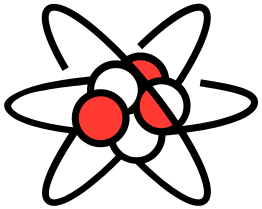
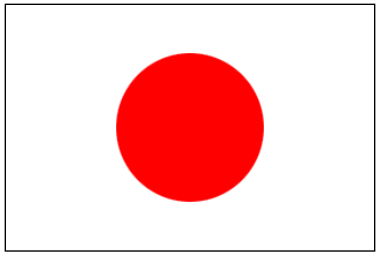


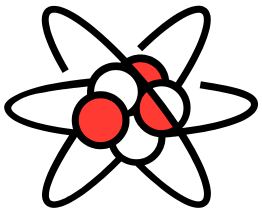


Fukushima Nuclear Power Plant #1 (Dai-ichi)

Reactor and Site Status as of May 2016

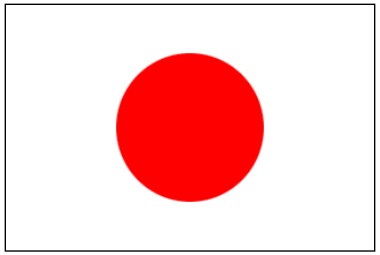
Compiled from many sources[1]

Gary L. Hoe, PE

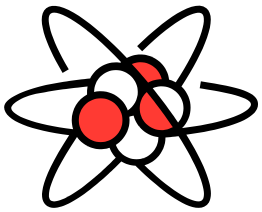


Reactor Theory

Part 1

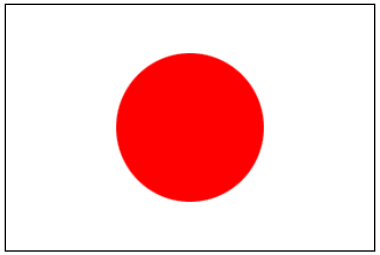


- Uranium metal is only 0.7% $^{92}U_{235}$
  - The rest is “depleted” $^{92}U_{238}$
  - Must enrichen to 3%-7% for a reactor
  - Must enrichen to 96%+ for weapons-grade
  - Critical mass at normal density is 51.9kg
- Energy produced in Electron Volts
  - One ev = only 1.602×10^{-19} joules, *but*
  - Room air raised to 1ev = 11,600ºK
  - *<u>One</u>* fissioning $^{92}U_{235}$ atom releases ~2×10^{8} ev
    - 10^{19} fissions/second ≅ 300 MW



Reactor Theory

Part 2

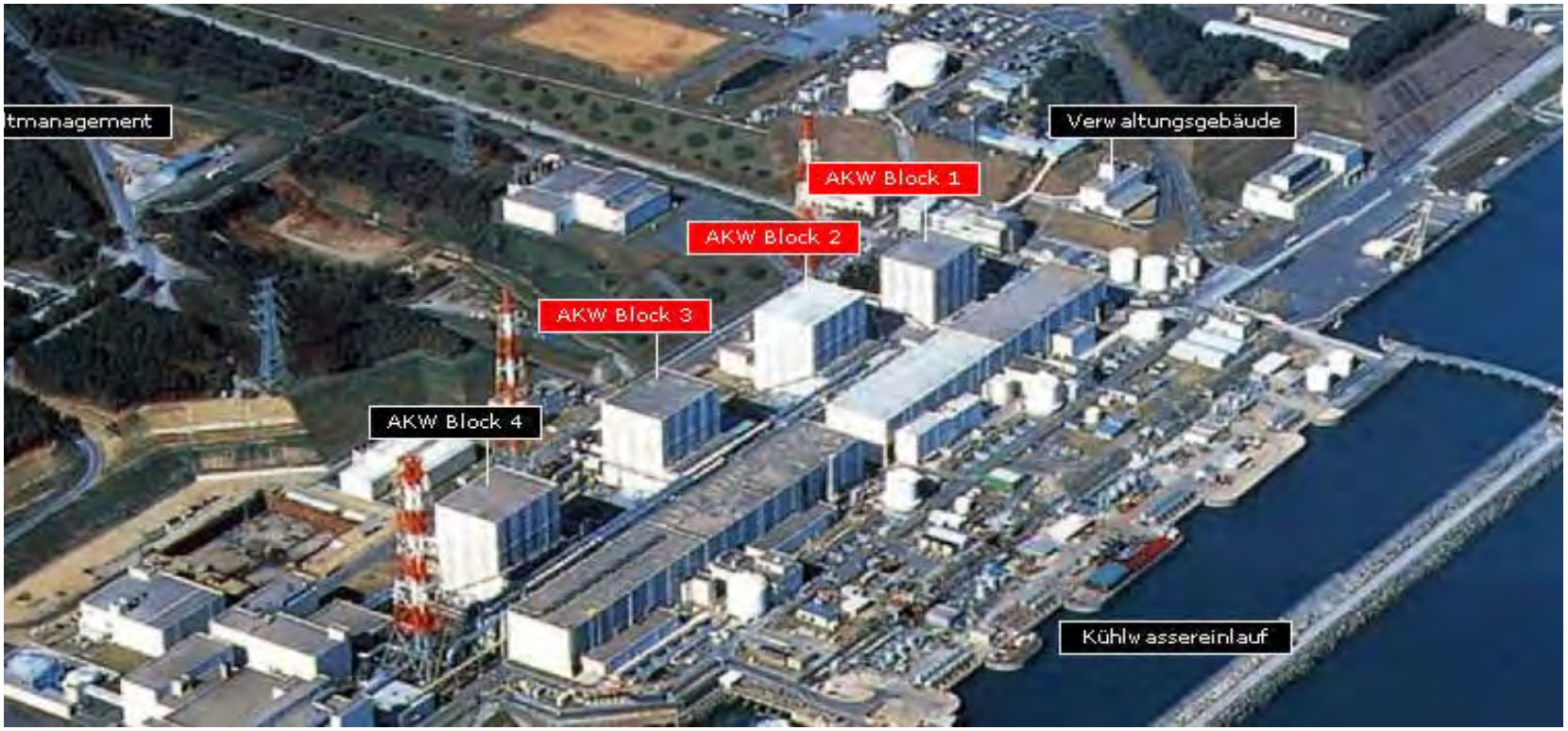


- $^{92}U_{235}$ fission produces heat and radiation
  - Radiation absorbed as heat in shielding
    - 9m water, 3.5m concrete, 1m iron, 30cm lead stops all of it
      - But they heat up from the absorbed energy
  - Fission fragments fly apart in fuel elements
    - Creates stress-heat in metallic lattice of the fuel
    - Eventually weakens fuel structural integrity
      - So fuel pellets are compressed UOx powder, not pure metal
- Heat removed by coolant to do work
  - Boiling-Water, Pressurized-Water, Gas, Liquid Metal
- Reaction controlled by borated rods
  - Reactor scram inserts all rods at once
    - Fission fragments still produce ~7% heat = Lots of MW !!

Fukushima Reactors

Fukushima Dai-ichi (Plant #I, 4696MW)

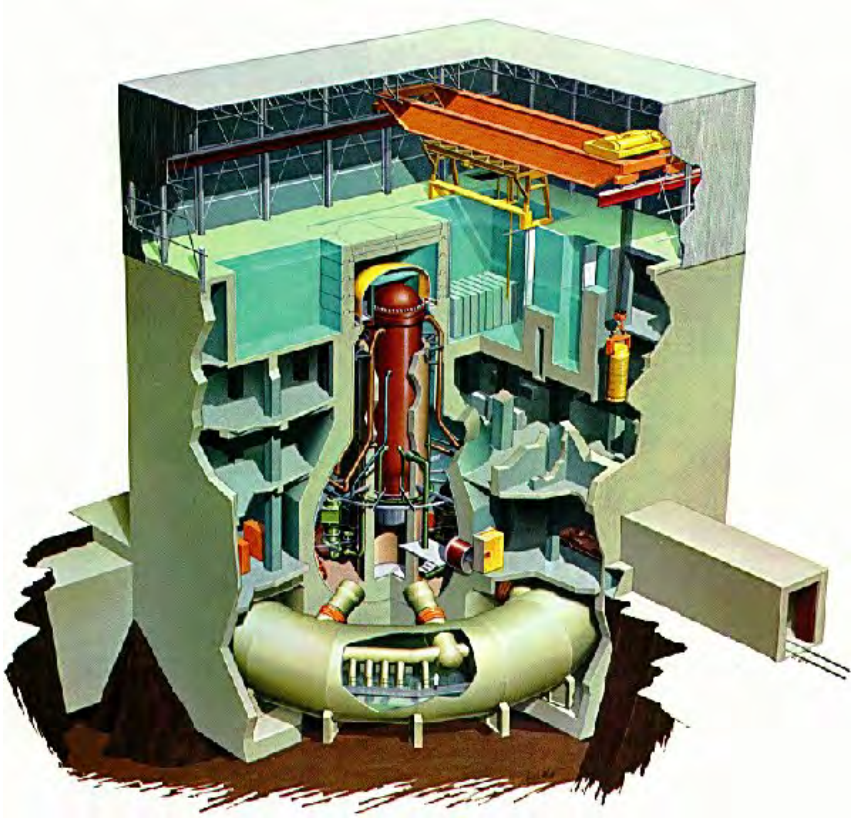
- **Unit I - GE Mark I BWR (460 MW), operating since 1971 (40 years)**
- **Units 2-5 - GE Mark I BWR (784 MW each), operating since 1974**
- **Unit 6 - GE Mark II BWR (1100 MW), operating since 1979**

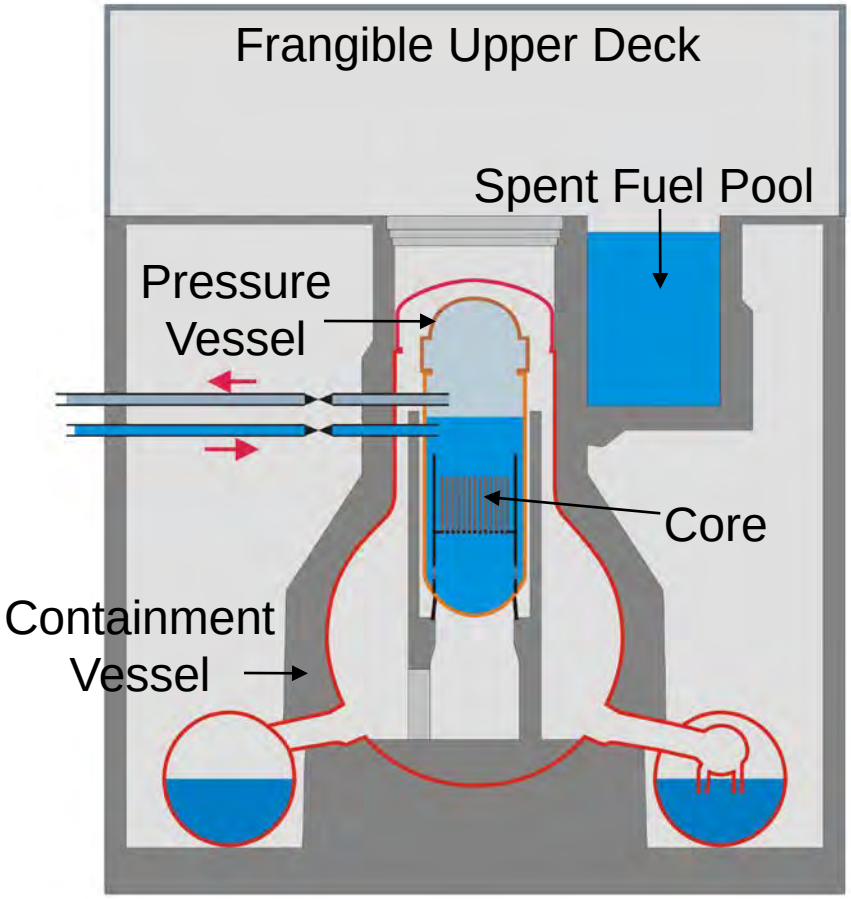


By comparison: PNM's San Juan station is 1848MW and burns 8,200,000 tons of coal per year

Fukushima Reactors

Boiling-Water, Generation 2





2:46pm, March 11, 2011:
Earthquake!

- Magnitude 9.0+ on Richter Scale
- 4th Largest Recorded Earthquake
- Energy release: 9.32 gigatons TNT

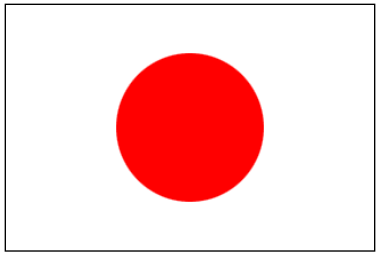
- Moved Japan 2.4m
- Shifted the Earth 10cm on its axis
- Shortened the day by 1.8μs

3:32pm, March 11, 2011:
Tsunami!

Inundated **675km** of Japan's east coast
Observed heights: **3-7+ meters**
8,805 Dead; 2,628 Injured; 12,664+ Missing (Apr '11)
4.4 Million Powerless; 1.5 Million Waterless

Sequence of Events

Part 1



- Earthquake hits; reactors auto-scram; plant goes off-line
  - Diesels start as designed; all systems powered up
  - Plant operators begin system checks prior to restart
- Tsunami hits; switchyard and Diesel tanks destroyed
  - Switchyard destruction disconnects plant from the grid
  - All Diesels stop within a few hours, except one unit
    - But it's connected to Units 5 and 6, which are defueled anyway
  - Only UPS batteries are left
- UPS batteries die after about 8-9 hours
  - Plant experiences its first-ever complete system blackout
    - And now – it's midnight
  - Valves close and pumps stop; emergency core cooling fails
  - Water levels in reactors drop as residual heat boil it away

Effects at Plant #1

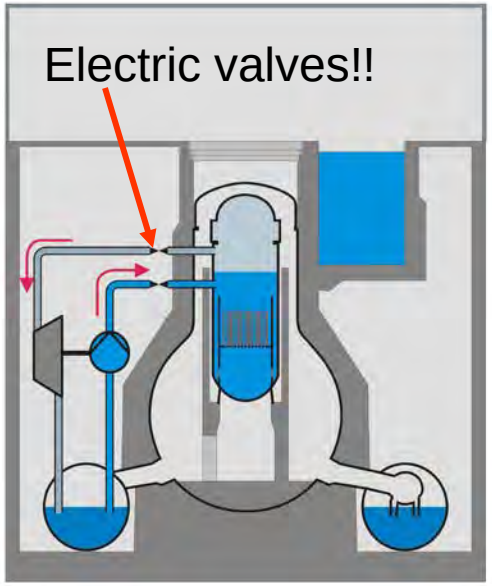
Cooling water outfall

Frangible Roof blown off

Switchyard destroyed

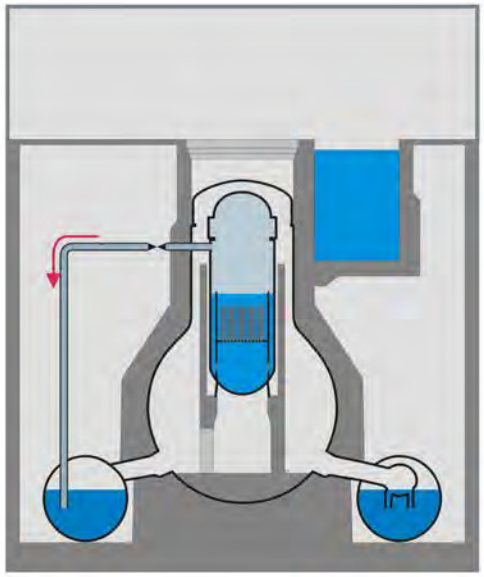
Diesel tanks destroyed; debris everywhere

Core Damage



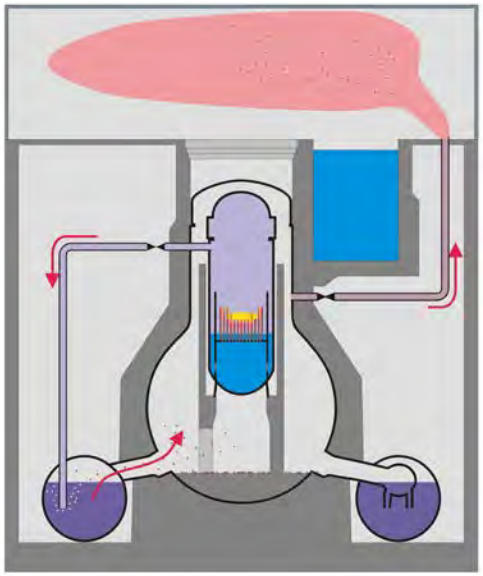
- Steam-driven core isolation pump starts
- But valves fail closed at 9+ hours when battery power is lost

Steam pump quits, relief valve dumps steam to wet well



Water level falls

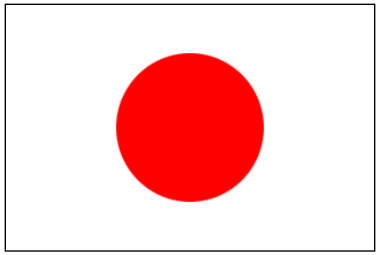
Without heat removal, wet well boils and relief valve vents gases to the building



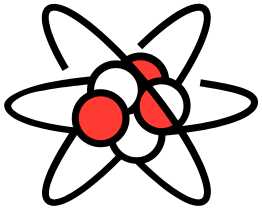
Core uncovered; melts

Sequence of Events

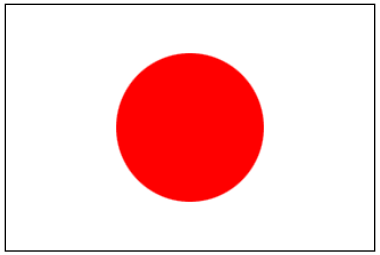
Part 2



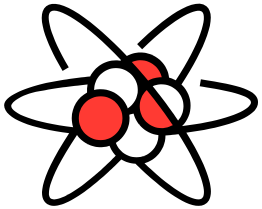
- Falling water levels uncover cores 1, 2, and 3
  - Cores mostly uncovered for 8 to 20 hours
  - Fuel temperature rises to 1200^{o}C and as much as 2500^{o}C
  - Zirconium cladding burns: **$Zr + 2H_20 = ZrO_2 + 2H_2$**
  - Hydrogen and fission gases vented as vessel pressure rises
    - But the vent's exhaust is <u>inside</u> the building's service level
  - Random spark ignites the hydrogen; blows off frangible panels
    - Looks much worse than it really is, structurally
- Spent fuel cooling pools also begin to dry up
  - Spent fuel still warm and hastens water's evaporation
  - Goes unnoticed because monitors are dead and no one up there
  - Unit 4's pool cracked, dries out; some particulates emitted
- Fire truck hoses replenishes all units with sea water
  - Further damage averted, but impure water adds to contamination



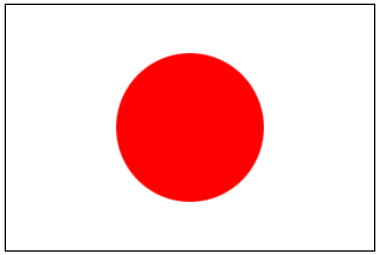
Site Contamination



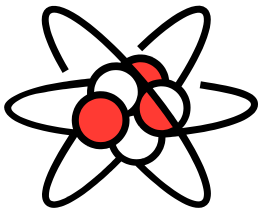
- Contamination is Particulates, Liquids, Gases
  - Nearly all particulates are in the water sumps
    - Most of that is inside the containment vessel, as designed
      - This is *not* another Chernobyl
    - Made up of crumbled fuel rod dust; solidified melts; and larger fission daughters.
      - $^{55}Cs_{137}$ has 30-year half-life; $^{38}Sr_{90}$ has 29-year half-life
  - Liquids also in the water, or vented with steam
    - Primary contaminant is a fission daughter, $^{53}I_{131}$
      - About 4.6 million Curies were emitted
      - But its half-life is only 8 days; it's all gone
  - Gases are all noble; vented and disbursed by wind
    - No lasting effect as fallout; most half-lives 2 to 5 days



Site Radiation

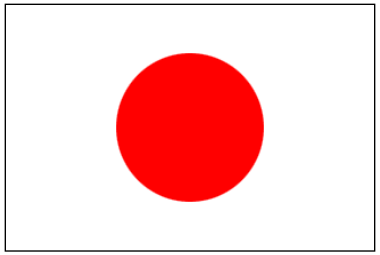


- Radiation is alpha, beta, x-ray, and gamma
  - Alpha and beta are particles; stopped easily
  - X-rays and Gammas are line-of-sight only
    - Reactor does not “spew” radiation into the air
    - Containment vessel walls block all of it except what is in the water wells and piping – and those can be shielded
    - Will be a concern mostly during clean-up
  - As of 23 May 2011 (two months later):
    - 7,800 plant workers had an average of only 0.77 REM
    - 30 of these had an exposure up to 10 REM, *maybe*
      - Radiological worker permitted dose is 5 REM annually
      - Takes 100 REM to sicken; 1000 REM to guarantee death
      - Cancer treatment routinely hits tumor with up to 5000 REM

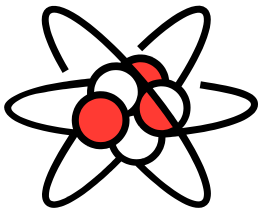


Where are we now?

Part 1

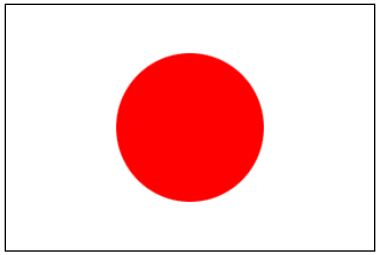


- Plant remains off-line from infrastructure damage
- All reactors and fuel assemblies are cooled
- No further contamination being released
- Some areas within Units 1, 2, and 3 are “hot” due to radioactive materials inside unshielded piping
  - Unit 4’s spent fuel pool is patched and refilled, but contaminated
- Farms within 20km had some of 2011’s harvest confiscated, but no long-term pollution found
- No one died or got sick from radiation poisoning
  - 1660 died from the tsunami-ravaged evacuation accidents
- Units 5 and 6 completely undamaged; Unit 4 reactor undamaged but spent fuel pool is a mess
  - Units 5 and 6 could restart whenever the switchyard is rebuilt
    - Except for the politics



Where are we now?

Part 2



- TEPCo inviting others to watch and help
- Desalinating cooling water to reduce corrosion
- Decontaminating the spent fuel pools
- Reactor temperatures a few degrees above ambient
- Spent fuel pool temperatures down to ambient
- Wide-area samples are below free-release limits
- Probably will entomb Units 1, 2, and 3 with salvage
- Possible to clean up Unit 4 and restart, but it’s aged
- Could restart units 5 and 6 with more safety features
- TEPCo has entered the four units with robots to map radiation and contamination to prepare for clean-up

Robots

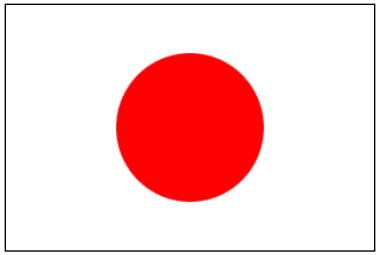
Mitsubishi's MEISTeR

Sandia's GEMINI

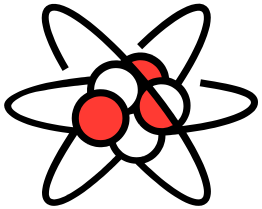
Fuji's IMVAC Drone

Where are we now?

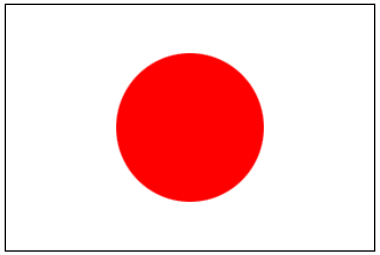
Part 3



- Kajima Co. & Kanazawa U. are studying ammonium and CO_2 ice compounds for decontamination
  - Refrigerated ice dam around plant blocks ground water seepage
  - Pumped-out water stored on site, but is almost drinkable
- Japan has set aside $62.5 billion for cleanup costs
- About 40 years to fully decommission Dai-ichi's reactors
- Undamaged Japanese reactors are restarting, slowly
  - Each one is being upgraded with lessons-learned features
  - Restarting half of them will save $20+ billion in fossil fuels
- All nuclear-power countries reviewing safety designs
- Zero radiation injuries around the plant
- Hurricane Sandy did not damage NE nuclear plants



Lessons Learned



- Worst possible scenario can get worse
- Do not depend on plant integrity alone
- Do not depend on one failure at a time
- Increase use of hardened cameras and sensors
- Add emergency hose taps to piping
  - Fire hose taps were cut into pipes and welded by hand
- Consider increasing redundancies
- Consider sharing protective technologies
- Consider moving inland and piping the ocean's cooling water to the plant
- You <u>can</u> recover – remember Hiroshima
  - But it will be economically and politically costly
  - Post-Fukushima fixes cost about $40 million per reactor site!

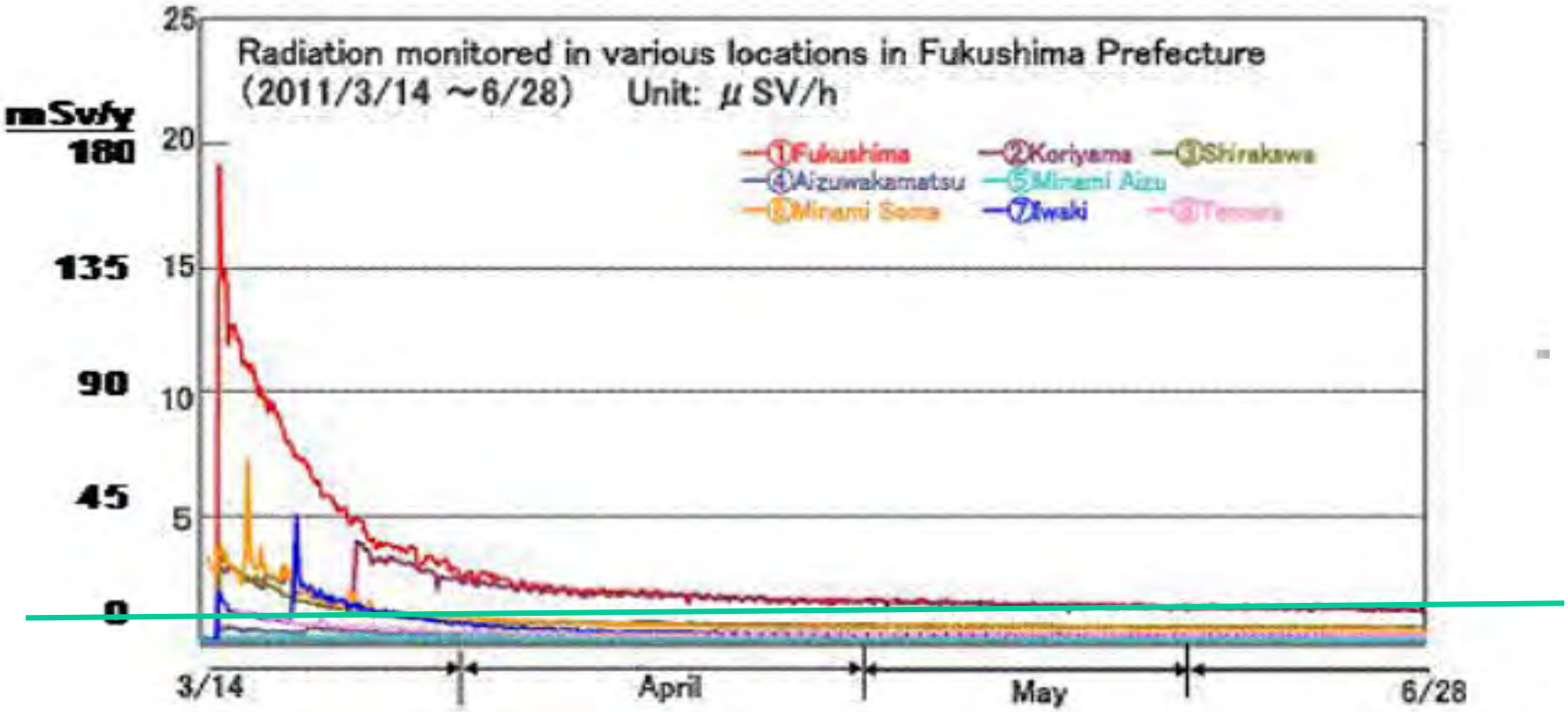
Hiroshima

1945: A nuclear device detonated with absolutely zero containment

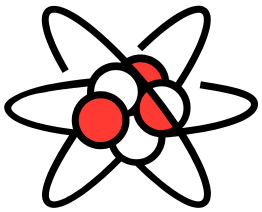
Less than 60 years later:

A modern city of 2.5 million and zero residual radiation

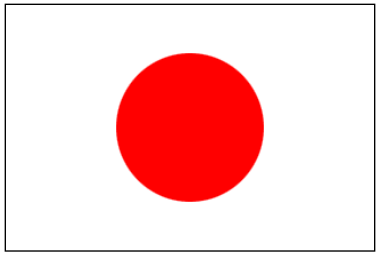
Radiation Levels at Fukushima



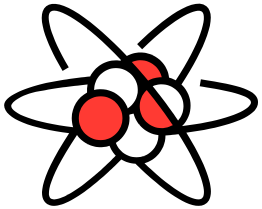
Green Line = Annual ABQ Background Dose of 0.3mSv



Nuclear Accidents to Date

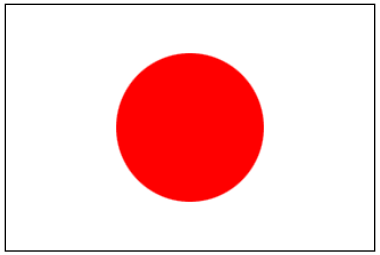


- Weapons
  - US has had 32 “Broken Arrows” involving only 47 weapons out of 69,000 weapons manufactured
    - No nuclear yield at all, contamination has been removed
  - Two sunken submarines with nuclear reactors
  - One radiological death during Manhattan Project
  - No deaths from atmospheric testing through 1962
- Reactors
  - Three Mile Island, 28 March 1979
    - No deaths, no contamination, no releases off site
  - Chernobyl, 26 April 1986
    - 47 site workers and 9 civilians died; flora and fauna rampant
  - Fukushima, 11 March 2011
    - No deaths, all releases off site were airborne and short-lived



Reactor Evolution

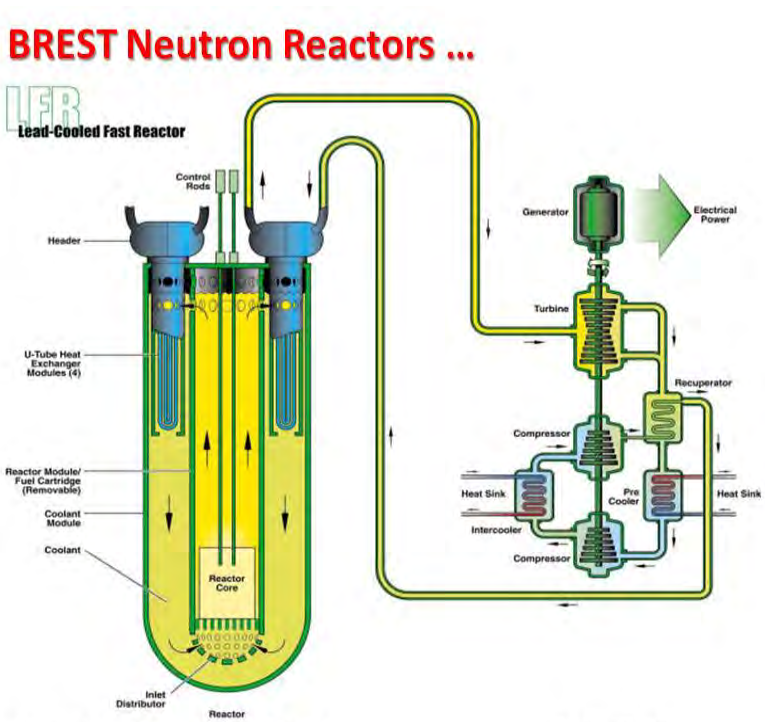
Part 1



- Generation I
  - Totally manually controlled and monitored, no safety features
  - All are Manhattan Project-era units; all are dismantled now
- Generation II and II+ (Fukushima 1-5)
  - 1960 to 1990 time frame, 100 are still in use in the USA
  - Remote monitoring; manually-initiated automatic controls
  - Emergency features self-initiate, but need power to work
- Generation III (Fukushima 6) and III+
  - 1985 and later; many passive safety features, reduced chance of core melt, more efficient “burn” with less waste, very long periods between refuelings, squib valves, 72-hour cooling “grace period”
  - Convection cooling with gravity-powered water replenishment
- Generation IV
  - Pebble-bed and liquid fuels; intrinsically-safe, modular, smaller
  - Very little waste, some use Thorium, refuel while operating

Reactor Evolution

Part 2



Source: reachingcriticalwill.org

Figure: 7-10

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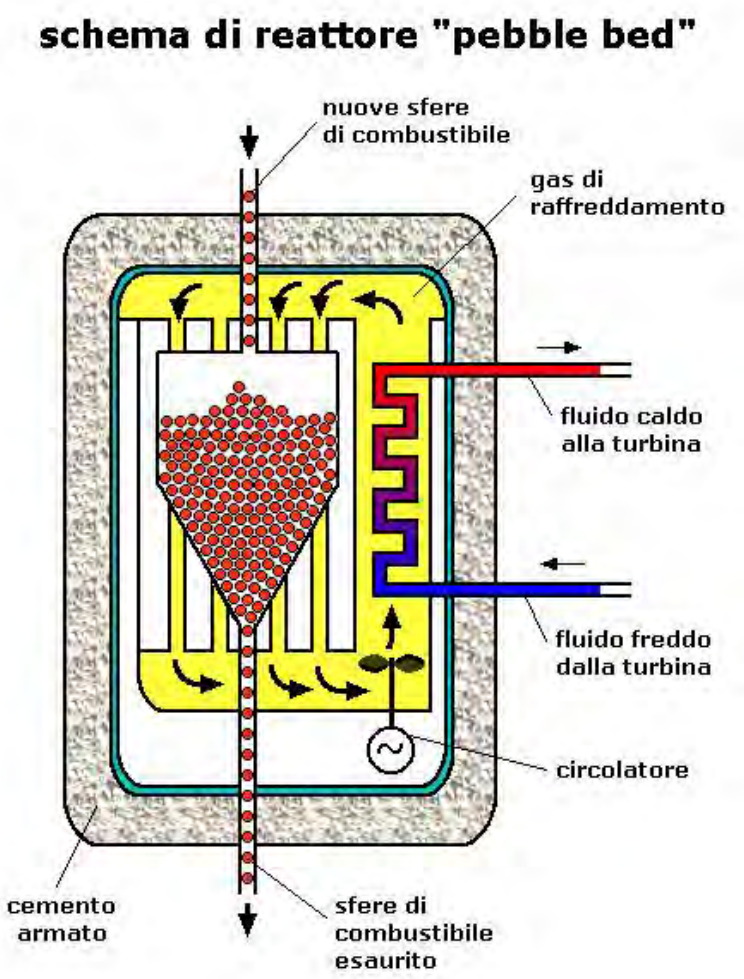
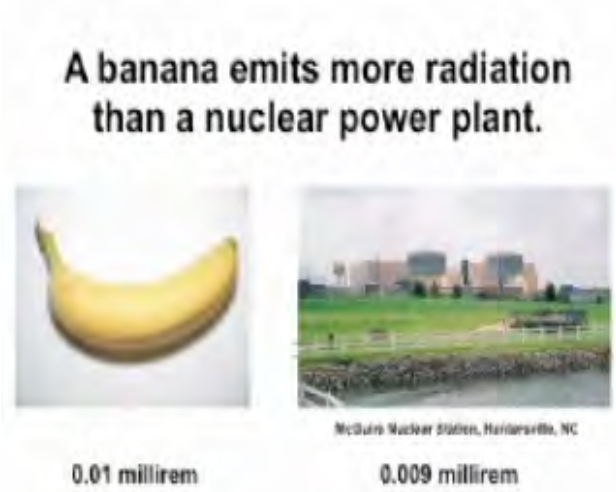
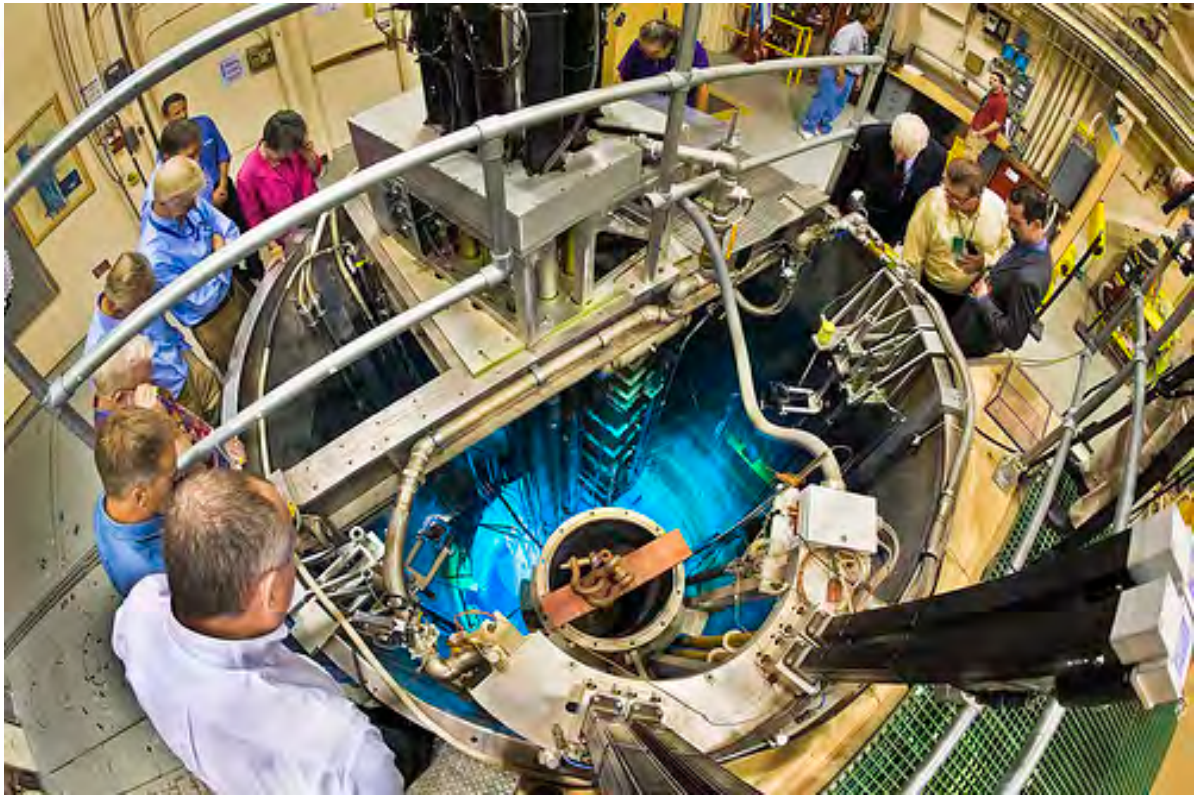


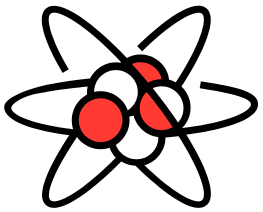
Relative Radiation Around You



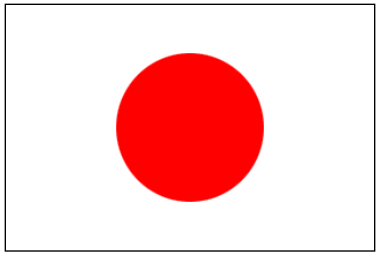
Also Radioactive:
Smoke Detectors
Kitty Litter
Sandia Peak
You

Sandia's ACRR
Pulses at 35GW





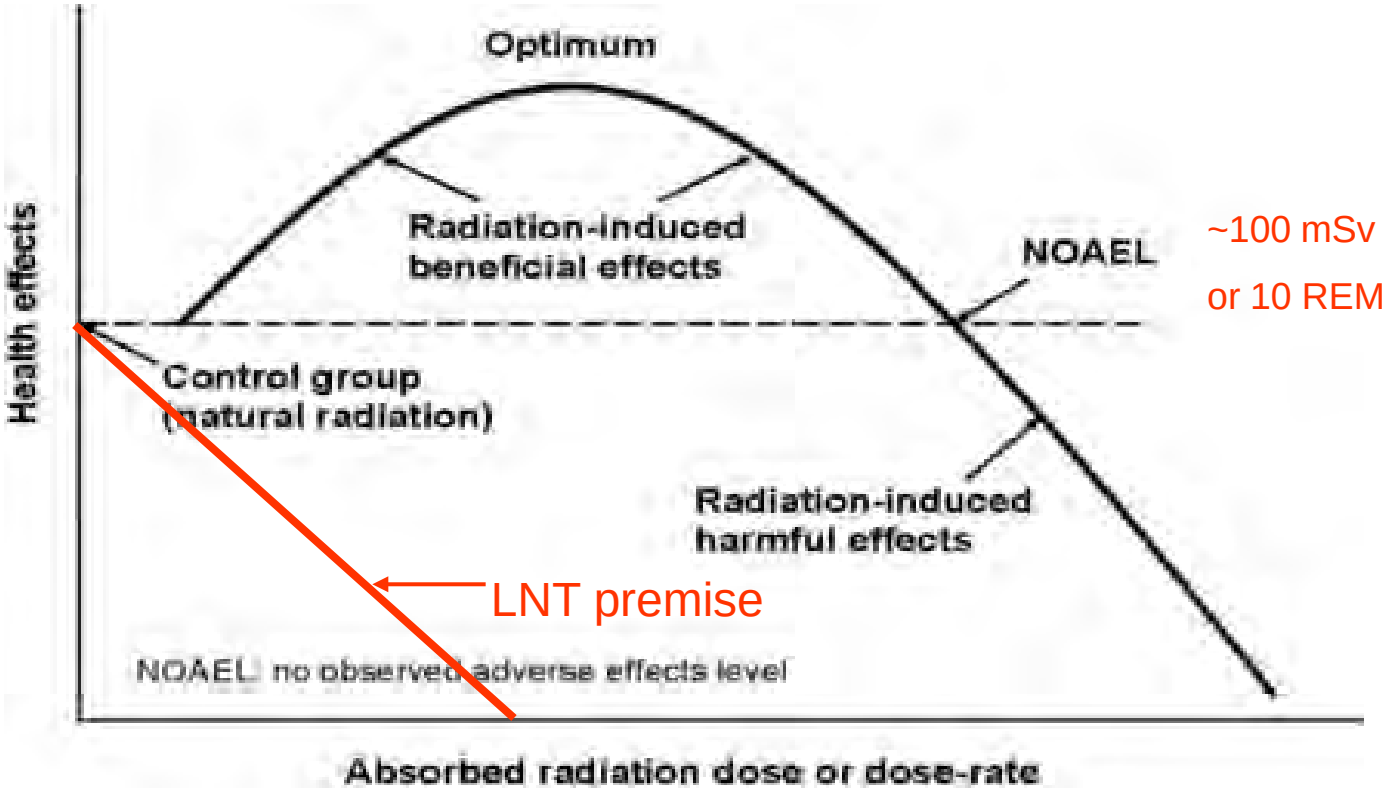
Radiation Equivalents



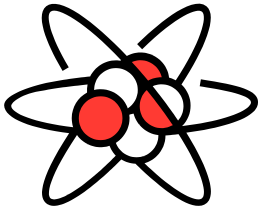
	Radioactivity	Absorbed Dose	Dose Equivalent	Exposure
Common Units	Curie (Ci)	Rad	Rem	Roentgen (R)
SI Units	Becquerel (Bq)	Gray (Gy)	Sievert (Sv)	Coulomb/kilogram (C/kg)

1 curie = 3.7 x 10^{10} disintegrations per second		1 becquerel = 1 disintegration per second
1 millicurie (mCi)	=	37 megabecquerels (MBq)
1 rad	=	0.01 gray (Gy)
1 rem	=	0.01 sievert (Sv)
1 roentgen (R)	=	0.000258 coulomb/kilogram (C/kg)
1 megabecquerel (MBq)	=	0.027 millicuries (mCi)
1 gray (Gy)	=	100 rads
1 sievert (Sv)	=	100 rems
1 coulomb/kilogram (C/kg)	=	3,880 roentgens

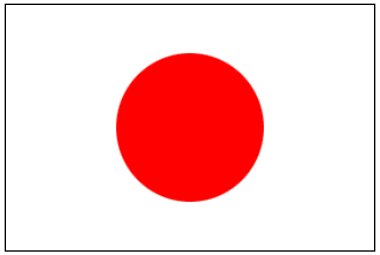
Linear No-Threshold Problem



LNT = Linear No Threshold model;
(there is no safe dose level)
NOAEL – No Observed Adverse Effects Limit



Linear No-Threshold Problem



"Erring on the side of caution is their justification and rationalization for what they have done. Our response has to be that they have erred on the side of endangerment - through mass forced evacuations, radiophobia that misleads patients and doctors into refusing or avoiding needed CT scans, prevention of funding for low-dose research, creating psychological obstacles to clean sustainable nuclear energy, and so on."

-- Dr. Mark Miller

"Zero dose does not exist. We are always soaked in natural radiation, cosmic rays and otherwise. We are radioactive, made up of carbon and potassium, among other things."

-- Dr. Chary Rangacharyulu

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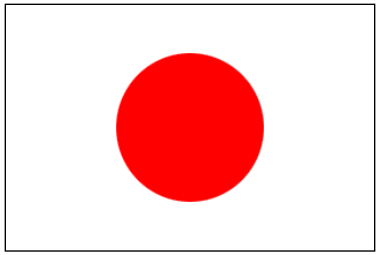

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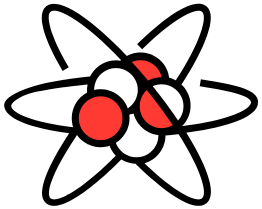

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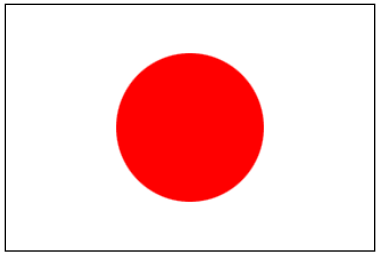


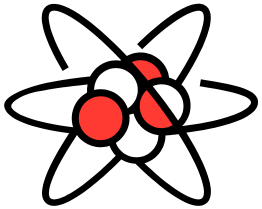
The **Nuclear Regulatory Commission voted to implement three new safety rules for existing reactors**. The rules will require facilities to have the tools needed to handle blackouts, as well as having "adequate instruments" to monitor used nuclear-fuel containment pools. Also, reactor models similar to those at Fukushima Dai-Ichi will be required to have hardened vents to relieve gas pressure. Bloomberg (3/2)

Tokyo Electric Power was aware that safety improvements were needed at its Fukushima Daiichi nuclear plant, but it delayed implementing them for fear of economic, legal and political consequences, the company said. TEPCO's internal reform task force said that adopting more-stringent safety standards based on previous tsunami evaluations was possible before the incident. ABC News/The Associated Press (10/11)

It's a mistake for countries to consider shutting down nuclear plants after the Fukushima Daiichi incident. Because of misinformation from anti-nuclear activists, Japan has changed its plans to expand nuclear energy and instead will close down every facility by 2040, and Germany and France plan to reduce nuclear's role in their energy mixes, Dyer writes. "More people die from coal pollution **each day** than have been killed by 50 years of nuclear power operations—and that's just from lung disease. If you include future deaths from global warming due to burning fossil fuels, closing down nuclear power stations is sheer madness," Dyer writes. Georgia Straight (Vancouver, British Columbia) (11/21)

More than two years after the earthquake and tsunami struck, studies are now showing that **radiation exposure levels were much lower than originally predicted**. Thus far, the only deaths directly attributed to the nuclear plant have been related to the evacuation of residents, and not to radiation exposure. “Even with multiple meltdowns and explosions, there were no radiation-related fatalities.” The performance of the plant has been a surprise to some. Media reports initially following the disaster predicted thousands, and in some cases, tens of thousands, of fatalities. **Electronics & Test** (4/26/2013)

Decontamination activities and rainfall may have contributed to a sharp drop in radiation levels in a nearly 50-mile radius around the Fukushima Daiichi nuclear plant, according to a government report. Radiation readings taken Nov. 16 were 40% lower than those taken about a year earlier. The Mainichi (Japan) (3/2)



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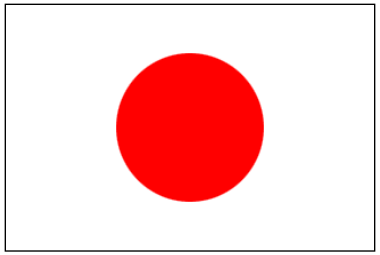

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