The Criticality Accident at Tokaimura: What We Know

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Big Ideas

- Go to school on everyone else's mistakes.
- Criticality is a sneaky, dangerous thing that should be treated with the utmost respect and control.
- Dosimetry of accidents is uncertain.
- Take everything you hear from the media with a grain of salt.

What happened?

- ABC News

  T O K Y O, Sept. 30 - As a uranium processing plant burned out of control in Japan, officials today told more than 300,000 people to stay indoors, closed nearby schools and told farmers to stop harvesting.

- NOT!

The plant...

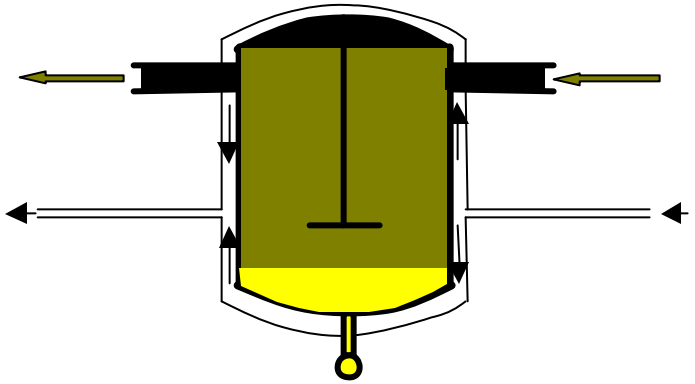
- Fuel fabrication plant
  - Converts UF6 gas to UO2 powder
  - Primarily LEU (<5% enriched) fuel for PWRs
- 140 km NE of Tokyo
- Close to public areas
- No shielding required - product is unirradiated
- Separate reprocessing plant also in Tokaimura
- No criticality accident response - not a credible scenario

The situation...

- **Process change** - 18.8% IEU for JOYU fast-breeder reactor
  - Not a new procedure, but hadn't been done in three years
- Three **inexperienced operators**
  - Two were either new or new to IEU campaign
  - One had a few months of experience
- Operational limits are either based on highest enrichment allowed, or are changed when the process changes

The operation...

- Precipitation process involving uranium dioxide and uranyl nitrate
- Uranyl nitrate added in batches to a sedimentation tank
  - Vertical cylinder
  - 50 cm diameter, dished bottom, 3 mm stainless steel walls
  - 2.5 cm thick water cooling jacket around sides and bottom



- A regulator-approved manual governs operations...
  - Material must first be weighed and added to **separate, small dissolution tank**
  - Resultant solution transferred to sedimentation tank via piping
  - Batch size: **operationally limited** to 2.4 kg U

The operation...

- Corporate officials approved a manual change 2-5 years ago without regulator concurrence or notification
  - Process is significantly accelerated (30 minutes with stirrer vs. 3 hours without)
  - Operators can use steel buckets and funnels to **bypass the dissolution tank**
  - Reports indicate 5L mop buckets were being used.
  - Officials would not have approved this change as UO2, nitric acid and steel can react to form toxic gases

The accident...

- Wednesday, 9/29 operators poured 9.2 kg of uranium from four buckets into the sedimentation tank.
- Thursday, 9/30 operators added 6.9 kg from three more buckets.
- Highly concentrated uranyl nitrate solution went critical
  - Blue flash
  - Operators immediately began feeling sick
  - No report of radiation alarms sounding or even being installed in the area
  - Everyone left the room quickly
- Would expect oscillation between super- and sub-criticality or quick shutdown (do to loss of moderator or disassembly)
- Reaction settled into a steady state for about 20 hours.

The accident...

- Tokyo Electric Power Company rushed 880 lbs of borated material to the plant.
- They couldn't use it because they had no way to remotely add it to the tank.
- The cooling water jacket (neutron reflector) was drained between 2 am and 6 am on 10/1.
- No mechanical damage to the building, but filters did not trap the fission products -- out the stack!
- Three operators took very large doses
- 37 or 38 other people received non-trivial doses

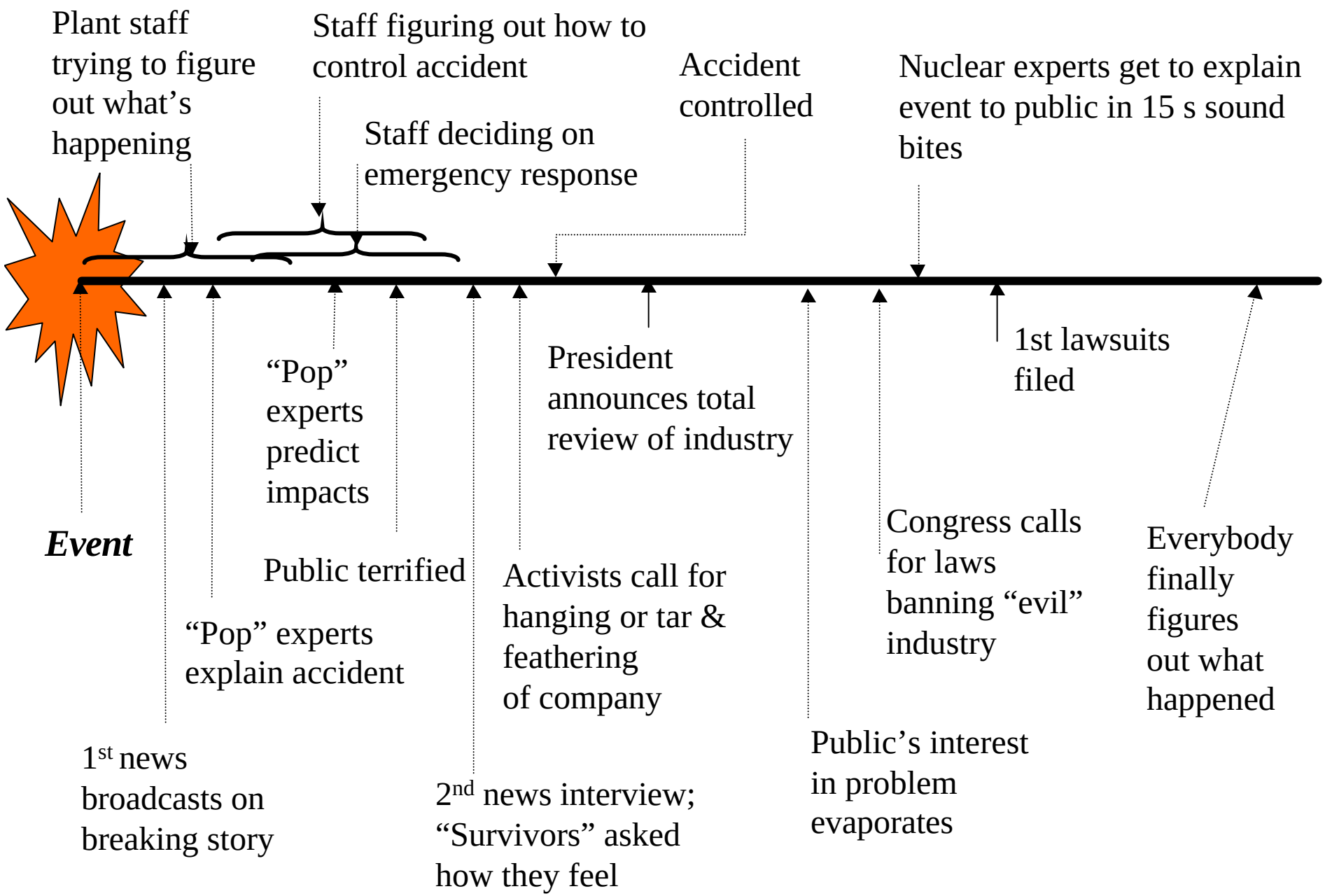
Features similar to previous accidents

- Operators did not follow procedures.
- The plant relied heavily on administrative controls.
- Non-favorable geometries were in use.
- Plant was in off-normal condition after process change.
- Evidence of production schedule overriding safety.
- No remote operation (hand pouring)
- Poor safety culture
  - No emergency response plan
  - Criticality accident not considered credible
  - No radiation alarms(?)
  - Operation not in compliance with regulatory agency

Lessons learned

- Use passively safe systems
  - Favorable geometries
- Become part of existing safety culture
  - ANS Criticality Safety Division
  - DOE
  - NRC
- Double contingencies
- Solutions are notoriously difficult to deal with
- Plan for the impossible
- Never underestimate the greed of corporations and ingenuity (stupidity) of humans

A General Time-Line for a Nuclear Accident



Data Sources

- Animal experiments (most of data)
- Human data
  - radiation therapy studies
  - Japanese survivors of Hiroshima & Nagasaki
  - Marshallese exposed to fallout
  - victims of accidents at nuclear installations:
    - Chernobyl
    - Oak Ridge
    - elsewhere

Early Lethal Effects

- Death occurs in few weeks
- Attributed to specific high-intensity exposure
- Early symptoms occur soon after exposure
  - ***prodromal radiation syndrome***
- Eventual survival time/mode of death
  - function of dose
  - not clearly defined

Syndromes

- ***Cerebrovasuclar Syndrome***
  - a.k.a., CNS
  - >10,000 rads
  - death occurs 24 - 48 hours
  - from neurologic and cardiovascular breakdown
- ***Gastrointestinal Syndrome***
  - 500 - 1200 rads
  - death occurs in days
  - from destruction of gastrointestinal mucosa

Syndromes, cont'd

- ***Hematopoietic syndrome***
  - a.k.a., bone marrow death
  - 250 to 500 rads
  - death of blood forming organs

Causes of Death

- ***Cerebrovascular***
  - unclear
- ***Gastrointestinal & Hematopoietic***
  - death is due to depletion of stem cells
    - epithelium of the gut or
    - circulating blood cells
  - time of death
    - population kinetics of different cell-renewal systems
    - radiation tolerance of two systems

Prodromal Syndrome

- Collection of symptoms
- Vary
  - time of onset
  - severity
  - duration

Prodromal, cont'd

- Dependent on dose
- 10's of Gy (1000's of rads) -
  - onset in 5 to 15 min
  - maximum reaction in 30 minutes
  - persist for few days
  - diminish in intensity
  - Symptoms ultimately merge with fatal CNS or GI syndrome
- Severe prodromal suggests poor clinical prognosis

Prodromal Syndrome

- Two main groups
  - Gastrointestinal
    - anorexia, nausea, vomiting, diarrhea, intestinal cramps, salivation, fluid loss, dehydration, weight loss
  - Neuromuscular
    - easy fatigability, apathy, listlessness, sweating, fever, headache, hypotension
- Presence of all symptoms indicate ***supralethal*** dose

Symptoms of Prodromal

NEUROMUSCULAR	GASTROINTESTINAL
Signs & Symptoms Expected at LD_{50}	
Easy fatigability	Anorexia Vomiting
Additional Signs After Supralethal Doses	
Fever Hypotension	Immediate diarrhea

Treatment of Radiation Accident Victims Close to the $LD_{50/60}$

- < 4- 5 Gy (400 -500 rads)
  - watch patients
  - treat in response to specific symptoms (antibiotics, fresh platelets)
  - Blood transfusions should not be given “prophylatically because it would delay the regeneration of blood-forming organs”

Treatment of Radiation Accident Victims Close to the $LD_{50/60}$

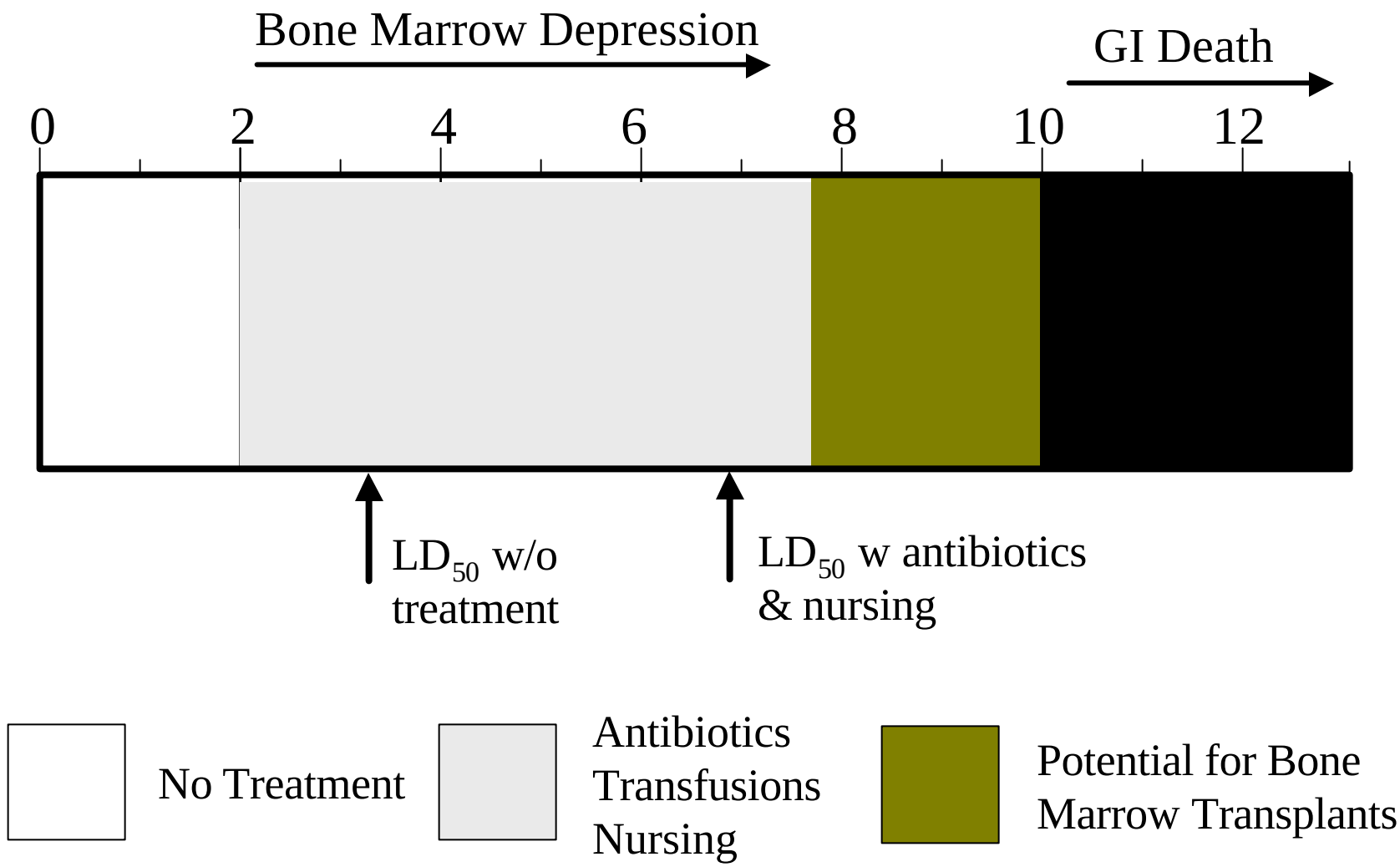
- > 5 Gy (500 rads)
  - death from hematopoietic syndrome is possible
  - isolation and barrier nursing can be attempted
    - sterilize victim (antiseptic solutions)
    - treat with large doses of antibiotics
    - isolate and fed sterilized foods
    - avoid infection/bleeding/physical trauma - allow bone marrow to regenerate
  - studies with animals have shown LD_{50} can be raised by factor of 2

Treatment of Radiation Accident Victims Close to the $LD_{50/60}$

- What about bone marrow transplantation?
  - Limited data set
    - 4 Yugoslav scientists got ~7 Gy
      - all grafts rejected
      - all survived anyway (in spite of transplants)
    - Chernobyl accident victims
      - 13 received bone marrow transplants
      - 2 survived
        - 1 exhibited autologous bone marrow repopulation
      - therefore, 1 successful transplant

Bone Marrow Transplantation

- Key - know the dose
- Narrow window of opportunity
- < 800 rad (8 Gy) careful nursing should suffice
- > 1000 rad (10 Gy) death from GI is inevitable, so bone marrow transplant won't work


Bone Marrow Depression
GI Death
0
2
4
6
8
10
12
LD50 w/o treatment
LD50 w antibiotics & nursing
No Treatment
Antibiotics
Transfusions
Nursing
Potential for Bone Marrow Transplants

U.S. Survivors of Radiation Accidents

- Last 50 y of nuclear “program”
- 70 workers in 13 separate accidents
  - medical history of survivors mirrors aging population
  - No ***high*** incidence of
    - shortened lifespan
    - early malignancies
    - rapidly progressing lenticular opacities
  - Probably due to small number of exposed individuals
    - e.g., 3 Gy acute dose doubles spontaneous cancer incidence
    - difficult to detect in small group of people

Implications for Japanese Incident

- Dosimetry of exposed patients unclear
- Prodromal response suggests doses in supralethal range
- Apparent “recovery” may simply be latency period before onset of more severe symptoms

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