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Nuclear energy, uncertain risks, and democratic decisions

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Summer School on Expertise, Trust, and Democracy
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August 12, 2019
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Tsunami stones: "Do not build your homes below this point!"

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Source: Ko Sasaki/*New York Times*

Why care about nuclear energy?

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- 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

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- 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 <u>understate</u> 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"

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- 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 <u>is</u> adequately independent

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

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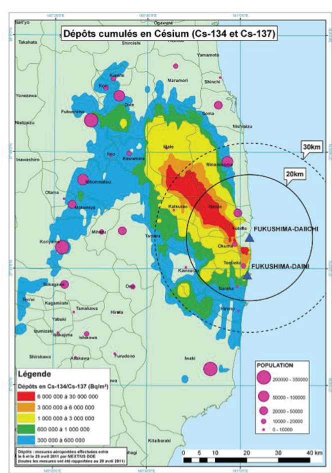
- Few human health consequences from radiation exposure
  - Basis of most nuclear regulation
  - <u>Far</u> greater health consequences from stress, mental health, life disruption
- Massive societal consequences:
  - >150,000 people evacuated
  - >>$100B in costs, TEPCO bankrupt
  - All Japanese reactors shut down for years (few now open)
  - Dramatic changes in electricity use, costs
  - Reduction in trust in government, industry
  - Most consequences <u>not</u> included in nuclear risk estimates



Source: IRSN

Fukushima: global reactions

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- 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

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- 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

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Preventing the Next Fukushima

Weak authority and largely voluntary standards limit global institutions' impact on nuclear safety and security.

Matthew Bunn* and Olli Heinonen

While this year's disaster at Japan's Fukushima Dai'ichi plant, the worst since Chernobyl in 1986, was caused by the one-two punch of a huge earthquake followed by an immense tsunami—a disaster unlikely to occur in many locations—it revealed technical and institutional weaknesses that must be fixed around the world. If nuclear power is to grow on the scale required to be a significant part of the solution to global climate disruption or scarcity of fossil fuels, major steps are needed to rebuild confidence that nuclear facilities will be safe from accidents and secure against attacks (*1*).

It is too soon to draw all the lessons from the Fukushima disaster. But it is clear that the reactors' abilities to maintain cooling in the event of a prolonged loss of power and to vent dangerous gas buildups were insufficient, as were the operators' ability to respond to large-scale emergencies and the regulators' degree of independence from the IAEA. Will Fukushima lead to new action to strengthen the global nuclear safety and security system?

So far, the signs are not promising. With competing proposals from several countries, little understanding of which ideas would help, and a lack of sustained leadership focused on building support for key initiatives beforehand, little consensus emerged at June's IAEA ministerial meeting, although the ministers directed the agency to prepare a suggested action plan. That plan, a 22 September United Nations conference on nuclear safety and natural disasters; reviews of the CNS; and the ongoing WANO effort to find ways to strengthen its operations all represent opportunities for progress.

Over the long term, new reactor designs with greater reliance on "inherent" safety measures, e.g., not requiring active pumps and valves to maintain safe operation, may reduce risks. But for the next few decades, most nuclear energy will be generated by

Operators should be required to install filtered vents, as some countries have done, which could greatly reduce the amount of radiation released if a dangerous pressure buildup in a reactor forces operators to vent gases, as occurred at Fukushima (*4*). Operators should also be required to put in place measures to prevent spent fuel from melting or burning if a spent fuel pool drains, such as installing survivable systems to spray the fuel in the pool with water. Ultimately, much of the fuel now stored in spent fuel pools should be moved to safer dry casks (*5*).

Institutionally, regulators must be wholly independent of those they regulate and have the authority, resources, expertise, and culture to be effective. For example, Japan has decided to separate its regulator from the ministry responsible for nuclear power.

The IAEA should recommend that states require steps such as these. The United States and other countries operating and exporting nuclear reactors, along with industry groups

Source: Science, **Sept. 16, 2011**

Risk is not a fact – it's a set of ways of thinking, perceiving

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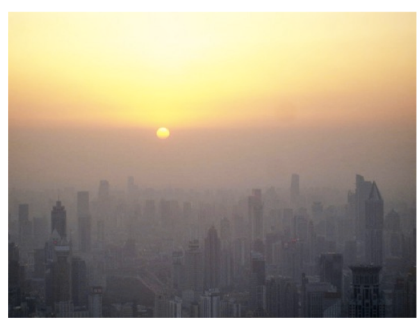
- Countries, groups vary in how they think about risk
  - Concerned with different dangers, for different reasons
  - Government approaches to managing risks differ
- Engineering-based, probabilistic assessments are one very important form of analysis
  - But what are the assumptions?
  - What is included, what is excluded?
  - We can only assess what we imagine
- Broader ways of conceiving the benefits, risks of technologies are also needed



Smog in Beijing. *Source:* inhabitat.com

Risk is not a fact – it's a set of ways of thinking, perceiving (II)

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- "Probabilistic risk assessment" is essential – but problematic
  - Key in systematically finding, addressing important risks in nuclear systems – but not as good at assessing <u>absolute magnitude</u> 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

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- 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 <u>organizational</u>

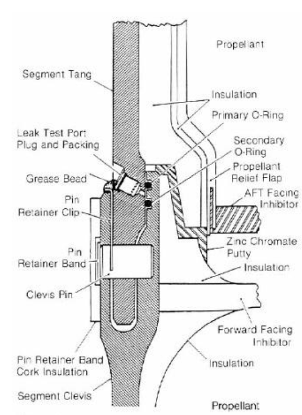

Figure 14
Solid Rocket Motor cross section shows positions of tang, clevis and O-rings. Putty lines the joint on the side toward the propellant

Source: Rogers Commission

Why do catastrophes happen?
Theory III: Complexity and tight coupling

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- 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"

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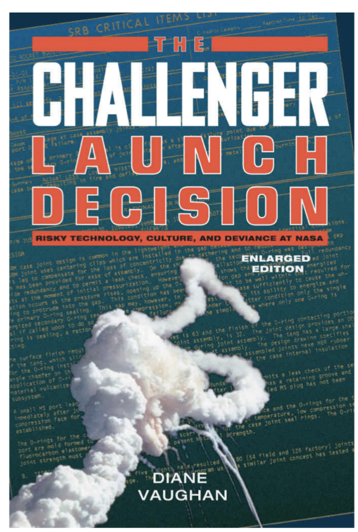
- Over time, in complex systems, practice drifts from initial rules
- Exceptions are made, and become "normalized" when nothing awful happens
- Organization rarely examines potential effect of the accumulation of exceptions
- Especially likely if there are strong cost, time pressures, little independent review



Why do catastrophes happen? Theory V: Risk delusions

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- 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

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- 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

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- 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 $1/10^5$ risk into a $1/10^6$ risk
  - Information is in many places – no one sees all of the risk

NRC and the backfit rule: underestimating probabilities and consequences?

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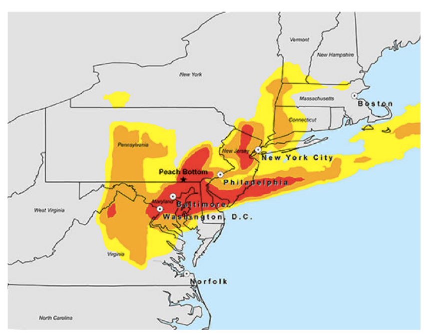
- NRC "backfit rule":
  - Don't require operators to take new safety steps unless societal benefit outweighs cost, <u>and</u> safety improvement is "substantial"
  - Some exceptions
- <u>But</u>, both probability and consequences uncertain, may be underestimated (or over)
  - Probability: different models 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

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- 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

Source: Army Corps of Engineers

Source: Air Photo Service, Japan

Democracy and nuclear energy: some (very partial) solutions

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- 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

Backup slides if needed…

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Nuclear energy: status after Fukushima

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- 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

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- 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

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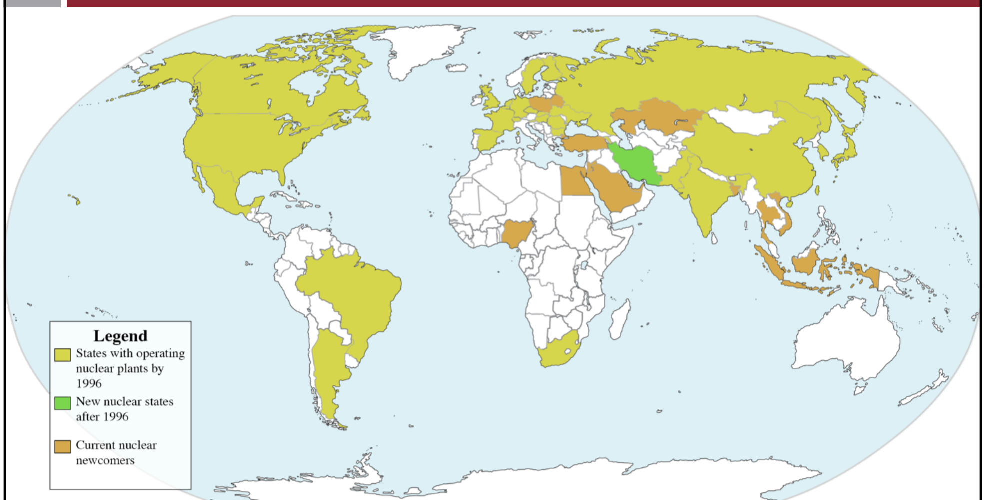

Source: IAEA PRIS Database, last retrieved April 15, 2016

Governance indicators of emerging nuclear power states

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Country	Control of Corruption	Regulatory Effectiveness
Bangladesh	23	17
Belarus	9	23
Chile	94	90
Egypt	49	41
Indonesia	43	28
Iran	3	22
Israel	81	75
Italy	78	59
Jordan	61	64
Kazakhstan	39	19
Kuwait	56	69
Malaysia	60	58
Morocco	52	51
Nigeria	26	15
Poland	79	71
Saudi Arabia	57	63
Thailand	62	51
Turkey	59	60
United Arab Emirates	69	81
Venezuela	4	8
Vietnam	31	37

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

Fukushima – what happened?

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- 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

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- 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

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- 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

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- 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

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- 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?

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- 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

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"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."

-- Admiral Hyman Rickover, memo, June 5, 1953, http://ecolo.org/documents/documents_in_english/Rickover.pdf

Small modular reactors

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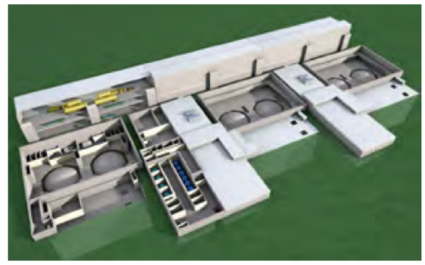
- Small modular reactors:
  - May make planning, financing easier with "bite size" plants
  - Both near-term and long-term varieties, different characteristics
  - Not clear if cost advantage of manufacturing scale will compensate for loss of advantage of physical scale
- Long-term concepts have some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

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- 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 22^{nd} 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

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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?* *Means to store it?*
End-use efficiency:	*Not enough informed, motivated end-users?*

Particulates may be as important as climate in driving clean energy

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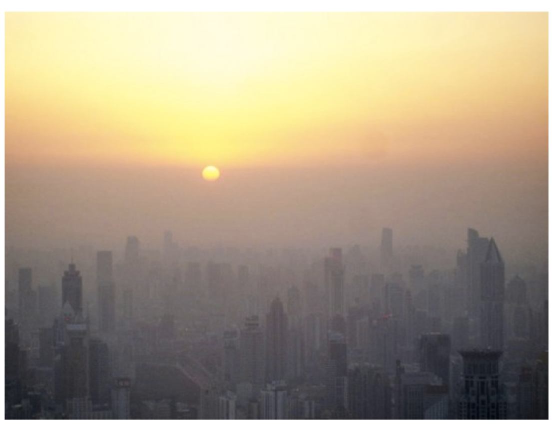

Smog in Beijing. *Source:* inhabitat.com

- **>3 million deaths/yr globally from fine particulates**

Steps to enable large-scale nuclear growth

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- 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

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- 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

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- 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?

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- 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