HARVARD Kennedy School
BELFER CENTER
FOR SCIENCE AND INTERNATIONAL AFFAIRS

Perspectives on proliferation-resistance (and terror-resistance): fuel cycles and advanced reactors

Matthew Bunn
Professor of Practice, Harvard Kennedy School

Briefing to National Academies Committee on Advanced Reactors and Fuel Cycles

17 May 2021

belfercenter.org/managingtheatom

1

Proliferation resistance and terror resistance – 2 separate questions

2

- How much would the materials, facilities, and expertise provided by a nuclear energy system facilitate a state's nuclear weapons program?
  - Or increase the likelihood of the spread of technologies that would facilitate nuclear weapons programs?
- How much would the materials, facilities, and expertise provided by a nuclear energy system
  - Make it easier for terrorists to acquire the materials for a nuclear bomb or radioactive exposure or dispersal device?
  - Offer attractive sabotage targets?

2

Nuclear energy affects proliferation – but is not the main driver

3

- Nuclear weapons programs drive nuclear energy demand more than nuclear energy tempts states to pursue nuclear weapons
  - Nuclear weapons programs driven by security, prestige, domestic politics, bureaucratic imperatives
- *But*, leaders will be more likely to seek nuclear weapons if they perceive that such a program will be:
  - Cheap
  - Quick
  - Secret
  - High-confidence
- Nuclear energy systems – particularly enrichment and reprocessing – can facilitate nuclear weapons programs, increase the probability of states pursuing them

3

Nuclear energy affects proliferation – but is not the main driver (II)

4

- Two things are *both* true:
  - No state has ever built a bomb with material from a safeguarded nuclear facility
  - Most nuclear weapons programs since civilian nuclear energy became widely established have had crucial contributions from the civilian sector
- Most programs: dedicated military production facilities for Pu or HEU, but civilian sector provided:
  - source for open or covert technology acquisition
  - "cover" for purchases actually intended for weapons program
  - buildup of infrastructure and expertise
- A few programs: Pu or HEU directly from ostensibly civilian facilities – or consideration of purchase of stolen fissile material

4

Making weapons-usable material is the hardest part of making a bomb

5

- >90% of the effort in the Manhattan project went to producing the material
  - Plutonium
  - Highly enriched uranium
- With enough Pu or HEU, most states, and even some terrorist groups, would be able to make at least a crude bomb
- Hence, most of the global nonproliferation is focused on limiting access to weapons-usable material, technologies to make it
  - IAEA safeguards focus exclusively on nuclear material
  - Export controls overwhelmingly focus on technologies related to producing, processing, plutonium or HEU
  - Intelligence, interdiction, other efforts also focused on materials
  - JCPOA is key example

5

Proliferation risk of nuclear energy is mainly from enrichment and reprocessing

6

- Any state with an enrichment or reprocessing plant has the technology and know-how to produce bomb material if and when it chooses
- Fortunately, only a few states without nuclear weapons have enrichment or reprocessing plants
  - And some of those are internationally owned, reducing risk
  - Some evidence risk declines once commercial plants are long-established
- "Advanced" approaches to reprocessing that do not provide pure plutonium still provide experience with chemical processing of intensely radioactive spent fuel, facilities that can be adapted… significant reduction in time and cost
  - Bush admin. NNSA study: on a scale of A-Z, with PUREX separating pure plutonium as Z, best processing methods about a W

6

Proliferation and terrorism risks of enrichment and reprocessing plants

7

- Use of plants to produce bomb material
  - Openly (if not inspected, or after ejecting inspectors)
  - Secretly (attempting to divert without inspectors noticing)
- Use of experience to build secret plants
- Leakage of technology
  - E.g., A. Q. Khan's theft of URENCO centrifuge technology
- Encouraging other states to establish similar facilities
- Terrorism:
  - Theft of weapons-usable material (reprocessing, not enrichment)
  - Sabotage (more important for reprocessing plants, with both spent fuel and high-level waste on-site)

7

Proliferation risks from safeguarded reactors <u>by themselves</u> are usually modest

8

- Most current and proposed reactors use fuel that is not weapons-usable
  - MOX and other plutonium fuels different – any state could easily separate pure plutonium from fresh fuel, some terrorist groups could
- Plutonium in spent fuel could not be used for weapons without a reprocessing facility
  - Reasonable chance secret facility would be detected
- Safeguards would have a good chance of detecting removal of spent fuel
- Materials, facilities, expertise from operating most reactors would contribute only modestly to reducing time, cost, observability, uncertainty of a nuclear weapons program

8

An assessment framework for proliferation resistance

9

Effect on:	Facilities	Expertise	Materials
Time			
Cost			
Observability			
Confidence			
"Cover" for activities			
Technology leakage			
Safeguards confidence			
Safeguards resources			

9

Proliferation-resistance: the wrong way to think about it

10

- Simple metrics based on characteristics of material in the fuel cycle, e.g.:
  - "I'll be OK if I have no pure separated plutonium"
  - "I'll be OK if the radiation field of the recycle material is more than *x* Sv/hr at 1 m"
  - "I'll be OK if the Pu-239 content of the recycle material is less than *y* percent of total plutonium"
  - "I'll be OK if I make sure there's not step in the fuel cycle where the material could be used in a bomb without processing"
- Such simplistic approaches miss most of the real proliferation problem – but are amazingly common in current discussions of R&D for proliferation resistance

10

Example: pyroprocessing

11

- Idea: retain minor actinides, some lanthanides with Pu in recycling system
- Somewhat better than PUREX -- reduces the risk of terrorist theft and use in a weapon
- *But,* if widely deployed, would mean large number of states building up expertise, facilities, operational experience with chemical processing of intensely radioactive spent fuel, and with plutonium metallurgy -- could significantly reduce time and cost to go from there to nuclear weapons program
- Material much easier to get Pu from than LWR spent fuel
- Paying attention to expertise and infrastructure -- what history suggests is nuclear energy's biggest contribution to weapons programs -- can lead to different answers than focusing only on material characteristics

11

Example 2: Simple, lifetime core systems

12

- Various concepts for nearly "plug and play" reactors – possibly factory-built, with high inherent safety, shipped to a site, operated for 10-20 years without refueling, returned to factory
- Need for nuclear expertise in each state using such reactors might be greatly reduced
- High burnup (and difficult reprocessing) could make spent fuel unattractive (though not impossible) for weapons use
- Conceivable could have large-scale, widely distributed deployment with modest contribution to proliferation risk (mainly from availability of enrichment technology used to support reactors)
- Been pursued largely for economics and possibility of wide deployment, but proliferation-resistance interesting also

12

Proliferation hazards of spent fuel repositories

13

- Sometimes argued disposal of spent fuel of current types in repositories would create large long-term proliferation hazard – fuel will cool, higher Pu isotopes will decay, safeguards may someday not be maintained
- *But:*
  - Low-cost safeguards on repositories likely to be maintained as long as nuclear energy is in use anywhere – can set aside endowment now adequate to fund them forever
  - World will look very different, proliferation issues it faces will be very different, centuries from now
  - Should not increase large near-term risks (e.g., by reprocessing) to decrease small and highly uncertain long-term risks
- Bottom line: if we could get to the point where Pu in spent fuel in repositories was biggest proliferation hazard remaining, would be a great victory

13

Proliferation hazards of the research infrastructure

14

- Proliferation impact of the civilian energy system does not come *only* from the power sector – research sector must be considered as well
- India made Pu for its bomb in research reactor; Iraq sought to use HEU from its research reactors for a bomb
- ~140 operating research reactors in >30 countries still use HEU as their fuel (MIT reactor uses ~12 kg of 93% enriched material in its core)
- Some have no more security than night watchman and chain-link fence
- 41 heavily armed terrorists who seized a theater and hundreds of hostages in Moscow in October 2002 reportedly considered seizing Kurchatov Institute – site with enough HEU for dozens of bombs

14

The dominance of economics

15

- In countries around the world, electricity is being wholly or partly deregulated, becoming more competitive, decisions on what plants to build increasingly in private hands
- Historical record indicates that except (possibly) for requiring more guards or safeguards inspectors, governments will *not* force private industry to adopt more expensive approaches to improve proliferation resistance
- Hence, a proliferation-resistant system is *only* likely to be broadly adopted if it is *also* the most economic – "how much more are we willing to pay for proliferation resistance?" is the *wrong question*
- New system must be *very* widely adopted to reduce global proliferation risk (building such systems in United States but not elsewhere would not help much)

15

Steps to reduce proliferation impact of the civilian nuclear energy system

16

- Reduce demand
  - More successful than often realized: e.g., Sweden, Italy, Argentina, Brazil, S. Africa, S. Korea, Taiwan…
- Secure all nuclear materials and facilities
- Minimize spread of sensitive facilities/activities
  - Including by providing assured fuel cycle supply
- Beef up controls on technology transfers
- Strengthen verification (safeguards)
- Establish international ownership, control of key facilities
- Improve technical proliferation-resistance

16

Terrorism-resistance

17

- 1st priority in terrorism-resistance is ensuring potential nuclear bomb material cannot fall into terrorist hands
  - Minimize use of separated Pu and HEU
  - Provide stringent security, accounting, and control for stocks that continue to exist
- 2nd priority is protection from catastrophic sabotage:
  - Security sufficient to prevent large radioactive release against full range of plausible adversary threats (outsider, insider, and combination)
  - Increased "passive safety," redundant means to maintain cooling – makes causing release more challenging

17

Nuclear thefts and terrorist consideration of nuclear terrorism are ongoing realities

18

- ~20 well-documented seizures of stolen plutonium or HEU
  - No strong evidence terrorists have ever acquired such material
  - Makes clear that some nuclear security was inadequate
- al Qaeda, Aum Shinrikyo, and Chechen terrorists all pursued various forms of nuclear or radiological terrorism
  - al Qaeda sought to get nuclear material, recruit nuclear experts – bomb program conducted crude explosive tests
  - al Qaeda also considered nuclear sabotage, some operatives sought "dirty bombs"
  - Aum Shinrikyo made extensive efforts to get nuclear weapons
  - Chechen teams carried out reconnaissance at nuclear weapon storage sites and transport trains, stole radiological material, planned sabotage attacks on nuclear reactors, considered seizing a research reactor
- Little publicly available evidence of focused Islamic State effort (though some hints)

18

How much difference does HALEU make?

19

- Proliferation risk:
  - Can be enriched to weapons-usable faster (or with fewer centrifuges) than standard LEU – reason for JCPOA ban
  - But still requires enrichment facility – and difference in enrichment work from standard LEU is fairly modest
  - Except in scenario of "race to make enough material for a bomb before military strike," difference is modest
- Terrorism risk:
  - Still can't be used in a bomb without further enrichment
  - May offer easier path to some radiation exposure devices (add'l assessment needed of how much easier)

19

How much can security be reduced for small reactors?

20

- Many advanced reactor developers proposing either "small modular reactors" or "microreactors"
- Vendors are arguing for reduced security requirements, on grounds of reduced chance of a large radioactive release
  - For some microreactors, the concept is no one on-site
  - For some, the concept is location in urban areas
  - Reduced cost of reduced security important to the business model
- Requires careful assessment
  - Any significant release beyond the site boundary in a populated area likely to cause panic, disruption – bigger consequence than radiation health impact (so "deaths/kw-hr" is the wrong metric)
  - Potential for removal of material (or even theft of entire reactor for some microreactor concepts) needs to be considered

20

Both proliferation risks and terrorism risks need to be carefully considered

21

- Advanced reactor and fuel cycle concepts could change many aspects of nuclear energy systems in ways relevant to proliferation and to terrorism risks
- Both proliferation risk and terrorism risk need to be carefully considered in evaluating future nuclear energy systems
- For proliferation risk, they key issue is enrichment and reprocessing – and how future systems might affect their spread
  - Advanced reprocessing systems only reduce the proliferation risks modestly, but may significantly reduce terrorist theft risks
- For terrorism risk key items are:
  - Minimizing (ultimately eliminating) civilian use of HEU and separated plutonium
  - Highly effective security systems
  - Design to make it difficult to cause substantial release

21

Extra slides if needed…

22

22

What is proliferation resistance?

23

- Definition:

  A nuclear energy system is *proliferation-resistant* if its deployment and use, on the scale and with the distribution envisioned by proponents, would not significantly increase the probability of proliferation of nuclear weapons.

  - Considering the full system life cycle (including all aspects of the fuel cycle)
  - Considering both *intrinsic* factors (e.g., difficulty of producing weapons material from material and facilities used in the system) and *extrinsic* factors (e.g., types of safeguards and security measures to be applied)

23

Proliferation resistance rule of thumb

24

- Ask yourself: Would the U.S. (and Israeli) governments have been comfortable in the 1990s if it was this system, rather than a once-through LWR under international safeguards, that Russia had agreed to build in Iran?

If *yes,* system is clearly "proliferation-resistant."

If *no,* there may still be aspects to be debated.

(More on the Iran case and its implications in a moment.)

24

Proliferation-resistance: neither side of the nuclear debate much interested

25

- Pro-nuclear view:
  - Existing safeguards provide sufficient protection against use of civilian nuclear energy for weapons – no country has ever used safeguarded nuclear material to make a bomb
  - Proliferation is a political issue, not a technical one – countries that are determined to get nuclear weapons will eventually do so, regardless of technology of civilian nuclear energy system
- Anti-nuclear view:
  - *All* nuclear energy systems pose proliferation risks – relying on enrichment, producing plutonium (or at least producing neutrons that could be used to produce plutonium)
  - These dangers cannot be substantially reduced without abandoning nuclear energy
- A middle view:
  - Real nuclear energy contribution to spread of nuclear weapons can be reduced significantly by technical and institutional measures

25

Proliferation-resistance: one key to acceptable nuclear energy expansion

26

- Civilian nuclear energy system has already made major contributions to the spread of nuclear weapons
- To make a major contribution to meeting 21st century carbon-free energy needs, nuclear would have to grow *dramatically* (e.g., 4-10x) – most new electricity demand is in developing world
- Governments and publics unlikely to accept such a massive nuclear expansion *unless* convinced that the expansion will *not* lead to additional spread of nuclear weapons
- How can nuclear energy be greatly expanded, deployed far more widely, without contributing to weapons programs?
- Cost, safety, security, waste management must also be addressed for large expansion to be acceptable

26

Case I: Iraq: 1970s-1991

27

- Iraq purchased the "Osiraq" research reactor from France – Israel destroyed it in an airstrike in 1981, so it could not be used to produce plutonium
- Pre-1991, Iraq was an NPT member in good standing
- Nuclear experts trained in U.S. and Europe – Iraqis sent to work at IAEA to learn how to evade inspections
- Iraq had a massive secret nuclear weapons program (expanded post-Osiraq) – with a huge web of procurement agents and front companies to buy technology illegally from sources around the world (for example centrifuge technology from civil programs in Europe)
- After invading Kuwait, Iraq launched a "crash program" to build one bomb using French-supplied and Soviet-supplied HEU fuel for its safeguarded civilian research reactors

27

Case I: Iraq: 1970s-1991: Lessons

28

- Military action against a nuclear weapons program may lead to intensified, covert efforts – difficult to bomb
- Safeguards at declared sites are insufficient to address covert sites (or even covert activities at other areas at declared sites)
  - IAEA need to pull together a comprehensive picture of all a state's nuclear activities – using all information they can get
- Civilian sector is a crucial source of illicit technology purchases
- Sometimes states *do* consider using nuclear material from safeguarded facilities for nuclear weapons (crash program)
- Research reactors, not just power reactors are important – for plutonium production, or as sources of HEU (Osiraq, crash program)

28

Case II: Iran

29

- Iran started both an open civilian nuclear power program and a secret nuclear weapons program under the Shah – both were dormant for a period after 1979 revolution
- Large numbers of nuclear experts trained in U.S. and Europe (esp. MIT) in the pre-revolutionary period
- In mid-1990s, Russia agreed to complete a power reactor the Germans had begun at Bushehr – throughout 1990s, U.S.-Russian disagreements over this deal and more sensitive transfers – 100s of experts trained in Russia
- We now know that Iran was receiving centrifuge technology from the AQ Khan network – technology that originated in Urenco; components from all over the world
- In 2002, Iran's Natanz enrichment facility revealed

29

Case II: Iran (II)

30

- Iran has always claimed that its program is entirely for peaceful purposes – using the civilian program as a cover for technology purchases and facility construction whose weapons purpose would otherwise be obvious
  - United States tried to cut off *all* civil cooperation with Iran worldwide, arguing would contribute to nuclear weapons effort
- Iran has remained within the NPT, but violated its safeguards agreement by lying to the IAEA for decades
- After violations were revealed, major global effort to impose sanctions, demand that Iran reverse course
- Recent negotiations have led to freeze on centrifuges and Arak reactor construction, blending down 20% stock
- Controversy continues – not clear which way it will go

30

Case II: Iran: Lessons

31

- Building up enrichment or reprocessing capabilities is not in itself a violation of the NPT
- Again, the IAEA needs to pull together a comprehensive picture of all the nuclear activities of a state
  - Partnership between the IAEA and state intelligence agencies is crucial – but raises concerns about credibility, objectivity
  - Remarkable amount of information can come from open sources
- Organizing effective international response to violations is possible, but very difficult
- Civilian sector and states outside the NPT are both crucial sources of illicit technology purchases
- Yet another proliferation role for research reactors: providing a rationale for enriching to 20-90%

31

Case III: India

32

- India's civilian and military nuclear programs have been deeply integrated from their inception
- Large numbers of nuclear experts trained in the United States and Europe
- India received a Canadian research reactor (CIRUS), with U.S. heavy water and training, provided with assurances of peaceful use – but no safeguards to verify assurances
- India built a reprocessing plant with a U.S.-provided design
- India used that reactor and plant to produce material for its "peaceful" nuclear explosion in 1974
- India was under nuclear sanctions from 1974-2005, when U.S.-India nuclear deal reached (approved by NSG in 2008)

32

Case III: India: Lessons

33

- Unverified peaceful use assurances are not enough
- Ostensibly civil purchases can provide crucial support for a nuclear weapons program
- A civil program also helps build up a broad base of nuclear expertise that can be used in a weapons program
- Past a certain point, capable states can continue their nuclear programs even if cut off from supply of nuclear technologies

33

A selection of other cases

34

- Taiwan: secret nuclear weapons program based on reprocessing, dropped under U.S. pressure
  - Now substantial nuclear expertise
- South Korea: secret nuclear weapons program based on reprocessing, dropped under U.S. pressure
  - Now tremendous nuclear expertise
- North Korea: dedicated military facilities that were publicly described as civilian, plutonium technologies from declassified Western designs, enrichment in part from Khan network
- Pakistan: dedicated military facilities, but based on civil technologies from Europe (some stolen, some illicit purchases)

34

Nuclear energy and proliferation: lessons from the cases

35

- In some cases, countries DO decide to make nuclear material in ostensibly civilian facilities (e.g., India), even facilities under safeguards (e.g., Iraq).
- In some cases, countries DO decide to use safeguarded weapons-usable material from their civilian program to make a bomb (e.g., Iraq).
- However, proliferation-resistance is NOT just about avoiding having separated plutonium or HEU in the cycle. Civilian programs also provide:
  - Source for acquisition of technology (e.g., Iraq, Iran, India)
  - Cover for building facilities whose military intent would otherwise be obvious (e.g., Iranian centrifuge plant)
  - Facilities that can later be turned to weapons production (same)
  - Buildup of core of nuclear experts that can later be turned to bomb program (e.g., Iranians being trained in Russia)

35

Proliferation-resistance: some better ways to think about it

36

- How might U.S. adoption of the technology *influence* other countries' adoption of sensitive technologies?
- By what percentage would access to the *material* in the proposed fuel cycle reduce the time and cost to produce weapons-usable material?
- By what percentage would access to the *facilities* and *technologies* used in the proposed fuel cycle reduce the time and cost to produce weapons-usable material? By what percentage might the difficulty of ensuring against *leakage of technology* increase or decrease if the proposed fuel cycle were implemented?
- By what percentage would access to the *experience* involved in operating the proposed fuel cycle reduce the time and cost to produce weapons-usable material?

36

Proliferation-resistance: some better ways to think about it (II)

37

- How many *people* with advanced nuclear training – who might also contribute to a weapons program – would be required in a country generating electricity using the proposed approach, to manage it safely and securely?
- By what percentage would the number of *inspection-days* per kW-hr generated increase or decrease in the proposed fuel cycle, compared to once-through LWRs? By what percentage would the *uncertainty* in meeting safeguards goals increase or decrease?
- Useful standard for comparison: better or worse than LWR once-through?

37

The 3 most important things: location, location, location

38

- Proliferation risk impact of technical specifics of fuel cycles is generally modest
- Most important factors:
  - What countries have enrichment and reprocessing plants?
  - What are those countries' intents?
  - Are those facilities under purely national, or international, ownership and management?
  - Are those facilities under safeguards?

38

Reactor-grade plutonium is weapons-usable

39

- Higher neutron emission rate:
  - For Nagasaki-type design, even if neutron starts reaction at worst possible moment, "fizzle yield" is ~ 1kt – roughly 1/3 destruct radius of Hiroshima bomb – more neutrons won't reduce this
  - Some advanced designs are "pre-initiation proof"
- Higher heat emission:
  - Various ways to deal with – for example, plutonium component can be inserted into weapon just before use (as in early U.S. designs)
- Higher radiation:
  - Can be addressed with greater shielding for fabrication facility
  - Last-minute insertion of plutonium component again
- *Reactor-grade plutonium is <u>not</u> the <u>preferred</u> material for weapons, but any state or group that can make a bomb from weapon-grade plutonium can make one from reactor-grade*

39

Reactor-grade plutonium is weapons-usable (II)

40

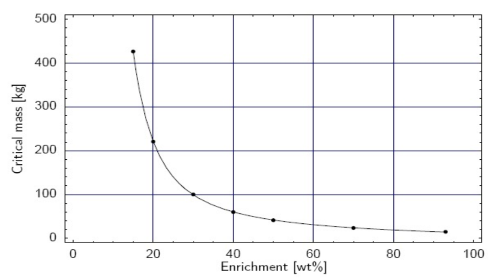
- "Virtually any combination of plutonium isotopes -- the different forms of an element having different numbers of neutrons in their nuclei -- can be used to make a nuclear weapon... At the lowest level of sophistication, a potential proliferating state or subnational group using designs and technologies no more sophisticated than those used in first-generation nuclear weapons could build a nuclear weapon from reactor-grade plutonium that would have an assured, reliable yield of one or a few kilotons (and a probable yield significantly higher than that). At the other end of the spectrum, advanced nuclear weapon states such as the United States and Russia, using modern designs, could produce weapons from reactor-grade plutonium having reliable explosive yields, weight, and other characteristics generally comparable to those of weapons made from weapons-grade plutonium.... Proliferating states using designs of intermediate sophistication could produce weapons with assured yields substantially higher than the kiloton-range possible with a simple, first-generation nuclear device."
  - *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives* (Washington, DC: DOE, January 1997)

40

HEU at far below "weapon-grade" is weapons-usable

41

Critical Mass of Reflected Uranium Sphere



Critical mass of a beryllium-reflected uranium sphere as a function of the uranium-235 enrichment in weight percent (wt%). MCNP 4B simulations at 300 K. Reflector thickness is 10 cm.

Source: Alexander Glaser, Science & Global Security, 2002

41

Properties of key nuclear explosive isotopes

42

Isotope	Critical Mass (kg)	Half Life (years)	Decay Heat (watts/kg)	Neutron Generation (neutrons/g-sec)
U-233	15	160,000	0.3	0.0009
U-235	50	700,000,000	0.0001	0.00001
Pu-239	10	24,000	1.9	0.02
Pu-240	40	6,600	6.8	900
Pa-231	162	32,800	1.3	0
Np-237	59	$2.1x10^6$	0.021	0.00014
Am-241	57	430	110	1.2
Am-242m	9-18 kg	141	n.a.	$5.8x10^7$
Am-243	155	7,380	6.4	.9
Cm-245	13	8,500	5.7	147
Cm-246	84	4,700	10	$9 x10^6$
Bk-247	10	1,400	36	0
Cf-251	9	898	56	0

Source: "Annex: Attributes of Proliferation Resistance for Civilian Nuclear Power Systems" in Technological Opportunities to Increase the Proliferation Resistance of Global Nuclear Power Systems (TOPS) *(Washington, D.C.: U.S. Department of Energy, Nuclear Energy Research Advisory Committee, 2000, available at http://www.nuclear.gov/nerac/FinalTOPSRptAnnex.pdf as of 9 January 2007), p. 4, with corrections and additions from "Chart of Nuclides" (Upton, N.Y.: Brookhaven National Laboratory), and David Albright and Lauren Barbour, "Troubles Tomorrow? Separated Neptunium-237 and Americium," in David Albright and Kevin O'Neill, eds.* The Challenges of Fissile Material Control, *(Washington, DC: Institute for Science and International Security, 1999)*

42

International control

- International control and ownership (as opposed to just verification) of all sensitive operations – e.g., enrichment, reprocessing, fabrication and use of Pu fuels – could increase the political barrier to withdrawing from the regime, using the material or facility for weapons program
- Host state *could,* in principle, still seize material or facility
- Would not prevent covert facilities – though international staff might notice if experts disappearing for days
- Would have only modest impact on problem of build-up of expertise, infrastructure for weapons program
- High political barriers to implementing this approach; dates back to Acheson-Lillienthal (concluded "unanimously" that security could not rest on verification of nationally-controlled nuclear activities alone)

Giving states incentives not to build enrichment and reprocessing

- Article IV of the NPT guarantees all parties access to civilian nuclear technologies
- Each party allowed to build enrichment and reprocessing facilities, even produce HEU and Pu, as long as under safeguards – come right up to the edge of a weapons capability while staying within the regime
- Iran case demonstrates the dangers
- Government-backed commercial consortium could offer a "new deal":
  - Guaranteed lifetime fuel supply and spent fuel management to any state that agrees no enrichment, no reprocessing of their own – and Additional Protocol to confirm that commitment
  - Some states would say "yes" – those that said "no" would immediately be the focus of international concern
  - Similar idea proposed in Bush speech 2/04, being worked

The threat of "dirty bombs"

45

- Dirty bomb could be very simple -- dynamite and radioactive material together in a box
- Modest amounts of radioactive material easy to get – millions of radioactive sources in industrial and medical use worldwide – only a fraction pose significant hazard
- Even with a lot of radioactive material – kilograms of plutonium or spent fuel – usually few would die from acute radiation poisoning, few hundred to few thousand from cancer many years later (undetectable against cancer background)
- *But,* fear of anything "nuclear" could create panic, would have to evacuate area for extended period, cleanup and disruption could be very costly (10s of billions worst case)

45

Nuclear facility and material security

46

- Designed to detect, deter, and prevent *theft* of material, or *sabotage* of facilities by unauthorized insiders or outsiders (not *diversion* by the host state – that's what international safeguards do)
- Physical protection:
  - Designed to detect, slow, and interdict any theft or sabotage attempt
  - Fences, alarms, access control, locked vaults, response forces
- Material control:
  - Designed to monitor and control material in real time
  - Cameras, seals, tags, alarms, two-person rule
- Material accountancy:
  - Designed to reveal thefts after they occur, or confirm that they have not occurred (and to support international safeguards)
- Nuclear safety systems make sabotage more difficult

46

A systems engineering approach similar to that used for nuclear safety…

47

- Step 1: Define actions to be prevented (theft, sabotage), vital targets to be protected
- Step 2: Define *design basis threat* (DBT) to be protected against (comparable to design basis accidents)
- Step 3: Assess vulnerability of existing security arrangements to DBT – identify adversary tactics most likely to succeed (worst vulnerabilities)
- Step 4: Design and implement upgraded security system having high probability of defeating DBT
- Step 5: Operate and maintain upgraded system
- Step 6: Regularly re-assess (and test) vulnerability, implement improvements as needed

47

Vulnerability assessment: a systems engineering approach to security

48

- Vulnerability assessment is a formal technique using event trees similar to those of probabilistic risk assessment, used for identifying key weaknesses in facility security systems and most cost-effective approaches to improving them
- Basic steps
  - Identify unpleasant events to be protected against (e.g., sabotage of power plant resulting in radioactive release, theft of bomb material)
  - Estimate likely characteristics of adversaries (insider/outsider, numbers, armament, training, etc.) -- "design basis threat"
  - Identify possible ***pathways*** by which adversaries might attempt to cause unpleasant events (e.g., possible routes from outside facility to location of bomb material)
  - At each step, estimate the security system's ability to ***detect, delay,*** and ***defend*** against the adversaries' actions -- goal is to ensure that system can reliably detect the adversaries early on, and delay them long enough for a force that reliably overcome them to respond

48

Modeling the layers of the protection system

49

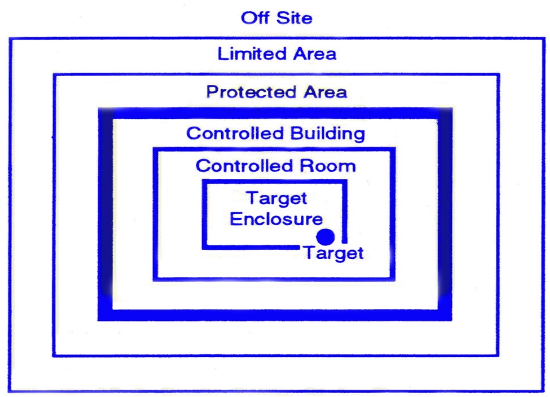


Figure 17–2. Basic Areas At An Example Facility

Source: Sandia National Laboratories

49

Multiple possible adversary pathways through each layer

50

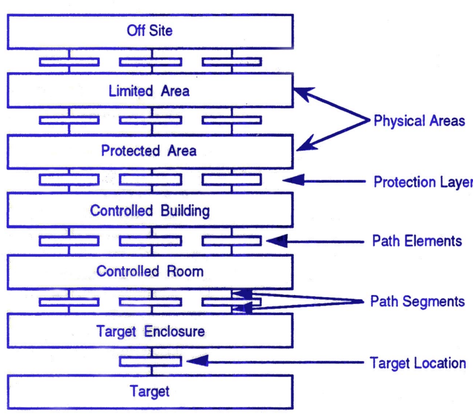


Figure 17–7. ASD Concept

Source: Sandia National Laboratories

50

Estimating probability of adversary sequence interruption – each pathway

51

Estimate of Adversary Sequence Interruption	Prob. of Guard Comm.		Response Force Time (in Seconds) Mean	SD
	0.95		300	90

Task	Description	P(Detection)	Location	Delays (in Seconds): Mean	SD
1	Cut Fence	0	B	10	3
2	Run to Building	0	B	12	3.6
3	Open Door	0.9	B	90	27
4	Run to Vital Area	0	B	10	3
5	Open Door	0.9	B	90	27
6	Sabotage Target	0	B	120	36
7					
8					
9					
10					
11					
12					

Probability of Interruption: 0.476

Source: Sandia National Laboratories

51

Estimating probability of adversary interruption: parsing the example

52

- This facility has a response force that takes 300 seconds (5 minutes) to arrive
- But the facility has no ability to detect adversaries cutting the fence – first hope of detection is when they blow through the door of the building
- After that door, it's only 220 seconds to a successful sabotage
- So, the protection system has less than a 50-50 shot at preventing sabotage on this pathway, against adversaries as capable as those predicted
- Possible fixes: add detection capability at the fence (likely cheapest); put in stronger vaults, etc. to increase delay time after going through door; decrease response force arrival time (e.g., move them closer to facility).

52

Assessing vulnerability assessment: problems with complexity

53

- Key issues are similar to those for PRA – system too complex to predict (and get probability data on) each sequence; unforeseen system interactions and common-mode failures particularly problematic
- ***In particular,*** predicting actions of intelligent adversaries extraordinarily difficult: assessors try to "brainstorm" all the possible attacks, but attackers may do something else
- Insiders particularly difficult to protect against: they know the system and its weaknesses (may be among assessors)
- Importance of realistic ***performance testing*** – does the system really protect, when faced with a credible adversary force (and/or insider) trying to overcome it?
- Assessment of ***absolute*** magnitude of vulnerability less reliable than identification of key areas for improvement

53

Sabotage is also an issue

54

- 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

54

POLICYFORUM

NUCLEAR SAFETY

Preventing the Next Fukushima

Matthew Bunn* and Olli Heinonen

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

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

55

Expanding nuclear energy <u>need not</u> increase terrorist nuclear bomb risks

56

- 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

56

Standard nuclear reactors pose real but modest proliferation risks

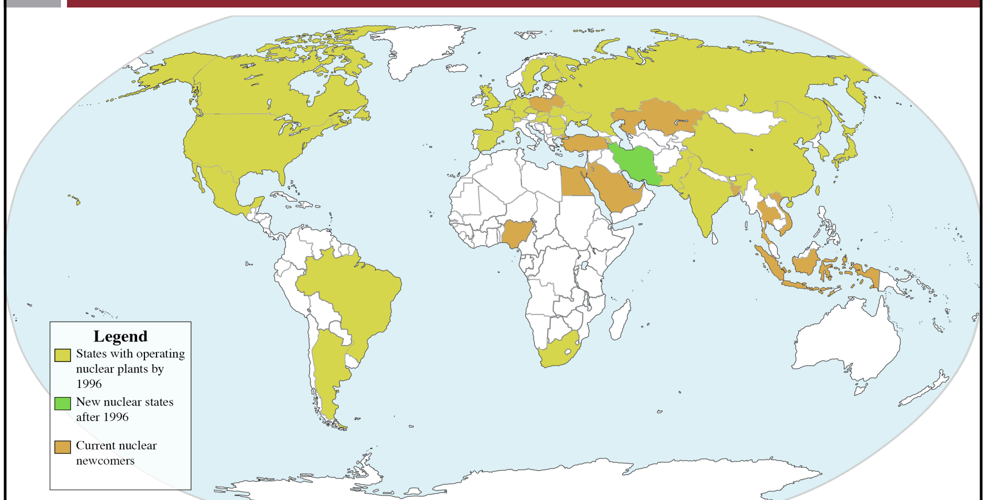
57

- 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

57

Nuclear growth implies nuclear spread: the story so far

58



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

58

Preventing nuclear proliferation

59

- 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 successful + resilient
  - 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

59

Limiting fuel cycle proliferation risks

60

- 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

60

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

61

- 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)

61

The scale of the control problem…

62

- 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

62

Addressing safeguards challenges

63

- 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

63