SOFIA: 50 YEARS AFTER FIRST CRITICALITY

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Abstract

The design features of the research reactor IRT-2000 in Sofia and accumulated experience in the past prior to the partial dismantling of obsolete reactor systems are outlined. The present status of the ongoing refurbishment to a low power reactor IRT-200 and its planned utilization are briefly described.

1. INTRODUCTION

Since early 1956, the Bulgarian government has officially favored the use of nuclear power. In 1957 Bulgaria ratified the Statute of the IAEA and became one of the IAEA states-founders. In June 1957 the Committee for Peaceful Use of Atomic Energy (CPUAE) within the Council of Ministers was established as the specialized state body to promote the nuclear research and applications as well as to control and coordinate the related activities in industry, agriculture, medicine and science. In support to this program the research reactor (RR) IRT-Sofia was contracted. The initial construction of a reactor of the same WWR type as in Poland, Czechoslovakia, Hungary and Rumania that started in 1956 was adapted for the IRT-type of reactor designed and constructed from 1957 to 1961 by the Kurchatov Institute, Moscow. The first chain reaction was accomplished at 20:15 h on September 18, 1961. The official inauguration took place on November 9, 1961. The Reactor underwent several upgrades from initial 500 kW: 1000 kW (1962), 1500 kW (1965) and 2000 kW (IRT-2000) in 1970.

The reactor was operated safely with a mixed (LEU-HEU) core for 28 years at power levels agreed upon user demands up to 2000 kW. After the Chernobyl accident (April 1996), nuclear safety requirements were raised worldwide. Accordingly, the project (1986-1989) for equipment modernization and upgrade for power to 5-8 MW was submitted for approval. In July 1989 the reactor was shut down for increasing of the level of nuclear and radiation safety by implementation of the project. Fresh fuel IRT-2M (36% enrichment) was delivered in 1990. The process was stopped due to the political changes in the 1990s.

In connection with the requirements of the Vienna Convention on Civil Liability for Nuclear Damage, in 1997 the Council of Ministers defined the Institute for Nuclear Research and Nuclear Energy (INRNE) as the operator of the IRT-2000 nuclear facility. Because of significant growing of Sofia in immediate reactor site surrounding a subsequent Resolution was passed in 2001 enacting the reconstruction the IRT-2000 Research Reactor into a reactor of low power up to 200 kW. Now the nuclear research reactor is in reconstruction.

All highly (HEU) and low-enriched (LEU) Russian-origin nuclear fuel was repatriated to Russia in 2003 (HEU fresh fuel: IRT-2M) and in 2008 (spent fuel HEU: C-36, 36% enrichment; LEU: EK-10, 10% enrichment)) in the frames of the Russian Research Reactor Fuel Return Program (RRRFR). To manipulate with fuel transport casks in the reactor hall a new 12.5 t crane was mounted. The work, equipment, approvals, organizational procedures, and international agreements to complete these shipments were elaborated by INRNE under the surveillance of IAEA and DOE National Nuclear Security Administration (NNSA, USA).

2. IRT-SOFIA

During the 28 years of the RR operation there were no accidents. The experience in operation and coping with ageing of IRT-2000 were reported earlier [1,2]. The description of the reactor building, assessment of the seismic hazard of the reactor site etcetera is presented in details. Information is given on the procedure for major repair of the reactor pool lining of aluminium alloy SAV-1 and the checks of fuel by gamma spectrometry scanning and optical inspection.

The IRT-2000 is a heterogeneous water-water pool-type reactor operated at nominal power of 2000 kW. The reactor core is with dimensions 527x429x500 mm^3. The reactor grid is fixed at the bottom of the 60 m^3 water pool and can contain 48 fuel assemblies with 14, 15 or 16 fuel pins each. The pins are cylindrical rods 1 cm in diameter and 50 cm in length. The meat is of pressed UO_2 enriched with 10 % ^{235}U (EK-10) or 36% (C-36). The corresponding cladding is 1.5 and 1.0 mm thick Al alloy SAV-1. The reflector is of 13 graphite blocks (graphite assemblies, SAV-1 cladding). The safety and control system consists of 2 safety rods, 4 shim rods and 1 automatic regulating rod. The cooling system includes 3 pumps, special ejector pipe, 2 heat exchangers, 4 ion exchange columns and 2 mechanical filters. The pool water and the 1.8 m thick heavy concrete walls of the reactor vessel provide radiation protection.

The Reactor has 11 horizontal and 11 vertical experimental channels; maximum thermal neutron flux at 2 MW - 3.2×10^{13} cm^{-2}s^{-1}. Measurements of the mixed neutron and gamma field parameters (thermal and fast fluxes, spectra) were carried out in different points of the reactor core and the shielding as well as in the vertical and horizontal experimental channels by means of the activation, ionisation and other radiometric methods and devices developed by our specialists. Based on these measurements and Monte Carlo simulations, optimal conditions for carrying out of scientific and applied reactor experiments were chosen. Examples of research and applied activities of the research groups at the IRT-2000 are:

- Neutron field distribution was investigated in reactor material components in order to clarify the neutron transfer theory in complex heterogeneous reactor media;
- Diffusion and thermalization constants in reactor neutron moderating media (homogeneous and heterogeneous) were measured;
- Heavy nuclei fission processes were investigated by measuring fission fragments energies and distribution angle;
- Very cold neutrons and ultracold neutrons were extracted by specific elaborated methods and the total cross sections of pure metals and gases were determined in 1972-1973 by the time of flight technique;
- Polarised neutron beam was extracted and used for neutron depolarization investigations of domain structure in amorphous magnetic glasses and crystalline magnetic materials;
- Neutron diffraction methods were developed and applied for determination of the short and long range order and phase transitions in crystalline and glassy systems;
- Texture formation studies were performed by neutron scattering methods;
- Lifetime of excited nuclear states by means of the (n,n) reaction was determined. A stand for investigation of atomic nuclei structure was built on the 6th horizontal channel. Data on gamma-gamma angular correlation, positron annihilation, lifetimes of excited nuclear states were obtained;

- Neutron activation analysis methods were developed and applied for simultaneous multielemental analysis of biological materials, minerals and ore specimens, for investigation of archaeological artefacts, art works and medical samples; analyses for the purposes of criminology were performed;
- Isotope dating investigation of the paints from the Sveshtari tomb, a monument of world significance, was conducted;
- Radiation stability and protection properties of common and novel stainless steels used in nuclear energy and military equipment were determined;
- Isotope production : ^{51}Cr, ^{82}Br, ^{60}Co, ^{24}Na, ^{46}Sc, ^{110m}Ag, ^{122}Sb, ^{56}Mn, ^{140}La and others.

3. PARTIAL DISMANTLING OF IRT-2000

A General Plan (GP) for partial dismantling was elaborated for identifying the roles, chain of command and responsibilities within the dismantling team, and interfaces with supporting organizations involved at the INRNE site. After GP approval, a Detailed Plan including assessment of RAW and personnel doses as well as Safety Analysis Report for Dismantling were prepared. The partial dismantling of obsolete reactor systems was successfully implemented in 2009 [3]. The disassembly of reactor systems, removal of the reactor core and internals and storage of old equipment on the site was carried out in strict compliance with Bulgarian legislation and the IAEA Safety Guides [4].

4. PROJECT IRT- 200

The biological shielding of IRT-2000 is preserved. The Laboratory part of the building is partly renovated. Some limited in scope civil construction work are to be carried out mainly for improving the anti seismic properties of the reactor hall and reorganising the hall access.

The IRT-200 (Table 1) is optimised for IRT-4M fuel assemblies containing 8 or 6 tubular fuel tubes with square cross section arranged concentrically (Table 2). The fuel meat is enriched UO_2 – Al dispersion fuel. The reactor core is with dimensions 676x640x950 mm^3. The 760x640 mm reactor grid has a pitch of 71.5 mm and can fix 54 fuel or beryllium reflector assemblies. The safety and control system consists of 3 safety rods, 5 shim rods and 1 automatic regulating rod. The first cooling circuit includes 2 pumps, ejector, filter system of 6 mechanical filters and between them 4 ion exchange columns, 2 heat exchangers. The reactor vessel is of stainless steel. The spent fuel storage pool of about 12 m^3 deionized distilled water also is with stainless steel lining. It has connections to the reactor pool and the radiochemical laboratory. This facilitates the regular inspections of spent fuel assemblies.

A radiochemical laboratory I grade is situated in the reactor building basement with manipulation boxes and four hot cells with remote manipulators. The hot cells are connected by a transfer line, and equipment for machine treatment of highly radioactive samples. The laboratory is supplied with medical locks, separate ventilation with filters and the necessary dosimetry and emergency equipment. Another radiochemical laboratory, II grade, with measuring premises, is situated in a separate outbuilding to the reactor hall. Thanks to its unique facilities - hot cells, radiochemical and measuring boxes - the radiochemical laboratory enables the work with radioisotopes, either produced in the reactor or imported from abroad, and the preparation of radiopharmaceuticals for medical applications, specimens for analyses in geology, chemistry, metallurgy, agriculture, etc.

TABLE 1: IRT-200 PARAMETERS

REACTOR PARAMETERS	LEU	
Core	Base critical state	Alternative critical state
Excess Reactivity (% Δk/k)	5.20	
Minimum Shutdown Margin (% Δk/k)	- 1.34	
Effective Delayed Neutron Fraction	0.00783	0.00783
Prompt Neutron Lifetime (μs)	84.9	94.2
Coolant Void Coefficient (% Δk/k/% void)	-0.288	-0.244
Coolant Temperature Coefficient (% Δk/k/°C)	-0.00987	-0.0104
Fuel Temperature Coefficient (% Δk/k/°C)	-0.00203	-0.00206

TABLE 2: PARAMETERS OF THE RT-4M FUEL

^{235}U Enrichment, wt %	19.7
Fuel Meat Material	UO_2-Al
Number of Fuel Tubes in Assembly	6 / 8
Number of Assemblies in Core	10 / 4
Fuel Assembly Pitch, mm	715
^{235}U Loading per Assembly, g	265 / 300
Uranium Density in Meat, g U/ cm^3	2.8
Dispersant Volume Fraction, %	32.1
Element Thickness, mm	0.7/0.45/1.6
Coolant Channel Thickness, mm	1.85
Meat Length, mm	600
Assembly Fuel Meat Volume, cm^3	483 / 551

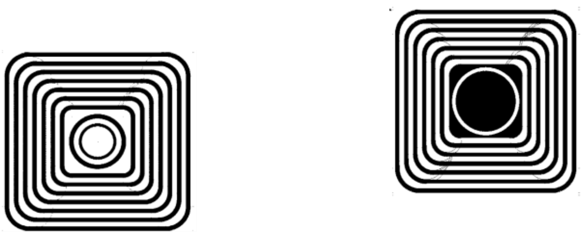

Fig. 1. Cross Sections of IRT-4M Fuel Assemblies: 8-Tube (left) and 6-Tube (right).

The following experimental channels are planned:

— Two vertical channels in the fuel assemblies to supply fast neutron flux 3×10^{12} $cm^{-2}s^{-1}$;
— Two vertical channels in beryllium blocks to supply thermal neutron flux 8×10^{12} $cm^{-2}s^{-1}$;
— Seven horizontal channels outside the reactor core with fast neutron flux 1×6.10^{12} $cm^{-2}s^{-1}$, and thermal neutron flux 5×10^{11} $cm^{-2}s^{-1}$ on the core vessel;
— Six vertical channels outside the reactor core with fast neutron flux 2×10^{12} $cm^{-2}s^{-1}$, and thermal neutron flux 7.10^{10} $cm^{-2}s^{-1}$ on the core vessel;
— Channel for BNCT with epithermal neutron flux 0.9×10^{9} $cm^{-2}s^{-1}$.

5. STATUS OF THE PROJECT IRT-200

During the operation of IRT-200, allowing short-period power increase up to 500 kW, annual doses for the public are far below the dose limit stated by Bulgarian Law and European Council Directive. The reactor will have negligible radiological impact to the environment at normal operational conditions as well as at accidents, including the whole class of beyond-design base accidents postulated. The calculations were performed using PARET/ANL (v 7.3), MCNP, SCALE, PC CREAM and other codes. The last updated sections of the Safety Analysis Report were submitted in early 2011.

The elaboration of the technical and work project for reconstruction of the reactor as well as of all of the documents needed for the Safety Assessment is done by the INTERATOM Consortium, in which main participants are Atomenergoproekt (Sofia), ŠKODA JS a.s. (Plzen), and RCC ‘Kurchatov Institute”(Moscow). The reconstruction is carried out with the strong support and surveillance of IAEA.

All components of the Physical Protection system are completely renewed. New engineering structures come along with a Central alarm station, Access control system, Access control point, Intrusion alarm system, Surveillance and situation assessment system, Communication and warning system. The National Police secures 24 – hour guard service.

The primary and secondary cooling systems, the radiation monitoring system (RMS) and a large part of the radioactive waste system are new and passed tests. The ventilation system efficiency is improved significantly and the ventilation stack is supplied with new radiation monitoring systems.

The task to assembly and put into operation the environment monitoring system for observation of the IRT-Sofia restricted site is already accomplished. The external radiation monitoring system includes monitoring of: gamma dose rate; alpha and beta activity; radon activity; Po-218, Po-214, Po-212; gamma radiation control of vehicles. The technological system for control of reactor gases was mounted and put into operation. It includes: Alpha-beta particulate monitor, Iodine monitor, Noble gases monitor, Stack flow monitor

The RMS is schematically shown on the figure below. All of the detectors in the RMS have connection with the RAMSYS server. They have online (real–time) visualization in two workstations with RAMVISION software. RAMVISION software offers the following functions: synthetic display of information on each measurement channel of the RAMSYS network; measurements; status (alarms and faults); display of measurement channels on several different layout views (topography/mapping); display of measurements in the form of trend curves; alarm signal and acknowledgement; management of operating historical trends of the measurement channels; management of mobile monitors; archival of measurements on a hard disk; management of an event log; launch of setup and maintenance software of RAMSYS monitors; data transfer to other digital outputs (optional).

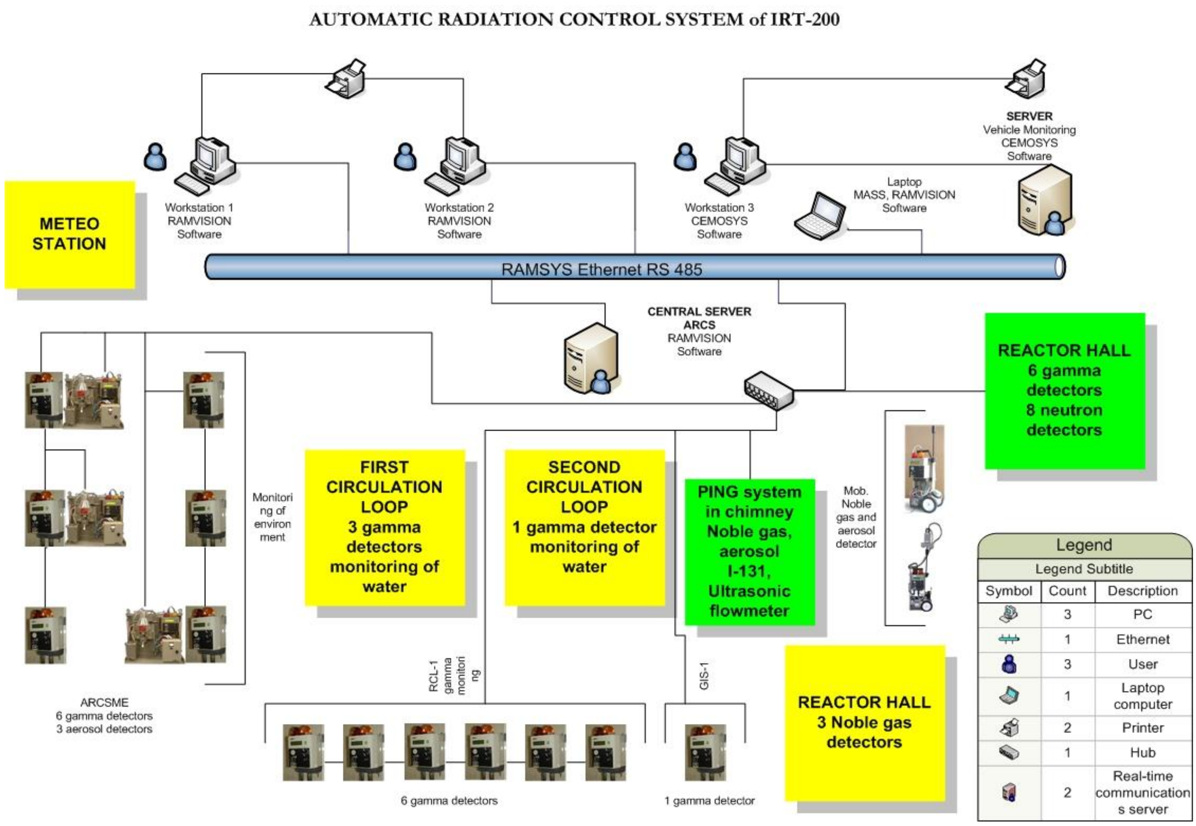

FIG. 2. Schematic view of the operational radiation control system of IRT-Sofia.

The monitoring of the restricted zone in reactor hall to this moment includes: two personal whole-body contamination monitors; gamma monitoring in reactor hall; neutron monitoring in reactor hall; mobile alpha beta particulate monitor; mobile noble gas monitor. Gamma monitors are mounted in other areas of the restricted zone for monitoring of the radiochemical laboratory premises and monitoring of the gamma-irradiation system (GIS-1).All mobile monitors may be connected with a laptop and by using the RAMVISION software the results from measurements can be visualized.

A new Radiometry laboratory was created for the needs of the Radiation Safety Department. This laboratory disposes with two laboratory gamma spectrometers with a HPGe detector of 50% efficiency, two Ultra low level alpha/beta analyzers, two shielded GM detectors with microprocessor estimation unit with local power supply, analytical balances.

The list of rest RMS to be assembled and put in operation includes: noble gas monitoring in reactor hall; gamma monitoring in radiometric laboratory; gamma monitoring of the water in the primary and secondary cooling circuits;; gamma monitoring of reactor equipment storage house; iodine monitoring of the special ventilation system (filters).

The dose control of the personnel in the reactor building is carried out by a system of stationary and portable dosimeters for radiation monitoring at each point inside and outside the reactor building, and thermoluminescent dosimeters for individual control.

6. IRT-SOFIA – PART OF THE NATIONAL ENERGY INFRASTRUCTURE

Nuclear energy plays a strategic role in the Bulgarian energy structure. IRT-2000 played a significant role for boosting the level of scientific and technical knowledge of Bulgarian specialists. It was a very important base for education and training of scientists and engineers in the field of atomic energy and application of radiation methods and technology. Also, the transition from a research reactor to a nuclear power plant was of great significance. The valuable experience gained by our specialists at the Research Reactor helps in developing various methods, computer codes and measuring instruments for control and evaluation of the Kozloduy NPP nuclear safety. Their main contribution is concentrated in particular in:

— Reactor physics analysis of the steady-state and transient processes in the reactor core;
— Reactor dosimetry for determination of neutron embrittlement of reactor vessel metal;
— Nuclear fuel performance analysis;
— Development and maintenance of digital reactivity meters for control of neutron field and subcriticality at reactor core loading;
— WWER reactor core nuclide inventory and the spent fuel characteristics;
— Safe transport and storage of spent fuel;
— WWER fuel performance, modelling and experimental support; the outcome helps improving of the understanding between fuel suppliers, designers, researchers and users, thus contributing to the enhancement of NPP operational safety and reliability;
— Thermomechanical analysis of the in-reactor fuel rods performance and evaluation of the fuel rod failure by means of the TRANSURANUS computer code at applying boundary conditions obtained by the RELAP5/MOD3.3 code.

7. IRT-SOFIA IN EDUCATION AND IN THE NATIONAL RESEARCH INFRASTRUCTURE

The Convention on Nuclear Safety (11:2) states: "Each Contracting Party shall take the appropriate steps to ensure that sufficient numbers of qualified staff with appropriate education, training and retraining are available for all safety related activities in or for each nuclear installation, throughout its life".

Specific regulatory requirements are stated by the Bulgarian Nuclear Regulatory Agency (BNRA) [5]. For a list of positions which involve activities in nuclear facilities with effects on nuclear safety and radiation protection, this regulation demands a Master degree in “nuclear power engineering (technical sciences – mechanical engineering)” or in “nuclear power engineering (natural sciences - physics)”. For each position in the list, one or either of these two types of university degree is explicitly required. Members of INRNE staff give lectures and seminars in neutron and reactor physics, neutron beam utilization, nuclear reactor operation, radiation dosimetry at the Faculty of Physics of Sofia University, Technical University in Sofia, Plovdiv University. Textbooks and manuals for higher educational institutions, technical schools and colleges were written. With its laboratories the IRT-Sofia continues to be an important place for university and post graduation education and training.

More than 50 scientific and research groups from all over the country express preparedness to resume or begin their investigations at the Reactor when put in operation. Feasibility study of a facility for Boron Neutron Capture Therapy (BNCT) by MCNP simulations are carried out for extracting a well-filtered and collimated neutron beam (epithermal neutron flux 9×10^{8} $cm^{-2}s^{-1}$).

The development of a metrological system for testing and calibration of instruments needed for measurements of neutron/gamma fluxes as well as of radiation field monitors for measurements of actual dose received is planned. In the past such a metrological system guaranteed uniformity of the neutron measurements in the country [6].

8. CONCLUDING REMARKS

Educational activities are one of the primary mission objectives for the IRT-Sofia reactor. Through the utilization of the internet and video conferencing technology, students at the Universities in Sofia and Plovdiv enrolled in nuclear physics and engineering programmes will be able to connect to the reactor website and observe experimental exercises.

Experiments such as approach to criticality, reactivity measurements, control rod worth measurements, reactor dynamics etc. performed in the past will be conducted again. Beside materials irradiation, neutron activation analysis, production of isotopes, neutron radiography, small angle neutron scattering, also an intense low-energy positron beam extraction and other reactor technological and commercial utilizations are under consideration

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