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What types of nuclear material require what levels of security?

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Judgments on what material poses what risks have consequences

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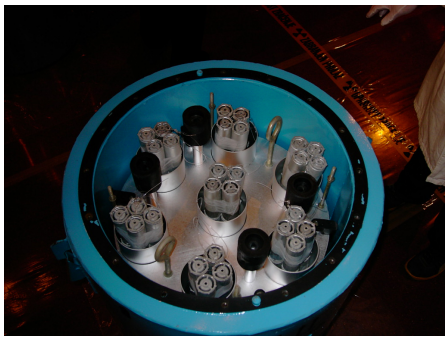
- August 2002: Project Vinca
  - Transport of 48 kg of 80% enriched HEU from research reactor to airport guarded by 1,200 troops
  - At a DOE site, would have been Category III material requiring very little security (<10% by weight U-235, <50 kg U-235)
- Similar issues arise all over the world
- We need a system that applies the most security to the material posing the highest risk
  - We need to pay more attention to 100 kg of 90% HEU metal than to 20 kg of 36% enriched HEU dispersed in research reactor fuel



Source: NTI

We need a risk-informed approach

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- "Risk-informed," rather than entirely "risk-based," as the impact of material form on risk is not well-understood
- Goal: minimize the combined probability that terrorists will succeed in:
  - Stealing material
  - Turning it into a nuclear bomb
- Concept:
  - Develop a "discount factor" for each set of material characteristics, based on how much these probabilities would be reduced compared to the "ideal" material for terrorists (enough weapon-grade HEU metal for a gun-type bomb)
  - Regulation could then allow higher probabilities of adversary success for materials with lower discount factors (for example, by a lower-capability DBT covering less of the threat spectrum or by permitting higher probability of failure against a fixed DBT)
  - Overall probability of success in theft plus turning it into a bomb could then be equalized across different material types – no risk outliers

We need graded safeguards – not cliffed safeguards

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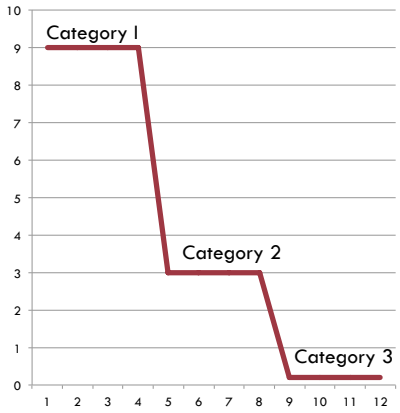
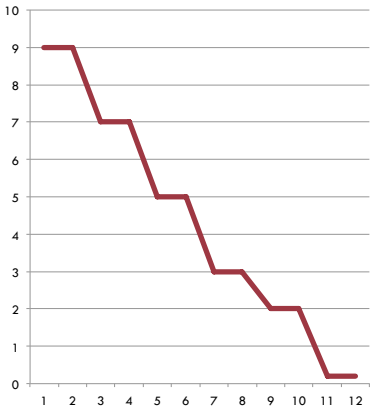
Not this…



But this



Current approaches include only some of the relevant factors

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Key factors to consider:

- Amount of HEU or Pu available
- Material for gun-type versus implosion-type bomb
- Size and mass of material to be stolen and processed
- Isotopics (different issues for HEU, Pu)
- Chemical processing required – how difficult?
- Radioactivity of material

IAEA categorization table includes only:

- Amount of HEU or Pu

DOE "attractiveness" approach includes many factors:

- Some not in a way that adequately reflects risk

Proposed NRC approach mainly adds weight percent factor

Gun-type bombs would be easier for terrorists than implosion-type bombs

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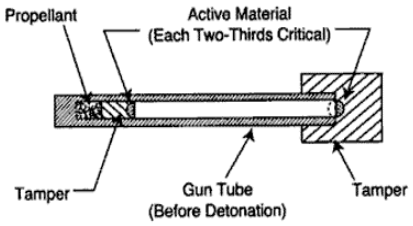
- Gun-type bombs – as obliterated Hiroshima – basically involve slamming pieces of HEU together at high speed
- Implosion bomb (required for plutonium) more difficult, still conceivable (especially if they got help)
  - Doesn't need to be as complex as Nagasaki bomb
- Debate over how *much* more difficult – propose "discount factor" of 0.6 for implosion



Source: NATO

Proposed material categorization: quantity

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	Pu or U-233	U-235 in HEU	Discount Factor
Category IA	≥ 15 kg (U-233)	≥ 50 eff. kg	1.0
Category IB	≥ 6 kg	≥ 18 eff. kg	0.6
Category IC	≥ 2 kg	≥ 5 eff. kg	0.4
Category II	≥ 500 g	≥1 eff. kg	0.2
Category III	≥ 15 g	≥ 15 eff. g	0.1

- Thresholds for Categories 1, 2, 3 same as existing tables
- But takes into account that having enough for a gun-type bomb (Category IA) or enough for a crude first-generation implosion bomb (Category IB) at a single site increases terrorists' chances of success
- Plutonium cannot be Category 1A, because it cannot be used to make asubstantia-yield gun-type bomb

Proposed material categorization: Uranium isotopics

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- Use IAEA "effective kilogram" figure (kilograms times square of fractional enrichment) to take into account increased amount needed at lower enrichments
  - Example 1: 100 kg 90% HEU=100*0.9^2=81 kg
  - Example 2: 100 kg 20% HEU=100*0.2^2=4 kg
- Consider HEU below ~ 40% U-235 as implosion-only material
  - Because of combination of quantity required and background neutrons for gun-type bomb)

Proposed material categorization: Plutonium isotopics

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- Reactor-grade plutonium is also weapons-usable
  - Neutrons, heat, and radiation can all be managed
  - Some current U.S. weapons are "pre-initiation proof"
  - Early U.S. nuclear weapons designed to have nuclear material inserted just before use – one option for heat management
  - Official U.S. statement:
    - At "lowest level of sophistication" can make bombs from reactor-grade with "assured, reliable yield of one or a few kilotons"
    - With "modern designs" can make weapons with yield, weight, reliability "comparable" to those with weapons-grade plutonium
    - Intermediate results with intermediate sophistication

    U.S. Department of Energy, *Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, pp. 37-39.
- Proposed discount factor for reactor-grade: 0.8

Proposed material categorization: Radioactive dose rate

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- Old 100 rad/hr at 1 meter "self-protecting" standard provides little deterrence against adversaries with little regard for their own health
- Actually disabling thieves during the course of a theft requires dose rates of 1000s of rad/hr
  - Commercial spent fuel often has such dose rates
  - Research reactor spent fuel often does not
- Dose rates during processing also matter
  - Forcing adversaries to use remote operations rather than glove boxes represents substantial additional barrier
  - Chemical processing experts may be less likely to be willing to accept large doses than those carrying out a theft
- Proposed discount factors:
  - Lightly irradiated: (20-400 rad/hr): 0.8
  - Requires remoted processing: (400-3,-10,000 rad/hr): 0.2
  - Disabling during theft (>3,000-10,000 rad/hr): .001

Proposed material categorization: Size, mass, chemical form, dilution

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- Size and mass of the objects mainly matter in how hard they are to steal
  - Some forms (e.g., HEU in tens of tons of dirt) impractical to steal
  - Size and mass may have large effect on covert insider threats
  - But outsiders capable of organizing weapons-usable material theft likely to be capable of bringing vehicle to carry one or a few moderately heavy objects
- Dilution matters to both ease of theft and ease of use
  - Must be very dilute to make theft difficult
  - At 10-20 weight %, only need to carry off 40-80 kilograms of material for significant quantity of plutonium, 125-250 kilograms for significant quantity of HEU
  - But dilution at those levels does force processing before use

Proposed material categorization: Size, mass, chemical form, dilution (II)

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- Chemical form:
  - Many forms require processing before use in a weapon
  - For most forms, processing required is not advanced, instructions in open literature
  - *But,* does take time, introduces opportunity for error
  - Processing 2-20x as much material (because of dilution) will take more time, but may reduce probability of success only modestly
- Proposed discount factors:
  - Compounds and mixtures not requiring chemical processing: 0.8
  - Compounds and mixtures requiring chemical processing: 0.5
  - Could be case-by-case reduction for compounds requiring especially difficult processing
  - Dilution requiring more than a readily available truck to carry away a significant quantity: 0.3

Risk reduction from forms requiring some chemical processing is modest

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- The requirement for chemical processing would rule out the "rapid improvised nuclear device" threat
  - Buys time; introduces more chances for the adversary to make mistakes
  - BUT most nuclear terrorist conspiracies likely to take weeks, months, or years in any case
  - AND detailed 1970s NRC study concluded that separating Pu from MOX requires "relatively modest facilities and effort" so "lowering the concentration of plutonium through blending should not be used as a basis for reducing the level of safeguards protection"
- NRC proposal for "immediate detection with pursuit" strategy for moderately dilute forms is not justified
  - What data shows that pursuit and recovery is reliable?
  - In substantial fraction of bank robberies and other major thefts, thieves succeed in eluding pursuit and are not caught for weeks or months, if ever
  - If adversary probability of success with time is substantial, containment strategy is needed

Proposed material categorization: quality

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Attractiveness Level	Material Type	Discount Factor
A: Weapons and Gun-Type Bomb Materials	Weapons, ≥50 eff. kg HEU metal (>40 percent enrichment)	1.0
B: Implosion-Type Bomb Materials	Pu metal, < 50 eff. kg HEU metal (>40 percent enrichment), HEU metal ≤ 40 percent enrichment	0.6
C: Compounds and Mixes Not Requiring Chemical Separation	Oxides, carbides, nitrates, other direct-use compounds, alloys and mixtures	0.8
D: Compounds and Mixes Requiring Chemical Separation	Alloys and mixes requiring chemical separation; fuel elements and assemblies; solutions	0.5
E: Reactor-Grade Plutonium	Plutonium containing >7% Pu-240	0.8
F: Lightly Irradiated Material	Emitting ~20-400 rad/hr at 1 m	0.8
G: Irradiated Material Requiring Remote Handling	Emitting ~400 to 3,000-10,000 rad/hr at 1 m	0.2
H: Highly Irradiated Material Imposing Disabling Doses During Theft	Emitting >3,000-10,000 rad/hr at 1 m.	0.001

The Bathke et al. "figure of merit" approach is useful but insufficient

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- Bathke et al. approach provides an integrated way to look at tradeoffs among (a) the mass of material needed for a critical mass; (b) the heat generated from the material, and (c) the radioactive dose rate from the material:

$$FOM_1 = 1 - \log_{10}\left(\frac{M}{800} + \frac{Mh}{4500} + \frac{M}{50}\left[\frac{D}{500}\right]^{\frac{1}{\log_{10} 2}}\right)$$

Where *M* is critical mass of the material in kg, *h* is heat generation in W/kg, and *D* is the dose rate of 1/5th of a critical mass at one meter from the suface, in rad/hr. FOM>2 is "preferred" for weapons use, 1-2 "attractive," <1 "unattractive."

- Usefully describes the weapon utility of material *in its current form* – but never intended to describe how difficult it would be to process it to a different form that would be more useful in weapons (e.g., lower critical mass, lower dose rate)

Implications -- examples

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- HEU-fueled research reactors
  - Dose rate of 100 rad/hr at one meter no longer eliminates need for Category I protection (increased incentive to ship spent fuel)
  - Use of "effective kilograms" would drop many facilities using medium-enriched material out of Category I
  - Increases focus on those facilities with high quality HEU in quantities sufficient for gun-type bomb
- Fresh MOX
  - Remains Category I
  - Some discount factor because (a) implosion material (b) requires chemical processing
  - But no further discount factor because only 7% by weight
  - Contrast to proposed NRC approach

Complications and objections

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- Particular choices of discount factors may be controversial
  - Expert views vary on the importance of particular factors
  - But method could still be used, with elicitation of broad range of expert views for each element
- Combining discount factors requires judgment
  - Unlike DOE tables, material can be in more than one category when it has more than one undesirable characteristic
  - Cannot simply multiply – because terrorists' ability to overcome one obstacle likely to be strongly correlated with ability to overcome another
  - But probability of terrorist success with two or more undesirable material characteristics clearly lower than with any one of those characteristics alone – estimating how *much* lower requires expert judgment
- Too complex?
  - Approach involves combining many factors
  - *But,* most operators do not have frequently changing material – those that do generally have some high-category material
  - Decision-tree similar to that in DOE Orders could be developed