SAND2016-1179C

http://csu-cvmbs.colostate.edu/academics/erhs/health-physics/Pages/default.aspx

Nuclear Safety (Week 8 / Day 2)

Lecture: Introduction to Worker Radiation Protection

(Occupational Radiation Protection)

SAND2016-XXXX

Gulf Nuclear Energy Infrastructure Institute – 2016 Fundamentals Course

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Week 8 / Day 2 Learning Objectives

- To understand the importance of Operational Radiation Protection to nuclear safety and a responsible nuclear energy program.
- Conduct an HPI-based assessment of the Three Mile Island reactor accident.

Week 8 / Day 2 / Lecture Outline

- Main Elements of a Radiation Protection Program
- IAEA Standards & Guidelines for Occupational Radiation Protection
- Key Elements of Occupational Radiation Protection
- Case Study #2: Three Mile Island Reactor Accident

Nuclear Safety

- IAEA Guidelines (Review)

Definition of "***Nuclear Safety***":

Operating conditions, prevention of accidents/mitigation of consequences, resulting in the ***protection of workers, the public, and the environment*** from undue radiological hazards.

Ref.: SAND2010-8826P

Nuclear Safeguards

Prevention and detection, through the use of material control and accountancy, of theft or diversion of special nuclear material from civilian facilities.

Nuclear Security

Prevention and detection of, and response to sabotage, unauthorized access, or other malicious acts involving nuclear material, other radioactive substances or their associated facilities.

Nuclear Safety (Cont.)

- IAEA Definition of '*Safety Culture*'

"… that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, protection and safety issues receive the attention warranted by their significance."

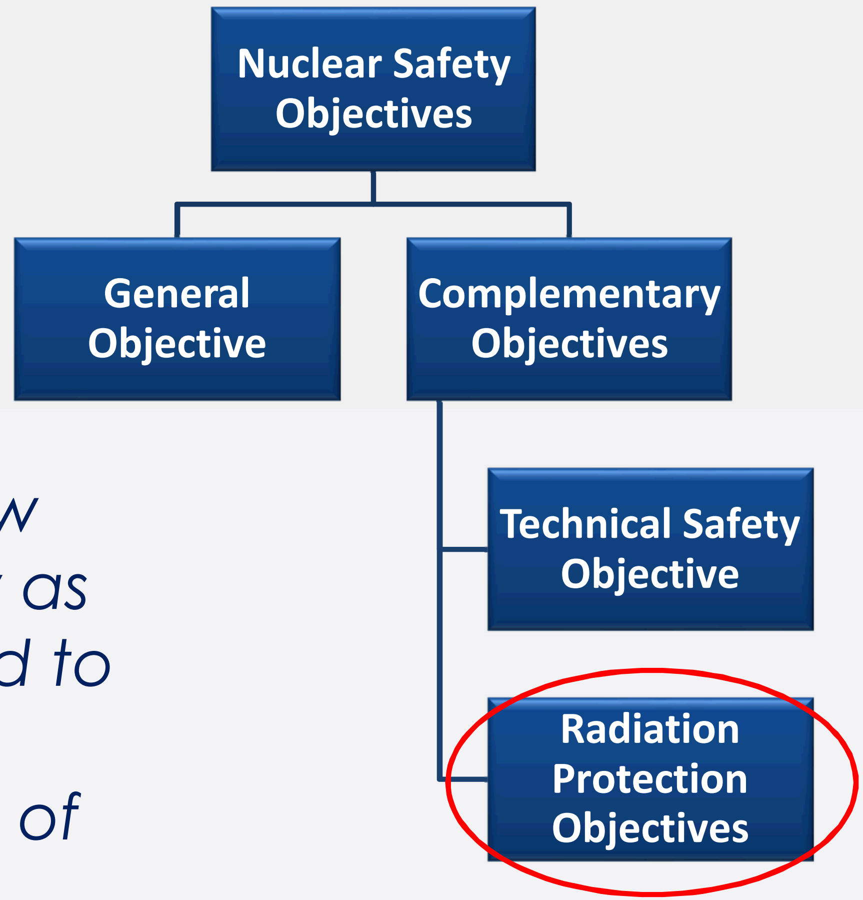
References:

1. *INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-R-3, IAEA, Vienna (2006).*
2. *INTERNATIONAL ATOMIC ENERGY AGENCY, Application of the Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-G-3.1, IAEA, Vienna (2006).*

Nuclear Safety (Cont.)

- Radiation Protection Objective (Review)

"To ensure that in all operational states, radiation exposure within the installation, or due to any planned release of radioactive material from the installation, is kept below prescribed limits and as low as reasonably achievable, and to ensure mitigation of the radiological consequences of any accidents."



References: IAEA Safety of nuclear power plants: Design, NS-R-1, 31 October 2000.
INTERNATIONAL ATOMIC ENERGY AGENCY, The Safety of Nuclear Installations, Safety Series No. 110, IAEA, Vienna (1993).

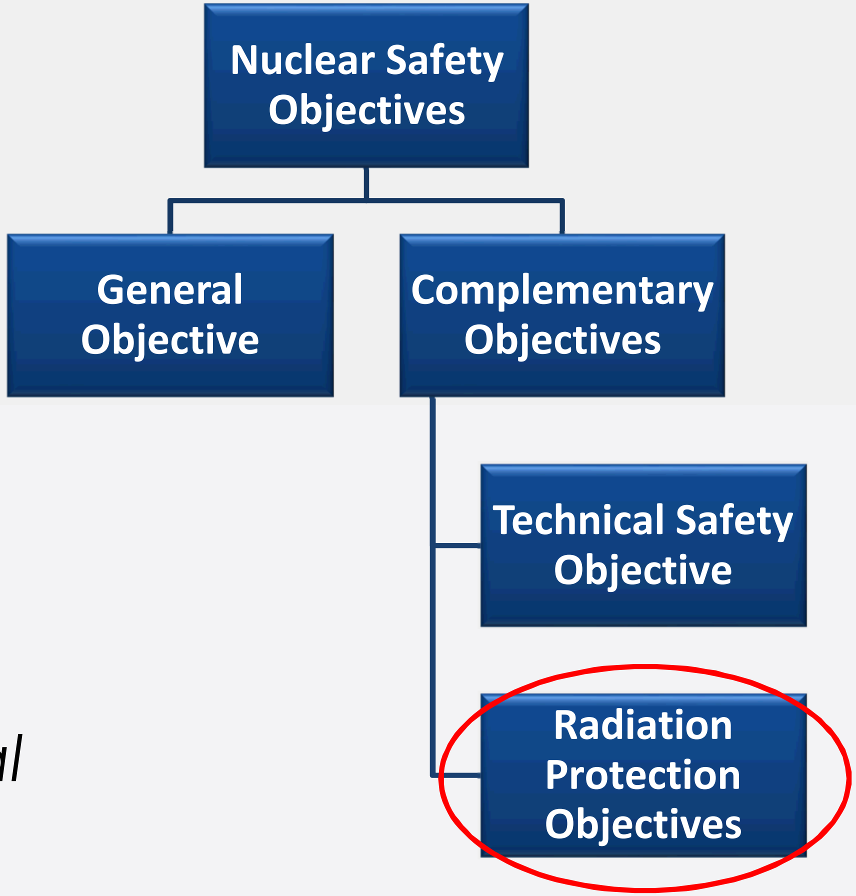
Nuclear Safety (Cont.)

- Radiation Protection Objective (*Paraphrased*)

- *Must Protect:*
  - ***Workers*** (Personnel)
  - ***Environment***
  - ***Public***

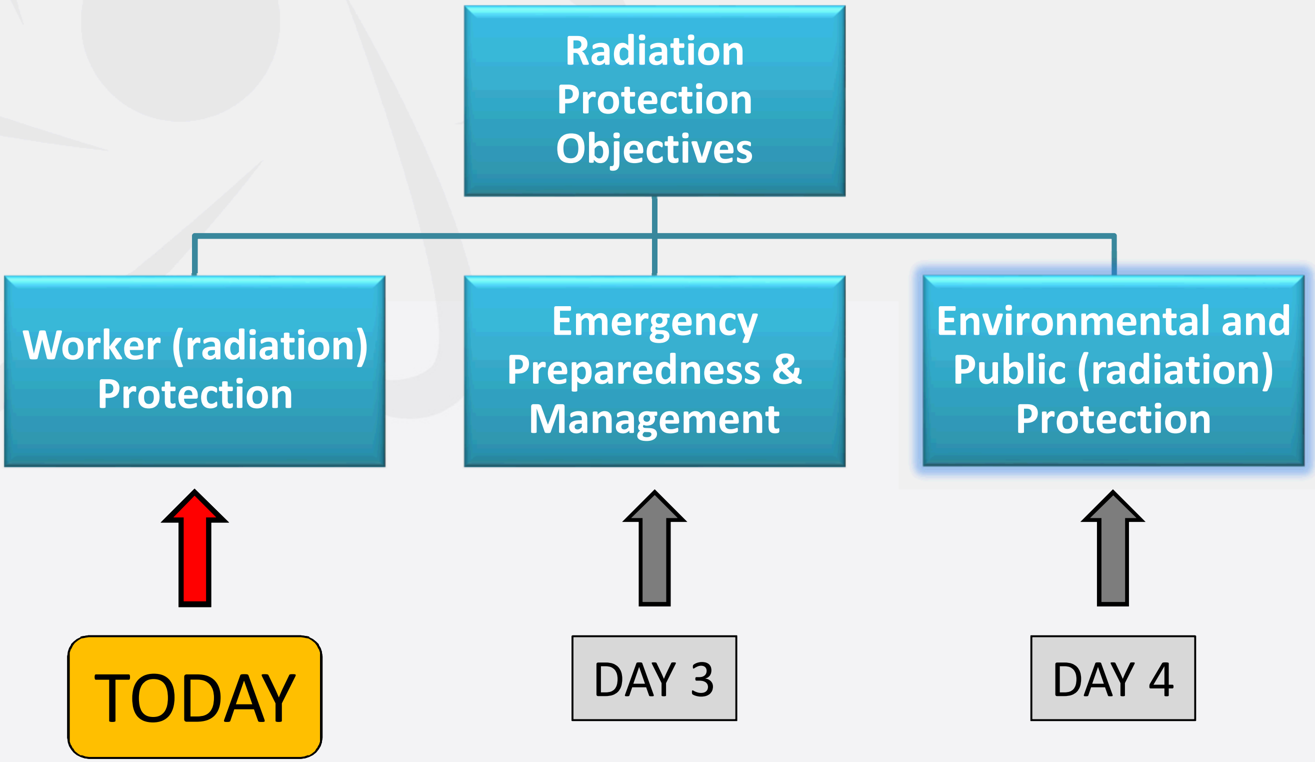
  during normal operations and emergency conditions

- *Must mitigate radiological consequences of any accidents*



Nuclear Safety (Cont.)

- Radiation Protection Objective (Cont.)



IAEA Standards & Guidelines

- Occupational Radiation Protection

Safety Fundamentals

Radiation Protection and the Safety of Radiation Sources

Safety Series No. 120

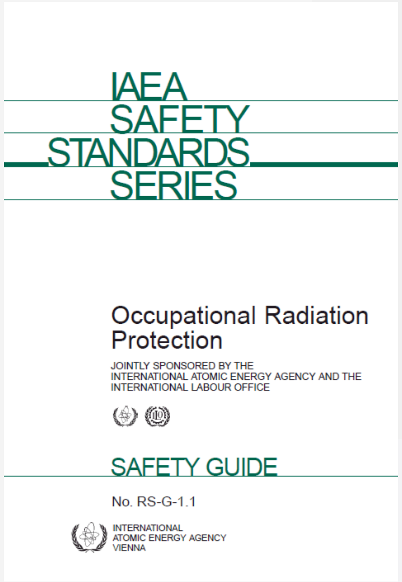
Safety Requirements

International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources

Safety Series No. 115

Safety Guides

- Assessment of Occupational Exposure due to External Sources of Radiation — **RS-G-1.3**
- Occupational Radiation Protection — **RS-G-1.1**
- Assessment of Occupational Exposure due to Intakes of Radionuclides — **RS-G-1.2**



Reference: International Atomic Energy Agency, Occupational Radiation Protection, IAEA Safety Standards Series No. RS-G-1.1, IAEA, Vienna, Austria (1999).

IAEA Standards & Guidelines (Cont.)

- Radiation Protection Objective

"The normal exposure of individuals shall be restricted so that neither the total effective dose nor the total equivalent dose to relevant organs or tissues, caused by the possible combination of exposures from authorized practices, exceeds any relevant dose limit specified …"

4 key processes:

- Pre-op ***predict and minimize*** *(ALARA)* exposure of workers,
- ***Monitor and measure*** the exposure of workers,
- ***Assess*** the **dose** received by workers, and
- ***Mitigate*** potential over exposure

IAEA Standards & Guidelines (Cont.)

- Responsibilities: Employers, Registrants, & Licensees

Overview: Employers, registrants, and licensees are responsible for:

- Protection of workers from occupational exposure; and
- Compliance with relevant requirements of the Standards

Note: "*Employers who are also registrants or licensees shall have the responsibilities of both employers and registrants or licensees.*"

IAEA Standards & Guidelines (Cont.)

- Responsibilities: Employers, Registrants, & Licensees (Cont.)

Employers, registrants and licensees shall ensure, for all workers engaged in activities that involve or could involve occupational *{radiation}* exposure, that:

a) Occupational exposures be limited as specified in regulations;

b) Occupational protection and safety be optimized in accordance with the relevant principal requirements of the Standards;

c) Decisions regarding measures for occupational protection and safety be recorded and made available to the relevant parties, through their representatives where appropriate, as specified by the Regulatory Authority;

IAEA Standards & Guidelines (Cont.)

- Responsibilities: Employers, Registrants, & Licensees (Cont.)

d) Policies, procedures and organizational arrangements for protection and safety be established for implementing the relevant requirements of the Standards

- priority to be given to design and technical measures for controlling occupational exposures;

e) Suitable and adequate facilities, equipment and services for protection and safety be provided

- nature and extent is to be commensurate with the expected magnitude and likelihood of the occupational exposure;

f) Necessary health surveillance and health services be provided;

IAEA Standards & Guidelines (Cont.)

- Responsibilities: Employers, Registrants, & Licensees (Cont.)

g) Appropriate protective devices and monitoring equipment be provided and properly used;

h) Suitable and adequate human resources and appropriate training in protection and safety be provided, as well as periodic retraining and updating as required in order to ensure the necessary level of competence;

i) Adequate records be maintained as required by the Standards;

j) Arrangements be made to facilitate consultation and co-operation with workers with respect to protection and safety; and

k) Necessary conditions to promote a safety culture be provided.

IAEA Standards & Guidelines (Cont.)

- Responsibilities: Workers

Workers shall:

a) Follow applicable rules and procedures for protection and safety specified by the employer, registrant or licensee;

b) Properly use the monitoring devices and the protective equipment and clothing provided;

c) Co-operate with the employer, registrant or licensee with respect to protection and safety, and radiological health surveillance and dose assessment programs;

d) Provide to the employer, registrant or licensee such information on their past and current work as is relevant to ensure effective and comprehensive protection and safety for themselves and others;

IAEA Standards & Guidelines (Cont.)

- Responsibilities: Workers (Cont.)

e) Abstain from any willful action that could put themselves or others in situations that contravene the requirements of the Standards; and

f) Accept such information, instruction and training concerning protection and safety as will enable them to conduct their work in accordance with the requirements of the Standards."

The Radiation Protection Program (RPP) is a key factor for the development of a safety culture, *"to encourage a questioning and learning attitude to protection and safety and to discourage complacency."*

IAEA Standards & Guidelines (Cont.)

- Optimization of Radiation Protection

Optimization Principle:

- Considers all possible actions involving the source(s) of occupational radiation exposure, and the workers' activities around the source(s);
- Implements a '*management by objective*' process: setting objectives, measuring performance, evaluating and analyzing performance to define corrective actions, and setting new objectives;
- Can be adapted to take into account any significant change in the state of techniques, available protection resources, or the prevailing social context; and
- Encourages personal accountability for eliminating unnecessary radiation exposure.

IAEA Standards & Guidelines (Cont.)

- Optimization of Radiation Protection (Cont.)

Optimization:

- Process that begins at the planning stage and continues through the stages of scheduling, preparation, implementation and feedback
  - Should be considered at the design stage of equipment and installations
  - Should be a regulatory requirement;
- Primary responsibility for optimization lies with management; and
- Management and worker commitment to good radiation protection is essential

IAEA Standards & Guidelines (Cont.)

- Dose Limits

The occupational exposure of any worker shall be controlled to ensure the following limits are not exceeded:

a) An effective dose of 20 mSv (2 rem) per year averaged over five consecutive years;

b) An effective dose of 50 mSv (5 rem) in any single year;

c) An equivalent dose to the lens of the eye of 150 mSv (15 rem) in a year; and

d) An equivalent dose to the extremities (hands and feet) or the skin of 500 mSv (50 rem) in a year.

IAEA Standards & Guidelines (Cont.)

- As Low As Reasonably Achievable

Purpose: Maintain occupational radiation exposures **A**s **L**ow **A**s **R**easonably **A**chievable (ALARA):

- Takes into account the benefits and risks associated with radiological work activities, the resultant radiation doses, and the controls to be implemented;
- Includes:
  - Physical design features (e.g., engineered controls)
  - Administrative controls (e.g., policies, procedures, training, posting/labeling, etc.)
  - Work controls commensurate with the hazards (e.g., permits)
  - Personal Protective Equipment (PPE) and clothing
  - Tracking & trending of personnel doses

IAEA Standards & Guidelines (Cont.)

- ALARA: Pre-Operational Prediction of Potential Exposure

Includes:

a) Identification of the source(s) of routine and reasonably foreseeable potential radiation exposures;

b) Realistic estimate of the relevant doses (and their probabilities);

c) Identification of the radiation protection measures needed to meet the optimization principle.

Information on the source inventory, the facility design, operational characteristics, worker activities, and the safety systems are used in this process.

IAEA Standards & Guidelines (Cont.)

- ALARA: Pre-Operational Prediction of Potential Exposure

Safety Assessments should critically review:

a) Nature and magnitude of potential exposures and the likelihood of their occurrence;

b) Limits and technical conditions for operation of the source;

c) Potential for, and consequences of, failures in structures, systems, components and procedures that could lead to potential exposures;

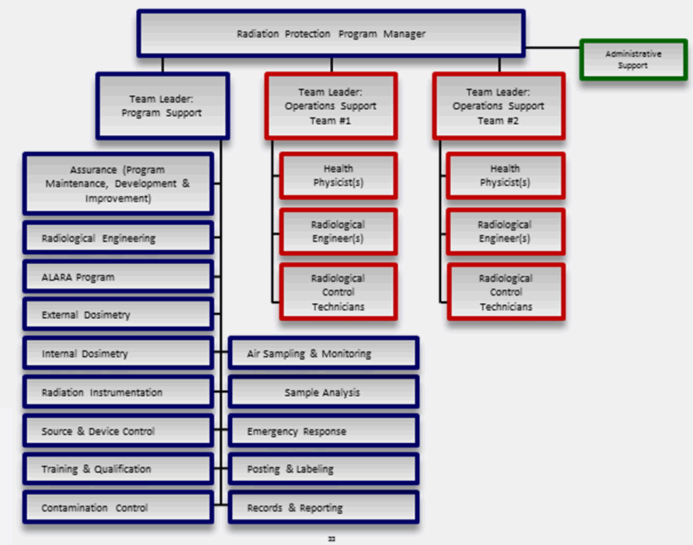
d) How environmental changes could affect worker protection or safety;

e) Potential for errors in radiation protection/safety operating procedures, and the consequences of such errors; and

f) Protection & safety implications of proposed modifications.

IAEA Standards & Guidelines (Cont.)

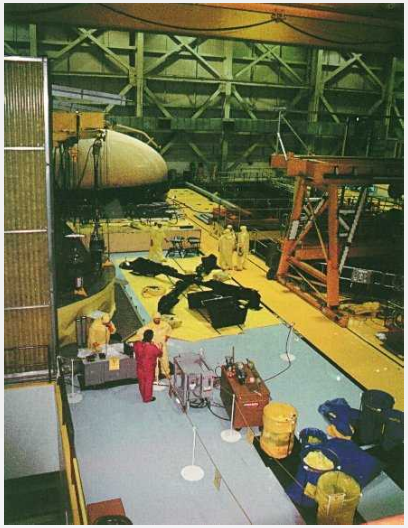
- ALARA: Minimization of Potential Exposure



- Set Scope and structure of the RPP
  - Organizational Chart
  - Recording and Reporting System
  - Education and Training Program
  - Assessments and Audits
  - Health Surveillance Program
- Assign Roles and Responsibilities
  - Example: Accountability for radioactive material
- Classification of Areas
  - Controlled Areas; Supervised Areas
- **Work Planning and Radiation Work Permits**
- Monitoring and Dose Assessment

IAEA Standards & Guidelines (Cont.)

- Monitoring & Measuring the Exposure of Workers



Two Main Elements:

- **Workplace (Indoor) Monitoring**
- **Individual (Worker) Monitoring**

IAEA Standards & Guidelines (Cont.)

- Workplace (Indoor) Monitoring

Monitor & assess individual exposures to airborne radioactive material, determine the need for respiratory protection, and provide early warning of unexpected increases in airborne radioactivity levels

- Characterize workplace conditions and detect changes in those conditions
- Verify the effectiveness of physical design features and process controls

Typical / Types:

- Fixed-head workplace samplers
- Real-time air monitoring
- Individual monitoring devices

IAEA Standards & Guidelines (Cont.)

- Individual (Worker) Monitoring: *External Dosimetry*

Monitor ***external*** occupational radiation doses resulting from radiological work activities and radiological hazards:

- Formal subprogram for monitoring/evaluating personnel exposures to external radiation
- Specific criteria used for monitoring personnel doses (e.g., Radiological Workers, Public)
- Resources: whole-body and extremity dosimeters, dosimeter processing equipment, supplemental dosimeters, personnel, etc.
- Accredited external dosimetry laboratory and services (e.g., DOELAP in USA)
- External dosimetry records, reporting, and investigation

IAEA Standards & Guidelines (Cont.)

- Individual (Worker) Monitoring: *Internal Dosimetry*

Monitor ***internal*** occupational radiation doses resulting from intakes of radioactive material:

- Formal subprogram for monitoring and evaluating personnel exposures to internal radiation (contamination)
- Specific criteria used for monitoring intakes (e.g., Radiological Workers, Public)
- Resources: whole-body counter, bioassay process, supplies and equipment, personnel, etc.
- Accredited internal dosimetry laboratory and services (e.g., DOELAP in USA)
- Internal dosimetry records, reporting, and investigation

IAEA Standards & Guidelines (Cont.)

- Assessment of Doses Received by Workers

Monitoring and measurement requires interpretation and assessment to demonstrate both the adequate protection and the implementation of optimization of protection

Results can be used for:

- Confirmation of good working practices;
- Information about conditions in the workplace;
- Estimation of the actual exposure of workers;
- Evaluation of operating procedures and design characteristics;
- Evaluation of doses in the event of accidental exposures.

IAEA Standards & Guidelines (Cont.)

- Workplace & Individual Monitoring: *Instrumentation*

Specialized instruments and equipment required to effectively monitor and measure radiological conditions:

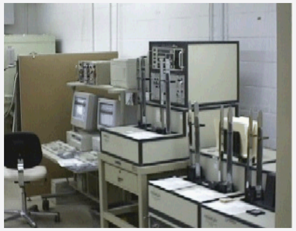
- Formal subprogram for procurement of appropriate radiation detection/measurement instrumentation
  - Radiation vs. contamination vs. airborne radioactivity
  - Stationary monitors (air samplers/monitors, portal radiation monitors, personnel contamination monitors)
  - Portable instruments (hand-held survey instruments)
  - Laboratory equipment (liquid scintillation, gamma spectrometry, etc.)

- Formalized acceptance testing, maintenance and calibration services
- Instrumentation calibration facility

- Workplace & Individual Monitoring: *Sample Analysis*

Radioactive sample analysis used for worker internal exposure assessments, evaluation of workplace contamination levels, and material analysis

- Formal subprogram that supports Internal Dosimetry, Air Sampling & Monitoring, Posting & Labeling, and Operations Support functions
  - Alpha Spectroscopy
  - Gamma Spectroscopy
  - Gas Proportional Counting
  - Liquid Scintillation
  - In-Vivo Monitoring
  - Drum Counting
  - Radiochemical Analysis



IAEA Standards & Guidelines (Cont.)

- Mitigating Potential Over-Exposure of Workers

- Cause(s) for potential over-exposures must be determined
- Using the ALARA concept, the cause(s) for such exposure(s) must be removed
- Effectiveness of measures to eliminate the cause(s) of over-exposure must be assessed through follow-up monitoring, measurements, and assessments
- Records of such actions must be maintained for future re-examination and lessons learned

Occupational Radiation Protection

- Key Elements

- Assurance
- Radiological Engineering
- Posting and Labeling
- Training and Qualification
- Contamination Control
- Radioactive Source Control
- Shipping and Transportation
- Support of Operations and Maintenance
- Records and Reporting

Occupational Radiation Protection (Cont.)

- Assurance (Quality Assurance)

Oversee Radiation Protection Program maintenance, development, and improvement:

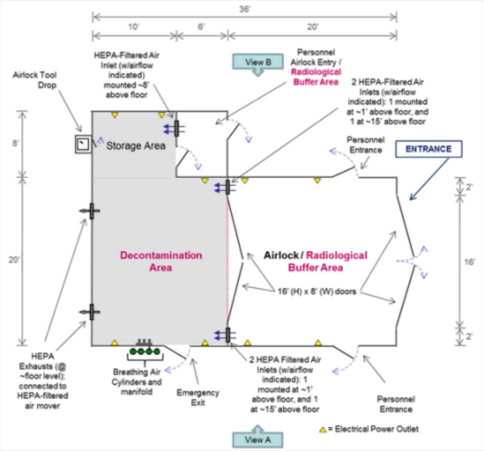
- Translate and communicate requirements, guidance and best practices into corporate processes
- Develop, maintain, and coordinate Radiation Protection operating procedures and implementation documents
- Develop and implement an internal self-assessment process
- Provide useful tools and technical support to assist the Line
- Conduct radiation-related incident evaluations
- Maintain Quality Assurance process
- Develop, track, and report performance indicators/metrics
- Coordinate and distribute RP lessons learned

Occupational Radiation Protection (Cont.)

- Radiological Engineering

Develop engineered solutions to radiological hazards (e.g., dose reduction, contamination reduction)

- Application of mathematics, science, and engineering in the design of nuclear and radiological facilities and related engineered controls
  - Shielding
  - Containment
  - Ventilation
  - Safety interlocks
  - Warning systems



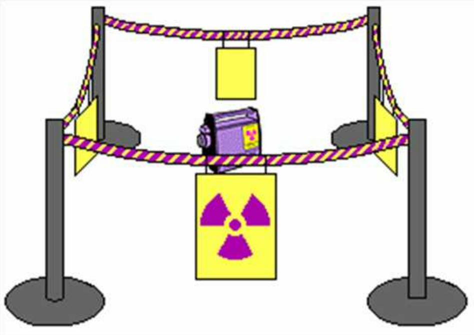
- Evaluation of new technologies in radiation detection and measurement
- Complex dose calculations

Occupational Radiation Protection (Cont.)

- Posting & Labeling

Identify & communicate radiological hazards to individuals, allowing them to take the appropriate protective actions

- Area Posting
- Material Labeling
- Equipment Labeling
- Device Labeling



Occupational Radiation Protection (Cont.)

- Training & Qualification

Ensure individuals are trained/qualified to work safely in and around radiological hazards, and to maintain their individual radiation exposure ALARA:

- Academic training (knowledge)
- Applied (hands-on) training (skill & ability)
- Written examinations, practical demonstrations
- Initial training and periodic retraining
- Depth & breadth of training commensurate with target audience
  - General Employees
  - Radiological Workers
  - Radiological Control Technicians

Occupational Radiation Protection (Cont.)

- Contamination Control

Provide warning of the presence of surface contamination, and help prevent the transfer of contamination to non-radiological areas:

- Physical design features
- Administrative control
  - Work authorizations
  - Access control
  - Posting & labeling
- Contamination monitoring (layered defense)
  - Work station / bench-top
  - Work area / room exits
  - Radiological Area exit points
  - Portal, laundry, and equipment monitors

Occupational Radiation Protection (Cont.)

- Radioactive Source Control

Control and monitor the use of radioactive sources to prevent unplanned exposures and loss of sources:

- Source accountability and control
  - Controlled process for procurement/acquisition
  - Source registration
  - Use of trained Source Custodians
  - Periodic inventory (e.g., every 6 months)
  - Radiation & contamination surveys
  - Monitored storage and use areas
  - Posting and labeling
  - Controlled process for transfer, transport, disposal
- Source inventory database (type/form, activity, location, custodian)

Occupational Radiation Protection (Cont.)

- Shipping & Transportation

Provide safe movement and transport of radioactive material (fuel, sources, etc.):

- Packaging and shipment of radioactive material must:
  - keep radiation and radioactive material from affecting the environment during transportation
    - must also prevent the environment from affecting the integrity of the radioactive material
  - keep radiation and radioactive material from affecting members of the general public during transportation

Occupational Radiation Protection (Cont.)

- Operational Support

Provide real-time radiation protection support services to organizations and facilities that perform radiological work:

- Perform and document workplace/activity monitoring of radiological hazards (routine and non-routine surveys of record)
  - Characterize workplace conditions and detect changes in conditions
  - Verify the effectiveness of physical design features and engineered controls
  - Identify and control potential sources of personnel radiation exposure
  - Determine exposure rates during entries to high and very high radiation areas

Occupational Radiation Protection (Cont.)

- Operational Support (Cont.)

Provide real-time radiation protection support services to organizations and facilities that perform radiological work:

- Interpretation / implementation of radiation protection requirements & guidance
- Radiological hazard analyses
- Developing appropriate engineered and administrative controls
- Review of Technical Work Documents

- Operational Support (Cont.)

Provide real-time radiation protection support services to organizations and facilities that perform radiological work:

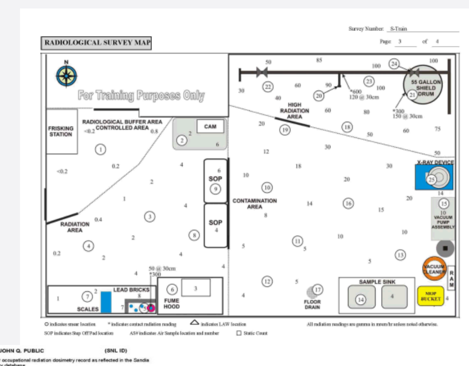
- Provide activity-specific ALARA recommendations
- Enforce the comprehensive contamination control program
- Provide radiation protection assistance for radiological emergencies

Occupational Radiation Protection (Cont.)

- Records & Reporting

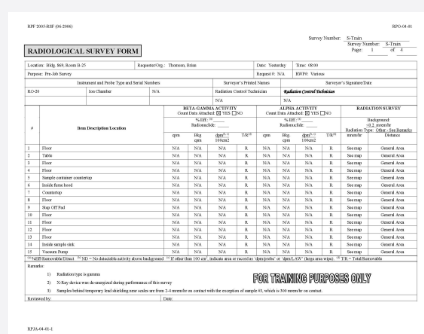
Document workplace radiological conditions, work policies, practices & controls, and occupational radiation doses received by workers over the history of the facility and its activities:

- Records required to support worker health studies and future disputes or claims
- Used to demonstrate regulatory compliance
- Should be high-quality, readily retrievable, and managed for the prescribed retention period

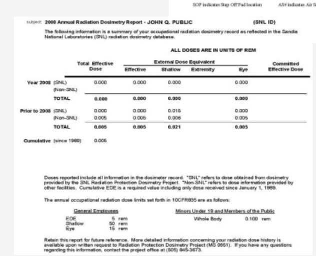

RADIOLOGICAL SURVEY MAP


RADIOLOGICAL PLANNING WORKSHEET

SECTION 1


RADIOLOGICAL SURVEY FORM

FOR TRAINING PURPOSES ONLY


2008 Annual Radiation Dosimetry Report - JOHN Q. PUBLIC

ALL DOSES ARE IN UNITS OF REM

References

- International Atomic Energy Agency, Radiation Protection and the Safety of Radiation Sources, Safety Series 120, IAEA, Vienna (1996).
- International Atomic Energy Agency, Occupational Radiation Protection, IAEA Safety Standards Series No. RS-G-1.1, IAEA, Vienna, Austria (1999).
- IAEA, Low Doses of Ionizing Radiation: Biological Effects and Regulatory Control, Proceeding of an international conference held in Seville, Spain, 17-21 Nov. 1997, IAEA Vienna (1998).

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Source: http://en.wikipedia.org/wiki/Three_Mile_Island_Nuclear_Generating_Station

Nuclear Safety (Week 8 / Day 2)

Case Study #1: Assessment of the Three Mile Island Reactor Accident

Gulf Nuclear Energy Infrastructure Institute – 2016 Fundamentals Course

Mr. Brian Thomson
Sandia National Laboratories

TMI Reactor Accident

- Environment, Safety, & Health Consequences

- Evacuation measures
  - On 3rd day, governor of Pennsylvania recommended evacuation of pregnant women and children
  - By end of weekend, half the population within 32 km left
  - Current guidelines would call for a precautionary evacuation

https://en.wikipedia.org/wiki/Dick_Thornburgh

TMI Reactor Accident

- Environment, Safety, & Health Consequences (Cont.)

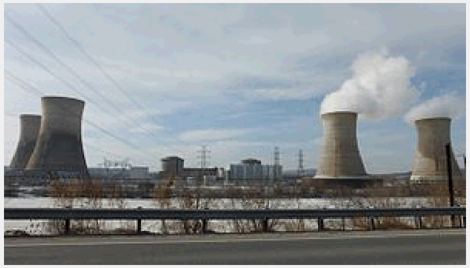
- Despite loss of core integrity, safety systems worked
  - Demonstrated the importance of inherent safety features, in particular defense in depth, multiple physical barriers concepts
- No damage to the public health or large radioactive releases
- However, ***large*** influence on nuclear power in the U.S.

http://en.wikipedia.org/wiki/Three_Mile_Island_accident

TMI Reactor Accident

- Environment, Safety, & Health Consequences (Cont.)

- TMI-2 Source Term:
  - 15 Ci Iodine (^{131}I)
  - 2,500,000 Ci of noble gas
- TMI-2 release occurred:
  - during controlled venting of the containment
  - through water transfer systems between containment and the outside
- Current guidelines would call for a precautionary evacuation



http://en.wikipedia.org/wiki/Three_Mile_Island_accident

TMI Reactor Accident

- Environment, Safety, & Health Consequences (Cont.)

- Average dose within 80.5 km = 0.015 mSv (1.5 mrem)
- Max actual off-site dose = 0.37 mSv (37 mrem)
- Projected excess cancer fatality = 1/2,000,000
- Normal cancer fatalities = 325,000/2,000,000

Ref: R. A. Knief, Nuclear Engineering – Theory and Technology of Commercial Nuclear Power, Hemisphere Publishing Corp. (1992) Note: reference does not use SI units

In-Class Assignment: Team #1

- Identify the ***Latent Organizational Weaknesses*** that:
  - triggered this event (directly or indirectly);
  - failed to prevent the event from occurring; and
  - contributed to the event (i.e., increased the severity of the outcome)
- Identify recommended solutions to address each identified *Latent Organizational Weaknesses*
- Prepare and conduct a 10-15 min. presentation that summarizes your findings and recommended solutions

In-Class Assignment: Team #2

- Identify the ***Error Precursors*** that:
  - triggered this event (directly or indirectly);
  - provoked human error; and
  - contributed to the event (i.e., increased the likelihood of the error or increased the likelihood of an adverse outcome)
- Identify recommended solutions to address each identified *Error Precursor*
- Prepare and conduct a 10-15 min. presentation that summarizes your findings and recommended solutions

In-Class Assignment: Team #3

- Identify the ***Flawed Defenses*** that:
  - triggered this event (directly or indirectly);
  - failed to prevent or catch human error, and/or failed prevent the event from occurring; and
  - contributed to the event (i.e., increased the severity of the outcome)
- Identify recommended solutions to address each identified *Flawed Defense*
- Prepare and conduct a 10-15 min. presentation that summarizes your findings and recommended solutions

Extra Slides

TMI Reactor Accident

- Pre-Existing Problems

- Reactor coolant leak from pressurizer to reactor coolant drain tank
  - NRC later concluded this leak exceeded tech spec limits
- Resin block in transfer line driving water between demineralizer and condensate pumps
- **Accident began when all condensate polisher isolation valves closed**
  - This caused one of two operating condensate pumps and both condensate booster pumps to trip
- **Event initiates on Wed., March 28, 1979, 4:00:36 am**

TMI Reactor Accident

- Contributing Factors

- Loss of Coolant
  - Pilot-operated relief valve (PORV) sticks open when the Reactor Coolant System (RCS) pressure drops below set-point at 13 sec.
    - ➢ **Mechanical failure**
  - Loss-of-Coolant Accident (LOCA) undetected because the control board indicating light signaled that PORV was closed
    - ➢ **Instrumentation failure**
  - If operators had manually closed valve at this point, event would have been terminated

TMI Reactor Accident

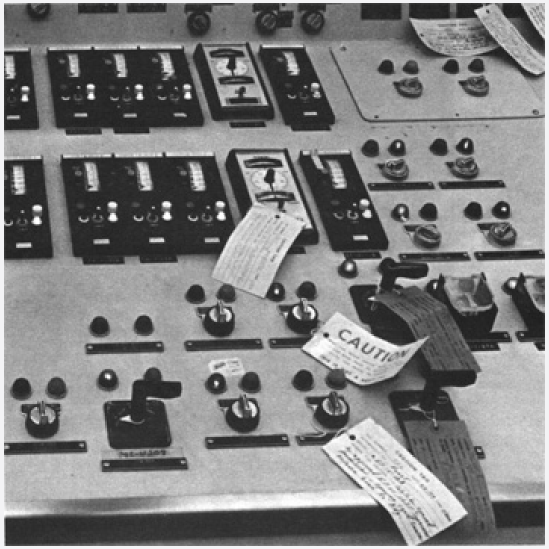
- Contributing Factors (Cont.)

- Operators did not detect open pilot-operated relief valve (PORV)
  - Neglected high temps in downstream pipe because of known leak
  - Ignored the rapid drop in RCS pressure
  - Reactor coolant drain tank pressure increased and tank's rupture disk blew after 15 min.
    - Meter was behind reactor console and out of sight
    - Data acquisition computer contained time history of tank pressure but data printout lagged significantly
  - **Inadequate information to operators + operator error**

TMI Reactor Accident

- Contributing Factors (Cont.)

- Loss of auxiliary feedwater
  - "Aux feed" to steam generators is designed to compensate for loss of main feedwater
  - Block valves were closed at the time of the accident
    - ➢ **Steam generators boil dry at 2 min.**
  - Operators discovered this 8 min. later
    - ➢ Tags on control room panel inadvertently covered indicator lights
  - **Multiple failures (that are attributable to who or what?)**



Source: http://www.animatedsoftware.com/hotwords/control_room/control_room.htm

TMI Reactor Accident

- Contributing Factors (Cont.)

- Heat-up of system continues
  - Reactor coolant reaches saturation temperature and starts to void within 6 min.
  - Emergency Core Cooling System (ECCS) automatically activates
- Operators shut off ECCS at 4:04:30
  - No level indicator in Pressure Vessel, only in pressurizer
  - Flow in pressurizer caused false "full" reading (operators thought valve shut)
- Pumps began cavitating due to lack of sufficient Net Positive Suction Head (~45 minutes into accident)
  - Operators shut them off to avoid damage
  - Further reduced core cooling

TMI Reactor Accident

- Contributing Factors (Cont.)

- Computer alarm printout prints one line/4 sec.
  - During accident, several alarms/sec. => several minute delay of notification to operators
  - **Undiagnosed Loss-of-Coolant Accident (LOCA) continues**
- Large reactor coolant voiding prevents refill
- Lack of core cooling
- Pilot-operated relief valve (PORV) block valve closed at 139 min.
  - **End of LOCA**

TMI Reactor Accident - Implications

- ***Plant Modifications***
  - Many items for small-break and transient initiated accidents
  - Considerable emphasis on improving operator-machine interface
- ***Operator Training and Licensing***
  - New stringent requirements for operator training, testing and licensing, as well as for shift scheduling and overtime
  - Increased use of reactor simulators (each nuclear power plant is now required to have a plant-specific simulator)
  - Extensive exercises added to qualification exams for Reactor Operators and Senior Reactor Operators
- ***Emergency Response Improvements***
  - Upgraded emergence preparedness and planning
  - Coordinated emergency response teams from industry, NRC, FEMA and local organizations
  - Dedicated emergency response facilities to act as joint information centers

Conclusions

- Proper design is essential
  - Mechanical
  - Human-to-Machine interface
- Proper human actions are essential
  - Ethical behavior
  - Accept responsibilities only if qualified
  - No bending the rules
- TMI-2 type of accident has been designed away

Conclusions (Cont.)

- Multiple failures combined to enable the TMI-2 severe accident sequence
  - No one single cause
- 20% of the core melted and relocated to the Reactor Pressure Vessel lower head
  - The Reactor Pressure Vessel successfully contained the melt
  - Very small releases occurred without risk to the public health

References

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