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RADIATION DOSE MANAGEMENT IN NUCLEAR POWER PANTS

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INTRODUCTION

The goal of radiation protection is to reduce the probability of radiation-induced diseases in persons exposed to radiation and any associated genetic effects to a degree that is acceptable and reasonably achievable in relation to the benefits from the activities that involve such exposure. To achieve this goal, various radiation protection guidelines and regulatory standards have been developed. These have undergone changes over the last several decades reflecting the development of radiation biology. The latest ICRP recommendations in its Publication 60 [ICRP, 1991], hereafter called ICRP-60, reflect the revised risk coefficient relating to exposure to ionizing radiation that became available in the second half of the 1980s. ICRP-60 also notes that stochastic deleterious health effects of radiation cannot be completely avoided because no threshold can be invoked for them.

The ICRP-60 has led to significant changes in attitudes and to a new culture of radiological protection. The primary dose limits for workers are an effective dose of 20 mSv per year averaged over five years with not more than 50 mSv in any single year. There is also considerable emphasis on the need to optimize protection within the constraints. Lower dose limits and the requirement to ensure that exposure is as low as reasonably achievable (ALARA) means that detailed attention must be given to radiation dose management in operating nuclear power plants as well as its design and decommissioning. An underlying theme is the optimization of protection in the management of exposed workers. The purpose of this paper is to review various approaches to the development of effective radiation dose management schemes in an operating nuclear power plant.

OVERVIEW OF RADIATION DOSE MANAGEMENT

ICRP-60 recommendations reflect an important development in basic principles of radiation protection. It provides justification for both the limitation of individual limits and the optimization of radiological protection (i.e., ALARA). The system proposed is not exclusively based on maximum doses as the upper limit for acceptable doses. ICRP60 notes misconceptions in practice as to the definition and function of dose limits: Dose limits are mistakenly seen as the boundary between that which is safe and that which is dangerous [Boehler, 1995]. This concept of limit is neither an assurance of quality radiological protection nor should be considered the ultimate purpose of radiation protection. A system of radiological risk management based on the "prudent avoidance" principle associated with the recognition of stochastic effects of radiation needs to be in place. ICRP-60 stresses not only the compliance with the principle of dose limitation but also a new logical, rational and effective approach to protection based on the quest for a balance between the cost of protection and levels of residual individual and collective exposure.

ICRP-60 states that both doses and risks should be optimized within the dose and risk limits laid down for individuals. Therefore the limitation is acting as an individual guarantee of protection only where some individuals are exposed to excessive doses. The optimization approach provides protection at the individual and collective levels in so far as it provides optimal protection for all individuals. The aim of optimization is not only to reduce exposure to levels ALARA, taking economic and social constraints into account, but also to give priority to reducing the exposure of those with the highest levels of individual doses.

With new ICRP60 recommendations, what is needed is the encouragement of a dynamic management approach to radiation protection in contrast to the strict application of individual dose limits. A management approach integrating various aspects of radiation protection optimizing individual and collective doses should be implemented. This requires an integrated understanding of the sources of exposure, variety of jobs and variety of means of controlling or reducing radiation exposures. Priorities should be given to the high-dose jobs and effectiveness of any control measure should be judged by the principle of cost/benefit comparison. The parameters that should be considered in this comparison include: (1) monetary value of dose reduction for the specified job (dollar per person-mSv), (2) capital cost, (3) engineering, design and analysis costs, (4) operations and maintenance cost, (5) work-hours saved (or increased), (6) dose avoided (or increased), (7) power replacement costs, (8) current interest and discount rates, (9) depreciation period, (10) any applicable taxes, (11) salvage value, (12) reliability, (13) waste disposal cost, (14) extension (or dearly termination) of existing plant license, and (15) decommissioning costs.

Various studies have identified high-dose jobs in nuclear power plants [Dionne and Baum, 1985; Moon, et al., 1998]. Repetitive high-dose jobs identified in US PWR nuclear power plants through the industry experiences in the 80s are shown in Table 1.

Table 1. Repetitive high-dose jobs in PWRs [Dionne and Baum, 1985].

cavity decontamination
CVCS repair and maintenance
fuel-shuffle, leak detection and inspections
in-service inspections (ISI)
instrument repair and calibration
insulation removal and replacement
operations-surveillance, routines and valve lineups
plant decontamination
pressurizer valve inspection, testing and repair
primary valve maintenance and repair
radwaste system repair, operation and maintenance
reactor assemble and disassemble
reactor coolant pump seal replacement
residual heat removal system repair and maintenance
scaffold installation/removal
secondary side of steam generator inspection and repair
snubbers, hangers and anchor bolts inspection and repair
steam generator eddy current testing
steam generator manway removal/replacement
steam generator tube plugging/sleeving

Table 2 also shows the comparisons of cost/benefit for different management options based on the US industry experiences in the 80s [Baum and Matthews, 1985]. Although the information may not reflect more recent technological development, it provides good examples of cost/benefit comparisons.

Various technological advancements have also become available to contribute to radiation dose management in nuclear power plant [Wood, 1987; Ocken and Wood, 1992; EPRI, 1997a; EPRI, 1997b]. These include exposure source reductions through material replacement, primary chemistry control, cobalt substitution, decontamination, preconditioning of materials, etc. Also the advancement of information technology and computers allows dramatic changes in the management of occupational dose in nuclear power plant [Bennett, 1996]. Instead of relying on manually kept records of film badge dose information, use of electronic dosimetry with computerized databases enables rapid and effective dose control. Application of remote dose-rate measuring instrument allows continuous monitoring of workplace. Real-time dose management of workers in the radiation area is possible by using radio-frequency technology and transmitting data from local radiation protection monitoring points to the main control area. Dose and time data for individuals and jobs are recorded on a common basis for all plants by using a centralized database with data transfer links to the various sites. Doses for future work can be predicted by using a computer based recording systems and data analysis. A predictive computer code capable of estimating dose-rates, doses and shielding requirements for tasks where historical data is not applicable can also be used. This allows effective planing for manpower requirements, identification of area requiring dose reduction effort, and monitoring the effects of any changes in work practice or plant modifications.

The Information System on Occupational Exposure (ISOE) represents an international effort in this regard [Robinson and Lazo, 1995]. ISOE is an international occupational exposure database and communications network for the purpose of dose optimization. Korea is also participating in this. The ISOE system consists of three databases: (1) Annual operational dosimetry data; (2) Plant configuration and administrative data, and (3) Details on the dosimetric results of specific operations. By properly planning, preparing, implementing, and reviewing jobs using these databases, significant reductions could be made in occupational exposures.

DOSE MANAGEMENT METHODS

The methods of dose management can be categorized into: (1) use of technology for radiation source reduction, (2) better dosimetry and accurate reporting of dose, (3) radiation protection planning, (4) exposure control during the execution of jobs. A general culture of supporting effective radiation dose management is also an important part of all of these methods.

USE OF TECHNOLOGY FOR RADIATION SOURCE REDUCTION

The most significant radionuclides which contribute to worker doses at nuclear power plant are the corrosion products radionuclides, Co-60 and Co-58 which are responsible for over 80% of out-of-core radiation fields. Cobalt-60 has 5.8 years of half-life and produces penetrating gamma rays (1.173 and 1.332 MeV, both 100%) through its decay. Co-60 is produced by the bombardment of its precursor, Co-59, with thermal neutrons: $^{59}\text{Co}(n,?)^{60}\text{Co}$. Cobalt-59 is the naturally occurring 100% abundant isotope of cobalt. Cobalt-58 is produced from ^{58}Ni which exists in alloys and steels in the primary coolant system by the fast neutron reaction $^{58}\text{Ni}(n,p)^{58}\text{Co}$. Cobalt-58 has a short half-life and its decay produces 0.81 MeV gamma ray. Cobalt-58 has a short half-life (70.88 day) producing 0.81 MeV gamma ray per decay. It contribute substantially in PWRs in early plant life.

Cobalt is present in nuclear reactors as a low-level impurity ($\leq 0.2\%$) in construction materials and at high levels ($\sim 50\%$) in the hardfacing alloys used in applications requiring resistance to mechanical wear [Ocken, 1985]. Cobalt is found as an impurity in the Inconel-600 used as steam generator tubing, in the Inconel-718 used as grid spacers in PWR fuel assemblies, in the Type 304 stainless steel tubing and sheathing used in boiling water reactor (BWR) control blades and recirculation lines, and in the Type 304 stainless steel and Inconel -625 used in PWR control rod cladding. The cobalt-base alloys are used in applications requiring superior wear resistance, such as bearing surfaces, valve trim, and reactivity control mechanisms. The most popular hardfacing alloys, which contain 50 to 60wt% cobalt, are generally referred to as Stellite (a trademark of the Cabot Corporation).

Radionuclides are transported by the coolant from the core, and then deposited on out-of-core surfaces either in the form of insoluble or colloidal particles or by incorporation into the corrosion film as an ionic form. Cobalt buildup is approximately proportional to corrosion rates [Wood, 1995].

Controlling Cobalt Sources

The largest contributors of cobalt sources in PWRs were identified [Young, et al., 1982; Bergmann, et al., 1982] as the corrosion release of cobalt from the Inconel steam generator tubing and the wear and corrosion of control rod drive mechanisms and valves. In BWRs 90% of the cobalt was attributed to the cobalt-base hardfacing alloys [Falk, 1982].

Controlling the source of cobalt in steam generators requires the replacement of steam generator tube materials. Alternative to the Incornel-600, the most common steam generator tube material, include Incornel-690 or Incalloy-690. These new materials are found to exhibit much higher resistance to corrosion along with the careful control of secondary side chemistry [Dutton, et al., 1995]. This option is not practical unless the steam generator is replaced.

To cope with wear and corrosion of cobalt-base hardfacing alloys, iron-based low-cobalt impurity hardfacing alloy has been developed as a generic substitute for Stellite. This is marketed as NOREM™. NOREM™ alloys provide outstanding resistance to galling (adhesive) wear and cavitation erosion wear [EPRI, 1999a]. Economic considerations are not likely to justify replacement purely for radiation control purposes. But for valves, seats, disks and other parts which have hard facing that are replaced or refinished, NOREM™ is recommended. A study [EPRI, 1996] showed that the potential for exposure reduction is significant only if the valve releases cobalt at high rate and personnel exposure at the unit is high. In addition, the cost of refurbishing large valves is disproportionally higher than refurbishing small valves. NOREM was found to perform much better for nuclear plant stop and swing check valves, globe valves, and butterfly valves [EPRI, 1999b]. However, Satellite's performance was also better for the cases characterized by large contact areas and long stroke length. Also in a 6-in gate valve test the leak rates were higher than a standard specified by Electricite de France (EdF) [EPRI, 2000] performed under simulated PWR operating conditions. This indicates that caution is appropriate when specifying NOREM hardfacing alloy for use in some gate valve applications. A primary concern surrounds gate valves where design and service conditions can lead to large contact areas between two surfaces hardfaced with NOREM.

A guideline available for the reduction of cobalt [EPRI, 1993] indicates that a review of hardfacing attributes and the valve design and the duty to which the valve is subjected during operation.

Brazed Inconel grids on the fuel assemblies of PWRs may contain up to 3.4 percent cobalt. These assemblies need to be changed during normal fuel replacement to fuel assemblies containing low-cobalt grids, as appropriate [NCRP, 1994].

Antimony-124 is also a contributor to the worker dose in nuclear power plant. Antimony-124 arises through the activation and erosion of antimony/ graphite bearings in the main coolant pumps. Use of antimony free bearings for reactor coolant pumps could be a remedial alternative [Dutton, et al., 1995].

Preconditioning of Replacement Components

Preconditioning the surfaces of replacement components can reduce radiation-field buildup by rendering the surfaces less susceptible to corrosion. Surface preconditioning include three steps: i.e., mechanical polishing, electropolishing, and pre-oxidation [Wood, 1995]. Mechanical polishing is necessary to remove the oxide layer and to attain the best surface smoothness. Mechanical polishing is applied in several successive steps, using successively finer grades of abrasive grinding materials such as flapper paper or belt cloth with aluminum oxide. Electropolishing is accomplished by controlled anodic dissolution of the metallic surfaces, using an electrolyte and a cathode suitably shaped to accommodate the geometry of the component surface [Asay, 1990]. Mechanically prepared surfaces without electropolishing are not as effective in reducing radioactivity buildup, and in some cases, may result in higher radioactive buildup regardless of the degrees of mechanical finish.

Pre-oxidation is pre-filming the surfaces to give a protective oxide layer before exposure to reactor water. This protective film effectively passivates the surface during subsequent exposure.

Additional protection can be provided by the use of advanced passivation technology. This advanced passivation includes modifying the surface of reactor components by depositing a thin layer of chromium [Wood, 1995; EPRI, 1999c].

Primary Chemistry Control

Minimizing corrosion product input and impurities in primary coolant water will minimize activation and deposition of radionuclides. Control of primary water chemistry has significant impact in this aspect and can affect reactor radiation fields significantly.

In PWRs, pH, lithium and boron concentrations are the important parameters in primary chemistry control [Wood, 1995]. Primary system pH greatly influences the crud buildup on fuels and radiation-field buildup on out-of-core surfaces. In the early 1980s, coordinated lithium/boron chemistry was the recommended chemistry control regime for the majority of plants in the U.S. [Solomon et al., 1984]. This regime involves coordinating lithium hydroxide and boric acid concentrations to maintain a constant pH of approximately 6.9 for most of the fuel cycle.

More recent studies [Driscoll, et al., 1991] on changes in corrosion product deposition as a function of pH showed that the nuclide deposition was highest at lower end (6.5) of the studied pH range and decreased as pH increased. The pH range between 7.2 and 7.5 was found to beneficial. The benefit of using high pH (6.9 to 7.4 at 300C) was also demonstrated by plant experiences [EPRI, 1990; EPRI, 1995a]. Elevated lithium concentration (2.2 ppm initially or higher) is required to maintain pH in the presence of high boric acid concentrations at the beginning of a cycle. This new regime requires the initial boron concentrations well in excess of the 1200 ppm typically used for annual cycles. The expected benefit of this approach is the lower build up of crud with a potential adverse effect of increased corrosion due to elevated lithium concentration. This indicates that the potential adverse effects of crud accelerating fuel cladding corrosion are greater than the potential corrosion effects of lithium.

Maintenance of a hydrogen overpressure to keep dissolved oxygen concentrations low is also found to be useful for radiation field reduction [NCRP, 1994]. Low concentrations of dissolved oxygen prevent the buildup of corrosion products on fuel and transfer to out-of-core surfaces. Zinc injection has also been suggested for both PWRs and BWRs as a means of radiation field control. In PWRs, it has been found that the use of zinc injection decreases shutdown radiation fields during outage. However, cladding corrosion is found to increase at the same time. Due to this concern, use of zinc injection needs to be carefully considered.

Reactor Shutdown Chemistry

To cause a controlled burst of corrosion products, hydrogen peroxide is added to the primary system of PWRs, when the temperature is below 366K, 93° C [NCRP, 1994]. The oxygenation of the system solubilizes the corrosion products, consisting mostly of nickel ferrite and containing minor amounts of other elements such as cobalt. The ^{58}Co and ^{60}Co in the mixture are cleaned up through the letdown system with a maximum cleanup rate and with pressure in the primary system. Even though the addition of hydrogen peroxide can result in localized high radiation areas in other areas of the primary coolant system, as a result of the migration of the crud removed from the reactor vessel, out-of-core radiation levels can be successfully reduced resulting in a reduction in worker dose.

If the hydrogen peroxide were not added, the corrosion product burst would occur spontaneously when venting the system or lifting the reactor head. At this time, the letdown cleanup system would not be as effective, and much of the corrosion product would remain in the system.

Early addition of borates during shutdown and careful reactor coolant temperature control has also been used to control the corrosion product burst. Thus the optimum shutdown methodology should be determined for each plant conditions through the combination of options [EPRI, 1993b].

Chemical Decontamination

Decontamination refers to the removal of radioactive deposits from the interior surfaces of piping and components. Decontamination has proven to be an efficient way of controlling radiation exposure [Wood, 1990; EPRI, 1999d]. Chemical decontamination uses chemical solvents to loosen and remove the corrosion product films. For nuclear plant system decontamination, relatively dilute reagent solutions that could be processed effectively by ion exchange resins for the removal of radioactive waste are used. There are two processes of using dilute chemical reagents exist, i.e., CANDECON process and LOMI process [Wood, 1995].

CANDECON process is an acid dissolution process using an organic acid reagents based on citric and oxalic acids (e.g., CITROX), sometimes combined with a chelating agents such as EDTA to retain dissolved corrosion products in solution. LOMI process is a reductive dissolution process using the low-oxidation-state metal ion which is a strong reducing agents.

LOMI is the process of choice for BWR recirculation piping while the regenerable CANDECON process is favored for systems with high surface/volume ratios, such as heat exchangers. These processes provide decontamination factors of 5 to 15 [Wood, 1995]. For situations where high-chromium oxides are present, both types of process may require an oxidizing pretreatment. Alkaline and/or acid potassium permanganate is used for this purpose, dissolving chromium oxides by oxidizing them to soluble chromate.

However, to carry out decontamination efficiently, proper systems enabling the operators to carry out the mission are necessary. These include the space, piping and hose connections, and ion-exchange resin columns.

If system decontamination facilities are not properly supported, higher doses to workers can be resulted in along with possible high liquid-effluent releases and significant levels of surface contamination. This could be due to the rupture of temporary hose connectors, exposure to partially shielded ion exchange columns, and lack of operating and maintenance space.

Approximately one-fourth of U.S. PWRs have elected to decontaminate their containment buildings to allow access either in street clothes or in clean modesty garments. These activities observed [EPRI, 1999e] that benefits of containment decontamination far outweigh adverse impacts. Those plants that have achieved clean containment status are very supportive of the concept and would strongly resist returning to a contaminated containment status.

Decontamination of a complete primary coolant system with fuels removed has been performed at Indian Point-2 in US in March 1995. In this, approximately 4000Ci of activity was removed, using about 2000 cubic feet of ion exchange resin, and decontamination factor of 7.8 was achieved. The utility estimates savings of over 8 person-Sv during the outage.

Economic evaluation suggests that full-system decontamination of a PWR with the fuel in place is cost effective. Visual examinations and nondestructive measurements of Zircaloy cladding oxide thickness showed that decontamination solvents do not have deleterious effect on fuel performance [EPRI, 1994].

Fuel failure control [NCRP, 1994]

Fuel failures are not generally a significant contributor to radiation fields in normal operation. However plant operation with defects in more than about 0.1 percent of the fuel rods increases primary piping radiation levels due to fission product buildup on piping. It also increases personnel exposure indirectly as a result of increased contamination controls.

Also irradiated fuel fragments can escape into the work environment from failed fuel and then escape from the primary system (when open or otherwise breached for maintenance). These high-specific activity-discrete radioactive particles ("hot particles"), although not a major source of occupational dose, are a potential source of exposure to workers' skin and can result in high but localized skin doses. The occurrence of hot particle contamination leads to less efficient operating and maintenance procedures.

Methods to prevent fuel defects include maintaining proper primary system chemistry, changing reactor power level at conservative rates, an aggressive material control program that prevent any loose parts or foreign objects from getting into the primary system during maintenance and refueling operations.

It is important to determine which fuel assemblies and to what extent the fuel is damaged if fuel failure does occur. This identification of defective fuel is accomplished normally during a scheduled refueling outage, by fission product detection (fuel sipping), ultrasonic testing or by remote visual observation using camera. Fuel assemblies with significant defects in cladding integrity in several rods should not be reused.

Use of Fine (Sub-micron) Purification Filters

The use of fine filters to reduce transport of corrosion products in the primary system can reduce out-of-core radiation fields [NCRP, 1994]. A substantial fraction of the debris exists as submicron particles. At some plants, installation of submicron mesh filters upstream of letdown demineralizers, and in purification of seal water for the reactor coolant pump in PWRS, has reduced in-reactor radioactivity and radiation levels in primary piping. During start-up and shutdown, absolute filters of 1 micron mesh are installed to handle particulate bursts. During operation, submicron filters are used.

Typically the radiation levels on the filters have not been very high [Comley and Roofthooft, 1988]. However, recent experiences tell that the buildup of C-14 activity in these filters may require additional considerations in waste disposal [Miller, 2000].

ACCURATE DOSE REPORTING

Use of accurate dosimetry devices is important as the basis for proper radiation dose management. It has been shown that dosimeter placement can affect the EDE measurement and that the widespread practice of supplementing a single front-worn dosimeter with additional dosimeter placed facing a radiation source can significantly overestimate EDE. Researches showed that effective dose equivalent for external exposure varies depending upon the direction of the beam striking the body [EPRI, 1998]. Studies using beam sources showed that beams striking the front of the body normal to the body's major axis (i.e., straight on) produce the largest effective dose equivalent. The next highest effective dose equivalent is produced by beams striking the rear of the torso, again normal to the body's major axis. Effective dose equivalent falls significantly if the incident radiation departs from these two orientations. For point sources in contact with the body, the effective dose equivalent is highest for males when the source is on the front of the torso near the gonads.

Experiences in a nuclear power plant also tell that the use of film badge for worker personal dosimetry for gamma and beta radiation can significantly overestimate the dose. Comparison of dose results between the use of film badges and Siemens Electronic Personal Dosimeters (EPDs) at the Sizewell B PWR station in UK showed that typically the monthly collective dose as measured by film badge was a factor of twenty higher than the dose measured by EPD over the same period [Renn, 1995]. EPDs also provide the real time display of dose and the alarming capabilities.

For the neutron personal dosimetry, the track etch device using poly-allyl diglycol carbonate (PADC) is known to have advantages over other neutron personal dosimeter of sensitivity, energy dependence of response, insensitivity to photons and ability to withstand harsh environmental conditions [Tanner, et al., 1995].

HEALTH PHYSICS PLANNING

The planning of work is a significant aspect of any radiation dose reduction program [NCRP, 1994]. The ALARA principle is integrated into the planning process, and the work groups performing the job incorporate dose-reduction and control techniques as necessary. An estimate of the expected collective dose should be developed to determine the amount of planning and review needed. In the process of planning, the job scope needs to be defined. Photos, video tape of video mapping can be used for remote visual walk-through. Results of previous radiological surveys should be available. The results of dose estimates can be used to prioritize the tasks where the dose can be best reduced and to determine the performance of the actual job in comparison to the planning. The principle of time, distance and shielding must be properly implemented in the planning for worker dose reduction along with other options of engineering control. Availability of radiological support personnel and the work schedule should also be considered.

Time

Under time, the related factors are plant and equipment reliability, ease of maintenance, operation inspection and access. These are mainly a concern for plant design. However, the same principle applies to the maintenance and replacement of equipment.

There is an inverse correlation between capacity factor and collective occupational dose in a plant [Wahlstroem, 1987]. When major essential reactor components fail, the effect on plant collective dose is significant. PWRs have experienced serious problems with intergranular stress corrosion cracking of steam generator tubing of Inconel-600 at the tube sheet and U-bends. Available engineering solutions include alternative alloys and improved methods of tube fitting. Improved valve packing, pump seals, and use of extended life light bulbs in radiation areas can lead to considerable dose savings at low cost.

Distance

Under distance, the factors are system layout, remote operation and robotics. Although these are mainly a concern in the design stage, the principles should be applicable in maintenance and operations stage.

Valves, sampling equipment, inspection ports, monitoring instrumentation and other operational equipment located in significant radiation fields should be shielded and/or remote operation capability for them are desired.

In Japan, use of robots proved to be cost-effective as replacement for skilled labor in a tight labor market. The robots include automatic machines for refueling, remote handling of control rod drives (CRDs), reactor pressure-vessel stud tensioning and cleaning, semi-automatic CRD disassembly and cleaning, remote lapping of valves, remote controlled inspection and monitoring devices, and use of an underwater disassembly and cleaning device for control drives. Other applications include steam generator channel head entries, reactor coolant pipe welding, decontamination, underwater work and surveillance in high-radiation areas

Shielding

Besides the design engineers' consideration for proper compartmentalization of systems and system components along with proper shield design, temporary shielding should be used in the maintenance and operations as much as practical. Various forms of lead shielding including lead blankets and bricks are available for gamma shielding. Hollow shield made of plastic, aluminum or steel can be moved in an unfilled condition and then filled with water on location for neutron shielding. Free standing scaffolds can be used to support lead shielding without putting weight on piping. Mobile shield racks can be moved to a desired location to provide a temporary shield wall with hanging blankets.

Other Engineering Control

Protective clothings are used in the radiation controlled areas of nuclear power plants to avoid skin contamination. However, use of protective clothings can lead to decreased efficiency for the workers, resultant longer stay times and more dose, increased physiological stress and risk of industrial accidents or heat exhaustion, and radioactive waste. A study [EPRI, 1997c] showed that protective clothings stress the cardiorespiratory system of a worker even during early exercise, when the subjects are well below heat exhaustion thresholds. Therefore the use of protective clothing has to be carefully reviewed in comparison to other alternatives such as appropriate contamination control techniques and engineering controls.

Full face piece air purifying respirators can be an effective means of decreasing worker inhalation of airborne radioactive particles in the nuclear power plant environment if properly used. Also its effectiveness needs to be examined in comparison to its disadvantages. A study indicated that the use of respirators did not increase the time workers need to perform certain tasks (a bolt tightening task requiring 350 ft-lbs of torque) [EPRI, 1995b]. However, the study was not designed to assess the effect of respirators on worker efficiency on tasks requiring communication between workers, poorly lit work spaces, or cramped working conditions. These tasks should be reviewed on a case by case basis.

Other engineering controls include the use of tents, containment bags and glove boxes or use of local ventilation [NCRP, 1995]. Use of tents and other containments can be effective to limit the high contamination areas to a relatively small size. This can also help to eliminate airborne radioactivity areas and allow general access. Use of local ventilation can also reduce airborne activity, help to minimize the need for respirators and can aid in keeping workers cool to avoid heat stress. This ventilation can be supplied by flexible hose extension from a building ventilation system or by providing a separate portable ventilation system involving a fan and appropriate filters. Since the setup and removal of equipment involve s external dose to installers, the use of these techniques should be evaluated to achieve a net benefit. The buildup of contamination within the confinement should also be monitored.

EXPOSURE CONTROL DURING THE EXCUTION OF JOBS

Exposure control during the execution of job require the application of the ALARA principle at the worker level. This requires the support and coordination of many functional groups including maintenance, operations, engineering and construction, and radiation protection.

Exposure Control During Job Setup

Radiation Work Permit (RWP) represents one of the primary methods for worker exposure control. The radiological conditions and radiation protection requirements must be clearly specified in the preparation of the RWP form. The following information should be included in the RWPs [NCRP, 1994]:

- Specific description of work to be performed
- Specific description of the work location
- Specific radiation hazards and precautions
- Work area dose rates (general area and hot spots)
- Contamination levels (general area and maximum levels)
- Airborne radioactivity levels
- Person-hours and collective dose estimations
- Protective clothing requirements
- Respiratory protection requirements
- Dosimetry requirements
- Contamination control requirements
- Engineering controls/ventilation requirements
- Exposure control requirements
- Electronic alarming dosimeter requirements
- Radiation protection personnel coverage requirements
- Communication requirements

Sufficient information should be provided during the preparation of RWP so that controls can be set up to reduce dose and spreading of contamination.

Decontamination of components/work area can be effective for labor intensive tasks in high radiation fields. Removing hot spots near work areas and general access routes, which have relatively high-dose rates in comparison to the local background, can be particularly effective.

Visual and/or audible alert/alarm systems can be provided by using electronic dosimeters at a preset dose or dose rate. These devices increase worker awareness of their accumulated radiation dose and the local dose rate, as well as to alert them of any unexpected changes in dose rates.

Results from the most recent radiation protection survey maps on the entrances to the area should be posted to improve workers' awareness of the radiological conditions including the need for protective clothing and/or respiratory protection. Low radiation areas can be used as waiting areas if it is necessary to remain in the work vicinity. For radiation and airborne monitoring to check for changes in radiological conditions during the job, proper portable and area radiation survey instrumentation must be made available. Neutron surveys must be performed in work areas where neutron radiation may be present.

Temporary shielding in various forms (lead blankets and bricks, hollow plastic, aluminum, or steel shields) should be used as applicable to reduce general area dose rates and hot spots. For the use of lead blankets, the followings should be considered: (1) potential accumulation of dose during installation and removal, (2) stress on the component or pipe shielded, (3) contamination of blankets, (4) accessibility to the shielded component, (5) safety concerns (lead slipping off pipe), (6) a control method to assure that the lead stays in place and is removed as necessary, (7) maintaining an adequate inventory, (7) careful handling to minimize ingestion of lead, (8) preventing the contact of bare lead with stainless steel to minimize potential detrimental structural effects from material degradation, and (9) preventing the radioactive contamination of lead - radioactively contaminated lead is considered a mixed (hazardous and radioactive) waste.

Jobs should be carefully coordinated with plant system configuration to maximize the shielding effect from filled components. For example, work in the vicinity of WPR steam generators should be performed with the secondary side water full to increase the shielding effect.

Pre-job briefing should be conducted by the work group supervisor covering the scope of work and the radiological conditions in the work area with the actual personnel performing the work and the radiation protection personnel monitoring the job.

External Exposure Control During Work Activities

During the work activities, the work group supervisor must periodically monitor the progress of ongoing work and provide support, as necessary, to assure that the job continues with the minimum practical exposure. The supervisor is responsible for reviewing plans, procedures, equipment and the work environment to identify techniques to reduce dose and the spread of radioactivity. Good communication and teamwork is important in this respect. Any radiation incidents, and other unsafe conditions including workers' radiological concerns and any associated corrective actions should be reported to management and the radiation protection group.

To detect jobs which are accumulating more exposures than expected, ongoing jobs should be tracked against their estimated dose by using proper electronic dosimeters. The workers must be updated on current radiological conditions during the work by a radiation protection technician who observe the job periodically or continuously. The work must be performed as quickly and accurately as possible to prevent having to repeat the job. If necessary, decisions to change the scope of a job must be carefully discussed with radiation protection personnel, and the necessary radiological precautions should be applied. If the radiological conditions or practices could or have jeopardized personnel or environmental safety, the job must be stopped. Doses to the radiation protection personnel should also be kept ALARA.

During the work activities, operation of auxiliary component that may affect the worker dose must be optimized to minimize their dose. At the job site, proper tools must be available at the job site. For certain repetitive jobs, dedicated tools can be specified to assure tool availability and to minimize the time for waiting for tools. Special tooling (e.g., special long-handled wrenches and filter handling tools for changing reactor water filters) can be developed for specific jobs to reduce time in high radiation areas and to increase distance from the radioactive source. Radio and video communication between the radiation protection technicians, workers, and the job supervisors can be effectively used to transmit work instructions and protection practices to the workers remotely and rapidly and to minimize entries to radiation areas.

Mock-up testing and training can be very useful to familiarize workers with the work and procedures and to verify the operability of the special tooling. The training leads to reduced work time and worker dose. Robotics and automated equipment should be used where practical.

For the protection of transient subcontractor workers who move frequently around the country, a centralized data system can be used [Daubert, 1995]. By centralizing the data from all of the units and regrouping all doses received by anybody on any of its sites, accurate picture of every worker dose can be obtained.

Post-Job Activities

To provide data for similar work in the future and to determine effectiveness of the ALARA program, cumulative dose by job must be recorded and compared to the estimated dose or historical levels and to those experienced by other utilities.

Detailed post-job review can be performed for the number of personnel actually used, the collective dose expended, radiological conditions throughout the course of the job, dose-reduction techniques used and their effectiveness, problem areas, identification of things that went well and recommendations for improvements. The recommendations to improve dose reduction and limit the spread of radioactivity should be documented for future use. For repetitive jobs, a job history file should be maintained to document radiation protection techniques used, problems encountered and corrective actions taken.

A package of ALARA procedures should be maintained and should contain information in an easily retrievable format for review during future similar work. Reports on ALARA procedures implemented are useful to summarize and document information for management on the effectiveness and accomplishments of the ALARA program.

A plant' s experience tells that, even without the use of computer based recording, good record keeping, monitoring and review can lead to effective dose reduction [Weston, 1995]. From this experience, activities proved most useful in supporting dose reduction are as following:

- Daily dose control reports issued to health physicists listing those people above a daily action level and those above a monthly, quarterly or annual action level - this allows for immediate investigation or intervention by a professional health physicist.
- Daily dose reports giving individual and collective doses for specific work areas and/or groups of workers.
- Monthly reports of doses issued to team leaders giving collective and individual doses for their team - this allows them to monitor the team's performance, compare individual doses and discuss the data at team meetings to explore ways to improve.
- Monthly report giving collective dose data as performance indicators for monitoring the department and location business plans - this allows for comparison of actual performance against the budget. These data include the "moving annual total" (the total for the previous 12 months) so that an increase or decrease is easily seen.
- Monthly report of the 12 highest doses - this allows the team to ensure that each of the highest doses can be satisfactorily justified.
- Monthly report showing the comparison between the result of the film badge and the total of the electronic dosimeters issued for the month - this serves as a quality control check on the dosimeters and the administrative systems that require electronic dosimeters to be issued and worn.

IMPLEMENTATION OF RADIATION PROTECTION CULTURE

Individual awareness of the importance of radiological protection is by far the most important basis for prudent radiation dose management [Boehler, 1995]. This requires the knowledge and skills in the field of radiological protection as provided by theoretical and practical training, through good distribution of information and by extensive experience feedback and the commitment of the management to a policy of radiological protection and the compliance of individuals with the aim of limiting exposure as far as is reasonably possible. Motivation for achieving the best radiation dose reduction must be provided and reinforced through the personal responsibility and self-discipline of all those concerned in terms of radiological protection. Proper supervision and monitoring and audits must be performed through a clear definition of the respective roles and responsibilities of those concerned from the operator to external contractors.

This requires a culture of radiological protection. This culture is as much a question of attitude as of structure, which concerns both individuals and organizations and which requires the on-going commitment of managers in the design and operation of nuclear installations. At the same time, the cost of achieving the required level of performance in radiation protection should be optimized not jeopardize the main aims of the company. Experiences in many US utilities demonstrate the success of radiation dose management. The dissemination of radiological protection culture will also contribute to improving the company's public and internal image.

SUMMARY AND CONCLUSIONS

According to the US experience, the factors contributing to savings in radiation exposures for the period of 1985 to 1994 are (in the order of rank) (1) radiation protection guidelines, (2) reductions in unscheduled special maintenance, (3) reductions in source of exposure through material replacement, (4) primary chemistry control, cobalt substitution, decontamination, and preconditioning, (5) shutdown chemistry control guidelines, and (6) automated in-service inspection methods, and heat stress management guide.

This illustrates that for successful radiation management, various factors must be included and integrated in the spirit of optimization. These factors are good planning and programming, use of technology, the culture to support ALARA among the management and workers, and the process of carrying out the actual tasks in details. Not only the control of radiation field through the implementation of technology is important but also the proper control of human involvement in radiation zone based on good planned programs and supportive culture is very important

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Table 2. Comparisons of cost/benefit for selected dose management activities [Baum and Matthews, 1985]

Project	Dose to install (person-mSv)	Dose saved (person-mSv)	Amortized period (yr)	Annual operating costs ($)	Cost effectiveness ($ per person-mSv)[a]	Benefit/Cost ($ saved per $ invested)[a]	Investment cost ($)	Collective dose saved (person-mSv)	Discounted Collective dose saved (per $ invested)[a]	Total saved ($)[b]
BWR-control rod drives hydrolyzing flange	50	100	30	0	35	27	5,900	3,000	0.29	333,000
SG head, portable shield	100	500	30	0	86	22	7,000	15,000	0.24	1,600,000
CVCS shields	0	10	30	0	100	9	1,800	300	0.094	33,000
Clean seal water	50	200	30	0	110	9.2	33,000	6,000	0.1	640,000
PWR power level monitor, N-16	0	80	30	0	120	7.4	16,000	2,400	0.088	260,000
Low cobalt coolant pumps	0	160	35	0	120	7.5	35,000	5,600	0.086	560,000
Low cobalt CRD mechanism	0	220	35	0	140	6.3	59,000	8,100	0.073	760,000
Low cobalt SG	0	1340	35	0	140	6.3	349,000	47,000	0.072	4,700,000
Reactor-head shield	0	35	25	400	180	24	1,900	800	0.29	100,000
Low cobalt fuel nozzles	0	31	30	600	190	c	c	930		97,000
Low cobalt coolant pump	0	92	35	0	200	4	35,000	3,200	0.049	310,000
Robotic inspection of ice condenser	0	90	30	880	210	5.8	21,000	2,700	0.076	280,000
Manway cover equipment	0	18	25	0	230	3.4	6,500	450	0.043	50,000
Mock-up training, SG jobs	0	980	30	21,000	270	19	63,000	29,999	0.27	2,900,000
Viewing windows in BWRs	15	75	30	0	290	2.5	36,000	2,000	0.036	220,000
PWR laydown head shield	0	30	30	0	310	2.2	16,000	900	0.033	88,000
CRD decontamination tank	20	90	30	0	330	1.9	53,000	2,700	0.028	100,000
PWR head shield	0	357	25	0	330	2.0	185,000	8,900	0.030	930,000
CRD electropolish tank	10	100	30	0	340	1.9	58,000	3,000	0.029	290,000

a: Based on present values discounted at 4 percent per year.
b: Dollar saved is calculated using $200 per person-mSv.
c: All costs were considered operational.