UTILIZATION OF THE DALAT RESEARCH REACTOR FOR RADIOISOTOPE PRODUCTION, NEUTRON ACTIVATION ANALYSIS, RESEARCH AND TRAINING

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1. INTRODUCTION

The Dalat Nuclear Research Reactor (DNRR) is a 500 kW pool type reactor loaded with a mixed core of HEU (36% enrichment) and LEU (19.75% enrichment) fuel assemblies. It was reconstructed and upgraded from the USA 250 kW TRIGA Mark II reactor built in the early 1960s. The first criticality of the renovated reactor was on 1 November 1983 and its regular operation at a nominal power of 500 kW started in March 1984 [1].

The reactor is used as a neutron source for the purposes of radioisotopes production, neutron activation analysis (NAA), basic and applied research and training. The reactor is operated mainly in continuous runs of 108 hours for cycles of 3-4 weeks for the above mentioned purposes. The remaining time between two continuous operation cycles is devoted to maintenance works and also to offer short beam times for reactor physics experiments. From the first start up until June 2010, the reactor was in operation about 34 500 hours, and the total energy released was about 700 MWd.

As a unique research reactor at present in Vietnam, the DNRR has played an important role in the research and development of nuclear technique applications as well as in the development of a nuclear power programme of the country. Safe operation and utilization of the reactor at least to the year 2025 are a long-term objective of the DNRR. So far the government has strongly supported many specific projects in order to upgrade the facility and improve its operation and utilization [2].

The current status of safety, operation and utilization of the reactor is given and some aspects for improvement of commercial products and services of the DNRR are also discussed in this paper.

2. BRIEF DESCRIPTION OF THE REACTOR [1]

The DNRR is a pool type reactor, moderated and cooled by light water. The main specifications of the reactor are listed in Table 1.

TABLE 1. SPECIFICATIONS OF THE DNRR.

Reactor type	Swimming pool TRIGA Mark II, modified to Russian type of IVV-9
Nominal thermal power	500 kW, steady state
Coolant and moderator	Light water
Core cooling mechanism	Natural convection
Reflector	Beryllium and graphite
Fuel types	WWR-M2, U-Al alloy with 36% enrichment and UO_2+Al with 19.75% enrichment, aluminium cladding
Number of control rods	7 (2 safety rods, 4 shim rods, 1 regulating rod)
Materials of control rods	B_4C for safety and shim rods, stainless steel for automatic regulating rod
Neutron measuring channels	6 combined in 3 housings with 1 CFC and 1 CIC each
Vertical irradiation channels	4 (neutron trap, 1 wet channel, 2 dry channels) and 40 holes at the rotary rack
Horizontal beam-ports	4 (1 tangential — No. #3 and 3 radial — No. #1, #2, #4)
Thermal column	1
Maximum thermal neutron flux	2.1×10^{13} $cm^{-2}s^{-1}$ (in the neutron trap at core center)
Main utilizations	RI, NAA, PGNAA, NR, basic and applied researches, nuclear training

The reactor core has a cylindrical shape with a height of 60 cm and a diameter of 44.2 cm, and is constituted of 104 WWR-M2 fuel assemblies, 7 control rods, a neutron trap at the core center and 3 in-core irradiation facilities (Figure 1).

Two types of fuels, one with a ^{235}U enrichment of 36% (HEU) of Al-U alloy and one with 19.75% (LEU) of UO_2+Al covered by aluminium cladding, are used. Each HEU and LEU fuel assembly contains about 40.2 g and 49.7 g of U-235, respectively, distributed on three coaxial fuel tubes, of which the outermost one is hexagonal shaped and the two inner ones are circular. The total length of the fuel assembly is 865 mm, of which the fuel part is 600 mm long.

A number of experimental irradiation facilities are present inside and around the reactor core, consisting of a central neutron trap, one in-core vertical wet and two in-core dry (pneumatic transfer) irradiation channels, a rotary specimen rack at the graphite reflector around the core, a graphite thermal column, and four horizontal beam ports. The neutron trap with the highest thermal neutron flux of 2.1×10^{13} $cm^{-2}s^{-1}$ and a cadmium ratio of R_{Cd}=2.5, and the in-core vertical wet channel at cell 1-4 with a fast neutron flux of 1.0×10^{13} $cm^{-2}s^{-1}$ have been used mainly for radioisotope production. The rotary rack providing 40 wet irradiation positions with thermal neutron flux of 5.0×10^{12} $cm^{-2}s^{-1}$ and a cadmium ration of R_{Cd}=3.4 has been used for NAA and for isotope production as well. The two pneumatic transfer channels at the core perimeter with a thermal neutron flux of 5.0×10^{11} $cm^{-2}s^{-1}$ have been used for NAA only.

There are two pneumatic transfer systems with vertical tubes penetrating the core at two peripheral cells. The first system with the tube occupying cell 7-1 is remote operated at a sample drive command terminal located about 50 m from the reactor. The second system with the tube occupying cell 13-2 is used for fast activation analysis; its sample drive command terminal is located just inside the reactor hall.

The rotary specimen rack located in a circular well of 30 cm depth within the upper part of the graphite reflector consists of an aluminium rack for holding specimens during irradiation inside a ring shaped, seal welded aluminium housing. The rack has 40 evenly spaced tubular aluminium containers (holes), open at the top and closed at the bottom, which serve as receptacles for specimen containers. The maximum internal space in each of the 40 holes is 31.75 mm in diameter by 274 mm in length. The rack was modified to operate completely in water.

The four beam ports penetrate the concrete shield and the aluminium tank and pass through the pool water to the graphite reflector (Figure 2).

Three of the beam tubes (No. #1, #2 and #4) are oriented radially with respect to the center of the core, and the fourth tube (No. #3) is tangential to the outer edge of the core. Two of the radial tubes (No. #1 and #2) terminate at the outer edge of the graphite reflector. The third radial tube (No. #4) penetrates into the graphite reflector and terminates at the inner surface of the reflector, just at the outer edge of the core. The tangential beam tube (No. #3) terminates at the outer surface of the reflector, but it is also aligned with a cylindrical void, which intersects the piercing tube in the reflector graphite. At present only two beam ports (No. #3 and #4) are used for neutron beam research and neutron radiography as well.

The thermal column, with dimensions of $1.2\times1.2\times1.6$ m^3, of the former TRIGA reactor remains unchanged. The column has waterproof walls made of aluminium and covered with boron. Graphite blocks with dimensions of $10.2\times10.2\times127$ cm^3 fill the volume of the column. The second pneumatic transfer system also uses this column for NAA.

The reactor can be operated at variable power levels up to a maximum of 500 kW without pulsing capability. At steady state maximum power, the average thermal neutron flux in the reactor is about 4×10^{12} cm^{-2}s^{-1}, and the maximum thermal neutron flux at the neutron trap at the core center is about 2.1×10^{13} cm^{-2}s^{-1}.

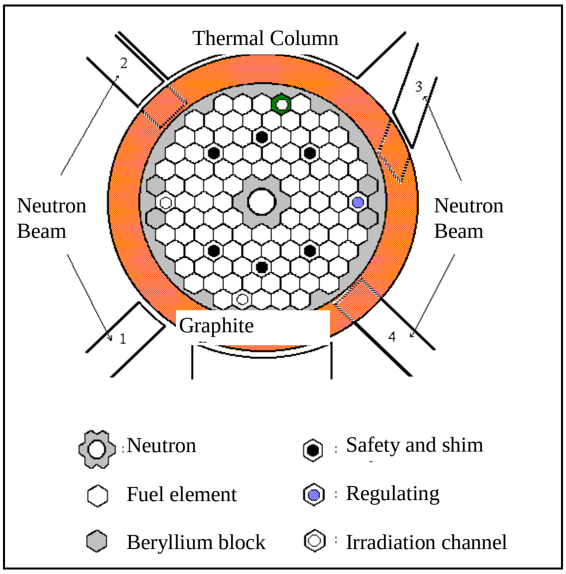

Fig. 1. Horizontal section view of the reactor core.

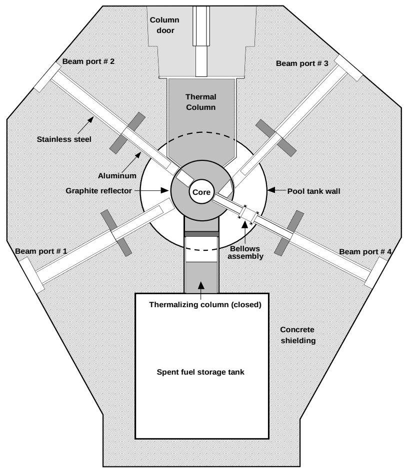

Fig. 2. Horizontal section view of the reactor.

3. REACTOR UTILIZATION

As the main neutron source of the country, the DNRR has been effectively used for the following purposes:

3.1. Radioisotope production [2]

The radioactivity of more than 350 Ci of ^{131}I, ^{99}Mo-^{99m}Tc, ^{32}P, etc., has been annually produced and supplied to hospitals throughout the whole country. In order to support the application of ^{99m}Tc, ^{113m}In and ^{153}Sm radioisotopes in clinical diagnosis and therapeutics, the preparation of radiopharmaceuticals kits forms was carried out. The main kits regularly manufactured and supplied by DNRI are phytate, gluconate, pyrophosphate, citrate, DMSA, EHIDA, DTPA, HSA macroaggregated, HEDP, HmPAO, MIBI and MDP. For therapeutic purposes radiopharmaceuticals labelling with ^{153}Sm and ^{131}I such as ^{153}Sm-EDTMP and ^{131}I-MIBG are also prepared and implemented in clinical trials. In addition, research in radiochemistry built the basis for the development of technologies suitable for radioisotope production in low power research reactors.

The routine production of radioisotopes has been focused on the main radionuclides used in nuclear medicine application, such as:

- ^{131}I in Na–^{131}I solution and capsules;
- ^{99m}Tc generators from Mo by the reaction ^{98}Mo(n, γ)^{99}Mo;
- ^{32}P in injectable orthophosphate solution;
- ^{32}P applicators for skin disease therapeutics;
- ^{51}Cr in injectable sodium chromate and chromium chloride solution;
- ^{153}Sm in solution applicable for labelling; and
- Other radioisotopes such as ^{65}Zn, ^{64}Cu, ^{24}Na, etc., have also been produced when requested.

These types of radioisotopes have regularly been supplied to more than 25 nuclear medicine centres in the country, allowing them to diagnose and treat hundreds of thousands patients per year. The ^{131}1 radioisotope labelled radiopharmaceuticals such as ^{131}I-Hippuran have also been supplied to hospitals. The record of radioisotope products is shown in Figure 3 and the status of supply and demand of radioisotopes and diagnostic kits in Vietnam is shown in Table 2.

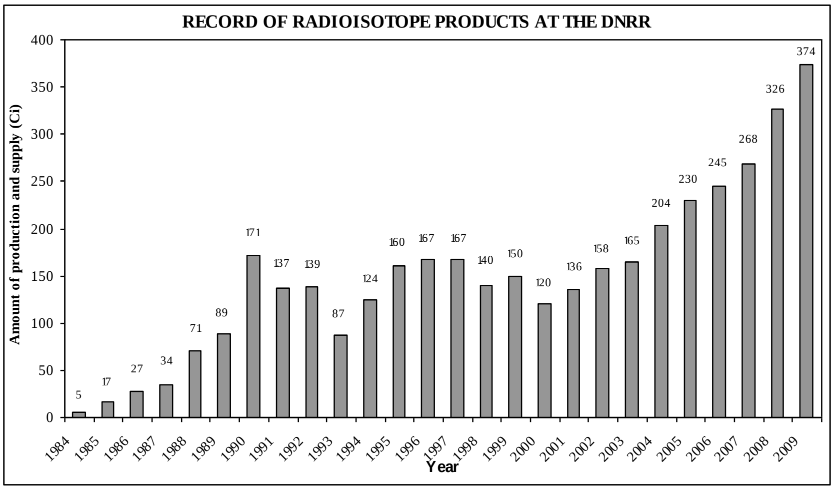

Fig. 3. Record of radioisotopes produced at DNRR for medical application yearly.

TABLE 2. STATUS OF SUPPLY/DEMAND OF RADIOISOTOPES AND DIAGNOSTIC KITS IN VIETNAM.

Product	Supply	Demand
^{131}I diagnostic and therapeutic capsule/solution	20 Ci/month –	40 Ci/month –
^{99m}Tc generator	10 generators (500 mCi each) per month	20 generators (500 mCi each) per month
^{32}P solution	200 mCi/month	200mCi/month
^{32}P applicator	30 Ci/month	30Ci/month
Kits for ^{99m}Tc labelling		
— MDP	300 kits/month	400 kits/month
— DTPA	100 kits/month	200 kits/month
— DMSA	100 kits/month	200 kits/month
— PHYTATE	100 kits/month	200 kits/month

By requirements of end-users, some radioisotopes such as ^{46}Sc, ^{192}Ir, ^{198}Au, etc., have also been produced for application in industry, agriculture, hydrology, scientific research and nuclear education and training.

3.2. Neutron activation analysis

Using two in-core pneumatic transfer systems and the rotary specimen rack for sample irradiation, the requests of many branches of the national economy for various types of samples have been answered. Practically, NAA techniques have an advantage in serving for geology and oil field studies. Both INAA and RNAA techniques have been developed. Environmental studies are also carried out efficiently with NAA and associated methods. Yearly about 4000 samples have been irradiated and analyzed at DNRR [2].

The k_0 method with k_0-DALAT software was developed and has been applied successfully for NAA at DNRR since 2000. Since 2009, research and applications of k_0-IAEA programme for NAA at DNRR have been carried out by the INAA Lab. Up to now, the analytical process of k_0 method using k_0-IAEA software is basically set up, and the whole procedure is going to be completed and evaluated [3, 4].

Since 2007, based on demands from archaeologists regarding many of the ruins of archaeology and cultural heritage which need to be studied, preserved, prepared and restored in Vietnam, and due to the capabilities of NAA methods that can make a contribution into the solution for above issues as well, a national project for research on provenance of archaeological materials was approved and supported. To expand the applications of NAA as well as to improve the effective utilization of the DNRR, the application of NAA in combination with the multivariate statistics method for provenance research has been developed for earthen archaeological objects. Three locations chosen for this project are the My Son holy land located in Duy Xuyen village, Duy Phu district, Quang Nam province of central Vietnam; the Emperor's rampart relic located in Nhan Hau village, An Nhon district, Binh Dinh province of central Vietnam; and the Cat Tien archaeological site located in Quang Ngai village, Cat Tien district, Lam Dong province of the southeast highlands [5, 6].

More than 400 samples of clay, ancient brick and pottery fragments were collected for analysis. Based on the obtained results, it could be concluded that (1) the NAA experimental process for 30 elemental determinations and data multivariate analysis programme using the principal components analysis (PCA) and the cluster analysis (CA) methods named Multivariate Statistical Analysis Program (MSAP) have been established and successfully applied to archaeological materials; (2) NAA, especially k_0-NAA, has a lot of potential in provenance research for archaeological materials with high accuracy and good re-productivity of results; and (3) the results will positively contribute into the studied and restored works of archaeological ruins in Vietnam [7, 8, 9].

3.3. Neutron beam research [2]

A research programme on the utilization of neutron beams at the horizontal experimental channels of the reactor was conducted during 1984. However, before 1988 the reactor was mainly used for radioisotope production and NAA and no beam port was utilized. In 1988 the filtered thermal neutron beam at the tangential channel No #3 was extracted using a single crystal silicon filter and since this time, it is used for neutron radiography, transmission experiments and prompt gamma neutron activation analysis (PGNAA). In 1990 the programme to extract filtered quasi-monoenergetic keV neutron beams at the piercing horizontal channel No #4 using the neutron filter technique was started. Utilization of these filtered neutron beams in nuclear data measurements and applied researches has been carried out so far.

At present, three main instruments have been installed: (1) the spectrometer for the summation of amplitude of coinciding pulses (SACP) with two gamma detectors at beam port No #3 for nuclear reaction studies (n,γ; n,2γ; n,n' reactions); (2) the PGNAA system at beam port No #4 to decrease background and increase neutron flux at sample position; and (3) the cyclic neutron activation analysis (CNAA) system for short-lived isotopes at thermal column. Based on the neutron filters setup thermal and quasi-monoenergetic neutrons of 25 keV, 55 keV, 144 keV, >1.2 MeV, etc., can be obtained and used for nuclear data measurements and other purposes. The recent research activities are focused on the following areas:

(i) Determination of average neutron cross sections and resonance parameters in the energy region of filtered neutron beams, including:

— Investigation of resonance self-shielding effect in total neutron cross sections, including measurement of the total cross sections with different sample thicknesses, Monte Carlo simulations of resonance structure of neutron cross sections in the unresolved region, fitting theoretical calculations with experimental data of transmission measurements to obtain average neutron resonance parameters, carrying out experiments on U-238 and some reactor materials;
— Measurement of average neutron radiative capture cross sections, including fitting experimental data with calculations to obtain average neutron resonance parameters, carrying out experiment on some nuclei given in the WRENDA 93/94;
— Theoretical calculations for determination of corrections for multiple scattering, resonance self-shielding and self-absorption effects, and writing programmes for simultaneously fitting experimental data on σ_t, σ_{ng}, and others;
— Investigation of the energy dependence of the isomeric ratio, as well as determination of the isomeric ratio of nuclei formed by nuclear reactions with neutrons of different energies, and fitting experimental data with theoretical calculations to obtain the nuclear density parameters;
— Some measurements of neutron cross sections for astrophysical applications, including measurements of cross section for (n, p) and (n, γ) reactions on the filtered neutron beams for some light nuclei such as ^{14}N, ^{33}S, ^{35}Cl, ^{36}Cl and ^{40}K;

(ii) Investigation of nuclear structure:

— Research on (n, 2γ) reactions using the spectrometer of summation of amplitudes of coinciding pulses;
— Construction of the level scheme and skeleton decay scheme for ^{172}Yb, ^{153}Sm.

(iii) Improvement and applications of PGNAA system:

— Measurement of the k_0 factor;
— Measurement of the hydrogen index in base rocks for oil fields; and
— Analysis of trace elements: B, S, N, P, C, Si, Gd, Cd, Sm, Al, Cl, Ti, Ca, etc., in biology and geology samples.

3.4. Nuclear education and training [2]

The reactor has been used for nuclear education for young researchers from institutions and university teachers, and for training of reactor operators and shift supervisors.

As a national nuclear training center has been set up in the Dalat Nuclear Research Institute (DNRI) since 1999, so far the following courses have been organized:

— Basic courses on radiation protection and safety;
— National basic professional course on nuclear safety;
— Application of nuclear techniques in environmental research;
— Application of nuclear techniques in industry;
— Application of nuclear techniques in agriculture and biology;
— Nuclear reactor engineering;
— Courses on NTD level-2 and level-3; and
— Specific courses (10 topics) for compulsory training of new employees in the nuclear sector.

In general, the DNRR is the most important scientific tool for carrying out R&D programmes of nuclear technique applications so far, as well as for the preparation of human resources for the nuclear power programme in Vietnam in the near future.

4. REACTOR IMPROVEMENT FOR FURTHER UTILIZATION [1, 2]

4.1. Reactor conversion from HEU to LEU fuel

In the framework of the programme on Russian Research Reactor Fuel Return (RRRFR) and the programme on Reduced Enrichment for Research and Test Reactor (RERTR), the DNRR core was partly converted from HEU (36% enrichment) to LEU (19.75% enrichment) in September 2007. At present, the mixed core is loaded with 92 HEU and 12 LEU fuel assemblies. The core has been considered for full conversion of all LEU fuel by mid-2011. For this purpose, in the cooperation with Argonne National Laboratory, the neutronics calculations and safety analysis have been done so far. Based on the obtained results, it can be concluded that a full LEU core configuration can be used for DNRR. In this aspect, the trilateral contract among the IAEA, TVEL Corporation in the Russian Federation and the Vietnam Atomic Energy Institute (VAEI) for supplying 66 LEU fresh fuel assemblies was implemented, and the commissioning programme with LEU core has been scheduled for May 2011.

4.2. Reactor control and instrumentation system modification

The control and instrumentation system (C&I) of the DNRR was designed and manufactured by the former Soviet Union; operation started in November 1983. Due to problems in procuring spare parts and using technology of the 1970s with discrete and low-level integrated electronic components, the system technology has become slightly obsolete and unadapted to a tropical climate.

The first renovation work was implemented during 1992 and 1993, and the renovated C&I system was commissioned at the end of 1993. The most important renovation task was to redesign and construct a number of electronic systems and blocks that play a key role in enhancing the reliability of the system. This renovation work was focused mainly on the process and instrumentation system, but not on the neutron measurement and data processing parts. Because of that, it was necessary to implement a second renovation and modernization during the years 2005–2007 with the replacement of neutron measurement and signal processing parts of the existing C&I system by the digital system named ASUZ-14R. The main items replaced under the second modification are neutron detector channels, the neutron flux control system (NFCS), the reactor protection system, the control console and control panels, the reactor protocol and diagnostic system and other systems.

The commissioning of the new C&I system was finished in August 2007 and an operating license was approved in October 2007.

5. CONCLUSION

The DNRR has been safely operated and intensively utilized for 26 years. To achieve that, maintaining and upgrading the reactor technological facilities have been done with a high quality. The reactor physics and thermal hydraulics studies have also provided important bases for safety evaluation and in-core fuel management to ensure its safe operation and effective exploitation. The safety and security of the reactor are one of the main issues with high relevance and strong support from the national and local authorities.

The main utilization of the DNRR is to operate for radioisotope production for medical purposes. However, due to the reactor’s low power, only limited amounts and types of radioisotopes can be produced for domestic users, but it is suitable for NAA, basic and applied research, and nuclear education and training.

A strategic and long term working plan for the DNRR has been set up in order to continue its safe operation and effective utilization at least to 2025.

It could be mentioned that a project for the establishment of a new nuclear research center with a high power research reactor that is expected to start operation before 2020 is now under preparation and consideration. Thus, the DNRR will be necessary and will play an important role in scientific research, applications and human resource development for Vietnam in the coming time.

6. REFERENCES

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