The Scientific Medical Effects of Ionizing Radiation Course, conducted once a year, focuses on the latest research about the medical effects of ionizing radiation to help clinicians, health physicists, and medical planners preserve troop health in the face of radiological/nuclear terrorism or warfare.

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Radiation Accidents, Medical Highlights
(Selections from the REAC/TS Registry)

AFFRI Scientific MEIR Course
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### Dose Criteria for Designation as a Radiation Accident

<table>
<thead>
<tr>
<th>Condition</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Dose to whole body; active blood-forming organs or gonads</td>
<td>25 (250)</td>
</tr>
<tr>
<td>2. Dose to skin of whole body or extremities</td>
<td>600 (6,000)</td>
</tr>
<tr>
<td>3. Dose to other tissues or organs from external source</td>
<td>75 (750)</td>
</tr>
<tr>
<td>4. Internal Burdens</td>
<td>1/2 NCRP maximum organ burden</td>
</tr>
<tr>
<td>5. Medical Misadministration</td>
<td>All misadministrations, provided they also result in a dose (if a radiation source) or a burden (if a radiopharmaceutical), equal to or greater than the criteria for conditions 1,2,3, or 4 above</td>
</tr>
</tbody>
</table>

Source: ERDA/NRC 1974
What Causes Radiation “Accidents”?  

Usually Human Error

✓ Lost or mishandled sources
✓ Medical misadministration
✓ Bypassing Interlocks
✓ Failure to use criticality control
✓ Calibration/programming errors
✓ Inadequate radiation protection programs, supervision/quality control, and training/written procedures
✓ Human factors
### REALITY: MAJOR RADIATION “ACCIDENTS” WORLDWIDE (1944-DEC 2007):
“CLASSIFICATION BY DEVICE”

<table>
<thead>
<tr>
<th>Radiation Devices</th>
<th>319</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sealed Sources</td>
<td>210</td>
</tr>
<tr>
<td>X-ray Devices</td>
<td>83</td>
</tr>
<tr>
<td>Accelerators</td>
<td>25</td>
</tr>
<tr>
<td>Radar Generators</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radioisotopes</th>
<th>93</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnosis and Therapy</td>
<td>38</td>
</tr>
<tr>
<td>Transuranics</td>
<td>28</td>
</tr>
<tr>
<td>Fission Products</td>
<td>11</td>
</tr>
<tr>
<td>Tritium</td>
<td>2</td>
</tr>
<tr>
<td>Radium Spills</td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Criticalities</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Assemblies</td>
<td>8</td>
</tr>
<tr>
<td>Reactors</td>
<td>6</td>
</tr>
<tr>
<td>Chemical Operations</td>
<td>6</td>
</tr>
</tbody>
</table>

**Total** 432

Source: REAC/TS Registry
Things To Consider

- There Are Different Types and Extents of Radiation Injury, Depending on the Accident Scenario.
  - Whole Body Irradiations (WBI vs TBI)
  - Partial Body Irradiations (PBI)
  - Local Radiation Injury (LRI)
  - Internal Contamination from Radioisotopes

- There May be Acute and Chronic effects.
An Industrial Radiography Example

Location

Yanango, 42 megawatt hydroelectric plant, located 300 km east of Lima, Peru.
Device

\(^{192}\)Ir “gamma camera” with a 1.37 TBq (37 Ci) source
### Dose Rates

For a 30 Ci $^{192}$Ir radiography source

<table>
<thead>
<tr>
<th>Distance [cm]</th>
<th>Dose Rate [rad/min] or [cGy/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>36,000</td>
</tr>
<tr>
<td>1</td>
<td>2,400</td>
</tr>
<tr>
<td>2</td>
<td>600</td>
</tr>
<tr>
<td>3</td>
<td>267</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>96</td>
</tr>
</tbody>
</table>
Medical

- 37 year old male put source in his pocket with ~6 hour exposure.
- Initial symptoms of nausea / vomiting and one episode of diarrhea.
- Erythema on upper posterior thigh
- Admission.
- Tx - IV fluids, 500mg Cipro bid, 8mg dexamethasone tid, Naprosyn-like pain meds
D+2 (Feb 22, 1999)
Blistering, vesicular lesion with inflammatory halo

D+5 (Feb 25, 1999)
Clindamycin 300mg tid started & Cipro ↑ 750mg bid
Absorbed doses in Gy

Normalized to 30 Gy at the rim of the lesion (radius = 5 cm)

Absorbed dose distribution for horizontal cross-section at source level with source-skin distance of 3 mm
D+28 19 March 1999 Ulcerative lesion 2cm deep - continues to expand.
D+39 First febrile episode.
Others Potentially Affected

- Workers at site
- 15 passengers on the mini-bus with the welder as he went home
- Immediate family at the residence
  - wife and 3 children ages 10, 7, and 18 months - no hematological changes observed in wife or children though wife did develop skin lesion
Examples of Accidents Involving Fissile Materials:

- Criticality Accidents
- Nuclear Reactor Accidents
- Nuclear Weapon Accidents
- Nuclear Industry/Lab Accidents
Criticality Comments

- A chain reaction is necessary for a criticality (sustained nuclear fission reaction) to occur.
- Subcritical System $\rightarrow$ Safe Storage
- Critical System $\rightarrow$ Nuclear Reactor
- Supercritical System $\rightarrow$ Nuclear Weapon

Criticality does **NOT** equal Nuclear Detonation.
Radiological Concerns for Criticality Accidents*

- Immediate:
  - prompt neutron & gamma exposure

- Short-term:
  - Release of $^{131}$I

- Long-term:
  - Releases of $^{90}$Sr, $^{137}$Cs, $^{235}$U, $^{239}$Pu

*Critical assembly, operating reactor, weapon detonation
# Notable Criticality Accidents

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1945</td>
<td>Los Alamos</td>
<td>1</td>
</tr>
<tr>
<td>1946</td>
<td>Los Alamos</td>
<td>1</td>
</tr>
<tr>
<td>1958</td>
<td>Oak Ridge</td>
<td>0</td>
</tr>
<tr>
<td>1958</td>
<td>Los Alamos</td>
<td>1</td>
</tr>
<tr>
<td>1961</td>
<td>Idaho Falls</td>
<td>3 (trauma)</td>
</tr>
<tr>
<td>1964</td>
<td>Rhode Island</td>
<td>1</td>
</tr>
<tr>
<td>1979</td>
<td>Three Mile Island</td>
<td>0</td>
</tr>
<tr>
<td>1986</td>
<td>Chernobyl</td>
<td>28 (2 trauma)</td>
</tr>
<tr>
<td>1999</td>
<td>Tokai-Mura</td>
<td>2</td>
</tr>
</tbody>
</table>
Tokaimura, Japan Map
Positions of Workers
Follow-up: Mr. O

- Severe skin damage over more than 50% of body
- Losing 2 L of fluid per day through diarrhea, although not bloody
- One episode of cardiac arrest in early December, but resuscitated
- Died from massive organ failure December 21, 1999, 82 days post-exposure
Follow-up: Mr. S (con’t)

- Antibiotic-resistant pneumonia contracted in March, 2000 (160 d post exposure)
- Pulmonary edema, placed on ventilator
- Intermittent kidney failure in April, 2000, treated by dialysis
- Oral mucositis and tissue shrinkage, could not swallow or open eyes, on parenteral nutrition
- Died of multiple organ failure April 27, 2000, 210 days post exposure
Doses based on symptoms

- Mr. O: marrow ablation, severe gastrointestinal syndrome, survival for 82 days with expert medical care: absorbed dose = 10 (+/- 2) Gy
- Mr. S: recoverable marrow damage, mild gastrointestinal syndrome, pulmonary fibrosis, survived 210 days: absorbed dose = 6 (+/- 1) Gy
- Mr. Y: minor marrow damage absorbed dose = 2 (+/- 0.5) Gy
- Skin doses for Mr. O & S > 20 Gy
Calculated Absorbed Doses

- Absorbed doses were calculated to be:
  - Mr. O: 5.4 neutron + 8.5 gamma = 14 Gy
  - Mr. S: 2.9 neutron + 4.5 gamma = 7.4 Gy
  - Mr. Y: 0.8 neutron + 1.3 gamma = 2.1 Gy

- The total absorbed doses (neutron + gamma) can also be bracketed by the clinical findings
### Initial Dose Estimates, Gy

<table>
<thead>
<tr>
<th>Method</th>
<th>Mr. O</th>
<th>Mr. S</th>
<th>Mr. Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na-24 blood (n only)</td>
<td>9.1</td>
<td>5.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Rings+dicen. (γ equiv.)</td>
<td>21</td>
<td>6.6</td>
<td>2.8</td>
</tr>
<tr>
<td>PCC (γ equiv.)</td>
<td>&gt; 20</td>
<td>7.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Na-24 WBC (n only)</td>
<td></td>
<td></td>
<td>1.6</td>
</tr>
<tr>
<td>Lymphocyte counts (γ eq.)</td>
<td>&gt;10</td>
<td>6-10</td>
<td>1-4.5</td>
</tr>
</tbody>
</table>
ARS: Dose-Mortality Relationship

Figure 1.18  Dose-mortality relationships for irradiation of bone marrow; from NRC, 1975, and from this study.
Reactor Accidents

- Loss of Coolant Accident (LOCA)

- Pipe breaks in the primary loop remove cooling water from the core, leading to an increase in core temperature

- Fuel rods fail, releasing volatile radionuclides (iodine, cesium, etc.)

- Core meltdown—all the way to China?
What Really Happens

- Fuel expands, reducing reaction rate
- Reactor scrams with gravity-induced lowering of control rods
- Emergency core cooling system activates and floods core
- Even if core does melt, containment systems works, as at TMI
Accident response

- Independent of the type of accident:
  - determine and control hazards to responders & victims
  - assess, treat, evacuate victims
  - implement further control procedures
  - assess personnel exposures
  - monitor clean-up
  - verify clean-up effectiveness
Plume Dispersion
**Exposure Pathways**

- External dose from plume overhead (cloud shine) or material on ground (ground shine)

- Internal dose due to inhaling materials directly from plume or from stirred dust

- Ingestion of contaminated materials in the form of food or water
Protective Actions Available to the Public

- Sheltering
- Evacuation
- Stable Iodine Prophylaxis
- Other actions to reduce dose
Guidance for Population Protection: 1st Principle

- Intervention to avoid serious prompt health effects should be carried out as a first priority
  - serious prompt health effects may be expected in susceptible populations at doses > 1 Gy (100 rad), and in all at doses > 2 Gy (200 rad) (whole-body)
  - evacuation is usually the only effective intervention measure in high dose situations
Guidance for Population Protection: 2nd Principle

- Protective actions to avoid delayed health effects should be initiated when they will produce more good than harm in the affected population
  - iodine prophylaxis in case of radioiodine releases
  - sheltering in place, evacuation, or temporary relocation
Guidance for Population Protection: 3rd Principle

- These actions should be introduced and withdrawn at levels that produce a maximum net benefit to the population
  - guidelines available from USEPA, IAEA, and IRPA
  - may well be driven primarily by logistical considerations (e.g., availability of transport, availability of temporary shelters, etc.)
Guidelines for Protective Actions

- Early phase: initiation of release to about 4 days
- Evacuate to avoid TEDE of 1 - 5 rem
- Shelter in place if equal or greater protection afforded by doing so
- Administer KI to prevent thyroid dose of 25 rem
Intermediate Phase PAG’s

- Intermediate phase: source or release is under control, and additional protective actions are being implemented; weeks to months
- Relocate to avoid 2 rem TEDE or 100 rem to skin in first year
- Apply dose reduction techniques (e.g., decontamination, hot spot removal) if less than 2 rem TEDE anticipated in 1st year
Logistical Requirements for Later Protective Actions

- **Temporary relocation:**
  - Transportation
  - Housing & furnishings
  - Security
  - Decontamination equipment & waste disposal

- **Permanent resettlement:**
  - Transportation
  - Housing & furnishings
  - Security
Three Mile Island
Three Mile Island

- Unit 2 feedwater pump tripped at 4:00 a.m. on March 28, 1979
- Reactor scrammed 8 seconds later
- Pressure relief valve stuck open, so ECCS water lost
- Pressurizer (only way of controlling water level and pressure in primary loop) filling up, so high pressure injection pumps shut down
State route 441 closed at 12:45 p.m.

Everything fairly calm the next day

Because of confusion and concern over the “hydrogen bubble”, evacuation advised for pregnant women and preschool children with 5 miles at 12:30 on March 30

Schools closed and further evacuation planned

Supplies of KI shipped in
TMI, con’t

- NRC did not share info that hydrogen bubble was really not a threat
- Many families, including health care providers, left on their own
- Schools reopened April 4
- 5-mile evacuation advisory withdrawn on April 9
- Final clean-up cost was $1E9
Possible Consequences of Reactor Plumes

- **Psychological**
  - Effects on individuals
  - Effects on families/co-workers
  - Effects on the general population
  - Effects on emergency response personnel
  - Effects on health-care personnel

- **Environmental**
  - Contamination of air, water, land
  - Waste management
  - Food chain

- **Economic**
  - Use loss
  - Import/export restrictions
  - Clean-up costs

- **Legal**
  - Impact on regulatory agencies
  - Damages and legal costs
  - Medical/legal uncertainties
Notable Weapons Accidents

- Palomares, Spain - January, 1966
- Thule, Greenland - January, 1968
- Damascus, Arkansas - September, 1980
Am-241 Inhalation, Case Study

- Two workers were transferring $^{241}$Am from a shipping barrel to a disposal container.

- The workers were wearing respiratory protection.

- But, a supervisor was also present, and not wearing respiratory protection.
Am-241 Case Study (continued)

- On exit, all three workers were noted to be contaminated – and room air samples were positive for alpha.

- Lung count bioassay was advised and performed the next day - all 3 patients were positive.

- 24 hr urine and fecal bioassay collections were advised and begun.
Day 1 Bioassay results

- Patient #1 (supervisor, male):
  - Lung content: 400 Bq
  - Urine: 1 Bq per day

- Patient #2 (female):
  - Lung content: 200 Bq
  - Urine: 0.12 Bq per day

- Patient #3 (male):
  - Lung content: 50 Bq
  - Urine: 0.06 Bq per day
Initial Intakes and Effective Dose Estimates

- Patient #1: 1.8 kBq, 210 mSv
- Patient #2: 0.63 kBq, 73 mSv
- Patient #3: 0.15 kBq, 17 mSv (?Stop DTPA?).

- Chelation Rx begun on day 2 with Ca-DTPA for the males and Zn-DTPA for the female, and continued daily with Zn-DTPA for 5-6 days.

- Bioassay measurements /DTPA Rx s/ dose aversion continued.
Case Involving Tritium Exposure (H-3)

- The physician on-call in the Poison Control Center is paged for a call for assistance.
- Six male teens at a university dormitory facility have broken open an exit sign, releasing approximately 10 Ci of tritium to the local environment.
- A radiological survey finds the highest levels of tritium to be on the public telephone (157,000 dpm). Urine samples are taken from all six teens and sent for tritium bioassay.
From liquid scintillation counting at a laboratory, the highest urine value is found to be 6.5 μCi/L in a 17 year-old male.

Using the rule of thumb that 1 μCi/L peak tritium concentration in urine corresponds to an integrated whole-body dose of 10 mrem (NCRP 65), the maximum estimated CEDE dose is approximately 65 mrem (0.65 mSv) whole body.

Prior to receiving the urine bioassay results, all teens were instructed to increase oral hydration to 3-4 l/d for 7 days.
Radiotherapy Accident

HDR source unknowingly broke off inside one of the catheters. Patient was transferred from the cancer treatment center back to the nursing home with the catheters in place. A second HDR treatment was scheduled the following week.
# Patient Absorbed Dose Estimates

For 4.22 Curie Ir-192 Source Over 92.75 Hrs

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Absorbed Dose (Gy)</th>
<th>Absorbed Dose (cGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectum (closest point)</td>
<td>7,770</td>
<td>770,000</td>
</tr>
<tr>
<td>Bladder (closest point)</td>
<td></td>
<td>2,080</td>
</tr>
<tr>
<td>Small bowel (closest point)</td>
<td></td>
<td>330</td>
</tr>
<tr>
<td>Small bowel (median point)</td>
<td></td>
<td>95.8</td>
</tr>
<tr>
<td>Left kidney (median point)</td>
<td></td>
<td>36.7</td>
</tr>
<tr>
<td>Right kidney (median point)</td>
<td></td>
<td>31.2</td>
</tr>
<tr>
<td>Bone Marrow (L1 Vertebral Body)</td>
<td></td>
<td>19.7</td>
</tr>
<tr>
<td>Heart (median point)</td>
<td></td>
<td>9.4</td>
</tr>
<tr>
<td>Lung (median point)</td>
<td></td>
<td>6.1</td>
</tr>
<tr>
<td>Brain (median point)</td>
<td></td>
<td>0.9</td>
</tr>
</tbody>
</table>
CONCLUSIONS

- No acute radiation effects seen in staff, other patients, or visitors
- Cytogenetic studies performed at REAC/TS (ORISE) in Oak Ridge, TN demonstrated that a certain group of staff and patients had a significant number of chromosomal abnormalities in peripheral lymphocytes
- The patient involved in the accident experienced severe acute radiation syndrome and the radiation accident was the cause of death
Goiania, Brazil

$^{137}$Cs Accident September 13, 1987
Cesium-137
Skin lesion initially diagnosed incorrectly
Individual Monitoring

- 112,000 people were screened

- 249 contaminated people:
  - 120 people had their clothes and shoes contaminated;
  - 129 people had external and internal contamination
HOW MUCH INTAKE and WHAT IS THE DOSE (CEDE)?

Step 1) Estimate the Intake Using Intake Retention Fractions.

At 190 days about 18% of Cs-137 Remains in whole body.
Assume Measured 1.48 MBq [40 uCi] of Cs-137 at 190 Days

Intake (Inhalation) = 1.48 MBq/0.18 = 8.2 MBq
[40 uCi/0.18 = 222 uCi ]

Step 2) Compare to Annual Limit on Intake (ALI).

ALI = 7.4 MBq [200 uCi ] for Cs-137
(Gives 0.05 Sv [5 rem ] CEDE)

So individual has 110% of ALI and
Dose of 0.55 Sv [5.5 rem].
# Initial Internal Contamination Measurements

<table>
<thead>
<tr>
<th>Range Bq</th>
<th>Range μCi/mCi</th>
<th>No. of Persons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^4$-$10^5$</td>
<td>0.27 - 2.7 μCi</td>
<td>11</td>
</tr>
<tr>
<td>$10^5$-$10^6$</td>
<td>2.7 – 27 μCi</td>
<td>15</td>
</tr>
<tr>
<td>$10^6$-$10^7$</td>
<td>27 – 270 μCi</td>
<td>23</td>
</tr>
<tr>
<td>$10^7$-$10^8$</td>
<td>270 μCi – 2.7 mCi</td>
<td>20</td>
</tr>
<tr>
<td>$10^8$-$10^9$</td>
<td>2.7 – 27 mCi</td>
<td>7</td>
</tr>
<tr>
<td>$10^{10}$</td>
<td>27 mCi</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>67</strong></td>
</tr>
</tbody>
</table>
### Results of Initial Cytogenetic Dosimetriy

<table>
<thead>
<tr>
<th>Range [Sv]</th>
<th>No. of Persons</th>
<th>Relative Frequency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 0.5</td>
<td>43</td>
<td>61.43</td>
</tr>
<tr>
<td>0.5 – 1.0</td>
<td>8</td>
<td>11.43</td>
</tr>
<tr>
<td>1.0 – 2.0</td>
<td>6</td>
<td>8.57</td>
</tr>
<tr>
<td>2.0 – 3.0</td>
<td>5</td>
<td>7.14</td>
</tr>
<tr>
<td>3.0 – 4.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4.0 – 5.0</td>
<td>3</td>
<td>4.29</td>
</tr>
<tr>
<td>5.0 – 6.0</td>
<td>3</td>
<td>4.29</td>
</tr>
<tr>
<td>6.0 – 7.0</td>
<td>2</td>
<td>2.58</td>
</tr>
<tr>
<td>Total</td>
<td>70</td>
<td>100.00</td>
</tr>
</tbody>
</table>
# Goiania Data

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (Years)</th>
<th>Insoluble Prussian blue dose (grams/day)</th>
<th>No. of Pts.</th>
<th>During Insoluble Prussian blue Treatment - $^{137}$Cs $T_{1/2}$</th>
<th>Off Insoluble Prussian blue Treatment - $^{137}$Cs $T_{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adults</td>
<td>&gt; 18</td>
<td>10</td>
<td>5</td>
<td>26 ± 6 days</td>
<td>80 ± 15 days (all 21 adult patients)</td>
</tr>
<tr>
<td>Adults</td>
<td>&gt; 18</td>
<td>6</td>
<td>10</td>
<td>25 ± 15 days</td>
<td></td>
</tr>
<tr>
<td>Adults</td>
<td>&gt; 18</td>
<td>3</td>
<td>6</td>
<td>25 ± 9 days</td>
<td></td>
</tr>
<tr>
<td>Adolescents</td>
<td>12 - 14</td>
<td>&lt; 10</td>
<td>5</td>
<td>30 ± 12 days</td>
<td>62 ± 14 days</td>
</tr>
<tr>
<td>Children</td>
<td>4 - 9</td>
<td>&lt; 3</td>
<td>7</td>
<td>24 ± 3 days</td>
<td>42 ± 4 days</td>
</tr>
</tbody>
</table>
### Acute Clinical Outcomes

<table>
<thead>
<tr>
<th>Individual</th>
<th>Radiological Information (approximate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF1</td>
<td>5.7 Gy <em>(died)</em></td>
</tr>
<tr>
<td>DF</td>
<td>7 Gy <em>(lived)</em> Possibly spent more time outside (fractionated)</td>
</tr>
<tr>
<td>MA1</td>
<td>10 MBq (270 μCi) intake, 4.3 Gy external (cytogenetics)</td>
</tr>
<tr>
<td>IS</td>
<td>4.5 Gy <em>(died)</em> Probable very acute dose.</td>
</tr>
<tr>
<td>AS</td>
<td>5.3 Gy <em>(died)</em> Probable very acute dose.</td>
</tr>
<tr>
<td>LF2</td>
<td>1 GBq (27 mCi) intake, 6 Gy external <em>(died)</em></td>
</tr>
<tr>
<td>GS</td>
<td>100 MBq (2.7 mCi) intake, 3 Gy, significant burn on shoulder</td>
</tr>
<tr>
<td>Dr. PM</td>
<td>1.3 Gy, negligible intake (left source in bag)</td>
</tr>
</tbody>
</table>
Thank you!

Questions?

albert.wiley@orise.orau.gov