Nuclear energy, uncertain risks, and democratic decisions

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August 12, 2019
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Tsunami stones: “Do not build your homes below this point!”

Source: Ko Sasaki/New York Times
Why care about nuclear energy?

- Nuclear energy provides:
  - Very low carbon emissions
  - Deep decarbonization at reasonable cost may require non-intermittent, low-carbon backup for renewables
  - Very low emissions of particulates and other pollution (likely more important driver in some countries)
  - Fuel diversity and low fuel costs

- But it comes with:
  - High capital costs
  - Nuclear accident risks
  - Nuclear sabotage risks
  - Nuclear waste
  - Proliferation risks

A key question: can nuclear energy be expanded enough to make a real difference for climate change?

Nuclear energy and other complex, high-consequence technologies challenge democracy

- Few citizens understand the technology well enough to make informed judgments
  - Fears of “dreaded risks,” invisible risks, things you don’t understand and can’t control, can lead to exaggerated perceptions of danger

- Those with more expertise are often biased
  - Insufficient real data, real understanding of emergent behavior of complex systems, to fully understand the risks
  - Motivated reasoning, other cognitive and organizational biases, often lead experts to underestimate the danger (more later)

- Broad, often unfocused societal interests vs. focused, well-resourced industry interests
  - Regulators typically more influenced by the industry than the public

- Secrecy adds to the problem
  - For some aspects of nuclear technology, key facts secret for security reasons
  - For many other industries, key facts secret for proprietary reasons
  - Knowledge is power: Industry advocates have more of it
Pre-Fukushima, perceptions that the safety problem was “solved”

- Quarter century since the last major nuclear accident (Chernobyl, ‘86)
  - Tougher regulations
  - Stronger safety cultures
  - New reactor designs with more “passive” safety

- In Japan in particular:
  - “Nuclear village” assertions of “absolute safety”
  - Severe accident risk “so small that from an engineering standpoint, it is practically unthinkable”
  - IAEA-led reviews raise few issues — conclude Japanese regulator is adequately independent

Consequences of Fukushima for Japan are still unfolding – were not envisioned

- Few human health consequences from radiation exposure
  - Basis of most nuclear regulation
  - Far greater health consequences from stress, mental health, life disruption

- Massive societal consequences:
  - >150,000 people evacuated
  - >>$100B in costs, TEPCO bankrupt
  - All Japanese reactors shut down for years (few now open)
  - Dramatic changes in electricity use, costs
  - Reduction in trust in government, industry
  - Most consequences not included in nuclear risk estimates

Source: IRSN
Fukushima: global reactions

- National reviews, widely varying decisions
  - Many countries: “stress tests,” in-depth inspections and reviews, more stringent safety standards in key areas
  - A few countries: nuclear phase-out (e.g., Germany, Switzerland)
  - Largest markets: likely continued nuclear growth (e.g., China, India, Russia…)

- Global institutions: modest steps
  - Little consensus at IAEA ministerial – new IAEA safety plan quite limited (though still unfolding, could strengthen)
  - WANO reviewing its procedures
  - Key focus is still national sovereignty over international accountability
  - Stark contrast to the response to Chernobyl – which led to the construction of much of the current safety regime

  *Security being almost entirely missed in these discussions…*

Catastrophes could also occur on purpose

- Terrorist action could potentially cause a reactor melt-down comparable to Fukushima
  - Redundant safety systems, defense in depth make sabotage more difficult
  - But actions that could cause prolonged loss of cooling, power could lead to catastrophes
  - Sabotage of spent fuel pools, reprocessing plants, spent fuel transports also a concern
  - Effective nuclear security measures required – not in place everywhere

- Terrorists have considered nuclear sabotage
  - Threats, plans by Chechen terrorists
  - Al Qaeda seriously considered attacking U.S. reactors
  - 5 Americans arrested in Pakistan, charged (among other things) with planning to attack a nuclear reactor
Risk is not a fact – it’s a set of ways of thinking, perceiving

- Countries, groups vary in how they think about risk
  - Concerned with different dangers, for different reasons
  - Government approaches to managing risks differ

- Engineering-based, probabilistic assessments are one very important form of analysis
  - But what are the assumptions?
  - What is included, what is excluded?
  - We can only assess what we imagine

- Broader ways of conceiving the benefits, risks of technologies are also needed
Risk is not a fact – it’s a set of ways of thinking, perceiving (II)

- "Probabilistic risk assessment" is essential – but problematic
  - Key in systematically finding, addressing important risks in nuclear systems – but not as good at assessing absolute magnitude of risk
  - NRC safety goal: <1/million chance of major release/reactor-yr – but 4 reactor releases in 18,000 reactor-years of operation, >200 times goal
  - TMI, Chernobyl accident sequences had never appeared on any PRA – Fukushima sequence dismissed as too low-probability to worry about
- “Deaths per kilowatt-hour” is not the only – or perhaps even the most useful – way of thinking about the risks of nuclear energy
  - What are the non-death societal impacts?
  - Totally legitimate to be more concerned about huge society-disrupting disasters than about isolated deaths over time
  - Who gets benefits, who bears risks and costs, who decides?

Why do catastrophes happen?
Theories I and II: Bad luck, bad managers

- Theory I: Bad luck
  - Risk was rational, acceptable, got a bad role of the dice
- Theory II: Bad managers
  - Managers rushed, cut corners, conscious of the risks they were running
  - Early theory of the Challenger shuttle disaster
- Strong tendency to focus on engineering answers – “the O-ring failed due to low temperature before launch”
  - In reality, the root causes are usually organizational

Source: Rogers Commission
Why do catastrophes happen?

Theory III: Complexity and tight coupling

- Complexity: System has difficult-to-predict emergent behavior different from the sum of the parts
- Tight coupling: Action in one part of the system propagates to other parts faster than people can respond
- If these are present, will accidents occur “normally”?
- Partial solutions:
  - Simple systems
  - Redundant systems
  - More delay to loosen coupling

Why do catastrophes happen?

Theory IV: “Normalized deviance”

- Over time, in complex systems, practice drifts from initial rules
- Exceptions are made, and become “normalized” when nothing awful happens
- Organization rarely examines potential effect of the accumulation of exceptions
- Especially likely if there are strong cost, time pressures, little independent review
Why do catastrophes happen?
Theory V: Risk delusions

- Fukushima does not well fit theories I-IV
  - Not (mainly) bad luck in a rational risk environment
  - Not (mainly) managers consciously accepting high risks
  - Not (mainly) complexity and tight coupling
    - Result of a large tsunami was well-understood, not unknown
    - Hours to days to respond had the site been prepared to do so
  - Not (mainly) normalized deviance
    - Site was operating within long-standing safety rules, not with exceptions to them

- Instead, accident caused by fundamental misunderstandings of risk – “risk delusions” – by both operators and regulators
  - Genuinely believed that probability of accident was so low as to be almost “unthinkable”
  - Politics and culture: Regulators deeply influenced by industry
  - Cognitive, organizational biases made risks invisible, forgotten – despite substantial contrary evidence

- This is a widespread global phenomenon, not limited to nuclear energy or to Japan

Risk delusions and regulation:
Key roles for self-interest, politics

- Companies reasonably want to achieve safety and security at minimum cost and inconvenience
  - Genuinely convince themselves that existing efforts are enough
  - Risk to the company often << than risk to society

- Regulators often heavily influenced by industry – partial “regulatory capture”
  - Often dependent on industry for most information
  - Staff experts often come from industry
  - Industry often the most likely source of next jobs
  - Staff often live in an industry environment – meetings, conferences, social gatherings…

“It is difficult to get a man to understand something when his salary depends upon his not understanding it!”
— Upton Sinclair, I, Candidate for Governor, and How I Got Licked, 1934
Risk delusions:
Cognitive, organizational biases contribute

- Avoiding cognitive dissonance
  - We look for, remember evidence that confirms what we believe
- Availability heuristic
  - If it’s hard to call to mind an example of a danger, we understate it
- Overconfidence bias
  - 90% of people believe they are above-average drivers
- Affect bias
  - Something that has one desirable characteristic is believed to have others
- Poor understanding of small probabilities
- Putting it off to tomorrow
- Organizational
  - Incentive is to focus on getting the organization’s main mission done
  - “The nail that sticks up gets pounded down”
  - No one gets promoted for making a $10^{-5}$ risk into a $10^{-6}$ risk
  - Information is in many places – no one sees all of the risk

NRC and the backfit rule: underestimating probabilities and consequences?

- NRC “backfit rule”:
  - Don’t require operators to take new safety steps unless societal benefit outweighs cost, and safety improvement is “substantial”
  - Some exceptions
- But, both probability and consequences uncertain, may be underestimated (or over)
  - Probability: different models show different chance of spent fuel fire; possibility of terrorism ignored
  - Consequences: NRC assumptions dramatically reduce number of people, time, for evacuation from spent fuel fire

Source: Michael Schoeppner, Princeton
NRC and the backfit rule: (II)
Some remarkable recent decisions

- No need for filtered vents
  - Such vents would allow reactors to release excess pressure without releasing much radiation
  - Now required in much of Europe, Japan
  - Commission voted against staff recommendation

- No need to reduce density of spent fuel pools
  - Could greatly reduce spent fuel fire risk

- No need to consider knowledge of natural disaster risks gained in decades since licenses were granted

Democracy and nuclear energy:
some (very partial) solutions

- Strengthen independence, resources, expertise of regulators
  - Provide alternative sources of expert analysis, advice
  - Provide meaningful approaches to public engagement

- Expand transparency
  - All safety-related information that can be made public without undue security dangers should be public
  - Some non-government, non-industry representatives should participate in withholding decisions

- Provide resources needed to sustain expert NGOs
  - Need sustainable career paths for experts outside industry, government

- “Technologies of Humility” -- citizen panels and others
  - Often, panels of citizens raise different issues and values than “experts” focus on
  - Need to acknowledge deep uncertainty, involve the public in decisions that affect their future
Nuclear energy: status after Fukushima

- 451 reactors worldwide, 400 Gwe (as of 8/2019)
  - 11% of global electricity, 2% of global final energy consumption
  - 31 countries
- Before Fukushima: slow growth, big visions
  - ~3 reactors/yr attached to the grid worldwide
  - 65 countries expressing some interest in first nuclear plant (of which ~14 serious)
  - 72 reactors under construction – 30 in China, also substantial growth in India, Russia...
  - Little prospect for growth in W. Europe or United States, for economic reasons
- After Fukushima: differing national responses
  - German phase-out, some newcomer states reverse course
  - China, Russia, India, others continue after brief pause
  - Long-term impact uncertain (IAEA projections down 8-16%)
Two narratives on the future of nuclear energy

- Narrative 1:
  - Nuclear energy is too complex, expensive, and problematic to provide more than a small fraction of world energy supply
  - Nuclear energy cannot play a major role in climate mitigation

- Narrative 2:
  - To cope with climate, large-scale nuclear growth is essential – only non-intermittent, readily expandable source of low-carbon electricity
  - Can be expanded dramatically, risks can be managed

Making Narrative 2 come true would require major institutional and technical changes

Nuclear growth implies nuclear spread: the story so far

Source: IAEA PRIS Database, last retrieved April 15, 2016
Governance indicators of emerging nuclear power states

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Source: Drawn from World Bank Governance Indicators and World Nuclear Assoc.

Fukushima – what happened?

- Prolonged station blackout
  - Earthquake cut off off-site power
  - Tsunami swamped diesel generators (in basement)
- Also loss of heat sink
  - Tsunami swamped ocean pumps
- Result: cooling systems failed
  - Units 1-3 melted
  - Hydrogen explosions destroyed buildings
  - Major radiation releases (est. ~15% of Chernobyl, but high uncertainty)
  - Large-scale evacuation, economic disruption, fear and stress
  - Many questions remain

Source: Air Photo Service, Japan
Fukushima: evolving narratives

- The 1st story: extraordinary bad luck, few lessons
  - Extraordinarily bad luck: tsunami was so far beyond what could reasonably be expected that no one could realistically be expected to be prepared for such things
  - Few real lessons for other facilities, keep on as before

- The evolving story: a preventable tragedy, many lessons
  - Japanese had clear data showing the danger of large tsunamis years before
  - Many aspects of Japanese system – lack of real independence of the regulator, lack of authority for on-site manager, belief in absolute safety, pro-nuclear bias of “nuclear village” contributed to disaster
  - Many of these weaknesses – and a variety of related vulnerabilities – exist in many other countries as well
  - Happened in one of the richest, most experienced countries, with high regulatory effectiveness, low corruption – sobering reality

Nuclear waste, *if properly managed, poses modest risks*

- After pool storage, spent fuel can be safely stored in dry casks for decades at low cost
  - Allows time, flexibility for more permanent options

- Scientific consensus that geologic disposal can provide safe management of nuclear waste
  - Risks are both modest and far in the future

- Recently, Finland and Sweden have successfully sited nuclear waste repositories with full support from the local communities

- *But*, the politics of nuclear waste and political perceptions of its dangers still pose a major problem for nuclear energy
Standard nuclear reactors pose real but modest proliferation risks

- Modern light-water reactors small contribution to a bomb:
  - Use low-enriched fuel that cannot be used in a bomb without technologically demanding further enrichment
  - Produce reactor-grade (but weapons-usable) plutonium in spent fuel (~1% by weight) – requires remotely-operated chemical processing to separate plutonium
  - Are under international inspection in non-nuclear-weapon states

- Key proliferation risks are from enrichment and reprocessing facilities – the nuclear fuel cycle
  - Facilities for civilian use can be readily turned to military use
  - International inspection can provide warning – but in time?
  - Potential for covert facilities (esp. enrichment)

- Reactors provide:
  - Means to build up expertise, bureaucratic power base
  - Rationale for pursuing more sensitive technologies

Public acceptance of nuclear energy

- Making nuclear energy a safe, secure, proliferation-resistant, reasonable cost option with well-managed waste would go a long way to addressing the public acceptance issue

- But deep fears (some rational, some not), deep distrust of government and industry (some justified) need to be addressed
  - Requires real engagement of broad range of stakeholders, genuinely voluntary approach for affected communities
  - Communication has to be two-way, not just industry “educating” the public

- Constraint is not as binding as some believe
  - In many cases, communities that have nuclear power plants (and the resulting jobs and tax revenue) are supportive of having more
Nuclear energy: is new technology the answer?

- Designs in development might offer:
  - Increased “inherent” safety and security (without relying on quick human action or mechanical pumps)
  - Smaller size, could ease financing, planning
  - Ability to “recycle” spent fuel (but comes with many risks and costs, relatively modest advantages)
  - High temperatures to provide industrial process heat
  - Some modest proliferation advantages (or disadvantages, in some cases)
  - Most experts do not expect significant overall cost improvement in the next couple of decades

- Will take decades to develop, test, license, build new reactor types — most nuclear energy generated by 2050 will be from types already available for purchase
  - Inherent, scale, complexity, barriers to entry suggest nuclear innovation likely to be slow

Rickover: Paper reactors will always beat real reactors

“An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little development will be required. It will use off-the-shelf components. (8) The reactor is in the study phase. It is not being built now.

On the other hand a practical reactor can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It requires an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of its engineering problems. (6) It is large. (7) It is heavy. (8) It is complicated.”

Small modular reactors

- Small modular reactors:
  - May make planning, financing easier with “bite size” plants
  - Both near-term and long-term varieties, different characteristics
  - Not clear if cost advantage of manufacturing scale will compensate for loss of advantage of physical scale

- Long-term concepts have some attractive features
  - Factory-built sealed-core systems might make possible widespread deployment with modest proliferation, safety, or terrorism risks

![Artist’s concept of 6 modules of 125-MWe “mPower” design](Source: Babcock and Wilcox)

Is nuclear energy sustainable?

- Uranium is abundant
  - Current use ~ 60,000 tU/yr
  - IAEA estimates 15.8 M tU available (known+speculative)
  - U being found faster than it’s being used – for decades
  - With huge nuclear growth, and no recycling, uranium resources might be an issue – in the 22nd century
  - 2010 MIT analysis suggests enough U to fuel 10x current nuclear fleet for 1,000 years before price increases enough to make reprocessing economic

- Hence, reprocessing and breeder reactors are not needed at least for many decades
  - Reprocessing – separating plutonium from spent fuel to recycle it – is much more expensive than not doing so, and raises proliferation, safety, and terrorism risks
Compared to what?
Every option has its problems

- Oil and gas: Not enough resources?
- Coal, tar sands, oil shale: Not enough atmosphere?
- Biomass: Not enough land?
- Wind & Hydro: Not enough good sites?
- Solar: Too expensive and intermittent?
- Nuclear fission: Too unforgiving?
- Nuclear fusion: Too difficult?
- Hydrogen: Energy to make it?
- End-use efficiency: Not enough informed, motivated end-users?

Particulates may be as important as climate in driving clean energy

Smog in Beijing. Source: inhabitat.com

- >3 million deaths/yr globally from fine particulates
Steps to enable large-scale nuclear growth

- Reduce costs, ease financing
- Avoid major delays, cost over-runs
- Address technical, personnel supply bottlenecks
- Avoid further accidents
- Avoid terrorist incidents
- Avoid further nuclear proliferation
- Manage nuclear waste successfully
- Make nuclear power suitable for more of the world
- Make nuclear power suitable for more purposes

Near term (2010-2030): primarily institutional changes
  - Main effect of new technologies comes later

Long term (2030-2070): institutional and technical changes

Nuclear role in 3 greatest global energy challenges

- Energy supply without greenhouse emissions
  - Massive growth required for nuclear to play a significant role
- Reducing energy supply vulnerabilities (esp. oil)
  - Nuclear currently provides baseload electricity, oil little-used for that purpose in most countries
  - Nuclear cannot currently make major contribution to transport fuel
  - May change in future
- Providing energy to the world's poor
  - Current huge, complex, expensive nuclear plants not the technology that will provide electricity to rural villages
  - May also change (at least somewhat) in future

Electricity <1/5 global final energy consumption – and most future demand growth is in developing countries with modest nuclear contribution so far
A personal view

- We should be doing what we can to fix the problems that have constrained nuclear growth, so that it can really be an expandable option to help cope with climate change.
- Will be more difficult to cope with climate without a significant contribution from nuclear – but will be difficult to get a significant contribution from nuclear.
- Poorly managed nuclear energy with weak rules will not, and should not, grow at the scale required.
- Well-managed nuclear, with stringent safety, security, and nonproliferation measures in place, and reduced costs, might grow on a scale that could contribute to climate change – but it won’t be easy.

What are the prospects for change?

- Near term, muddling through likely
  - Modest nuclear energy growth, reversals in a few countries
  - Modest but genuine institutional improvements
- Long term, several scenarios possible
  - Large-scale growth with acceptable risks would require major institutional and technical changes, beginning soon
  - Real risks of moving forward without such improvements
- Widespread complacency
  - Most nuclear companies focused on cost, acknowledge need to convince the public on safety, see little need for new action on security, nonproliferation, disarmament
  - Most states unwilling to agree to new measures that involve even modest compromises in sovereignty
  - Sluggish economies, polarized politics, foreign dangers all shrink the attention senior policy-makers are likely to give