CANDU Safety
#2 - Risk from Nuclear Power Plants

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What is the Public Hazard?

- chemical? Chlorine for water treatment as in fossil plants
- biological? None
- physical? Nuclear explosion impossible
- radiological? Small risk of delayed health effects, very small risk of prompt health effects, even in severe accidents
The Chernobyl Disaster

- More than 12,500 of the 350,000 people who worked on the Chernobyl cleanup have since died.
- For a population of the age and sex distribution of the “liquidators” in 1986, the normal mortality rate was 3 per 1000 per year. Thus the “expected” number of deaths would be:
  \[ 350,000 \text{ people} \times 12 \text{ years} \times \frac{3}{1000} = 12,600 \]
- The number should be larger (by 50%) because the normal rate of 0.3% increases as the group ages.
- Is reporting inadequate? Does monitoring improve the life expectancy of the liquidators?
Effects of Radiation

- prompt health effects (deterministic, non-stochastic)
  - dose of $>1$ Sv: illness
  - dose of $>3$ Sv: increasing risk of death (LD 50 is 3 to 10 Sv)

- delayed health effects (random, stochastic)
  - risk of cancer
    - $0.25$ Sv gives approx. $0.5\%$ increase in individual risk
  - risk of damage to foetus
  - risk of genetic damage
    - not observed in humans
EXAMPLES OF RADIATION DOSE

0.000001  Max. in Canada, banned food
0.000003  Typical from CANDU
0.000083  Maximum, Three Mile Island
0.002     Natural, in Toronto, /yr.
0.005     Accident limit in CANDU (single failure)
0.01      Natural, in Kerala, /yr.
0.25      Severe Accident limit in CANDU (dual failure)
1        Nausea
0.25      Firefighters at Chernobyl

Dose (Sv)
What Is Risk?

Risk = Frequency of an event x consequences of the event

- Examples of risk:
  - annual individual risk of death
  - annual nuclear plant risk of core damage
  - annual nuclear plant risk of a large release of radioactivity
  - risk of psychotic reaction to malaria drug, per dose
### Safest and Most Dangerous Occupations*

<table>
<thead>
<tr>
<th>Occupation</th>
<th>Fatalities / 100,000 / year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Administrative support, clerical</td>
<td>1</td>
</tr>
<tr>
<td>Executive &amp; Managerial</td>
<td>3</td>
</tr>
<tr>
<td>News Vendors</td>
<td>16</td>
</tr>
<tr>
<td>Police</td>
<td>17</td>
</tr>
<tr>
<td>Truck drivers</td>
<td>26</td>
</tr>
<tr>
<td>Farm Workers</td>
<td>30</td>
</tr>
<tr>
<td>Construction labourers</td>
<td>39</td>
</tr>
<tr>
<td>Miners</td>
<td>78</td>
</tr>
<tr>
<td>Pilots &amp; navigators</td>
<td>97</td>
</tr>
<tr>
<td>Lumberjacks</td>
<td>101</td>
</tr>
<tr>
<td>Sailors</td>
<td>115</td>
</tr>
</tbody>
</table>

*US, 1995
“Acceptable” (since accepted) Occupational Risk?

5 per 100,000 per year \( (5 \times 10^{-5} \text{ per year}) \)

to

100 per 100,000 per year \( (1 \times 10^{-3} \text{ per year}) \)
Non-Occupational Accidental Fatalities*

<table>
<thead>
<tr>
<th>Accident</th>
<th>Fatalities / 100,000 / year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightning</td>
<td>0.06</td>
</tr>
<tr>
<td>Poisoning</td>
<td>1.5</td>
</tr>
<tr>
<td>Firearms</td>
<td>1.1</td>
</tr>
<tr>
<td>Drowning</td>
<td>3.6</td>
</tr>
<tr>
<td>Fires</td>
<td>3.6</td>
</tr>
<tr>
<td>Falls</td>
<td>8.6</td>
</tr>
<tr>
<td>Motor vehicle</td>
<td>27</td>
</tr>
</tbody>
</table>

*US, 1970
"Acceptable" (since accepted) Public Risk?

4 per 100,000 per year \( (4 \times 10^{-5} \text{ per year}) \)
to

27 per 100,000 per year \( (3 \times 10^{-4} \text{ per year}) \)

Total risk of accidental death = \( 4 \times 10^{-4} \text{ per year} \)

Note that these are population-average risks
Some groups will be considerably more (or less) at risk than others.
Many Factors Determine “Acceptability”

- occupational risk vs. public risk
- presence of offsetting benefit
- voluntary vs. involuntary risk
  - can one really eliminate risk from motor vehicles by not driving??
- “dread” factor (cancer vs. automobile accident)
- perceived ability to control risk
- knowledge and familiarity (coal mining vs. operating nuclear plant)
Safety Goals for Nuclear Power Plants

- Safety goal - an acceptable value of risk
  - risk from NPPs chosen to be very small in comparison to comparable activities
- Risk of prompt fatality from NPP should be << risk of prompt fatality from all other causes
- Risk of fatal cancer from NPP should be << risk of cancer from all other causes

Risk of fatal cancer just from “natural” radiation in Canada =

\[0.002 \text{Sv/year} \times 0.02 \text{ cancers/Sv} = 4 \times 10^{-5} \text{ per year}\]

(according to linear dose-effect hypothesis)
**Risk Goals**

The only significant health effects from a nuclear power plant are from a large release.

A large release can only occur if:
1) There is severe core damage, *and*
2) The containment does not work or is damaged.

Nuclear safety goals therefore focus on:
1) Preventing a large release
2) Preventing severe core damage.
Example #1

- Three Mile Island
  - severe core damage (~20 tons of molten fuel)
  - the pressure vessel was thinned but did not fail
  - the containment was not damaged but some liquids and gases escaped through lines which bypassed the containment
  - public health effects were minor: ~1 additional (statistical) cancer case in the surrounding population
Example #2

- Chernobyl
  - the core was severely damaged due to a reactivity increase which was made worse by the shutdown systems
  - the containment was ineffective as the steam explosion blew off the top cover of the reactor & exposed the core
  - about 32 prompt fatalities among station staff
  - most volatile fission products were released to atmosphere
  - public health effects: predict several thousand (additional) cancer cases in the surrounding area
  - an increase in thyroid cancers in children has been observed (mostly curable)
Numerical Safety Goals for Nuclear Power Plants

- For existing nuclear power plants:
  - risk of a severe core damage accident must be $< 10^{-4}$ per plant per year
  - risk of a large release must be $< 10^{-5}$ per plant per year

- For new nuclear power plants:
  - factor of 10 lower on both counts
  - the factor of 10 must therefore come from:
    - severe accident management & mitigation procedures
    - residual containment effectiveness
How is Risk Calculated?

λ For frequent events - easy - just collect the observed statistics
λ For rare events - build up from combinations of more frequent components
λ e.g., risk / year of plane crash on Shanghai University =
  risk of a plane crash per kilometer of steady flight
  x number of flights / year landing or taking off from Shanghai airport
  x fraction of flights which fly over the University
  x diameter of University in km.
  – does not account for evasive action, skyjacking
Fault trees and Event trees

- to determine the risk from rare events:
  - calculate frequency or probability of a system failure (fault tree)
  - calculate consequences of the system failure (event tree)
  - in the event tree, assume each mitigating system either works or fails; if it fails, account for the probability of failure
- end result is the frequency or probability and consequences of a family of events
Douglas Point

- an early risk assessment in Canada in the 1960s for the first prototype CANDU
- goal: risk from nuclear power plant must be 5× less than coal
- only prompt effects well known then, so compared prompt fatalities from mining and nuclear power
- e.g., large release frequency = initiating event frequency × unavailability of shutdown × unavailability of containment
- must set targets for & measure:
  - frequency of initiating events (process system failures)
  - unavailability of each safety system
Frequency and Reliability Targets

λ process system failures:
  – must be less than 0.3 events / year
  – deliberately chosen high so it could be confirmed

λ safety system unavailability:
  – each must be less than $10^{-3}$ years / year (8 hours / year or 1 failure in 1000 tries)

λ can one multiply the numbers?
  – e.g., small LOCA + LOECC + containment failure to isolate
    $= 10^{-2} / \text{year} \times 10^{-3} \text{years/year} \times 10^{-3} \text{years / year}$
    $= 10^{-8} / \text{year} ???$

λ only if there are no cross-links