Investigation of Radiation Tolerance Characteristics for Emergency Response Robots in NPP

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1. Introduction

Although the probability of a large-scale nuclear power plant (NPP) accident is extremely low, it is necessary to develop robots capable of responding in the event of a severe accident similar to the Fukushima disaster. The Korea Atomic Energy Research Institute (KAERI) is currently developing robotic platforms capable of responding to predefined severe accident scenarios such as SGTR (Steam Generator Tube Rupture) and ISLOCA (Interfacing System Loss-of-Coolant Accident). Among the required performance specifications for such robots, radiation tolerance is the most critical.

Analysis results indicate that the total radiation dose received by a robot operating under the SGTR scenario is approximately 700 Gy, while under the ISLOCA scenario it ranges from several mGy up to 4,000 Gy, depending on the conditions [1].

In this study, the radiation tolerance characteristics of various Armstrong components currently used by KAERI are evaluated. Additionally, the radiation resistance of hydraulic systems, which may be used as the robot's drive source, is investigated.

2. Radiation tolerance characteristics of robot components [2]

2.1. Experimental results for Armstrong components

Radiation tolerance tests for various components were conducted at the high-level radiation irradiation facility in Jeongeup. The main results are as follows:

<u>Controller</u>

- SBC using Intel Quad Core processor: tolerance up to 100 Gy (at 490 Gy/h) – lowest among tested units
- Arduino AKC 89C51: tolerance around 600 Gy (@490 Gy/h) – relatively high
- ATmega328P SMS: 287 Gy (@648 Gy/h)

<u>Power supply</u>

- Battery: >3,000 Gy (@133.5 Gy/h) – excellent tolerance
- DC–DC converter: up to 1,300 Gy (@161 Gy/h), but COP200 series can withstand up to 3,800 Gy (@161 Gy/h)

<u>Communication module</u>

- Commercial RF relay (433 MHz remote switches): functional degradation or damage start below 50 Gy
- Space-grade RF: >1 kGy
- ZigBee: 640 Gy
- LoRa network: 400 Gy

Table I: Radiation resistance by type of communication protocol [3]

Method	Resistance(Gy)	Failed component
ZigBee	640	CPU & transceiver
WirelessHART	167	transceiver
ISA100.11a	200	transceiver
LoRa network	400	CPU & transceiver
433 MHz RF	260	CPU
915 MHz RF	1,140	CPU

<u>Actuators (electric motors)</u>

- Servo motors with integrated control boards: functional failure at ~200 Gy
- DC motors: operate normally up to 1.5 kGy
- General DC/AC servo motors: typically order of MGy or higher
- ROBOTIS actuators: 200 Gy (@50 Gy/h) – low tolerance;
- Resolvers: order of MGy or higher
- Typical radiation-hardened vendors are shown in Table II.

Table II: Possible radiation-resistant component vendors [4]

Item	Resistance (Gy)	Vendor (possible radiation-resistant component)
AC motor class H, type RH	2 M	Reliance Electric
Resolvers	10 M	Northern Precision Laboratories
LVDT	10 G	Schoeritz
Electrical connectors	10 M	Lemo
	100 M	VEAM
Electric wire cable	6 T	Kyle Technologies
	2 M	Boston Insulated Wire
Proximity detectors	6 T	Capacitek

<u>Actuator drives</u>

- Elmo driver: 70 Gy (@91 Gy/h)
- Commercial motor controllers (Aadvance Motor Controllers 10A8, 30A8T): 200–270 Gy

Encoders

- Optical type: 247 Gy (@108 Gy/h)
- Magnetic type: >3 kGy (@121 Gy/h)

Cameras (CCD/CMOS)

- CCD monochrome: image loss at 300 Gy (@200 Gy/h)
- CCD color: operational up to 245 Gy (@31 Gy/h); stopped at 875 Gy; grayscale transition and image loss at ~110 Gy under 30 Gy/h irradiation
- CMOS: operational up to 380 Gy (@30 Gy/h), partial recovery after 4 days without radiation
- RGB-D camera: failed below 300 Gy; noisy data from 200 Gy

LiDAR

- 2D LiDAR (RPLidar A3): 270 Gy (@53 Gy/h)
- 3D LiDAR (Realsense D435i): 234 Gy (@39 Gy/h)

A summary of the radiation tolerance test results for Armstrong components is presented in Fig. 1. Almost all parts used in the Armstrong system exhibit radiation tolerance levels far below those required for either the SGTR or ISLOCA scenarios. Therefore, if the current Armstrong system were to be deployed, specific components must be replaced with radiation-hardened equivalents and/or adequately shielded to withstand the expected total dose of approximately 700 Gy of SGTR senario or 4 kGy of ISLOCA senario.

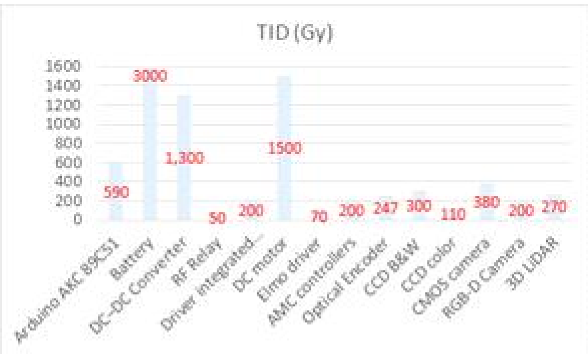

Fig. 1. Radiation tolerance of Armstrong components

2.2. Literature survey on other sensors [5]

SNL(Sandia National Laboratory) conducted a survey on robotic applications in radioactive environments and analyzed the radiation tolerance performance of robotic system components. The results are shown in Table III.

Table III: Radiation resistance characteristics of various sensors

components	Resistance (Gy)	comments
CCD video camera	250	
Vidicon video camera	1 M	Chalnicon type
infrared camera	10	Amplifier is sensitive
photoelectric rangefinder	1 M	
laser rangefinder	100 k	He-Ne type
infrared thermometer/scanner	1 M	Exergen sensor
Ultrasonic range finder	10	Processing IC is weak.
		Proximity switch >100 kGy
gas detection instrument	10 k	
humidity sensor	100 k	
Joint encoder (particular)	10~100 k	Some electronic technology is applied
pressure transducer	100 k	careful selection of insulating & adhesive
strain gauge (force/torque sensor)	100 k	insulator & adhesive

3. Radiation tolerance characteristics of hydraulic servo systems (literature review)

3.1. Key components affected by radiation

Literature on the radiation tolerance of hydraulic servo systems is limited. In the early 1960s, the Oak Ridge National Laboratory (ORNL) investigated the radiation resistance of hydraulic servo systems used in aircraft and spacecraft [6]. Despite being dated, the components of hydraulic servo systems have remained largely unchanged, rendering this data valuable for current assessments. The key components susceptible to radiation effects are shown in Fig. 2.

- O-rings (static seals) between manifold block and servo valve
- Piston rings (dynamic seals) preventing cylinder leakage
- Motor coil wire insulation in servo valve actuators
- Hydraulic working fluid (oil)
- Position or velocity measurement sensors

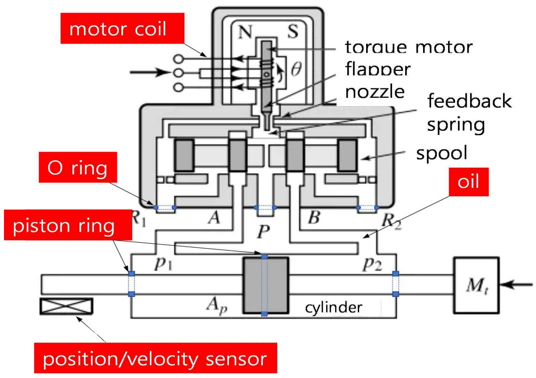

Fig. 2. Key components affected by radiation

Seal materials (O-ring, piston ring)

- Rubber-based materials are generally vulnerable to radiation (embrittlement under exposure)
- Viton A and Buna N have relatively good resistance among Rubber-based materials
- When their radiation resistance is compared with the findings of recent studies and the manufacturers' specifications (Table V), notable differences in performance characteristics become apparent
  - Literature & catalogs: Viton A (FKM); 7×10^6 rad, Buna N; 10^4~10^5 rad
  - ORNL report: Viton A; 1×10^8 rad, Buna N; 2×10^8 rad
- Many recent studies[7, 8] report 10^4~10^5 rad for Buna N, which appears more reliable

Table IV: Temperature and Radiation Resistance Properties of Various Seal Materials (ORNL Report[6])

Seal Material	Maximum Temperature (°F)	25% Threshold Limit (rads)
Viton A	550	1×10^8
Buna N	300	2×10^8
Teflon	450	4.5×10^5
Silicon 550	480	7.5×10^6
Neoprene	200	3×10^7
Polyethylene	210	1×10^8
Glass teflon	550	1×10^9
Ceramic Asbestos	600	2×10^9

Table V: Material properties of Viton A and Buna N (recent papers[7, 8, 9])

Property	Viton A (FKM)	Buna N (Nitrile, NBR)
Heat Resistance	Excellent (approx. -20 °C to +200 °C)	Moderate (approx. -30 °C to +100 °C)
Mechanical Strength	Excellent	Excellent
Price	High (premium material)	Low
Radiation Resistance	Excellent (withstands up to ≥ 7×10^6 rad) [9]	Poor to moderate (typically withstands up to 10^4–10^5 rad) [7,8]
Property Retention under Gamma/Electron Irradiation	Some hardening, but generally stable	Rapid degradation (cracking, hardening, property loss)
Main Effect	Slight hardening/increased strength	Embrittlement, cracking, loss of ductility
Recommended Applications	Nuclear, aerospace, radiation exposure environments	General industry with little to no radiation exposure

Glass Teflon and Ceramic Asbestos/Metallic Asbestos also show high tolerance; however, Glass Teflon has poor formability and is better suited for static sealing, while Ceramic Asbestos is suitable for dynamic seals (e.g., piston rings)

For reference, domestic Viton A O-ring suppliers are as follows:

- GMORS Korea
- Aegis Sealing Technology
- MISUMI Korea

Motor coil wire insulation

- AL_2O_3, Mg_2O_3, polyethylene, and boron-containing fiberglass have high tolerance
- Mica, porcelain, and quartz have high resistance but are unsuitable for cable sheathing.

Hydraulic working fluid (Oil)

- Most mineral-based oils are susceptible to radiation, which can induce viscosity changes and localized gel formation.
- MLO-8200 shows no performance change up to 3×10^8 rad
- While OS-45 demonstrates greater radiation resistance than mineral-based oils, its overall performance remains insufficient for the intended application.
- In dynamic conditions(operation condition), viscosity increases due to radiation but is compensated by temperature rise from operation
- In static conditions, viscosity increases noticeably

Position/velocity sensors

- Radiation effects on sensor cables must be considered

3.2. ORNL radiation tolerance experiment

Experimental conditions

- Servo valve torque motor: 3.5×10^3 Gy/h for 281.6 h (total: 9.8×10^5 Gy)
- Position sensor (Schaevitz differential transformer): 1.65×10^4 Gy/h for 281.6 h (total: 4.6×10^5 Gy)
- Oil temperature: 150 °F ± 2 °F; quantity: 1.84 gallons
- Operating pressure: 2,500 psi

Results

- Servo valve: response slowed significantly; unsatisfactory performance
- No oil leakage through O-rings
- Oil viscosity: gel formation blocked filters; viscosity decreased from 25.65 cs to 20.83 cs
- Torque motor: insulation discoloration (white to brown), strong odor after opening
- Actuator response: system gain slightly decreased with higher dose
- Coulomb friction in actuator piston decreased from 315 lb to 129 lb
- Internal leakage in piston rings: negligible change
- Actuator chamber pressure: dropped from 800

psi to 400 psi near end of test.

ORNL's conclusions

- Radiation significantly slows system response, but feedback control can partially compensate
- Gel formation in oil can block filters, causing pressure increase and malfunction – most critical issue

4. Design considerations for radiation-hardened robots

4.1. Cost of radiation-hardened components

Producing radiation-hardened parts requires the application of specialized manufacturing processes. This significantly increases the cost of the parts. While many manufacturers can produce hardened parts, demand is limited. This means they cannot secure the "continuous production" capacity of commercial products, which can lead to prices that can be thousands of times higher.

4.2. The approach to radiation hardening design

The approach to radiation hardening design can be very complex, and should, at a minimum, include the following steps which is recommended by SNL[5].

First, preliminary assessment of the radiation hardness of the robotic system components being considered for use in the system should be performed.

Second, the extent of the potential exposure should be established, including any minimization of TID.

Third, determine the design based on required function and available hardening alternatives. Radiation dose monitoring capability should be included in the hardware for real-time determination of dose.

Fourth, a detailed evaluation of the hardness of the final design, with or without the assistance of a radiation effects expert, which may require that additional TID(Total Ionizing Dose) testing be carried out on select parts.

Fifth, preventive maintenance based on system hardness and the environment should be planned.

Sixth, system conditions should be monitored during operation.

Finally, withdraw from the environment in a timely manner when simulation or monitored conditions indicate exposure rates are approaching the failure range.

5. Conclusions

In this study, the radiation tolerance characteristics of Armstrong components currently used by KAERI were investigated, and, in preparation for high-load operations, the radiation resistance of hydraulic systems was also examined. The major findings are summarized as follows:

For SGTR accident response operations, if the current Armstrong system were deployed, following components must either be replaced with radiation-hardened equivalents and/or shielded to withstand the expected total dose (700 Gy):

- RF relay for communication, motor driver (Elmo), CCD camera, RGB-D camera, and LiDAR units

During an ISLOCA event, exposure can reach up to approximately 4000 Gy, making it difficult for Armstrong to cope with ISLOCA. It is necessary to develop more radiation-hardened robots.

In the case of hydraulic systems, the radiation tolerance is approximately three orders of magnitude higher than that of other components, making it generally less problematic. However, given that radiation exposure significantly slows system response, control systems must be designed accordingly. In addition, since the working fluid (oil) may significantly change in viscosity under irradiation, leading to hydraulic pressure rise and potential malfunction, it should be replaced periodically.

The radiation-hardening design approach recommended by SNL should be considered an essential guideline when designing for radiation tolerant components.

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