Radiation-Tolerance Assessment of a Redundant Wireless Device

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Abstract— **This paper presents a method to evaluate radiation-tolerance without physical tests for a commercial off-the-shelf (COTS)-based monitoring device for high level radiation fields, such as those found in post-accident conditions in a nuclear power plant (NPP). This paper specifically describes the analysis of radiation environment in a severe accident, radiation damages in electronics, and the redundant solution used to prolong the life of the system, as well as the evaluation method for radiation protection and the analysis method of system reliability. As a case study, a wireless monitoring device with redundant and diversified channels is evaluated by using the developed method. The study results and system assessment data show that, under the given radiation condition, performance of the redundant device is more reliable and more robust than those non-redundant devices. The developed redundant wireless monitoring device is therefore able to apply in those conditions (up to *10 M Rad (Si)*) during a severe accident in a NPP.**

***Index Terms*— COTS, radiation-tolerance assessment, rad-hardened by design**

I. Introduction

SEMICONDUCTOR-BASED electronic systems are highly susceptible to high energy particles present in strong radiation fields, such as those in aeronautics and space sectors, nuclear power plants, and the nuclear warfare. Taken Fukushima Daiichi nuclear disaster as an example, one of the lessons learnt is the level of difficulty to obtain environmental conditions inside the plant due to the presence of large amount of radioactive substances, which can cause damages to semi-conductor based devices and systems. One approach to levitate such a problem is to employ radiation hardened (rad-hardened) devices in such systems. Preliminary analysis indicates, however, that this approach is prohibitively expensive. Furthermore, many new data processing algorithms and communication technologies require devices to support high speed, large storage, and low power consumption. Rad-hardened devices may not even meet those advanced system requirements. Another approach is to rely on regular commercial off-the-shelf (COTS) devices, but to utilize rad-hardened techniques to reduce the vulnerability of radiation effects and to prolong the life of the system during the mission of the deployment. One approach is to take advantage of the triplication of important circuits and subsystems to detect and to correct radiation induced errors. Needless to say, the assessment of the radiation-tolerance is a critical step in such design.

In general, the performance of rad-hardened systems can be evaluated in two ways: (1) physical tests: which uses external perturbation sources (natural and accelerated particle radiation, laser beam, pin forcing, etc.) to create a similar radiation environment to evaluate the performance of the design. This approach is very precise but could be excessively complicated and expensive; and (2) simulation with analysis: which uses logic relationships of the circuits and systems to access internal elements and insert the effect of a radiation induced fault according to the fault model. However, a limitation of this approach is that it is difficult to assess the radiation-tolerance of the whole system [1]. To address these issues, a new approach by combining the radiation protection and the rad-hardened design is developed. To demonstrate this method, a wireless monitoring device is developed for high level radiation fields during a serve accident in nuclear power plants.

The reminder of the paper is organized as follows. Post-accident environments, radiation damages on electronics, as well as potential solutions are described in detail in Section II with the problem statement. Subsequently, the evaluation of radiation protection scheme is discussed in Section III. The radiation-tolerance assessment of a redundant architecture is discussed in Section IV. Finally, using a wireless monitoring device as an example, the implementation and the assessment of its radiation-tolerance are presented in Section V.

II. Analysis of Radiation Damages

A. Post-Accident Environments in NPPs and Radiation Effects on Electronics

In the event of a nuclear accident, a significant amount of radiation can be released, which may include alpha (α), beta (β) particles, gamma (γ) rays, *x*-rays, and neutron particles [2]. Taken Fukushima Daiichi disaster as an example, in February 2017, the level of radiation particles from melted fuel has been estimated up to 530 *Sv/h* inside the containment of No.2 reactor [3]. This level of radiation is so high that can cause severe damages to electronic devices if deployed there.

In general, radiation particles lose their energy through either non-ionization processes (displacement damage) and/or ionization processes when they pass through semiconductor devices. Radiation effects on electronics can generally be classified into three categories:

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(1) Displacement damage (DD), which is caused by long-term non-ionizing effects, when incident particles have enough energy to knock an atom free from its normal lattice structure in the semiconductor and onto an interstitial site. It will change properties of the device and lead to permanent damage [4];

(2) Total ionizing dose (TID), which refers to the total amount of energy deposited by the particles passing through semiconductor materials. It is an important consideration when semiconductors devices are exposed to a strong radiation environment [5]; and

(3) Single event effect (SEE), which is primarily caused by single particle ionization and/or secondary particle formation. According to the failure mechanism of semiconductor materials, a single event effect can further be divided into two types: (1) non-destructive effects, which can be recovered by performing a system reset, or data re-initialization, including single event transient (SET), single event upset (SEU), and single event functional interrupt (SEFI); and (2) destructive effects, which are terminal and cannot be recovered, including single event latchup (SEL), single event snapback (SES), single event burnout (SEB), and single event gate rupture (SEGR) [6].

This work mainly focuses on the damages due to ionizing radiation. Displacement damages are therefore not considered. Considering short-term radioactive release (less than *24* hours) in each stage of a nuclear accident [7], it is assumed that the post-accident monitoring devices have to survive the first 24 hours of the accident. Taking the highest level of radiation in the Fukushima accident (*530 Sv/h*) as the radiation rate, the total radiation dose after the first *24* hours can be obtained as follows:

$$R = 530\,Sv/h \times 24\,h = 12720\ Sv = 1272.0\ K\ Rad\ (Si).$$

Total radiation dose (*10 M Rad (Si)*) are considered as the limit in this work.

B. A Potential Solution

1) Radiation Protection to Mitigate Damages of Total Dose

As shown in Fig.1, most semiconductor devices will experience radiation damages when the total radiation dose is more than *20 K Rad (Si) (1 Gy = 100 Rad (Si))* [8]. Electronic systems made with regular COTS components will definitely be damaged if it is directly exposed to a radiation environment whose total dose is *10 M* Rad (Si). Radiation protection is an effective solution to mitigate radiation damages for the total dose. The reliability and the lifespan of electronic systems are determined by the type of radiation it is exposed to, the radiation resistance of its semiconductors, and the properties of the shielding materials used [9]. In this work, radiation protection is used where ever necessary to reduce the total dose to less than *20 K* Rad (Si).

2) Radiation Protection to Mitigate Damages of Total Dose

On the other hand, radiation shielding is not effectively against single event effects [10]. Since system recovery and

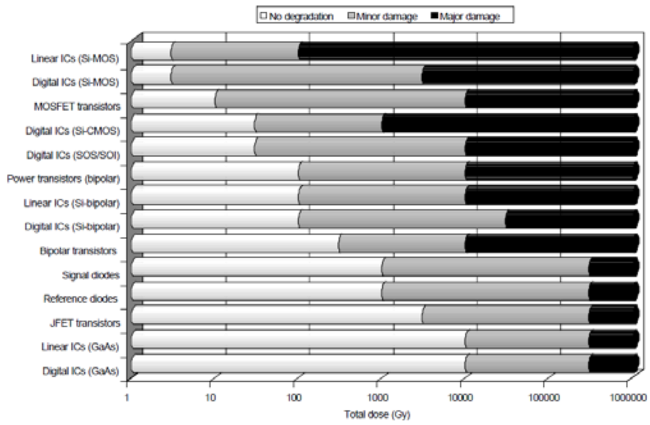

Fig. 1. Radiation tolerance by a family of COTS components [8]

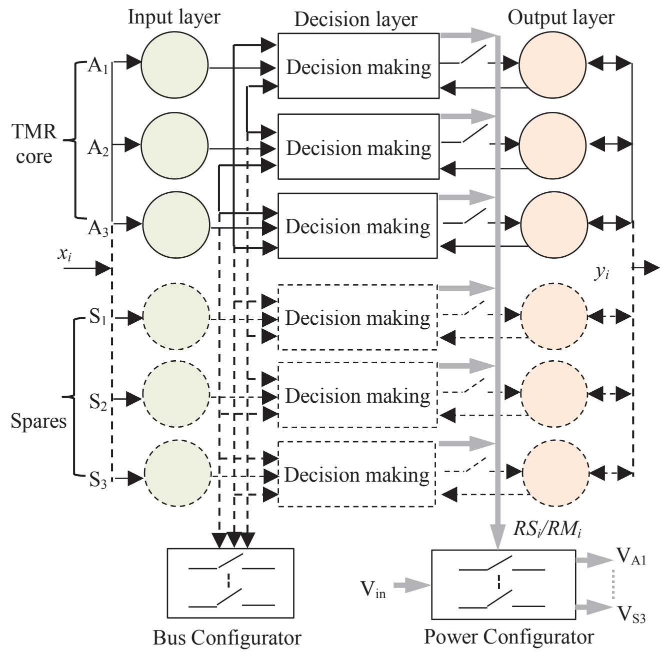

Fig. 2. The proposed rad-hardening architecture

timely power off reset can be effective against radiation damages, in this work, a radiation-tolerant architecture, shown in Fig.2, is developed to prolong both device and system life through independent built-in redundant channels, on-line fault detection, real-time preventive remedial actions, and rapid power off/on recovery, as well as reduction of common-mode damage modes. The architecture consists of an active triple modular redundancy (TMR) core with spare units for replacement of the failed active one. Both measurements and self-diagnosis functions are accomplished in the TMR core.

Each channel can be divided into three layers: the input layer, the decision layer, and the output layer. Self-diagnostic functions, such as fault detection, fault diagnosis, prognostic assessment, and reconfiguration suggestions, are accomplished in the decision layer. The decision layer has two types of buses: an internal bus, which is used to exchange information with other channels; and an *IO* bus, which is used for the master selection. All buses are independent, so other channels will work normally when one channel fails or has faults. More specifically, a "configurator" is designed to guarantee that the system only ever has three channels working simultaneously and is built with passive devices, such as resistance, capacitance, and non-electronic relays, etc., which are not sensitive to ionizing radiation. The configurator therefore can withstand a high level radiation.

The operating principle of the proposed system works as follows: when one channel has faults or fails to operate, which will be detected by the function of self-diagnosis and/or the function external-diagnosis; then, decision-making units in other channels will generate the reconfiguration suggestions to cut power supply in a timely manner and its space channel will power-on to form a new TMR core. A number of radiation tolerant strategies are involved in protecting the system when one channel encounters radiation damages. These are summarized in Tab. I.

C. *Problem Statement*

The objective of this paper is to:

(1) To evaluate the effectiveness of the proposed radiation protection architecture; and

(2) To establish reliability assessment model against radiation damages.

III. Evaluation of Radiation Protection

A. *Notations*

u	the attenuation coefficient of shielding material
u_l	the linear attenuation coefficient of shielding material
p	the density of shielding material
d	the shielding material thickness
I	the intensity after passing the shielding thickness d
I_0	the original intensity
B	the build-up factor, is greater than 1
E	the energy of the gamma radiation

B. *Attenuation of Gamma Radiation*

When gamma radiation passes through a material under conditions of a 'good' geometry, as shown in Fig.3, a straight-line relationship between the logarithm of the intensity and the thickness of the shielding can be illustrated as follows [11]:

$$I = I_0 e^{-ud}. \tag{1}$$

The linear attenuation coefficient (u) is the probability per unit thickness that particles interact with the material. This value is dependent upon the atomic number Z of the material and its density (p). This relation can also be described through the use of the linear attenuation coefficient as follows [12]:

$$I = I_0 e^{-(u_l/p)(pd)}. \tag{2}$$

C. *Build-up Factor*

However, under conditions of a 'poor' geometry, as shown in Fig.4, Eqn. (1) underestimates the required shielding thickness. The shielding thickness can be estimated by the use of a build-up factor (B), which is defined as the ratio of the intensity of the radiation at any point in a beam to the intensity of the primary radiation only at that point; it can be a function of the total attenuation coefficient, the thickness of shielding material, and the energy of the gamma radiation [10-13]. Eqn.2 can, therefore, be estimated by Eqn.3 [11].

$$I = B(ud, E)\cdot I_0 \cdot e^{-(u_l/p)(pd)}. \tag{3}$$

Build-up factors have been calculated for different levels of gamma energies and for various shielding materials, which can be found in "American National Standard for Gamma-Ray Attenuation Coefficients and Buildup Factor for Engineering Materials", ANSI/ANS-6.4.3-1991 [14].

TABLE I
Summary of Radiation-Tolerant Strategies

Tolerant strategies	Description
Hardware selection	To investigate radiation hardness of different semiconductor technologies and devices; and to select COTS components with high radiation resistance.
Diversity	Enforcing differences, such as different semiconductor technologies but functionally equivalent components, different software and algorithms for the same function, etc., are applied to achieve the diversity.
Multi-processor cooperation	Redundancy communication buses and *IO* checking bus; when one channel has non-responsive failure or wrong messages, it will be reset or power off.
Self-test technology	Self-test techniques, such as monitoring voltage and current, CPU self-checking, etc.; the recovery strategies will be triggered when they are out of range.
Watchdog timer	Combined with hardware watchdog and software watchdog.
Modular software design	Many modules with different functions, error detection and correction are used for the recovery strategies.
Prognostic assessment	Accurately prediction of the circuit performance according to present measurement and the analysis of devices responses, then make a decision to the reconfigurator.
Fault detection and diagnosis	Online analysis of radiation responses of devices and circuits to timely diagnose the radiation fault for fast recovery.

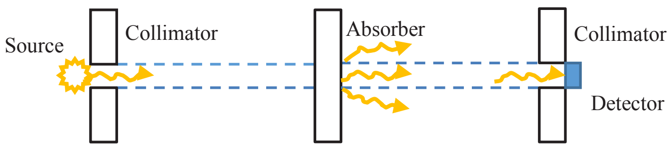

Fig. 3. Measurement of the attenuation of gamma radiation under conditions of 'good' geometry [11]

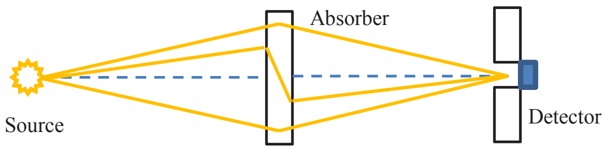

Fig. 4. Gamma radiation attenuation under conditions of broad beam geometry [11].

D. Calculation of Shielding Thickness

As previous discussion, with the given radiation source, the given radiation dose rate, and the known shielding material, based on Eqn.1 to Eqn.3, the required shielding thickness under a poor geometry can be calculated as follows:

$$d = \ln\left(B \cdot {}^{I_0}\!/_{I} \right) \Big/ u. \tag{4}$$

According to this equation, various shielding materials can be selected and compared, then the designed shielding thickness can be also evaluated to achieve the design objective, which is to reduce the total dose to less than *20 K* Rad (Si).

IV. Reliability Assessment

A. Attenuation of Gamma Radiation

$R(t)$	reliability of an item at time t
$R_{ij}(t)$	reliability of the jth layer in the channel i at time t
$R_{C_i}(t)$	reliability of the channel i at time t
$R_S(t)$	reliability of the proposed system at time t
$R'(t)$	reliability of an item at time t under total radiation dose D_t
$R'_{ij}(t)$	reliability of the jth layer in the channel i at time t under total radiation dose D_t
$R'_{C_i}(t)$	reliability of the channel i at time t under total radiation dose D_t
$R'_S(t)$	reliability of the proposed system at time t under total radiation dose D_t
m	the number of redundant channels in the system
λ	the failure rate of an item
λ_{ij}	the failure rate of the jth layer in channel i
λ_{ij_k}	the failure rate of kth component of the jth layer in channel i
Δ	radiation degradation factor under total radiation dose D_t
P_0	the value of a characteristic parameter before exposure
P_t	the value of the characteristic parameter after a total radiation dose D_t
P_f	the value of the characteristic parameter at failure of total radiation dose D_f

B. Assessment Model

The reliability function $R(t)$ represents the probability that an item (component, subsystem, or system) will perform the designed functions over a given time interval $[0, t]$ under specific operating environment and conditions [15]. Conventional analysis methods for system reliability are dependent on probabilistic approaches, which incorporate all failure events as random events. These methods are based on two fundamental assumptions: (1) binary state assumptions, where the system can only be in either of the two states (fully functioning or fully failed); and (2) probability assumptions, where the system failure behavior is fully characterized by the probability measures [16]. However, there are many uncertainties when a device or system works in a harsh environment, which may include the strong levels of radiation, extremely high temperature, and high humidity, etc.; those uncertainties challenge the assumptions in the "conventional" reliability analysis of the components and increase the probability of failure of the item (component, subsystem, and/or system) [17]. Therefore, the analysis employed by the conventional methods may not represent a realistic situation in a harsh environment. Radiation effects should be considered in the reliability analysis.

This work first establishes the assessment model for non-radiation conditions through the failure rate, in order to obtain the reliability of the proposed architecture under radiation conditions. The failure rate $\lambda(t)$ of an item expresses the "possibility to failure" of the item after time t has passed [15]. It is estimated from the mean number of failures per unit time, which can be expressed by failure in time (*FIT*) as follows:

$$1\ FIT = 10^{-9} \quad failure/hour.$$

The reliability $R(t)$ of the item can then be determined from the failure rate $\lambda(t)$ with the consideration of $R(0) = 1$ as follows [15]:

$$R(t) = e^{-\int_0^t \lambda(\tau) d_\tau}. \tag{5}$$

Assuming that the failure rate is independent of time (t), then $\lambda(t) = \lambda$, Eqn.5 can be simplified to [15]

$$R(t) = e^{-\lambda t}. \tag{6}$$

Considering that the proposed architecture consists of an input layer, a decision layer, and an output layer; and the reliability of diversified channels are all different, the reliability of the jth layer in the channel i, which consists of n_l components, can be evaluated using the formula.

$$R_{ij}(t) = e^{-\lambda_{ij} t} = \prod_{k=1}^{n_l} e^{-\lambda_k t} = e^{-\sum_{k=1}^{n_l} \lambda_{ij_k} t} \quad (i = 1, \ldots, m;\ j = 1, 2, 3). \tag{7}$$

The reliability of the channel i can be described as follows:

$$R_{C_i}(t) = e^{-\lambda_{C_i} t} = \prod_{j=1}^{3} e^{-\lambda_{ij} t} = e^{-\sum_{j=1}^{3} \lambda_{ij} t} \quad (i = 1, 2, 3). \tag{8}$$

Under non-radiation conditions, the reliability model of the proposed architecture can then be described as follows:

$$R_S(t) = \left(1 - \prod_{i=1}^{m}\left(1 - R_{i1}(t)\right)\right) \times \left(1 - \prod_{i=1}^{m}\left(1 - \left(R_{i2}(t) \times R_{i3}(t)\right)\right)\right). \tag{9}$$

Specifically, as previously discussed, cases of all three channels simultaneously encountering failures are not considered in this work, common cause failure (CCF) is therefore not considered.

C. Radiation Degradation Factor

To take radiation effects in consideration in system reliability analysis, a new method for electronic systems has been developed in [17], [18]. This method uses radiation degradation factors(Δ), instead of the usual failure rate data of an item in the reliability model, as input to describe the radiation response of this item under a total radiation dose D_t, which will lie in the interval $[0, 1]$ and can be defined as follows:

$$\Delta = \min\left\{\left|\left(P_0 - P_t\right)/\left(P_0 - P_f\right)\right|, \quad 1\right\}. \tag{10}$$

A detailed description of the radiation degradation factor can be found in [18]:

$$\Delta = \begin{cases} \left(P_0 - P_t\right)/\left(P_0 - P_f\right) & for\ P_0 \geq P_t > P_f\ or\ P_0 \leq P_t < P_f \\ 0 & for\ P_t > P_0 > P_f\ or\ P_t < P_0 < P_f \\ 1 & for\ P_0 > P_f > P_t\ or\ P_0 < P_f < P_t \end{cases}. \tag{11}$$

Previous research [17], [18] has derived the parameter values of radiation degradation from real radiation test data; with radiation degradation function which are used to describe how the material and/or components change their properties under given radiation conditions. Radiation degradation functions are separated into three categories in [18], as shown in Fig.5:

1) Piece-wise linear radiation degradation function, with logarithmic dose values and linear parameter values;

2) Linear radiation degradation function in the entire range of exposure; and

3) Constant radiation degradation function. The value 1 is up to D_f, and the value 0 is assumed to fail abruptly at the threshold dose.

Due to the fact that semiconductor components may have a number (n_p) of critical parameters, in this study, the radiation degradation factor is defined as the mean value of those degradation factors of all critical parameters, which can be described as follows:

$$\Delta = \frac{\sum_{i=1}^{n_p} \min\left\{\left|\left(P_{i_0} - P_{i_t}\right)/\left(P_{i_0} - P_{i_f}\right)\right|, \quad 1\right\}}{n_p}. \tag{12}$$

The reliability ($R'(t)$) of the item under total radiation dose

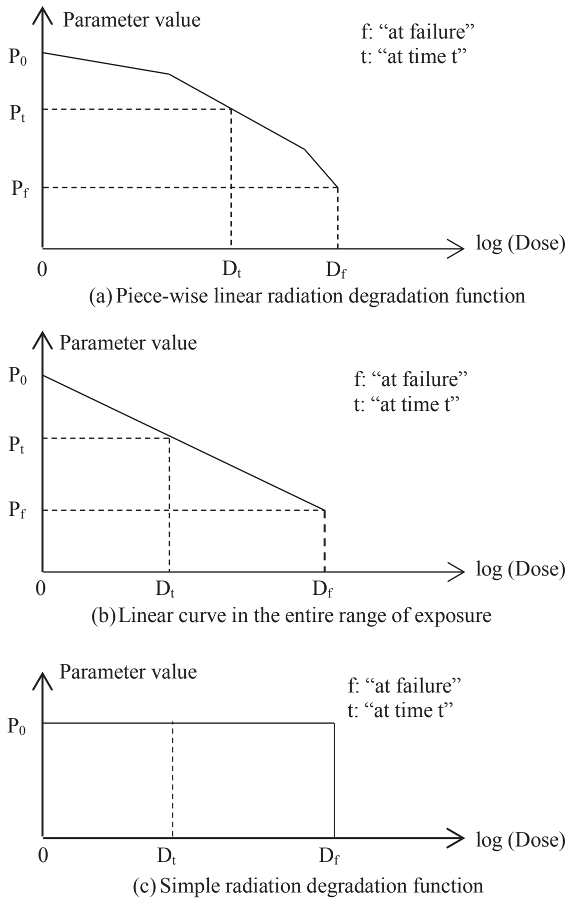

Fig. 5. Radiation degradation function [18].

D_t can then be described in Eqn.13.

$$R'(t) = (1 - \Delta) \cdot R(t) = (1 - \Delta) \cdot e^{-\lambda t}. \tag{13}$$

The reliability of the jth layer in the channel i under the total radiation dose D_t can be evaluated in Eqn.14.

$$R'_{ij}(t) = \prod_{k=1}^{n_l} (1 - \Delta_k) e^{-\lambda_k t} \quad (i = 1, ..., m;\ j = 1, 2, 3). \tag{14}$$

Assuming that the channel i consists of n_c components, the reliability of the channel i under total radiation dose D_t can be described in Eqn.15.

$$R'_{C_i}(t) = \prod_{k=1}^{n_c} (1 - \Delta_k) e^{-\lambda_k t} \quad (i = 1, 2, 3). \tag{15}$$

Based on Eqn.5 and Eqn.15, the reliability model of the redundant architecture mentioned in Fig.2 under total radiation dose D_t can be derived as Eqn.16.

$$R'_S(t) = \left(1 - \prod_{i=1}^{m}\left(1 - R'_{i1}(t)\right)\right) \times \left(1 - \prod_{i=1}^{m}\left(1 - \left(R'_{i2}(t) \times R'_{i3}(t)\right)\right)\right). \tag{16}$$

V. A Case Study

A. Development and Evaluation of Radiation Protection

1) Radiation Shielding

To enhance the radiation tolerance, the proposed radiation-tolerant architecture in Fig.2 is further protected by a structure of radiation shielding as illustrated in Fig.6 to increase the radiation tolerance while to avoid common-mode damage. This design consists of three protection layers, with the second and third layers (Fig.6 (b)) inserted into the first protective layer (Fig.6 (a)). The third layer is smaller than the second, and each layer is composed of different materials, which are determined by the particular semiconductor devices used in the electronic system. The layout of the proposed architecture is also illustrated in Fig.6 (c).

The detailed parameters of radiation shieling are listed as follows:

- The material of the first shielding is copper, the size is *26cm*26cm*20cm*, and its thickness is *1cm*;
- The material of the second shielding is lead, the size is *24cm*24cm*18cm*, and its thickness is *6cm*; and
- The material of the third shielding is tungsten, the diameter is *4cm*, and its thickness is *1cm*.

2) The Evaluation of Radiation Shielding

As illustrated in Fig.6, with different shielding materials for different layers, shielding thickness, radiation angle, and radiation locations, all have different effects on the radiation exposure experienced by electronic systems in the six identified areas, as shown in Fig.6(a) ($A_1 - A_3, S_1 - S_3$). Using Co-60 as a radiation source, the capability of the protections can be summarized as follows:

- Under the condition with dose rate *2700 Sv/h*, at the given *24h*, the highest total dose in six areas is about *100 K Rad (Si)*;
- Under the condition with dose rate *1350 Sv/h*, at the given *24h*, the highest total dose in six areas is about *50 K Rad (Si)*;
- Under the condition with dose rate *530 Sv/h*, at the given *24h*, the highest total dose in six areas is about *24 K Rad (Si)*;
- Under the condition with dose rate *70 Sv/h*, at the given *24h*, the highest total dose in six areas is about *2.6 K Rad (Si)*.

B. Design and Assessment of Redundant Wireless Monitoring Devices

1) Implementation of Monitoring Devices

As previously mentioned, TMR core of the developed radiation-tolerant architecture consists of an input layer, a decision layer, and an output layer. More specifically, the input layer consists of input sources, a source encoder, and a channel encoder; the decision layer consists of the decision-making unit; and the output layer consists of a digital modulator and transceiver. For simplity, only one temperature sensor is considered herein.

Component selection is an important step in the design phase of COTS-based rad-hardened systems. Radiation effects are different on different devices, circuits and systems, depending on their unique materials, structure, manufacturing

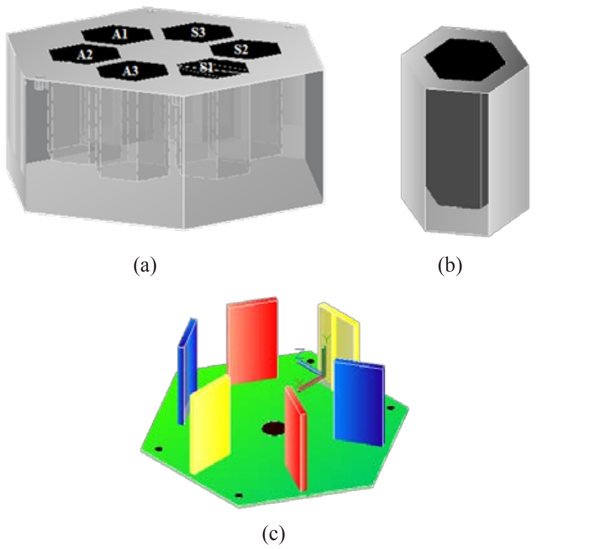

Fig. 6. (a), (b) The proposed structure of radiation protection. (c) The mounting of electronic circuits in the proposed radiation-tolerant architecture.

technologies, and applications. In this work, referring to radiation test data from the NASA Goddard Space Flight Center [19], all wireless channels and their spares are implemented with diversity hardware, whose detailed implementation and related information are listed in Table II. Specifically, those components such as resistance, capacitance, etc., are not listed due to their robustness to radiation.

2) The Reliability Assessment of Monitoring Device

In the assessment process for system reliability in Eqn.16, the reliability model considers only the factor of total radiation dose. The difficulty of the assessment lies in determining the degradation factors for semiconductor devices. Most of radiation degradation factors under different radiation doses in this study come from NASA Goddard Space Flight Center radiation test data [19], which are available from on-line resources; others are derived from the existing literature [20-22].

In this work, the failure rates of semiconductor components listed in Column (7) of Table II come from the online resources of their manufacturers, while those radiation degradation factors listed in Column (8) to (11) of Table II. Specifically, P_f of some components are not easy to obtain from the NASA database and literature, and are instead derived from specification limits of electronic parameters.

According to Eqn.5 to Eqn.16, under four different total radiation doses (*10 K Rad (Si), 20 K Rad (Si), 50 K Rad (Si), 100 K Rad (Si)*), the system reliabilities of the developed wireless monitoring node are shown in Fig.7. It shows that system reliability decreases significantly when total radiation dose increases. Moreover, according to the compassion result for the reliabilities of different channels (*A1/S1, A2/S2, A3/S3*) and redundant systems (*FT (m=3), FT (m = 6)*), also shown in Fig.7, the reliability of the developed redundant architecture is much improved than those of non-redundant channels under the given radiation conditions.

TABLE II
THE IMPLEMENTATION OF RADIATION-TOLERANT WIRELESS MONITORING DEVICE

Channel	Function	Type	Q.	Tech.	Manu.	FIT	R.D.F.	Δ_{10K}	Δ_{20K}	Δ_{50K}	Δ_{100K}	Radiation effects
A1&S1	*Source encoder*	NPN BJT	1	Bipolar	Semicoa	2.45	A	0.194	0.3201	0.4267	0.4591	TID
		Voltage reference	1	Bipolar	TI	3.30	A	0.0774	0.1010	0.2104	0.3432	SEU, SEL, TID
		OP amp	3	Bipolar	National Semi.	1.85	A	0.0208	0.0365	0.0383	0.0365	SEL, SET, TID
	Channel encoder	Voltage reference	1	Bipolar	TI	3.30	A	0.0642	0.1099	0.5158	0.5786	SEU, SEL, TID
		AD	1	Bipolar	Analog Devices	0.20	A	0.0178	0.0486	0.0633	0.0649	SEU, SEL, SEFI, TID
	Decision making& Digital modulator	E^2PROM	1	CMOS	Atmel	2.2	A	0.0023	0.0244	0.1341	0.1326	SEU, SEL, SEFI, TID
		Micro controller	1	CMOS	Microchip	3.3	A	0.0187	0.0465	0.1001	0.1179	SEE, TID
	Transceiver	Voltage reference	1	Bipolar	Linear	3.30	C	0.0000	0.0000	0.0000	0.0000	SEU, SEL, TID
		Diode	1	Bipolar	Toshiba	3.30	A	0.0000	0.0577	0.0145	0.0769	SEU, SEL, TID
		433MHz RF	1	Bipolar	RFMD	1.90	A	0.0395	0.0745	0.1503	0.1810	SEE, TID
A2&S2	*Source encoder*	Voltage reference	1	BiCMOS	TI	3.30	A	0.1510	0.0181	0.0087	0.0094	SEU, SEL, TID
		OP amp	3	CMOS	Analog Devices	0.28	A	0.0409	0.0770	0.2989	0.2168	SEL, SET, TID
	Channel encoder	OP amp	1	CMOS	Analog Devices	0.28	A	0.2377	0.3964	0.6620	0.6537	SEL, SET, TID
		Voltage reference	1	CMOS	TI	3.30	A	0.1408	0.3371	0.3204	0.3846	SEU, SEL, TID
		AD	1	BiCMOS	Analog Devices	0.25	A	0.1735	0.1503	0.2741	0.3345	SEE, TID
	Decision making& Digital modulator	Micro controller	1	CMOS	Atmel	5.60	A	0.0638	0.0654	0.0985	0.1190	SEU, SET, SEL,SEFI,TID
		Logic gate	1	CMOS	TI	0.50	A	0.133	0.0244	0.1850	0.2432	SEU, SEL, TID
	Transceiver	433MHz RF	1	CMOS	Freescale Semi.	2.0	A	0.1026	0.1336	0.2310	0.2451	SEE, TID
A3&S3	*Source encoder*	Voltage reference	1	HSCMOS	Allegro	3.3	A	0.1408	0.3371	0.3204	0.3846	SEU, SEL, TID
		OP amp	3	BiFET	TI	0.2	A	0.0689	0.1551	0.3673	0.5151	SEL, SET, TID
	Channel encoder	Voltage reference	1	TTL	Analog Devices	3.3	A	0.0039	0.0216	0.0223	0.0644	SEU, SEL, TID
		AD	1	LC^2MOS	Analog Devices	1.6	A	0.0181	0.0229	0.0246	0.0209	SEE, TID
		OP amp	2	Hybrid	MOTOR OLA	0.2	A	0.1360	0.0764	0.1757	0.2717	SEL, SET, TID
	Decision making& Digital modulator	Micro controller	1	TTL	SILICON	2.26	A	0.0109	0.0134	0.0149	0.0168	TID, SEU, SET
		Logic gate	1	TTL	TI	3.3	A	0.0469	0.0494	0.0480	0.0724	SEU, SEL, TID
	Transceiver	433MHz RF	1	TTL	SILICON	1.90	A	0.0479	0.0781	0.1108	0.1567	SEE, TID
		Voltage reference	1	BiMOS	TI	3.3	A	0.0055	0.0269	0.0238	0.0646	SEU, SEL, TID

R.D.F. (radiation degradation function) – A (piece-wise linear radiation degradation function), B(linear curve in the entire range of exposure), C (simple radiation degradation function)

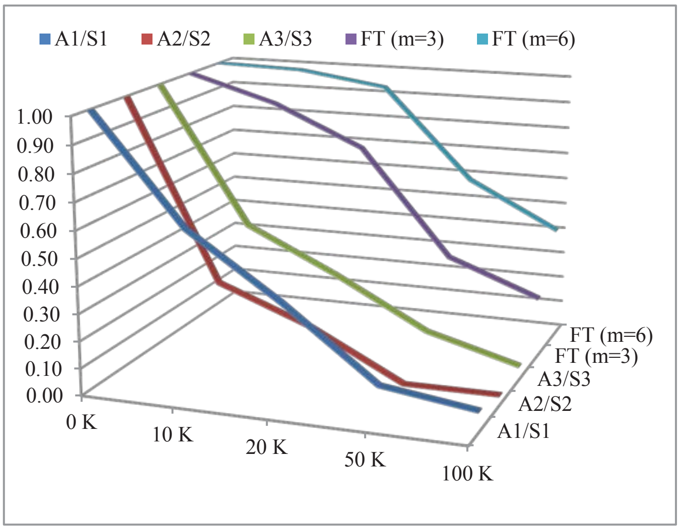

Fig. 7. The compassion of the reliability of the developed redundant system and no-redundant channels under the given total dose (0, 10 K Rad (Si), 20 K Rad (Si), 50 K Rad (Si), 100 K Rad (Si)).

In a summary, radiation assessment of the developed wireless device for various dose rates under the given time (*24h*) is illustrated in Fig.8. It shows that the reliability of the developed wireless device under dose rate *530Sv/h* at *24 h* is about *89.6%*. The developed wireless device can therefore work in those high level radiation fields and meets the design objective.

VI. CONCLUSION

In this work, the assessment of radiation-tolerance of a wireless monitoring device is given for high level radiaiton fields, which is developed by using radiation protection and radundant techniques. The study results show that total dose can be effectively decreased. In addition, the radiation assessment shows, under given radiation conditions (*10 K Rad (Si)*, *20 K Rad (Si), 50 K Rad (Si), 100 K Rad (Si)*), the reliability of the developed system (*99.0%, 94.2%, 59.6%, 42.3%*) can be much improved than those of non-redundant channels (*60.3%, 37.5%, 11.9%, 7.2%; 33.6%, 20.7%, 3.2%, 3.4%; and 48.5%, 32.5%, 14.3%, 5.1%*).

According to assessment studies, the developed device can work in high level radiation fields whose total dose is up to *1 M Rad (Si)*; and it may be available used in those conditions with total dose *10 M Rad (Si)*. It therefore provides an effective and economical solution to obtain up-to-date information during a severe accident in a nuclear power plant.

ACKNOWLEDGMENT

This work is financially supported by the University Network of Excellence in Nuclear Engineering (UNENE) and the Natural Sciences and Engineering Research Council of Canada (NSERC).

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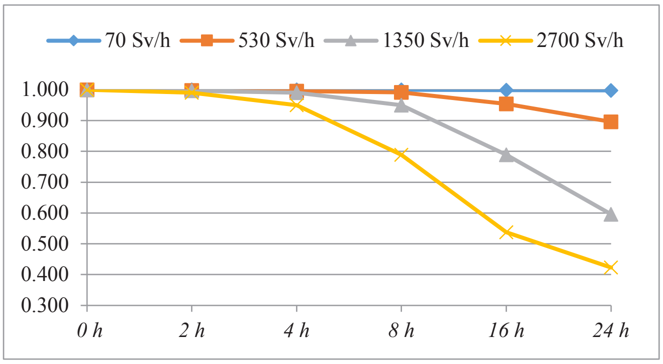

Fig. 8. Radiation assessment of the developed wireless device under various dose rates.

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