EXPERIENCE IN UTILIZING RESEARCH REACTORS IN YUGOSLAVIA

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Abstract–Résumé–Аннотация–Resumen

EXPERIENCE IN UTILIZING RESEARCH REACTORS IN YUGOSLAVIA.

The nuclear institutes in Yugoslavia possess three research reactors. Since 1958, two heavy-water reactors have been in operation at the 'Boris Kidrič' Institute, a zero-power reactor RB and a 6.5-MW reactor RA. At the Jožef Stefan Institute, a 250-kW Triga Mark II reactor has been operating since 1966. All reactors are equipped with the necessary experimental facilities. The main activities based on these reactors are: (1) fundamental research in solid-state and nuclear physics; (2) R and D activities related to nuclear power program; and (3) radioisotope production.

In fundamental physics, inelastic neutron scattering and diffraction phenomena are studied by means of the neutron beam tubes and applied to investigations of the structures of solids and liquids. Valuable results are also obtained in n-γ reaction studies. Experiments connected with the fuel-element development program, owing to the characteristics of the existing reactors, are limited to determination of the fuel-element parameters, to studies on the purity of uranium, and to a small number of capsule irradiations. All three reactors are also used for the verification of different methods applied in the analysis of power reactors, particularly concerning neutron flux distributions, the optimization of reactor core configurations and the shielding effects. An appreciable irradiation space in the reactors is reserved for isotope production. Fruitful international co-operation has been established in all these activities, on the basis of either bilateral or multilateral arrangements.

The paper gives a critical analysis of the utilization of research reactors in a developing country such as Yugoslavia. The investments in and the operational costs of research reactors are compared with the benefits obtained in different areas of reactor application. The impact on the general scientific, technological and educational level in the country is also considered. In particular, an attempt is made to envisage the role of research reactors in the promotion of nuclear power programs in relation to the size of the program, the competence of domestic industries and the degree of independence where fuel supply is concerned.

UTILISATION DES REACTEURS DE RECHERCHE EN YOUGOSLAVIE.

Les établissements nucléaires yougoslaves disposent de trois réacteurs de recherche. Depuis 1958, deux réacteurs à eau lourde, à savoir un réacteur RB de puissance nulle et un réacteur RA de 6,5 MW, fonctionnent à l'Institut Boris Kidrič. En 1966, un réacteur Triga Mark II de 250 kW a été mis en service à l'Institut Jožef Stefan. Ces réacteurs sont dotés de toutes les installations expérimentales nécessaires. Ils sont essentiellement affectés aux travaux suivants: 1) recherches fondamentales en physique de l'état solide et en physique nucléaire; 2) études et réalisations dans le cadre du programme d'énergie nucléaire; 3) production de radioisotopes.

En physique fondamentale, la diffusion inélastique des neutrons et les phénomènes de diffraction sont étudiés à l'aide de tubes à faisceaux neutroniques et les résultats sont appliqués aux recherches sur la structure des solides et des liquides. L'étude des réactions n-γ donne également des résultats intéressants. En raison des caractéristiques que présentent les réacteurs actuels, les expériences effectuées dans le cadre du programme d'étude des éléments combustibles se limitent à la détermination des paramètres de ces éléments, à des travaux sur la pureté de l'uranium et à l'irradiation d'un petit nombre de capsules. Les trois réacteurs servent aussi à la vérification de différentes méthodes employées pour l'analyse des réacteurs de puissance, notamment en ce qui concerne la distribution du flux, l'optimisation de la configuration du cœur et les effets du blindage. Un espace assez important dans les réacteurs est réservé à la production d'isotopes. Toutes ces activités font l'objet d'une coopération internationale fructueuse dans le cadre d'accords bilatéraux ou multilatéraux.

Les auteurs procèdent à un examen critique de l'utilisation de réacteurs de recherche dans un pays en voie de développement comme la Yougoslavie. Ils indiquent les frais d'investissement et d'exploitation afférents à ces réacteurs en les comparant aux avantages que ces installations permettent d'obtenir dans divers domaines. Ils examinent l'influence qu'elles exercent sur les sciences, la technologie et l'enseignement dans l'ensemble du pays. Ils s'efforcent notamment de dégager le rôle incombant aux réacteurs de recherche dans l'établissement des programmes d'énergie nucléaire, en ce qui concerne l'importance de ces programmes, la compétence de l'industrie nationale et le degré d'indépendance du pays en matière d'approvisionnement en combustible.

ОПЫТ РАБОТЫ ИССЛЕДОВАТЕЛЬСКИХ РЕАКТОРОВ В ЮГОСЛАВИИ.

Югославские ядерные институты располагают тремя исследовательскими реакторами. В Институте им. Бориса Кидрича, начиная с 1958 года, работают два тяжеловодных реактора: реактор нулевой мощности RB и реактор RA мощностью 6,5 МВт. В Институте им. Иозефа Стефана с 1966 года работает реактор TRIGA MARK II. Все эти реакторы оснащены необходимым экспериментальным оборудованием. На этих реакторах проводятся следующие основные работы: 1) фундаментальные исследования по физике твердого тела и ядерной физике; 2) исследования и опытно-конструкторские работы по программе ядерной энергетики; 3) работы по получению изотопов.

В области фундаментальной физики с помощью каналов для вывода нейтронных пучков изучаются процессы неупругого рассеяния нейтронов и диффракция нейтронов, которые используются для исследования структуры твердых тел и жидкостей. Важные результаты получены также при изучении n-γ-реакций. Эксперименты, связанные с осуществлением программы разработки тепловыделяющих элементов, благодаря характеристикам существующих реакторов, ограничиваются определением параметров тепловыделяющих элементов, изучением чистоты урана и проведением небольшого количества радиационных испытаний оболочек тепловыделяющих элементов. Все три реактора используются также для проверки различных методов, применяемых при анализе работы энергетических реакторов и связанных в основном с распределением нейтронного потока, оптимизацией геометрии активной зоны реактора и изучением эффектов защиты. Значительная часть каналов в реакторах используется для получения изотопов. По всем этим работам были установлены полезные международные контакты как на двусторонней, так и на многосторонней основе.

В докладе дается критический обзор применения исследовательских реакторов в такой развивающейся стране, как Югославия. Проводится сравнение капиталовложений и текущих затрат на исследовательские реакторы с экономическими выгодами, полученными в различных областях применения атомных реакторов. Рассматривается также влияние реакторостроения на общий научный, технический и общеобразовательский уровень в стране. В частности, сделана попытка учесть роль исследовательских реакторов в развитии программы по ядерной энергетике в отношении объема этой программы, конкурентоспособности собственной промышленности и степени зависимости от источников атомного сырья.

EXPERIENCIAS REALIZADAS CON REACTORES DE INVESTIGACION EN YUGOSLAVIA.

En Yugoslavia existen tres reactores de investigación. En el Instituto Boris Kidrič se hallan en operación, desde 1958, dos reactores de agua pesada, el RB de potencia cero y el RA de 6,5 MW. En el Instituto Jožef Stefan funciona desde 1966 un reactor Triga Mark II de 250 kW. Estos reactores están provistos de las necesarias instalaciones experimentales.

Las principales actividades desarrolladas con estos reactores son: investigación fundamental sobre estado sólido y física nuclear; labor de investigación y desarrollo relativa al programa de energía nuclear, y producción de isótopos radiactivos. En el campo de la física fundamental, utilizando los haces disponibles a través de accesos experimentales, se estudian los fenómenos de dispersión inelástica y de difracción de neutrones, los cuales se aplican a la investigación de las estructuras de sólidos y líquidos. También se han obtenido valiosos resultados en el estudio de la reacción n-γ. En relación con el programa de desarrollo de elementos combustibles y teniendo en cuenta las características de los reactores existentes, los experimentos se han limitado a la determinación de los parámetros del elemento combustible, de la pureza del uranio y a la irradiación de un pequeño número de cápsulas. Los tres reactores se utilizan también para la comprobación de los diferentes métodos que se aplican al análisis de reactores de potencia, en particular al análisis de las distribuciones de flujos de neutrones, a la optimización de configuraciones del núcleo y al estudio de los blindajes. Una parte importante de la zona de irradiación en los reactores está reservada a la producción de isótopos. En todas las actividades mencionadas ha sido establecida una fructífera cooperación internacional por medio de convenios bilaterales o multilaterales.

El informe incluye el análisis crítico de la utilización de reactores de investigación en un país de desarrollo como es Yugoslavia. Las inversiones y costes de operación para reactores de investigación se confrontan con las ventajas obtenidas en los diferentes campos de aplicación de reactores. También se considera la influencia general ejercida sobre el nivel científico, técnico y educativo del país. Se examina el papel de los reactores de investigación en la promoción de programas de energía nuclear, en particular con respecto a la amplitud de dichos programas, la competencia de las industrias nacionales y el grado de independencia nacional para el abastecimiento de combustible.

1. INTRODUCTION

Nuclear research activities were initiated early in Yugoslavia. By the beginning of the nineteen-fifties, three nuclear research centres had been founded: the 'Boris Kidrič' Institute of Nuclear Sciences in Belgrade, the 'Ruder Bošković' Institute in Zagreb and the 'Jožef Stefan' Institute in Ljubljana. The installation of these nuclear centres was in accordance with government policy for science in general and nuclear sciences in particular. This policy was based on the urgent need for rapid growth in the national economy at that time and the constant demand of all industrial branches for low cost electricity. In a country that was taking its first steps towards industrialization and electrification, the potential nuclear fuel resources offered an abundant source of energy for the future. On the other hand, the main area of progress in science and technology was at that time in nuclear research and development. In all industrialized countries, nuclear activity was expanding rapidly, stimulating the development of technology in a number of industries. This led to the logical conclusion that the development of nuclear sciences and engineering could contribute effectively to the introduction of modern technology in national industry. Scientific and engineering staff trained at nuclear institutes can be employed at universities and industrial laboratories and for industrial plant operation to introduce modern scientific knowledge and techniques in education and industry.

With these premises in the early stages of development, general nuclear activities were stimulated, particularly nuclear physics, chemistry, electronics and uranium technology. Subsequently, these activities were concentrated in a nuclear power program which was formulated to take into account the existing requirements in the country. The technical objectives of the program were to build a nuclear power station, possibly in co-operation with a foreign partner, and to develop domestic fuel production to ensure independence from imported fuel. It can now be seen that these objectives were based, to some degree, on overestimation of the technical and economic potential of the country. They certainly imposed a heavy obligation to educate the necessary scientific and engineering staff, to build the nuclear installations needed for research and to organize nuclear centres.

With heavy pressure on national economic resources and some reduction of emphasis on the needs of other scientific branches for a decade, well equipped nuclear research facilities were developed. In early 1958, at the 'Boris Kidrič' Institute, the first critical facility was built with the intention of giving impetus to the development of reactor physics. In 1959, the medium-power heavy-water research reactor RA was started up to initiate isotope production, promote research in solid-state and nuclear physics and provide a strong source of neutrons for material irradiation. At the 'Jožef Stefan' Institute in Ljubljana, it was planned to install a low-power research reactor in early 1960 to concentrate on nuclear engineering and, particularly, on reactor shielding and safety, but, because of temporary complications in financing and some delay in siting, a 250-kW Triga reactor was not put into operation until 1966.

These three research reactors were considered to be a good combination with which the technical objectives of the anticipated nuclear power program could be achieved. They were also a nucleus on which to concentrate the various research groups and unify their research activities.

2. OPERATIONAL EXPERIENCE WITH RESEARCH REACTORS

The main design information on research reactors in Yugoslavia is presented elsewhere [1]. Reactor RB is a bare heavy-water critical assembly which has been in use since 1958. It represents a flexible system with a changeable core configuration, intended for lattice studies, intracell neutron measurements, reactor oscillator work and zero power reactor kinetics studies. Owing to the design characteristics and the experimental programs, it operates discontinuously. On the average, the reactor is in operation 150 days per year with about 500 hours on power. The number of new core configurations installed and studied per year have varied from 30 to 50. The normal steady power is a few watts, increased for particular sample irradiations up to 100 W. The staff engaged in the preparation of experiments and in operation includes four technicians and one graduate physicist.

The research reactor RA is a heavy-water reactor with 2% enriched fuel. The maximal thermal neutron flux is 6×10^{13} n/cm$^2 \cdot$ s. The main irradiation facilities are 45 vertical channels, 6 horizontal beam tubes and a thermal column. In one beam tube, a pneumatic rabbit system has been installed. Hollow fuel elements are used for capsule irradiation in the fast-neutron flux. The reactor operates continuously on a nominal power of 6.5 MW which can be raised to 10 MW for short irradiation periods.

The four-shift operation and the maintenance and health-physics services require a staff of 75 people, including 5 engineers and 17 technicians. The average thermal energy production per year is 40 000 MWh. The total operating cost per year, including fuel consumption but without the amortization of the installation, is around US $500 000.

The TRIGA reactor is operated according to the requests from experimental groups and for irradiation of samples. Thus, the reactor is in operation either continuously or only a few hours per day. On the basis of current experience, the reactor is in operation from 2500 to 3800 hours per year. The staff consists of one engineer and six technicians. Two qualified reactor operators are normally in each shift. Total operating expenses amount to US $100 000 per year, including regular additions of fresh fuel elements and improvements to the reactor and its experimental facilities.

3. UTILIZATION OF THE RESEARCH REACTORS

The utilization of the research reactors can be divided into three main categories: (a) fundamental research; (b) research related to the nuclear power program; and (c) radioisotope production and sample irradiations.

(a) Fundamental research

Five horizontal channels are used at the RA reactor for studying phenomena in solid-state physics [2].

The neutron triple-axis spectrometer with monocrystal Al (111) as a monochromator is used to measure neutron inelastic scattering by the diffraction method. In particular, the dynamics of spin systems have been studied [3].

The neutron time-of-flight spectrometer with a Be polycrystalline filter and a chopper has been used for investigations of localized and virtual magnon levels in different systems [4].

The neutron crystal spectrometer has been adapted for the Be detector method [5]. The ferroelectrics of KH_2PO_4 and Rochelle Salt [6] were successfully studied with this spectrometer.

The spectrometer for magnetic critical neutron scattering is a combination of a neutron monochromator and a Fermi chopper with a multi-channel time analyser. Some measurements of neutron critical scattering in nickel, iron and similar systems were performed and compared.

The neutron diffractometer was used for structure measurements on the U-O system and on some ferroelectrics [7].

Time-of-flight experiments used up most of the TRIGA reactor time during the first two years of operation. The time-of-flight spectrometer with four flight paths, combined with a cold neutron source in the tangential beam (solid methane moderator), was used to study the dynamics of phase transitions in ferroelectrics [8]. Lately, interest has been concentrated more on liquid crystals, in particular on the measurement of rotational diffusion in all phases of liquid crystals [9].

To assist experiments with the time-of-flight spectrometer and to offer services to other institutions interested in crystallographic work, a double axis neutron diffractometer was constructed. At present, it is being rebuilt for automatic operation and to connect it to the CDC 1700 digital processor for on-line data acquisition.

In co-operation with the nuclear physics group, experiments on neutron capture gamma spectra with the thermal-column tangential through-tube are in preparation. The set-up will also be used for prompt gamma activation analyses in co-operation with the radiochemical activation analysis group.

The first experiments on neutron radiography were performed recently. Applications of the results are expected in the field of metallurgy.

The theoretical work is oriented towards current problems in ferroelectrics, dielectrics and the magnetic properties of solids. Success has been achieved in improving general methods for the theoretical analysis of anharmonic effects in crystals [10], in developing methods for the interpretation of experimental results, and in devising new measurements [11].

During the last ten years of research activity, fruitful international co-operation was established, especially through joint teams of researchers (with Poland, Hungary, Czechoslovakia, Romania, the Soviet Union, Sweden, Belgium, etc.).

(b) Research related to the nuclear power program

Extensive theoretical and experimental work has been performed in reactor physics. Different methods of calculating cell parameters and burn-up have been developed and compared with the experimental results obtained on the RB and RA reactors. Some results of this activity are included in other papers in these Proceedings [12].

As part of the fuel-element development program, appropriate experimental methods for material and final product testing are being developed. To test the purity of uranium oxide in various phases of the sintering process, the reactor oscillator method is applied. A reactor oscillator installed on the reactor RB has been used extensively to determine nuclear impurities in uranium and other materials.

Due to the limitations of the laboratory techniques, we are not in a position to produce more than one type of fuel element. Hence, an experimental technique to determine the fuel element parameters, based on single-rod experiments, has been developed. The neutron source and neutron sink were selected as representative fuel element parameters. The experimental technique is based on the measurement of the neutron flux around the fuel element situated in a large thermal neutron cavity inside the RB reactor [13].

The research reactor RA with its high neutron flux is a good tool for fuel irradiation in capsules, although it is not convenient for fuel element in-pile loop experiments. Capsules with fuel pellets are normally inserted inside the hollow fuel element and irradiated with a fast neutron fluence of the order of 10^{20} n/cm^2. Thermal conductivity measurements are performed continuously to observe fuel pellet behaviour during irradiations. Capsule irradiations of structural materials such as steel, zircalloy, etc. are also carried out [14].

Reactor shielding experiments are performed with the TRIGA reactor. The bulk shielding facility with a ^{235}U converter plate was used at the beginning. To improve its usefulness, it was reconstructed as a dry-cell facility. In the new dry-cell, precise calibration of a set of threshold detectors for fast neutrons in a pure fission spectrum was done [15]. The intercalibration of threshold detectors to check the unfolding methods for the determination of spectra from threshold activation data is performed with spectra obtained by means of the single proton recoil spectrometer, NE-218.

Experiments on reactor kinetics and control were performed on all three reactors, the power spectra being measured by oscillator and noise techniques. Efforts have recently been directed towards digital processing and data acquisition from experiments and towards on-line digital control with two CDC 1700 computers connected to RA and TRIGA.

The logging, supervision and safety functions for the TRIGA reactor are programmed on a CDC 1700 computer to reduce the manpower requirements for steady-state operation of the reactor facility during night shifts. The hardware for the digital supervision system was developed in co-operation with the Rade Končar Electrotechnical Institute. This is a continuation of co-ordinated efforts in reactor control, started in 1967 when the reactor control system of that institute was tested by means of a synchronous reluctance motor on the TRIGA reactor [16].

(c) Radioisotope production and sample irradiation

The vertical channels of the RA reactor are used extensively for isotope production. During the last ten years, 14 756 specimens of different radioactive materials were delivered with a total activity of 45 610 Ci. The number of users (industrial enterprises, medical and scientific institutions) increased steadily, so that, by the end of 1970, there were 119 users in Yugoslavia and 33 abroad.

Isotope production with the TRIGA reactor is limited to short-lived isotopes, which are used for medical therapy, for research and for industrial applications, but mostly by the university or its institutes.

The irradiation facilities of TRIGA are used mainly for activation analysis. Of particular importance are the environmental studies, centred on the problem of mercury contamination of the biosphere. The distribution around the mercury mine and distillation plant, Idrija, Slovenia, is being measured to establish the tolerance levels and the possibility of living organisms adapting to increased concentrations [17].

4. CURRENT TRENDS IN RESEARCH REACTOR UTILIZATION

With the present situation on the world market, nuclear power stations can easily be purchased abroad and favourable arrangements can be made for the supply of fuel. For this reason the nuclear power research program in Yugoslavia has been substantially changed. It is now obvious that the nuclear power stations will be purchased and that domestic industry, in co-operation with a foreign partner, will be engaged in the production of plant components. For the first power station there is no direct need for fuel element development. According to present estimates, the role of the research and design organization will be to consult the power producing companies on the selection of the power plants and on their effective utilization.

The programs of the nuclear institutes in general and the research reactor program in particular must therefore be thoroughly revised. The lack of an extensive power research program reduces the utilization of the research reactors to meeting the direct needs of the nuclear centres and to future commitments in the technical development of the country. The reduction of the power research program and the decrease of funds for reactor operation make the situation rather complicated from the point of view of financing and future orientation. The need for reactors for fundamental research, isotope production and sample irradiation, and for training staff which will be solely occupied in nuclear activities will certainly not diminish. However, if these needs are taken into consideration, nuclear centres will find it difficult to estimate the economics of reactor operation, since a cost-benefit analysis in this respect is generally of little value.

The funds for basic research in solid-state and nuclear physics are limited in the government budget and such contributions represent only a fraction of the total reactor operating costs.

Radioisotope production cannot normally cover reactor operating costs either. The sale of isotopes depends to a large degree on the world prices and the capacity of the local market. In the case of the Yugoslav market, the sales can only cover additional costs for isotope production such as those for chemical treatment, hot-cell operations and transport, but sample irradiation costs must be covered separately.

Staff training is a good argument for reactor operation, especially if this kind of activity is directly related to university needs and includes student training and university research. Nevertheless, this activity is seldom provided with much financial support and can hardly contribute to the economical operation of research reactors.

In such a situation, the operating costs of a research reactor are of great concern to a research centre which has a limited power program, especially if the operation is expensive, which is always the case with high-power research reactors.

The Yugoslav research centres have experienced that the reactor operating costs are not too heavy a burden if they are a small fraction of the expenses of the research done with the reactor. This is the case with the TRIGA reactor, where the operating costs are only one third of the budget of the research groups using the reactor. Of the total Institute budget, the operating costs here represent less than 10%.

The research reactor RA has substantially higher operating costs due to its large operating staff and high fuel consumption. Much effort has been made to reduce the costs and to improve the experimental and irradiation facilities of the reactor. This effort is directed along the following lines:

- to reduce the operating staff to the minimum, while maintaining the safety of the reactor at an adequate level;
- to reduce fuel consumption by appropriate fuel management schemes;
- to increase the neutron flux by a change in fuel enrichment and by a flux-trap core arrangement, which will enable the production of isotopes with higher specific activity which obtain a higher price, and attract other research groups to utilize the reactor.

All these measures should reduce the operating costs to a level which could be acceptable when the nuclear power program is reduced to a minimum and the Institute is seeking new program orientation. There is always the last alternative, i.e. to cease reactor operation if the measures undertaken prove to be inadequate.

5. CONCLUSIONS

It is obvious that the role of research reactors in the promotion of nuclear activities should be considered within the framework of an existing nuclear research program. For a developing country like Yugoslavia, there are no reasons to give exceptional priority to nuclear research. In a new, balanced program the role of research reactors can be important if (i) the country has a need for nuclear power and (ii) specific plans in that respect are formulated. In such a case, the type and power of the reactor should be carefully selected. Some optimum must be found between the installation costs, operating expenses and the possibilities for experiment. For a country with limited funds for scientific research, this optimum should always tend towards a reactor with low operating costs. This is due to the fact that the most direct benefit should be expected from the education and training of staff who will be employed in various nuclear fields. Even a reactor with limited performance can here be adequately used. Basic research can also contribute to efficient utilization, but could hardly be the only reason for purchasing and operating a reactor. The domestic production of radioisotopes can stimulate their use in industrial and medical applications. This is one more reason for running a reactor, but the sale of radioisotopes cannot be expected to cover any significant fraction of the operating costs.

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