



Nuclear Power post-Fukushima?

What happened?

What will likely happen?

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**This presentation represents the views and opinions of the authors and do not necessarily state or reflect those of the University of Chicago, the United States Government or any agency thereof, or Argonne National Laboratory.*

Panel Discussion on the Implications of the Japanese Nuclear Crisis

Harris Public Policy Institute, Chicago, IL

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THE HARRIS SCHOOL

Energy Policy Institute | University of Chicago

To start: some ‘truth in advertising’!

- ‘Nuclear energy’ is an extremely contentious topic
 - Nuclear energy is probably the most contentious of the available energy technologies ...
 - Its close connection to nuclear weapons has been an issue from the start ...
- So you can expect extensive disputes about
 - Costs/economics
 - Safety and environmental impacts, ...
 - Security and proliferation risks ...
 - Honesty – about ‘why nuclear’, about risks, about ...
- You can expect advocates to dominate discussions – ‘honest brokers’ are few & far between ...
 - *As a result*: Policy discussions in energy/climate are often only weakly coupled to quantitative analyses, and ‘facts’ tend to be elusive ...
- SO: to be very clear – we are nuclear power proponents, but with some **significant** caveats ...

What we will talk about ...

- The events at Fukushima Dai-ichi Nuclear Power Station – so far ...
 - The information to date remains partial, confused, ... , and a fully accurate account remains to be written
 - Hence: audience, beware!!!!
- A brief overview of the ‘nuclear renaissance’ – here and abroad
- The technical – and other reasons – for the absence of a ‘nuclear renaissance’ in the U.S. – and why these reasons play out very differently abroad
 - Why we might want some progress in building new nuclear plants – even if we were not proponents of nuclear energy ...
 - Some of the constraints on – and desirable properties of – new nuclear power in the U.S.
- Questions and answers ...
- ... and major thanks to Argonne colleagues, including esp. Walt Kirchner (who are not responsible for the opinions voiced here – we are!!)

Six BWR Units at Fukushima Dai-ichi Nuclear Station

Unit 1: 439 MWe BWR-3, 1971 (unit was in operation prior to event)

Unit 2: 760 MWe BWR-4, 1974 (unit was in operation prior to event)

Unit 3: 760 MWe BWR-4, 1976 (unit was in operation prior to event)

Unit 4: 760 MWe BWR-4, 1978 (unit was not in operation prior to event)

Unit 5: 760 MWe BWR-4, 1978 (unit was in not in operation prior to event)

Unit 6: 1067 MWe BWR-5, 1979 (unit was in not in operation prior to event)



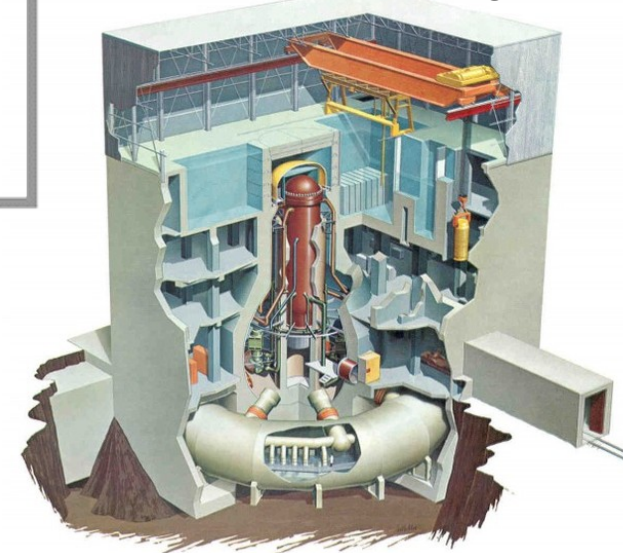
Fukushima Daiichi Nuclear Power Station



Context: 54 operating reactors (30 BWRs/24 PWRs) in Japan supply ~30% of grid

- ~17% of grid power supplied by BWRs
- ~2% of grid power supplied by the 4 damaged BWRs at Fukushima Dai-ichi ...

A horizontal line with arrows at both ends is divided into two sections. The left section is labeled 'Reactor' and the right section is labeled 'Balance of Plant'. A double arrow points from the 'Reactor' section to the 'Balance of Plant' section, indicating a signal or material flow.



General BWR Plant Design Features – part 1

■ Mechanism of Boiling Water Reactor Power Station

Primary Containment Vessel (Dry Well)

It would confine radioactive substances discharged from the reactor facilities if some pipes were broken by accident.

Reactor Pressure Vessel

It is made of 12cm thick steel and contains fuel, control rods, jet pumps, steam-water separator and steam dryer.

Primary Recirculation pump

It circulates water in the reactor pressure vessel and changes reactor power by changing water quantity.

Control Rods

They are used to start and stop the reactor and to change reactor power (amount of nuclear fission) by individually inserting and extracting from the bottom of the reactor.

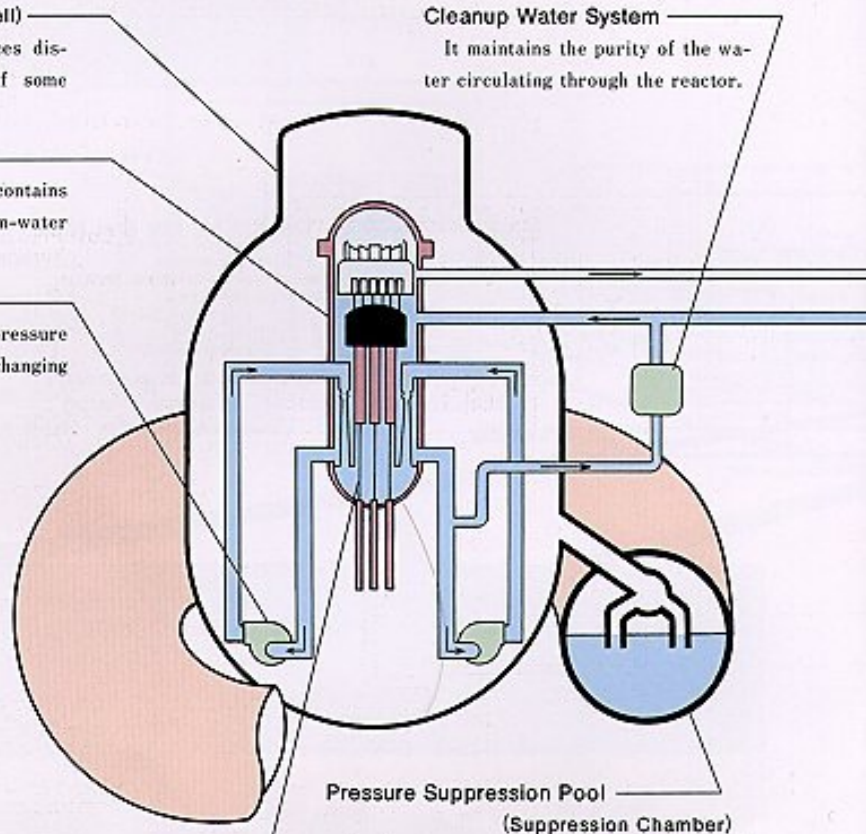
Cleanup Water System

It maintains the purity of the water circulating through the reactor.

Pressure Suppression Pool

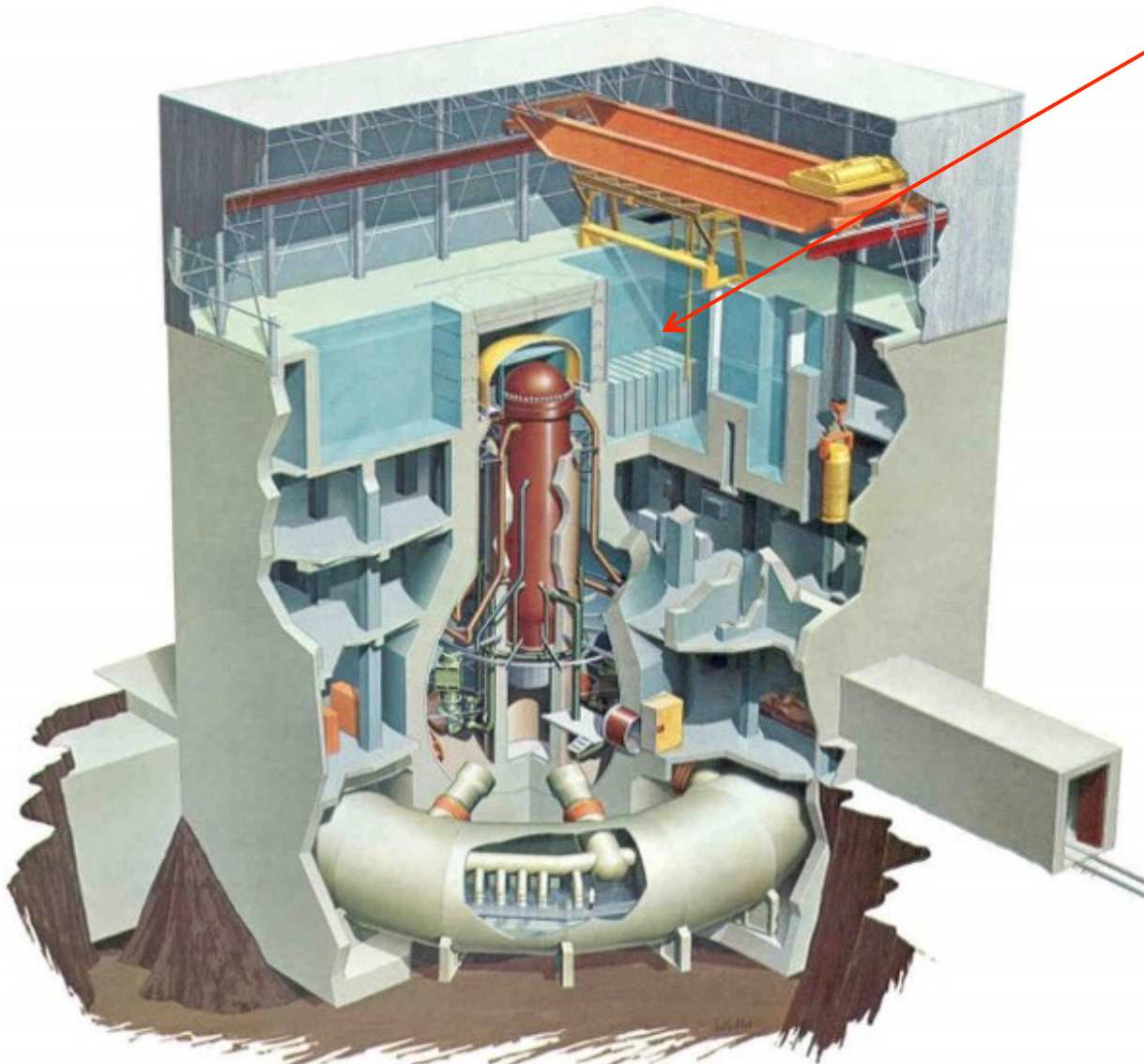
(Suppression Chamber)

It always contains water. Should pipes in the primary containment vessel ever break, leaked steam would be conducted into the pool, where it would be cooled down and condensed with a large amount of water to suppress any rise in pressure in the primary containment vessel.



- This drawing identifies the key elements of the BWR design
- Until the backup systems lost emergency power, all of these elements functioned as expected

General BWR Plant Design Features – part 2



- ‘Spent’ fuel pool at upper level of reactor building is normally continuously cooled – thus needs AC power
- 23 reactors in the U.S. utilize Mark I containment systems similar to those at Dai-ichi Units 1-4
- Following TMI and 9/11, NRC required licensees to develop comprehensive “*beyond design basis*” mitigation strategies for these and all U.S. plants (e.g., total loss of offsite power)

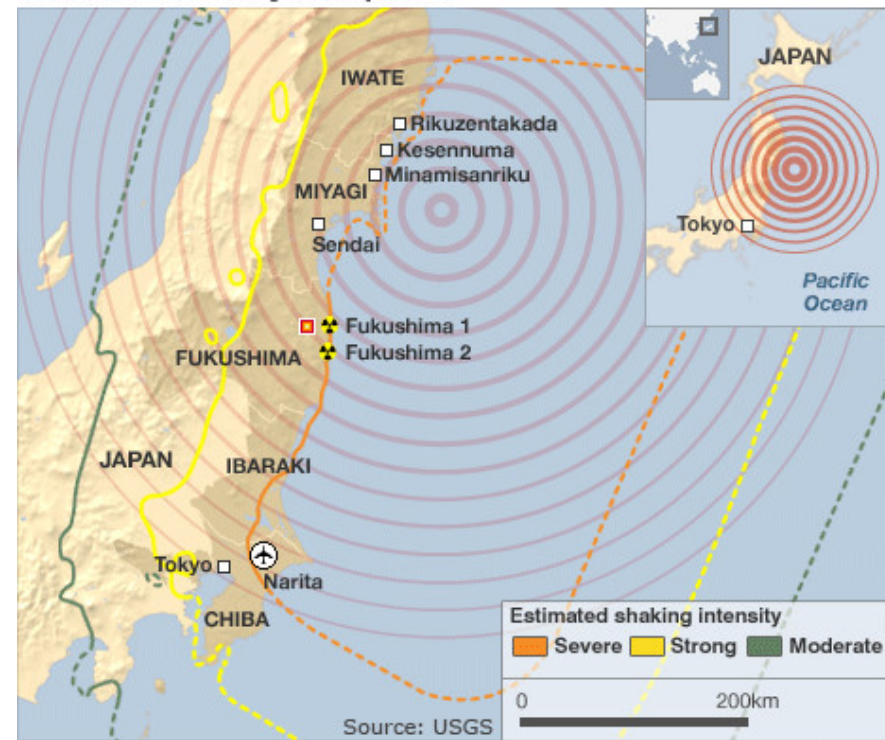
* Picture reprinted from the World Nuclear Association

Event Initiation

March 11, 2011

- About 14:46, a 9.0 magnitude earthquake struck with an epicenter at sea ~200 km north of Fukushima – TEPCO reported that the design basis earthquake for the plant was 8.2
- Within an hour, a tsunami ~14 meters high inundated the site, whose design basis for the seawall was 5.7 meters – the reactors and backup diesel power sit roughly 10 to 13 meters above sea level
- The impacts up and down the northeast coast resulted in tragic loss of lives, damage, and destruction of infrastructure
- Eleven reactors shut down automatically: Fukushima Dai-ichi Units 1-3; Fukushima Daini Units 1-4; Onagawa 1-3, and Tokai 2

Areas affected by the quake

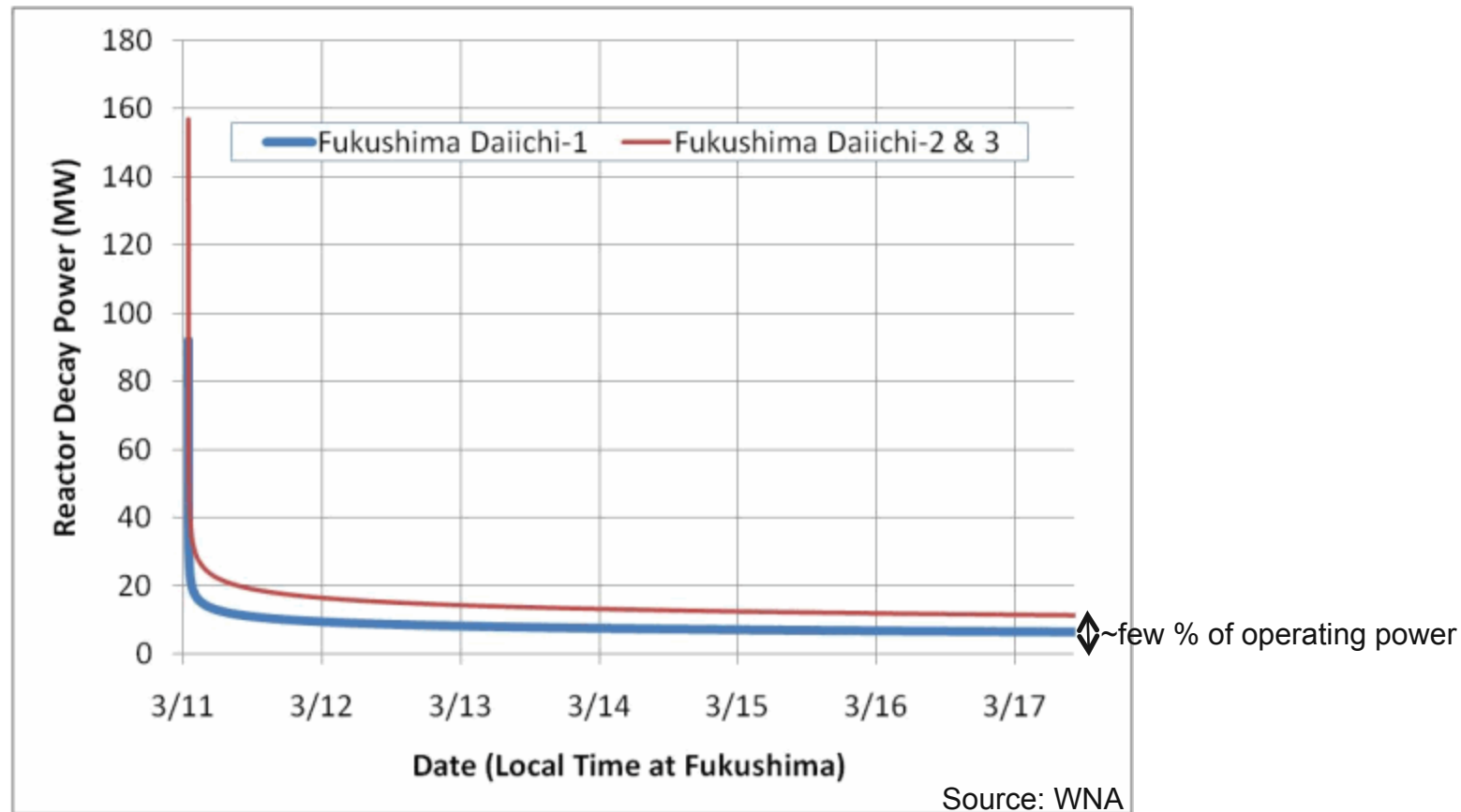


Initial Response

- Nuclear reactors shutdown automatically: Within seconds control rods are inserted into cores, and chain reactions stopped
- Cooling systems were placed into operation to remove decay heat, about 3% of the heat load under normal operating conditions (shown in graph on next slide ...)
- The earthquake resulted in loss of offsite (i.e., grid) power, which is the normal supply to the plant
 - As best as we know now, the seismic shaking did not damage the reactors
- Emergency diesel generators started and powered emergency cooling systems
- About an hour later, the tsunami struck and took out all the multiple sets of backup emergency power generators
 - Specifically: the tsunami took out the diesel tanks & the electric switch yard ...
- Reactor operators were able to utilize emergency battery power to provide core cooling for about 8 hours (Unit 1), after which the batteries were discharged and could not be recharged
- Incident postmortems will show how well the reactor staff followed established abnormal operating procedures and emergency operations procedures ...

Reactor Decay Heat Load at Units 1-3 after Shutdown

- Operating power:
 - Unit 1 – BWR-3 439 MWe
 - Units 2-3 – BWR-4 760 MWe
- Decay power: due entirely to decay of fission products – chain reaction shut down completely

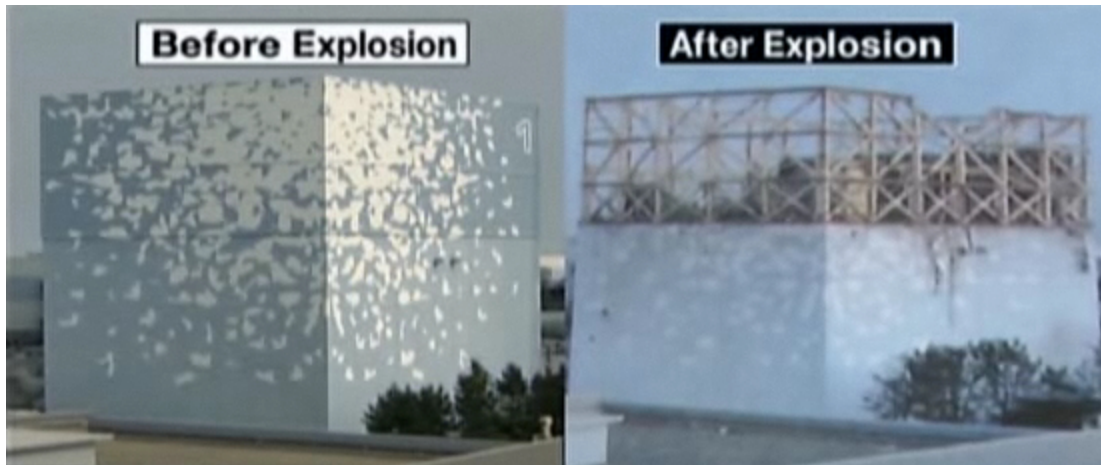


Immediate Aftermath

- Offsite power could not be restored, and delays were encountered in obtaining and connecting portable generators
- After batteries ran out, the residual heat load could no longer be carried away
- Reactor temperatures increased, water levels in the reactor vessel decreased, eventually uncovering and overheating the core
- Hydrogen was produced by oxidation of zirconium metal in cladding – zirconium-water reactions in core start at about 1000°C
- Operators vented the reactor pressure vessel to relieve pressure – steam (and hydrogen) were discharged to primary containment (drywell), causing primary containment temperatures and pressures to rise
- Operators were then forced to vent the primary containment to control pressure (and hydrogen) levels to prevent its failure
- Primary containment venting is through a filtered path that travels through duct work in secondary containment to elevated release point
- A hydrogen detonation subsequently occurred while venting secondary containment, which occurred shortly after an aftershock at station, likely ignited by spark – **the key issue likely was hydrogen encountering free oxygen outside the primary containment vessel ...**

Hydrogen Detonation at Unit 1

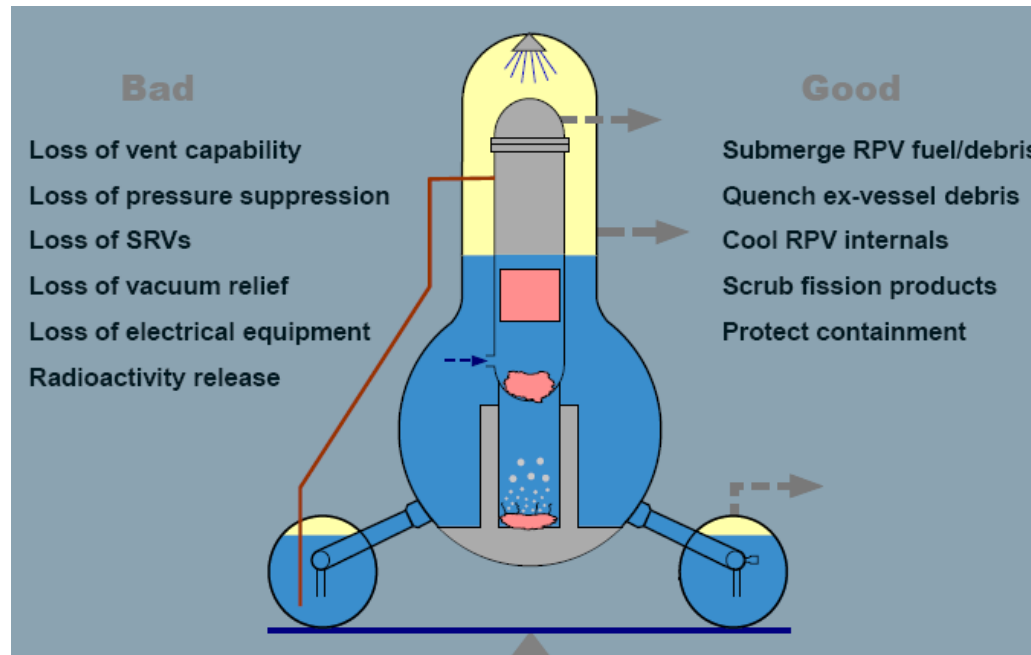
March 12 –
15:30



←Refueling Level

Mitigating Actions

- The operators were able to deploy portable generators and utilize portable pump(s) to inject seawater into reactor vessels and primary containments
- This has the effect of flooding the primary containment to cool the reactor vessel and any core debris that may have been released into primary containment. The corrosive seawater also ruins the reactor.
- Boric acid was added to seawater to provide a neutron “poison” to prevent re-criticality, and also to reduce iodine release by buffering the containment water pH



Subsequent Events

- A **General Emergency** was declared in response to the initial events at Unit 1, with evacuation of public within 20 km (12.5 miles) of plant – about 200,000 peoples evacuated
- The station was able to deploy portable generators and utilize portable pumps to inject seawater into reactor vessel (3/12 pm) and primary containment (3/13 am) in Unit 1 (mitigating actions)
- Seawater was also injected into Units 2 and 3; a hydrogen explosion occurred in Unit 3 (3/14 am), followed by an explosion likely in suppression chamber of Unit 2 (3/15 am)
- Spent fuel pool temperatures rise precipitously in Unit 4 (possible wall damage indicated), and a fire later that extinguishes, with subsequent significant fire damage (3/16 am)
- Begin injecting water to pools (3/15-16), helicopter dumping of water on reactor buildings (3/17), and begin spraying water from ground (3/17-18), continuing...
- Begin to re-energize power systems (3/19-20), and restore electrical power and cooling functions ...
- Offsite radiation detected as result of venting, uncontrolled releases from hydrogen detonations, fires, and failures of secondary containments – potassium iodide pills distributed to public – measures implemented to control affected contaminated food supplies and further protect public from exposure

See NEI website (<http://www.nei.org/>) for updates and DOE website (<http://www.energy.gov/>) for current radiological assessment

What Next ? Initial Thoughts

■ Short-term

- First order of business has to be stabilizing the situation by restoring electrical power (and backup systems) and re-establishing closed cooling (internal) systems to deal with residual decay heat of fuel (debris) in **both reactors and pools**
- Second, efforts will have to focus on preventing further significant dispersal of radioactivity into the environment – airborne, liquid, and ground contaminants
- A thorough assessment of local contamination and radiation fields is required to both protect workers and plan how to conduct cleanup work on site, with a concern toward minimizing occupational exposures and dose reduction

■ Near-term/Interim

- The spent fuel pools contain significant inventories of high-level radioactive material* that will need to be continually cooled and sufficiently covered to provide radiation protection for worker access to the reactor buildings and environs; additionally, integrity of pool structures and spent fuel is in doubt, likely making dealing with the spent fuel a first priority, particularly with the threat of further natural events
- Removal of spent fuel to interim storage is highly desirable, a task considerably complicated by the extensive damage to the reactor building structures
- Initial decontamination of auxiliary buildings/surroundings will likely be required first to gain eventual access to reactor buildings

* Unit 1 – 50 tons, Unit 2 – 81 tons, Unit 3 – 88 tons, Unit 4 – 135 tons (Washington Post 3/17/11)

What Next? – 2 Initial Thoughts

■ Long-term

- The extent of damage and relocation of fuel and debris, both highly radioactive, is largely unknown at this juncture, but clearly the damage is very severe
- Ultimate recovery of material and disposition will likely require entirely remote, highly customized, robotic operations
- Occupational dose management may be the limiting factor in such recovery, stretching out timelines

For context, the accident at TMI Unit 2, March 28, 1979, resulted in over half of the core being melted, but the bulk of debris material was largely contained within the reactor vessel – defueling of the reactor vessel commenced in 1985, and was completed in 1990.

Now, what about the bigger picture?

- Abroad?
- The nuclear renaissance?

the table does not include the completion or construction at Watts Bar Unit 2 (TVA-US) and the construction underway at the Vogtle site (Southern –US)

Reactor Design	China	France	Japan	South Korea	Russia	Other countries	Total GW
Gen II							
CPR-1000	18	-	-	-	-	-	19.4
CNP series	3	-	-	-	-	-	2.0
OPR-1000	-	-	-	4	-	-	4.0
VVER series	-	-	-	-	7	4	12.3
Gen III							
APR-1400	-	-	-	2	-	-	2.7
ABWR	-	-	2	-	-	2	5.4
APWR	-	-	2	-	-	-	3.1
Gen III+							
AP-1000	4	-	-	-	-	-	4.8
EPR	2	1	-	-	-	1	6.6
Subtotal (#)	27	1	4	6	7	7	
TOTAL GW	-	-	-	-	-	-	60.3 at 52 plants

... and this is what the 'renaissance' looks like in the U.S.:

- 104 operating
 - 69 PWRs
 - 35 BWRs
- No new starts since 1977
- One being completed:
 - TVA's Watts Bar 2 (PWR), by ~2012
- The COL applications for approx. 33 reactors (through 2010 - before Fukushima) will probably lead to *at most* ~4-5 new GW-scale reactors online by 2020
- Most COL applications have been suspended



Graphic courtesy WNA

What happened to the ‘nuclear renaissance’ in the U.S.?

- It is useful to start answering this question by asking why nuclear plants are being built abroad ...
 - Energy security and diversity
 - Economics
 - Environmental concerns ...
 - Building a ‘nuclear hedge’ ...

- Do any of these justifications apply to us?
 - Energy security and diversity **PERHAPS**
 - Economics **NO***
 - Environmental concerns ... **PERHAPS****
 - Building a ‘nuclear hedge’ ... **NO**

* While the economic case in the U.S. for GW-scale nuclear reactors is weak (especially in deregulated markets), there is considerable evidence that the economic viability of small modular reactors (SMRs) is potentially strong, under the assumption that the ‘first of a kind’ cost barrier (and the associated learning curve to get to the ‘N-th of a kind’ regime) is overcome by federal support.

** The relevance of the widely acknowledged low-carbon impact of nuclear power is critically dependent on one’s views on the subject of global climate change – and within the U.S., there is considerable skepticism about the anthropogenic cause of observed global climate change indicators.

Let's look at these 4 justifications for nuclear power in more detail ...

■ Energy security and diversity

- Nuclear power is unique among energy sources by virtue of its weak coupling of the cost of electricity to the price of fuel – unlike other technologies, the cost of **new** nuclear power-generated electricity is dominated by the capital construction costs of new plants – however, in the U.S., this matters relatively little in an environment in which North American-sourced natural gas is cheap and carbon is not priced
- In a ‘flat Earth’ in which the price of raw materials is set by global markets, there is some advantage in the price stability of nuclear power-generated electricity ...

■ Economics

- In the absence of pricing carbon, and in the present regulatory environment, nuclear power cannot compete with either coal or natural gas as a source of base power
- For relatively modest levels of carbon pricing (viz., ~\$25/ton CO₂ equivalent), a DOE-sponsored economic analysis shows SMRs to be potentially economically viable in the U.S. – assuming that the ‘first of a kind’ barrier is overcome

■ Environmental concerns ...

- Nuclear fission is the only sustainable low-carbon base energy supply source whose technology is well-understood, based on extensive operating experience
 - *This is not the case for any of the proposed carbon sequestration methods ...*

■ Building a ‘nuclear hedge’ ...

- We have no need for more fissile material – we’re net consumers!

There are also a few additional issues to care about ...

- We should not forget that – aside from the cost issue – there are other issues that mitigate against a significant revival of nuclear power in the U.S. ...
 - **The frozen ‘back end’ – now under discussion by a Presidential Commission**
 - *A final repository remains to be identified – and Yucca Mt is off the table ...*
 - *We don’t currently have a coherent interim storage strategic plan in place ...*
 - *We have not had a consensus on the nature of the fuel cycle – once through, limited reprocessing (e.g., MOX), or closing the fuel cycle*
 - **The transparency issue ...**
 - *Canada’s experience – based on the workings of the Nuclear Waste Management Organization (NWMO) – has shown that transparency when dealing with things nuclear can transform the debate, from mistrust to consensus ...*
 - *We are not quite there – and perhaps cannot be there, given our political culture ...*
 - Utilities have much improved their public relations efforts – but still tend to ‘hunker down’ when faced with unpleasant news ...
 - ‘Back end’ discussions have traditionally not had the transparency of comparable Canadian efforts ...
 - **Remaining fears** – stoked by safety and security problems world-wide ...
 - *Chernobyl and Three Mile Island, Fukushima ...*

But why might we want nuclear power, even if it's not the cheapest choice?

- **Environment:** Even for 'climate deniers, nuclear is a critical technological hedge against the possibility that carbon sequestration at the volume levels required to power U.S. demands turns out to be either technically or economically impractical, and that renewable energy sources cannot make up the difference
- **Nuclear weapons proliferation:** The credibility of the U.S. in matters of promoting nuclear non-proliferation depends to a considerable degree on our (perceived) technical expertise
 - We do not want to lose that ...
 - *Our technical assistance in closing/modifying HEU research reactors abroad depends on such expertise ...*
 - This expertise needs to be 'open', i.e., not reside solely within the 'nuclear Navy' and the DOE/NNSA programs ...
- **Economics:** A domestic nuclear industry – focused on export – has the potential of making a very large amount of money ...
- **Thus, even if you are not a proponent of nuclear power within the U.S., you might want to consider the (unintended and painful) consequences of a U.S. departure from the nuclear power arena ...**

So, what might constraints on – and desirable properties of – new nuclear power in the U.S. look like?

■ Costs

- Loan guarantees can initiate a new era of building nuclear power plants, but cannot sustain it long-term
- The long-term evolution of nuclear power will depend on bringing down capital construction costs to levels consistent with the relatively low capitalization of U.S. power generating companies ...
 - *This is a key motivation for Small Modular Reactors (SMRs)*

■ Safety

- The design evolution of (Gen III+ and Gen IV) advanced reactors drives in the direction of passive safety, for example deploying
 - *Natural convective cooling – no pumps needed ...*
 - *Thermal expansion of core – reaching subcriticality in the event of off-normal core temperature rise*

■ Security

- Below-grade placement of reactor pressure vessel
- Enhanced protection of cooling pools for used fuel
- ...

... but none of these issues are likely to be addressed satisfactorily without significant R&D investments ...

■ Consider the airline industry in the early to mid-1950s ...

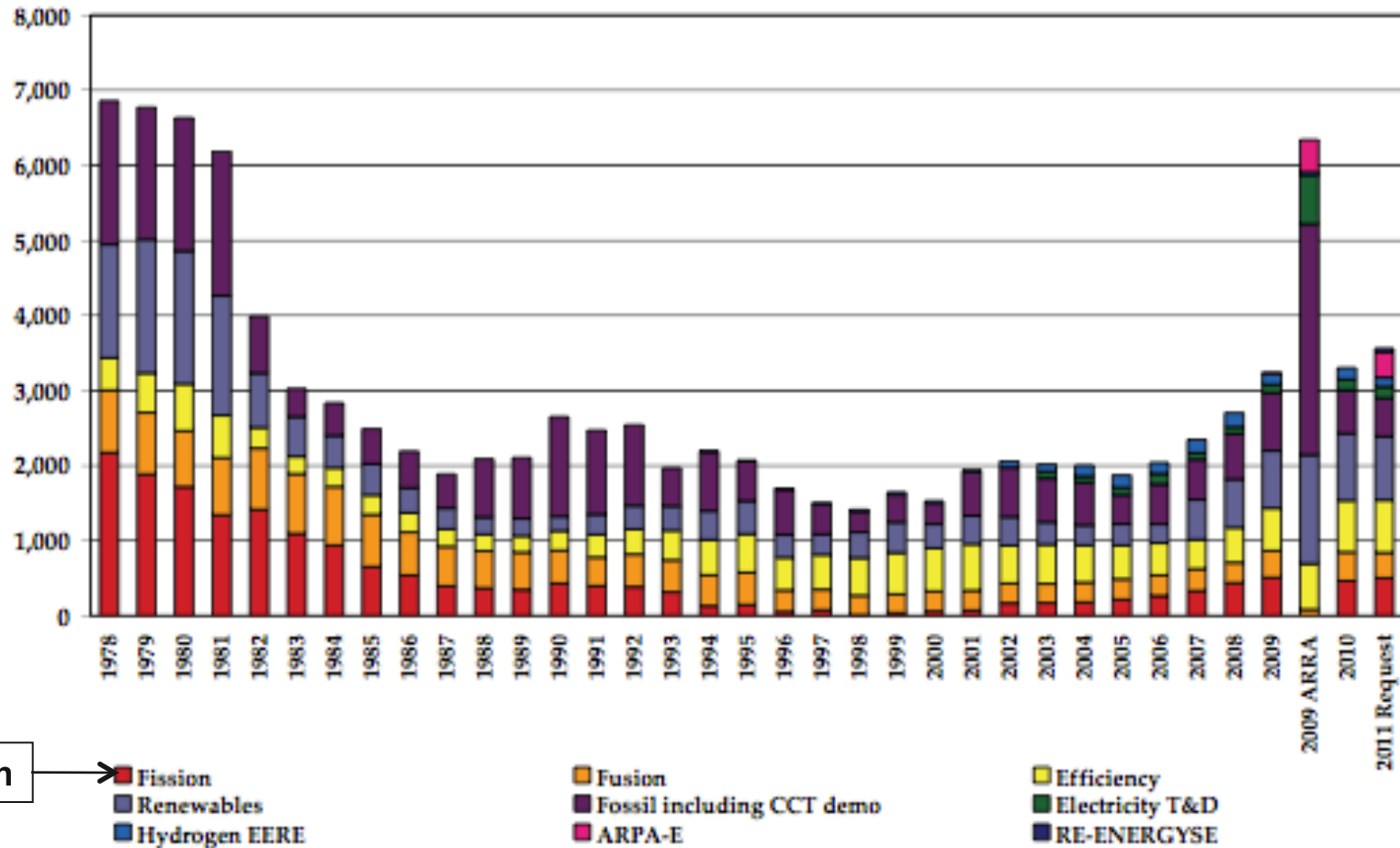
- De Havilland's Comet – two incidents in which plane disintegrated in flight ...
- Lockheed's Electra – two incidents in which wings tore off fuselage ...
- **These were not confidence-inspiring events**, in an industry that was (and remains) heavily regulated and heavily dependent upon positive public perceptions for economic survival ...
- Industry **and** governments responded by significantly increased R&D – and identifying and fixing the safety problem (= stress cracking ...)
 - *When was the last time you looked out the window of your flight to check whether the wings were still attached???*

■ Consider the U.S. nuclear industry since 1979 (e.g., since TMI)

- U.S. federal investments in nuclear R&D plummeted ...
- Nuclear engineering in the U.S. went into a tailspin ...
- Recovery has been slow and painful ...

... and here's the sad story ... at least the recent slope is positive

Energy RD&D Funding by DOE

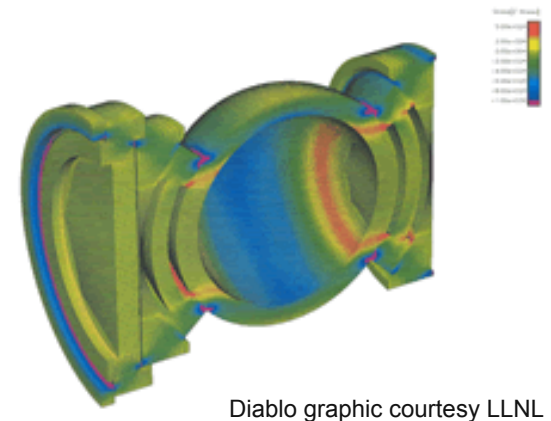
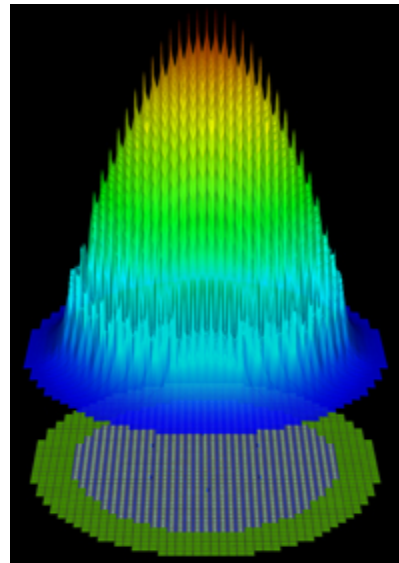
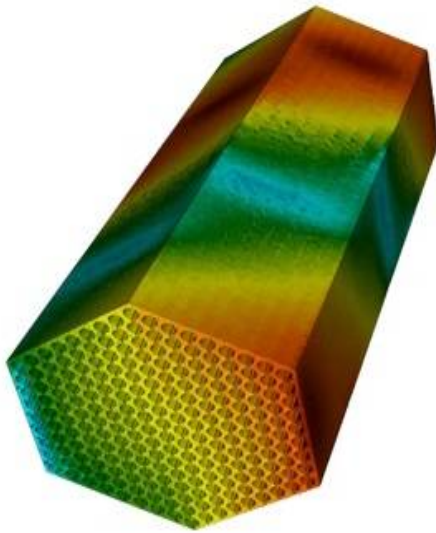


Courtesy Kelly Gallagher, Kennedy School of Gov't

Nuclear Power Post-Fukushima

So our end story leaves some questions ...

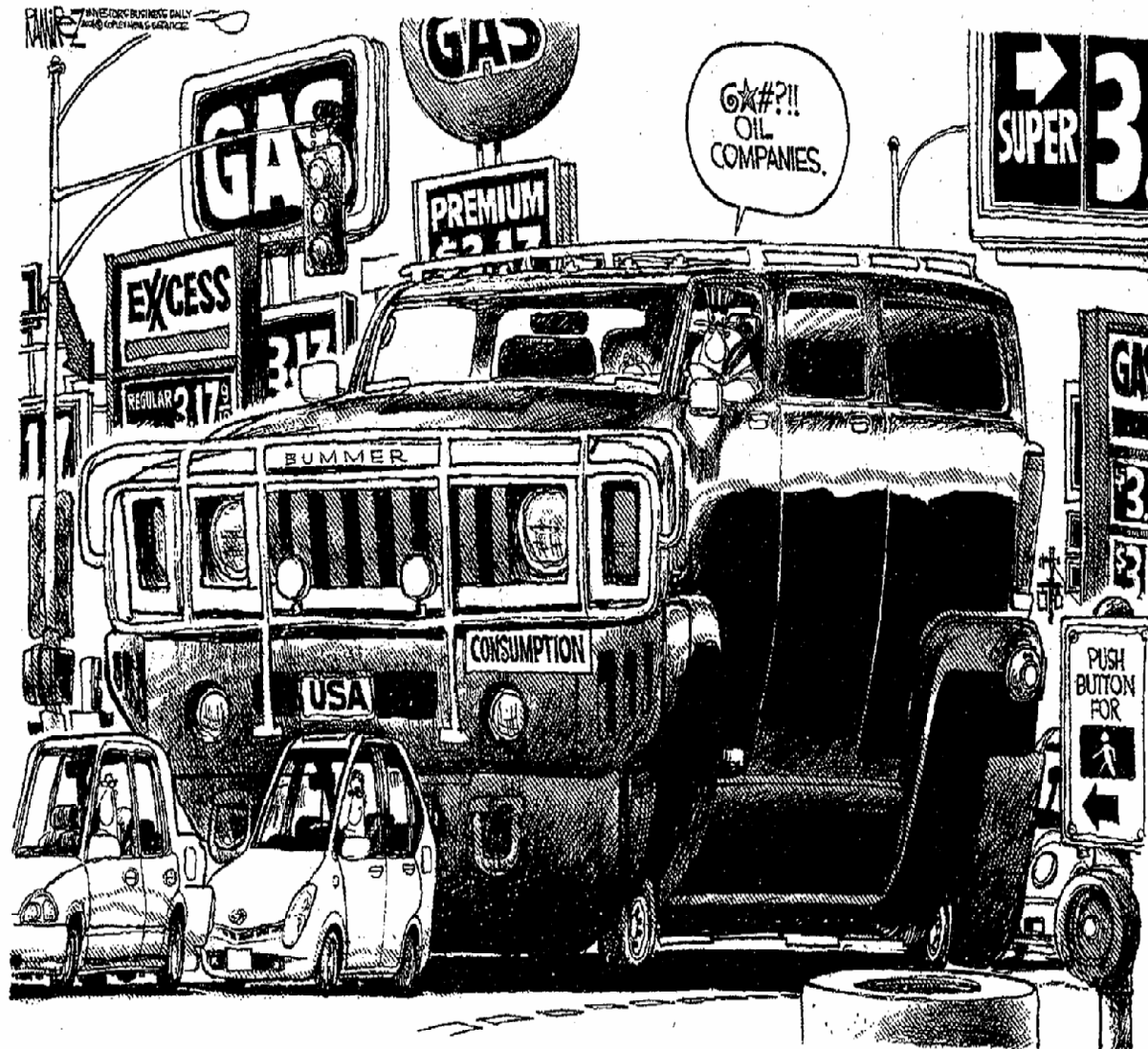
- How will we in the U.S. respond to the technical challenges of nuclear power in light of the safety issues – and its promise of a low-carbon future?
 - Will we focus mostly on the regulatory process, on increased surveillance, ... , or perhaps stop nuclear power altogether?
 - Or will we go beyond increased safety vigilance to also expend the effort (and \$\$) to make substantive adjustments we can identify, based on 60+ years of operating experience and a series of significant safety failures?



Diablo graphic courtesy LLNL

Thermal hydraulics and neutronics graphics courtesy ANL/CESAR project

... which brings us to questions and discussion



www.investors.com/cartoons

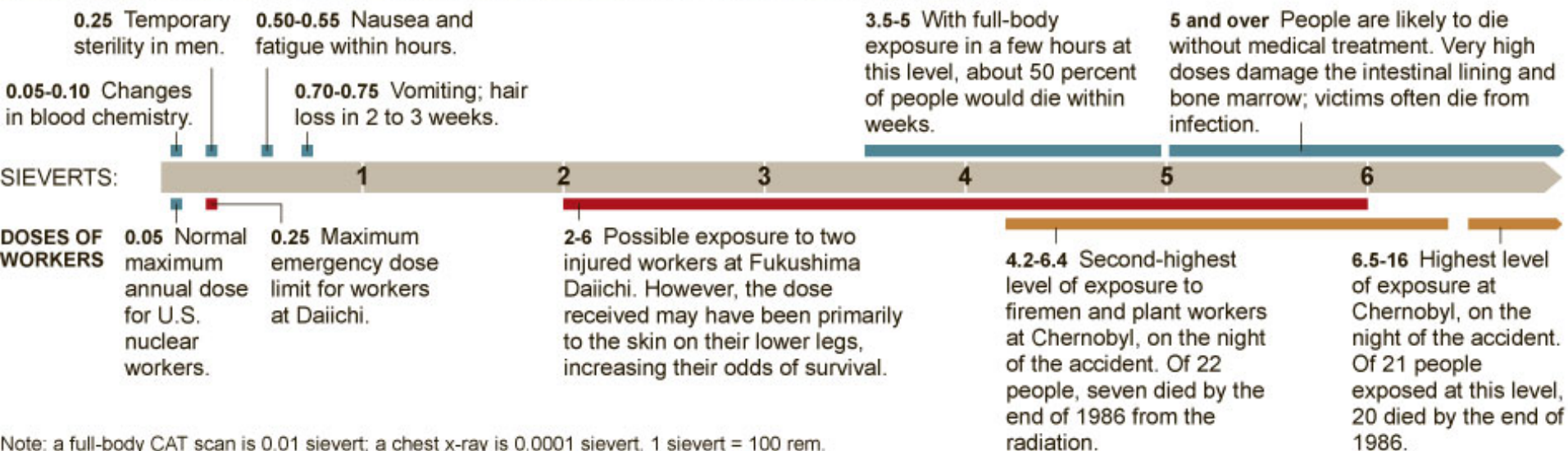
By Michael Ramirez, Investor's Business Daily, Copley News Service

Nuclear Power Post-Fukushima

Backup slides ...

Radiological effects on humans ...

LIKELY HEALTH EFFECTS FROM ACUTE RADIATION EXPOSURE For full-body exposure to gamma rays



Graphic from NY Times, 3/27/2011

■ The NY Times graphic does not explain an important detail about the units used ...

- **Sieverts** measure the radiation absorbed by a human (so does the old unit ‘rem’: 1 rem = 0.01 Sievert)
- **Grays** measure the radiation absorbed by any material
- The numerical difference between them depends on details: the type of radiation **and** the nature of the biomaterial, e.g., the effectiveness of radiation in interacting with various types of biological materials:
 - $1 \text{ Sv} = 1 \text{ Gy} * w$
 - *The weighting factor w depends on BOTH the type of radiation ($w=1$:electrons+photons; $=5-20$:neutrons; $=20$:alphas) and the type of biomaterial (gonads being most sensitive, skin/bone surface least) – thus, the seriousness of exposure depends on what’s exposed to what ...*