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# COLD NEUTRON IRRADIATION FACILITY FOR THE BRAZILIAN RESEARCH REACTORS

**Dante L. Voi[1], Daniel Ting[2], Francisco J. O. Ferreira[1], Luiz H. Claro[3] and Wilson J. Vieira[3]**

[1] Instituto de Engenharia Nuclear (IEN-CNEN-RJ)
Caixa Postal 68550
21945-970 Rio de Janeiro - RJ, Brazil
dante@ien.gov.br

[2]Instituto de Pesquisas Energéticas e Nucleares (IPEN-CNEN-SP)
Av. Lineu Prestes 2252
05508-000 Cidade Universitária - S.Paulo – SP, Brazil
dksting@ipen.br

[3]Instituto de Estudos Avançados (IEAv-CTA-MA)
Caixa Postal 6044
São José dos Campos - SP, Brazil

## ABSTRACT

Neutron irradiation in research reactors and accelerators can be realized at appropriated neutron guides or beam holes shared around a cold neutron source (CNS) with neutron of variable intensity and energy. An irradiation facility for multiple applications including an intense CNS was calculated for the three Brazilian research reactors and can be utilized as a first concept for the new research reactor to be designed, the Brazilian multiple purpose research reactor (RMB). A study about coolant and moderators properties, and simulations with neutron physics and thermal codes, may be important for the definition of the type of the CNS to be utilized. Some earlier results of MCNP simulations and a discussion about the different factors involved in the definition of its installation in the Brazilian research reactors are here presented. One suggests an international cooperation for the design development of this system and posterior construction of a prototype in the Argonauta reactor at the Instituto de Engenharia Nuclear (IEN-CNEN-RJ). It is also being considered the inclusion of other devices as a neutron fiber to guide the neutron beams away of the gamma radiation and fast neutron background. The cold neutron facility increases the intensity of cold neutrons, without the need of additional fuel burn up.

## 1. INTRODUCTION

No one doubts that a neutron source of high intensity and its facilities for material irradiation will always be of great interest for the nuclear laboratories around the world, but in general it is necessary high flux reactors, which demands high fuel burn up.

Neutron irradiation techniques are important for non-destructive material analysis. The recent results in the nanosciences and the genoma projects are examples of the needs for treatment in the atomic scale. However, it is limited for scientific investigations because it requires lower energy neutron beams, which are also limited to low intensities[1-3].

Neutron spectrometry and diffraction, tomography, and neutrongraphy are some examples of these techniques and they are the most widely used in material investigations.
Efforts has been done in the world to design and built research reactors and accelerators more economic and profitable. For most application it is necessary more and more intense cold neutron beams, and a CNS is indicated for these purposes [4].

In the southeast region of Brazil there are three research reactors with low and medium power. In the context of a CNS, in the 1970s an arrangement called Be-filter and time-of-flight spectrometer, it was constructed in the IEA-R1 reactor of the IPEN-CNEN-SP and used for inelastic scattering measurements. However, the low intensity of the neutron beam, resulted in several merit national and international publications[5].

At the IEN-CNEN-RJ in the 1990s studies were initiated to gain efficiency in the use of the neutron beams and improve neutron intensities in the Argonauta reactor. All the parameters involved in the design of neutron traps, mirrors and supermirrors, fibers and other devices were studied, specially cold, very cold and ultra cold neutron sources[4]. After this, the efforts went into the calculations of different types of CNSs. Monte Carlo simulations using the MCNP code for ours three research reactors for different geometry and moderators were performed with the cooperation of the Instituto de Estudos Avançados (IEAv-CTA-MA) group[6,7].

## 2. APPLICATION & JUSTIFICATION FOR THE INSTALLATION OF A CNS IN THE RMB

The facility one intends to construct permits to increase the local cold neutron flux with low thermal neutron flux perturbation in the reactor core, in such way to not expend more reactor fuel. It also permits the system utilization by several users at the same time with the CNS installed in a horizontal beam tube that supply cold neutrons to neutron guides. High neutron flux research reactor around the world have this type of installations.

### 2.1. High Flux Reactor (HFR) at ILL as a Reference

The HFR reactor at the Institute Laue-Langevin(ILL)-Grenoble-France is a reference in the world with its installations for investigations using neutrons. In contrast to earlier research reactor, all other functions ( irradiation materials, production of radio-isotopes, etc.) were excluded in order to avoid a diminution and perturbation of the neutron beams.

The core is under-moderated to constitute a neutron source for supplying the external heavy water reflector where the fast neutrons would be slowed down, creating a maximum thermal flux 15cm from the core. It is a form to attenuate the fast neutron and gama radiation background in the beams emerging from the reactor. The thermal neutron flux is $1{,}5 \times 10^{15}$ $n/cm^2/s$ in this location[8].

Neutron sources of different energy ranges it were installed in the heavy water reflector and sufficient space to provide room for the largest possible number of experimental beam-tubes. Thermal, epi-thermal and hot neutrons sources are distributed around the reactor core. In addition cold neutron sources also are disposable, supplying neutron guides for many experiments and also for production of very cold neutrons ($v \sim 50m/s$) and ultra cold neutrons ($v < 6m/s$) by the arrangement named neutron turbine. At side of these different neutron sources there are several types of instruments with many techniques using the neutrons of different energy ranges such as triple-axis spectrometers (TAS), time-of-flight spectrometry (TOF), small angle neutron scattering (SANS) and others[9] .

Considering the vast use in the fundamental physics, the applications are most realistic nowadays in the other areas of the sciences including medicine, biology and industry.

Internal protein dynamics is studied for example by quasielastic neutron scattering on TOF spectrometers for understand the steps of the photosynthetic transformation of light energy into storable chemical energy[10]. In the ship building industry, residual stresses in steel structures is the cause of rework at high cost of the assembly of the welded plates. Neutron diffraction measurements allow to manage the welding process[11].

## 2.2 Other Applications

The major CNS application view is in "1/v isotopes" irradiation, so that the reaction rate increases with the decreasing of the neutron energy. As example, the He-3 detectors used in neutron spectrometry and diffraction are more efficient for cold neutrons. The same happens in tomography with the boron position sensitive detector, and also in neutrongraphy, with gadolinium converter, improving the beam exposition time in the irradiations[4,5].

Taking B-10 for example, the reaction rate depends of its absorption neutron cross section that increases from ~ 900 barns to ~ 1700 barns as the neutron energy is lowered from 50meV to 5meV. Hence, there is a two fold increase in the reaction rate. The same occurs with other neutron absorbers isotopes such as Au-198, Cd-113, Dy-163 and In- 115.

The earth rare isotopes Gd, Er, Yb, Lu, Eu, Hf, W and Re, also give better results at irradiation in cold neutron flux, because the reaction rate is increased by a factor 3 or more. Many other applications are expected in other areas of the sciences such as, in medicine, for diagnostic and therapy. In biology, for cell studies, in the molecular structure and dynamics determinations of amino acids, proteins, enzymes, nucleic acids, and other cell components. It is also applicable in geology for datation, as well as for radioactive and not radioactive material analysis. One could even add applications in chemistry, metallurgy, agriculture, environment sciences and industry in general.

# 3. CNS CONCEPTUAL DESIGN, NEUTRON GUIDES AND OTHER ACESSORIES

Presently, are being prepared two CNS conceptual designs for the Argonauta reactor at the IEN-CNEN-RJ. One, with the CNS installed in the thermal column and another in a graphite moderator in the irradiation channel named plug–1 or plug-2. There is a prevision for radial cold neutron beams to be extracted from the CNS and could be distributed around the reactor hall and used by several experiments at the same time. Some of them could be taken in a appropriated room far from the CNS[12].

There are also two projects of CNS in study for the IPR-R1 reactor, one for extract neutron beam by vertical beam holes[13] and another, more elaborated, requires underground engineering works for the installation of horizontal beam holes.

At the IEA-R1 reactor, a new CNS design can be elaborated to improve scientific applications of the reactor. The reactor disposes of several beam holes for irradiations, but the CNS must be installed in the water pool or in a graphite or beryllium moderator near the reactor core.

The option of a neutron fiber used to bend the beam and to allow working without the fast neutron and gamma radiation background is being considered for the three reactors. Other facilities and instruments are being studied and can also be simulated by Monte Carlo codes

[9,14].

## 4. RESULTS

### 4.1. General CNS Design Calculation

In an attempt to design a CNS for our reactors, Monte Carlo simulations were performed for a heavy water CNS inserted in the water pool for the geometry of the IPR-R1 and IEA-R1 reactors, and for the CNS installed in the thermal column of the Argonauta reactor. The cold neutron intensity obtained for the CNS installed in water moderator is not as good as in graphite and it was showed in earliest publications [6,7].

As a principal result, in Figure 1 is shown the calculated neutron flux distribution in graphite moderator without and with the CNS , at normal ( 295K), liquid $N_2$ (77K), liquid $H_2$ ( 20 K) and liquid He (4.2K) temperatures. At 5meV energy, the cold neutron flux increases three decades in the heavy water as compared to the neutron flux in graphite.

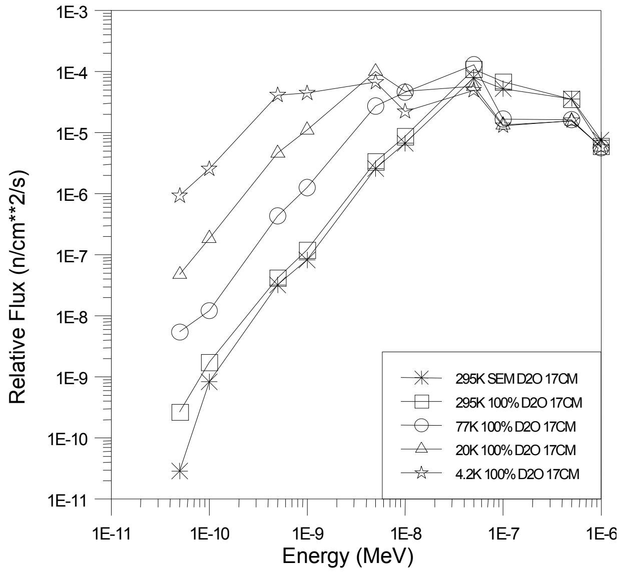

**Figure 1. Calculated Cold Neutron Flux for the CNS at Different Temperatures of D2O, Installed in a Graphite Moderator**

Following this general calculations it is made an analysis about the several possibility of the CNS installation and their facilities for each Brazilian reactor including the RMB.

## 5. PERPECTIVES FOR THE CNS OF THE RMB

### 5.1. CNS Installation in the Brazilian Research Reactors

The definition for the installation of a CNS prototype in one of the Brazilian reactors depends on the analysis of different factors. The neutron physics simulations with MCNP code is only one of them. Considering the nuclear heat generated where the CNS is located in the reactor core and the refrigeration of the CNS moderator, also are important thermal and structural simulations. Other aspects it needs to be discuss.

### 5.1.1. Neutron Physics Point-of-view

The installation of the CNS in the water pool of IPR-R1 TRIGA Mark I reactor, results in lower cold neutron intensity than if it were installed near the core in graphite moderator. Considering also the reactor conception that permits only vertical beam holes, becomes difficult to install any type of spectrometer at the level of the control room of the reactor.

Any arrangement of the CNS in the pool of the IPEN IEA-R1 reactor allows one to obtain good intensity of cold neutrons because of the high flux from the core. Throughout the beryllium or graphite moderator in the core, the cold neutron flux can achieve two or three decades more than the arrangement calculated for the IPR R-1 reactor. The problem is the reactor shut-down for a long period for the installation of these devices with the prejudice for the production of radioisotopes and its utilization for researches.

The CNS installed in a graphite moderator in the beam holes "plug-1" or "plug-2", as in a thermal column of the Argonauta reactor serves to define by the construction of a prototype to acquire knowledge, competence and human resources formation. It is usual to specify the gain factor of the cold moderator by the ratio between the cold neutron flux with and without the cold moderator. The installation in the direction of the channel J-9, the principal irradiation beam, gives origin to the higher thermal neutron flux and the cold neutron flux reaches gain factor of 30.

New calculations could be made with other cold moderators such as $H_2$, $D_2$, He, methane, ethane, etc., to get higher cold neutron intensity values. By the other side, the versatility of the Argonauta reactor for moving its parts is another important point to define it as a model to apply in the CNS of the RMB. However in this CNS, the materials could not be the same as the prototype, will be easy to perform it with the knowledge acquired. Also considering no new technology will be used because it is within the parameters of a number currently operating CNS around the world (ILL, FRM II, NIST, etc.)

### 5.1.2. Thermodynamics Point-of-view

In order to maintain the liquid moderator (in the case of $D_2$, $H_2$ or He) in the moderator chamber at the required cryogenic temperature of 20 K at about 0.2 MPa, the heat deposited by the neutrons during moderation must be removed, while maintaining the cryogenic conditions.

To have a comprehensive understanding of all parameters involved in the heat transfer processes occurring in the system under these odd pressure and temperature values, the thermodynamic properties of the $H_2$, $D_2$ or He must be determined as well as their physical properties such as the thermal conductivities, heat capacities and viscosities. Another challenge is to define the proper correlations to be used for the calculations of the convection heat transfer coefficients. Due to fairly significant temperature difference between the external environment and the moderator, radiation heat transfer might play an important role. A thorough bibliography research will be conducted and in some cases, experimental setups may be needed.

A first model based on a simple steady state heat balance with uniform temperature for each region will be developed to understand the heat transfer processes involved in an order of magnitude precision basis.

For detailed and precise modeling of the system, a full 3D model will be developed using a computational fluid dynamic program named CFX from ANSYS system. Calculations will be performed both for steady state operation as well as for an accidental condition like a sudden loss of cryogenic coolant flow which can cause a rise in the moderator chamber pressure with a potential for rupture of the vessel. In this later condition two phase flow models should be included.

In the experimental setup being proposed at the Argonaut reactor, some of the experiments to be conducted should include measurements which will allow for the verification of this thermal model.

## CONCLUSIONS

No one doubt that IPEN IEA-R1 reactor, a CNS facility can show the better results because of its higher flux than the others one. However comparative calculation must be made to prove these hypothesis, mainly because the calculation indicates that the better installation of the cold neutron source is in a thermal column

The installation of a CNS prototype in the Argonaut reactor is more indicated considering the results obtained in the graphite moderator as the surrounding medium the versatility to move accessories in the beam holes and to work near the core.

By the other side, the implementation of this project will bring, for our institutes, international cooperation, with exchange of know-how, and the participation of technicians of several areas of knowledge.

## REFERENCES

1. P.A. Egelstaff, “Thermal Neutron Scattering”, *Academic Press*, London and N.York, p.142-170, (1965B).
2. S. Hautecler. Et W. Van Dingenen, “ Étude Systématique de Sources de Neutrons Froids”, *Proceeding of the Symposium of Inelastic Scattering of Neutrons in Solids and Liquids*, Vienna, 11-14 Oct, (1960).
3. P. Ageron, “Neutron Research Facilities at the ILL High Flux Reactor”, Institut Laue-Langevin, Grenoble, France, Edition June (1986).
4. D.L. Voi, “Estudos de uma Armadilha de Nêutrons Frios para Aplicação em Geologia”, III ENAN, Águas de Lindóia, SP, (1995).
5. R. Zimmerman et all. “Neutron Cross-Sections of Praseodymium, Yterbium and Lutetium”, Publicação IEA nº75, November(1974).

6. D.L. Voi e outros, " Fonte de Nêutrons Frios para Aplicação em Reatores e Aceleradores", VII CGEN, Belo Horizonte, MG, 31/8 a 03/09, (1999).
7. D.L. Voi, "Design of a Multiple Purpose Neutron Irradiation Facility for the Argonaut Reactor", INAC 2005, Santos, SP, Brazil, August 28 to September 2, (2005)
8. Franzetti, F. " The ILL High Flux Reactor", ILL 20th Aniversary Publication, (1987).
9. Maier-Leibnitz,H. "The Early Stages of Instrument Development at the ILL, ILL 20th Aniversary Publication, (1987).
10. Biehl, R. et all."NSE Revels Protein Domain Motions in Space and Time" Annual Report ILL , (2008).
11. Davie,C.M. et all. " Managing Weld Distortion in Thin Steel Plates", Annual Report ILL , (2008)
12. Voi, D.L. " Multiple Purpose Irradiation Facilities for the Brazilian Research Reactors", World Triga Owners Conference, Minas Centro, Belo Horizonte, MG, Brazil, August (2006).
13. R.Stasiulevicius , "Experimentos Realizados com o Atual Extrator de Nêutrons e Perspectivas Futuras para o Reator TRIGA IPR-R1", *International Nuclear Atlantic Conference, INAC 2005*, Santos, SP, Brazil, August 28 to September 2, (2005)
14. E.Farhi et all. "Simulation of Neutron Guides and Instruments", *ILL Annual Report*, (2001)