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Uranium enrichment, proliferation, safeguards – and the importance of nuclear security

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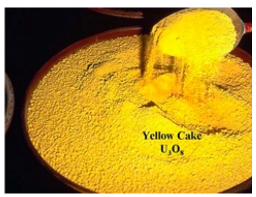
Making weapons-usable material is the hardest part of making a nuclear bomb

- >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 effort 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 a key example

Reprocessing and enrichment: steps on the two paths to bomb material

Conversion to UF6 → Enrichment

Mining → Milling



Conversion to metal or UO2, fuel fabrication → Reactor

→ Reprocessing

Enrichment → Conversion to metal and fabrication

Reprocessing → Conversion to metal and fabrication

Enrichment: large cascades, accelerating success, civilian work MORE demanding

- Need to hook up centrifuges in "cascades" of hundreds or thousands to get substantial enrichment of kilograms or tons
- Exponential process – going from 0.7% U-235 to 4.5% is ~ 2/3 of the work of making 90% U-235
- Why JCPOA required Iran to eliminate 98% of its LEU
- Power reactors require tens of tons of fuel – bombs require kilograms to tens of kilograms

Source: DOE

Secret centrifuge plants: hard to find

- Centrifuges take up little space, little power
- Plant to make enough HEU for 1 bomb per year could fit in this building, use less power than typical supermarket
- Uranium leakage is modest
- How to find them?
- North Korean centrifuge plant only identified when Siegried Hecker visited it

North Korean centrifuge plant at Yongbyon
Source: ISIS, image from Digital Globe

Proliferation risk of nuclear energy is mainly from enrichment and reprocessing

- 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, <u>best</u> processing methods about a W

Proliferation and terrorism risks of enrichment and reprocessing plants

- ***Breakout:*** Kick out inspectors, start producing bomb material
- ***Diversion:*** Try to remove material from inspected facility without inspectors noticing
- ***Sneakout:*** Use knowledge, experience (in party from open plants) to build secret plants
- ***Leakage-transfer:*** Technology may be stolen, sold to others
- ***Influence:*** Encouraging other states to establish similar facilities
- ***Sabotage:*** Reprocessing plants, with both spent fuel pools and high-level waste on-site, offer dangerous targets
- ***Theft:*** Theft of weapons-usable nuclear material (reprocessing and its fuel cycle, not most enrichment)

Examples from the JCPOA

- ***Breakout:*** Reason for limiting centrifuge capacity, stocks of enriched uranium
- ***Diversion:*** Reason for daily access to enrichment plants
- ***Sneakout:*** Key reason for restraints on advanced centrifuge R&D (easier to hide centrifuge facility with small number of more advanced centrifuges)
- ***Leakage-transfer:*** Centrifuge technology from Pakistan, originally stolen from URENCO contractors…
- ***Influence:*** Saudi Arabia saying we need whatever Iran has
- ***Sabotage:*** Major sabotage of Natanz plant (apparently Israeli) – to slow progress, not for radiation release
- ***Theft:*** Not a major issue for enrichment plants handling LEU

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

- 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

IAEA safeguards – the traditional approach

- States declare their nuclear materials, locations
- Inspectors check to confirm declared material has not been diverted
- Intended as an alarm bell – "deterrence of diversion by the risk of early detection"
- Particularly challenging when tons of weapons-usable material is being processed (reprocessing, plutonium fuel fabrication) or for enrichment

Source: IAEA

IAEA safeguards – the Additional Protocol and the state-level concept

- 1991 Iraq experience – major nuclear weapons program beyond declared locations
- Additional Protocol – if states have agreed to one – requires broader declarations, more access
- IAEA now attempts to understand the nuclear program of states as a whole – are there discrepancies, unanswered questions?
- How to have similar "objective" criteria?

Source: IAEA

Steps to reduce proliferation impact of the civilian nuclear energy system

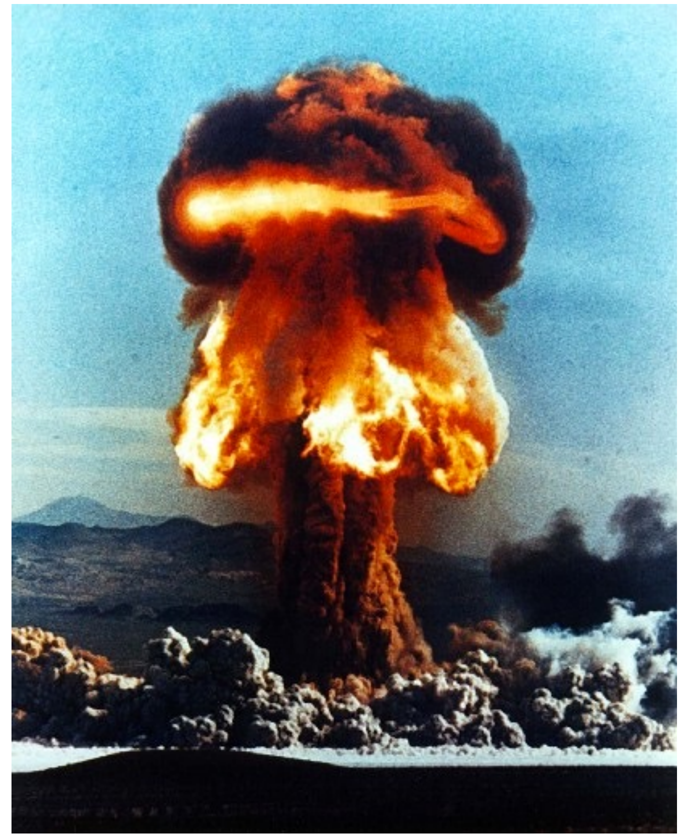
- Reduce demand
  - More successful than often realized: e.g., Sweden, Italy, Argentina, Brazil, S. Africa, S. Korea, Taiwan…
- Secure all nuclear materials and facilities
- Minimize spread of sensitive facilities/activities
  - Including by providing assured fuel cycle supply, international spent fuel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

Terrorism-resistance

- 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

3 types of nuclear terrorism

- Nuclear explosives
  - Incredibly catastrophic
  - Difficult for terrorists to accomplish (though not as implausible as some believe)
- Nuclear sabotage
  - Very catastrophic *if* highly successful (limited if not)
  - Could cause a Fukushima-scale accident, or worse
  - Also difficult to accomplish
- "Dirty Bomb"
  - "Weapons of mass disruption" – few if any deaths, but potentially $10s of billions in disruption, cleanup costs
  - Far easier to accomplish



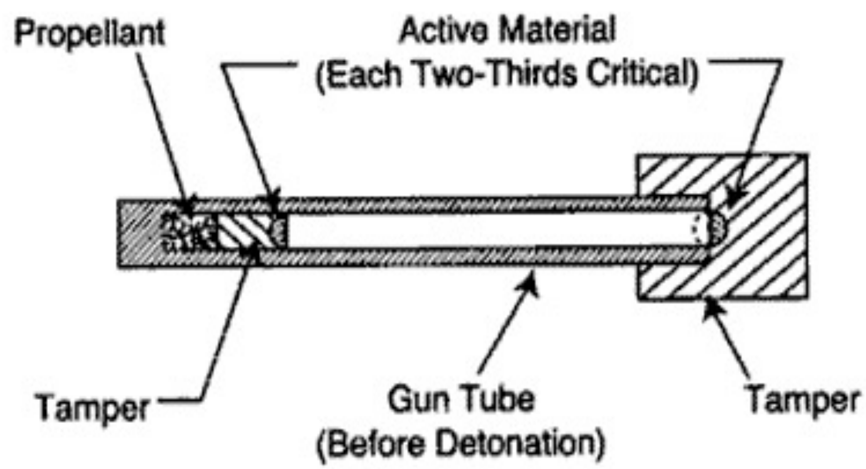
Source: DOE

Terrorist groups have pursued all three

- Aum Shrinkyo – Japanese terror cult
  - Conducted nerve gas attacks in Matsumoto in 1994 and in Tokyo subways in 1995
  - Previously had focused efforts to get nuclear, biological weapons
- "Core" al Qaeda
  - Focused effort to get nuclear weapons
    - Reported directly to Zawahiri
    - Carried out conventional explosive tests for the bomb program in desert
  - Also considered attacks on nuclear reactors
  - Affiliates pursued rad material for "dirty bomb"
- Chechen terrorists
  - Planted dangerous radiological source in a Moscow park as warning – threatened to use "dirty bombs"
  - Repeatedly threatened, planned attacks on reactors
  - Russian officials report catching terrorist teams scoping nuclear weapon storage sites, transports

With nuclear material, terrorists may be able to make crude nuclear bombs

- With HEU, gun-type bomb – as obliterated Hiroshima – very plausibly within capabilities of sophisticated terrorist group
- Implosion bomb (required for plutonium) more difficult, still conceivable (especially if they got help)
  - Doesn't need to be as complex as Nagasaki bomb



Source: NATO

<u>Doesn't</u> take a Manhattan Project -- >90% of the effort was focused on producing nuclear material. And making a crude terrorist bomb is *far* easier than making a safe, reliable weapon

Rapidly evolving threats

- ISIS and future groups
  - Not mentioned in 1/14 threat assessment
  - Seized much of Iraq and Syria by 6/14
  - How will these groups evolve next?
- Cyber
  - Constant discovery of new vulnerabilities
  - Nuclear facility requirements still at early stages in many countries
- Drones
  - Commercially available drones getting more advanced every year
  - Could nable wide range of tactics that require defenders to rethink approaches
- What's next?
  - How to keep up with the threat while having some regulatory stability?

A recent example: insider sabotage and a cleared terrorist at Doel-4 nuclear plant

- August 2014: An insider at Doel-4 reactor in Belgium drains lubricant, destroys reactor turbine
  - ~$200 million damage
  - Investigators unable to find culprit
  - Sabotage intended to cause economic damage, not radiation release
- Investigation finds that long before, contractor Ilyass Boughalab had access to vital area
  - Passed security clearance review in 2009
  - In late 2012, left to fight for terrorists in Syria (reportedly killed later)
  - Later convicted as part of "Sharia4Belgium" terrorist group

Source: Kristof Pieters

Insider threats are the most dangerous nuclear security problem

- The known HEU and Pu thefts, and most sabotages, involved insiders
- People don't want to believe their friends and colleagues could betray the organization
  - Leads to serious lapses in protection against insider threats
- Getting people to report suspicious behavior is *very* difficult
- Often even obvious "red flags" go unreported, unaddressed
- Bunn-Sagan book offers case studies, "Worst Practices Guide" on lessons learned from past mistakes

http://www.belfercenter.org/publication/insider-threats

Nuclear security: the global picture

- Global stockpiles include:
  - ~13,000 nuclear weapons
  - ~ 520 tons of separated plutonium
  - ~1335 tons of HEU (+/- 125 tons)
  - <1/3 of plutonium and HEU is physically in nuclear weapons
- Stocks located in 100s of buildings, bunkers, in ~ 22 countries
- Widely varying security
- No global rules specify how secure nuclear weapons or the materials to make them should be

W-48 nuclear artillery shell, one of many thousands of tactical nuclear weapons that have been dismantled

Source: U.S. Department of Energy

Theft of 0.01% of world stockpile could cause a global catastrophe

Global nuclear security: A system no one designed…

- Imagine a system with100s of nodes:
  - Little or no central control
  - Failure of any node could cause catastrophic damage
- To reduce risk in such a system, you could try to:
  - Strengthen each node (e.g., technical cooperation)
  - Increase central control (e.g., international accords)
  - Reduce the number of nodes (e.g., nuclear material removals)
  - Reduce the consequences of node failure (e.g., reactors where failure could cause only limited release, materials difficult to use in a bomb)
  - Increase ability to recover after a node failure

No engineer in his or her right mind would design such a system

Key steps to reduce the nuclear terrorism risk

- Police and intelligence:
  - Detect and disrupt terrorist nuclear-related plots
  - Aum Shinrikyo disrupted after nerve gas attacks
  - Multiple al Qaeda-related plots successfully disrupted after 9/11
- Security for weapons, materials, and facilities:
  - Make it harder for terrorists to get essential ingredients of weapon or sabotage a facility – major progress in last quarter century
- Block nuclear smuggling
  - Radiation detection, targeted police and intelligence
  - Enormous challenge: once stolen, material could be anywhere
- Prepare to reduce consequences

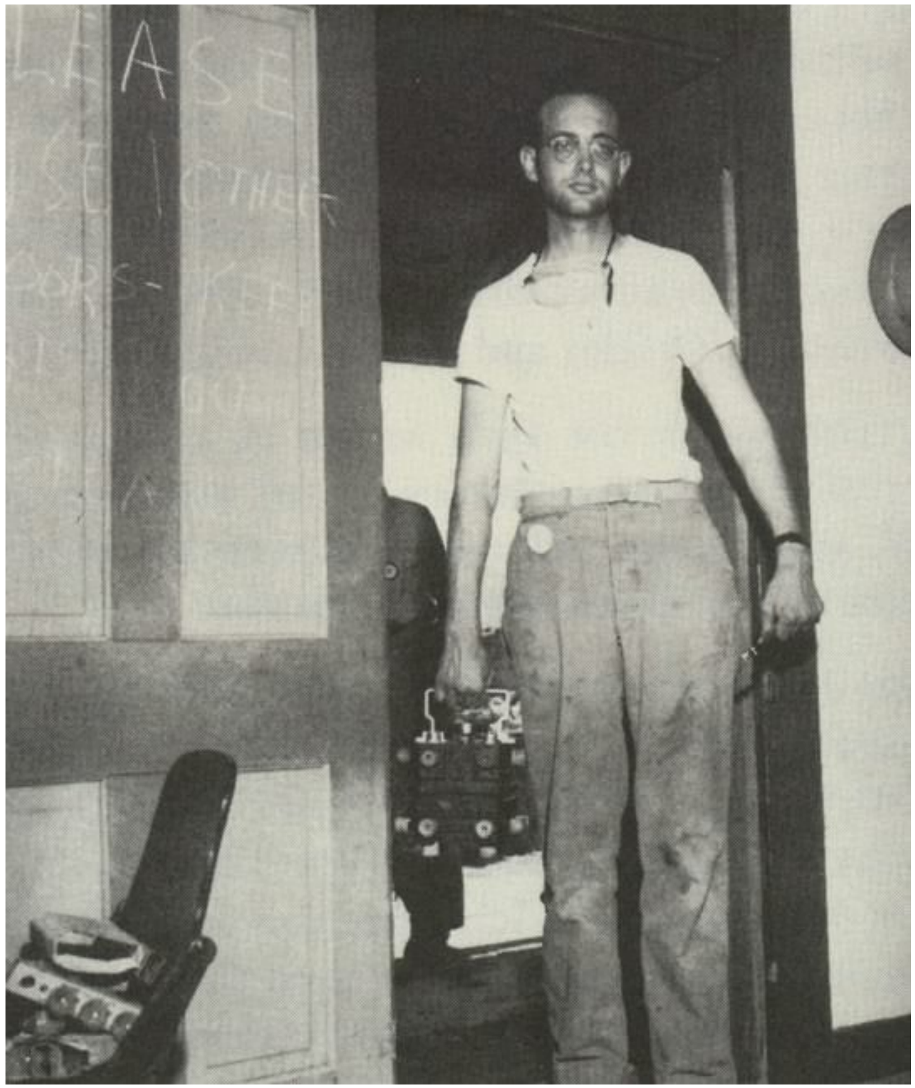
Effective security for nuclear weapons, materials, facilities as the highest leverage in reducing the risk

Extra slides if needed…

Further reading and background material

- *Revitalizing Nuclear Security in an Era of Uncertainty* (2019): https://www.belfercenter.org/NuclearSecurity2019
- *The U.S.-Russian Joint Threat Assessment of Nuclear Terrorism*: https://www.belfercenter.org/publication/us-russia-joint-threat-assessment-nuclear-terrorism
- *Insider Threats* (Cornell, 2018)
- Selected presentations and publications: https://scholar.harvard.edu/matthew_bunn/nuclear-terrorism-and-nuclear-security?admin_panel=1
- Full text of Managing the Atom publications: *http://belfercenter.org/mta*

Nuclear material is not hard to smuggle – plutonium box for first-ever bomb



Source: Los Alamos

The international nuclear security framework

- Key purpose of *international* and *national* frameworks is to ensure effective *local* nuclear security
  - International accords seek to influence national policies, which seek to influence local action – very indirect effect
- International framework includes many elements – a "regime complex," not a single regime
  - Binding agreements
  - International recommendations
  - Technical cooperation
  - Summits and other high-level discussions
  - IAEA services
  - Requirements of supply agreements
  - Best practice exchanges
- Constrained by complacency, sovereignty, secrecy, politics, bureaucracy, cost…

Steps to reduce the nuclear theft and sabotage risks

- Nuclear theft:
  - Reduce the number of facilities and transports with HEU and Pu (fewer facility-years per year)
    - More sites, transports with separated plutonium means more risk
  - Increase security for remaining facilities (lower chance of theft per facility-year)
    - Better protection against both outsiders and insiders
    - Critical issue: strengthening security culture – "Good security is 20% equipment and 80% culture."
- Nuclear sabotage:
  - Increase security for reactors, other high-consequence facilities
  - Increase passive safety (making large-scale release more difficult for saboteurs to achieve)
    - Example: move cooled spent fuel to dry casks

Substantial nuclear security progress over past 25 years…

- Most egregious weaknesses essentially all resolved
- U.S. in particular has spent billions helping others improve – and launched series of "nuclear security summits"
- > 50% of all countries that once had weapons-usable material on their soil have eliminated it
- Many particular improvements
  - Most countries that had no armed guards (even for plutonium and HEU) have corrected that
  - Most countries with major nuclear activities now have a "design basis threat" operators must protect against
  - More countries doing realistic assessment, testing, of nuclear security systems
  - More attention to insider threats
  - More attention to security culture

With “nuclear security summits” in the past, progress is slowing…

- Little high-level political attention, little sense of urgency
- U.S. international nuclear security programs dramatically reduced
- Some key elements of cooperation cut off or slowed
  - Almost no remaining US-Russian cooperation, post-Crimea seizure
  - Very modest cooperation with wealthy countries (some of which have a lot of material)
  - U.S.-China, U.S.-India cooperation real but modest
  - U.S.-Pakistan cooperation was substantial, most urgent agreed items completed – many items Pakistan not interested in cooperating on
  - Most politically, technically feasible removals of nuclear material already done
- Still much to do – but each step forward now more difficult

North Korea and Iran are likely small parts of the nuclear terrorism problem

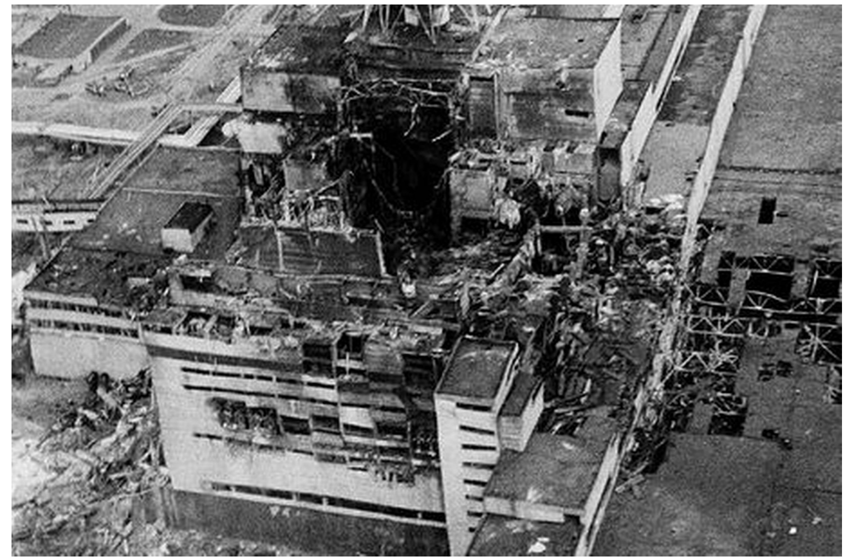
- Nuclear security:
  - North Korea has only a few bombs' worth of plutonium in a tightly controlled garrison state – theft very unlikely
  - Iran has not begun to produce weapons-usable material – has only a small amount of HEU research reactor fuel
- Conscious state transfer:
  - Regimes bent on maintaining power unlikely to take the immense risk of providing nuclear bomb material to terrorist groups who might use it in a way that would provoke overwhelming retaliation
  - Transfers to other *states* – who are likely to be deterred from using nuclear weapons – a very different act
- High-level "rogues" within states
  - As stocks of material grow, could an "A.Q. Kim" sell secretly?
- State collapse:
  - Could have worrisome "loose nukes" scenario

Spread of nuclear power <u>need not</u> increase terrorist nuclear bomb risks

- Most nuclear reactors do not use nuclear material that can readily be used in nuclear bombs:
  - Low-enriched uranium fuel cannot be used to make a nuclear bomb without technologically demanding further enrichment
  - Plutonium in spent fuel is 1% by weight in massive, intensely radioactive fuel assemblies (but R-Pu <u>is</u> weapons-usable)
- Reprocessing (separating plutonium from spent fuel) could increase risks, requires intensive security and accounting
  - Poor economics, few additional countries pursuing – South Korea and China only countries currently considering shift to reprocessing
  - Reprocessing does not solve the nuclear waste problem – still need a nuclear waste repository
- Power reactors <u>do</u> pose potential targets for sabotage
  - Sabotage would mainly affect nearby countries, global nuclear industry – strong security measures can reduce the risk

Nuclear security is quite different from nuclear safety, in several dimensions

- Safety: preventing, preparing for *accidental* events
- Security: preventing, preparing for, *intentional* human actions
  - Changes the statistics – multiple failures no longer independent
- Many overlaps – some conflicts
- Nuclear security involves:
  - Lower, more controversial threat perception (no widely known incidents)
  - Lower public interest
  - More secrecy
  - Less organizational focus, resources
  - More separation from the rest of the operating organization



Source: The Millenium Report

Key core al Qaeda nuclear operatives still at large

Ayman al Zawahiri  Source: FBI	Now head of the group. Nuclear project reported directly to him.
Abdul Aziz al-Masri  Source: NCTC *aka* Ali Sayyid Muhamed Mustafa al-Bakri	CEO of al Qaeda's nuclear program, oversaw explosives experiments in Afghanistan.

Sayf al-Adel  Source: FBI	Senior al Qaeda operational planner, reportedly personally approved attempted purchase of 3 nuclear bombs in 2003
"Pakistani Nuclear Expert" 	2003 communications from al Qaeda leaders reportedly approved purchase of nuclear devices if the Pakistani expert confirms they are real – U.S. Government has never identified or found this expert

Security culture matters: Propped-open security door

Source: U.S. Government Accountability Office

International assessments of the danger of nuclear terrorism

"Nuclear terrorism is one of the most serious threats of our time. Even one such attack could inflict mass casualties and create immense suffering and unwanted change in the world forever. This prospect should compel all of us to act to prevent such a catastrophe."

– U.N. Secretary-General Ban-Ki Moon, 13 June 2007

"The gravest threat faced by the world is of an extremist group getting hold of nuclear weapons or materials."

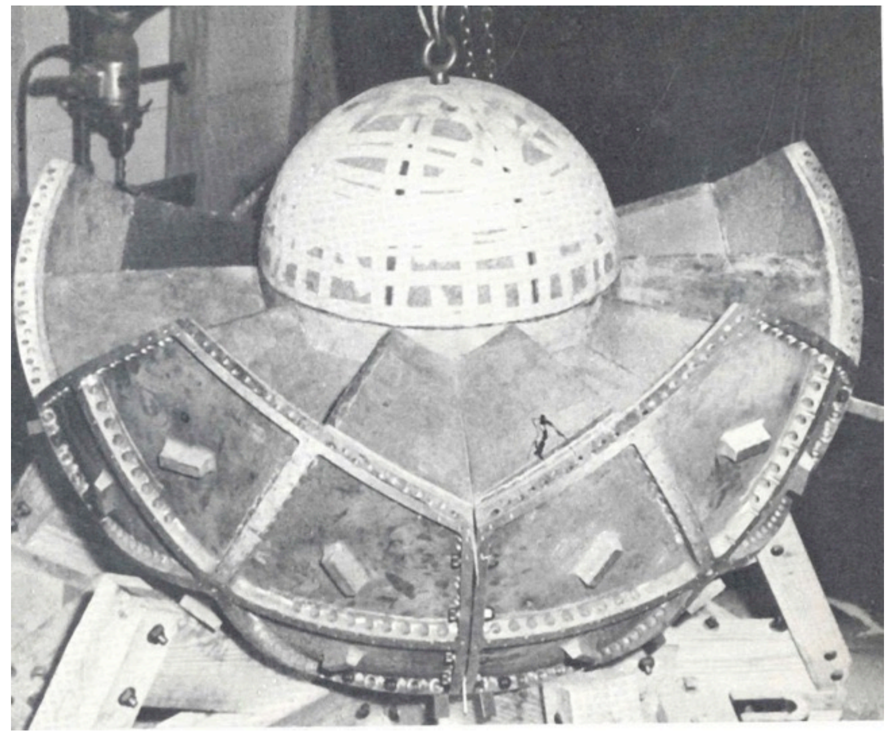
– then-IAEA Director-General Mohammed ElBaradei, 14 September 2009

"We have firm knowledge, which is based on evidence and facts, of steady interest and tasks assigned to terrorists to acquire in any form what is called nuclear weapons, nuclear components."

– Anatoly Safonov, then counter-terrorism representative of the Russian president, former head of the FSB, 27 September 2007

Implosion-type bombs

- Much more efficient than gun-type bombs
- Only type that offers substantial yield with plutonium
- Significantly more complex to design and build
  - More difficult for terrorists, still conceivable (esp. if they got knowledgeable help)
- Main approaches require explosive lenses, millisecond timing of multiple detonations
- Some approaches less complex than Nagasaki bomb



Source: Rhodes, *The Making of the Atomic Bomb* (orig. Los Alamos)

Reactor-grade plutonium is weapons-usable

- 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

The amounts of material required are small

- For simple "gun-type" bomb (with reflector): ~ 50-60 kg of HEU (Hiroshima bomb was 60 kg of 80% enriched material)
  - Fits in two 2-liter bottles
- For 1st-generation implosion bomb:
  - ~6 kg plutonium (Nagasaki)
  - ~ 3x that amount of HEU

The size of the plutonium core for the Nagasaki bomb

Source: Robert del Tredici

Nuclear security is the foundation for the three pillars of the NPT

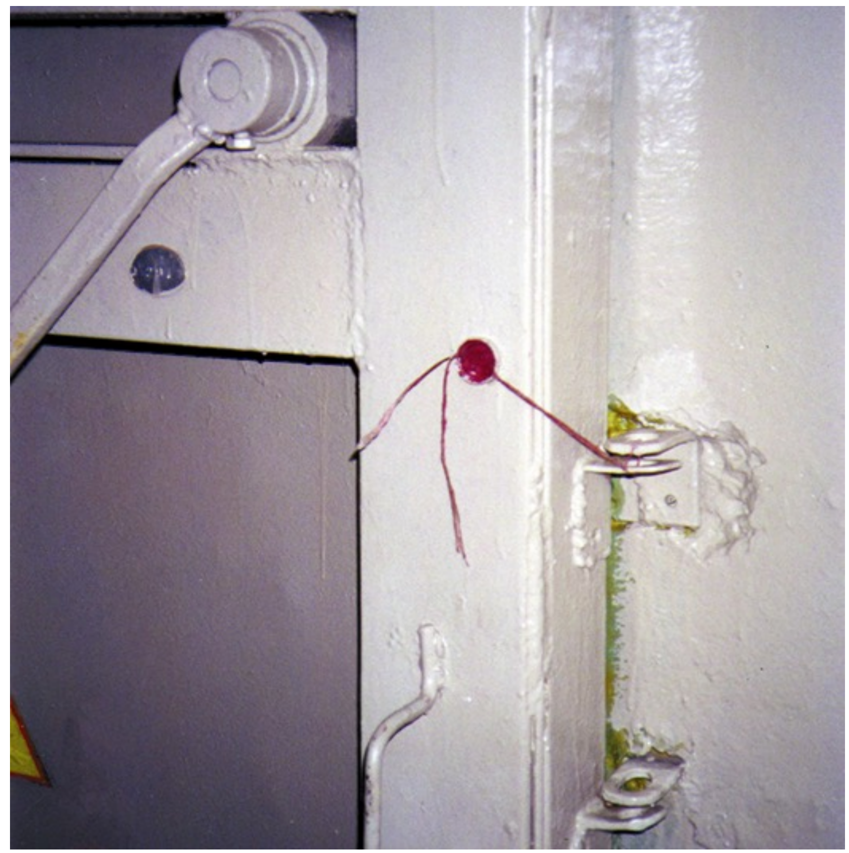
- Disarmament:
  - Nuclear weapon states will not disarm if insecure nuclear material could allow other states or terrorist to rapidly get nuclear weapons
- Peaceful uses:
  - Nuclear energy will not gain needed support unless people are confident that it is safe and secure
- Nonproliferation:
  - Efforts to stop the spread of nuclear weapons will not work if Insecure nuclear material offers states or terrorist groups a rapid path to the bomb

In all these areas, nuclear security is important to the security of all countries around the world

Belief in the threat – the key to success

- 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

Ineffective padlocks and seals for nuclear material in Russia, 1990s



July 2012: Protester intrusion at Y-12

Graffiti from Y-12 Break-In

- 2012: 82-year-old nun and two other protestors enter Y-12 facility
  - Passed through 3 alarmed fences, setting off multiple alarms – no one responded for extended period
  - New instrusion detection system setting off 10x as many false alarms
  - Cameras to allow guards to see cause of alarm had been broken for months
  - Major breakdown in security culture

Nuclear security: Why do countries decide to require more or less?

- Nuclear security rules, approaches vary widely
  - Among countries
  - Within countries over time
  - Among facilities within a country
- How do these decisions get made?
- What key factors help explain the variations?
- How can this help us understand how to convince states to strengthen nuclear security?

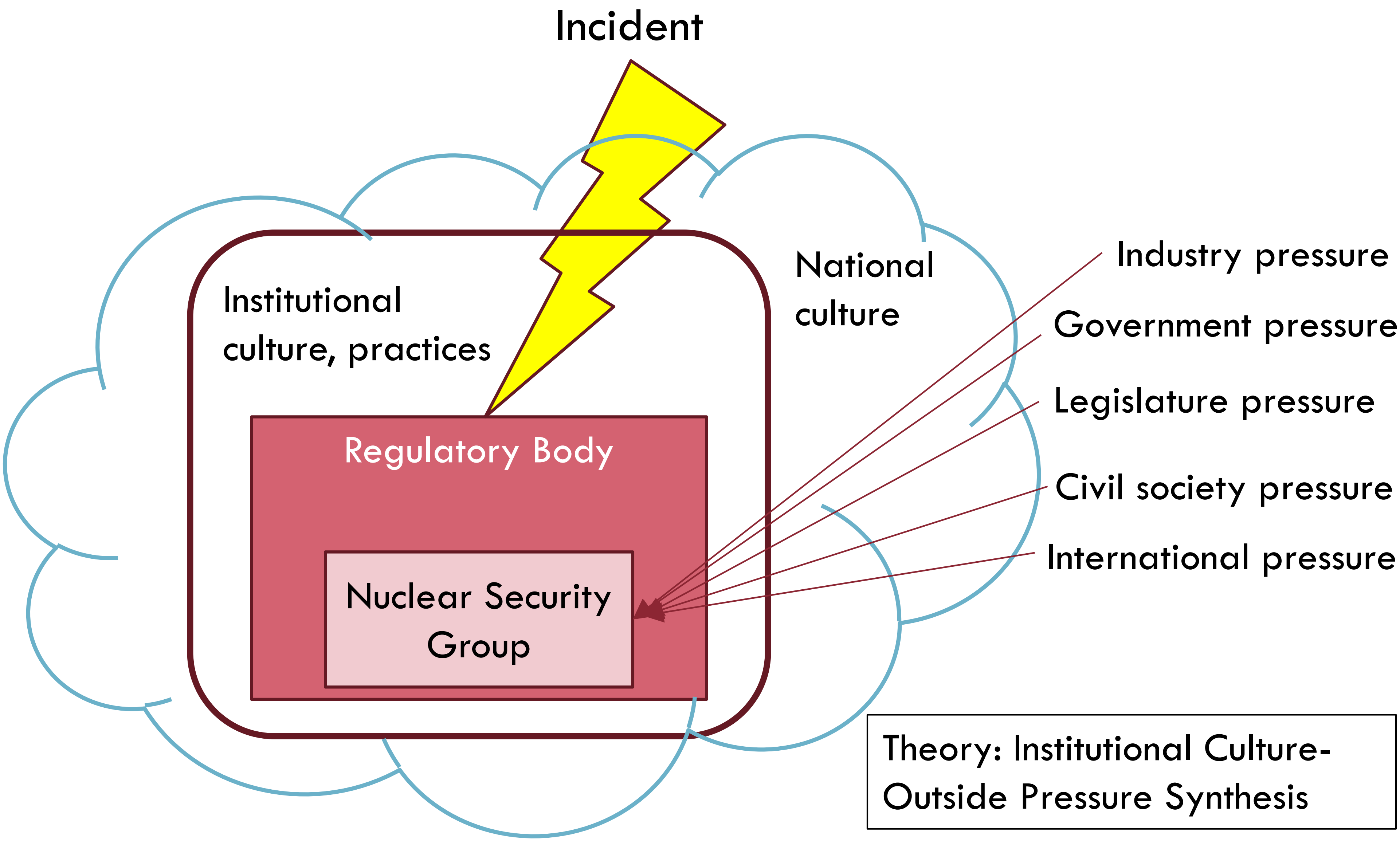
The available evidence is problematic

- There are no agreed measures to judge whether nuclear security in one place is "better" or "worse" than at another
  - Even "better" or "worse" is incorrect – imposes a one-dimensional spectrum on a multi-dimensional topic
  - Attempts at indices have not adequately captured the issues
  - No agreement on “how much is enough”
- Most nuclear security measures are secret
  - Limits availability of data on current status
  - Limits availability of data on historical evolution
- Most nuclear security changes go largely unnoticed
  - Little if any public debate, reporting in the press
  - In most countries, there is little civil society engagement on nuclear security, so few non-government experts observing

But it's clear that many ideas are wrong

- Realist idea that all states with nuclear weapons and weapons-usable material will provide strong security for them is clearly wrong
  - Wasn't true even in the United States for much of the nuclear age
- Rational-actor idea that regulators will set regulations at optimum balance of cost and risk is clearly wrong
  - No data to do this – don't know any of the relevant probabilities
  - Little evidence of serious regulator cost-benefit assessments
- Largely an incident-driven system
  - Complacency about existing security until an incident occurs
  - How system responds to incidents depends on regulatory structures, security culture, and more…

Reactions to incidents are modulated by institutional and national culture, pressures



Theory: Institutional Culture-Outside Pressure Synthesis

Nuclear security: 3 layers of action

- Local: At facilities and transports
  - What security measures to prevent theft are actually implemented day-to-day?
  - How well are they implemented?
  - How are staff trained and motivated?
- National: National policy and regulation
  - What nuclear security measures are required?
  - What kinds of inspections and enforcement activities are carried out?
- International: Agreements, initiatives, cooperation
  - What do treaties and international recommendations call for?
  - What are international efforts motivating or helping countries to do?
  - What processes are there for dialogue, making commitments, and tracking progress?

National regulation and policy

- Various questions countries must answer:
  - What threats should nuclear weapons, HEU, plutonium, and nuclear reactors be protected against?
  - What specific security measures should be required?
  - How should these vary with the type of material, and how hard it would be for terrorists to use to produce a nuclear blast?
  - How much will it cost, and who should pay?
  - How do we strengthen security culture?
  - Who's in charge in the event of a real incident, and how do we ensure different parties involved are properly coordinated?
- Many of these are answered in regulations. Key questions:
  - Are the regulations strong enough that, if followed, effective nuclear security would result?
  - How well are the rules implemented and enforced?

National regulation and policy (II)

- Strong regulation is crucial to effective, sustainable nuclear security
  - Most nuclear managers will not invest in expensive nuclear security systems unless governments tell them they have to
  - A critical element: the design basis threat (DBT) – the threat nuclear security systems must be designed to protect against
- *But*, a culture only focused on following the rules will not achieve excellence in nuclear security
  - Need a culture focused on continual improvement of security – always looking for ways to find and fix vulnerabilities
  - Requires convincing key managers and staff that the threat is real and effective security is part of their mission (not so easy to do)
  - *Incentives* are a crucial part of the story – how to structure?

The international nuclear security framework

- Key purpose of *international* and *national* frameworks is to ensure effective *local* nuclear security
  - International accords seek to influence national policies, which seek to influence local action – very indirect effect
- International framework includes many elements – a "regime complex," not a single regime
  - Binding agreements
  - International recommendations
  - Technical cooperation
  - Summits and other high-level discussions
  - IAEA services
  - Requirements of supply agreements
  - Best practice exchanges
- Constrained by complacency, sovereignty, secrecy, politics, bureaucracy, cost…

Legally binding international instruments on nuclear security

- *Not* the NPT or IAEA safeguards
  - NPT does not require any security for nuclear material
  - "Safeguards" are not about either safety or guarding – inspections to confirm material has not been diverted
- 1980 Physical Protection Convention
  - U.S. originally hoped would be effective, binding global standard
  - Least common denominator: covers ONLY security for material in international transport – and only civilian material (~15% of total)
  - Minimal, vague security requirements
  - Includes extensive legal provisions, requiring all parties to pass laws making nuclear theft a crime and giving them authority to arrest and prosecute or extradite nuclear thieves from elsewhere

Legally binding international instruments on nuclear security (II)

- 2005 Amendment
  - Covers civilian material in domestic use
  - Extends criminal law provisions to sabotage, other acts related to nuclear theft and terrorism
  - Parties must have a rule on nuclear security and an agency charged with implementing it – but what should it say?
- 2005 Nuclear Terrorism Convention
  - All parties to take "appropriate" nuclear security measures – unspecified
  - Mostly focused on legal response to theft, smuggling, terrorism
- UNSC Resolution 1540
  - All states must provide "appropriate effective" nuclear security and accounting – but no one has specified what this means

International nuclear security recommendations and initiatives

- International recommendations
  - IAEA "Nuclear Security Series," especially INFCIRC/225/Rev. 5
    - More specific, but still quite general – should have a fence with intrusion detectors, but how hard should they be to defeat?
    - Compliance voluntary (though most countries do)
- Technical cooperation and funding
  - Nunn-Lugar, comparable programs
  - Global Partnership
  - Substantial progress – but varies greatly from site to site, country to country; many security elements can't be much influenced from outside; new measures may not be sustained; U.S.-Russian cooperation cut off
- Best practice exchanges
  - WINS
  - U.S.-Russia-UK, others (largely in past)
  - Little data on implementation, some countries do not participate

International nuclear security recommendations and initiatives (II)

- Global Initiative to Combat Nuclear Terrorism
  - 85 nations participating
  - Helps to convince countries of reality of threat
  - Sharing of experience, best practices, capacity-building
  - Mostly focused on emergency response, forensics, smuggling… modest focus on upgrading nuclear security
- Proliferation Security Initiative
  - > 70 countries participating
  - Focused on interdiction of proliferation-sensitive shipments
  - Also information sharing, excercises
  - Unlikely to stop smuggling of nuclear material that would fit in a suitcase

The role of the IAEA

- IAEA develops guidance, offers advice, provides services – but only when states request them
  - Broad range of guidance documents
  - >100 member states now have "Integrated Nuclear Security Plans" agreed or in development
  - IAEA offers nuclear security reviews – especially International Physical Protection Advisory Service (IPPAS) (but only a few a year)
  - IAEA provides countless training programs
  - Manages database of illicit trafficking incidents
  - Helps with HEU removals, recovery of orphan sources
  - Provides limited hardware assistance in some cases

The nuclear security summit process

- The up side
  - Brought together leaders from 50+ countries and organizations
  - Elevated issue from technical experts to political leaders
  - Transformed international debate – greatly increased international attention, decision moments drove new commitments and action
  - More specific "house gifts" and "gift baskets" – most of the latter now IAEA documents open to all
  - Discussion continuing in Nuclear Security Contact Group
- The down side
  - Consensus process led to vague communiqués that probably did little to drive decisions to beef up on-the-ground security
  - Did not agree on any nuclear security standards or any new nuclear security architecture
  - Momentum fading as summits recede into the past

We need more effective global governance of nuclear security

- Currently we have:
  - No international standards that specify what levels of security nuclear weapons, plutonium, or HEU (or major power facilities) should have
  - No regular international mechanism to build confidence that states are putting effective nuclear security in place
  - No forum for continuing high-level discussion of nuclear security
- Current patchwork of nuclear security agreements, initiatives is clearly insufficient
  - But efforts to negotiate new treaties are unlikely to succeed in a timely way
  - More likely to succeed with political commitments among groups of like-minded states

Comparing governance: nuclear safety and nuclear security

- International standards
  - Safety: IAEA safety standards and guides in wide range of areas, widely respected and used, fairly detailed (e.g., instructions on how to model potential tsunami threats)
  - Security: IAEA security series recommendations, not standards, less widely followed, not as detailed
- Sharing and learning from experience
  - Safety: Facilities report on incidents, root causes, lessons learned; IAEA/NEA and WANO maintain databases, analyze, and distribute
  - Security: no comparable mechanism
- Peer review
  - Safety: Several varieties of IAEA peer review services; all power reactors members of WANO, agree to accept peer reviews
  - Security: IAEA offers peer review, only a few HEU and Pu facilities have ever had one; no industry peer reviews

Comparing governance: nuclear safety and nuclear security (II)

- Discussion, identifying next steps
  - Safety: Regular review meetings of the Nuclear Safety Convention; WANO meetings; many others
  - Security: Nuclear security summits – but no other comparable mechanism
- Sharing best practices
  - Safety: Extensive sharing through WANO, IAEA
  - Security: Limited sharing through World Institute for Nuclear Security
- Independent advice
  - Safety: International Nuclear Safety Group (INSAG) publishes annual letters on safety priorities, wide range of analyses and reports; many NGOs providing analysis and critique
  - Security: AdSec provides confidential advice to IAEA, does not publish reports; small number of NGOs involved

Nuclear energy affects proliferation – but is not the main driver

- 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

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

- 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

An assessment framework for proliferation resistance

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

Proliferation-resistance: the wrong way to think about it

- 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

Example: pyroprocessing

- 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

Example 2:
Simple, lifetime core systems

- 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

Proliferation hazards of spent fuel repositories

- 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

Proliferation hazards of the research infrastructure

- 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

How much difference does HALEU make?

- 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 <u>much</u> easier)

Nuclear thefts and terrorist consideration of nuclear terrorism are ongoing realities

- ~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)

The Islamic State – good news and bad news

- Ideology envisions final war with “crusader” forces – powerful weapons needed
- Islamic State produced, used its own chemical weapons
- Clear capacity for disciplined manufacture, technical innovation
  - Manufactured mortars, shells, other arms to precise tolerances
  - Drone and IED efforts repeatedly built, tested new ideas
- Monitoring of Belgian nuclear official hints at nuclear interest
  - Hours of monitoring of official’s private home, by operatives involved in Paris attacks
  - Senior official at facility with HEU, rad sources, research reactor…
- BUT: IS did nothing with the large Co-60 sources under their control
  - Large sources were in territory they controlled, now back in government hands

Reactor-grade plutonium is weapons-usable

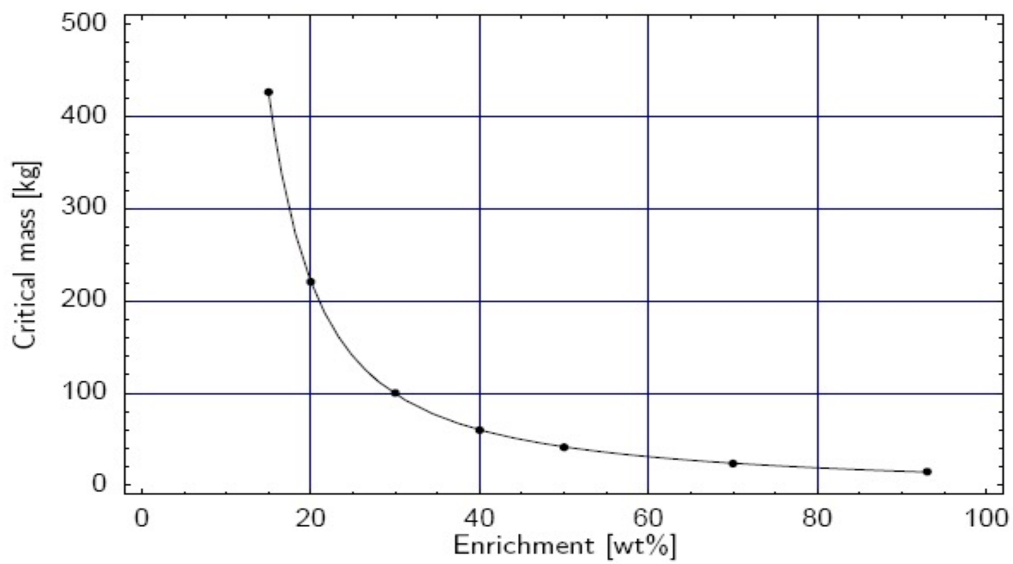
- Higher neutron emission rate:
  - For Nagasaki-type design, even if neutron starts reaction at worst possible moment, "fizzle yield" is ~ 1kt – roughly 1/3 destruct radius of Hiroshima bomb – more neutrons won't reduce this
  - Some advanced designs are "pre-initiation proof"
- Higher heat emission:
  - 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*

Reactor-grade plutonium is weapons-usable (II)

- "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)

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

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

Properties of key nuclear explosive isotopes

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)*

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

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.

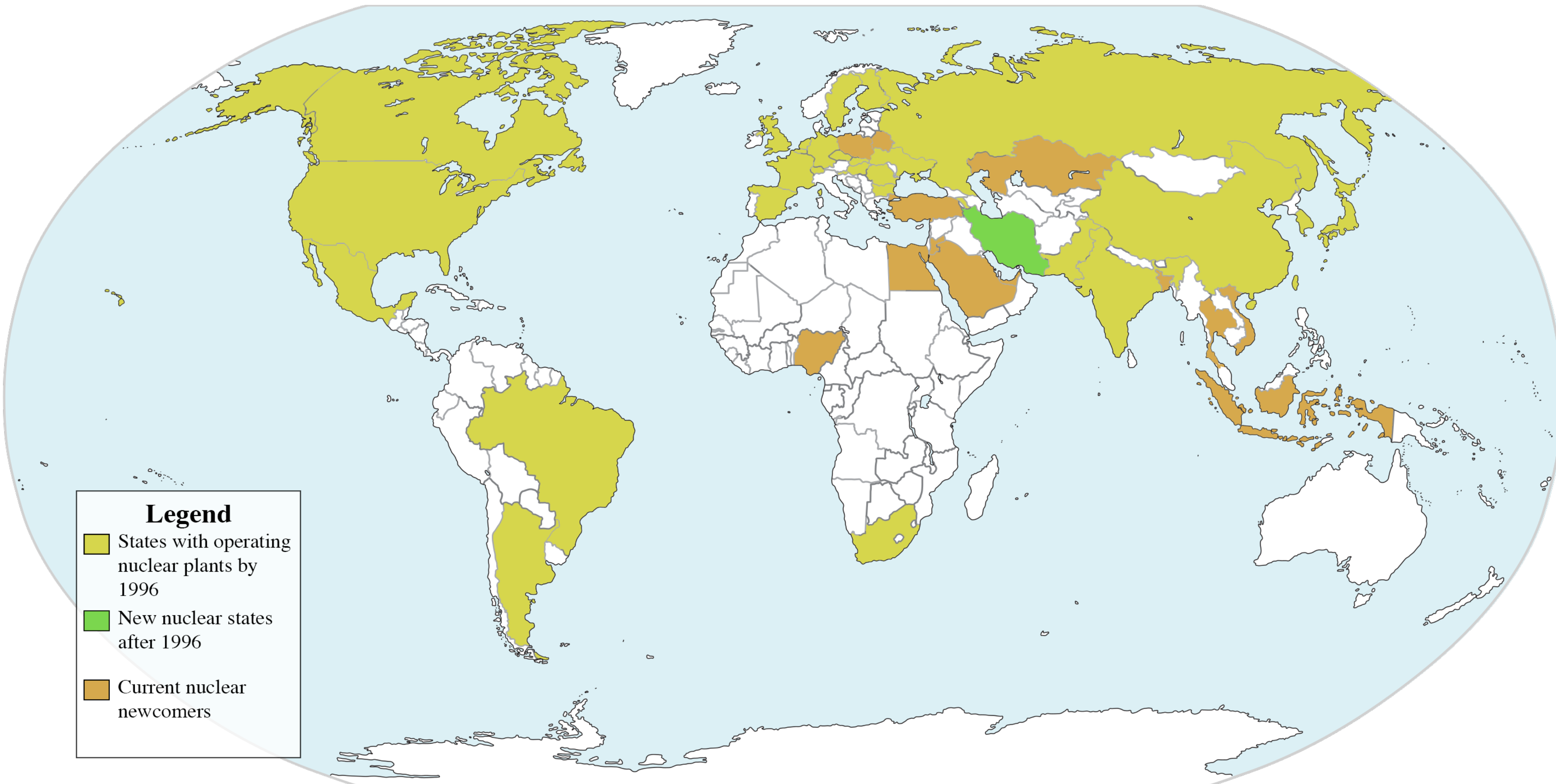
The IAEA should recommend that states require steps such as these. The United States and other countries operating and exporting nuclear reactors, along with industry groups

Source: Science, Sept. 16, 2011

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

- 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

Nuclear growth implies nuclear spread: the story so far



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

Comparing nuclear safety and nuclear security risks: the historical record

- U.S. safety goal: 1/10,000 per reactor-year chance of major core damage; 1/100,000 chance of major release
  - Obviously haven't met this goal so far
  - 4 reactors with major releases (Chernobyl and 3 at Fukushima Daichi) in 16,000 reactor-years of operation – 1/4,000 reactor-years
  - Other core damage events (TMI, Fermi I…)
  - But goal remains valid – and given horrifying consequences, goal for preventing nuclear terrorist attack should be *more* stringent
- Nuclear theft:
  - ~300 global facilities with HEU or Pu -- ~ 7,500 facility-years over last 25 years
  - ~20 seizures of stolen HEU or Pu in that time (some from same theft)
  - > 1/400 per facility-year
  - Most from Russia (but also most facilities there); several seizures may be from same theft – but still, shows rate far too high

Comparing nuclear safety and nuclear security risks: the historical record (II)

- Nuclear sabotage
  - During ~16,000 reactor-years of operation:
  - 1 case in which insider placed explosives on steel pressure vessel and detonated them*
  - 1 case (very recent) in which insider sabotage destroyed reactor turbine
  - 1 case in which terrorists overwhelmed and captured the guard force, were in full control for extended period before leaving when off-site response arrived*
  - 1 case of RPG being fired at, hitting reactor
  - Multiple cases of terrorist groups planning attacks on reactors
  - ~ 1 major incident per 3-4,000 reactor-years

Both theft and sabotage risks appear to be very high compared to safety goals

*reactor not yet operational

The scale of the control problem…

- 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