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ISNP/GNEIS Facility in Gatchina for Neutron Testing With Atmospheric-Like Spectrum

Oleg A. Shcherbakov, Alexander S. Vorobyev, Alexei M. Gagarski, Larisa A. Vaishnene, Evgeni M. Ivanov, Vasily S. Anashin, *Senior Member, IEEE*, Linaris R. Bakirov, and Aleksandr E. Koziukov, *Member, IEEE*

***Abstract*—A description of the testing facility ISNP with spectrum resembling that of terrestrial neutron radiation developed at the PNPI (Gatchina) is given. A broad spectrum (1–1000 MeV) spallation neutron source of the facility with a neutron flux of $4 \cdot 10^5$ n/(cm^2·s) is used for accelerated soft error testing. High-quality collimation of the neutron beam in conjunction with the TOF-technique enables to carry out precise and reliable monitoring of the neutron beam. The results of recent tests carried out at the ISNP by the Branch of JSC "URSC" - "ISDE" (Moscow) are presented.**

***Index Terms*—Accelerated soft error test, standard spectrum, terrestrial neutrons, time-of-flight method.**

I. Introduction

At PRESENT the standardized accelerated soft error tests of electronic components using facilities with atmospheric -like neutron spectra are carried out at several centers, the LANSCE (Los Alamos, USA) Ice House being the best known one. Recently, the ROSCOSMOS testing facility ISNP (testing facility of the electronic components hardness control to atmospheric neutrons) [1] with the energy spectrum resembling that of atmospheric neutrons in a broad energy range 1–1000 MeV, the only one in Russia, has been developed at the B. P. Konstantinov Petersburg Nuclear Physics Institute of the National Research Centre "Kurchatov Institute" (Gatchina). In this report we present a description of the ISNP and its parameters in comparison with other similar facilities. The results of the electronic device tests and SEU cross section measurements recently carried out at the ISNP by the Branch of Joint Stock Company "United Rocket and Space Corporation"-"Institute of Space Device Engineering" (Moscow) are also presented.

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O. A. Shcherbakov is with the B. P. Konstantinov Petersburg Nuclear Physics Institute of National Research Centre "Kurchatov Institute", Gatchina 188300, Russia (e-mail: shcherba@pnpi.spb.ru).

A. S. Vorobyev, A. M. Gagarski, L. A. Vaishnene, and E. M. Ivanov are with the Petersburg Nuclear Physics Institute of National Research Centre "Kurchatov Institute", Gatchina 188300, Russia (e-mail: alexander.vorobyev@pnpi.spb.ru; gagarski@pnpi.spb.ru; vaishnen@pnpi.spb.ru; ivanovem@pnpi.spb.ru).

V. S. Anashin, L. R. Bakirov, and A. E. Koziukov are with the Branch of JSC "URSC"-"ISDE", Moscow 111250, Russia (e-mail: conf@niikp.org; npk1@niikp.org; npk1@niikp.org).

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II. Description of the ISNP

The ISNP facility was developed at the neutron time-of-flight spectrometer GNEIS (Fig. 1) based on the 1000 MeV proton synchrocyclotron of the PNPI [2]. The spectrometer was constructed to study neutron-nucleus interactions using the TOF technique at neutron energies ranging from $\sim 10^{-2}$ eV to several hundreds of MeV. The lead target located inside the accelerator vacuum chamber produces short (of width $\sim$10 ns) pulses of fast neutrons with a repetition rate of 45–50 Hz and average intensity up to $3 \cdot 10^{14}$ n/s. Five neutron beams are transported by means of evacuated flight tubes through the 6 m thick heavy concrete shielding wall of the accelerator main room into the experimental hall of the GNEIS. The beams are equipped with brass/steel collimators, steel shutters and concrete/steel beam dumps. A neutron beam #5 is ideally suited for accelerated tests of electronics with atmospheric-like neutrons because its axis comes through a surface of the neutron-production target. It has the hardest neutron spectrum in comparison with other beams of the GNEIS whose beam lines "look" at a polyethylene moderator (not shown in Fig. 1).

An arrangement of the experimental equipment of the ISNP testing facility is displayed in Fig. 2. During the irradiation of a DUT (device under test) located at the 36 m flight path of beam #5, control of the neutron beam shape/intensity and profile is carried out by means of the fission ionization chamber (FIC, beam monitor) and position sensitive multiwire proportional counter (MWPC, beam profile meter), respectively. The FIC is permanently placed in the neutron beam to continuously monitor its intensity during irradiations of the DUTs. The MWPC is installed close (downstream) to the FIC and is used either during the beam adjustment or during the whole irradiation shift. A data acquisition system of ISNP utilizes the 250 MSamples/s 12-bit Flash-ADC's for monitor and profile meter signals processing.

The internal diameter of the final collimator (1 m of length, nearest to the DUT location) has 3 fixed values of 50, 75, and 100 mm which can be changed before and during the irradiation test. The DUT(s) are located at fixed position(s) on a supporting table at room temperature or enclosed in a special box which can be moved with high accuracy in vertical and horizontal directions. The temperature inside the box can be changed by using an air heater within a range of $20\,^\circ\mathrm{C} - 120\,^\circ\mathrm{C}$. The box (DUT) position and internal temperature are controlled remotely from the operator control room which is located inside the GNEIS building at a distance of $\sim$25 m from the DUT location.

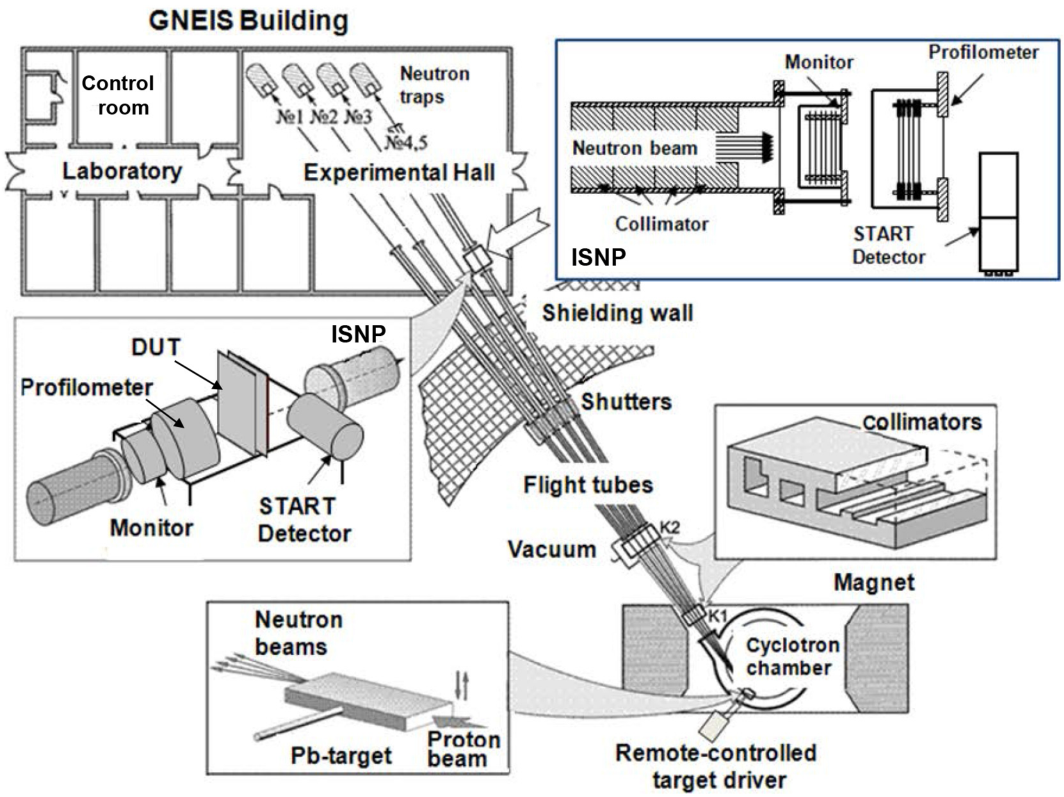

Fig. 1. General layout of the neutron time-of-flight spectrometer GNEIS and ISNP testing facility.

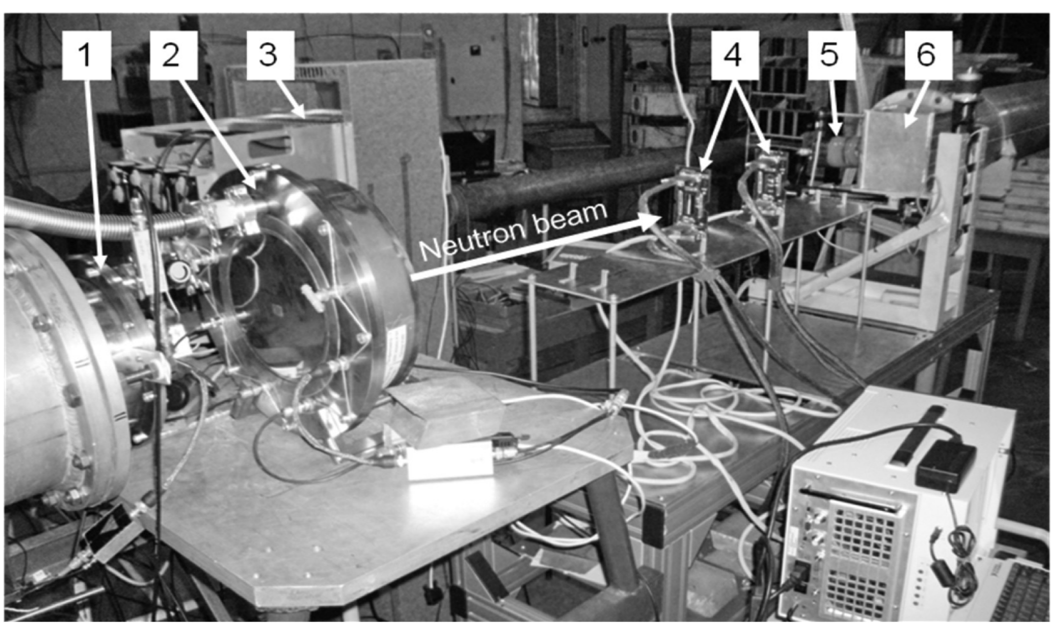

Fig. 2. Photo of the neutron beam line and experimental equipment of the ISNP facility: (1) FIC–beam monitor; (2) MWPC–beam profile meter; (3) data acquisition system; (4) DUTs; (5) START–detector; (6) box of the DUT- positioning/heating assembly.

III. Neutron Beam Parameters

The neutron beam of the ISNP facility has the following parameters:

1. neutron energy range: 1–1000 MeV;
2. neutron flux: $4 \cdot 10^5$ n/(cm$^2 \cdot$ s) (at the 36 m flight path);
3. beam diameter: 50–100 mm (at the 36 m flight path);
4. uniformity of the beam profile plateau: $\pm 10\%$.

The neutron flux of $4 \cdot 10^5$ n/(cm$^2 \cdot$ s) given above is an integral over neutron spectrum $F_{ISNP}(E)$ in the energy range 1–1000 MeV. It corresponds to the maximum value of 3 μA of the average internal proton beam current dumped into the neutron-production target.

The neutron flux and shape of the neutron spectrum are measured using FIC and TOF-technique. The FIC is a fast

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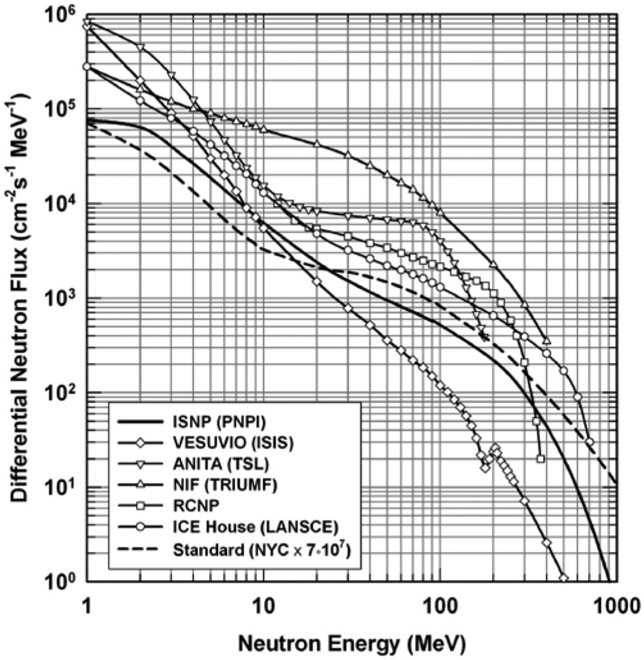

Fig. 3. Neutron spectrum $F_{ISNP}(E)$ of the ISNP facility compared to standard terrestrial neutron spectrum from JESD89A [5] and neutron spectra of five other testing facilities [6]–[10].

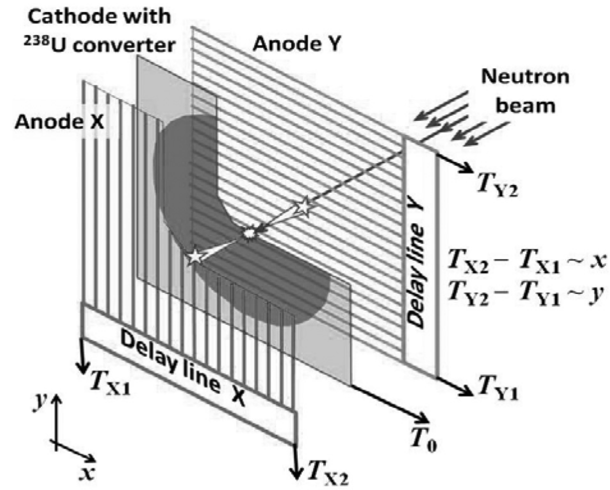

Fig. 4. Schematic view of the MWPC- neutron beam profile meter.

parallel-plate ionization chamber which contains two double-sided targets of ^{235}U and ^{238}U 120 mm in diameter and $200 - 300\ \mu\mathrm{g/cm}^2$ of thickness deposited on a 0.1 mm thick Al-foil backing. A choice of ^{235}U and ^{238}U as reference materials is explained by a fact that neutron fission cross sections of these nuclei are recommended standards in the energy range 1–200 MeV. These data are taken from the ENDF/B-VII.1 Library [3]. Neutron fission cross sections of ^{235}U and ^{238}U above 200 MeV are taken from the JENDL High Energy Library [4]. The TOF-spectra measured with ^{235}U and ^{238}U targets are transformed into the neutron energy spectra and after averaging are fitted with the analytic expression

$$F_{ISNP}(E) = 4.281 \cdot \exp(9.7999 + 0.5557 \cdot (\ln E) - 1.4006 \cdot (\ln E)^2 + 0.3706 \cdot (\ln E)^3 - 0.0312 \cdot (\ln E)^4) \quad (1)$$

where $F_{ISNP}(E)$- neutron energy spectrum, $\mathrm{n/(cm^2 \cdot s \cdot MeV)}$; E- neutron energy, MeV.

The neutron spectrum $F_{ISNP}(E)$ of the ISNP facility is shown in Fig. 3 in comparison with the JEDEC standard terrestrial neutron spectrum $F_{JEDEC}(E)$ from JESD89A [5] referenced to New York City (at sea level, outdoors, mid-level solar activity) and multiplied by scaling factor $7 \cdot 10^7$. Also given in Fig. 3 are the neutron spectra of the other testing facilities [6]–[10]. A brief comparison of the ISNP with other facilities shows that the shape of neutron spectrum of our facility is very close to the standard one competing with the ICE House (LANSCE) and having an advantage of ~200 MeV higher upper energy edge. At the same time, it is obvious that the ISNP neutron flux available at the DUT position is lower than that of other facilities. A more detailed comparison is given in Section IV.

The neutron beam profile is measured by means of MWPC– the two-coordinate position sensitive multiwire proportional counter $140 \times 140\ \mathrm{mm}^2$ of size. It is used for registration of fission fragments from the $^{238}\mathrm{U(n,f)}$-reaction induced by neutrons in a $100 - 150\ \mu\mathrm{g/cm}^2$ thick U- converter deposited on a 2 μm aluminized Mylar backing.

The MWPC consists of a cathode with U-converter and X, Y-anodes made of 25 μm gilded tungsten wires with 1 mm spacing and 3 mm anode-cathode gaps. Anode wires (140 in all) are connected parallel in pairs to the 70 taps of a delay line with a specific delay of 2 ns/step for coordinate information readout.

The timing signals from corresponding ends of the delays carry information about the position of neutron interaction with converter material and, therefore, about the beam profile. A spatial resolution of the MWPC is determined by wire spacing and lies within a range of 2 mm $< \mathrm{FWHM} <$ 4 mm. Schematic view of the MWPC and the principle of its operation are displayed in Fig. 4.

The 3D - distribution of neutron intensity in the beam measured using the MWPC with final collimator 75 mm in diameter is shown in Fig. 5. Horizontal and vertical neutron beam profiles obtained as sections of the 3D-distribution along X- and Y-axes, respectively, are shown in Fig. 6. The uniformity of the beam was evaluated by a calculation of a standard deviation of the data points within a plateau of distributions shown in Fig. 6: $\mathrm{StD(Y)} \approx 10\%$ and $\mathrm{StD(X)} \approx 11\%$. It should be mentioned that the 10–11% variations observed include the effect of counting uncertainties, the latter being equal to $1/\sqrt{\mathrm{N}} \approx 5\%$. Assuming that all uncertainties are independent and summed in quadrature, the beam uniformity was evaluated as equal to 9–10%. The background events observed on the "wings" of the profile distributions are mainly due to the "non-ideal" collimation of the neutron beam and separation of the fission fragments from other products of neutron-induced reactions in structural materials of the MWPC and the electronic noise. Anyway, the level of total background does not exceed ~1%.

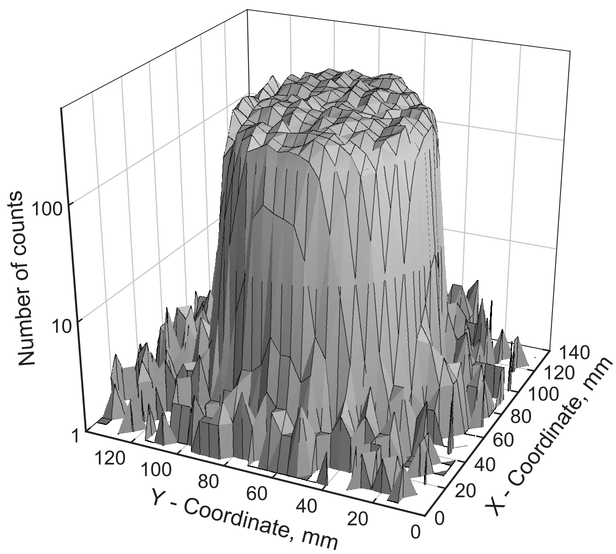

Fig. 5. 3D- neutron beam profile measured with the use of MWPC.

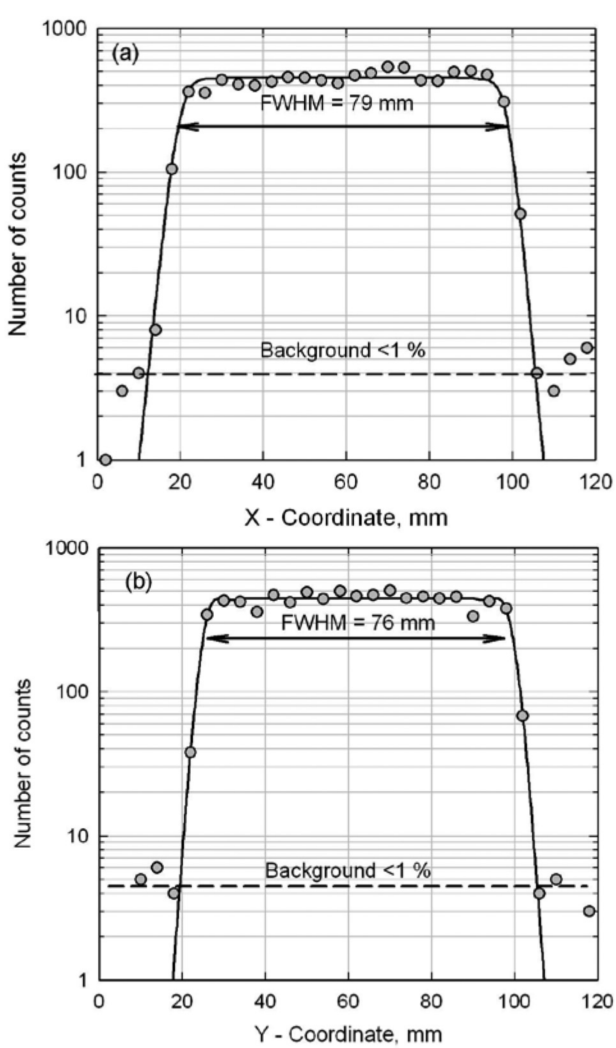

Fig. 6. Horizontal (a) and vertical (b) neutron beam profiles.

TABLE I
ACCELERATION FACTOR OF NEUTRON TEST FACILITIES

Facility (location, particle energy, target material)	Acceleration factor, A
ISNP (PNPI, Gatchina, Russia, 1000 MeV, lead) [1]	$4.6\cdot 10^7$
ICE House (LANSCE, Los Alamos, USA, 800 MeV, tungsten) [6]	$1.3\cdot 10^8$
ANITA (TSL, Uppsala, Sweden, 180 MeV, tungsten) [7]	$2.7\cdot 10^8$
RCNP (Osaka University, Japan, 400 MeV, lead) [8]	$1.8\cdot 10^8$
NIF (TRIUMF, UBC, Vancouver, Canada, 500 MeV, aluminum) [9]	$7.6\cdot 10^8$
VESUVIO (ISIS, RAL, Chilton, UK, 800 MeV, tungsten/tantalum) [10]	$1.5\cdot 10^7$

IV. COMPARISON WITH STANDARD AND OTHER NEUTRON SOURCES

Besides the ISNP test facility at the PNPI, there are at least five other facilities with atmospheric-like neutron spectra, currently used by semiconductor industries for accelerated tests of electronics [6]–[10]. These facilities use high-energy proton accelerators as neutron sources of various intensities, operation modes (continuous or pulsed), and neutron spectrum shapes. The simplest comparison of the various facilities can be done by taking into account only the neutron fluxes of these facilities. For this purpose, for any facility with differential neutron flux $F_{ACC}(E)$, the acceleration factor A defined by Eq. (2) is calculated, which characterizes its integral neutron flux relative to that of the standard terrestrial neutron spectrum:

$$A = \int_{E_{\min}}^{\infty} F_{ACC}(E)dE / \int_{E_{\min}}^{\infty} F_{JEDEC}(E)dE \qquad (2)$$

where E_{min} is the minimum neutron energy necessary to produce a SEE. In the JESD89A, it is postulated that $E_{min} = 10$ MeV. Acceleration factors calculated for the ISNP facility and other test facilities [6]–[10] using Eq. (2) are presented in Table I. It should be noted that current acceleration factors depend on a state of tune of the accelerator facilities. Therefore the data given in Table I must be taken as indicative values only.

For more realistic comparison of the testing facilities with different neutron spectrum shape and intensity, it's an accepted practice to use accelerated soft error rate (SER) calculated in accordance with Eq. (3):

$$R_{ACC} = \int_{E_{\min}}^{\infty} F_{ACC}(E)\cdot\sigma(E)dE \qquad (3)$$

As it is postulated in JESD89A, the energy dependent neutron soft error cross-section $\sigma(E)$ of a DUT can be approximated by a Weibull distribution

$$\sigma(E) = \sigma_0 \cdot (1 - \exp(-((E - E_0)/W)^S)) \qquad (4)$$

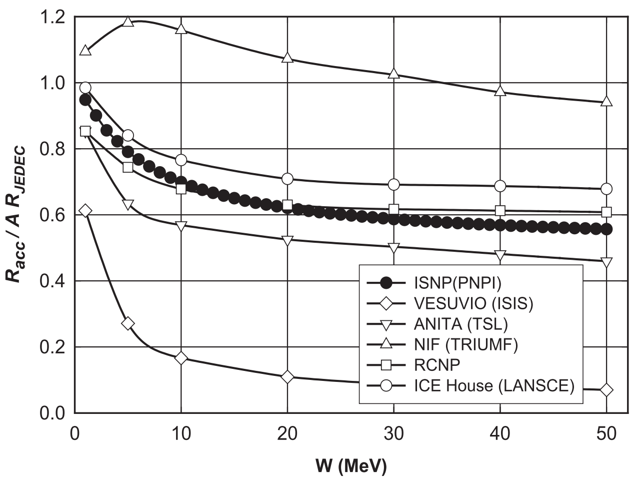

Fig. 7. Error in the SER estimate as a function of width parameter W for cutoff energy $E_0 = 1$ MeV and shape parameter $S = 1$.

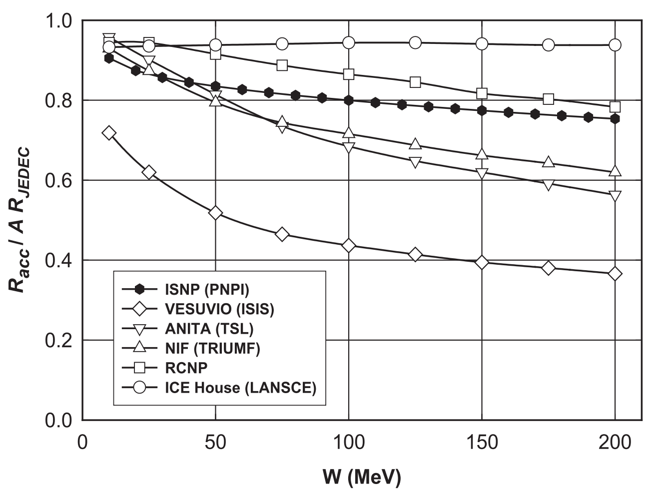

Fig. 8. Error in the SER estimate as a function of width parameter W for cutoff energy $E_0 = 10$ MeV and shape parameter $S = 1$.

where σ_0 is the asymptotic cross-section, E_0 is the cutoff energy, W and S are the width and shape parameters, respectively. The ratio of the accelerated SER measured at a given facility and the value obtained using standard JEDEC spectrum $R_{ACC}/A \cdot R_{JEDEC}$, calculated as a function of E_0, S and W parameters and normalized using the acceleration factor A, enables to evaluate the error in measured SER due to the deviation from the standard. As it was proposed by S. P. Platt et al. [11] and C. Slayman [12], [13], this ratio can be used for effective comparison of various testing facilities. Following C. Slayman, we have calculated the ratio $R_{acc}/A \cdot R_{JEDEC}$ for the ISNP and compared it with other facilities included in Table I. Fig. 7 to Fig. 11 show the ratio as a function of W with shape parameters $S = 1$ or 4 and cutoff energy parameter $E_0 = 1$, 10 or 100 MeV. With a given set of the parameters, it is possible to cover practically all types of the commercially available devices, including those produced using modern technologies.

The data presented for the case of electronic devices with especially low critical charge ($E_0 = 1$ MeV) predict that the

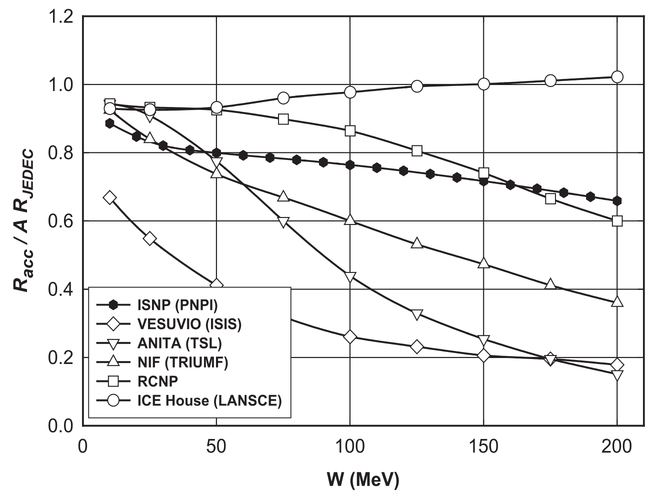

Fig. 9. Error in the SER estimate as a function of width parameter W for cutoff energy $E_0 = 10$ MeV and shape parameter $S = 4$.

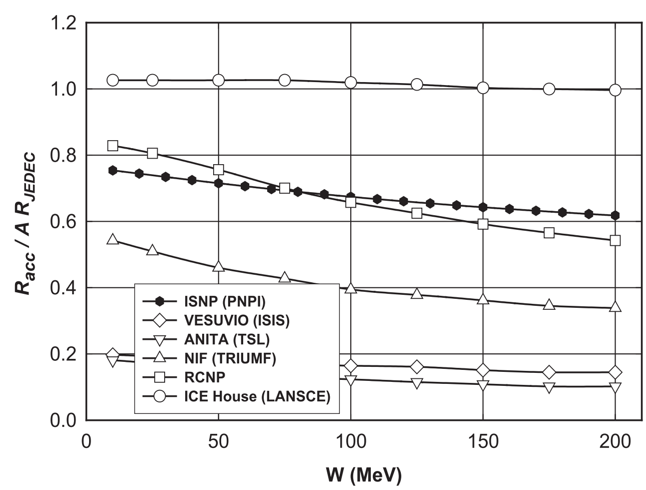

Fig. 10. Error in the SER estimate as a function of width parameter W for cutoff energy $E_0 = 100$ MeV and shape parameter $S = 1$.

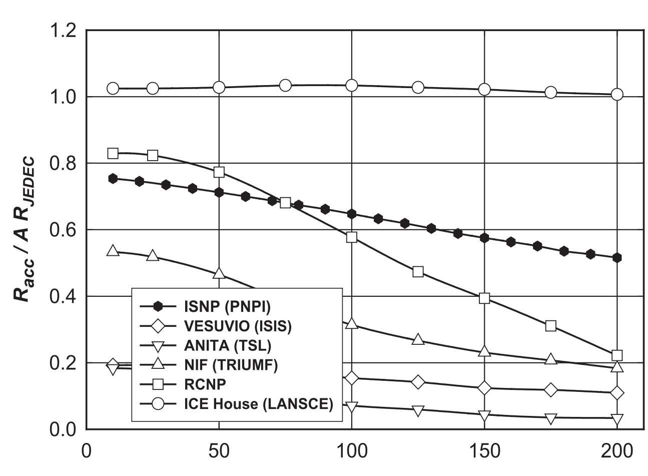

Fig. 11. Error in the SER estimate as a function of width parameter W for cutoff energy $E_0 = 100$ MeV and shape parameter $S = 4$.

value of SER measured at ISNP is 10–50% lower than the JEDEC standard measurement, the result comparable with that of LANSCE and RCNP. The data obtained for higher cutoff energy $E_0 = 10$ or 100 MeV (for devices with high critical charge) predict that a difference between ISNP and standard also does not exceed 25–50%.

A comparison with other facilities shows that the ISNP neutron beam has excellent characteristics for accelerated neutron testing. Summarizing, it should be emphasized that comparison of the test facilities regarding their neutron spectrum shape and applying the Weibull distribution is not undoubted. It needs further validation as the new experimental data on the energy dependence of SEE cross sections are accumulated. Also, such comparison is not intended for facility ranking but it can be used for planning and analysis of the SEE testing of vast variety of semiconductor devices.

V. Results of Electronic Component Tests at the ISNP

Various types of SRAMs have been tested at the ISNP facility. Upsets control was realized in a dynamic mode “Write-Store-Read-Compare-Write” as cycling execution of special “March” sequence consisting of alternating “0” and “1” stored in the memory, and then read and compared with the original. The simplified “March” algorithm in the form of Eq. (5) which is presented below:

$$\{\downarrow \mathrm{wX}; \downarrow (\mathrm{rX}, \mathrm{wY}, \mathrm{rY}); \downarrow (\mathrm{rY}, \mathrm{wX}, \mathrm{rX})\} \tag{5}$$

where $\downarrow -$ direction of address changing (from max to min); wX (wY)–operation of writing X (Y) value into memory with required address; rX (rY)–byte reading operation comprising X (Y) value (expected value during reading procedure).

During function control, a value of X in Eq. (5) is set to 55 h (5555 h) and value of Y is set to AAh (AAAAh). Procedure ($\downarrow$ wX) is executed before irradiation.

Elements $\downarrow (\mathrm{rX}, \mathrm{wY}, \mathrm{rY})$ and $\downarrow (\mathrm{rY}, \mathrm{wX}, \mathrm{rX})$ are cycled in SEU observation mode. All errors (faults) during operations rX and rY are stored for further analysis. For SEU effect the criterion of an error is incorrect values of X or Y during $\downarrow (\mathrm{rX} \ldots.)$ and $\downarrow (\mathrm{rY} \ldots.)$ operations executing.

In case of a mismatch, another reading operation was carried out, to be sure that the error is really an event in memory, rather than coming from a glitch in the signal line. In case of repeated discrepancy between the original data and read data both of these values were logged.

The results of the tests of 6 types of commercial Cypress SRAMs carried out recently by the Branch of JSC “URSC”-“ISDE” (Moscow) at the ISNP facility are shown in Table II. The SEU cross-section, σ_{SEU}, was calculated using the Eq. (6)

$$\sigma_{SEU} = \frac{N_{SEU}}{F_{ISNP} \cdot T \cdot N_{bit}} \tag{6}$$

where N_{SEU} is a the number of upset events in time T for a neutron flux F_{ISNP}, and N_{bit} is a number of bits per device under testing. The values of σ_{SEU} are given in column 6 of Table II, while the corresponding values of neutron fluence $F_{ISNP} \cdot T$ are given in column 5. The uncertainties of the measured values of σ_{SEU} calculated with 95% confidence level and 10% fluence precision are given in column 7 as upper and lower bounds of a confidence interval, σ^U_{SEU} and σ^L_{SEU}, respectively. The analogous data [14], [15] on σ_{SEU} for 256 Kbit - 4 Mbit and 130–500 nm technologies SRAMs from Cypress and other manufacturers demonstrate the same scale of σ_{SEU} cross sections. Average cross sections measured at LANSCE (Table III, Ref. [14]), $4.9 \cdot 10^{-14}$ cm^2/bit, and that of TRIUMF (Table II, Ref. [15]), $2.7 \cdot 10^{-14}$ cm^2/bit, are in agreement with our data, $5.5 \cdot 10^{-14}$ cm^2/bit, within a factor of 1.1 and 2, respectively. These results lead to the same conclusions which could be inferred from comparisons shown in Figs. 7 to 11. Admittedly, such an agreement should be perceived with reasonable caution taking into account a limited volume of analyzed statistical data.

TABLE II
Results of the SRAM Tests on Neutron Radiation Hardness

Part type	Process technol., nm	Size	Operat. Voltage, V	Fluence, n/cm^2	σ_{SEU}, cm^2/bit	σ^U_{SEU}, σ^L_{SEU}, cm^2/bit
A	250	1 Mbit	4.5	$2.0 \cdot 10^{9}$	$2.3 \cdot 10^{-14}$	$3.2 \cdot 10^{-14}$ $1.7 \cdot 10^{-14}$
B	90	256 Kbit	4.5	$9.2 \cdot 10^{9}$	$1.5 \cdot 10^{-14}$	$2.2 \cdot 10^{-14}$ $1.0 \cdot 10^{-14}$
C	350	64 Kbit	4.5	$1.7 \cdot 10^{10}$	$3.3 \cdot 10^{-14}$	$4.8 \cdot 10^{-14}$ $2.2 \cdot 10^{-14}$
D	90	4 Mbit	4.5	$1.0 \cdot 10^{9}$	$2.3 \cdot 10^{-13}$	$3.0 \cdot 10^{-13}$ $1.8 \cdot 10^{-13}$
E	150	4 Mbit	3.0	$5.0 \cdot 10^{8}$	$2.0 \cdot 10^{-14}$	$2.8 \cdot 10^{-14}$ $1.4 \cdot 10^{-14}$
F	90	4 Mbit	3.0	$6.6 \cdot 10^{8}$	$7.9 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$ $4.7 \cdot 10^{-15}$

The represented data correspond to the neutron fluence in the energy range 10–1000 MeV.

VI. Conclusion

The ROSCOSMOS testing facility ISNP with a broad atmospheric-like neutron spectrum has been developed at the PNPI. The main parameters of the ISNP neutron beam, namely: neutron spectrum shape in the energy range 1–1000 MeV, differential/integral neutron intensity, uniformity of the beam spot and quality of the beam collimation meet the requirements of the electronic industry standards for accelerated components testing. User-friendly possibilities are also available at the ISNP: user control of the beam intensity, remote control of the DUT-positioning/heating system with laser alignment, easy access to the DUT position without regard to the beam state (on or not), low neutron/gamma dose level in the user area, and on-line neutron/gamma alarm dosimetry. Besides the neutron tests, the proton radiation tests of components and systems are carried out at the PNPI using the special-purpose 1000 MeV and 200–1000 MeV proton beams [16]–[18].

The characteristics of the ISNP facility and practical results of the accelerated tests of various types of electronic components performed at the ISNP shows that it can be qualified as a high-grade neutron testing facility.

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