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Mitigating climate change: How much can nuclear energy plausibly do?

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Welcome to Zoom discussions…

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- Click on blue hand to raise your hand (we won't be able to see all of you if you physically raise your hand)
- You can also pose questions, offer comments in chat
- Let us know if you're having an issue
  - Sound not working
  - Screen not showing what I'm talking about
- I'll try to leave time for discussion and questions – so I won't cover everything!

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Why care about nuclear energy?

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- Nuclear energy provides:
  - Very low carbon emissions
  - Very low emissions of particulates and other pollution (likely more important reduction in social cost)
  - Baseload, non-intermittent power
  - 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?

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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, 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

The climate problem is so huge that for any energy source to make a major contribution, you have to be talking about terawatts

4

Particulates may be more important than climate in driving clean energy

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Smog in Beijing. *Source:* inhabitat.com

- >8 million deaths/yr globally from outdoor fine particulates

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With large-scale growth, nuclear <u>could</u> play a key role backing up renewables

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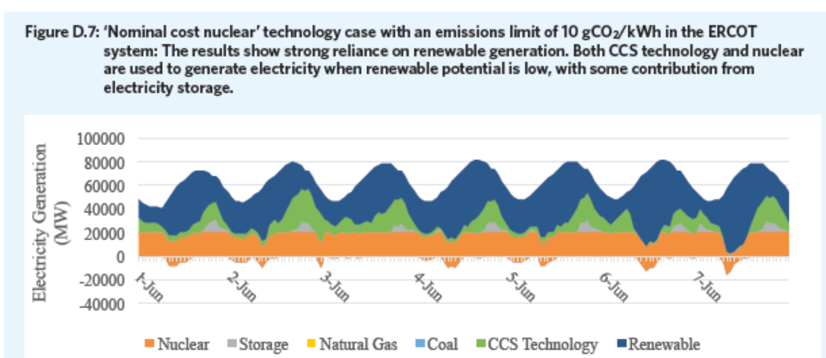

Source: MIT, *Future of Nuclear Power in a Carbon-Constrained World*, 2018

- Even with storage, non-intermittent low-carbon sources are important for deep decarbonization at reasonable cost
- Ideally, want not just steady power but peaking power

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Nuclear could potentially also play a role in other energy markets

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- Transportation
  - Could provide electricity for EVs
  - Or heat from nuclear could be used to produce liquid fuels
- Industry
  - High-temperature plants could provide industrial process heat
- Heating and cooling
  - One plant could provide district heating for a substantial town
- Desalination
  - Will be increasing needs for fresh water with climate change

Making a serious dent in these other markets would require even larger-scale growth…

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Constraints on nuclear energy growth may mean only a modest role by mid-century

8

- IAEA "high" nuclear growth case (2019):
  - 715 GWe by 2050
  - Providing 11% of global electricity
  - Electricity is 26% of total energy
  - So nuclear would be providing only 3% of global energy in 2050
- Historically, real growth has been far lower than the IAEA "high" nuclear case
- Projections have have been falling year-by-year since the 2011 Fukushima Daichi nuclear accident
  - First post-Fukushima "high" projection was 1228 GWe – 42% higher
- Nuclear industry's own "stretch" goal is 1000 GWe – would provide <5% of global energy

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International Energy Agency projections tell a similar modest story for nuclear

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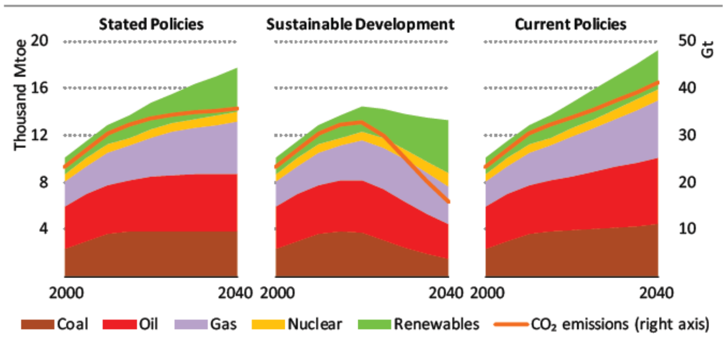
Figure 1.1 ▷ World primary energy demand by fuel and related CO_2 emissions by scenario



Existing policies and announced targets slow growth in global emissions to 2040, but they are not strong enough to force a peak in an expanding energy system

Source: International Energy Agency, *World Energy Outlook 2019*

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Nuclear energy's share of the emissions gap under the IAEA high growth case

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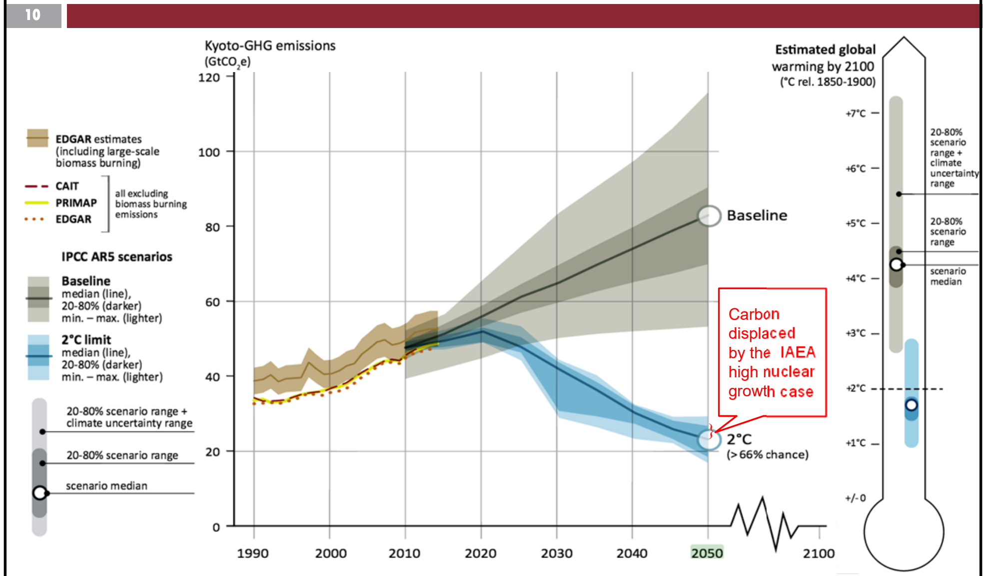

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Key constraints on nuclear energy growth to the terawatt scale

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- Cost – and financing
- Safety risks – real and perceived
- Security risks – real and perceived
- Nuclear waste management – mostly politics
- Siting and public acceptance
- Limited government and industry capacity
- Stringent regulation
- Proliferation risks – mainly from the nuclear fuel cycle
- U supply: Not likely to be a constraint this century

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Both policy and technology might help address constraints

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- New policies, e.g.:
  - Lower-cost financing
  - Flexible regulation – faster approvals, siting
  - Strong safety regulation, incentives – reduced accident risk
  - Strong security regulation, incentives – reduced terrorism risk
  - Controls, incentives to limit spread of enrichment and reprocessing
  - Capacity-building for newcomer states
- New technologies, potential to:
  - Reduce overnight capital cost
  - Allow plants to produce both electricity and process heat (e.g., for producing transport fuels)
  - Increased passive safety (also helps security)
  - Reduced need for enrichment
  - More efficient use of uranium resources
  - Reduced and/or shorter lifetime waste

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Cost is the biggest constraint on large-scale nuclear energy growth

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- In many markets, *new* nuclear is not competitive:
  - Very high capital costs
  - High costs of financing (with extra premium for nuclear risks – delays, cost over-runs…)
  - Where there are low gas prices, no carbon prices, no government-backed financing, nuclear uncompetitive
  - Not chosen by profit-focused utilities in competitive markets
- Some markets provide favorable conditions:
  - Government financing or government-enforced high prices (e.g., UK guarantee of ~2x current electricity price)
  - *Same* reactor cost can be competitive in one market, uncompetitive in another – because of different financing costs
  - Government choice or government-influenced choice of plant
- Growth to terawatt scale likely to require substantial progress on cost reduction

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Nuclear costs: a forgetting curve?

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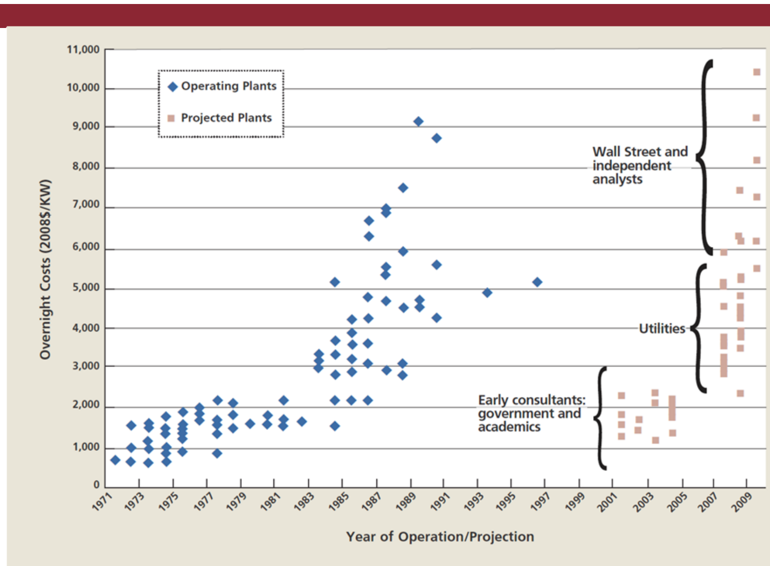

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Nuclear costs: most experts are not expecting a breakthrough

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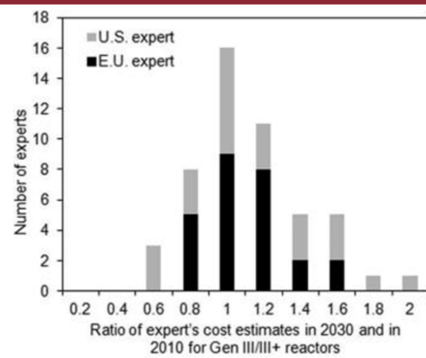

Source: Anadon, Bosetti, Bunn, Catenacci, Lee, *Environmental Science & Technology*, Vol. 46, 2012

- Most experts in a recent elicitation expected Gen. III reactor costs to *increase* by 2030
- *Higher* average projected costs for Gen. IV and small reactors

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Where to put them? Public acceptance and siting are major constraints on nuclear growth

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- Publics in many countries have protested new nuclear sites
  - Fukushima Daiichi accident increased public concerns
  - Protests have repeatedly led to cancellations, delays, relocations
  - Even in China, multiple sites have been abandoned after protests
  - Chinese government has not yet approved construction at any inland sites – and few suitable coastal sites remain
- Various options for building public acceptance
  - In-depth engagement with, fulfilling promises to, local communities – genuinely voluntary approach
  - Communication has to be two-way, not just industry "educating" the public
  - Advanced designs have more passive, demonstrable safety
  - Communities that already have a reactor, with the jobs and tax revenues it brings, are usually supportive – but there are limits to how many can be built at existing sites

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Post-Fukushima, perceptions of safety are a major part of the siting constraint

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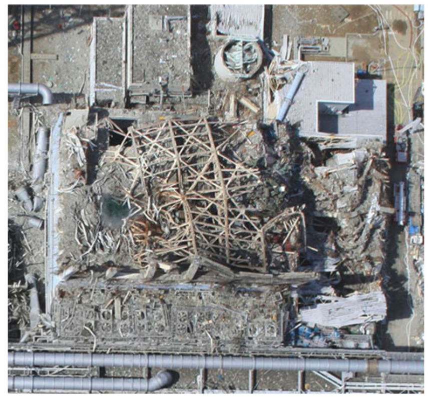
- Nuclear energy is an unforgiving technology
  - Requires high performance of operators, regulators
  - Raises deep issues of organizational performance and culture
  - "Newcomer" states have not had a chance to build up safety infrastructure – and on average are more corrupt and have weaker regulation
- New designs are safer
  - But a week with no power or heat sink, as at Fukushima, would be a problem for any design currently available for construction



Source: Air Photo Service, Japan

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Sabotage is also an issue

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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 is also a concern
  - Effective nuclear security measures are required – and are 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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POLICYFORUM

NUCLEAR SAFETY

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**

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Nuclear growth implies nuclear spread: the story so far

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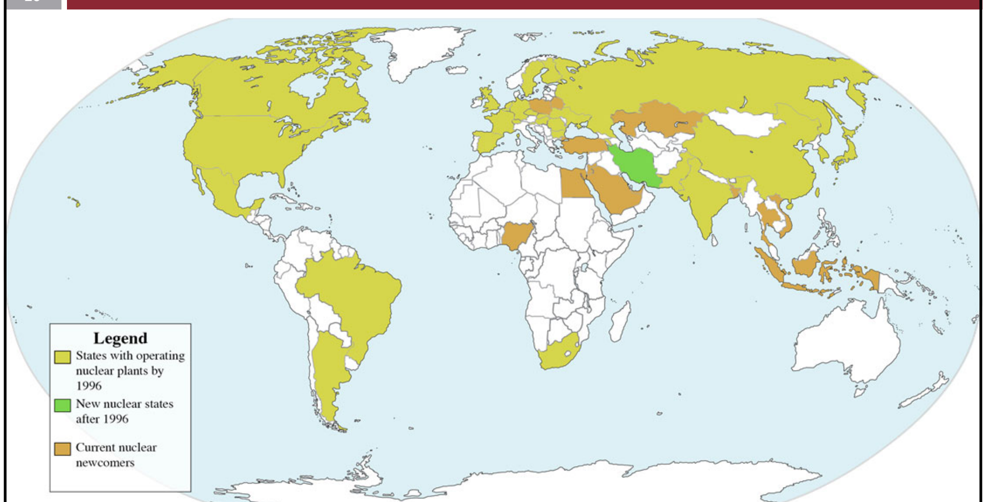

Source: IAEA PRIS Database, last retrieved April 15, 2016

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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.

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Will new technology help? Ex.: fluoride high-temperature reactors

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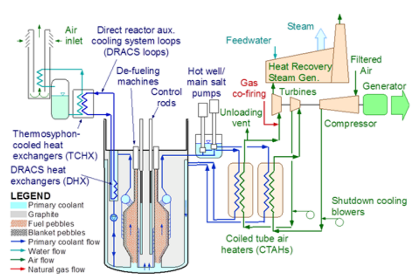
- Idea:
  - Fluoride salt coolant (> 1300° C boiling temp)
  - Fuel in TRISO particles embedded in graphite pebbles
  - High temperature → high efficiency, ability to make chemicals when electricity price is low → much better economics
  - Excellent safety: "I can't figure out how to cause a release with this reactor"
- Conceived at MIT, Berkeley, and Wisconsin
  - China funding 1st test systems



Flow schematic for Mark 1 pebble-bed fluoride high-temperature reactor

Source: fhr.nuc.berkeley.edu

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Nuclear innovation: reasons for optimism

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- Exciting new ideas:
  - Hoped-for lower costs (and smaller size to ease financing), passive safety, high temperature to provide process heat
  - 2 classes of concepts:
    - Near term: variants on light-water reactors
    - Longer term: different coolants, fuels, etc.
- Dozens of start-up firms
  - Drawing in venture capital, new people
  - Some large firms also pursuing new concepts
- New technologies that were not available before, e.g.:
  - Radically improved computer simulation
  - New materials
  - Modular and factory construction approaches

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Nuclear innovation: reasons for pessimism

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- Market and technology structure:
  - Commodity market
  - Low-cost gas means little profit potential
  - EXTREMELY conservative buyers – utilities
  - Product life-cycle measured in decades
  - Billion-dollar tests – few real "shots on goal"
  - Stringent, conservative regulation
  - HUGE barriers to entry
- Past experience:
  - No really new reactor concept has been commercialized for >50 years
  - 0% of past predictions of new cheap systems have proved to be correct
  - Current "Gen. III" reactors were supposed to be cheaper than Gen. II – are more expensive

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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

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Nuclear innovation: a thought experiment

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- Imagine:
  - Prototype of a new reactor concept starts operation in 10 years (very aggressive schedule)
  - 2 years of operation is enough to sell 10 GWe of commercial plants, which take only 3 years to build
  - 2 years after those sales, 20 GWe more are sold
  - Then increases to 40, 60, etc. every 2 years, and stabilizes at 100 GWe/yr (reaching that level in 2048)
  - Even that extremely aggressive (and highly unlikely) schedule leads to ~1100 GWe in 2050 – an important, but ultimately modest, contribution
- For near-term bending of the climate curve, new policies are likely to be more important than new technologies – most electrons from nuclear power by 2050 likely to be from existing reactors or types

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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
- It will be harder to cope with climate without a significant contribution from nuclear – but it will be hard 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

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Managing the Atom opportunities

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- Managing the Atom is the hub of nuclear policy research at HKS
  - ~ 15 fellows, staff
  - Several associated faculty
  - Research, policy outreach
- Weekly seminar: 10-11:30 Wednesdays (now via Zoom)
  - To get added to the invitation list, email Jacob_carozza@hks.harvard.edu
- Currently hiring
  - Full-time research associate
  - Part-time student associate (now, and summer)
- https://belfercenter.org/managingtheatom

Source: Chuck Kennedy, Official White House photo

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Backup slides if needed

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New policies likely more important than new technologies – for now

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- Financing
  - Can we find politically acceptable ways to reduce financing costs?
- Regulation
  - Can all relevant countries maintain very high safety and security standards?
  - At the same time, can we develop more flexible, less cumbersome approaches – especially for new technologies?
- Public acceptance
  - Can we build real dialogue with host and neighbor communities, address their concerns in a way that genuinely builds trust?
- Fuel cycle
  - Can we manage the fuel cycle in ways that minimize proliferation risk?

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Nuclear energy: status today

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- 442 operating reactors worldwide, 390.5 GWe (3/2020)
  - 10% of global electricity, 2% of global final energy consumption
  - 30 countries + Taiwan
- 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 were 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 34-42%)

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Constraints on nuclear growth are leading to pessimistic projections

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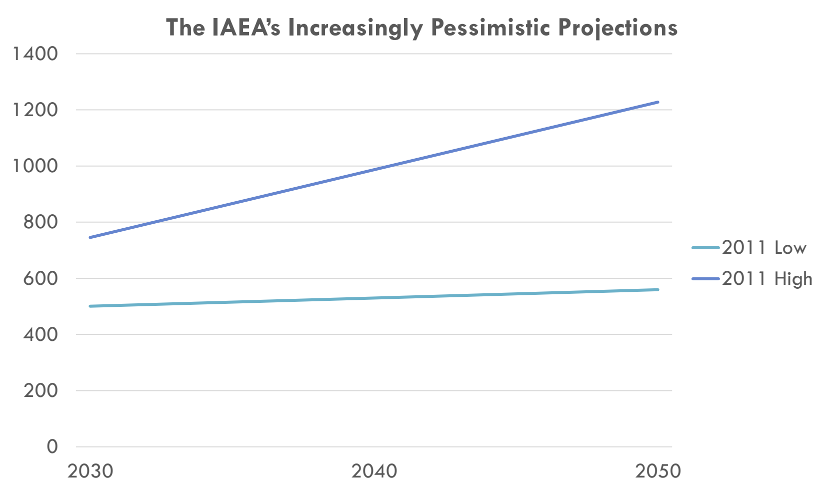

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Constraints on nuclear growth are leading to pessimistic projections

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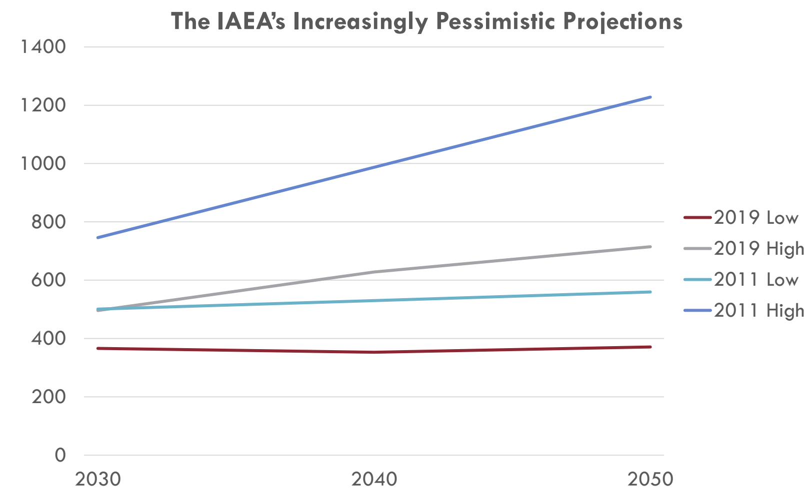

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The energy-climate context

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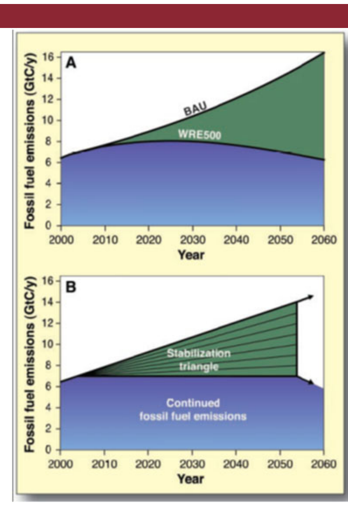
- *Dramatic* nuclear growth required for climate contribution large enough to be significant
- To provide *one* of seven "wedges" needed to stabilize CO2 at 500 ppm, nuclear would have to add 700 GWe of capacity by 2050 – and replace most existing capacity
- 2 wedges – as in Stern report – may be unobtainable
- Latest science suggests 10-15 "wedges" may be needed



Source: Pacala+Socolow, "Stabilization Wedges," *Science* **305** 968-972 (2004)

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For a nuclear "wedge," huge increase in construction needed

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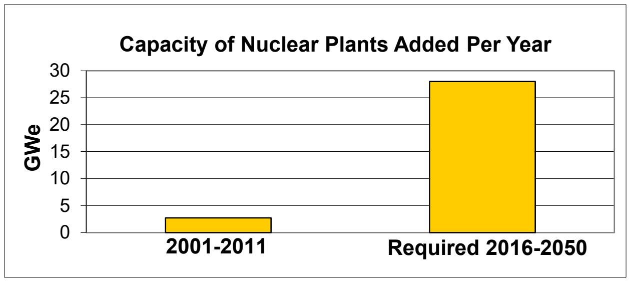

- Need to shift from 3 to 28 GWe/yr
- Nuclear must become dramatically *more* attractive to governments and utilities than it was before Fukushima – a difficult challenge
- Any further disaster, from accident or terrorism, would doom any realistic prospect for growth on this scale

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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

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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

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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

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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

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Small modular reactors

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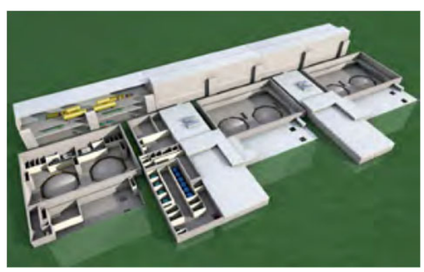
- Small modular reactors:
  - *May* make planning, financing easier with "bite size" plants
  - Both near-term and long-term varieties, different characteristics
  - Not clear if cost advantage of manufacturing scale will compensate for loss of advantage of physical scale
- Long-term concepts have some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

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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 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

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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?*

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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

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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

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Making nuclear energy broadly available

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- Complex 1-1.6 GWe LWRs not appropriate for many countries, regions
  - Requires substantial infrastructure of trained personnel, regulation, safety and security culture…
  - Grids can't support that much power at one spot
- Potential for small and medium factory-built reactors
  - More appropriate for smaller, less well-developed grids, or off-grid locations
  - Much lower capital cost per reactor eases financing (even in U.S.)
  - Smaller sizes make safety design easier – potential for "walk-away safe" designs (still to be demonstrated), underground siting
  - Could be built with lifetime fuel built-in, sealed core, no access to nuclear fuel by host state

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Making nuclear energy available for a broader array of purposes

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- Electricity beyond the baseload
  - Nuclear reactors could generate electricity when needed, storable products (e.g., hydrogen) when not
  - Hydrogen could provide additional peaking power – could even back up intermittent renewables
  - Economics as yet unproven
- Transportation fuel
  - Electricity for electrics and hybrids
  - Heat and hydrogen for refineries and biorefineries (could cut land area needed for biomass fuels in half), and for oil shale recovery
- Heat for desalination and many industrial processes
  - Many applications require high-temperature reactors

More R&D required to explore these many possibilities

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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

47

Two things we shouldn't do

48

- Plutonium reprocessing
  - Separates plutonium from spent fuel to recycle as new fuel
  - Could also provide plutonium for bombs
  - Fortunately, there's plenty of uranium, reprocessing is expensive and provides only modest benefits, dry cask storage provides a safe alternative for decades
- Widespread uranium enrichment
  - Same technology used to produce low-enriched fuel for reactors can produced highly enriched uranium for bombs
  - Most countries with nuclear power do not enrich their own fuel
- Institutional steps can help
  - E.g., "fuel leasing" – offering lifetime fuel supply and spent fuel take-back for states that rely on international fuel supply

48

Safety culture matters: Davis-Besse vessel head hole

49

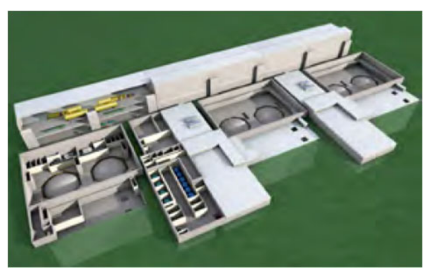
Source: FirstEnergy

49

Small modular reactors

50

- 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

50

New nuclear power in the United States – what are the prospects?

51

- Subsidies: 2005 EPAct provides production tax credit for first 6 plants; $18.5B in loan guarantees authorized (industry wants $100B); insurance against reg. delays
- Four AP-1000 reactors started construction – all in cost-plus regulated markets
  - Two plants at Summer canceled after huge delays, cost overruns
  - Two plants Vogtle billions of dollars over budget, years behind schedule
- Economics has led several companies to reconsider
  - $2-$5 natural gas; no carbon price
  - Escalating nuclear construction costs, nuclear "risk premium"
  - Post-Fukushima worries and politics a smaller factor
- Prognosis: no near-term U.S. plants except at government sites, or with major government subsidies

51

Expanding nuclear energy need not increase terrorist nuclear bomb risks

52

- Could have global nuclear energy growth with no use of directly weapons-usable nuclear material in the fuel cycle
  - Low-enriched uranium (LEU) fresh fuel cannot be made into a bomb without technologically demanding enrichment
  - Plutonium in massive, intensely radioactive spent fuel beyond plausible terrorist capacity to steal and process
- *If* scale of reprocessing, transport, and use of plutonium from spent fuel expands, nuclear energy contribution to nuclear terrorist risks would increase
  - Reprocessing converts plutonium into portable, not very radioactive, readily weapons-usable forms
  - With major exception of Rokkasho in Japan, current trend seems to be away from reprocessing – reduced operations at La Hague and Mayak, phase-out at Sellafield

52

Preventing nuclear proliferation

53

- Global nuclear nonproliferation regime is under severe stress – Iran, North Korea, the A.Q. Khan network, the global spread of technology, potential growth and spread of nuclear energy, disputes over disarmament, India deal…
- *But*, the regime has been both <u>successful</u> + <u>resilient</u>
  - 9 states with nuclear weapons today – 9 states 25 years ago
  - More states that started nuclear weapons programs and verifiably gave them up than states with nuclear weapons – nonproliferation succeeds more often than it fails
  - Every past shock has led to parties introducing new measures to strengthen the system
  - All but 4 states are parties to the NPT, and believe it serves their interests
- With right policies today, can hope to have only 9 states with nuclear weapons 20 years from now – or fewer

53

Limiting fuel cycle proliferation risks

54

- Incentives for states not to build their own enrichment and reprocessing facilities
  - International centers in which all states can participate (but not get sensitive technology), such as Angarsk IUEC
  - Fuel banks (including Russian, U.S., IAEA-controlled)
  - Offers of "cradle-to-grave" fuel services
    - Regional repositories
    - "Fuel leasing"
    - "Reactor leasing"
  - Potential role for marketing factory-built small and medium reactors, with "cradle-to-grave" fuel and reactor services
- Restrain technology transfers (licit and illicit)
- Move step-by-step to increased multinational control over sensitive fuel cycle facilities

54

Nuclear role in 3 greatest global energy challenges

55

- 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 <1/3 global primary energy – and most future demand growth in developing countries with modest nuclear contribution so far

55

The foundation for large-scale growth: near term institutional steps

56

- Government policies can reduce costs, ease financing
  - Expedited licensing
  - Low-cost financing, government-backed insurance, other subsidies
  - After decades of subsidies, how much more subsidy is justified?
- New policies can reduce accident risks
  - Range of measures can help ensure cores stay cooled, radiation is better contained
  - Strengthened peer reviews to find and fix the least safe reactors
  - Shut-down or take major safety steps for oldest, least safe reactors
  - Help "newcomer" states establish safety infrastructures, culture
  - Build toward effective, binding global nuclear safety standards, with mandatory international peer review, for long term
- New policies can reduce terrorism risks, too
  - Beefed up security measures, enhanced peer review…

56

Near term institutional steps (II)

57

- Actions to strengthen protection against nuclear terrorism
  - Strengthen security measures for all nuclear weapons, HEU, plutonium worldwide – major progress, still much to do
  - Minimize HEU and plutonium use, number of sites
  - Strengthen reactor protection against sabotage worldwide (many countries have no armed guards, few insider protections)
  - Expand exchanges of security best practices, peer reviews
  - Targeted programs to strengthen security culture
  - Move toward effective, binding security standards for long term

57

Near term institutional steps (III)

58

- Approaches to manage nuclear wastes
  - Establish dry cask storage of spent fuel wherever needed
  - Establish democratic, voluntary approaches to siting repositories
  - Move toward increased international cooperation – including regional or international spent fuel storage, disposal
  - Move toward "fuel leasing" and "reactor leasing" – "cradle to grave" fuel services

58

Near term institutional steps (IV)

59

- Steps to avoid nuclear weapon proliferation
  - Engage the hard cases (North Korea, Iran)
  - Strengthen IAEA safeguards
  - Stop black-market nuclear technology networks
  - Reduce the risks of enrichment and reprocessing
  - Toughen enforcement
  - Reduce demand
  - Keep the weapon states' end of the bargain

59

What are the prospects for change?

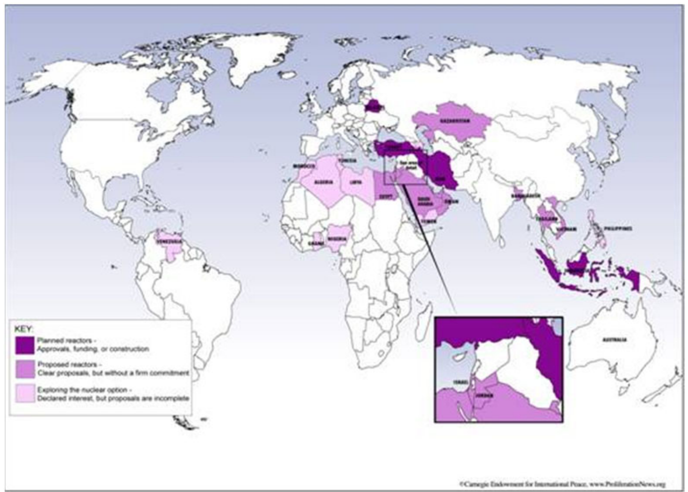
60

- 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 economieis, Iran, Afghanistan, the Middle East, all shrink the attention senior policy-makers are likely to give

60

Large-scale nuclear growth implies nuclear spread – the picture so far

61



Source: Carnegie Endowment for International Peace

61

Some longer-term measures to control the civilian-military link

62

- Control of sensitive nuclear activities needs to be rethought if we are serious about deep nuclear reductions, possibly someday to zero
  - Purely national control of (a) stocks of nuclear material equivalent to thousands of bombs; (b) facilities capable of producing thousands of bombs' worth of material per year will likely no longer be acceptable
  - Need to move toward some form of international/multinational ownership/control
  - Need far-reaching verification measures, for all sensitive nuclear activities (military and civilian – incl. in weapon states)
- In a world with far more nuclear energy, will need to:
  - Satisfy fuel cycle needs without spread of nationally-controlled enrichment and reprocessing facilities
  - Develop, deploy more proliferation-resistant systems (e.g., "nuclear battery" reactors with small staffs, sealed cores, "cradle to grave" fuel services)

62

The scale of the control problem…

63

- Making roughly 15 kilograms of highly enriched uranium (HEU) for one bomb requires ~ 3500 units of enrichment work
  - Current global *civilian* enrichment capacity enough to produce material for >13,000 weapons/yr – would have to triple for stabilization wedge on once-through fuel cycle
- Making one bomb from plutonium requires ~ 4-8 kilograms of plutonium
  - Current global *civilian* plutonium separation ~ 20 t/yr, enough for > 3,000 weapons/yr (capacity is larger, but underutilized)
  - Nuclear stabilization wedge with plutonium fuel cycle (mix of fast reactors and thermal reactors) would require reprocessing ~835 tonnes of plutonium and minor actinides/yr – amount needed to produce ~140,000 bombs
- Controls must prevent diversion of 1 part in 10-100,000, *and* limit the spread of the technology – daunting challenge

63

Addressing safeguards challenges

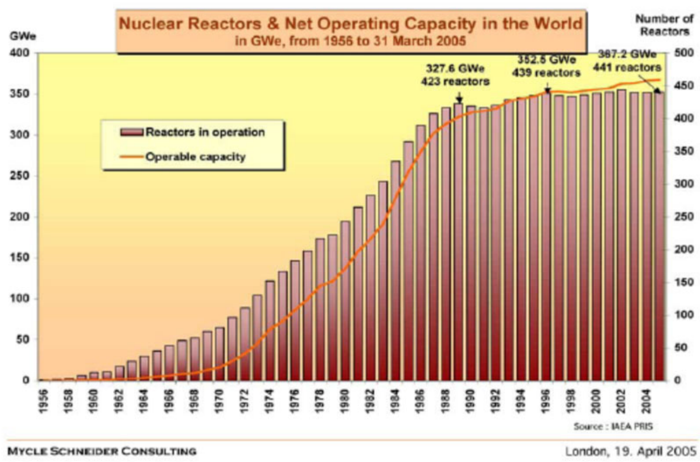
64

- Convince states to give IAEA resources, information, authority, personnel, technology it needs to do its job
  - Provide substantial increase in safeguards budget
  - Press for all states to accept Additional Protocol, make this condition of supply
  - Limit spread of fuel-cycle facilities
  - Provide information from intelligence, export control (denials, inquiries, etc.), other sources
  - Reform IAEA personnel practices to attract, retain best-qualified experts in key proliferation technologies
  - Reinvest in safeguards technology, people (e.g., "Next Generation Safeguards Initiative")
  - Adopt philosophy of "safeguards by design" for new facilities
  - Develop technologies and procedures to safeguard new fuel-cycle technologies before deploying them

64

A fragile revival? TMI + Chernobyl stopped nuclear growth

65

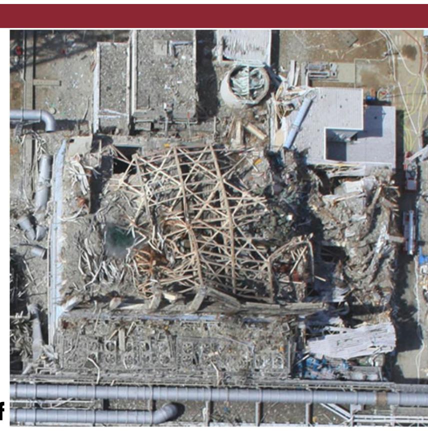


65

Fukushima – what happened?

66

- 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

66

Recommended next steps to respond to Fukushima

67

- First: more stringent national and international standards
  - Ability to respond to prolonged loss of off-site power
  - Ability to respond to damage to cooling systems
  - Emergency response
  - Protection against terrorist attack
  - Seismic, flood safety
  - Management of spent fuel
- Second: independent, international peer review
  - All countries operating major nuclear facilities should request
- Third: toward more binding obligations
- Fourth: expanded int'l cooperation – exchanging experience and…
- Long-term: shift toward greater "safety by design" and "security by design" in new reactors

67

Fukushima: evolving narratives

68

- 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

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Fukushima: questions and lessons

69

- Questions:
  - Why didn't Japanese regulators, operators, respond to data indicating a risk of very large tsunamis?
  - How can we structure incentives in organizations to get people to focus on fixing low-probability, high-consequence risks?
  - How can we avoid regulators becoming "captured" by the industries they regulate?
- Lessons:
  - Need better ability to cope with prolonged loss of power
  - Need faster ability to maintain, restore cooling
  - Need safer management of spent fuel pools
  - Need stronger emergency response
  - Need better approaches to public, international information and communication
  - Existing regulatory approaches are insufficient

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Nuclear safety: complexities

70

- *Huge* quantity of energy, radioactive toxicity in small volume in core
  - *Must* be cooled continuously, or "meltdown" will occur
  - "Fire that won't go out" – reactor keeps generating heat from intense radioactive decay, needs cooling, long after shut-down
  - Reactors need (a) water and (b) electricity to operate cooling systems to prevent accidents
- "Defense in Depth" philosophy
  - Multiple layers of protection – the fuel itself, the reactor vessel, the containment
  - Redundant safety systems
  - Are complex, tightly coupled systems inherently prone to accident?
- Two major radiation releases in 14,400 reactor-years for commercial reactor – >10x more than regulatory safety goals

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Fukushima: global reactions

71

- 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…

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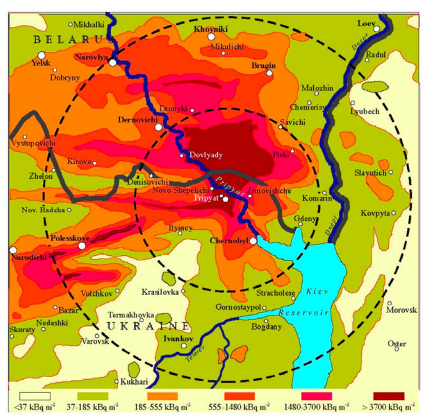
Chernobyl – an epic disaster

72



Cs-137 contamination after Chernobyl.
Source: **UNSCEAR, 2000**

72

Nuclear terrorism remains a real danger

73

- Some terrorists are seeking nuclear weapons and materials
- Some terrorists could plausibly make a crude nuclear bomb if they got needed nuclear material
- ~ 20 real cases of theft or smuggling of HEU or plutonium (most recent March 2010)
  - Inadequate security measures to defeat demonstrated threats in many countries
- Devastating consequences – would reverberate worldwide
  - Even small probability is enough to motivate action

Source: Block/AP

73

How might nuclear growth and spread affect sabotage risks?

74

- Chance of major release caused by malevolent action may well be higher than chance from pure accident
  - Yet industry focus overwhelmingly more on safety than security
- Number of sabotage attempts likely to be driven by level of terrorist groups' interest, *not* number of reactors
- *But:*
  - More reactors in more places means more chances for security mistakes that could create a sabotage vulnerability – *unless* security measures strengthened as nuclear energy grows
  - Even more than with safety, small numbers of poorly secured plants can dominate total risk – terrorists more likely to choose them, and more likely to succeed if they do
  - Focus should be on ensuring effective security for all major nuclear facilities

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Strengthening nuclear security

75

- Rapidly upgrade security for all nuclear warheads, HEU, plutonium, and high-consequence nuclear facilities and transports (esp. in high-threat countries)
  - Tools from bilateral technical cooperation to international treaties
  - Need to strengthen international nuclear security "regime complex," provide effective forum for dialogue when summits come to an end
  - As with safety, develop more stringent standards, expand peer review, strengthen international cooperation
  - Expand security-focused training, programs to strengthen security culture, exchange of best practices, peer reviews

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Security culture matters: Propped-open security door

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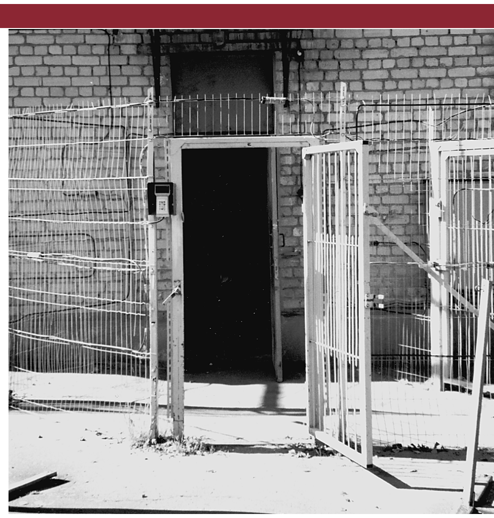


Source: GAO, Nuclear Nonproliferation: Security of Russia's Nuclear Material Improving, More Enhancements Needed *(GAO, 2001)*

76

Belief in the threat – the key to nuclear security success

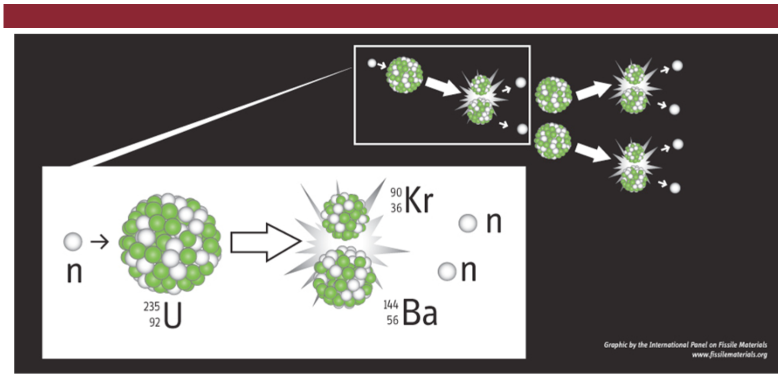
77

- Effective and lasting nuclear security worldwide will not be achieved unless key policymakers and nuclear managers around the world come to believe nuclear terrorism is a real threat to *their* countries' security, worthy of investing their time and resources to address it
- Steps to convince states this is a real and urgent threat:
  - Intelligence-agency discussions – most states rely on their intelligence agencies to assess key security threats
  - Joint threat briefings – by their experts and our experts, together
  - Nuclear terrorism exercises and simulations
  - "Red team" tests of nuclear security effectiveness
  - Fast-paced nuclear security reviews – by teams trusted by the leadership of each country
  - Shared databases of real incidents related to nuclear security, capabilities and tactics thieves and terrorists have used, lessons learned

77

Nuclear fission: a <u>lot</u> of energy from a little material

78



- ≈ 200 million electron volts (MeV)/fission
  - ≈ 10 million times more than chemical reactions
  - Energy for bombs, or for civilian power
- Can generate huge amounts of energy (and toxicity) in a small space with a modest amount of material
  - Source of safety, security issues

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Nuclear reactors – a complicated way to boil water

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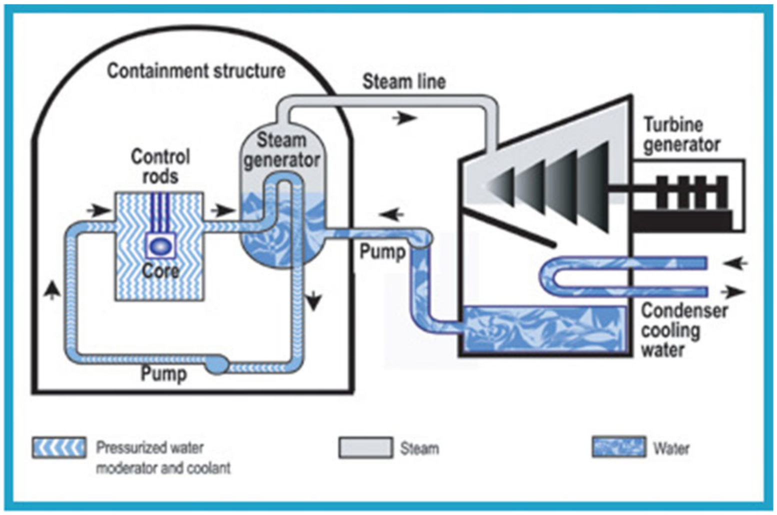

Source: www.world-nuclear.org

79

Japan: political impacts

80

- Broad public opposition to nuclear power
  - But high costs of other options
  - Strong industry opposition to proposed phase-out
  - New government reversed phaseout, seeks to restart reactors
- Dramatic reduction in trust in government, nuclear industry
  - Public has faulted response to both tsunami and nuclear accident
  - Election tossed out yet another PM
  - Public protests against nuclear policies
  - New nuclear regulatory agency has proposed tight new rules
- Some potential geopolitical impacts:
  - Increased Japanese dependence on Middle East oil, gas
  - Possible Japanese LNG imports from United States?
  - Increased oil demand – impact on world price?

80

Nuclear costs: financing, schedule are crucial

81

- For capital-intensive energy sources, cost of capital is key:
  - 3% government rate radically different from 10-12% private, unregulated rate
  - *Same* physical construction cost can be better than other energy sources with one financing package, worse with another
- Risk from huge scale of financing required
  - 'Betting the company" on $10-$20B project
  - Requires complex, time-consuming deals to spread risk
- Schedule has a major effect on cost
  - Interest during construction
  - Inflation (nuclear inflation higher than other)
- South Korea, China build reactors for lower costs on shorter schedules – with lower-cost financing

81

Managing nuclear waste

82

- Nuclear reactors generate intensely radioactive spent fuel – will remain dangerous for >100,000 years
- Stored initially in pools – once cooled, can be stored safely for decades in concrete and steel dry casks
- Two choices (with many variants) for final disposition:
  - (1) Direct disposal – bury fuel in deep geologic repository
  - (2) Reprocessing – chemically process to recover plutonium, uranium, for reuse, dispose of fission products in deep geologic repository
  - Reprocessing extends resource, but is currently more costly, poses greater safety, security, and proliferation risks
  - Dry casks make it possible to postpone decision, let technology, economics, politics evolve

82

Managing nuclear waste (II)

83

- Nuclear waste carries enormous political controversies, but modest risks to human well-being
  - Solid materials in remarkably strong canisters deep underground
  - Potential post-disposal leakage only over 1000s of years – modest doses to small number of people in distant future
- Different countries are taking different political approaches, with different results:
  - Finland and Sweden – highly voluntary, consensus-building approach, sites picked with full support of local communities
  - United States – 49 states ganged up on Nevada. Obama has now canceled Yucca Mountain, leaving the entire U.S. program in crisis
- More severe problems with nuclear waste arise *before* disposal – especially with liquid wastes from reprocessing

83

Nuclear waste repositories

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Source: **Nature,** ***4-20-06***

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