Role of Nuclear Generation
in
Energy-Food-Water Security

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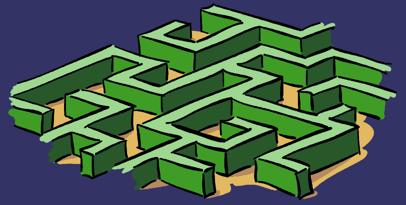
Dr Stuart Nettleton
UTS Faculty of Engineering & IT

Research areas:
Global-Mulitregional New Computable General Equilibrium Integrated Assessment Models
Model selection using Bayesian & Probabilistic Graphical Models

stuart.nettleton@uts.edu.au +612 9514 2626

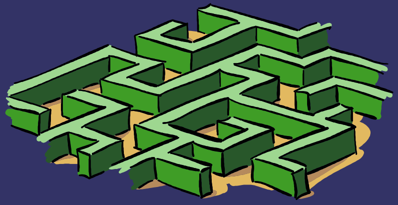
Presentation Structure

- Interpretation of Energy Food Water Challenge
- Concept of Safeguards
- Impact of megacities
- Current controversy: old nuclear plants
- Deficiencies in understanding new nuclear technology & applications
- Research gap to be considered
- Objectives
- Methodology (Sceptre Global-Multiregional New CGE)
- Outcomes



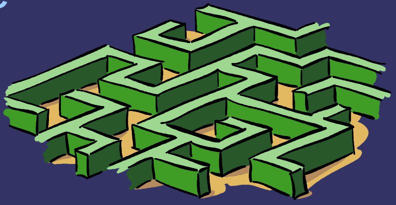
Interpretation of the Energy-Food-Water Security Challenge

- Existentialism
  - I exist, I choose to continue to exist
    - Personally preferring pleasure over pain
    - Wanting the ones that I love to prosper
  - From this arises
    - Aspiration for personal freedom & free markets
    - Democracy for collective action to assure these things
- Enlightened governments' role
  - Maintain order
    - Individual freedom, free markets and democracy
    - Framework for a virtuous upward spiral of growth in prosperity
  - Prevent chaos
    - Threats - identify, evaluate and respond to all threats that may compromise these fundamental principles
    - Safeguards - eliminate all threats or reduce these to acceptable levels where fundamental principles are no longer compromised



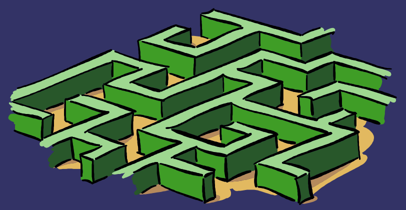
Government challenge: safeguarding resource risks

- Global population
  - Expanding to 9 or 10bn requiring 30% more resources
- Achievement of improved living standards
  - 3bn new middle class
- Social & economic efficiency of mega-cities
  - Fabric of society is becoming ever more complex
  - New York 20m, Tokyo/Yokohama 37m
  - 28 megacities in 2013 rising to 70 in 2050
- Everything changes with new constraints
  - Geo-political balances (China, S.E. Asia)
  - Geo-physical constraints (climate change)
  - Supply & demand for scarce resources
  - Global location where resources have best use and entrepreneurs will pay the highest price
  - Infrastructure, production & technology functions



Importance of the Energy-Food-Water Security Challenge

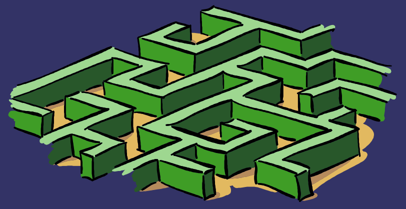
- Upward spiral in freedom and prosperity
  - Bottom-line for complex societies - safeguards “non-negotiable”
  - Complete availability of resources without risk & at an acceptable price
  - Megacities are risk hotspots
- Megacity new major food-water-energy links
  - Electricity generation, process heat & water desalination
  - Electricity generation, hydrogen production & transport
  - Generation & transmission footprint, costs & environmental
  - Distributed generation (solar pv & small modular nuclear)
- Systemic global risks
  - Participation in international alliances to ameliorate these risks



Safeguards: the approaching trade-off

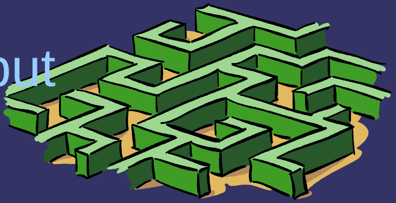
Climate change safeguards
versus
Nuclear proliferation safeguards

Competing issues of international trust



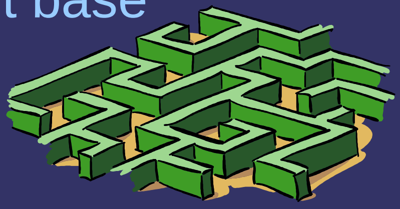
Nuclear Advantages

- 1 atom $^{235}U = 10^8 \times 1$ atom ^{12}C
    - ^{235}U fission is self-sustaining
- Uranium is abundant
    - 2-4ppm in earths crust
    - As only 0.7% of mined uranium is fissile ^{235}U, need to enrich nuclear fuel to 3%-5%
- Australia's position
    - 31% of world uranium resource (Kazakhstan 2nd)
    - 3rd largest producer of uranium
    - Silex Global Laser Enrichment process licensed to GE Hitachi (2008)
    - Commonwealth Environment Protection and Biodiversity Conservation Act 1999
        - s.140A specifically prohibits nuclear power generation
    - Influential Australian of the Year 2010 Prof Tim Flannery changed to global pro-nuclear in 2006 but hopes Australia can manage with renewables

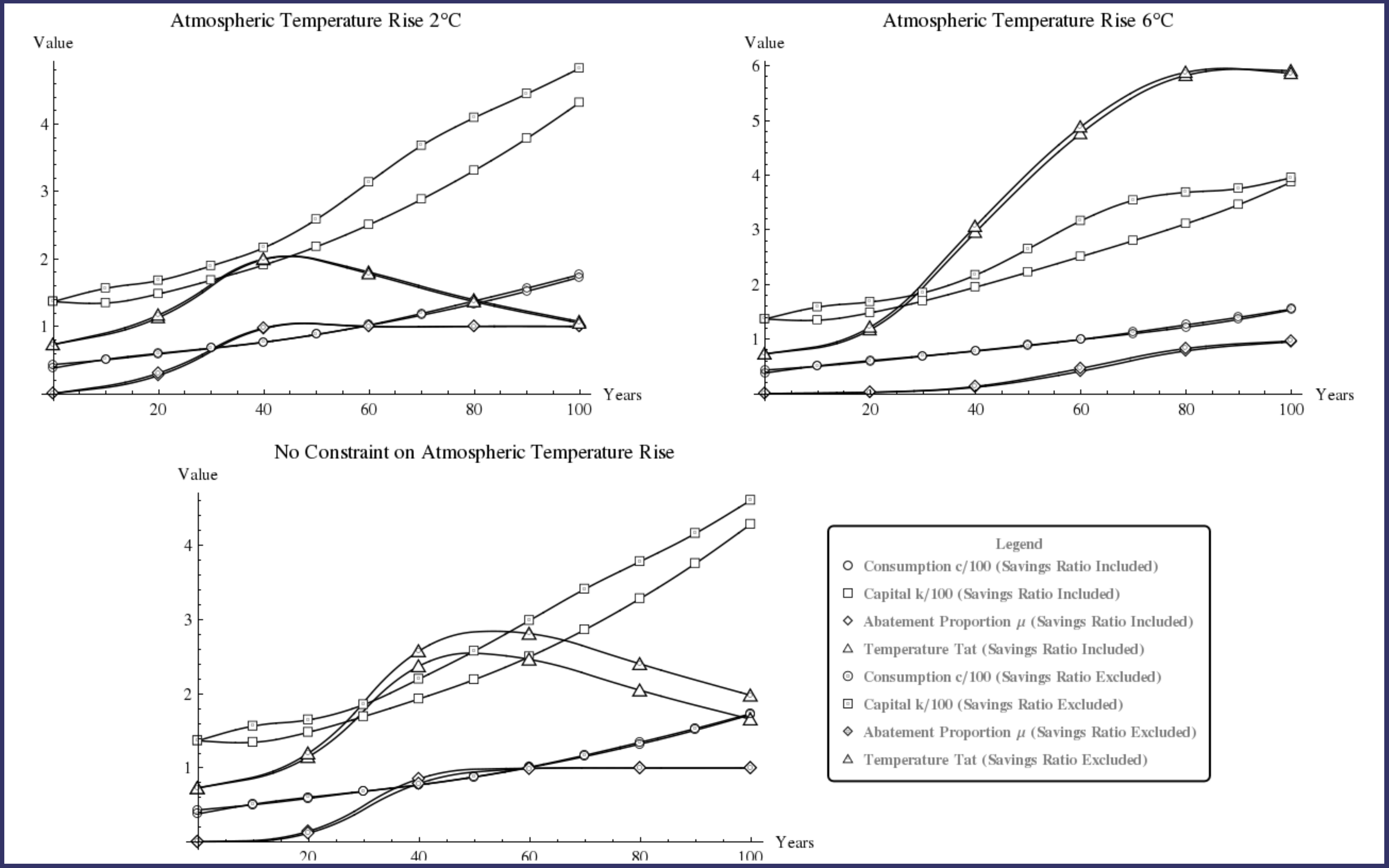


Status of current research on the role of nuclear generation in the Energy-Food-Water Security Challenge

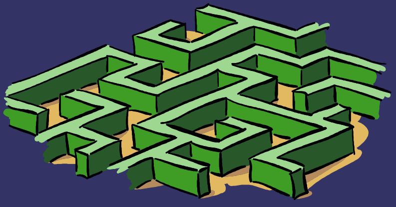
- Absence of peer-review research
  - Clinton & Gore stopped nuclear development in 1994
  - Bill Blees (US) & Dr Barry Brook (Uni of Adelaide)
- Nuclear unfashionable
  - Regulatory Environment Uncertain / Market Risk/ High Capex
  - Almost no new US nuclear plants even though most fossil plants at retirement age
  - Nuclear plants 40 years old have major question mark
- Discussion of nuclear power very difficult
  - Nuclear is a pariah in several countries (eg “Germany has allowed unfounded nuclear aversion to damage the economy and to set new records for carbon emissions” Keith Woodward)
  - Illegal in several non-nuclear countries (eg Australia)
  - Traditional Green politics of “No nuclear, no not ever”
  - High profile “nuclear greenies” have no support base
  - Nuclear is an anathema to the solar & wind competitors who see themselves as the only legitimate clean green players



Action Imperative
Continuous DICE 2007 Model research (Nettleton 2013)

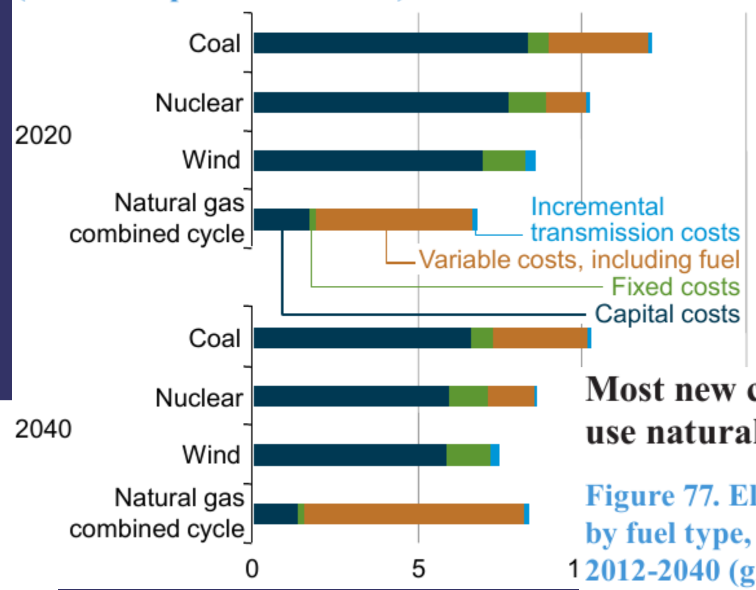


- 2ºC leading to dangerous climate change requires 50% carbon free within 25 years & 100% within 40 years (8.6bn people)
- 3ºC for best consumption profile requires 50% carbon free within 35 years & 100% within 50 years



Entrenched attitude: gas & wind are the cheap solution

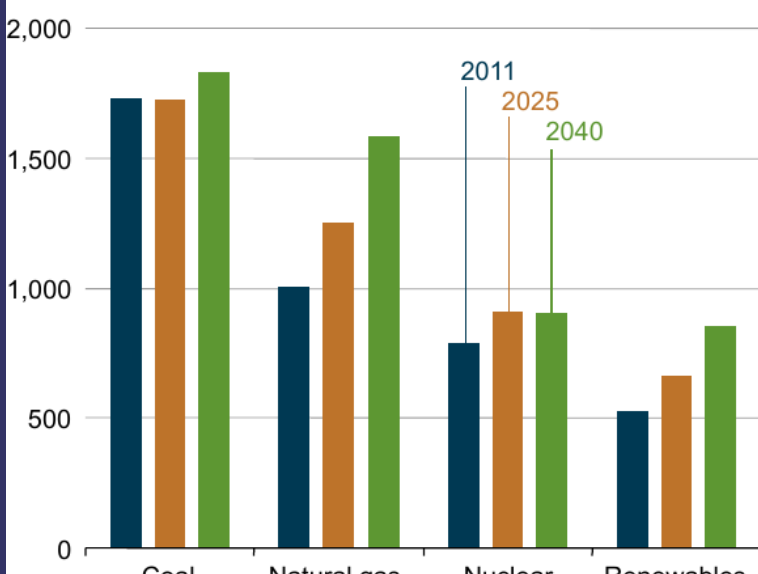
Figure 80. Levelized electricity costs for new power plants, excluding subsidies, 2020 and 2040 (2011 cents per kilowatthour)



Annual Energy Outlook 2013 with Projections to 2040 (US Energy Information Administration) DOE/EIA-0383(2013)

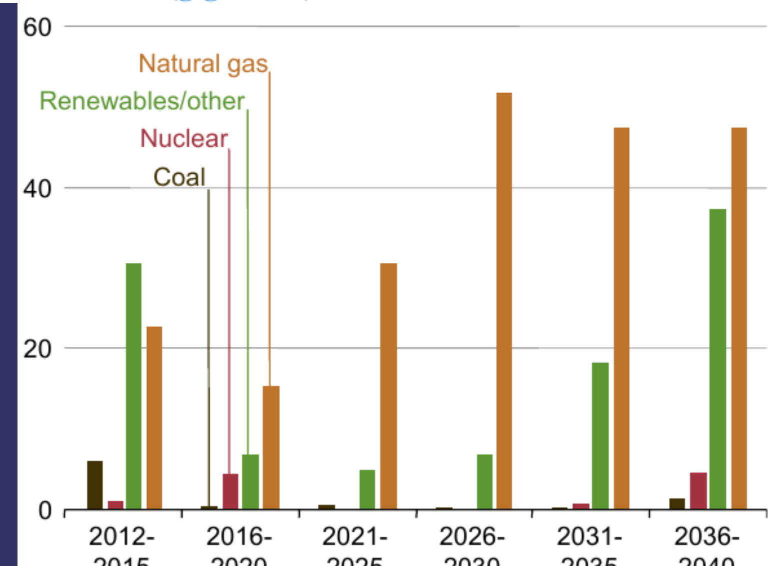
Coal-fired plants continue to be the largest source of U.S. electricity generation

Figure 76. Electricity generation by fuel, 2011, 2025, and 2040 (billion kilowatthours)



Most new capacity additions use natural gas and renewables

Figure 77. Electricity generation capacity additions by fuel type, including combined heat and power, 2012-2040 (gigawatts)



Real comparison of total costs

Table 1. Estimated levelized cost of new generation resources, 2018

Plant type	Capacity factor (%)	U.S. average levelized costs (2011 $/megawatthour) for plants entering service in 2018				
		Levelized capital cost	Fixed O&M	Variable O&M (including fuel)	Transmission investment	Total system levelized cost
Dispatchable Technologies						
Conventional Coal	85	65.7	4.1	29.2	1.2	100.1
Advanced Coal	85	84.4	6.8	30.7	1.2	123.0
Advanced Coal with CCS	85	88.4	8.8	37.2	1.2	135.5
Natural Gas-fired						
Conventional Combined Cycle	87	15.8	1.7	48.4	1.2	67.1
Advanced Combined Cycle	87	17.4	2.0	45.0	1.2	65.6
Advanced CC with CCS	87	34.0	4.1	54.1	1.2	93.4
Conventional Combustion Turbine	30	44.2	2.7	80.0	3.4	130.3
Advanced Combustion Turbine	30	30.4	2.6	68.2	3.4	104.6
Advanced Nuclear	90	83.4	11.6	12.3	1.1	108.4
Geothermal	92	76.2	12.0	0.0	1.4	89.6
Biomass	83	53.2	14.3	42.3	1.2	111.0
Non-Dispatchable Technologies						
Wind	34	70.3	13.1	0.0	3.2	86.6
Wind-Offshore	37	193.4	22.4	0.0	5.7	221.5
Solar PV[1]	25	130.4	9.9	0.0	4.0	144.3
Solar Thermal	20	214.2	41.4	0.0	5.9	261.5
Hydro[2]	52	78.1	4.1	6.1	2.0	90.3

Nuclear Cost Estimates from Recent Public Service Commission Filings

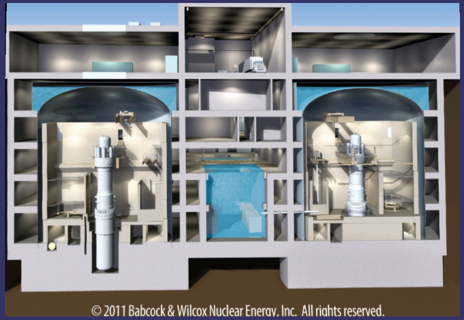
Company	Plant Capacity (MWe)	Overnight Capital Cost ($/kWe)	Total Project Cost (Billion $)
SCE&G/Santee Cooper	2,200	3,719	9.8
FP&L	2,200	3,483 – 5,063	12.1 – 18.0
Progress	2,200	4,260[6]	17.2 – 22.5

The Cost of New Generating Capacity in Perspective for Generation III/III+ (Nuclear Power Institute Feb 2013)

Assumes gas prices will stay at very low US 2011 levels (however already very high in Europe & elsewhere)

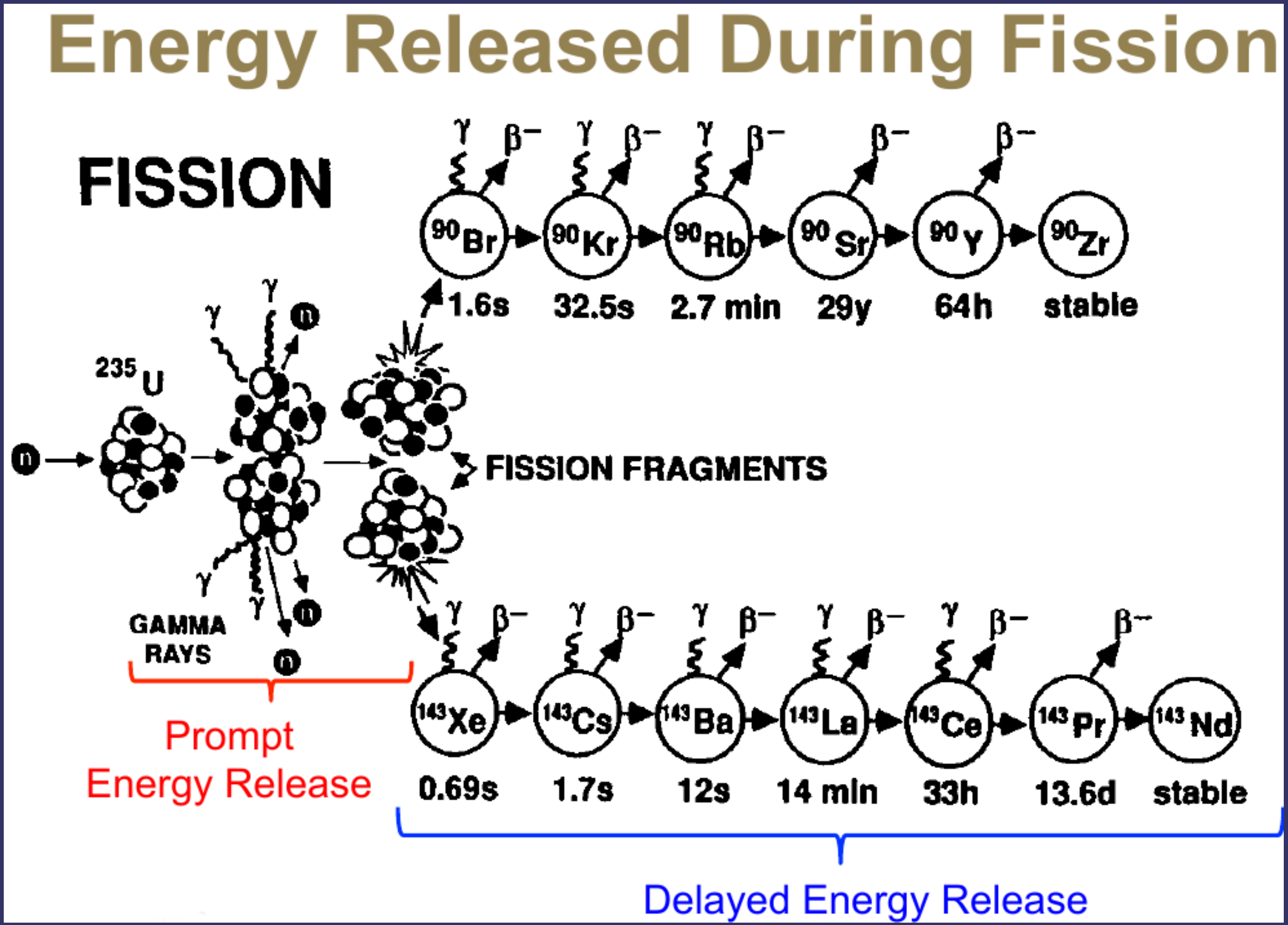
Assumes nuclear prices will stay at very high 2011 levels - low cost coming

Lot of funding of Small Modular Reactor 125-180MW air-cooled passively safe life 60 yrs (100s of mini-reactors manufactured in factories & transported on trucks)



Levelized Cost of New Generation Resoures in the Annual Energy Outlook 2013 AEO2013 Early Release Overview

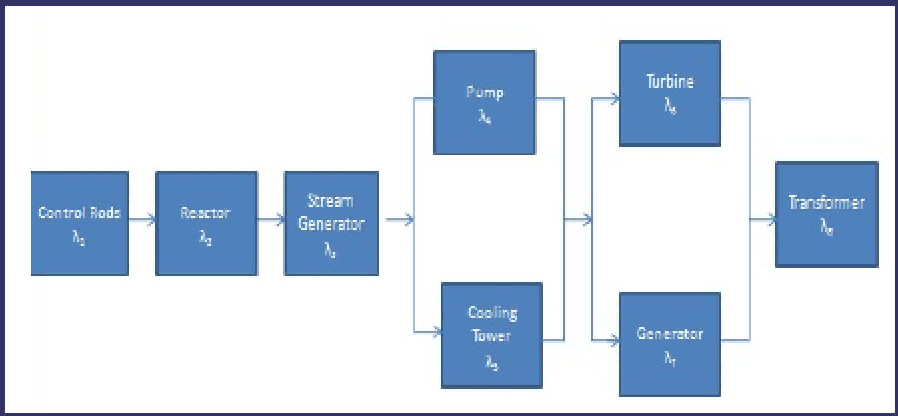
Nuclear Problem 1: Fission Delayed Energy Release
eg resulting from Fukushima Daiichi failure March 2011



Reprinted from MOOC: Nuclear Reactions and Radiation, L. R. Foulke 2013 (Module 3.2 Neutrons are special) note 2 with ithe permission from the American Nuclear Society. Nuclear Engineering – Theory and Technology of Commercial Nuclear Power by Ronald Allen Knief, 2nd Edition. Copyright 2008 by the American Nuclear Society, La Grange Park, Illinois

- Slow decay of fission products - γ radiation, beta particles & neutrons
  - ~7.5% @ shutdown
  - ~1.3% @ 1 hr
  - ~0.4% @ 1 day
  - Rest released over decades to centuries
  - Shutdown 3000MW reactor need to remove 220MW of radioactivity & heat

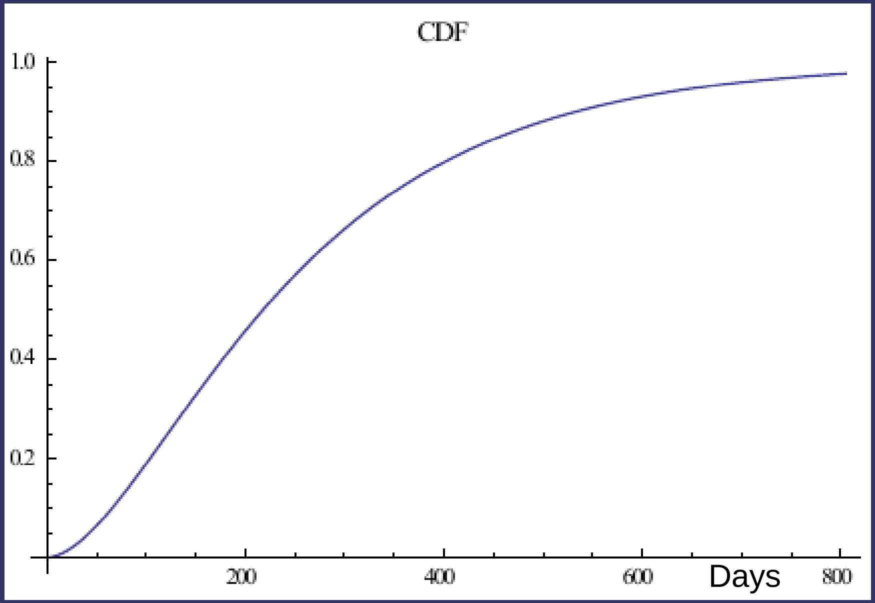
Nuclear Problem 2a: Failure of key components
Capstone project research, Sikander Bassi 2013



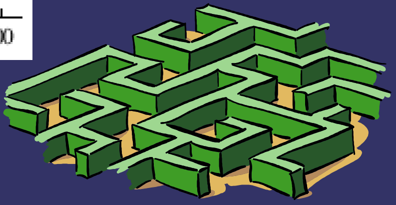
Block model for reliability analysis

Cumulative probability of system failure. Mean time to failure just 270 days (of course, maintenance extends this period)

Component Type	Mean Failure Values (per day)
Control Rods	3.0E-5/d
Reactor	3.0E-5/d
Stream Generator	1.1E-5/d
Pump	3.8E-4/d
Cooling Tower	5.7E-3/d
Turbines	5.0E-3/d
Generator	5.8E-6/d
Transformer	2.4E-5/d

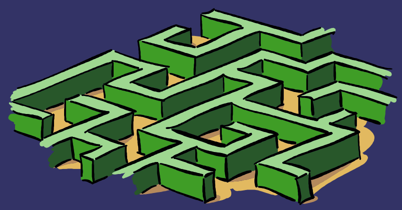


IAEA, "Component reliability data for use in Probabilistic Safety Assessment," 1988. M. Modarres, M. Kaminiskiv, and V. Krivtsov



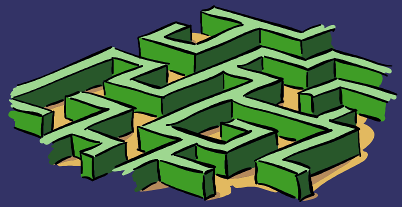
Nuclear Problem 2b: Failure of primary coolant and reactor core vessels

- Neutron flux changes properties of metal
  - Embrittles, swells & decreases corrosion resistance
  - Impurity production, atom displacement & ionization
  - Big issue in pressure vessels operating at 2,000 psi
- Core vessel life around 60 years
    - R. A. Knief 2008 (problem 3.19) Vessel has maximum tolerance for 10^{21} neutrons/cm^2 of high energy neutrons (i.e. Fast Fluence >1MeV). Reactor has 5×10^{11} neutrons/cm^2-sec of Fast Fluence. Life of core = 10^{21} / 5×10^{11} = 63 years
- Regulatory approval for increased life
  - Most reactors approaching end of 40 year life
  - Extend life from 40 to 60 years?
    - Should the life of existing reactors be extended?
    - Germany's decision “no”
    - Lot of ongoing research in these areas!



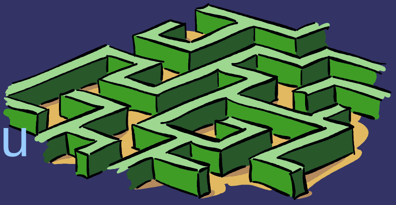
Nuclear Problem 3: Proliferation of Weapons grade Plutonium (Pu)

- ^{235}U fission leads to chain of Pu isotopes
  - 1st stage isotope is weapons grade ^{239}Pu
- “Reactor grade plutonium” is end waste
  - Mix of ^{239}Pu, ^{240}Pu, ^{241}Pu & ^{242}Pu
  - Very hard to use for weapons
  - Spontaneous neutron fission
  - Predetonation
- Nuclear waste from traditional reactors
  - ^{239}Pu & ^{240}Pu remain active for 10,000 years
  - Repositories for spent fuel don't exist

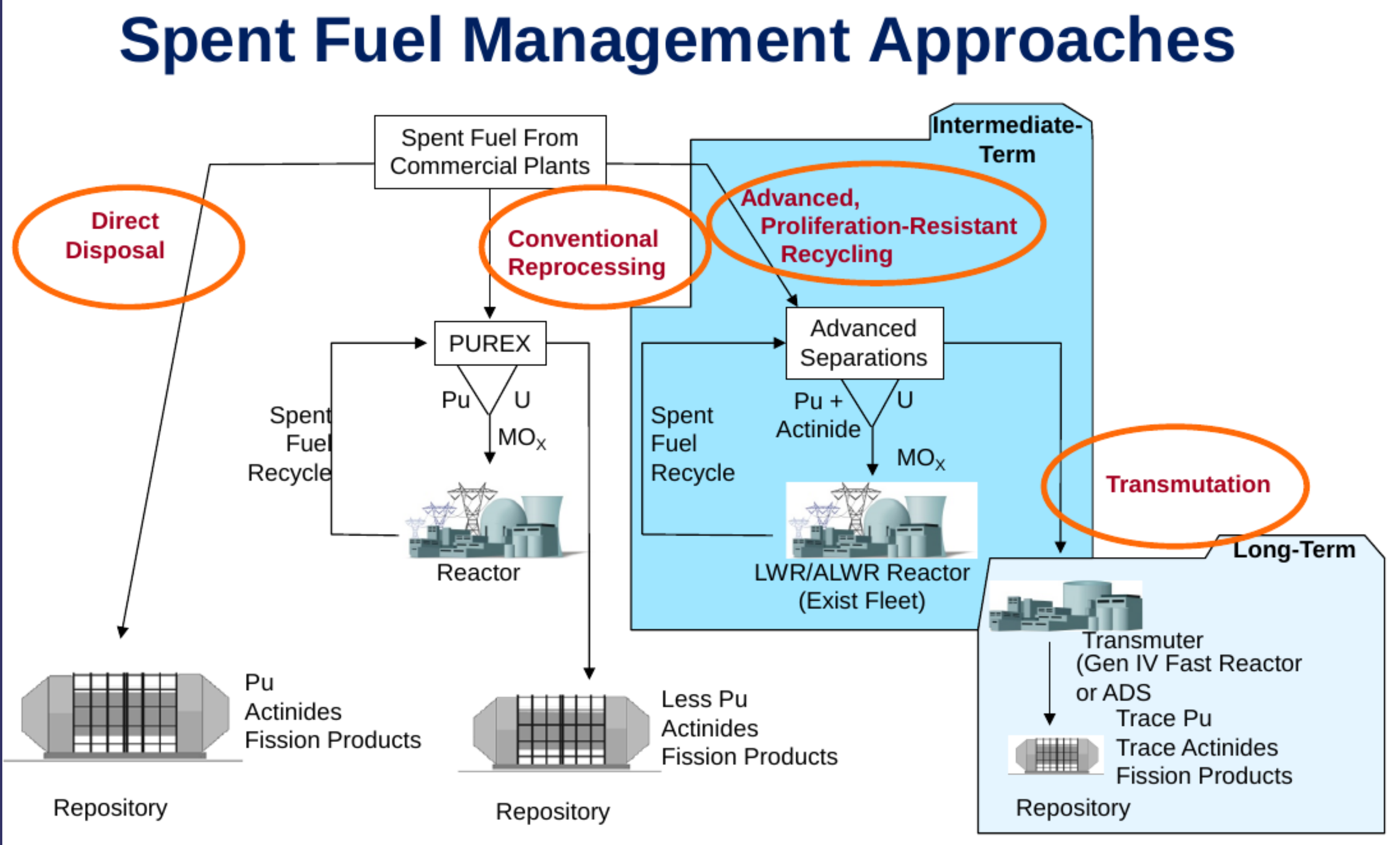


Nuclear Renaissance
Generation IV (IFR, fast, breeder, transmutation)

- Transmutes non-fissile to fissile atoms
    - Never have to enrich uranium
    - Only enough breeding takes place to satisfy what is burned
    - Use of nearly 100% of fuel (not 0.5% as with earlier reactors)
    - Can't extract weapons grade Pu
    - No Fukushima-like meltdown - turn off systems reactor stops
- Nuclear waste
  - Trace Pu and Actinide fission products in glass or ceramic form to a repository (just 1 tonne per 1GWe)
  - Proliferation “protected”
    - Complexity of the fission products and high levels of radioactivity – means thermally very hot and difficult to handle
  - Need second Gen II/ III or research reactor to extract Pu
    - License Gen IV as a “complete system” including protocols, material supply & waste disposal
    - Condition no second research reactor
  - Half-lives of 300 years
    - Much shorter than 10,000 years of ^{239}Pu & ^{240}Pu



Advanced Proliferation Resistant Recycling & Generation IV Transmutation



Transmutation

The Manhattan Project transmuted abundant ^{238}U to weapons grade ^{239}Pu with neutron irradiation causing radioactive decay sequence:

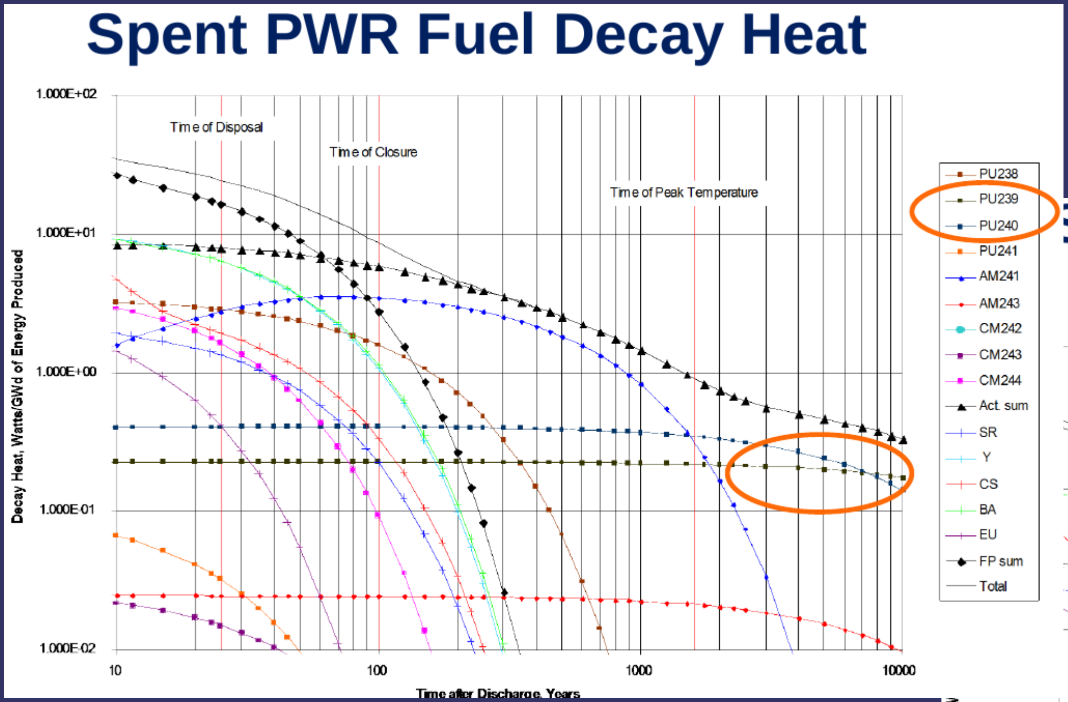
$^{238}U \rightarrow {}^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$

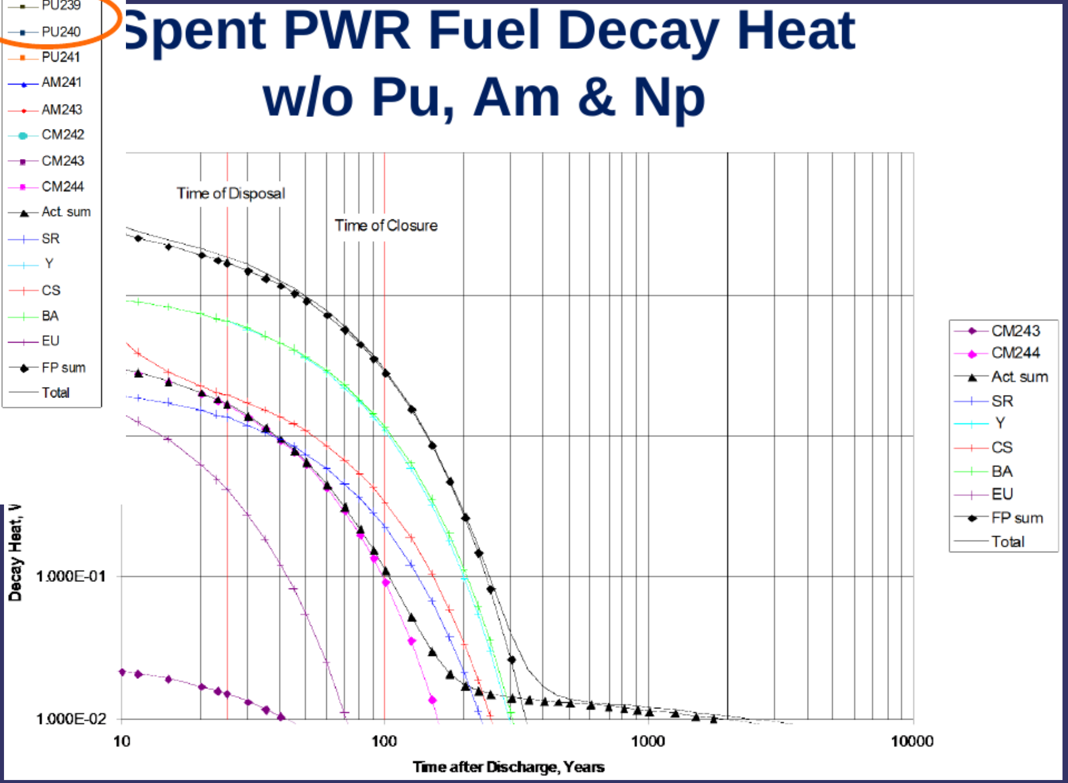
Other transmutation of abundant sources:

$^{232}Th \rightarrow {}^{233}U$ (eg India)
$^{240}Pu \rightarrow {}^{241}Pu$

- Reprinted from MOOC: Nuclear Reactions and Radiation, L. R. Foulke 2013 (Module 1.5 Grand Tour of the Nuclear Fuel Cycle – Back End Concluded) note 5 Goldner, F. (2003). Advanced Fuel Cycle Initiative (AFCI) - DOE Nuclear Energy International Programs – ADS Related Activities. International Meeting on Accelerator Driven Transmutation System Technologies, Las Vegas, Nevada. http://hrcweb.nevada.edu/rsatg/atw/pdffiles/Microsoft PowerPoint - Goldner.pdf

Benefit of Gen IV Transmutation
Transmutation of actinide elements such as the isotopes of plutonium, neptunium, americium & curium





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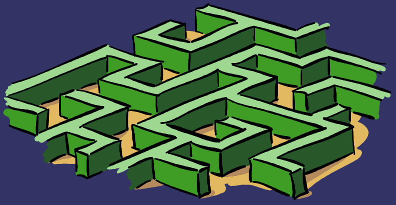


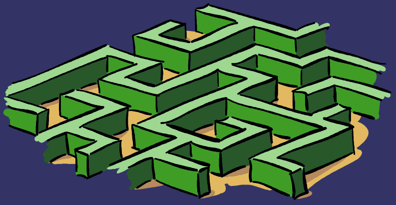
US selected six types of Gen IV fast reactor

Fast Neutron Reactors

E = experimental, D = demonstration or prototype, C = commercial

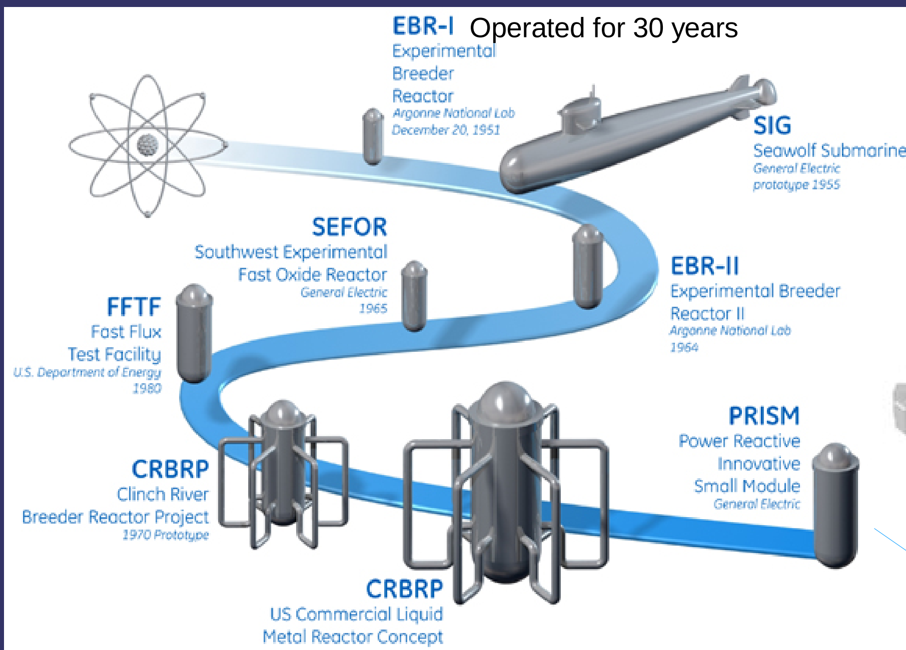
Output	MWe	MW (thermal)	Operation
USA			
EBR 1	0.2	1.4	1951-63
EBR II (E)	20	62.5	1963-94
Fermi 1 (E)	66	200	1963-72
SEFOR		20	1969-72
Fast Flux Test Facility (E)		400	1980-93
UK			
Dounreay FR (E)	15	60	1959-77
Protoype FR (D)	270	650	1974-94
France			
Rapsodie (E)		40	1966-82
Phenix* (D)	250	563	1973-2009
Superphenix (C)	1240	3000	1985-98
Germany			
KNK 2 (E)	21	58	1977-91
India			
FBTR (E)		40	1985-
PFBR (D)	500	1250	2012-
Japan			
Joyo (E)		140	1978-
Monju (D)	280	714	1994-96, 2010-
Kazakhstan			
BN 350* (D)	135	750	1972-99
Russia			
BN 1/2		1/0.1	1950s
BR 5 /10 Obninsk (E)		5 /8	1959-71, 1973-
BOR 60 Dimitrovgrad (E)	12	55	1969-
BN 600* Beloyarsk 3 (D)	600	1470	1980-
BN-800 Beloyarsk 4 (C)	880	2000	2014-
China			
CEFR (E)	20	65	2010-

- Sodium cooled
- Gas cooled
- Lead cooled
- Supercritical water
- Molten fluoride salt
  - Low capex, low operating cost, fast construction
  - 44% to 60% net thermal efficiency
- Very high temperature
  - 1000°C outlet temperature provides process heat for hydrogen production, petrochemicals & desalination
  - Core a passively safe graphite ball pebble-bed

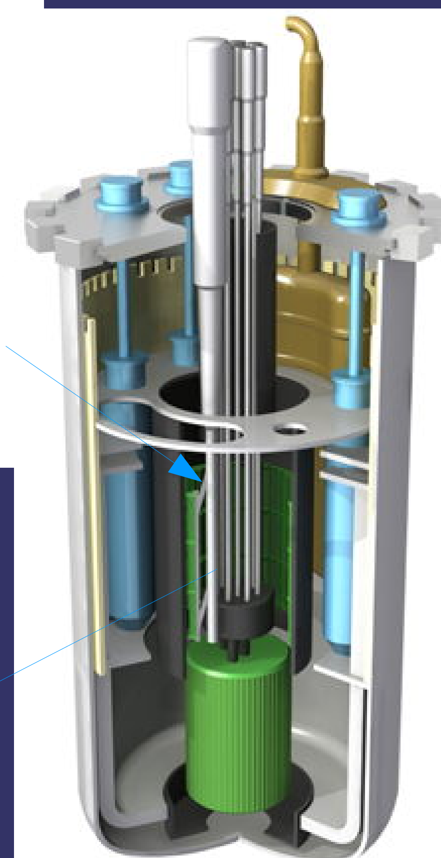


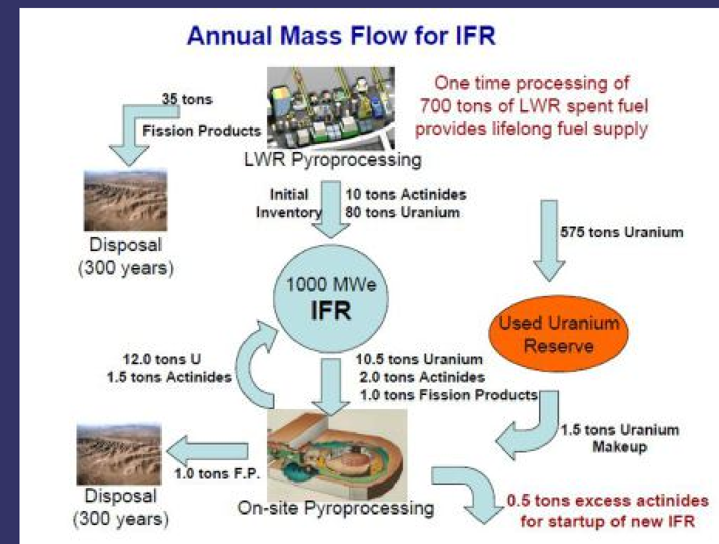
- World Nuclear Association Fast Neutron Reactors: About 20 Fast Neutron Reactors (FNR) have already been operating, some since the 1950s, and some supplying electricity commercially. About 400 reactor-years of operating experience have been accumulated to the end of 2010.
- http://www.world-nuclear.org/info/Current-and-Future-Generation/Fast-Neutron-Reactors/#.UeT48U1T25Y

Generation IV PRISM
Power Reactor Innovative Small Module

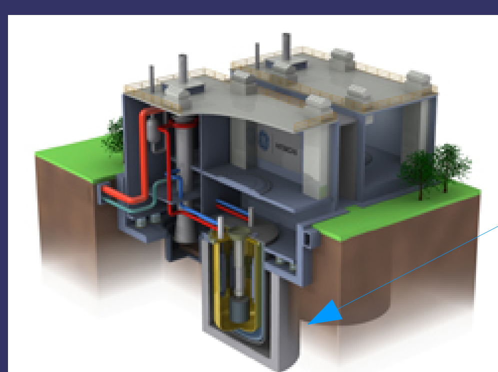


- 622 MW PRISM block
  Sodium Cooled &
  Passively air cooled





- UK Chief Scientist says the new 'fast' plants could provide enough zero-emission electricity to power the UK for more than 500 years with existing Pu stocks

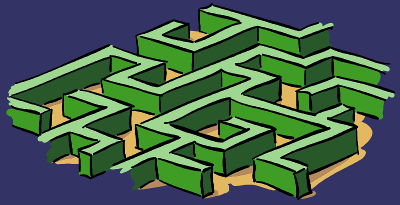


- Source: Barry Brook The Case for Near-term Commercial Demonstration of the Integral Fast Reactor, 23 October 2012 http://bravenewclimate.com/2012/10/23/the-case-for-near-term-commercial-demonstration-of-the-integral-fast-reactor/#more-5949

- Sources:
  http://www.ge-energy.com/products_and_services/products/nuclear_energy/prism_sodium_cooled_reactor.jsp
- http://www.theengineer.co.uk/energy-and-environment/in-depth/prism-project-a-proposal-for-the-uks-problem-plutonium/1016276.article

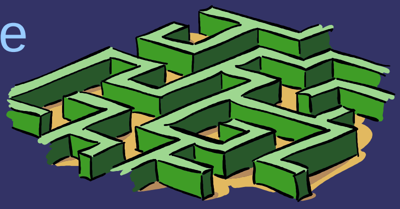
Research gap to be considered

- Gen IV technological advances
  - Integrated Fast Reactors (IFR), breeder, transmutation
  - Gen IV “clean-up of nuclear waste” means “renewables club”
- Socio-industrial complex
  - Decisiveness required by industry & generators
    - Wide scale end-of-life for existing fossil fuel & nuclear plants
  - Global fossil fuel companies
    - Intense resistance to climate change & lobbying for fossil fuels
  - Choosing nuclear rollout a “courageous” political decision
    - More nuclear (including issues like loan guarantees)
    - Initial nuclear (e.g. Australia)
    - Risk in new technologies like Gen IV
- Water-food-energy nexus for high density
  - Population increase & demographic changes
  - Trend to mega-cities
  - New climate change constraints
  - Water desalination requirements
  - New geo-political scenarios
  - Regional industry competitiveness & jobs



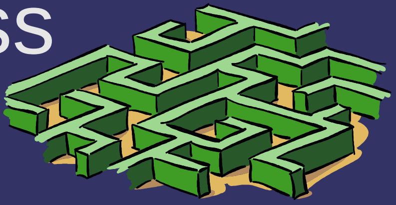
Objectives of research

- Evaluate food-water-energy nexus
  - 7bn people now & rising to 9-10bn by 2040
  - Water resources for extra 2-3bn people
  - Irreversible trend to mega-cities (28 in Mar 2013 to 70 in 2050)
  - Economic & social efficiency & complexity
- Evaluate new climate change constraints
  - 50% carbon free within 25 years & 100% within 40 years
- Evaluate energy market development
  - 2050 generation mix
  - 3 renewables already established in base load despatch
  - Technological development in solar, wind & nuclear
  - Imperatives and lead time
- Government policy development
  - Framework for a virtuous upward spiral in regional prosperity
  - Identify, evaluate and address threats that may compromise fundamental principles
  - Safeguards to eliminate threats or reduce these to acceptable levels where fundamental principles are no longer compromised

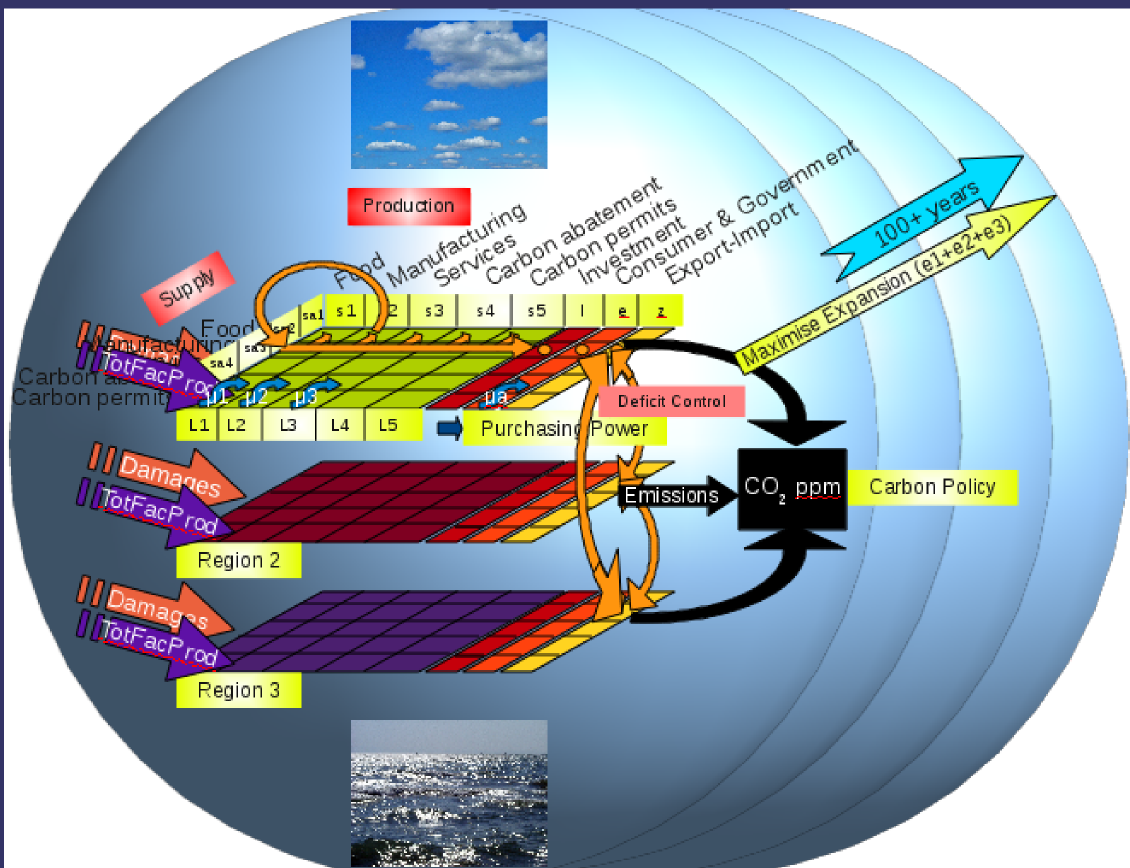


Research Methodology

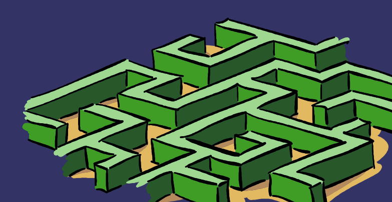
- Qualitatively formulate policy scenarios
    - Geo-political
    - Geo-physical (climate change)
    - Generation mix
    - Food-water-energy relationships
- Quantitatively evaluate regional performance
  - Sceptre Computable General Equilibrium (CGE)
    - Spatial Climate Economic Policy Tool for Regional Equilibria
    - "New CGE" with simultaneous volume & price settlement
    - Networked production infrastructure
    - 129 regions & 57 commodities (Global Trade Analysis Project)
  - Continuous version
    - Conversion of discrete decade model to continuous
    - Fast solution for interactive testing of policy scenarios
    - Expand from 1,000 to 10,000 regional free markets
- Interact with policy makers in process
    - Directly
    - Indirectly - publish & contribute to public debate



Spatial Climate Economic Policy Tool for Regional Equilibria (Sceptre) Global Multiregional New CGE



- **“New CGE”**
  - Simultaneously settling price-volume in constrained non-linear systems using shadow prices / marginal utilities
- **Tradition of:**
  - John von Neumann
  - Paul Samuelson
  - Wassily Leontief
  - Michael Farrell
  - Thijs ten Raa



Expected Outcomes of Research

- Practically inform policy
  - Along with renewables, maximise the use of nuclear power
  - Effectively deal with complexity of high density population areas such as megacities
    - Water desalination
    - Transport fuels - replace with electricity, hydrogen, boron & syngas to eliminate transport emissions, minimise the energy contest for arable land & minimise risk of global famine
  - Understand and expand regional industry competitiveness & jobs
- Enhance Sceptre policy tool
  - Investigate policy alternatives
  - Fast & interactive
  - Comprehensive & consistent
  - Potential for mobile app