Environmental Thermal Neutron Flux in a Concrete Building for Implantable Device Therapy Assessment

Kamrun NAHER*, Hiroki IWAMOTO*, Yoshinori FUKUI*, Yusuke KOBA*, Minoru IMAMURA*, Yusuke UOZUMI* and Masahiro NAKANO**

*Graduate School of Engineering, Kyushu University
**University of Occupational and Environmental Health

(The paper was received on Sept. 15, 2008.)

Abstract: Since implantable device therapy utilizes microcomputers, soft-errors due to radiations are becoming the dominant reliability-failure mechanism. The environmental thermal neutron is one of serious causes of soft-errors. For analyzing thermal neutron fluxes, neutron measurements were conducted in a concrete building of Kyushu University of 11 stories by the use of two types of neutron detectors; one is bare \(^{3}\)He counter that is sensitive to thermal neutrons, and the other a neutron dose meter that consists of a \(^{3}\)He counter but sensitive to higher energy neutrons. Cosmic muons, which can produce neutrons via nuclear reactions, were also measured by a parallel plate plastic scintillator counter. The floor variation of flux has been compared with simulation results of the code PHITS and discussed.

Keywords Environmental neutrons, Thermal neutron flux, Single-Event upset, Implantable device therapy, Implantable Cardioverter-Defibrillator.

1. Introduction

Device therapy using an implantable cardioverter defibrillator or a programmable pacemaker has demonstrated its usefulness in recent years, and the number of patients receiving device therapy has risen exponentially. An implantable cardioverter defibrillator (ICD) is used to prevent sudden death from cardiac arrest due to tachycardia of abnormally fast heart rhythms. The ICD is a small electronic device installed inside the chest, and monitors the heart rhythm. When the ICD detects a life-threatening tachycardia or fibrillation, it delivers electrical shocks to the heart to terminate the abnormal rhythm.

Since ICD devices contain microcomputers that run sophisticated programs, they are susceptible to hit of charged radiations [e.g., 1-3]. When particulate radiations strike a sensitive region in a semiconductor device, they generate a dense local track of electron-hole pairs. This may be collected by a \(p-n\) junction resulting in a current pulse of very short duration termed a single-event upset (SEU), which may cause a bit flip in some latch or memory element. Thereby a SEU can alter the state of the system resulting in a soft error. Especially, memories contain huge number and density of bits susceptible to particle strikes. As process technology scales below 100 nanometers, high-density, low-cost, high-performance integrated circuits, characterized by high operating frequencies, low voltage levels, and small noise margins will be increasingly susceptible to SEUs and that this will result in unacceptable soft error failure in the ICD.

Recent studies on modern electronics [4] show that the use of boron-based glasses and BPSG (Borophosphosilicate glass) in integrated circuits makes them very sensitive to thermal neutrons, which are of energies of around 0.025 eV, because of the \(^{10}\)B(n, \(\alpha\)) reactions. An understanding of the soft-error rate is vitally important for the high reliability requirements and life-supporting nature of the application. The flux of thermal neutrons was measured by several authors. However, the measurement locations were limited...
solely to sea level or very high altitude [5, 6]. No reports so far has appeared on the flux measurement inside high-rise concrete buildings, where soft-errors may occur at a higher frequency than other places.

In the present work, we measure the flux of thermal neutrons in an eleven-story concrete building by using two different detector systems. Cosmic muons are also measured because they are one of possible sources of terrestrial neutrons. The resultant floor variation of flux is compared with PHITS [7], which is one of the most powerful simulation codes for the radiation transport.

2. Experiments

The number of neutrons was counted by the use of typical counter systems. Two types of $^3$He counters were used; one was a cylindrical tube with 30-mm diameter and 300-mm length. The other was a neutron dose meter which was operated under a pulse mode. Both of them were commercial gas proportional counters filled with the $^3$He gas. The former one is sensitive to thermal neutrons, meanwhile the latter sensitive to fast neutrons of a few MeV range. The electronics system for counting signal pulses was the most typical one constructed with the standard slow NIM modules. The detectors and the electronics are shown in Figs. 1 and 2, respectively.

Cosmic muons were measured by a parallel-plate counter, which was composed of three plastic scintillator plates having a 28-cm long, 20-cm wide and 1-cm thick. Each plastic scintillator was connected to a HAMAMATSU photomultiplier tube (PMT). Signals from each PMT were fed into a fast discriminator and a coincidence module, as shown in Fig. 3. Then, output logic signals of the NIM standard were counted up by a CAMAC counter. The timing coincidence generated by the NIM module was used to identify events of muons that passed through three plastic scintillators. The lowest energy of recordable muons was 30 MeV, which is high enough to induce nuclear reactions leading to neutron productions.

Measurements for neutrons and muons were carried out at a Kyushu University building in its Ito campus, Nishi-ku, Fukuoka-shi, Japan. The building is a concrete one of 11-stories on the ground and one-story underground. The thickness of the floor concrete is 15 cm, and each floor has a 3-m height. We conducted measurements at floors of 11th, ninth, eighth, seventh, third, first and underground in the period from August 2007 to June 2008.

![Fig. 1 Photo of the bare $^3$He detector (left) and the neutron dose meter (right).](image1)

![Fig. 2 Diagram of electronics for neutron counting system coupled to $^3$He detector.](image2)

![Fig. 3 Sketch and diagram of electronics for cosmic muon measurement system. Muons penetrating three scintillators are only recorded.](image3)
scatter broadly, and hence only average values are shown here. The solar activity has been reported to be almost constant [8] in our measurement period. It must be noted that our data are just the raw data, and have not been normalized in terms of the detector efficiencies. Therefore, absolute values have no sense in our present data. The procedure to determine the neutron detection efficiency is very complicated and needs a special place of the standard neutron field. The efficiency of the muon detector depends on its solid angle and the angular distribution of muons, which is known only in atmospheric circumstance but not known in a concrete building. These efficiency studies and the normalization for absolute fluxes will be made in our future work.

In Fig.4, the muon flux shows a clear tendency of exponential attenuation from the eleventh floor down to the underground. This tendency would be reasonably accountable by the muon loss in concrete floors. Since muons are a charged particle which has a very similar nature to electrons, they lose their kinetic energies and can be stopped in concrete slabs via the electronic interaction with the concrete material.

As for neutron fluxes, the almost same tendency can be found between the thermal and the fast neutrons: Both of them show an exponential attenuation from the eleventh floor to the seventh, and then rise up rather significantly at the third floor. The underground fluxes are also considered to be larger than the values expected from a simple exponential attenuation from the upper floors.

4. Discussion
4.1 Window effect of neutron fluxes
The neutron flux of the third floor seems to be too large. This would be understood in terms of window effect, which is that neutrons in atmosphere can enter a concrete building through glass windows. It has been pointed out [9] that the neutron flux inside a concrete room increases with the window area. They found a roughly proportional relation between the flux increase and the window area.

The room of the third floor has a large window as about double as other rooms. All other rooms used in the present experiments have the same window area except for that of the underground floor. Therefore, we made the value of the third floor data a half, and the resultant thermal neutron flux is plotted in Fig.5. It
should be remarkable that the data from the 11th floor to the third are on an exponential line. It means that the floor variation would be accounted for cosmic neutron attenuation by concrete floor thickness, \( x \). The neutron flux \( f(x) \) can possibly be written by

\[
f(x) = \phi_n^0 \exp\left(-\frac{x}{\lambda_n}\right),
\]

where \( \phi_n^0 \) is the neutron flux before absorption by concrete, and \( \lambda_n \), the neutron attenuation length. Values of \( \lambda_n \) for concrete are estimated to be about 11 cm at 5 to 30 MeV, and 49 cm above 250 MeV from the nuclear data base [10]. The present result is consistent with that of high-energy neutrons. Nuclear reactions producing neutrons might be an essential source of neutron flux in concrete buildings.

This slope is about three times larger than that of the muons. The typical absorption lengths in the low altitudes atmosphere [6] are known as

- Neutrons: \( L_n = 148 \mu g/cm^2 \),
- Muons: \( L_\mu = 520 \mu g/cm^2 \)

This difference implies that neutrons are absorbed about 3.5 times more than muons. Hence, this may be consistent with the slope difference of about three times.

The cause which rises up the value of the underground data should be understood from different view points. The first possible cause may be ascribed to the neutrons scattered back from the ground soil. Terrestrial cosmic neutrons have an extremely wide energy distribution up to several GeV. A great number of neutrons have enough energy to penetrate the building, and back scattered by the thick ground soil. The second one may be \((\alpha, n)\) reactions, which are induced by \(\alpha\)-ray emitters in atmosphere. It is widely known that the \(\alpha\)-emitter, \(^{222}Rn\) is the most abundant background radiation in the atmosphere. It is the production in the \(\alpha\)-decay chain of the uranium series:

\[
^{238}U \rightarrow \cdots \rightarrow ^{226}Ra \rightarrow ^{222}Rn \rightarrow ^{218}Po \rightarrow \cdots,
\]

and this series finally terminated at stable \(^{206}Pb\). Since this series takes place in concrete, rock and soil, basement air concentration is expected to be quite higher than outdoor. The third one might be muon-induced nuclear reactions. As shown in Fig. 4, the muon flux decreases gradually from the higher floor to the lower, but the neutron flux decreases much faster. Therefore, the contribution of muon-induced reactions may become higher and rather noticeable than in the upper floor.

4.2 Comparison with PHITS simulation

There has been developed several large-scale codes for radiation transport simulations. The code PHITS is one of the most powerful tools covering almost full range of electronic and nuclear processes and applied for dose estimation in radiation therapy [11] in recent years. Since the code PHITS is expected in the field of SEU, it is useful to examine its predictive power through comparison with our data. The simulation condition in the work was that of the source area
of 15 by 15 cm\(^2\) and the energy differential flux of
cosmic neutrons given in Ref. [5]. And the information
of the Kyushu university building, such as thickness
and material of floors and roof was taken into consid-
eration. The surrounding walls were ignored and each
floor was assumed to be infinitely wide.

Resultant fluxes of energy distribution and floor
variation are shown in Figs. 6 and 7, respectively. Due
to poor statistics, low-energy neutron data scatter very
much. It is, however, clear that the lower energy neu-
trons are lost too rapidly in this simulation. It should
be noticed that neutrons of near thermal energy range
are absorbed by the 15-cm thick concrete wall.

Since the present PHITS simulation ignored \((a,n)\)
reactions and neutrons reflected by the ground, the
calculated results may underestimate in the lower
floors. The more serious problem is that the source
area might be too narrow. It was chosen for reasonable
CPU time of a few days, but should be wide enough
for neutron diffusion to reach equilibrium.

5. Conclusion

We measured the flux of thermal neutrons, fast
neutrons and cosmic muons in a concrete building of
Kyushu University for implantable device therapy
assessment. The muon flux shows a clear tendency of
exponential attenuation. As for neutron fluxes, it de-
creases in an exponential way in the higher floors, but
rather unexpected rise-up appears at the lower and
underground floors. The cause of this enhancement
was discussed but further research is indispensable.
Simulation results of the PHITS calculation are found
to give too much less of neutrons, and some improve-
ments are needed to be used in the assessment study.
For more precise and quantitative discussion, neutron
detectors are needed to be recalibrated at a standard
neutron field, and then the possible SEU rate will be
investigated.

Acknowledgement

One of authors, K.N. is deeply grateful to Japanese
Ministry of Education, Culture, Sports, Science and
Technology for their support in Japan.

References

[1] Rodriguez, F., Filimonov, A., Henning, A., Coughlin,
C., Greenberg, M.; Radiation-induced effects in

multiprogrammable pacemakers and implantable de-
induced by radiotherapy, Pace, vol.17, pp.270-273,
1994.
[3] Bradley, P. D., and Normand, E.; Single Event Up-
sets in implantable cardioverter defibrillators, IEEE
Trans. Nuclear Sciences, Vol. 45, pp.2929-2340,
1998.
\(^{10}\)B fission as a major source of soft errors in deep
submicron SRAM devices, Proceedings of IEEE
Terrestrial Thermal neutrons, IEEE Trans. Nuclear
transport code system, Radiation Measurements, Vol.
Atmospheric Cosmic-ray Spectrum”; http://
www.jaea.go.jp/04nsedcrs/radiation/rpro/EXPACS/
expacs.html
Natural Background Neutron Dose, IEEE Trans.
[10] National Nuclear Data Center of Brookheven Na-
tional Laboratory: ENDF/B-VI: neutron-induced
Monte Carlo Code PHITS for Heavy Ion Therapy,
Journal of Nuclear Science and Technology, Vol. 42,