Fukushima Daiichi Accident: Overview & Impact

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*with materials from Alexander Brandl and Jessica Gillis*
Items and Discussions

• A Natural Disaster and Its Consequences
• Events at the Fukushima Nuclear Power Plant
  • “Nuclear Meltdown”
  • Hydrogen explosions
• Dose, Dose Rate, Contamination and Other “Technical Terms”
• Biological Effects of Ionizing Radiation
• Consequences Due to the Fukushima Accident
Japan, 11mar2011

- Earthquake
  - followed by tsunami
- epicenter Pacific, off Japanese coast
Earthquake

• 14:45 local time (05:45 UTC, 22:45 MST)
  • earthquake of magnitude 9.0
    • significant damage to local infrastructure
  • some damage to nuclear power plants in the region
    • safety systems cause proper emergency shutdown
      • automatic shutdown in four power stations
  • fire at Onagawa plant rapidly extinguished
  • “heightened alert” at Fukushima Daiichi
    • designed for 8.2 magnitude
  • No serious damage to reactors
  • tsunami warning for 50 countries in the Pacific
    • as far as Central America
• Approximately 1 h after earthquake (3:42 pm)
  • 15 meters high!
    • Second wave 8 minutes later
• destroys remaining infrastructure and kills 3 workers at plant Daiichi and Daiini
• complete power outage
• disruption of water supply
• ~ 15,000 dead, 8,000 missing
• Turbine floor of Daiichi was under 5 m of water
Natural Disaster

- Tsunami hits Fukushima Daiichi
  - webcam
Natural Disaster (II)

- Tsunami
- landfall
Natural Disaster (II)

• After the tsunami
• Fukushima Daiichi in the background
Event sequence following earthquake (timing from: 14:46, 11 March)

<table>
<thead>
<tr>
<th>Event</th>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Unit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of AC power</td>
<td>+ 51 min</td>
<td>+ 54 min</td>
<td>+ 52 min</td>
</tr>
<tr>
<td>Loss of cooling</td>
<td>+ 1 hour</td>
<td>+ 70 hours</td>
<td>+ 36 hours</td>
</tr>
<tr>
<td>Water level down to top of fuel*</td>
<td>+ 3 hours</td>
<td>+ 74 hours</td>
<td>+ 42 hours</td>
</tr>
<tr>
<td>Core damage starts*</td>
<td>+ 4 hours</td>
<td>+ 77 hours</td>
<td>+ 44 hours</td>
</tr>
<tr>
<td>Reactor pressure vessel damage*</td>
<td>+11 hours</td>
<td>uncertain</td>
<td>uncertain</td>
</tr>
<tr>
<td>Fire pumps with fresh water</td>
<td>+ 15 hours</td>
<td></td>
<td>+ 43 hours</td>
</tr>
<tr>
<td>Hydrogen explosion (not confirmed for unit 2)</td>
<td>+ 25 hours service floor</td>
<td>+ 87 hours suppression chamber</td>
<td>+ 68 hours service floor</td>
</tr>
<tr>
<td>Fire pumps with seawater</td>
<td>+ 28 hours</td>
<td>+ 77 hours</td>
<td>+ 46 hours</td>
</tr>
<tr>
<td>Off-site electrical supply</td>
<td></td>
<td>+ 11-15 days</td>
<td></td>
</tr>
<tr>
<td>Fresh water cooling</td>
<td></td>
<td>+ 14-15 days</td>
<td></td>
</tr>
</tbody>
</table>

Note that unit 4 was in refueling shutdown, and explosion was due to cross linked venting system with unit 3. Spent fuel cooling was a problem in unit 4.
Nuclear Power Plant

- Nuclear power plant
  - schematic Boiling Water Reactor (BWR)
Fukushima Events

- Fukushima
  - status prior to earthquake

- Reactors 1, 2, and 3 operating
- Reactors 4, 5, and 6 shutdown for maintenance, inspection, refueling
Fukushima Events (II)

• Earthquake
  • control rods inserted automatically
  • chain reaction in reactor core stopped
• Earthquake disrupts off-site power supply
  • primary power supply for plant
    • safety functions
      • cooling
      • ventilation
    • lights, computers, controls (other than emergency)
• Primary backup: emergency diesel generators
  • start up as designed
  • provide core cooling (~ few % operational power)
Tsunami
  - larger than plant design basis of 10 m
  - takes out all multiple sets of backup diesel generators except one at unit 5 & 6
Secondary emergency backup: batteries (unit 3 & 4, destroyed in units 1 & 2)
  - systems start up as designed
  - can only maintain minimal emergency power
  - limited battery life (design: ~ 8 h)
Offsite power could not be restored in time
  - complete plant blackout
Fukushima Events (IV)

- Defense-in-Depth
- ceramic pellets
- cladding
- pressure vessel
- drywell
- wetwell
- reactor building
Fukushima Events (V)

- Plant design
- Regular operation
Fukushima Events (VI)

- Plant design
- Emergency (battery) operation
Fukushima Events (VII)

- Complete station blackout
- Steam generation in pressure vessel
- Fuel rods uncovered
Fukushima Events (VIII)

- Complete station blackout
- Pressure buildup
- Radionuclide load in drywell
Fukushima Events (IX)

- Complete station blackout
- Emergency pressure release
- Hydrogen buildup
Hydrogen Explosion

- Reaction of hydrogen and oxygen
  - Hydrogen generated as high temperature reaction with zircalloy cladding
    - Zr + 2 H₂O → ZrO₂ + 2 H₂
  - Exothermic reaction
  - Rapid combustion with oxygen (explosion)
    - "Chemical" explosion
    - Not nuclear explosion
      - I.e., nuclear weapon
      - No nuclear chain reaction
  - Design feature
    - Blowout panels
    - Designed to leave main safety systems intact
  - Release of radioactive material in reactor atmosphere
    - Noble gases
    - Volatile radionuclides (iodine, cesium, etc.)
Hydrogen Explosion (II)

- Large scale damage to buildings
- "visible" / newsworthy disaster indicators
• Activity [Becquerel or Curie]
  • number of nuclear disintegrations per second
  • property of the radioactive material
    • material containing atomic nuclei that disintegrate / decay spontaneously
  • no direct relation to “dose”
    • type of radiation (alpha, beta, gamma, etc.)
    • energy of the emitted radiation

• Contamination
  • unsealed radioactive material in the environment
    • dispersion in air, deposition on a surface, in water or food
  • no direct relation to “dose”
Does radiation make you radioactive?
- in most cases: no, but ...
  - radioactive material
    - can contaminate the body externally
      - removal by “decontamination” (i.e., personal hygiene)
    - can enter the body
      - inhalation of contaminated air
      - through food water
    - can remain in the body for a long time
      - depends on type of material
  - prevention or limitation of intake
• Stochastic effects
  • late effects: cancer, cataract, birth defects
  • no direct causal relationship
  • probability to incur detriment increases with dose
    • severity independent of dose
  • extrapolation of data to “zero dose”
    • data based on high exposures
    • mathematical model for exposures at low dose
      • current model reflects current knowledge
      • appears reasonable for occupational exposure
      • NOT applicable for very low doses to large number of exposed persons in general public
• Data
  • atomic bomb survivors
  • animal studies
  • use of ionizing radiation early in the 20th century
  • occupational and public exposure data
  • Chernobyl liquidators
  • radio-biology studies
• International effort
  • UNSCEAR, IAEA
  • ICRP
  • BEIR, NCRP
**Biological Effects (III)**

- BEIR VII (National Academy of Sciences, Biological Effects of Ionizing Radiation)
- cancer risk estimates

<table>
<thead>
<tr>
<th>Table ES-1</th>
<th>The Committee’s Preferred Estimates of the Lifetime Attributable Risk of Incidence and Mortality for All Solid Cancers and for Leukemia</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All Solid Cancers</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Males</td>
</tr>
<tr>
<td>Excess cases (including nonfatal cases) from exposure to 0.1 Gy</td>
<td>800 (400, 1600)</td>
</tr>
<tr>
<td>Number of cases in the absence of exposure</td>
<td>45,500</td>
</tr>
<tr>
<td>Excess deaths from exposure to 0.1 Gy</td>
<td>410 (200, 830)</td>
</tr>
<tr>
<td>Number of deaths in the absence of exposure</td>
<td>22,100</td>
</tr>
</tbody>
</table>

**NOTE:** Number of cases or deaths per 100,000 exposed persons.

*95% subjective confidence intervals.*
Biological Effects (IV)

• Chernobyl Forum (IAEA, WHO, UNSCEAR, FAO, UN-OCHA, etc.)
  • ARS
    • diagnosed in 134 emergency workers
    • 28 died within 1 year + 2 due to conventional injuries + 1 due to coronary thrombosis
  • main health impact
    • increased childhood thyroid cancer
      • more than 4000 diagnosed
      • treatable
    • no clear increase in solid cancer or leukemia
      • projected: up to few thousand in ~ 100,000
  • clear increase in psychological problems
    • stress and anxiety
Contribution of Various Sources to Average Annual Dose

- Terrestrial (background) 3%
- Internal (background) 5%
- Conventional radiography & fluoroscopy 5%
- Interventional Fluoroscopy 7%
- Nuclear Medicine 12%
- Radon and Thoron 37%
- Consumer goods 2%
- Industrial <0.1%
- Occupational <0.1%
- Computed Tomography 24%
- Terrestrial (background) 3%
- Internal (background) 5%
- Space 5%

6.2 mSv per year total

Fukushima Contamination:
- Exclusion zone > 50 mSv/y
- Limited access 20-50 mSv/y
- Allow @ < 20 mSv/y (2.3 µSv/h)
Terrestrial Biota – Population effects at > 100 μGy/h (extended period) (approximately 100 μSv/h)

(UNSCEAR, 2013)
Ambassador Program Locations

Fukushima City
Koriyama
Soma
Minami Soma
Namie
Aizu Wakamatsu
Kitakata
Kawauchi
Tomioka
Iwaki
Fukushima Ambassador Program Dosimetry Results, 2014

Fukushima Contamination:
Exclusion zone > 50 mSv/y
Limited access 20-50 mSv/y

Allow @ < 20 mSv/y (2.3 µSv/h, 55.2 µSv/d)
CSU ~4 µSv/d
~12 µSv during each flight

Possibly around a nuclear medicine patient or other similar inadvertent exposure

Suspect dosimeter stopped working correctly

Colorado Control

Flight from Narita to LAX
IAEA Expert Mission, conclusions
- given the extreme circumstances
  - local emergency management best possible
- insufficient defense-in-depth provisions for tsunami hazards
- larger impact prevented by dedicated and devoted officials and workers
- suitable follow-up program for health monitoring recommended
- control of radiation exposures appears effective
WHO / FAO

- other countries affected?
  - NO indication
  - radioactive material released to environment
  - radiation levels in other countries far below “background levels”
  - do not present health or transportation hazards
    - as early as 08apr2011
    - further radioactive decay since
  - minute amounts of radioactivity could be detected by very sensitive detection methods
    - well below acceptable levels
    - would not pose a health concern
Effects

- Physical devastation, > 20,000 deaths from earthquake and tsunami, loss of property and relocation to temporary housing
- Primarily psychological devastation from the nuclear accident
  - Exposures
    - Zero acute fatalities
    - 146 workers and 21 contractors received doses > 100 mSv (US annual limit for radiation workers is 50 mSv for no observable increase in cancer risk above background)
    - Almost 100,000 evacuated
      - Estimate >1000 deaths due to evacuation (World Nuclear Associate OCT15)
    - Most doses < 10 mSv, a few 10-50 mSv
  - Zero deterministic (acute) radiation effects expected
  - Contamination concerns, lack of public education on radiation and radiation protection
  - Fear, distrust, and displacement are major hurdles to recovery
Radiological Health Effects to Region

– Zero acute fatalities, zero deterministic (acute) radiation effects, zero teratogenic effects
– Exposures to workers
  • 99.3% of workers received doses < 100 mSv (10 rem)
  • Risk for some cancers/some age groups might be elevated
    – 13 emergency workers with thyroid doses from 2-12 Gy
    – 173 individuals above this averaged 140 mSv (14 rem)
      » Expect small increased risk of cancer (2 or 3 additional cases beyond 70 case baseline)

– Biota doses would not affect populations
– Contamination concerns
Radiological Health Effects to the Region

- Zero acute fatalities, zero deterministic (acute) radiation effects, zero teratogenic effects

- Exposures to workers
  - Risk for some cancers/some age groups might be elevated
    - 99.3% of workers received doses < 100 mSv (10 rem)
    - 173 individuals above 100 mSv averaged 140 mSv (14 rem)
      » Expect small increased risk of cancer with effects statistically indistinguishable from natural cancer rate
    - 12 emergency workers with thyroid doses from 2-12 Gy (200-1200 rad)

- Biota doses would not affect populations
  - < 0.1 mGy/h (10 mrem/h) terrestrial (some elevated for short term)
  - < 0.4 mGy/h (40 mrem/h) aquatic (marine effects confined to immediate area)

- Contamination concerns limit return to some areas

(WHO, 2013) (UNSCEAR, 2013)
Today’s challenges

- Tsunami
- Earthquake
- Nuclear Accident
- Negative Preconceptions
“FUKUSHIMA”

- prefecture
- city
- university
- last name
- two nuclear power stations
Technological disasters, on the whole, cause more health problems than natural disasters of the same magnitude.

- Technology has changed the way we view disaster.

- Feeling that disasters could have been prevented increases their psychiatric morbidity.
RADIOACTIVE CONTAMINATION AS SEEN BY:

- People in Tohoku
- People in Kanto
- People in Hokkaido
- TEPCO
- People in Kansai
- People in Okinawa
- People around the world
- Japanese Politicians
National Oceanic & Atmospheric Administration

Tsunami wave heights [cm]
FUKUSHIMA

NUCLEAR

USHIMA
So what are the dominant health effects from nuclear disasters?

- Official records exclude residents who committed suicide owing to fears and other indirect causes of death
- “1,656 people have died in the prefecture from stress and other illnesses related to the nuclear crisis”

(APF-JIJI, 2014)
Psychological Effects

• UNSCEAR Report
  – **Mental health problems** and **impaired social well-being** were the major impacts observed
  – Initial observations identified **severe psychological effects** among the emergency workers:
    • distress/anxiety, harsh working conditions, loss of family members, separation from family, difficult conditions, worries, and stigma associated with being a rad worker

• WHO Health Risk Assessment
  – Does not quantitatively assess social/psychosocial hazards (suggests a Health Impact Assessment)

• IAEA Chernobyl Forum
  – Direction of current efforts should be changed to focus on:
    • Social and economic restoration
    • Elimination of the psychological burden on the general public and emergency workers
Nuclear Disaster Effects

- Mental health problems and impaired social well-being were the major impacts observed.
- Initial observations identified severe psychological effects among the emergency workers:
  - distress/anxiety, harsh working conditions, loss of family members, separation from family, difficult conditions, worries, and stigma associated with being a rad worker.
- No quantitative assessment of social/psychosocial hazards.
- Recommend a focus on:
  - Social and economic restoration
  - Elimination of the psychological burden on the general public and emergency workers.

Lessons Learned from TMI & Chernobyl

• Emotional consequences were independent of actual doses received
• Perceived risk affected self-rated health and mental health
• Poor mental health is associated with physical health conditions, early mortality, disability, and overuse of medical services.
• Mothers of young children and cleanup workers were the highest risk groups

*Those who believed their health was affected had significantly higher manifestation of symptoms.*

(Bromet, 2013)
Lessons Learned from TMI & Chernobyl

- Mental Health Consequences
  - Poor subjective health evaluation
  - Depression
  - Anxiety
  - Post-traumatic stress disorder
  - Somatic symptoms
  - Suicide ideation
  - Suicide
  - Severe headaches
  - Job tension
  - Anger

- Results in Common
  - Emotional consequences independent of actual doses received
  - Mothers of young children and cleanup workers were the highest risk groups
  - Perceived risk affected self-rated health and mental health

*Those who believed their health was affected had significantly higher manifestation of symptoms.*

Poor mental health is associated with physical health conditions, early mortality, disability, and overuse of medical services.
Social consequences

- At the end of 2013, more than 100,000 were still displaced.
- Refugees live in temporary housing designed for 2 year occupancy.
The Story of Kawauchi Village

- Moving back home can be difficult when there isn’t even a grocery store in town
• Indoor playgrounds provide a way to return to normalcy
Good science & community efforts
Cleaning & decontaminating
Collaborative Work with Fukushima University

• First jointly appointed faculty in Japan
  – Dr Thomas Hinton
• One student currently working on wild boar model
• One student finishing on fate of Cs-134, 137 and Sr-90 in soils
• Fukushima Ambassador Program (11 students so far in 2014, 2015)
• Five students have already started the process for doing research at Fukushima University this summer
Proposed Projects

• Measurement of doses to wild boar and monkeys in the exclusion zone (already ongoing)
  – Blood, ESR and collars
• Predication of doses from using irrigation ponds
• Partitioning of plutonium and cesium in wild boar and monkeys
In Summary

- Effects of a nuclear disaster are not bounded by the actual doses received
  - Mental/social detriment are extended health effects
  - Radiation units and risks are very poorly understood
- Spread good information to build credibility
  - As always: communicate better, be more transparent, and increase education
- Some recovery efforts are more effective than others
- People will recover

Stories from more than just me: Google “Today at CSU Fukushima”
References