# Making Nuclear Energy Suitable for More of the World's Energy Supply: Issues and Prospects

Matthew Bunn
Harvard Kennedy School
Energy Policy Seminar
7 December 2010
http://www.managingtheatom.org


Many ideas in this talk elaborated in recent report

# Two narratives on the future of nuclear energy

- Narrative 1:
  - Nuclear energy too complex, expensive, and problematic to provide more than a small fraction of world energy supply
  - Nuclear energy cannot play a major role in climate mitigation
- Narrative 2:
  - To cope with climate, large-scale nuclear growth is essential – only non-intermittent, readily expandable source of low-carbon electricity
  - Can be expanded dramatically, risks can be managed

*Making Narrative 2 come true would require major institutional and technical changes*

# Nuclear role in 3 greatest global energy challenges

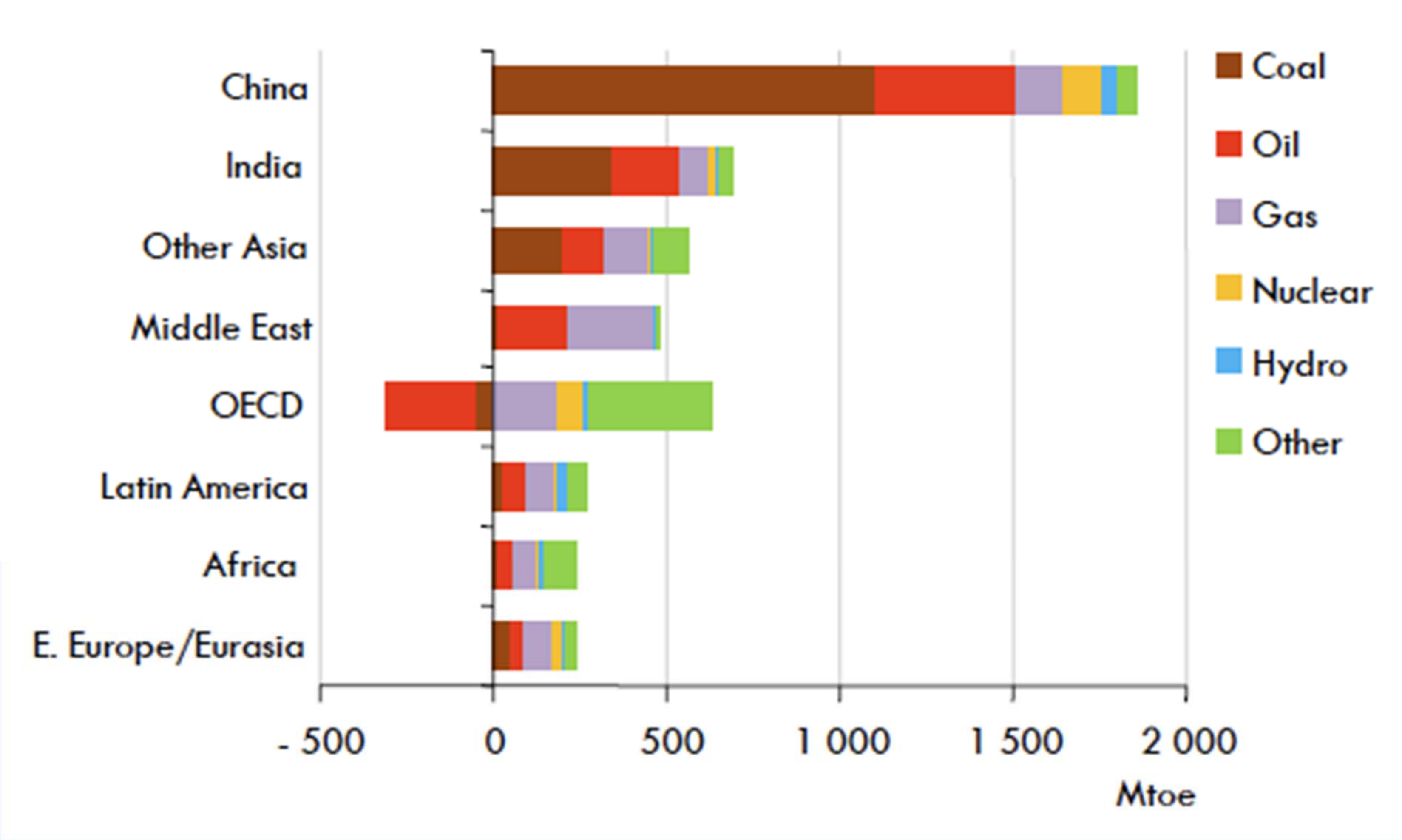
- Energy supply without greenhouse emissions
  - Massive growth required for nuclear to play a significant role
- Reducing energy supply vulnerabilities (esp. oil)
  - Nuclear currently provides baseload electricity, oil little-used for that purpose in most countries
  - Nuclear cannot currently make major contribution to transport fuel
  - May change in future
- Providing energy to the world’s poor
  - Current huge, complex, expensive nuclear plants not the technology that will provide electricity to rural villages
  - May also change (at least somewhat) in future

*Electricity <1/3 global primary energy, and most future demand growth is in developing countries – need to make nuclear energy able to fill more purposes in more locations*

# Nuclear energy – current status

- Modest current contribution to global energy supply
  - 441 reactors operating worldwide (376 GWe)
  - 29 countries
  - 14% of global electricity production
  - 5.7% of global primary energy supply
- Modest current growth
  - 2008: 0 reactors connected to the grid worldwide
  - 2009: 2 reactors connected to the grid worldwide
  - 58 reactors under construction worldwide (some little activity)
  - 2 reactors under construction in Western Europe; 1 in U.S.
  - Even solar and wind capacity being added faster
  - World's largest nuclear construction program is in China – *might* be a few percent of electricity supply by 2030 if targets are met
  - IEA *World Energy Outlook 2010* "Current Policies" scenario projects no growth in nuclear share of electricity to 2035

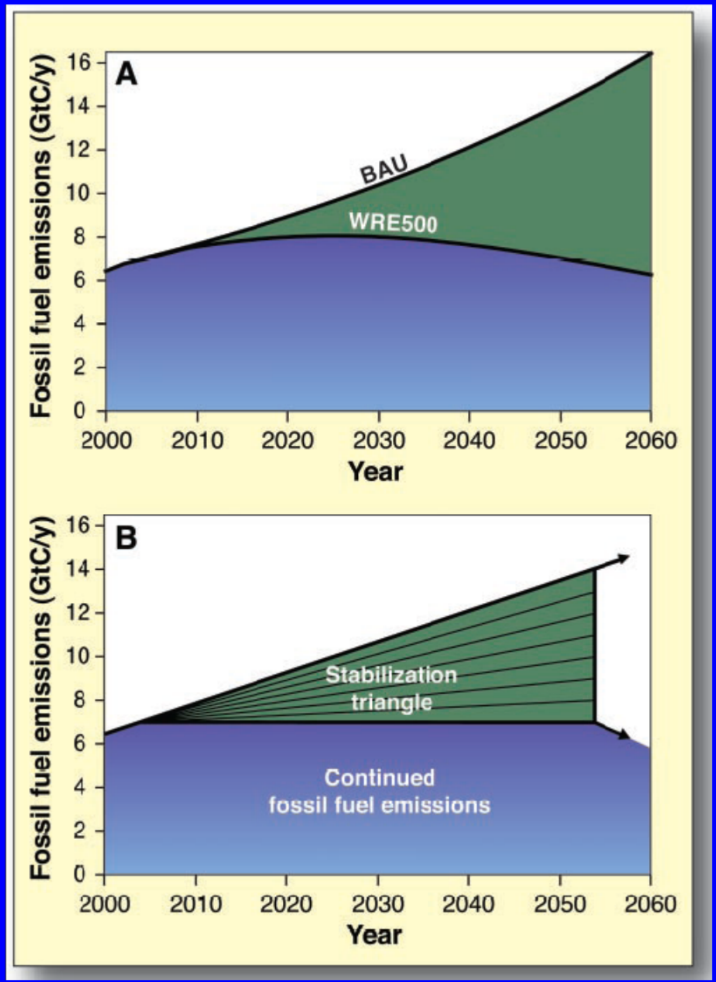
# Change in primary energy demand by fuel, reference scenario, 2007-2030




*Source:* International Energy Agency, *World Energy Outlook 2009*

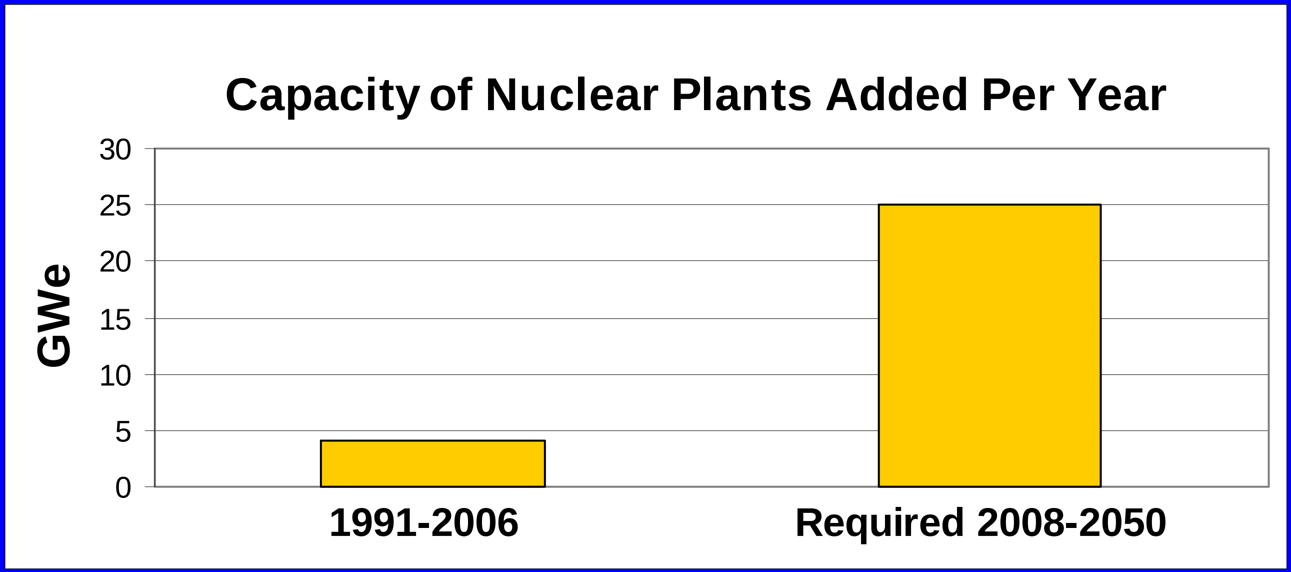
# The energy-climate context

- *Dramatic* nuclear growth required for climate contribution large enough to be significant
- To provide *one* of seven "wedges" needed to stabilize CO2 at 500 ppm, nuclear would have to add 700 GWe of capacity by 2050 – and replace 369 GWe of existing capacity
- 2 wedges – as in Stern report – may be unobtainable
- Latest science suggests 10-15 "wedges" may be needed



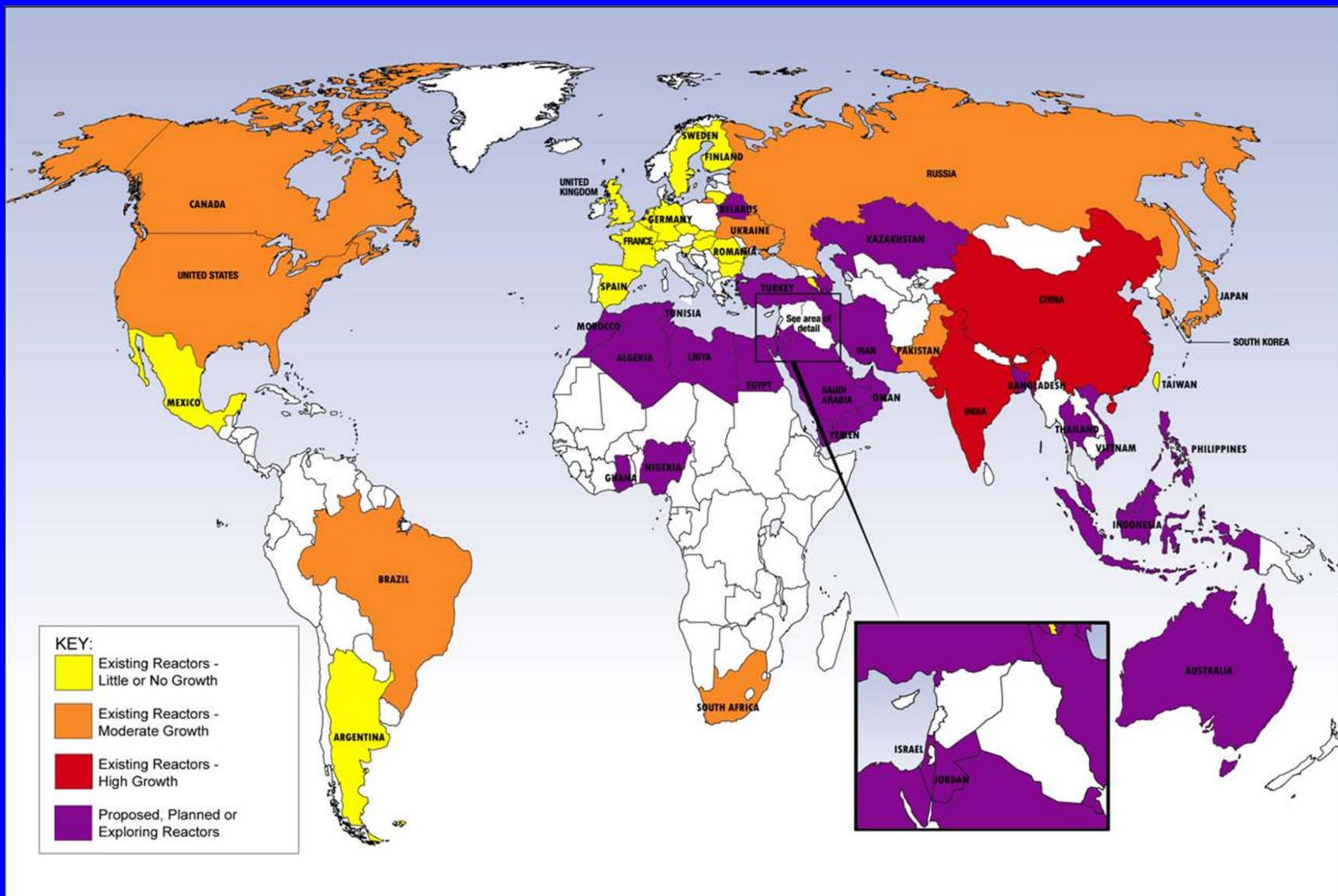

*Source:* Pacala+Socolow, "Stabilization Wedges," *Science* **305** 968-972 (2004)

# For nuclear stabilization wedge, huge increase in construction needed




- Need to shift from 4 to 25 GWe/yr
- Nuclear must become dramatically more attractive to governments and utilities than it has been
- Any major disaster, from accident or terrorism, would doom any realistic prospect for major nuclear contribution to the climate problem

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




*Source:* Sharon Squassoni, Carnegie Endowment for International Peace

# Governance indicators raise concerns over emerging nuclear power states

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

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

# Steps to enable large-scale nuclear growth

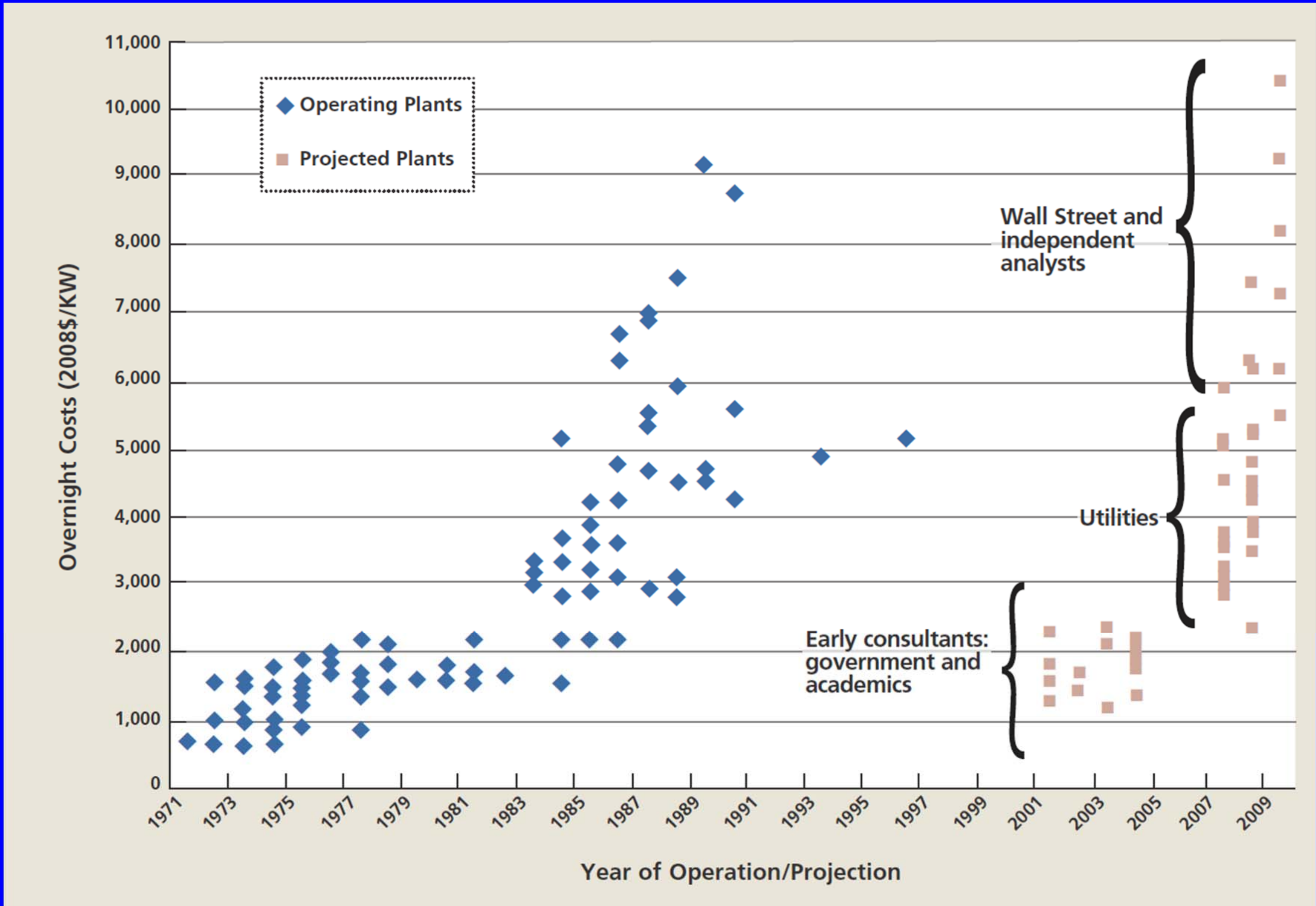
- Reduce costs, ease financing
- Avoid major delays, cost over-runs
- Address technical, personnel supply bottlenecks
- Avoid accidents
- Avoid terrorist incidents
- Avoid further nuclear proliferation
- Manage nuclear waste successfully
- Make nuclear power suitable for more of the world
- Make nuclear power suitable for more purposes

*Near term (2010-2030): primarily institutional changes*

- *Main effect of new technologies comes later*

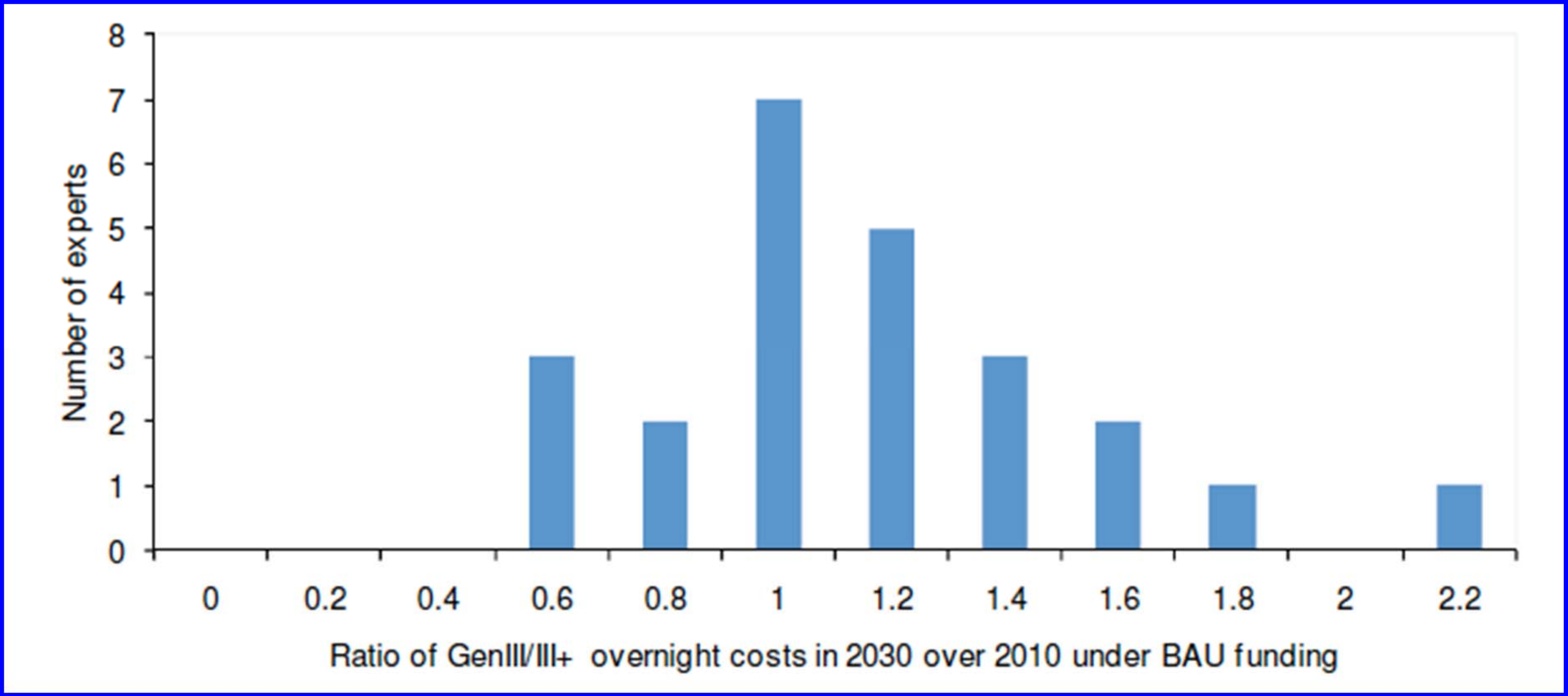
*Long term (2030-2070): institutional and technical changes*

# Nuclear costs: a forgetting curve?




Source: Cooper 2009.

# Nuclear costs: most experts are not expecting a breakthrough




*Source:* Anadon, Bunn, et al., to be published

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

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

- Policies to reduce costs, ease financing
  - Expedited licensing
  - Low-cost financing (from gov't funds in some countries, loan guarantees or low-cost loans in others…)
  - Government-backed insurance (e.g., Price-Anderson, EPAct)
  - Government support for waste management
  - Production tax credits, other subsidies
  - After decades of subsidies, how much subsidy is justified?
- New steps to reduce accident risks
  - Strengthened peer reviews to find and fix the least safe reactors
  - Shut-down or take major safety steps for oldest, least safe reactors
  - Help "newcomer" states establish safety infrastructures, culture
  - Build toward effective, binding global nuclear safety standards, with mandatory international peer review, for long term

# Expanding nuclear energy need not 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, current trend seems to be away from reprocessing (despite GNEP) – reduced operations at La Hague and Mayak, phase-out at Sellafield

# Near term institutional steps (II)

- Actions to strengthen protection against nuclear terrorism
  - Strengthen security measures for all nuclear weapons, HEU, plutonium worldwide – major progress, still much to do
  - Minimize HEU and plutonium use, number of sites
  - Strengthen reactor protection against sabotage worldwide (many countries have no armed guards, few insider protections)
  - Expand exchanges of security best practices, peer reviews
  - Targeted programs to strengthen security culture
  - Move toward effective, binding security standards for long term
- Approaches to manage nuclear wastes
  - Establish dry cask storage of spent fuel wherever needed
  - Establish democratic, voluntary approaches to siting repositories
  - Move toward increased international cooperation – including regional or international spent fuel storage, disposal
  - Move toward "fuel leasing" and "reactor leasing" – "cradle to grave" fuel services

# Near term institutional steps (III)

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

# Limiting fuel cycle proliferation risks

- 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"
  - Potentially key role for multinational consortium marketing factory-built small and medium reactors, with "cradle-to-grave" fuel and reactor services (more later)
- Restrain technology transfers (as NSG is discussing)
- Move step-by-step to increased multinational control over sensitive fuel cycle facilities

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

- 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 – in weapon states as well)
- 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)

# Making nuclear energy broadly available

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

# Potential for a small and medium reactor consortium

- Suppliers could form consortium to market factory-built reactors
- Reactors built in factories with all fuel sealed inside, returned at end of life
- Suppliers might also operate reactors when requested
- Could make possible large-scale, widespread nuclear energy deployment with modest proliferation, safety, or terrorism risks

Artist's concept of 6 modules of 125-MWe "mPower" design

*Source:* Babcock and Wilcox

# Small and medium reactors: current status and prospects

- Many countries have proposed designs in various stages of development – but minor focus of R&D at present
  - Russia just launched *Academician Lomonosov*, ship with two KLT-40 reactors (derived from icebreakers), for Russian north
    - Does not have designed-in inherent safety, security, nonproliferation systems future designs might have
  - Two U.S. designs preparing to apply for licenses (B&W “mPower” and NuScale) – based on standard light-water designs
  - Many other concepts farther out, some not small (e.g., TerraPower)
  - Obama administration proposed R&D in FY11, not yet approved
- Cost remains a major question
  - Would lose economies of scale of large reactors
  - Could they make it up in economies of manufacturing scale? How do they get enough contracts to do that before low cost is proved?

# Making nuclear energy available for a broader array of purposes

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

*More R&D required to explore these many possibilities*

# Uranium and repository space: not likely to be major constraints

- Uranium is abundant
  - Current use ~ 60,000 tU/yr
  - IAEA estimates 15.8 M tU available (known+speculative)
  - More is being found more rapidly than it is being consumed
  - 2010 MIT analysis suggests enough U to fuel 10x current nuclear fleet for *1,000 years* before price increases enough to make reprocessing economic
- If repositories can be sited at all, space in them is not likely to be a major constraint on nuclear power
  - Yucca Mountain 70,000 ton limit legislated, not physical
  - Other countries pursuing large areas of granite, could expand repository by simply drilling tunnels further
  - First states to get political approval (Finland, Sweden) plan direct disposal of spent fuel without reprocessing

# What are the prospects?

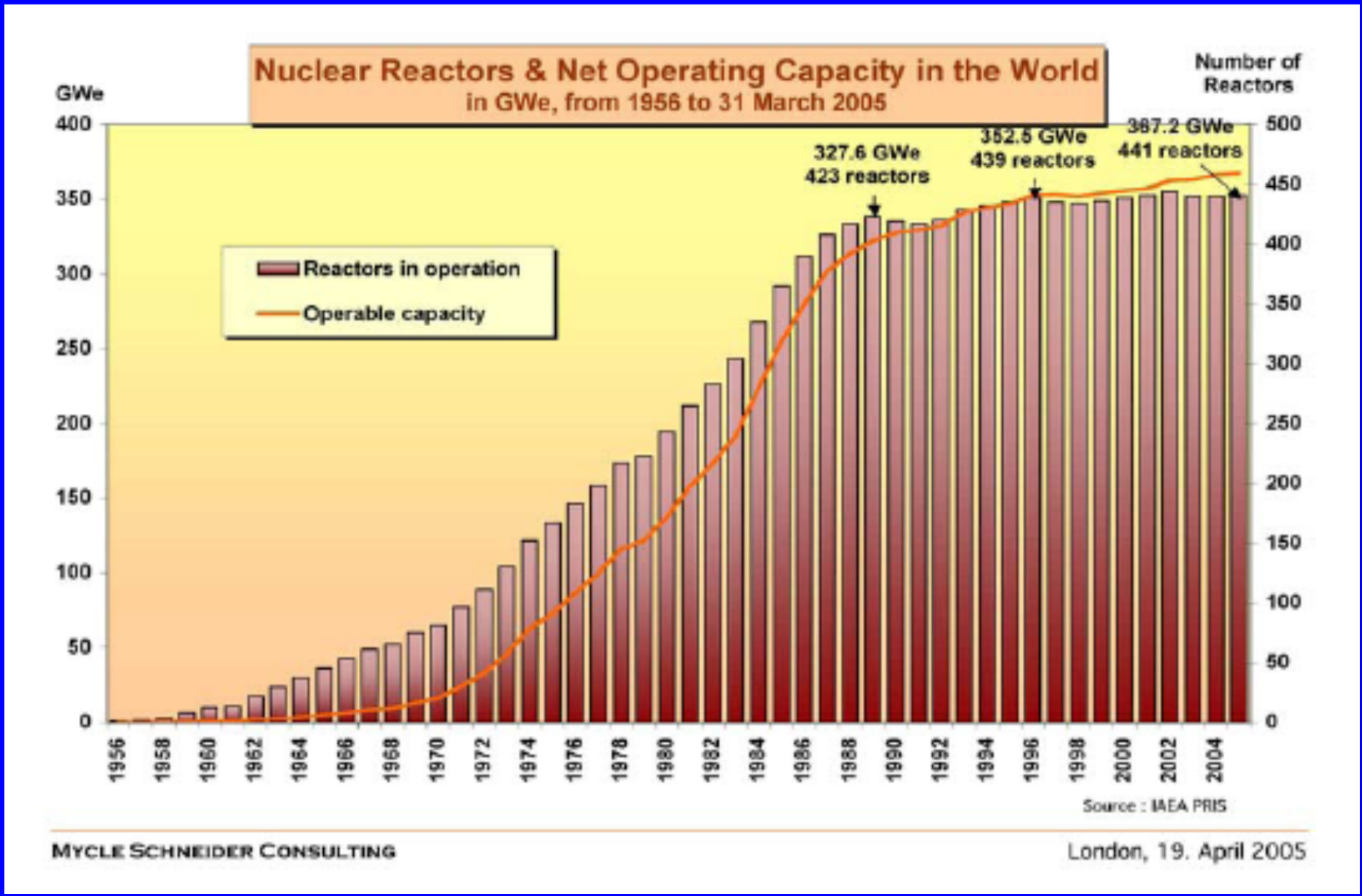
- Near term, muddling through likely
  - Modest but steady nuclear energy growth
  - Modest but genuine institutional improvements
- Long term, several scenarios possible
  - Large-scale growth with acceptable risks would require major institutional and technical changes, beginning soon
  - Real risks of *not* moving forward with such improvements
- Widespread complacency
  - Most nuclear companies have as much demand as they can handle, see no need for new action on safety, security, nonproliferation, disarmament
  - Most states unwilling to agree to new measures that involve even modest compromises in sovereignty
  - Financial crisis, Iraq, Afghanistan, the Middle East, all shrink the attention senior policy-makers are likely to give

# Backup slides if needed

# Preventing nuclear proliferation

- Global nuclear nonproliferation regime is under severe stress – Iran, North Korea, the A.Q. Khan network, the global spread of technology, potential growth and spread of nuclear energy, disputes over disarmament, India deal…
- *But*, the regime has been both <u>successful</u> + <u>resilient</u>
  - 9 states with nuclear weapons today – 9 states 20 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

# A fragile revival? TMI + Chernobyl stopped nuclear growth



# How might nuclear growth and spread affect sabotage risks?

- Chance of major release caused by malevolent action may well be higher than chance from pure accident
  - Yet industry focus overwhelmingly more on safety than security
- Number of sabotage attempts likely to be driven by level of terrorist groups' interest, *not* number of reactors
- *But:*
  - More reactors in more places means more chances for security mistakes that could create a sabotage vulnerability – *unless* security measures strengthened as nuclear energy grows
  - Even more than with safety, small numbers of poorly secured plants can dominate total risk – terrorists more likely to choose them, and more likely to succeed if they do
- Highest likely current and future risks:
  - Older Soviet-design reactors with few redundant safety features
  - Reactors with minimal security measures (e.g., 0 armed guards)
  - Reactors in newcomer states with little nuclear security experience

# 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

# Addressing safeguards challenges

- 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

# How strong a nuclear revival? Near term vs. long term

- Near term: modest growth, some spread
  - Past decade: ~ 4 reactors connected to grid/yr
  - ~2% of total capacity additions (< renewables)
  - Major construction in China, India, Russia
  - A few reactors in "newcomer" states
  - Low gas prices may continue for many years (shale gas) may suppress all capital-intensive electricity production
  - Few states interested in enrichment, reprocessing
- Long term: potential for huge growth, drastic spread
  - Only readily expandable low-carbon baseload electricity source
  - Future technologies may reduce costs, make nuclear more suitable for more of world's population, more different energy uses
  - Growth to 3-5 times current deployment by 2050 *possible* – not clear if this is likely
  - More states may want enrichment and reprocessing
  - Potential move toward deep nuclear reductions/disarmament

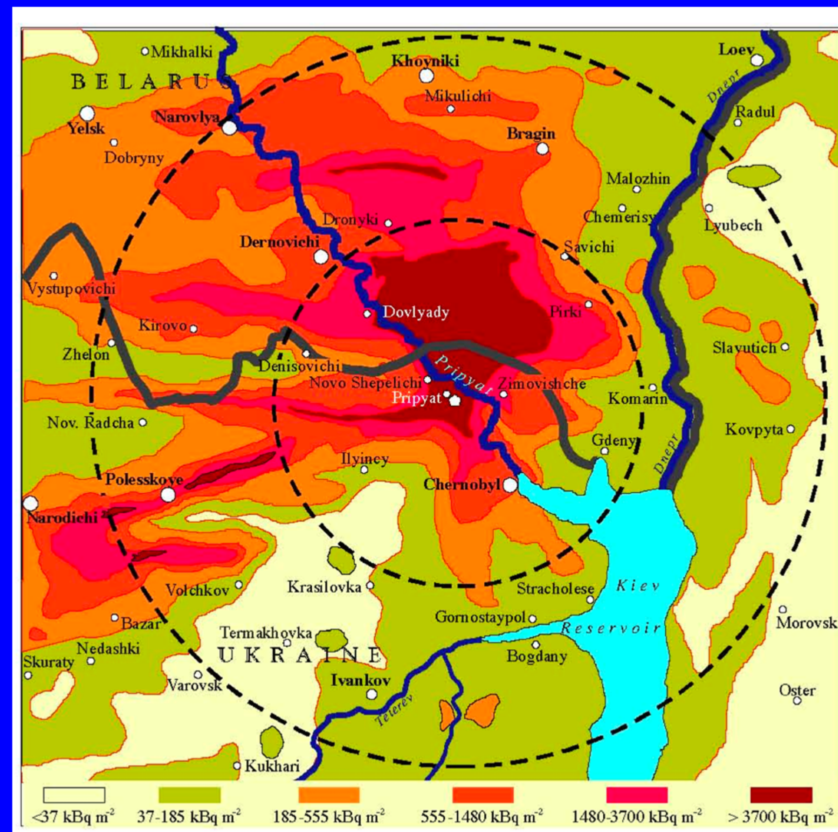
# Risks of nuclear accidents

- Nuclear power today substantially safer than in the days of TMI, Chernobyl
  - Demonstrated by wide range of numerical indicators
  - NRC requires no more than 1/100,000 risk of major release per reactor-year – new reactor designs safer still
  - *But*, continuing issues – Davis Besse provides compelling example
- Accident risks estimated using "probabilistic risk assessment"
  - Extremely useful tool for identifying biggest contributors to risk
  - But extremely difficult to model complex system-level human-machine interactions
  - TMI, Chernobyl, Davis-Besse *all* scenarios never envisioned in such analyses
  - "Safety culture" a major issue – and difficult to model

# Safety culture matters: Davis-Besse vessel head hole


*Source:* FirstEnergy

# Chernobyl – an epic disaster




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

# Reducing terrorist nuclear bomb risks

- Create fast-paced global campaign to prevent nuclear terrorism, focused particularly on effective nuclear security
  - Steps to build sense of urgency among leaders, nuclear managers
  - Obama call to secure all nuclear material worldwide in 4 years
- Seek to ensure that *all* caches worldwide are protected
  - Against threats terrorists and criminal have shown they can pose
  - In ways that will work (includes strong security culture)
  - In ways that will last (sustainability)
- Establish effective global nuclear security standards
  - Can build from UNSC 1540 requirement
- Consolidate to smallest practicable number of sites
  - Expand facilities, materials covered, policy tools used
- Expand sustainability, security culture efforts

# Reducing sabotage risks

- Rapidly upgrade security for all high-consequence nuclear facilities and transports (esp. in high-threat countries)
  - Gain political-level agreement on this goal (e.g., through G-8)
  - Develop effective global standards for sabotage security (e.g., in revision to IAEA recommendations)
  - Add at least limited efforts to reduce sabotage risks to U.S. nuclear security assistance programs
  - Expand security-focused training, programs to strengthen security culture, exchange of best practices, peer reviews
- Ensure that all new reactors are designed and operated to protect them against demonstrated terrorist threats
- Work with “newcomer” states to ensure that infrastructure focused on “3 S’s” – safety, security, safeguards – established from the beginning

# Security culture matters: Propped-open security door

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

# The dominance of economics

- 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)