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Radiation Protection Considerations for Nuclear Power Expansion to Nations with Limited Technical Infrastructure

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Abstract
Future nuclear power expansion to nations with limited technical infrastructure presents unique challenges to establishing a coherent and integrated radiation protection organization that supports the challenging work at a nuclear power station. The implementation of a successful radiation protection program requires that its various elements work effectively together and with the various plant work groups. Successful implementation is strongly influenced by the cultural norms of the host nation as well as facility specific standards and expectations. The organization will be most successful if it fully incorporates a diverse work force that reflects the nation's demographics, encourages mutual respect, promotes a questioning attitude, and seeks continuous improvement.

Keywords
radiation protection organizational structure; cultural influence on performance; future Radiological performance issues; dose optimization

1.Introduction

Radiation protection or health physics programs in nations with established nuclear power reactors are well established and based on a technological base that slowly evolved from the post World War II development era through Generation I, II, and III power reactors [1-3]. These programs adapted over decades to fit the cultural and social components of society including evolving relationships between union workers, professional staff, management, and regulatory personnel [4].

In the US, this evolution was strongly influenced by naval nuclear power personnel and their strong operating and engineering training. These trained individuals provided a sound technical and management base for the commercial nuclear power industry to grow and prosper in a manner that reflected high standards. Naval personnel also formed the foundation of radiation protection programs and provided qualified technicians, supervisors, radiological engineers, and management. Unfortunately, this base of naval personnel is not available to nations newly entering the nuclear power arena.

Emerging nuclear countries establishing nuclear power programs in the 2020 - 2050 time frame must develop and mature more quickly if high levels of performance and radiological safety are to be achieved and maintained. Achieving this level of performance will be challenging without an extensive technical and experience base [5,6]. A well designed radiation protection organization is contingent upon developing these essential elements.

This paper reviews requirements for radiation protection programs and the approaches to achieve high levels of performance. Good radiological performance is enhanced if qualified personnel are accepted as equals and have the opportunity to develop and advance their skills in an open, challenging, and positive goal oriented environment [7-10]. For the purposes of this paper, the terms radiation protection and health physics are used interchangeably.

2. Anticipated nuclear power expansion

There are currently 22 cites in the world with populations greater than 10 million [6,11]. By 2040, 31 additional cities will join this group.

This expansion in urbanization includes an associated increase in electrical demand. Most of these additions will occur in China (9) and India (8). This trend toward urbanization is closely associated with energy demand. Significant increases in electricity demand are also forecast for Brazil, Egypt, Indonesia, Iran, Mexico, Nigeria, Saudi Arabia, South Africa, Thailand, and Turkey. Several of these nations have nuclear generating capacity or are contemplating the addition of nuclear generation to their energy mix.

The link between urbanization and energy demand is related to several considerations [6]. First, urban expansion creates demand for iron, steel, cement, building materials, and industrial goods that require significant energy for their production. Second, urban income levels tend to be higher than those in rural areas. Third, energy-intensive industries locate near cities. Fourth, the household size in urban areas is smaller than in rural areas that leads to more households with associated larger energy requirements. These considerations contribute to a non-uniform energy demand that favors base-load facilities such as nuclear power plants over renewable energy sources. In addition, the higher levels of air pollution in urban areas favor clean technology including nuclear power generation. Urbanization also expands life style expectations, which are tied to electricity demand associated with larger homes with the associated air conditioning and heating systems, modern appliances, and a variety of electronic devices.

The aforementioned considerations are reflected in IAEA energy estimates for the 2020 - 2050 period [11]. The North American and Western European nuclear projections are indicative of minimal growth. However, the Far Eastern, Middle Eastern, and South Asian electricity demand is significant. Given these demand levels, the expansion of nuclear power facilities to less developed countries is likely. The projected electrical generation estimates for 2020-2050 are summarized in Table 1.

Table 1. Nuclear Electrical Generating Capacity Estimates (GW)[a]

Geographic Location	Year			
	2012	2020[b]	2030[b]	2050[b]
North America	115.6	118-124	101-143	64-163
Latin America	4.3	5-6	7-15	13-59
Western Europe	113.8	94-117	68-124	33-137
Eastern Europe	48.5	64-75	79-104	79-138
Africa	1.9	1.9	5-10	10-42
Middle East and South Asia	6.0	13-22	27-54	47-142
South East Asia and the Pacific	0	0	0-4	5-20
Far East	82.8	112-158	147-268	189-412

[a] Ref. 11.
[b] Nuclear capacity estimates take into account the scheduled retirement of the older units at the end of their lifetime.

3. Required health physics infrastructure

A nation attempting to build its first nuclear power plant must develop the requisite construction, licensing, and operations infrastructure [5]. The first plant constructed in a new nuclear nation will utilize significant foreign resources until its nuclear infrastructure matures.

This initial dependence is illustrated by the training of operators for the Emerates Nuclear Energy Corporation's (ENEC) Barakah-1 reactor [12]. This training program is developed in conjunction with ENEC's prime contractor, Korea Electric Power Corporation (KEPCO). The training includes on-the-job instruction at KEPCO's facilities in South Korea followed by ENEC's Simulator Training Center at Barakah.

The use of foreign resources is an expected step in the process of developing the requisite domestic nuclear infrastructure. This infrastructure includes the development of human resources and a supporting educational system. These two elements are key components of a nation's nuclear power infrastructure.

A mature human resource development program produces scientists, engineers, and technicians with an in-depth knowledge of health physics and the ability to apply that knowledge to implement a successful power reactor radiation protection program. A functioning human resource structure provides a constant stream of health physics personnel to sustain these programs at the initial and subsequent nuclear facilities. In addition, health physics personnel must be sufficiently trained to support applied research, advances in nuclear power technology, and all related fuel cycle activities.

The supporting educational system includes national programs in health physics, radiation biology, radiological engineering, nuclear engineering, and nuclear physics. These health physics and related programs must exist at the technologist, undergraduate, and graduate levels. Educational institutions should incorporate laboratories and workshops with state-of-the-art computers and radiological instrumentation.

These academic programs should be closely linked to the domestic nuclear power industry. Specific program elements include internships with nuclear operators, nuclear design organizations, national laboratories, regulators, and fuel cycle facilities.

Recent IAEA efforts are investigating developing infrastructure for new nuclear power programs [13, 14]. The IAEA guidance is somewhat generic, but consistent with the content of this paper. This work focuses on a single aspect of a nuclear power program, and reviews the requisite requirements for nuclear power plant radiation protection and associated programs.

4. General radiation protection program requirements

This section describes the key elements of a radiation protection program (RPP) at a nuclear power plant and their relationship to other facility organizations. The discussion is necessary to illustrate the importance of the RPP. Subsequent discussion notes factors that influence the success of the RPP including a qualified staff, management support, and cultural influence. Each of these factors must be carefully balanced to ensure a sustained and successful radiation protection program.

A facility's operating license requires that a radiation protection program be implemented [15-21]. Procedures and engineering controls are established to ensure that occupational and public doses are as low as is reasonably achievable (ALARA). The license also requires that records of the radiation protection program be maintained and retained.

The radiation protection program describes the organizational structure, training requirements, procedures, and conduct of facility radiological operations. Each program element reflects the features and operating practices of the facility including radiation survey and surveillance frequencies and philosophy to control radiation exposures.

Radiation protection programs include a set of basic elements that are organized into three fundamental areas [15-21]:

1. Establish the organization and operating philosophy including the training and qualification of personnel. The program's operating philosophy is affected by a nation's cultural norms. The direct adoption of a Western operating model may not produce optimum results for all developing nations.
2. Conduct the program in a manner consistent with the defined operating philosophy and operating requirements.
3. Evaluate the program's quality and content to assess its effectiveness in meeting the established regulatory requirements.

The development of human resources and national nuclear power infrastructure contribute to the effectiveness of a power reactor's radiation protection program. This program ensures the radiological safety of the facility staff and environment and includes supporting program elements to achieve these goals.

The RPP ensures that occupational radiation exposures are as low as reasonably achievable. The power reactor's radiation protection program also provides control over the receipt, handling, possession, use, transfer, storage, and disposal of sealed and unsealed byproduct radioactive material; and source and special nuclear material. An RPP complies with the nation's radiation protection regulations. In the US, these requirements include (1) 10CFR Part 20, *Standards for Protection Against Radiation* [20], (2) 10CFR Part 50, *Domestic Licensing of Production and Utilization Facilities* [21], (3) US Nuclear Regulatory Commission Regulatory Guide (USNRC RG) 1.8 *Qualification, and Training of Personnel for Nuclear Power Plants* [17], (4) USNRC RG 8.10, *Operating Philosophy for Maintaining Occupational Radiation Exposures as Low as Is Reasonably Achievable* [15], and (5) US Nuclear Regulatory Commission NUREG-1736, Consolidated Guidance: 10 CFR Part 20 — Standards for Protection Against Radiation [18]. Specific RPP elements are described in subsequent discussion.

4.1 Establishment of a radiation protection program

The radiation protection program should have the support of senior management committed to providing the necessary resources to ensure the program's success and stability. Senior management must be personally involved in monitoring the performance of the program by establishing standards and expectations for plant workers, supervisors, and line managers for their group's radiation protection performance. To emphasize the importance of the health physics organization, the radiation protection manager (RPM) has direct access to the plant manager for radiological issues. This becomes most apparent when the RPM reports directly to the plant manager.

To facilitate accountability, the RPP objectives and goals should be clearly defined and included in all employee's performance appraisals. The applicable RPP elements include (1) written standards for compliance with radiation protection requirements, (2) periodic internal and external evaluations and assessments of performance, (3) employee accountability for their radiological performance, and (4) worker, group, and station goals for program improvement and performance. These standards apply to station, corporate, and contractor personnel.

4.1.1 Organization and administration

The RPP explicitly defines the essential aspects for the organization and administration of the program. In addition to the specific functions of the radiation protection program, the radiological responsibilities of line organizations are defined. These organizations include operations, maintenance, engineering, chemistry, fire protection, licensing, quality assurance, emergency preparedness, nuclear assurance, work planning, in-service inspection, and training groups as well as the associated corporate support.

4.1.2 Qualification and training

A training and qualification program including continuing training are developed and implemented to facilitate the successful implementation of the RPP. Training should ensure proficiency in task completion and workers must be qualified before performing critical radiological functions. The training for general employees ensures that workers are qualified to access controlled areas (e.g., radiation areas, high radiation areas, very high radiation areas, airborne areas, contaminated areas, and radioactive materials areas).

Radiological training requirements vary with skill level (i.e., technicians, supervisors, professional staff, and management). For example, technician training encompasses all radiation protection program areas with a particular emphasis on surveys, postings and labeling, instrumentation, equipment operation, contamination and radioactive material control, radiological work coverage, personnel monitoring, dose control, and ALARA.

4.1.2.1 National and International Radiation Protection Certification Organizations

Academic training and industry experience provide the requisite knowledge to health physics personnel. Recent graduates have the academic skills required for success, but must gain experience in power reactor health physics and in controlling radiation and radioactive materials in the unique power reactor environment. Experienced health physicists must continue to develop new skills as their careers mature and the station radiation protection program evolves.

Sustainable development and recognition are achieved by the professional certification of individuals after they achieve specified educational and experience levels. These certification programs should parallel the American Board of Health Physics (ABHP) for professional health physicists and the National Registry of Radiation Protection Technologists (NRRPT) for technical staff [1,2,17,18]. The national certification programs should incorporate the societal and cultural norms of the nation, but should eventually reach the competency levels of the well-established ABHP and NRRPT programs. Certification should form a portion of the basis for promotions and salary increases.

4.1.2.2 Industry Radiation Protection Organizations

In the US, the Institute for Nuclear Power Operations (INPO) provides training standards for power reactor radiation production programs. These training and qualification requirements can be used to benchmark specific national requirements. As an intermediate step, the World Association for Nuclear Operations, International Atomic Energy Agency, and INPO can provide technical assistance until a nation's program meets the desired training and qualification level.

4.2 Conduct of the RPP

The organization and administration of a radiation protection program provides a framework to ensure that all program elements, requirements, and goals are achieved. This includes the control of radiation exposures and workplace activities, and assessment of release consequences.

4.2.1 Control of Radiation Exposures

Worker doses are effectively controlled through a variety of individual program elements. These elements include source control, limiting worker doses, personnel monitoring and dose control, engineering controls, respiratory protection, optimizing exposure, surveillance, and ALARA reviews.

4.2.1.1 Radiation Source Control

A key aspect of a radiation protection program is the control of radiation sources that result in occupational exposure. Methods to control radiation sources include control of reactor coolant chemistry to minimize the activity concentration, utilization of primary system components with low cobalt content, reducing reactor coolant filter pore sizes, preconditioning metal surfaces to minimize radioactive materials accumulation, and decontamination of contaminated systems, structures, and components.

Leakage of radioactive fluids requires the timely decontamination of surfaces and repair of leaking components. Systems should be flushed to reduce the quantity of contained radioactive materials and decontaminated to reduce the source term. Maintenance of components (e.g., valves and pumps) is facilitated by decontaminating before maintenance is performed.

4.2.1.2 Dose Limits

Dose control systems are established for evaluating, controlling, monitoring, tracking, and recording doses. Occupational exposures are controlled by minimizing the effective dose and not by limiting its individual internal or external components. The radiation protection program controls external exposures through monitoring and minimizing external radiation sources. This is accomplished by implementing an effective ALARA Program that should facilitate radiological input into system designs and subsequent modifications and work scheduling and planning activities [22,23].

The identification and control of surface and airborne contamination areas are essential for the effective control of internal doses. This is accomplished by the utilization of engineering controls, stay time limitations, establishing access controls, and if warranted respiratory protection. However, the controls used to minimize the effective dose must be optimized and not focus attention on overemphasizing the use of respirators to control the internal dose [22,23].

4.2.1.3 Personnel Monitoring and Dose Control

The radiation protection program defines the methods and associated procedures for controlling and monitoring effective dose. This includes defining the methodology to analyze, record, and report the measured effective doses.

The internal dosimetry program defines the methodology for assessing the equivalent dose from depositions of radioactive materials. This includes the selection and use of various bioassay approaches, the selection of operational personnel to be included in the program, and the frequency of their bioassay measurements. Dose control and optimization programs describe the methodology and procedures to ensure that personnel doses are maintained within the national dose limits [20]. Procedures and methods to ensure dose optimization and ALARA are an integral aspect of the dose control program.

Given the unique nature of a power reactor environment, specific attention should be directed toward tritium, iodine, fission product, and activation product bioassay. The use of *in vivo* whole body and thyroid counting and urine sampling should be specifically addressed.

In addition, controls to limit the spread of contamination including hot particles should be implemented [1,2]. Hot particles are microscopic corrosion and wear products that are activated through exposure to the core's neutron fluence. These particles are generated by valve and pump operation, and cutting, griding, and welding activities that deposit residual particulate material into the reactor coolant system. Hot particles present an external radiation hazard when on the skin or eye surface, and can also be inhaled and ingested. These particles deliver large localized doses that can exceed regulatory limits [1,2].

4.2.1.4 Engineering Controls

Effective doses are minimized using a variety of techniques including stay time restrictions, respiratory protection, and engineering controls [22,23]. Engineering controls are a preferred approach since the source term is reduced without imposing a physiological stress on the body or requiring limitation times. These controls include local ventilation systems, confinement structures, hoods, glove boxes and bags, and leakage containment systems.

4.2.1.5 Respiratory Protection

Procedures and techniques for evaluating and controlling potential airborne radioactivity concentrations are defined in the RPP, including criteria for air sampling, and the issuance, selection, use, and maintenance of respiratory protection devices and requisite air quality for air supplied devices. In addition, medical screening and training programs as well as fit testing for respiratory protection equipment are required [20].

The respiratory protection program should emphasize the need to minimize the effective dose, not the internal dose [22,23]. An emphasis on the evaluation of process and engineering controls before the use of respiratory protection should be emphasized. The program should explicitly discuss the accepted methods and procedural requirements for the minimizing personnel radiation exposures for work requiring the use of respiratory protection.

4.2.1.6 ALARA/Optimizing Exposure

The ALARA program ensures optimization of the effective dose and establishment of dose control measures through all radiological work activities [20,23]. In particular, ALARA elements are incorporated into decontamination practices, facility instrumentation and control systems, radiation shielding evaluations, radiological area access requirements, source term control efforts, and waste handling operations.

Personnel should receive ALARA training that includes effective methods of dose control. The use of dedicated crews for high dose tasks, task specific training, mockup training, job specific dose monitoring and tracking, shielding, use of robotic equipment, specialty tooling, and post job critiques are all effective dose optimization approaches if properly implemented [22,23].

4.2.1.7 Surveillance

The RPP specifies the requisite instrumentation to monitor facility external radiation, surface contamination, and airborne contamination during normal, abnormal, and emergency operating conditions. Surveillance programs describe the methods, frequencies, and requirements for conducting radiation surveys. These requirements are embodied into procedures and checklists for the use of portable monitoring systems to measure alpha, beta, gamma, and neutron radiation and sample and analyze for airborne radioactive materials including radioiodine in plant areas.

The surveillance program is effectively implemented through a well-developed set of procedures. These procedures specify the survey locations and required type, instrumentation to be utilized in the survey, facility conditions requiring a survey, and survey frequency. The surveys are sufficient to ascertain the facility radiological conditions. These surveys are used in work planning, developing work packages, radiation work permit development, ALARA reviews, and establishing facility radiological postings

Posting radiological areas and properly marking radioactive materials packages and tools and equipment to indicate the presence of fixed and removable surface contamination are basic requirements of a radiological controls program. Posting and labeling is contingent on properly executed radiological surveys.

The physical and administrative controls for restricting access to radiological areas should be defined. These controls specify the entry and work requirements for access to radiation, high-radiation, very-high-radiation, surface contamination, airborne contamination, and radioactive materials areas [20].

Specific requirements for area posting and boundary specification are defined by the RPP. These requirements address both external and internal sources of radiation exposure.

Radiation work permits rely on accurate radiological survey data and practical skill to interpret these data to define the requirements for task completion and entry into radiologically controlled areas. The criteria for development and issuance of an RWP and the required information are specified by the radiation protection program.

4.2.1.8 ALARA Reviews

ALARA reviews provide a formal evaluation that focuses on optimizing the dose for a task or a series of related jobs. Radiation surveys, previous task history, and the specific task features are used to optimize job elements to minimize the effective dose. The ALARA review is incorporated into final work packages, radiation work permits, and the task completion sequence.

4.2.2 Control of Workplace Activities

The radioactive material contained within the facility requires appropriate controls to ensure the safety of workers and the public. Procedures are established to control radioactive materials, prevent the spread of contamination, establish sound radiological work practices, and limit and generation of radioactive waste. These control measures emphasize the importance of personal accountability in implementing the requirements of the RPP.

4.2.2.1 Control of Radioactive Materials

The radioactive materials control program defines the methods and procedures that ensure the control, accountability, movement, inventory, and proper storage of radioactive materials. This includes materials that are outside the radiologically controlled area, and are not associated with contaminated facility areas or within plant systems. This RPP area also includes the shipment and packaging of radioactive materials for transport as well as their receipt. The associated procedures ensure radioactive materials are controlled and that inadvertent intakes, external exposures, and releases to the environment are minimized.

Procedures specify the criteria for the release of radioactive materials from radiologically controlled areas. These criteria include allowable external radiation levels and fixed and dispersible contamination levels for alpha, beta, and gamma radiation types.

4.2.2.2 Contamination Control

The radiation protection program defines the bases and methods for monitoring and controlling contamination. Specific contamination limits for station personnel, facility equipment, and plant areas are essential elements of a well-defined program. Surface contamination control minimizes the extent of contaminated areas, reduces the intake of radioactive materials by station personnel, minimizes skin contamination events, and reduces the probability for the loss of control of radioactive material and the possibility of release of this material to the environment.

The contamination control program includes the associated surveillance requirements to preclude the inadvertent release of radioactive materials from radiologically controlled areas. In addition, decontamination procedures for personnel, plant areas, and equipment are defined.

An effective contamination control program minimizes the use of protective clothing and respirators and reduces the associated radioactive waste and laundry costs. The contamination control program is enhanced with an effective preventative maintenance program and the timely repair of leaking valves, pumps, and instrument lines.

4.2.2.3 Control of Radiological Work Practices

Radiological planning and associated practices are an essential element of a facility’s work control process, which integrates the activities of all work groups. An efficient work control system requires an effective training and qualification program and as job-specific training. This training includes the use of facility and equipment mock-ups to improve efficiency and minimize task doses. High dose tasks should incorporate mock-ups, dedicated work crews, and task specific ALARA reviews to limit radiation exposures.

The radiological control program ensures that worker doses are optimized. This is achieved by ensuring that procedures are properly implemented and supported by work control documents and their associated radiation work permits and ALARA reviews.

4.2.2.4 Waste Management

The generation of solid radioactive waste is an expected artifact of nuclear power operations. Radioactive waste generation and worker doses are closely related with low waste volumes being indicative of lower doses and an effective RPP. This occurs since the techniques used to minimize worker doses (e.g., work planning and contamination control measures) limit the volume of radioactive waste.

4.2.2.5 Compliance Monitoring and Evaluation

Sound radiological work practices should be seamlessly integrated into the facility work control program. This integration is based on personal accountability and supervisory oversight to ensure that radiological work practices are implemented in a manner consistent with the facility RPP. Periodic monitoring and observation by independent organizations are an integral aspect of the RPP evaluation process.

4.2.3 Release Consequence Assessment

Any releases from the facility require accurate and timely assessment of their radiological and environmental impacts. A number of RPP elements including effluent monitoring instrumentation, environmental monitoring programs, and dose assessments of released radioactive materials are essential consequence assessment program elements. For significant releases, these assessments are supported by the facility's emergency preparedness program. Assessment results are communicated to the public, stakeholders, and regulators through an effective risk communication organization.

4.2.3.1 Effluent Monitoring

Historically, the facility's operating license through its technical specifications (TS) contains the detailed requirements for effluent monitoring. In the US, the licensee also has an option to transfer the detailed environmental monitoring requirements to the facility's off-site dose calculation manual (ODCM). The ODCM contains the specific methodology and model parameters for determining effluent monitor set points and for calculating offsite effective doses from effluent monitor values.

Limiting effluent doses for various air and water pathways are specified as part of the facility design basis. In the US, these requirements are specified in 10CFR50 [21] Appendix I that defines the limiting dose limits by effluent release pathway. Air pathways include releases resulting from containment purges, condenser air ejector operations, waste gas decay tank discharges, and station vent releases. Liquid release pathways include tank discharges, miscellaneous liquid sources including laundry water, circulating water releases, and steam generator blowdown effluent.

4.2.3.2 Environmental Monitoring

The radiological environmental monitoring program [1,2] obtains direct radiation and sampling data (e.g., air, water, soil, crops, fish, and milk) to characterize the effects of facility operations on the area surrounding the nuclear power facility. Monitoring programs include the establishment of the preoperational radiation environment near the proposed nuclear facility and characterization of the effects of the facility through the operational environmental monitoring program. This includes the collection of samples and establishment of pathways from the facility to various receptors.

The preoperational program characterizes the natural radiation environment and establishes the baseline level of radioactive materials including cosmogenic radionuclides (^{3}H, ^{7}Be, ^{14}C and ^{22}Na), fission products from atmospheric weapons tests and major reactor accidents (e.g., ^{90}Sr and ^{137}Cs), and radioactive members of the ^{232}Th and ^{238}U natural series [1,2].

4.2.3.3 Environmental Dose Assessment

The results of the environmental monitoring program are evaluated in terms of established release pathways. Environmental monitoring data and pathways are used to calculate effective doses to offsite receptors. These calculations are compared to regulatory requirements [21] to demonstrate compliance with annual effective and equivalent dose limits for individual members of the public [20].

4.3 Evaluation of Program Performance

The evaluation of performance is a key feature of an effective RPP. Program evaluation includes self-assessments and well as independent audits of the content, quality, and implementation effectiveness of the RPP.

4.3.1 Evaluation of Program Trends and Deficiencies

The evaluation of trends and deficiencies is an important program element because it determines the corrective actions that are essential for improving a radiation protection program. An effective evaluation program includes well-defined criteria to facilitate the identification and evaluation of radiological events, abnormal events, and RPP deficiencies. The program also includes the rigorous evaluation of these events and determination of their root and contributory causes.

The evaluation program includes the documentation, classification, evaluation, tracking, and trending of radiation protection deficiencies. Tracking and root cause determinations are particularly important features of the evaluation program.

All radiological events are evaluated including incidents involving exposure control, contamination control, loss of control of radioactive material, violations of high radiation barriers, dosimeter alarms, unanticipated intakes of radioactive materials, spills of radioactive materials, and breakdown of RPP program elements. These evaluations ensure that the RPP evolves and undergoes continuous improvement.

4.3.2 Corrective Action Program

Corrective action programs are constructed to prevent the recurrence of radiological events and deficiencies and to prevent the development of adverse trends. A key aspect of the corrective action program is the development and dissemination of lessons learned and ensuring these lessons are incorporated into program improvements and continuing training.

4.3.3 Reviews and Audits

Radiological reviews and audits assess key program elements including procedural compliance, program implementation and effectiveness, and regulatory compliance. Audits and reviews identify program areas that have a negative trend or could result in a noncompliance with station or regulatory requirements. In particular, trends in individual, work group, and station dose are evaluated to ensure that optimization is achieved and performance is continuously improving. Observations of work practices are incorporated as an integral aspect of the audit process. Training contributing to work practices and radiological performance are also evaluated. An evaluation of the effectiveness of the root cause program is also performed.

A diverse group of personnel should perform reviews and audits. This group includes corporate staff and management, facility radiation protection supervisors and managers, the onsite quality assurance organization, corporate radiation protection personnel, national industry groups, independent organizations including the IAEA, INPO, WANO and utility radiation protection personnel from other facilities and nations.

The key findings and recommendations of these audits and reviews should be carefully evaluated and incorporated into the station radiation protection program. Audit findings and recommendations should be tracked to ensure they are properly dispositioned and responsible individuals are assigned corrective actions.

4.4 Related Programs

The radiation protection program supports a number of facility work groups that rely on it for technical support and proper implementation. These program include risk communications, emergency preparedness, decontamination and decommissioning, security and nuclear safeguards, licensing and regulatory compliance, work control and outage planning, litigation support, and decontamination services.

4.4.1 Risk Communications

Effective risk communications requires an organization that exchanges information with the public in an effective and timely manner. The organization includes specialists in media relations as well as support from plant personnel including health physics personnel to clearly explain the radiological aspects of plant events and proposed activities. The accidents at Three Mile Island, Chernobyl, and Fukushima Daiichi illustrated the importance of radiological communications with the public [1,2,24-26]. Public understanding of the severity of an accident and its implications are important in establishing credibility during future recovery and reentry activities.

4.4.2 Emergency Preparedness

Emergency preparedness programs are designed and implemented to respond to declared events at a nuclear power facility. Since abnormal events may involve the release of radioactive material to the environment, emergency preparedness programs focus on protecting the three fission product barriers. These barriers are the fuel and associated cladding, the reactor coolant system and its included piping, and the containment building [1,2,25,26].

Emergency preparedness programs incorporate radiation protection personnel into both onsite and offsite response organizations. The onsite organization manages the plant emergency response activities to preserve the fission product barriers and minimize offsite releases of radioactive material. Offsite organizations perform dose assessments, communicate the emergency plant status to regulators and government officials, and develop protective action recommendations. Radiological monitoring teams are dispatched from the plant to characterize the nature and severity of the release. These field measurements are used in conjunction with plant effluent monitors to further understand the nature of the radiological accident and its consequences.

4.4.3 Decontamination and Decommissioning

A nuclear power plant should anticipate eventual decontamination and decommissioning by providing procedures for the final disposition of equipment and facility structures. Operating procedures minimize contamination of the facility and the environment, facilitate decommissioning, and minimize radioactive waste generation.

Sound radiological practices during power operations minimize the contamination of facility systems, structures, and components. With limited contamination, decontamination activities are reduced which facilitates decommissioning. The success of the radiation protection organization in implementing the facility's RPP governs the complexity of subsequent facility decontamination and decommissioning.

4.4.4 Security and Nuclear Safeguards

Security organizations provide protective services for the plant and its personnel. Since this organization functions in both radiological and non-radiological plant areas, health physics support is required for the effective Security and Nuclear Safeguards program. Radiological support is particularly important during an emergency when security forces encounter elevated dose rates and contamination levels.

Detecting illicit material or diversion of fuel or radioactive material is an important nuclear safeguards function. Radiological support includes measurement of dose rates as well as analyzing spectra to detect any diversion of fuel and radioactive materials. The selection of appropriate instrumentation and the calibration and proper use of these devices are inherent health physics functions.

4.4.5 Licensing and Regulatory Compliance

Health physics resources are needed to support a variety of licensing and regulatory compliance requirements. These requirements include regulatory audits and inspections to verify that licensing requirements are achieved and that the radiation protection program is effectively implemented. In addition, radiation related licensee event reports require health physics support for their completion. Health physics support is also required to develop the facility's Final Safety Analysis Report, Offsite Dose Calculation Manual, Technical Specifications, and Emergency Plan and subsequent revisions.

4.4.6 Work Control and Outage Planning

Much of daily work activities are performed on the radiologically controlled portion of the power reactor and these activities require coordination with and support by the health physics organization. This support includes development of specific radiation work permits and ALARA reviews, job coverage by technicians, and radiological planning support to integrate the work schedule into a coherent approach that optimizes worker doses.

During outage periods, work planning becomes more significant since most tasks involve primary system work activities that typically involve higher doses than non-outage tasks [1,2]. These tasks also encounter higher levels of contamination and require rigorous radiological controls to minimize the spread of contamination and intake of radioactive materials.

4.4.7 Litigation Support

Most litigation associated with a power reactor involves radiation exposures and intakes of radioactive materials. The litigation often alleges that a cancer or genetic defect was caused by the worker's radiation exposure or intake of radioactive materials.

The radiation protection organization is involved in discovery, depositions, records retrieval, dose assessments, preparing dose histories, and witness preparation. These activities require strong technical knowledge of health physics principles as well as practical knowledge of radiological work practices and controls.

Litigation support utilizes resources from both the facility as well as corporate organizations. In addition, health physics consultants serve as independent expert witnesses.

4.4.8 Decontamination Services

The decontamination of plant equipment and contaminated areas are important considerations in minimizing worker doses and generation of radioactive waste. Health physics personnel support these tasks and provide job coverage as well as technical support. Although decontamination tasks are not complex, they require careful implementation to ensure that doses and internal intakes are minimized.

5. Nuclear safety culture

Nuclear operations are governed by the safety culture of the operating utility and the dissemination of this philosophy throughout the organization [4,24]. The safety culture is distinct, but influenced by the sociological structure of the host nation. Effects of the national culture are addressed in subsequent discussion.

The safety culture of operating utility organizations changes as the nuclear industry evolves [4]. This initial culture was deemed to be acceptable prior to the Three Mile Island Unit 2 (TMI-2) accident in spite of the growing pains exhibited by the nuclear industry [1-4]. A significant improvement in safety culture occurred following the TMI-2 accident when the industry was faced with the reality of a major accident with core damage. The Chernobyl Unit 4 accident illustrated the need for management involvement in evaluating infrequently performed tests and experiments [1-4]. A further enhancement to the safety culture followed the Fukushima Daiichi accident [25,26].

Analyses of these accidents, illustrate that key aspects of strengthening the safety culture include the importance of a questioning attitude, safety-based decision-making, respecting the unique aspects of the nuclear technology, and organizational growth and development leading to continuous improvement. Specific cultural improvements from the three reactor accidents are noted in subsequent discussion [25,26]. In addition, emerging nuclear nations should learn from these accidents and incorporate their lessons learned into the basis for their radiation protection programs.

5.1 TMI-2

The Three Mile Island Unit-2 (TMI-2) accident demonstrated that major events at commercial nuclear power plants result from decisions and actions that reflect flaws in assumptions, values, and beliefs of operating and regulatory organizations [1-4,24-26]. During the Three Mile Island accident flawed assumptions regarding the pressurizer water level resulting in the reduction in emergency core cooling system flow rates that led to core uncovery and fuel melting. Fuel melting triggered another series of assumptions regarding the accident source term with significant iodine and noble gas components. The TMI-2 accident release pathway [1,2,24-26] severely limited the iodine source term, but dose projections and subsequent emergency response actions were based on the flawed iodine source term assumption. This assumption led to an evacuation order based, in part, on the flawed source term.

5.2 Chernobyl Unit-4

The Chernobyl accident also involved severe core damage and the release source-term had the expected noble gas and iodine character [1-4, 24-26]. This event was a reactivity excursion that obliterated the primary coolant system and reactor core and resulted in the combustion of the graphite moderator. The core and burning moderator were expelled from the reactor vessel during the severe reactivity excursion.

The accident was caused by a poor safety culture that led to the failure to control core reactivity and operate the plant in accordance with its design basis and operating procedures. The lack of questioning attitude and failure to follow operating procedures allowed a sequence of poor decisions to proceed without challenge. These decisions disabled safety systems and directly contributed to the accident.

The accident and its massive source term challenged the station radiation protection organization. Decisions were made that caused dozens of fatalities because optimum radiation protection controls were not effectively implemented to limit emergency worker doses during attempts to control the fire and radiological release.

5.3 Fukushima Daiichi

The Fukushima Daiichi event also revealed the need for a strong nuclear safety culture that includes a questioning attitude and the fortitude to challenge assumptions including the possibility that a large tsunami could flood the plant and disable safety systems required for core cooling. In addition, a questioning and challenging attitude could have assisted in maintaining core cooling during the accident when communications were limited and reliable plant data was unavailable [1-4, 24-26].

The accident also emphasized the need for flexibility in utilizing dose limits during an emergency. During a radiological emergency, dose limits should not impede plant personnel from performing the actions required to mitigate the event. These actions must proceed in a manner that incorporates dose optimization. As part of the optimization process, workers should be well trained and understand the risk of acute, accident radiation doses.

This did not occur at Fukushima Daiichi since the initial dose limits did not allow flexibility during the event response. While the 100 mSv dose limit was established for all site workers before the accident, there was no mechanism for adjusting this limit if warranted by an evolving event. Without this flexibility, operators were limited in their ability to access containment vent valves. This inaction contributed to containment vessel pressures remaining elevated for an extended time, which restricted cooling water injection into the primary reactor vessel [24].

Shortly after the accident, the government changed the emergency dose limit to 250 mSv. However, this change was not effectively communicated to the workers or interested stakeholders. Poor communication of the dose limit revision contributed to a loss of trust between the workers, management, stakeholders, and the government [24-26].

6. Cultural Factors

Each nuclear power reactor site has a unique culture determined by the operating philosophy of station management and the cultural norms of the facility staff and host nation. These cultural factors include the nation’s inherent belief structures, socio-economic system, ethnic composition, and political system. These factors vary significantly and are difficult to analyze in a general manner. However, a recent review of an Asian security force is illustrative [7].

Tran’s analysis [7] indicates that cultural issues are important considerations in an organization’s effectiveness. Since these cultural factors vary by nation and possibly between various regions within a nation, only a general discussion of the importance of culture can be provided in this paper. However, these factors have a significant influence on the RPP and its effective implementation.

As an illustrative example, Tran [7] performed a focused examination of the performances and practices of Indian domestic security forces. Performance issues within the security force are compounded by the diverse demographics within the country. Tran’s analysis attempted to determine if differing caste, religion, or ethnicity in the composition of Indian security forces affects performance of duties in a multi-ethnic society.

Based on eyewitness accounts and detailed operations reports, Tran concluded that a caste-based policy for military forces alters the behavior of service members. Tran's findings should be considered in the approach that national governments adopt in criteria regarding nuclear utility staff selection and evaluation of their performance. Consideration of specific ethno-religious groups, language barriers and differences, cultural differences, bias against minority groups and women, and minority representation are elements that vary by nations, but are factors that must be considered in staff selection, training, development, and work force integration.

6.1 Implications on Training and Qualification of Minority Groups and Women

Nuclear facility training focuses on specific subject matter content and the best methods to present that material. Although these are important considerations in achieving the desired result of a qualified radiological workforce, trainers must be cognizant of student attitudes and the associated social dynamics in the classroom and nuclear facility [8-10]. Minority and women students present significant challenges in cultures where their value has been historically diminished.

Cultural norms may cause these students to question if they belong in the training class, if they are smart enough to successfully complete the training and their radiological qualifications, and if the instructor and classmates respect them. The interaction between these internal concerns and the social dynamic of the classroom and facility affects their training success, capability to complete their qualification program, and ability to perform the requisite tasks in a nuclear facility environment. Individuals that perceive themselves as different or not being accepted are significantly affected by cultural dynamics and more likely to encounter difficulty in completing training and successfully qualifying for plant positions [10]. In a workplace environment, beliefs about intelligence and awareness of negative stereotypes are particularly important in the success of minority and women trainees.

The success of trainees is enhanced if these cultural considerations are incorporated into the radiological training and qualification program. These cultural aspects are effectively incorporated through a series of interventions summarized in Table 2. The interventions may be difficult to adopt in some cultural settings, but their successful implementation is essential for an effective RPP that provides long-term support to the power reactor. Their implementation requires considerable effort and must have the full support of management.

These interventions include the need for social belonging, development of a growth mindset, affirmation of values, and critical feedback with assurance. Each of these interventions has value and provides support to all trainees particularly those in groups not usually accepted by national cultural norms. These interventions and the approach to their successful resolution are summarized in Table 2.

Cultural norms create a sense of belonging to most trainees, but a natural exclusion to others. This cultural exclusion naturally leads to initial management decisions regarding the composition or cultural demographics for the facility. If only the culturally accepted groups are admitted as trainees, the issues summarized in Table 2 do not exist, but many excellent candidates are excluded. This is a particular concern at a nuclear power plant where the diversity of opinion and thought process are important. A monolithic plant organization comprised of a single group with common bias and beliefs can lead to a lack of critical thinking (e.g., groupthink) that limits innovation when needed at a critical time. For example, the accident at Three Mile Island could have benefited from an individual who thought through the problem and verified that the power operated relief valve was open. This thought process would have closed the motor operated block valve to isolate the reactor coolant system leakage and terminated the event. Similar issues arose at Fukushima Daiichi in allowing multiple hydrogen detonations in Units 1, 3, and 4, before the upper level of Unit 2 was opened to dissipate the accumulation of hydrogen.

Fostering diversity of opinion with a collaborative environment is a positive trait to be instilled in a nuclear organization. There is a

Table 2. Interventions and Implementations[a]

Intervention Type	Implementation		
	Psychological Concern	**Intervention Action**	**Intervention Format**
Social Belonging	Feelings of exclusion or disrespect create social unease.	Inclusion and respect are enhanced as qualification tasks are successfully completed.	The training and qualification process fosters social belonging if instruction is unbiased and based on merit.
Growth Mindset	Difficulties in meeting qualification requirements challenge trainee confidence.	Challenges and struggles stimulate personal growth if properly managed by instructors.	Additional instruction and qualification opportunities enhance success and build confidence in trainees.
Values Affirmation	Negative stereotypes limit trainee success and create impediments to success.	Classroom training presents opportunities for success that diminishes stereotyping.	The training and qualification process and its successful completion eliminate stereotyping if it is implemented in a fair and equitable manner.
Critical Feedback with Assurance	Critical feedback can create an impression that the instructor has a bias against the trainee.	Instructors consistently provide constructive and critical feedback because they have high standards and desire for trainees to achieve a high level of performance.	Consistent feedback to all students creates an atmosphere where standards and expectations are conveyed as a means to enhance performance.

[a] Ref. 9.

Table 3. Specific Traits of Specified Cultural Types[a]

Cultural Types				
Pathological	**Reactive**	**Calculative**	**Proactive**	**Generative**
Passive compliance	Costs dominate decisions	Focus on current issues	Benchmark and adapt	Benchmark and involve all organizational levels
Audits after accidents	Costs dominate decisions	Periodic audits of known hazard areas	Audits are positive tools for improvement	Continuous informal investigations of non-apparent issues
No safety planning	Safety planning based on past experience	Emphasizes hazard analyses	Planning is standard practice	Planning anticipates problems Safety processes are continuously reviewed
Training is a requirement	Training is a consequence of accidents	Knowledge is tested	Ongoing training assessments	Employee development is a continuous process
Punishment for failure	Disincentives for poor performance	Passive approval for positive safety performance	Some rewards for safe performance	Safety performance is self-rewarding
Employee fired after accident	Accident reports not disseminated	Management reacts negatively to accidents	Management is disappointed in accidents	Senior management is present in the workplace to emphasize safety standards and expectations
Safety is expensive	Can afford preventative measures	Safety and profit are managed or balanced	Profit is the priority followed by safety	Safety improves profits

[a] Refs. 28 and 29.

long-term benefit to a dynamic, culturally diverse organization that functions as a coherent team. Assembling, training, and maintaining this team is challenging and requires significant effort. These actions will challenge nations with cultures that require uniformity of thoughts and actions. In some cases, the challenge may be more than the culture can bear. In spite of well-written procedures, monolithic thinking can lead to significant consequences and lead to future accidents and radiological events. Accordingly, overcoming the tendency to exclude minority or underrepresented groups must be overcome for a nuclear organization to maximize its long-term success.

An example of the inclusive approach is the nuclear power program established at the University of Sharjah [27] in the United Arab Emirates (UAE). In April 2008, the UAE initiated work to establish a nuclear power program leading to a bachelor's degree in nuclear engineering. The program accepted its first group of students in 2012. Currently, the program has in excess of 70 students almost half of whom are women. In addition, the program recently established an American Nuclear Society Student Section to establish ties to the international community. This program provides a solid basis for future staffing of the Barakah reactors [12] noted in Section 3.0.

6.2 Guiding Principles

An inclusive approach involving all stakeholders is an essential element in promoting a successful radiation protection culture within the health physics organization and at a nuclear power facility [28,29]. Strong leadership, education and training, proactive behavior, and responsive communications among all staff have a positive impact on the radiation protection culture [29].

Radiation protection cultures naturally evolve [29]. The initial stage involves basic compliance with safety training programs, work conditions, procedures, and regulations. Compliance is passive with minimal enthusiasm for improvement.

The second stage involves self-directed implementation with workers ensuring compliance. Workers take personal responsibility for training and regulatory requirements. This stage emphasizes active compliance.

In the third stage, behaviors enhance compliance. Individuals are trained to search for hazards, focus on safe behaviors to prevent radiological hazards, and to act safely. This stage emphasizes interdependence within the workforce and an attitude that safety is everyone's responsibility. Table 3 illustrates a layered approach to the development of a radiological safety focused culture. Specific traits of these cultural types are noted. Cultural types included in Table 3 include pathological, reactive, calculable, proactive, and generative [28,29]. As the culture evolves, its perception of a radiation protection organization evolves from a necessary evil to an integrated organization that is part of a process for continuous improvement and enhancing worker safety. The objective of cultural evolution is to move the radiation protection organization towards the highest development stage and cultural type.

The author has experienced this evolution as the Radiation Protection Manager at US reactors. In a reactive culture, work delays are blamed on the health physics organization and its job coverage requirements. As the culture matures, work groups involve health physics in the task planning process and radiological requirements are integrated into work packages. With a fully mature organization, line organizations (e.g., operations and maintenance) incorporate radiological requirements in their daily work activities and utilize health physics as a partner in task performance. In addition, ALARA Committees are led by the organizations with support from the health physics group. When line organizations consider radiological requirements on an equal status with production goals, the station's organization has reached the desired culture level as noted in Table 3.

7.0 Conclusions

The radiation protection program includes a number of elements that are essential for a nuclear power facility to be successful. Optimizing worker radiation doses are only a small portion of the contribution to a radiation protection organization. The radiation protection organization supports plant operations, facilitates maintenance and surveillance activities, monitors the facility's environmental impact, and contributes to a variety of licensing and regulatory functions required for facility operations. The organization functions in an optimum manner if personnel diversity is promoted and stakeholders are included in the organization's activities.

Cultural sensitivity and inclusion of stakeholders in radiation protection improvements create an environment in which leaders have credibility, are present in the facility, and demonstrate their commitment to safety through their decisions and actions. These leaders establish an environment where personnel accountability is fostered and encouraged and all individuals take personal responsibility for radiation protection.

Cultural sensitivity promotes trust and respect throughout the organization. Communications are timely and accurate and focus on safety. This open environment creates an atmosphere in which all personnel feel free to raise safety concerns without fear of discrimination, harassment, intimidation, or retaliation. All employees, including women and minority groups, are included in decisions, have the opportunity for advancement, and are equal partners in the radiation protection program and in enhancing radiation safety performance.

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