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■ 論 文 ■

Radiation Exposure Reduction in APR1400

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Abstract – The primary contributors to the total occupational radiation exposure in operating nuclear power plants are operation and maintenance activities during refueling outages. The Advanced Power Reactor 1400 (APR1400) includes a number of design improvements and plans to utilize advanced maintenance methods and robotics to minimize the annual collective dose. The major radiation exposure reduction features implemented in APR1400 are a permanent refueling pool seal, quick opening transfer tube blind flange, improved hydrogen peroxide injection at shutdown, improved permanent steam generator work platforms, and more effective temporary shielding. The estimated average annual occupational radiation exposure for APR1400 based on the reference plant experience and an engineering judgment is determined to be in the order of 0.4 man-Sv, which is well within the design goal of 1 man-Sv. The basis of this average annual occupational radiation exposure estimation is an eighteen (18) month fuel cycle with maintenance performed to steam generators and reactor coolant pumps during refueling outage. The outage duration is assumed to be 28 days. The outage work is to be performed on a 24 hour per day basis, seven (7) days a week with overlapping twelve (12) hour work shifts. The occupational radiation exposure for APR1400 is also determined by an alternate method which consists of estimating radiation exposures expected for the major activities during the refueling outage. The major outage activities that cause the majority of the total radiation exposure during refueling outage such as fuel handling, reactor coolant pump maintenance, steam generator inspection and maintenance, reactor vessel head area maintenance, decontamination, and ICI & instrumentation maintenance activities are evaluated at a task level. The calculated value using this method is in close agreement with the value of 0.4 man-Sv, that has been determined based on the experience and engineering judgement. Therefore, with the As Low As Reasonably Achievable (ALARA) advanced design features incorporated in the design, APR1400 design is to meet its design goal with sufficient margin, that is, more than a factor of two (2), if operated on an eighteen (18) month fuel cycle.
Key words: ALARA, occupational radiation exposure, APR1400

INTRODUCTION

APR1400, a pressurized water reactor with 1400 MWe class power output, is designed to be operated and maintained with an average annual collective radiation dose of less than the Korean Utility Requirement Document (KURD) goal of 1 man-Sv per reactor unit[1]. Improvements in the plant design, maintenance methods, and robotics have produced a decreasing annual collective dose for U.S. plants over the past 10 years. Additionally, as plants have matured and the required post-TMI plant modifications have been completed, the number of modifications being performed annually has been significantly reduced. This has also contributed to reductions in average plant radiation exposure totals in recent years. As reported by the NRC in the latest issue of NUREG-0713, the five-year average dose per PWR (Pressurized Water Reactor) year from 1994 through 1998 is 1.315 man-Sv. The decreasing trend can be illustrated by comparing to the 1993 annual collective dose of 1.99 man-Sv per PWR year [2].

The Palo Verde nuclear generating station is selected for comparison purpose in determining the average annual collective dose. The Palo Verde nuclear generating station is selected as the reference plant since it has similar component arrangement, size, and basic operation method with APR1400 and has accumulated a significant amount of operating experience. Sufficient occupational radiation exposure data are available to draw conclusions regarding the effectiveness of advanced design features in reducing the occupational radiation exposure for advanced light water reactors. The Palo Verde nuclear generating station has also recently adopted some of the advanced design features that are under consideration for APR1400. Comparison of data from before and after the application of these features allows to assess the effectiveness of these features. Figure 1 provides a comparison of occupational radiation exposure at the Palo Verde nuclear generating station to other U. S. PWRs [2]. As can be seen in Figure 1, the Palo Verde occupational radiation exposure is, on average, significantly less than the average PWR exposure.

Yonggwang units 3 & 4 also provide useful data for comparison of the effectiveness of the advanced design features of APR1400. These plants have been operated for a relatively short period of time, hence adequate amount of detailed occupational radiation exposure data are not readily available. However, the Yonggwang plants are the first plants to incorporate most of the recommended TMI design changes for the initial design and have also benefited from lessons learned at Palo Verde [3].

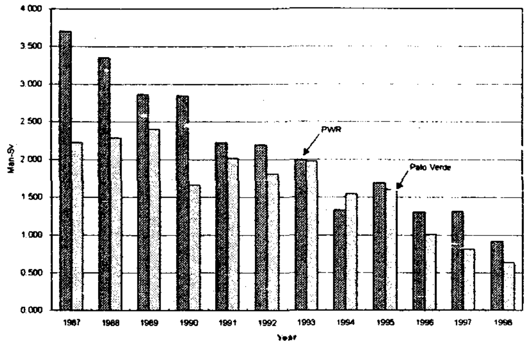

Figure 1. Comparison of ORE in U.S. PWRs and PVNGS

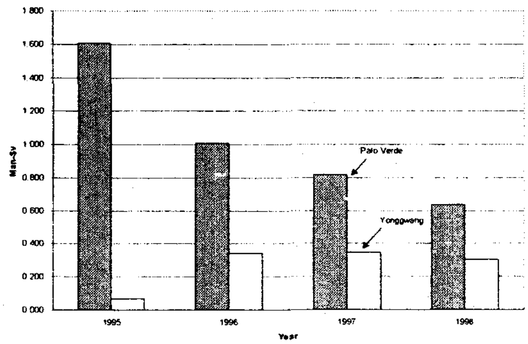

Figure 2. Comparison of ORE for Palo Verde and Yonggwang

Figure 2 provides a comparison of the occupational radiation exposure between Palo Verde and Yonggwang plants.

The main differences between Palo Verde and Yonggwang plants are the less fuel failures at Yonggwang, use of improved water chemistry from the initial plant startup, increased segregation of clean and radioactive equipment, and divisional separation. Additional features of the Yonggwang plants that contribute to a lower occupational radiation exposure are:

- Separation of the auxiliary building into safety-related and non-safety related buildings,
- Simplified and improved ALARA design,
- No high-energy line breaks in safety areas outside the containment,
- Elimination of most fire wrap and structural fire

coating,
- Minimal seismic support for non-safety-related components,
- Reduction in pipe supports by about 50%,
- Reduction of snubbers in large bore piping systems,
- Elimination of pipe whip restraints resulting from Leak-Before-Break (LBB) application to main loop pipes, surge line, safety injection line, and shutdown cooling line, and
- Steam Generator (SG) improvement against flow induced vibration.

As can be seen from Figure 2, the average annual occupational radiation exposure at Yonggwang units 3 & 4 is substantially less than that at Palo Verde. In order to better understand possible reasons for this difference, it is useful to compare the average annual occupational radiation exposure at newer U.S. PWRs with the annual average for all PWRs as shown in Figure 3 [2].

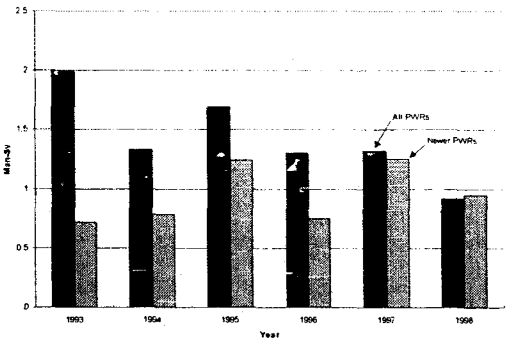

Figure 3. Comparison of all PWRs to newer PWRs in U.S.

The newer plants in Figure 3 were placed in commercial operation between 1989 and 1994. These plants include Comanche Peak (2 units), Harris (1 unit), Seabrook (1 unit) and South Texas (2 units), and have similar design to the older PWR units. However, like Yonggwang units 3 & 4, these plants are believed to have operated with improved water chemistry and fewer fuel failures. This suggests that the water chemistry and the number of fuel failures are important contributors to the average annual occupational radiation exposure.

REFERENCE PLANT OCCUPATIONAL RADIATION EXPOSURE

The Palo Verde nuclear generating station has shown a substantial reduction in the average annual occupational radiation exposure during the recent refueling outages as well as the normal plant operation. These reductions can be attributed to the application of advanced design features, improvements in water chemistry, improved planning of work activities and the higher plant capacity factors. Total occupational radiation exposure for nine (9) recent refueling outages prior to the complete implementation of the radiation reduction features is 1.265 man-Sv while total occupational radiation exposure for two (2) outages that have occurred after the implementation of the radiation reduction features is 0.797 man-Sv. The major radiation reduction features implemented are the permanent refueling pool seal, quick opening transfer tube blind flange, improved hydrogen peroxide injection at shutdown, improved permanent steam generator work platforms, and more effective temporary shielding.

APR1400 ALARA FEATURES

This section describes the As Low As Reasonably Achievable (ALARA) features that are incorporated in the APR1400 design, and presents differences in the average annual occupational radiation exposure from the reference plant. The following discussion provides information on these enhancements and their occupational radiation exposure reduction effects from the reference plant based on the experience and engineering judgment.

1. The structure for supporting and aligning cables over the reactor vessel has been designed as an Integrated Head Assembly (IHA). The Control Element Drive Mechanism (CEDM) cooling components and the missile shield are also integrated in the IHA, which will eliminate separate handling of the missile shield, cable trays and CEDM cooling components. The elimination of

these operations is estimated to reduce approximately 0.03 man-Sv of exposure per refueling outage.

2. A permanent refueling pool seal will be installed, closing the gap between the reactor vessel flange and the refueling pool liner. In all previous plants, this gap was required to be kept open during power operations to allow adequate blowout area on guillotine pipe breaks. With the incorporation of LBB technology in the APR1400 design, the requirement for this blowout area was eliminated. Installation and removal of the refueling pool seal has historically been a labor intensive, high radiation exposure effort. The installation of a permanent refueling pool seal is estimated to reduce approximately 0.03 man-Sv of exposure per refueling outage.
3. The removal (and reinstallation) of the blind flange on the fuel transfer tube at the containment boundary has historically been a high radiation exposure operation with a high potential for personnel contamination. The APR1400 design incorporates a quick acting mechanism on this flange and amount of time required to engage the flange using the remote handling equipment is significantly less than the time required for the previous bolted flange design. The installation of a hydraulic closure device on the fuel transfer tube is estimated to reduce approximately 0.03 man-Sv of exposure per refueling outage.
4. Controls of the fuel handling equipment have been significantly automated in the APR1400 design. The incorporation of computerized sequencing in the machines and monitoring of operations by a TV camera at a low-dose location, away from the machines, reduces the man-hours required to be expended on these machines. The automation will also provide a capability to perform fuel position verification during the fuel handling operations. These improvements are estimated to reduce approximately 0.02 man-Sv of exposure per refueling outage.
5. Incorporation of the LBB technology in the APR1400 design will significantly reduce the number of pipe supports and whip restraints required on the Reactor Coolant System and connected piping. All of the supports and restraints eliminated will result in an exposure time savings in the in-service inspection and testing, direct inspections, and relocation of restraints to allow testing. It is estimated that the elimination of this equipment will result in savings of approximately 0.04 man-Sv per unit per refueling outage.
6. De-tensioning and tensioning of the reactor vessel closure studs are another labor intensive operation that will be simplified in the APR1400 design. The design includes multi-stud tensioners, which will greatly reduce the man-hours required in the proximity of the reactor vessel flange for every refueling. The APR1400 design is improved from the Palo Verde tensioners which are 50 percent tensioners to 100 percent tensioners. It is estimated that the use of 100 percent multi-stud tensioners for the reactor vessel studs will reduce approximately 0.02 man-Sv of exposure per refueling outage over the Palo Verde multi-stud tensioner.
7. The APR1400 design includes several features which enhance accessibility during maintenance and inspection activities on the steam generators, reduce occupational radiation exposure in the vicinity of the primary heads, and decrease the amount of inspection and repair required during the outage. These features include:
   - Utilizing automatic/robotic equipment for inspection and maintenance activities.
   - Providing adequate staging and laydown areas to facilitate activities.
   - Providing permanent platforms in proximity to steam generator manways to minimize the setup and tear down times.
   - Increasing the size of manways to 21 inches to provide easier, faster access for

personnel and equipment.

- Providing removable insulation to facilitate weld inspections.
- Providing handhole access above SG tube sheet to facilitate sludge removal activities, leading to reduced corrosion and crud induced radiation.
- Utilizing Inconel 690 for SG tubes to reduce degradation of steam generator tubes, resulting in little or no tube repair time and reduced inspection requirements.
- Using single nozzle dams to permit remote installation, minimizing occupational radiation exposures during this activity.

It is estimated that the above enhancements will reduce approximately 0.27 man-Sv of exposure per refueling outage.

8. Inadequate equipment laydown and maintenance staging areas often resulted in the maintenance and refueling operations being conducted in close proximity to major radioactive components such as the reactor vessel head assembly. The APR1400 containment arrangement is designed to minimize these hazards. It is estimated that the enhanced laydown and staging arrangements in the APR1400 design will result in a saving of approximately 0.05 man-Sv of exposure per refueling outage.
9. Area radiation dose in the APR1400 will be reduced through a hydrogen peroxide injection at shutdown to reduce the activity in the reactor coolant system. It is reported that this injection has reduced the area doses at Palo Verde by approximately 50 percent in recent outages. Assuming that one-quarter of the occupation radiation exposure can be reduced by the hydrogen peroxide injection, the savings will be approximately 0.12 man-Sv.
10. The original reactor coolant pump seals provided to the Palo Verde nuclear generating station units require replacement at each refueling. The RCP seal has been redesigned to extend its life. The APR1400 seal changeouts are expected to occur on an alternate outage basis, reducing the man-hours expended in the radiation fields surrounding the pumps by half. This improvement is estimated to reduce approximately 0.04 man-Sv of exposure each refueling outage.
11. The reactor coolant pumps originally installed at Palo Verde nuclear generating station units 1 & 2 contained the antimony material in the journal bearings and wear rings. The activation and normal wear of these components resulted in a large number of hot particles throughout the first cycles of operation. The antimony material was replaced with different, less active material in units 1 & 2 as well as in unit 3 before its initial startup. The result of this changeout has been a reduced hot particle problem in unit 3 and a decreasing problem in units 1 & 2. The reactor coolant pumps in APR1400 will not contain antimony in these parts. This results in significant savings in occupational radiation exposure during normal operations and an estimated reduction of 0.02 man-Sv during refueling outage.
12. The purification filter elements can be changed to those with smaller sized pores as the system is cleaned to provide better capture of hot particles without excessive changeouts from the system. This enhancement will result in a reduced crud trap/hot spot activity and will contribute to maintaining lower radiation levels throughout the facility. The manufacturers data indicate that the reactor coolant activity is reduced by over 95 percent with fine filtration, and the dose rates in equipment rooms and at the spent fuel pool are reduced by a factor of 6 or more. This will reduce the annual exposure during normal operation and 0.08 man-Sv during refueling outage.
13. Improvements in the water chemistry and reduction in the amount of cobalt in materials will contribute to the reduction in

occupational radiation exposure. Additional reductions will result from the increased reliability of the fuel assemblies. These features are estimated to contribute an 0.08 man-Sv reduction during refueling and contribute a significant reduction during normal operation.

14. APR1400 incorporates additional ALARA features which the Palo Verde plants do not have. Some of these features are :
  - Adequate spacing around equipment for easy access of equipment for maintenance and inspections,
  - Large staging areas inside and outside the equipment hatch and personnel airlocks to allow pre-staging before movements and to facilitate efficient radiation controls,
  - Small pumps flanged into systems (rather than welded) to facilitate removal to low radiation areas for maintenance.
  - Ion exchangers located in pits to enhance their shielding. They are designed for complete draining and remote resin removal and flushing. Manways are easily accessible and internal components are easily removable through manways with minimal disassembly.
  - The radwaste building with remotely operated equipment and components to reduce the need for local operations or local readings. Piping and components will be designed to minimize crud traps and buildup in radwaste systems. Spent ion exchange and filter media will be handled and stored in a shielded area.

These specific and general features along

Table 1. Summary of APR1400 ORE Reduction Features

	ORE Reduction Features	Reduction (man-Sv)
1	Integrated Head Assembly	0.03
2	Permanent Refueling Pool Seal	0.03
3	Quick Opening Transfer Tube Blind Flange	0.03
4	Fuel Handling Equipment Automation and Increased Operating Speeds	0.02
5	Leak-Before-Break (LBB) Technology to Reduce Snubber/Restraint Inspection and Maintenance	0.04
6	Improved 100% Multiple Stud Tensioner for Reactor Vessel	0.02
7	Decreased Steam Generator Tube Inspections and Equipment Improvements	0.27
8	Improved Equipment Arrangement for Maintenance	0.05
9	Hydrogen Peroxide Injection for RCS Cleanup at Shutdown	0.12
10	Improved Reactor Coolant Pump Seals	0.04
11	No Antimony in Reactor Coolant Pump Seals	0.02
12	Decreased Filter Mesh Size	0.08
13	Water Chemistry Improvements/Zero Fuel Failures	0.08
14	Miscellaneous Features	0.03
	Total Reductions	0.86

with good operating and maintenance practices will contribute to reducing occupational radiation exposure by an estimated 0.03 man-Sv during refueling. These features will also reduce the occupational radiation exposure during normal plant operation.

As discussed above, the primary contributors to the total occupational radiation exposure are operations and maintenance activities during refueling outages, and the expected reductions in the occupational radiation exposure for APR1400 during refueling outages are summarized in Table 1.

APR1400 ORE ASSESSMENT

The basis of the average annual occupational radiation exposure assessment for APR1400 is an eighteen (18) month fuel cycle with maintenance performed to steam generators and reactor coolant pumps during the refueling outage. The outage duration is assumed to be 28 days. The outage work is performed on a 24 hour per day basis, seven (7) days a week with overlapping twelve (12) hour work shifts. The worker productivity and skill level are based on typical nuclear industry workers.

Based on the detailed assessment of APR1400 ALARA features in the previous section, the total unit exposure for normal activities during one refueling outage can be as low as 0.405 man-Sv. This value is determined by subtracting the total expected reductions of 0.86 man-Sv (see Table 1) from the Palo Verde average refueling occupational radiation exposure of 1.265 man-Sv recorded prior to the implementation of improvements. Comparing the average occupational radiation exposure prior to and after implementation of the advanced design features, Palo Verde has reduced the occupational radiation exposure by 0.468 man-Sv. Since a large portion of the remaining exposure is related to the steam generator inspection and repair, the Palo Verde nuclear generating station data strongly suggest that the reductions above are realistic.

Normal operations and maintenance activities conducted during normal operation will result in less than 0.03 man-Sv per calendar quarter. This value is also supported by the Palo Verde nuclear generating station quarterly exposure data contained in the U. S. NRCs Performance Indicators for Operating Commercial Nuclear Power Reactors report for the period starting with the second quarter of 1995 through the third quarter of 1997. During this period, the average quarterly exposure for non-refueling quarters is 0.046 man-Sv. The benefits of the aforementioned APR1400 ALARA features that will directly impact normal plant operation result in a reduction to 0.03 man-Sv. The Palo Verde units have in fact equaled or bettered this value in nine (9) recent quarters. Normal plant operation includes anticipated transients and maintenance activities performed while the plant is operating.

The average annual occupational radiation exposure is determined over a three (3) year period (12 quarters). This period includes two (2) refueling outages and one (1) year with no refueling outage based on the eighteen (18) month refueling cycle. The refueling outage length is 28 days or approximately 2/3 of a calendar quarter for two (2) refueling outages.

Occupational Radiation Exposure per refueling = 0.405 man-Sv

For two (2) outages $0.405 \times 2 = 0.81$ man-Sv (total refueling exposure)

Quarters of normal plant operation during three (3) years = $12 - 2/3 = 11.33$ quarters

Total exposure during normal operation = 11.33 (quarters)$\times$0.03 (man-Sv/quarter)= 0.34 man-Sv

Combined refueling and normal operation exposure = $0.81 + 0.34 = 1.15$ man-Sv in three (3) years

Average annual occupational radiation exposure = $1.15 / 3 = 0.383$ man-Sv

Based upon an 18 month cycle with a 28 day refueling period, these exposure estimates for APR1400 result in an average annual exposure of 0.383 man-Sv per unit.

ALTERNATE METHOD OF APR1400 ORE DETERMINATION

The occupational radiation exposure for the APR1400 design was also determined by an alternate method. The alternate method consists of a study of the exposures expected for major activities during refueling outages. The major outage activities for fuel handling, reactor coolant pump maintenance, steam generator inspection and maintenance, reactor vessel head area maintenance, decontamination, and ICI & instrumentation maintenance activities are studied at the task level. These activities are those that represent the majority of the total radiation exposure during a refueling outage. The tasks performed during the outage are the activities using the normal outage [4]. The reactor vessel head related activities were modified to reflect the differences between the tasks and those required for the APR1400 Integrated Head Assembly.

The staffing requirements in radiation areas were determined for each task. A radiation dose rate was assigned to each task based on the System 80+ radiation zone maps [5], adjusted for assumed higher levels close to the equipment and good ALARA practices, such as moving into low radiation areas whenever possible. Task staffing includes support functions such as health physics technicians, crane operators and supervision. The activity durations and dose rates were selected to be conservative. This conservatism provides a margin for activities that were not specifically identified in the task area. As an example, the duration for changing two (2) reactor coolant pump seals is assumed to be approximately six (6) days. The Yonggwang units 3 & 4 reactor coolant pump specification requires a test, which was successfully performed, to demonstrate the seal can be changed in six (6) hours per pump. Table 2 provides the calculated occupational radiation exposure for the refueling outage.

The calculated value of 0.385 man-Sv is in close agreement with the value of 0.405 man-Sv provided in the previous section. The difference of 0.02 man-Sv provides a margin for other activities that were not specifically considered in this calculation. The normal operation occupational radiation exposure is assumed to be the same as the previous value of 0.03 man-Sv per quarter. Using the same basis of a three (3) year period to calculate the average annual occupational radiation exposure, eighteen (18) month fuel cycle and 28 day refueling outages, results in an average annual occupation radiation exposure of 0.37 man-Sv.

Table 2. APR1400 Refueling Outage Occupational Radiation Exposure

Task Description	Man-Sv/Outage
Reactor Vessel Head Removal, Installation, Maintenance	0.034
Steam Generator Inspection and Maintenance	0.085
Valve Maintenance	0.017
RCP Maintenance	0.054
Pressurizer Maintenance	0.009
Shutdown Cooling and CVCS System Mechanical Maintenance	0.035
Other Systems Mechanical Maintenance	0.031
I&C and Electrical Related Maintenance	0.060
In-Service Inspection	0.019
Core Loading and Unloading	0.022
Decontamination	0.019
Total	0.385

CONCLUSION

Based on the operating experience at Palo Verde nuclear generating station, Yonggwang units 3 & 4, and other units recently put into operation in the U. S., APR1400 is to meet the Korean Utility Requirements Document (KURD) goal, less than 1 man-Sv average per year. With the As Low As Reasonably Achievable (ALARA) advanced design features incorporated in the design, APR1400 is to meet the KURD goal with sufficient margin, that is, more than a factor of two (2), if operated on an eighteen (18) month fuel cycle.

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REFERENCES

1. KEPCO, *Korean Utility Requirements Document*(1998).
2. M.L. Thomas and D. Hagemeyer, "Occupational Radiation Exposure at Commercial Nuclear Power Reactors and Other Facilities", NUREG-0713, Vol. 18 (1999).
3. T.D. Crom, C.L. Naugle and R.S. Turk, "System 80+ Standard Design Incorporates Radiation Protection Lessons Learned", NUREG/CP-0143, Proceedings of the Third International Workshop on the Implementation of ALARA at Nuclear Power Plants(1995).
4. D.M. Matteson, "Refueling and Maintenance Outages for System 80+", ALWR-ME-RR-002, ABB-Combustion Engineering Inc. (1995).
5. D.M. Matteson, "Operation and Maintenance Benefits of System 80+", ALWR-ME-RR-003, ABB-Combustion Engineering Inc. (1995).