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Radiation Dose Analysis of Accident Response Robots to NPP ISLOCA

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SUMMARY: Although the probability of a large-scale accident in nuclear power plants is extremely low, it is essential to develop robots capable of responding in the event of a major accident similar to Fukushima. In this study, we calculated the radiation dose a robot would receive while operating under various nuclear severe accident scenarios, focusing on ISLOCA (Interface System Loss of Coolant Accident). An ISLOCA occurs when a pipe connected from the Reactor Coolant System (RCS) to a low-pressure boundary system such as the Shutdown Cooling System (SCS) ruptures, causing a LOCA. In this scenario, based upon our MELCORE simulation results, fuel damage begins 126 minutes after the accident onset, leading to the release of radioactive sources into the environment. The mission of the deployed robot is to access the damaged pipe location and repair it. While the task seems straightforward, the approach path is complex, and the high radiation environment makes robot development challenging. High mobility (including stair navigation) and strong radiation tolerance are required. Based on the ISLOCA scenario, source term release fractions along the robot's travel path were obtained using the MELCOR severe accident analysis code. A program was developed to calculate the dose rate in the robot's surroundings, and the absorbed dose from each radionuclide was computed. The results indicate that before fuel failure (within 126 minutes of accident onset), the robot would receive approximately 4 mGy. After fuel failure begins (beyond 126 minutes), the maximum dose could reach 4 kGy, which is extremely high and poses significant challenges for robot development.

***Keywords :** ISLOCA, emergency response, radiation dose, robot*

1. Introduction

The Interface System Loss-of-Coolant Accident (ISLOCA) is a specific type of LOCA that occurs when a pipe connecting the Reactor Coolant System (RCS) to a low-pressure boundary system (such as the Shutdown Cooling System, SCS) fails [1]. In a severe ISLOCA, fuel damage begins approximately 126 minutes after accident initiation (according to our simulation [2]), at which point radioactive source terms begin to escape into the environment.

To prevent radioactive releases to the environment, the damaged pipe must be repaired. However, the Low Pressure Safety Injection (LPSI) room, where the rupture occurs, is characterized by extremely high radiation and elevated temperatures, due to both fission products released from the fuel and high-temperature primary coolant. These conditions render human access both difficult and unsafe.

In this study, we examine a scenario in which a robot, rather than a human operator, is deployed to perform the repair. We estimate the radiation dose that such a robot would receive, providing key design guidance for radiation-hardened robotic systems. First, an accident response scenario is established. Based on this, the radiation dose rates in the LPSI room and along the robot’s travel path are calculated. Finally, the absorbed dose is determined according to the robot’s path and operational durations.

2. Scenario

2.1 ISLOCA scenario

The ISLOCA progression was modeled using reference data from [3], with the pipe rupture parameters modified to better reflect realistic conditions (Table I). Event timings are based on MELCOR analysis results. The rupture is assumed to occur in the LPSI room (SCS piping; outer diameter: 27.3 cm; wall thickness: 1.27 cm) and takes the form of a 1 cm diameter hole.

Table I: Accident progression during an ISLOCA event

Event	time (s(m))
Accident start, MFW stop	0
RCP trip	78 (1.3)
Core uncover start	129 (2.2)
SRV(pressurizer) first open	5037 (84)
SG1 dryout	6926 (115)
SG2 dryout	7000 (117)
Fuel gap release start	7589 (126)
Core dryout(Level<-6.09m)	8380 (140)
RPV failure	14383 (240)
SIT start injection	14514 (242)
SIT depleted	15073 (251)

2.2 Robot response scenario

The robot response sequence is illustrated in Fig. 1:

① ISLOCA occurs (coolant leakage from low-pressure boundary piping).
② Fission products from the primary coolant and/or fuel are released into the environment.
③ Deploy robot (route in Fig. 2: from Room 930

hallway → through right-hand door → down stairs from Rooms 924 to 920 → through Room 910 hallway → down stairs in Room 900 to the leaking pipe).

④ Robot activates spray system.
⑤ Robot repairs the pipe to halt fission product release.
⑥ Robot exits via the reverse path to Room 930 and then outside.

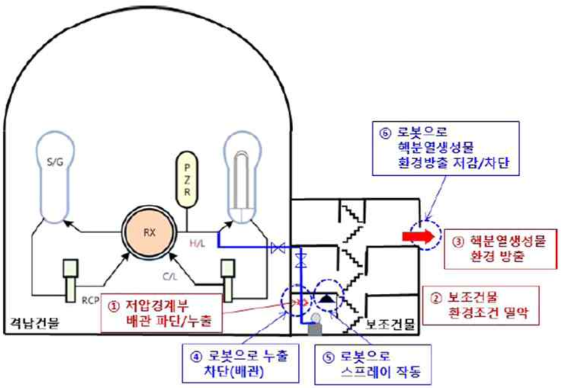

Fig. 1. Robot response scenario to ISLOCA

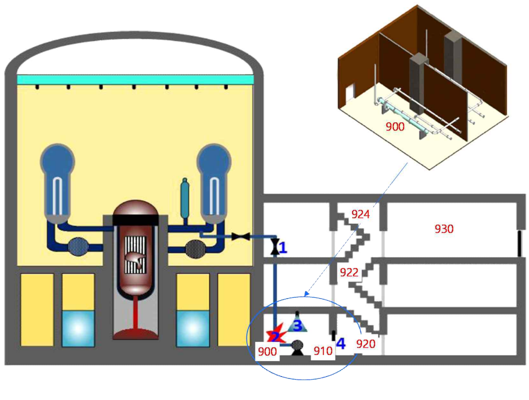

Fig. 2. Layout of LPSI room and surrounding rooms

3. Radiation dose calculation

3.1 Calculation method

Dose rate calculations were divided into two phases - before and after fuel failure (126 minutes) - and followed the sequence shown in Table II.

3.2 Dose Rate Before-fuel-failure

1) Calculation procedure

The absorbed dose rate at the robot's location was calculated as follows:

① Determine environmental radioactivity based on coolant leakage into each room.
② Calculate gamma fluence rate from the identified radioactivity.
③ Estimate the effective distance (heq) between the robot and the radiation source.
④ Apply shielding corrections for water and piping.
⑤ Compute the absorbed dose rate at the robot's position.

Table II: Calculation method of dose rate

Before-fuel-failure (0 < t < 126 min)	After-fuel-failure (t ≥ 126 min)
① Determine specific radioactivity of source terms in primary coolant (using FSAR data [4]).	① Determine radioactivity of source terms in fuel (using fuel inventory).
② Coolant mass: Determine coolant mass in each room from MELCOR analysis.	② Source terms fraction: Calculate radioactivity in each room based on source term fraction using MELCOR.
③ Determine effective distance (heq) between robot and source term (varying with the geometry of room, walls, water, and pipe).	
④ Apply attenuation factors for shielding by pipes and water.	
⑤ Calculate absorbed dose rate and integrate over exposure time to obtain total dose.	

Detailed mathematical derivations are omitted here due to space limitation; refer to [2] for the complete methodology.

2) Dominant source terms in the primary coolant

To identify the nuclides most affecting the robot, the product of specific radioactivity × leakage fraction × energy × yield was computed (Fig. 3). The most influential isotopes were Xe-133, Xe-135m, Xe-135, Kr-87, Kr-88, I-132, I-133, and I-135, which were then used in the dose rate calculations.

3) Primary coolant flow distribution

MELCOR simulations (Fig. 4) show that most leaked coolant enters the LPSI room, with smaller amounts reaching Room 910. Since the robot passes through Room 910 quickly, radiation exposure in this space is minimal; the majority of exposure occurs in the LPSI room where the repair is performed.

4) Dose rate in the LPSI room

Dose contributions from the air, walls, pipes, and water were calculated (Fig. 5). Water shielding effects were modeled using the half-value layer of each isotope in water. The water's contribution in the piping remained constant over time due to the steady volume of coolant in the piping. The total dose rate peaked at 47 mGy/h, relatively low because the primary coolant's activity is modest until the fuel damage.

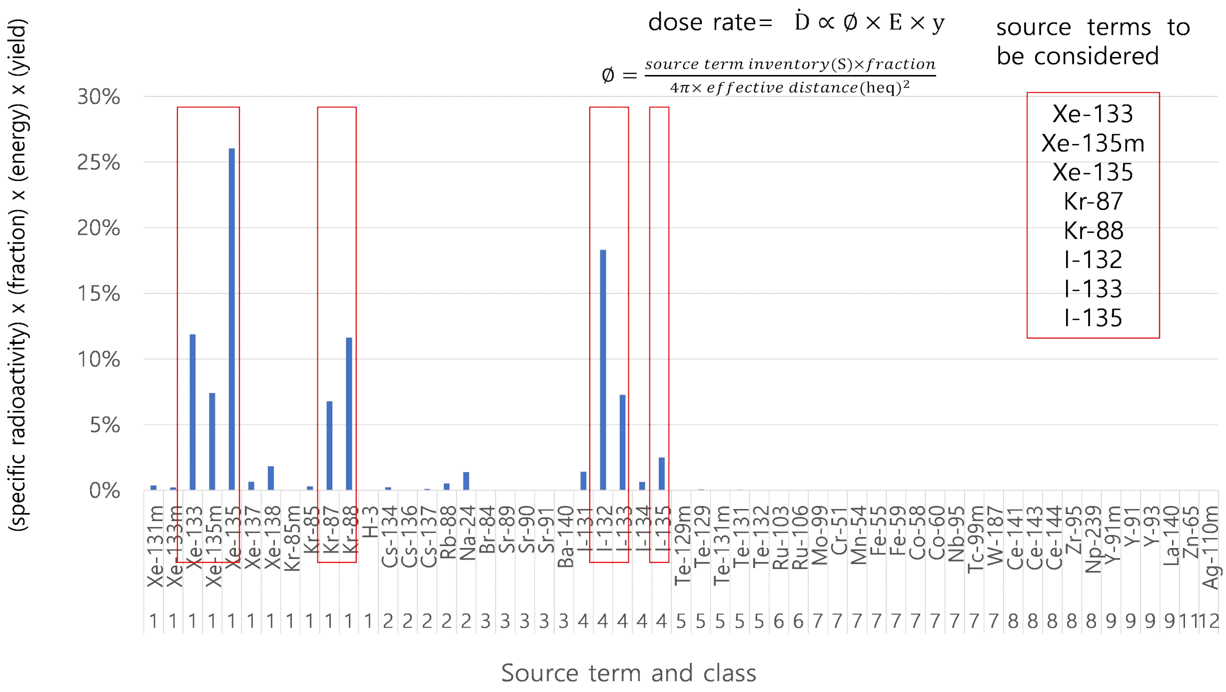

Fig. 3. Values of product of specific radioactivity, fraction, energy and yield

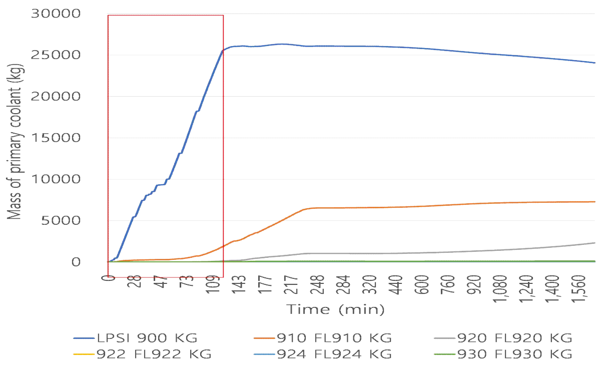

Fig. 4. Primary Coolant Flow Distribution

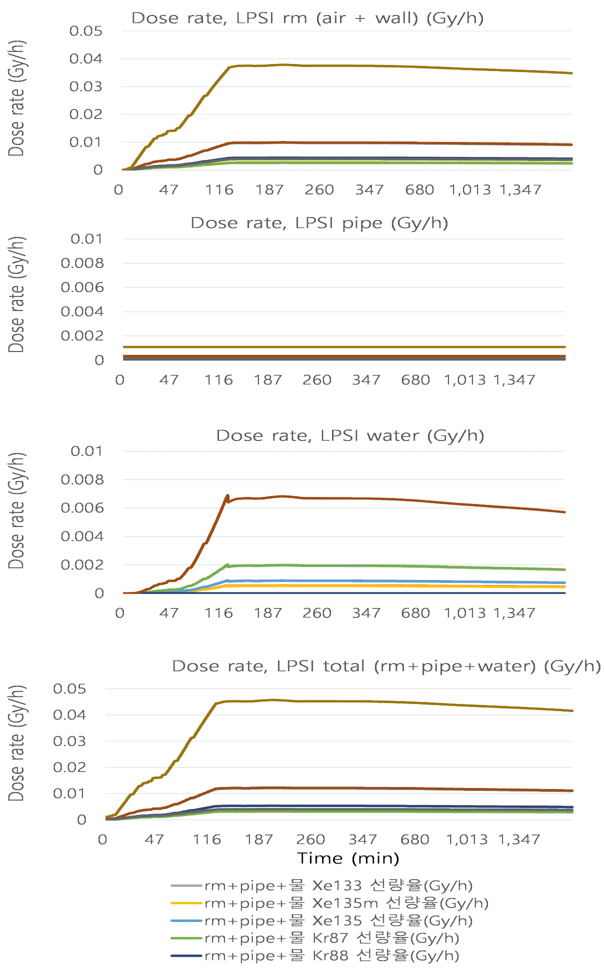

Fig. 5. Dose rate in the LPSI room

5) Robot path and operation time

In order to calculate the dose rate for each robot path, the path and working time were assumed as shown in Table III.

A. Robot Path

The robot path(see Fig. 2) is:
Outside → CV930 hallway → CV924~920 stairs → CV910 hallway → CV900 (LPSI room; stairs and work position) → reverse path to Outside.

B. Robot working time

Operation times are listed in Table III: deployment at 2 minutes post-accident and return at 60.8 minutes. Considering the speed of the robot currently being tested at KAERI, the robot's movement speed is assummed as 1 m/s on flat ground and 0.3 m/s on stairs.

6) Dose rate by location

Except for the LPSI room, other rooms contain negligible coolant and thus very low dose rates. Fig. 7 shows dose rate trends, with contributions decreasing in the order: I-132, Xe-135, Kr-88, I-133. In the LPSI room, the dose rate was approximately 7.5 mGy/h during descent, 8.0 mGy/h at work start, 8.0~14.0 mGy/h during sealing, and 14.2 mGy/h during ascent.

Table III: Robot mission and operation time

	mission	duration (min)	Cumulative time (min)
0	preparation	2.0	2.0
1	move down the hallway	2.3	4.3
2	stairway	1.1	5.4
3	open door	16.0	21.4
4	Stop pipe leaks	20.0	41.4
5	Spray operation (starts simultaneously with pipe leak blocking)	20.0	(41.4)
6	open door	16.0	57.4
7	stairway	1.1	58.5
8	move down the hallway	2.3	60.8

7) Total dose before-fuel-failure

By integrating the dose rate in Fig. 6 over time, the total dose can be obtained as follows(Fig. 7),

- Deployment(0~21.4 min): 0.16 mGy
- LPSI work (21.4~41.8 min): 3.76 mGy
- Return(41.8~60.8 min): 0.36 mGy
- total: 4.28 mGy

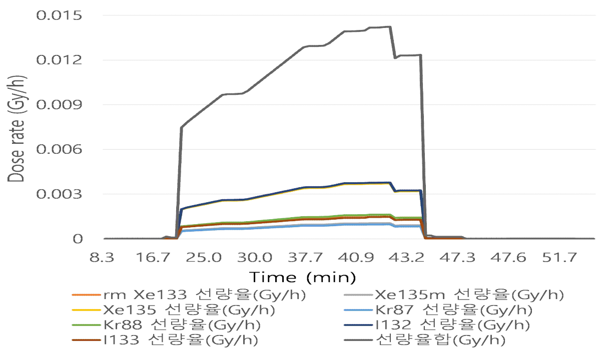

Fig. 6. Dose rate with respect to time

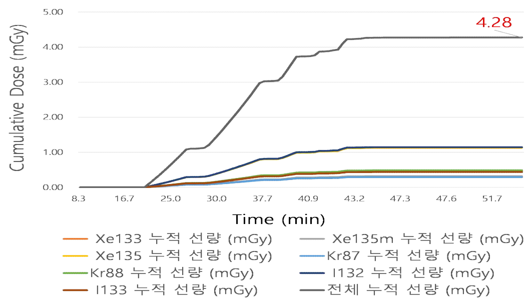

Fig. 7. Cumulative radiation dose of robot

3.3 Dose rate after-fuel-failure

1) Dominant source terms

For after-fuel-failure conditions, the dose rate was calculated using the same methodology as in the before-fuel-failure case, but with source terms originating from damaged fuel. The dominant radionuclides identified were Xe-133, Cs-134, I-131, I-133, and Te-132 (Fig. 8).

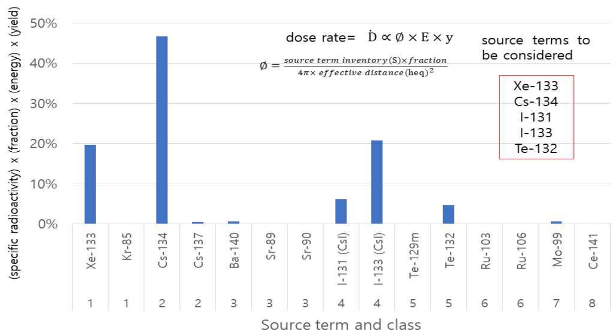

Fig. 8. Values of product of specific radioactivity, fraction, energy and yield

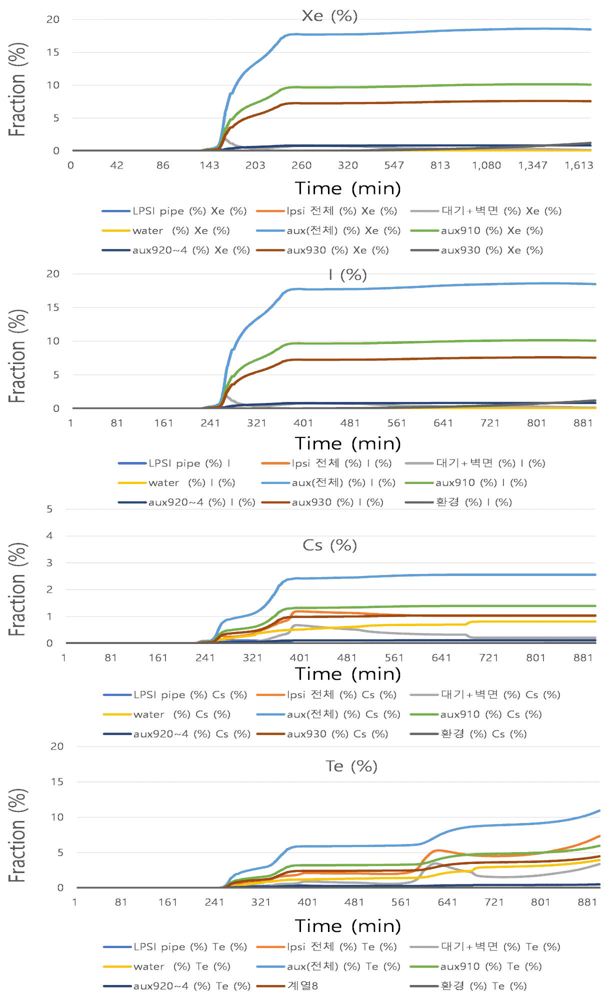

Fig. 9. Fracton of primary coolant flow rate released to each room

2) Distribution of source terms by room

The fraction of source terms released into each room via the leak path was determined using MELCOR simulations (Fig. 9).

The fraction of source terms is:

- For Xe and I, the distribution from highest to lowest was: Room 910, Room 930, Rooms 920–924, and the LPSI room in the AUX building.
- For Cs and Te, the order was: Room 910, Room 930, LPSI room, and Rooms 920–924 in the AUX building.

Fig. 10 shows the distribution of source terms among the LPSI room's walls, air, water, and piping:

- The total inventory in the LPSI room decreased in the order Te > Cs > I ≈ Xe.
- Te and Cs exhibited high concentrations on walls, in water, and within pipes, whereas I and Xe were nearly absent in these components.
- In the LPSI room air, I and Xe concentrations were greatest during the early stages of the accident, while Te and Cs dominated during later stages.
- The amount of source terms in piping was roughly one-tenth of that on the walls or in the air over a certain period.

3) Dose rate at the robot's working position in the LPSI room

Using the spatial distribution of source terms shown in Fig. 10, the dose rate at the robot's working position in the LPSI room was calculated (Fig. 11).

- The total dose rate—sum of contributions from air, walls, pipes, and water—peaked at approximately 11 kGy/h.
- The dose rate from water was about one-twentieth of that from air or walls due to the water's shielding effect.

4) Robot path and operation time

The robot's path and movement/operation times were identical to those assumed for the before-fuel-failure case.
Deployment was modeled to occur at the time of maximum dose rate (t = 150 minutes) to estimate the worst-case exposure.

5) Dose rate by location

Table IV summarizes the calculated dose rates and cumulative doses for each location during the robot's movement and work.
The highest dose rate occurred in Room 910 (18.6 kGy/h), followed by Room 930 (11.8 kGy/h), Rooms 920–924 (2.6 kGy/h), and the LPSI room (1.8 kGy/h).
This ranking reflects the decreasing distribution fraction of the source term as shown in Fig. 10.
In before-fuel-failure case, the robot's primary exposure occurred in the LPSI room. In after-fuel-failure case, however, significant additional exposure occurred in Rooms 910 and 930.

6) Total robot radiation dose

As shown in Table IV, the total cumulative dose to the robot was approximately 4,058 Gy:

- Transit to the LPSI room: 3,341 Gy
- Work in the LPSI room: 717 Gy

This dose level is extremely high, making it technically unfeasible for a current-generation robot to survive under such conditions. Consequently, effective ISLOCA response requires robot deployment before fuel failure, i.e., within 126 minutes of accident onset.
Moreover, in any ISLOCA scenario, it is essential not only to minimize work time in the LPSI room but also to maximize movement speed through other high-radiation areas.

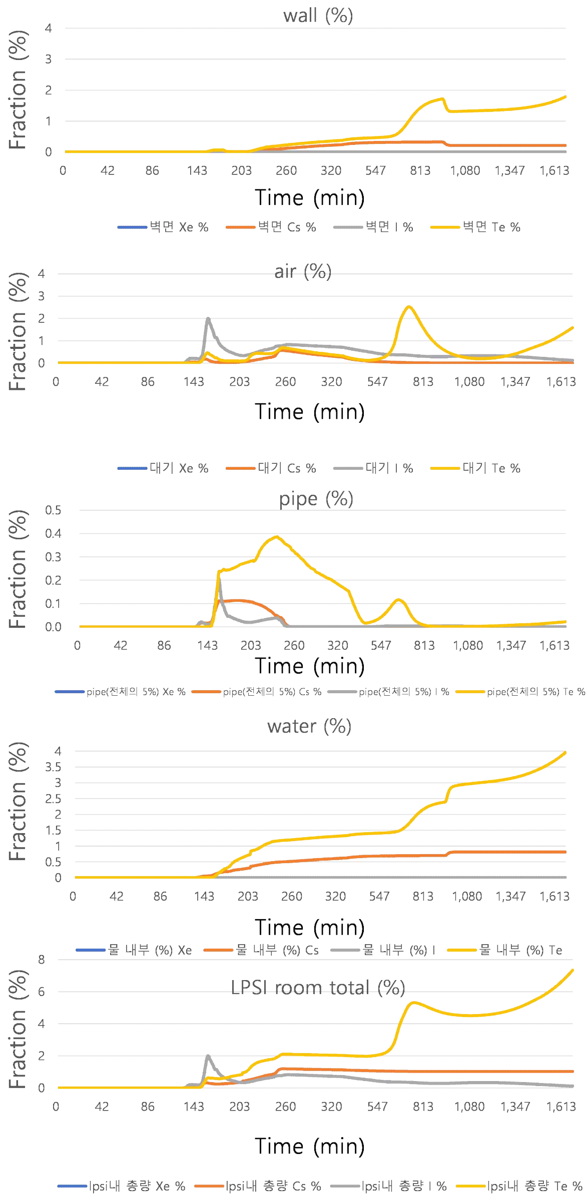

Fig. 10. Source term fraction in the LPSI room

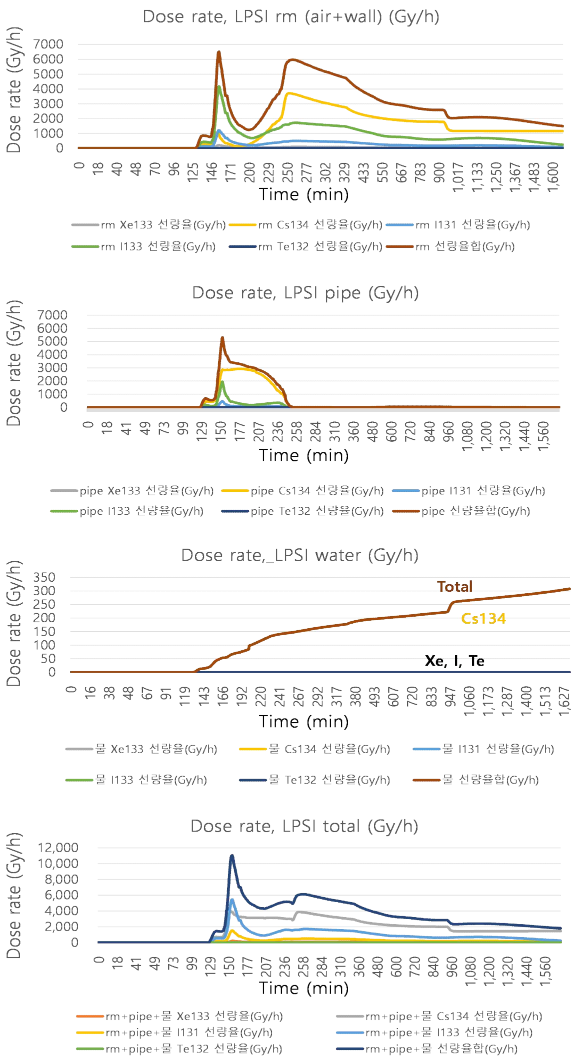

Fig. 11. Dose rate at the robot's working position in the LPSI room

4. Conclusion

This study evaluated radiation doses received by a robot responding to an ISLOCA scenario:

1. Before-fuel-failure: Total dose ≈ 4.28 mGy - tolerable for robots with modest radiation resistance.
2. After-fuel-failure: Total dose ≈ 4,058 Gy - far beyond survivability limits.
3. Robots must be deployed before fuel failure (within 126 minutes of accident onset).
4. If after-fuel-failure deployment is unavoidable, minimize work time in the LPSI room and maximize travel speed in other rooms.
5. In addition to radiation tolerance, robots must withstand high temperatures (100~200°C) from hot coolant and steam.
6. Waterproofing is essential, as coolant leakage and spray operations can cause water depths up to ~60 cm in the LPSI room.

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Table IV: Robot moving and work time and radiation dose (after nuclear fuel failure)

	CV	CV900 end work	CV900 start work	CV900 stair	open door 900	CV910 hallway	open door 910	CV920 stair	open door 920	CV922 stair	open door 922	CV924 stair	open door 924	CV930 hallway	open door 930	open door 1,2	Preparation
	door number (assume 1 door at each rm)				8		7		6		5		4		3	1,2	
	Length (m)	7.0		7.0		90.8		3.7		5.6		3.4		48.8			
IN	work time (min)	20.0		0.4	2	1.5	2	0.2	2	0.3	2	0.2	2	0.8	2	4	2.0
	cumulative time (min)	41.422	21.422	21.422	21.036	19.036	17.523	15.523	15.315	13.315	13.002	11.002	10.814	8.814	8.000	6.000	2.000
	coolant amount (kg)	8174	4264	4150	195	195	4.2	4.2	2.1	0.21	0.7	0.7	6	6	0	0	0
	coolant water level (m)	0.199	0.100	0.100	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000			
	robot location	9	9	9←8	7	7←6	5	5←4					3	3←2	1		
	dose rate (Gy/h)	1856~1832		1757	18591	18593	1589	2555					7044	11780	0	0	
	dose (Gy)	717		11	620	469	53	201					235	160	0	0	
	total at each interval	717		1748													
OUT	work time (min)			0.4	2	1.5	2	0.2	2	0.3	2	0.2	2	0.8	2	4	
	cumulative time (min)			41.8088	43.8088	45.3220	47.3220	47.5301	49.5301	49.8423	51.8423	52.0307	54.0307	54.8447	56.8447	60.8447	
	coolant amount (kg)			8203	8600	284	293	7.5	7.6	2.6	2.6	1	1.1	8.3	8.4	0	
	coolant water level (m)			0.200	0.210	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
	robot location			9→8	8	7→6	6	5→4					4	3→2	2		
	dose rate (Gy/h)			1721	1406	18619	10973	2558					3108	11790	7049		
	dose (Gy)			11	47	470	366	201					104	160	235		total
	total at each interval			1593													4058