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Radiation Dose Distribution for Workers in South Korean Nuclear Power Plants

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***Abstract*—**A total of 33,680 nuclear power plants (NPPs) workers were monitored and recorded from 1990 to 2007. According to the record, the average individual radiation dose has been decreasing continually from it 3.20 mSv/man in 1990 to 1.12 mSv/man at the end of 2007. After the International Commission on Radiological Protection (ICRP) 60 recommendation was generalized in South Korea, no nuclear power plant workers received above 20 mSv radiation, and the numbers of relatively highly exposed workers have been decreasing continuously. The age distribution of radiation workers in nuclear power plants was composed of mainly 20-30-year-olds (83%) for 1990 ~ 1994 and 30-40-year-olds (75%) for 2003 ~ 2007. The difference in individual average dose by age was not significant. Most (77%) of NPP radiation exposures from 1990 to 2007 occurred mostly during the refueling period. With regard to exposure type, the majority of exposures were external exposures, representing 95% of the total exposures, while internal exposures represented only 5%. External effective dose was affected mainly by gamma radiation exposure, with an insignificant amount of neutron exposure. As for internal effective dose, tritium (^3H) in the pressurized heavy water reactor (PHWR) was the biggest cause of exposure.

***Keywords*—**Dose distribution, External exposure, Nuclear power plant, Occupational radiation dose

I. Introduction

WHEN Kori unit 1 began commercial operation on April 29, 1978, South Korea's nuclear power generation was born. As of 2008, 20 nuclear power plants, with 16 units of pressurized water reactors (PWRs) and four units of pressurized heavy water reactors (PHWRs), have operated. And it is the world's sixth largest nuclear power plant.

Additionally, four units of OPR-1000 (optimized power reactor 1,000 MWe), the Korean standard nuclear power plant, and four units of APR-1400 (advanced power reactor 1,400 MWe), the next most common Korean nuclear reactor, are under construction. The Korean domestic generation capacity of 70.5 GWe in 2006 is expected to grow to 88 GWe in 2017. Nuclear power generation is anticipated to be 26.6 GWe (30%), supplying 47% of demand (214 TWh). At the end of 2006, the nuclear capacity was 17.7 GWe net (28% of total), supplying 39% of demand (141 billion kWh net in 2006)[1].

To promote the ALARA (As Low As Reasonably Achievable) principle and to comply with the dose limits for radiation workers, the national authorities arranged for the collection, analysis, and discussion of radiation dose statistics. Consequently, high-quality monitoring systems, registration, and control of individual occupational exposure are required.

II. Materials and Methods

A. Quality Assurance Procedures

The normal dose limit according to Korean national nuclear law is 100 mSv. During any given five-year period, the effective dose is not allowed to exceed 50 mSv in any single year.

The Korean National Dose Registry, managed by the Korea Radio-Isotope Association (KRIA) entrusted by the Ministry of Education, Science and Technology (MEST), maintains records of occupational dose due to ionizing radiation. The registry publishes a quarterly external effective dose report and a yearly internal effective dose report. These numbers are reported to the KRIA[2].

The Korea Hydro & Nuclear Power Co. (KHNP) follows the ICRP 60 recommendation and national nuclear law regarding dose limits. The doses obtained from the assessment of occupational exposures from external radiation and radioisotope intake are combined to determine the total effective dose. Total effective dose for demonstrating compliance with dose limits is calculated by

$$E \cong H_P(10) + E(50), \quad (1)$$

where E is the total effective dose, $H_P(10)$ is the personal dose equivalent from external exposure, and E(50) is the committed effective dose from internal exposure[3].

The deep dose, $H_P(10)$ for NPPs workers is estimated using a Thermoluminescent Dosimeter (TLD). Radiation workers can be exposed to inhomogeneous radiation during the maintenance of reactor coolant pumps, pressurizer, and water chambers of steam generators during NPP overhaul. In inhomogeneous radiation fields, radiation workers are required

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to wear an additional TLD badge on the back as well as one on the chest, if any body part is expected to receive a total exposure exceeding 2 mSv, or 1.3 times the chest dose, and the dose rate of the working area is expected to exceed 1 mSv/hr. In this case, the whole body effective dose is calculated according to the following NCRP 55/50 algorithm[4]-[5].

$$H_E = 0.55[H_P(10)]\ (\text{chest}) + 0.50\ [H_P(10)]\ (\text{Back}), \quad (2)$$

where HE is the whole body effective dose, $[H_P(10)]$ (Chest) is the deep dose $[H_P(10)]$ of the chest, $[H_P(10)]$ (Back) is the deep dose$[H_P(10)]$ of the back, and 0.55 and 0.50 are weighting factors for TLD locations.

Radiation workers also wear additional extremity TLDs if the hands and/or feet are expected to receive an exposure exceeding 4 mSv or two times that of the whole body effective dose[6].

TLDs of NPP workers are read monthly with quality assurance manual authorized by the MEST. When an alarm dosimeter is lost or destroyed,, when one displays an over-range reading, or when a radiation worker is exposed to a higher-than-normal dose, the TLDs are read promptly. Every two reactors of an NPP have a TLD reading facility, which is audited yearly by the MEST to confirm the implementation of the quality assurance manual. This manual covers information, including the quality controls of the dose reading system, the performance criteria appropriate for evaluating the dose from ANSI N13.11, the technical skills of the person in charge of the system, the dose reading procedures, the lower limits of detection (LLD), the calibration periods, and the methods[7].

All NPP radiation workers are tested for internal exposure once per year using a whole body monitor (WBM); if a worker performs a potential high-exposure job, internal exposure examination is performed promptly. In facilities with PHWRs, when exiting from a radiation control area (RCA), every worker should submit a urine sample for an internal exposure evaluation to identify any possible tritium (^3H) intake. A liquid scintillation counter (LSC) is used to determine the activity of tritium in a liquid sample.

Every nuclear power plant having two reactors and an internal dose assessment facility adheres to the nuclear guidelines regarding internal dosimetry, measurement method and procedure, requirement of workers to undergo bioassay, bioassay system requirements, and management of documentation. Measurement procedures cover the operation method of the system, the technical skills of the person in charge of the system, the system surveillance and calibration methods, the evaluation method for intake of radioactive material, and the committed effective dose. Facilities are audited yearly by the MEST[8]. Korea Hydro & Nuclear Power Co. has implemented a radiation safety management system, including a dose registry of NPPs radiation workers, in order to execute effective radiation management. The company maintains the dose registry, and the application for the system has been continuously renewed. In the year 2003, this system was renewed under what is called a radiation management (RAM) system, based on enterprise resource planning (ERP). A radiation management system tracks and manages the names of the designated radiation workers, the issue of radiation work permits, control of RCAs, any release of radioactive materials, and various external/internal radiation dose registries. The national dose registry system, however, tracks only the external and internal effective doses of the NPP radiation workers.

A previous South Korean study on occupational radiation dose did not provide a specific radiation dose distribution for NPP radiation workers. The objective of this study, therefore, was to investigate the detailed distribution and trend of occupational radiation exposure to workers at NPPs using doses recorded by the RAM of KHNP.

A.Registry information

The dose registry of the KHNP maintains records of occupational doses by ionizing radiation for NPP radiation workers. The registry contains radiation dose records for 33,680 persons tested between 1990 and 2007, with 11,435 of them monitored in the year 2007. The information in the registry includes individual worker exposure history, including the worker's name, gender, date of birth, identification number, job classification, monthly external and internal dose data, the beginning and end date of measurement, work group, and plant location. External dose information includes the deep dose, shallow dose, skin dose, alarm dosimeter dose for β and γ radiation, and neutron dose. The RAM system also includes internal dose information as a result of whole body analysis for γ emitters and liquid scintillation counts for tritium. The radiation workers at nuclear power plants were grouped into four occupational categories: operation, inspection and maintenance, research and audit, and radiation management service. All monitored workers were individuals to whom a dosimeter was issued, while measurably exposed workers are those who received an average annual effective dose higher than 0.1 mSv. All dose data were based on measurements from the TLDs for external exposures and the WBM/LSC for internal exposures. All of the instruments used at the facilities were calibrated semiannually.

B.Calculation of Dose distribution

We calculated two radiation dose variables based on the following algorithms from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) report[9] to investigate their distributions: 1) the average annual effective dose, 2) the annual collective effective dose. These were estimated for all monitored workers. We analyzed the exposure data with respect to worker age, occupational group, operation state, and exposure type[10]-[13].

III. Results and Discussion

A total of 33,680 NPP workers were monitored from 1990 to 2007, with the number continuously increasing over time. The average annual effective doses have been continuously decreasing for all monitored workers.

The detailed data on occupational dose are presented in

Table I, II and III. The Korea Hydro & Nuclear Power Co. initiated ALARA activities for its radiation workers in order to comply with the new occupational exposure limit proposed by the ICRP In 1990. For example, both short- and long-term comprehensive grades are being performed in order to improve equipment, such as steam generators and reactor coolant pumps, reactor head open-close tools, the removal or minimization of snubbers and reactor coolant loop RTD (resistance temperature detector) bypass lines, and remote control device installations, which are known to result in high worker exposure[14].

TABLE I
NUMBER AND AVERAGE ANNUAL EFFECTIVE DOSE OF NPP WORKERS BY CALENDAR YEAR

Year	Monitored workers	Annual collective effective dose (man-mSv)	Average annual effective dose (mSv)	
			Monitored workers	Measurably exposed workers
1990	4651	14863	3.20	4.85
1991	4060	8181	2.02	3.22
1992	4725	11557	2.45	4.16
1993	4627	11445	2.47	4.24
1994	5416	10968	2.03	3.67
1995	6004	12853	2.14	4.20
1996	5965	11702	1.96	3.62
1997	7903	10032	1.27	3.01
1998	9326	14496	1.55	3.65
1999	8410	12678	1.51	3.23
2000	8073	11393	1.41	2.87
2001	8336	10749	1.29	2.89
2002	8345	9315	1.12	2.69
2003	8743	10289	1.18	2.71
2004	9870	13029	1.32	3.05
2005	9810	11933	1.22	2.78
2006	10190	10960	1.08	2.34
2007	11435	12811	1.12	2.45

TABLE II
COLLECTIVE EFFECTIVE DOSE BY EXPOSURE TYPE

Year	Collective effective dose by exposure type (man-mSv)			
	External		Internal	
	Gamma	Neutron	PWR	PHWR
1990	14125	15	0	723
1991	7896	62	0	223
1992	10805	31	0	721
1993	11159	96	0	190
1994	10163	177	0	628
1995	12024	373	0	456
1996	10988	211	0	503
1997	9327	197	1	507
1998	13330	377	4	785
1999	11498	333	0	847
2000	10477	310	0	606
2001	9767	329	0	653
2002	8382	409	3	521
2003	8926	548	6	809
2004	11781	452	3	793
2005	10463	644	1	825
2006	9664	639	2	655
2007	11661	419	3	728

TABLE III
RADIATION DOSE DISTRIBUTION OF NPP WORKERS BY CALENDAR YEAR

Year	NPP workers dose distribution (mSv)						
	< 0.1	≥ 0.1	≥ 1	≥ 5	≥ 10	≥ 15	≥ 20
1990	1587	982	1033	553	286	122	88
1991	1522	1042	938	358	140	43	17
1992	1946	920	1081	420	209	107	42
1993	1926	899	1053	388	195	117	49
1994	2427	1158	1073	429	211	103	15
1995	2942	1182	1018	455	229	106	72
1996	2735	1248	1136	515	213	105	13
1997	4566	1439	1194	494	143	60	7
1998	5357	1517	1397	642	283	120	10
1999	4490	1591	1425	564	256	84	0
2000	4105	1716	1494	512	181	65	0
2001	4621	1515	1489	478	178	55	0
2002	4884	1541	1300	447	131	42	0
2003	4942	1719	1388	487	155	52	0
2004	5592	1901	1477	546	253	101	0
2005	5518	1912	1577	543	209	51	0
2006	5513	2295	1682	519	168	13	0
2007	6200	2578	1857	516	240	44	0

As a result of those activities, the number of radiation workers receiving relatively high exposure doses has been decreasing since 1990. After 2000 when the ICRP 60 recommendation was adopted in Korea, no NPP worker received a dose above 20 mSv/yr. Moreover, the number of NPPs workers who received doses greater than 15 mSv/yr and 10 mSv/yr also decreased.

In the case of NPPs, it is not easy to classify occupational groups in detail, unlike in other fields of industry. The dose registry system (RAM) of KHNP also does not classify workers by occupational group. Instead, starting with the data from 1990, we classified the workers using allocated company codes and statistically processed the significant data.

We grouped people into four occupational groups of Operations, Inspection & Maintenance, Research & Audit, and Radiation Management Services. All of the KHNP plant workers were classified into the Operations group. The mechanical, electrical, and maintenance contractor workers were placed into the Inspection & Maintenance group, people from external institutes and regulatory bodies who inspected and audited facilities were assigned to the Research & Audit group. The Radiation Management Services group consisted of all special contractors in radiation control occupations, such as health physics, radiation protection, decontamination, and radioactive waste treatment.

Figure 1 indicates the average effective dose value by occupational group during the period from 1990 to 2007. The average dose for the Operation group was 0.46 mSv, that of the Inspection & Maintenance group was 2.27 mSv, the Research & Audit group was 0.18 mSv, and the Radiation Management Services group was 2.44 mSv. The individual average effective dose has also been continuously decreasing in all occupational groups, although the two groups Inspection & Maintenance and Radiation Management Services received relatively higher doses when compared with the other two groups, Operations and Research & Audit.

Analyzing the 2007 individual average effective dose distribution by age shows that the workers in their 20s had the highest average exposure of 1.35 mSv, followed by the 1.32 mSv of those in their 30s, the 1.00 mSv of those in their 40s. Finally, the group aged 50 and older had the lowest individual average effective dose of 0.69 mSv. There was little difference in average exposure by age.

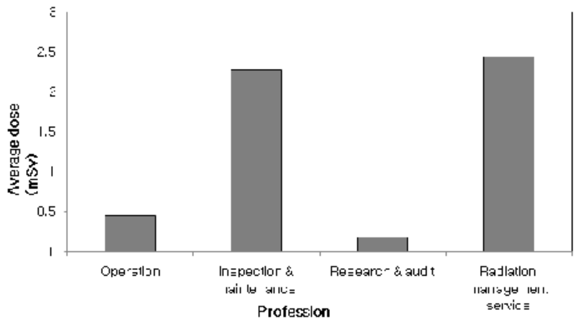

Fig. 1 The mean average annual effective doses of NPP workers by occupational group from 1990 to 2007.

Representing 39.94% of the total NPP workforce, workers in their 30s were the largest age group of NPPs workers, followed by the 31.92% of workers in their 40s, 14.23% in their 20s, and 13.91% aged 50 years or older. The 30s and 40s are the predominate age groups among all NPP workers. As the number of women working at NPPs was too small to process, we did not analyze the data with respect to gender. For instance, only 30 of the 11,435 people working in nuclear power plants in 2007 were women.

Most radiation exposure occurred during refueling. When averaging the collective effective doses of 1990-2007, the percentages of exposure occurring during normal operations and refueling were 23% and 77%, respectively.

The detailed dose distributions by exposure type are presented in Table 2. As shown, external exposure accounted for 95% of exposures, and internal exposure occurred in only 5% of exposures. The external effective dose was affected mainly by gamma radiation, with insignificant amounts due to neutron exposure. The biggest contributor to internal effective dose for PHWR workers was tritium (^{3}H), and the internal effective dose of PWR workers was induced by the intake of gamma radioisotopes, such as ^{58}Co and ^{60}Co.

According to the data provided by the World Association of Nuclear Operators, the annual collective effective dose per unit in South Korea has continually been lower than that of the world average[15]-[16].

IV. CONCLUSION

The number of radiation workers in Korea has been increasing steadily since Kori-1 started commercial operation in 1978 and is expected to increase continuously in the future. Korea currently has 20 functioning nuclear reactors, with eight more under construction as of 2008. Additionally, the Korean government plans to increase nuclear power from its current generation rate of 35.5% to one of 59% by 2030.

In contrast, the average annual individual dose has been showing a constant downward trend due to the

radiation protection activities of KHNP that have been implemented to assure compliance with the ALARA reinforcement policy to optimize radiation protection. Included in these protective acts are the recommendation of a decreased dose limit and the dose constraint guidelines established by the ICRP.

Actually, KHNP has performed a substantial amount of equipment improvements, design changes, and procedure amendments in order to meet the dose limitations of the ICRP recommendation. In addition, new plants are being constructed with an enhanced design based on the experiences of the existing plants.

From the software point of view, training, procedure development and exposure reduction plants are constantly being updated.

Because of these proactive measures, the Korean annual average individual radiation exposure dose is expected to remain low.

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