Intergenerational justice and its policy implications for nuclear waste management

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International seminar: Nuclear Waste - Burden or benefit?

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Based on two joint papers

- Taebi, B. and A. C. Kadak. 2010. Intergenerational Considerations Affecting the Future of Nuclear Power: Equity as a Framework for Assessing Fuel Cycles. *Risk Analysis* 30 (9): 1341-1362.

- Taebi, B. and J. L. Kloosterman. Forthcoming. Designing for nuclear safety, security & sustainability: a philosophical discourse of reactor design. In *Handbook of ethics and values in technological design*, edited by J. van den Hoven, I. Van de Poel and P. Vermaas. Dordrecht: Springer.

Organization of the talk

- First part
  - Proposing a methodology to assess future nuclear fuel cycles using criteria of intergenerational justice
  - Elucidating (implicit) trade-offs for policy-makers

- Second part
  - Evolution of safety in nuclear reactor design
  - Conflicting values at stake when designing nuclear reactors
  - Trade-offs in an ex-ante analysis

Part I:

intergenerational justice criteria for assessing fuel cycles

A problem of fairness between generations

- "The Pure Intergenerational Problem" (PIP) - (Gardiner)
  - In a world of temporally distinct groups
  - and each generation has access to temporally diffuse goods
  - Engaging activities with these goods raises a problem of fairness
- In nuclear energy production such a fairness problem occurs
  - Long-lived waste is produced that must be isolated
  - Uranium is a non-renewable resource
- This problem of fairness occurs between Gen. 1 and subsequent generations

Future interest in decision-making

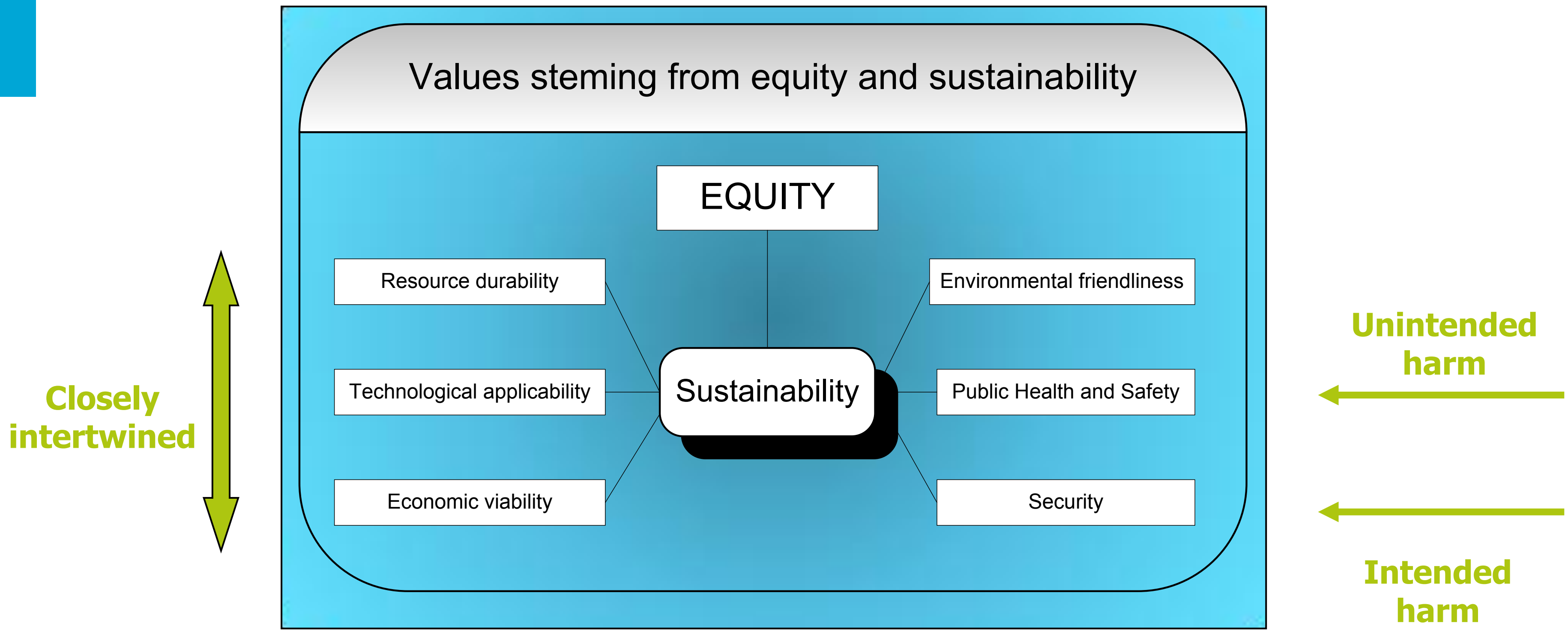
- A methodology is presented here to assess fuel cycles based on criteria of intergenerational justice

- We first conceptualize sustainability as a moral value

1) We should sustain human health and environment
   - Nuclear waste, if not appropriately disposed of, could harm future people and future environment

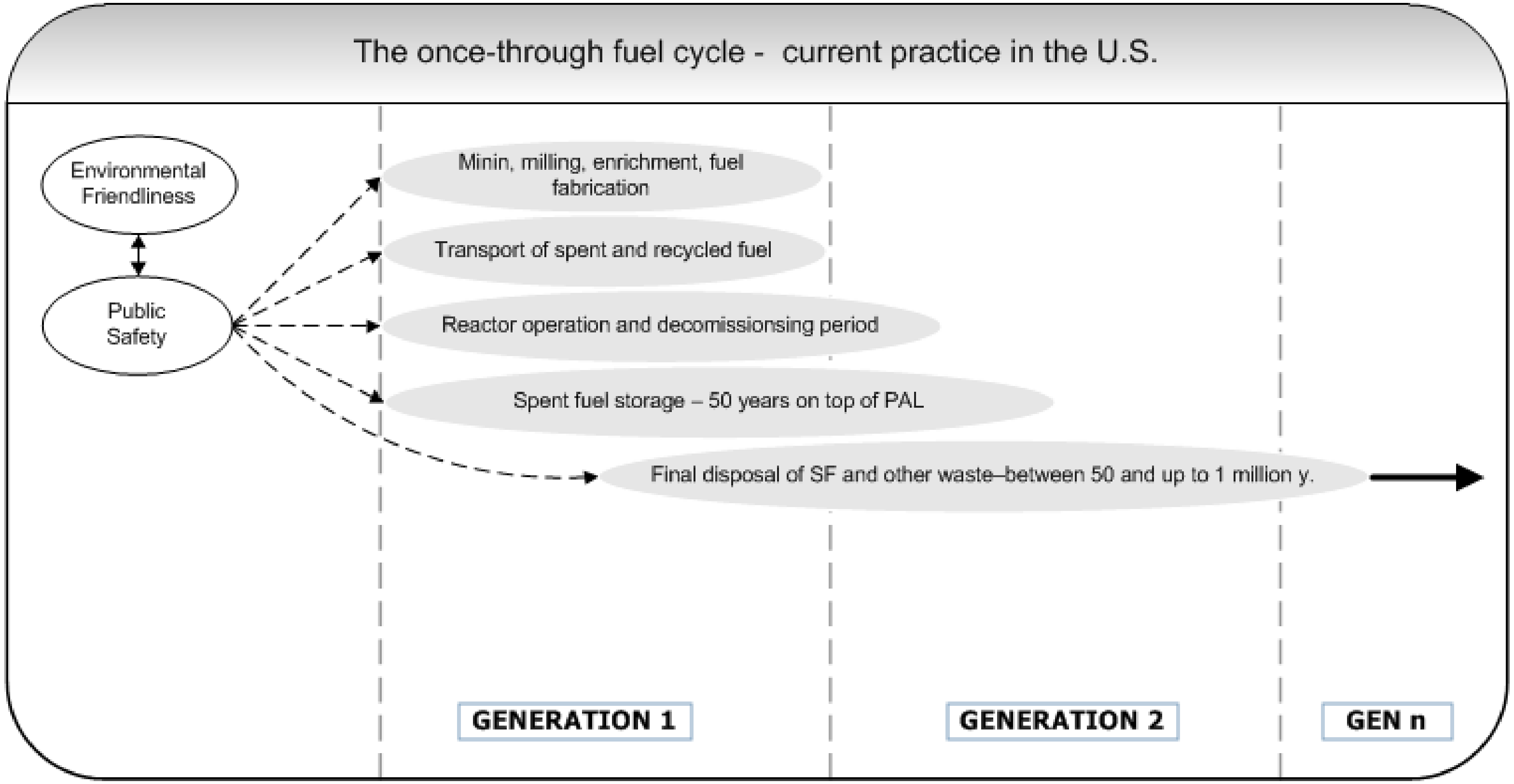
2) We should sustain well-being
   - Energy resources are a necessary condition for well-being
   - Uranium is a finite resource

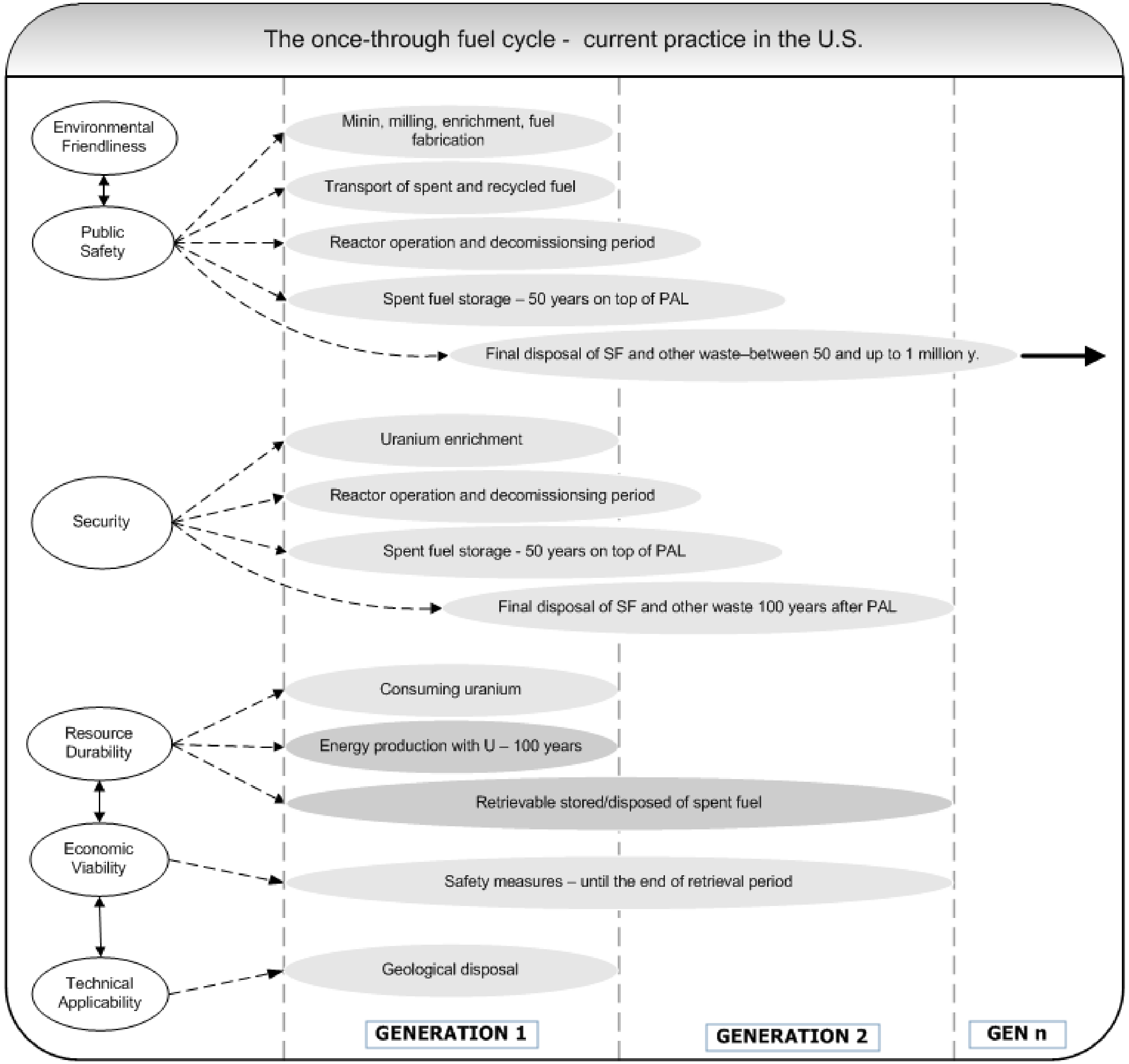
Sustainability as a moral value



Three fuel cycles compared

- Current practice in the U.S. and Sweden
  - Irradiating the fuel once in a Light Water Reactor (LWR)
  - Disposing of spent fuel as waste
- GNEP approach (or transmuter option)
  - Recycling spent fuel and only reusing uranium
  - Transmuting nuclear waste (incl. Pu) in fast reactors (FR)
- Using Breeders
  - Fast reactors could also be used in breeder configuration
  - …in order to breed (make) more fuel (plutonium) during operation


The once-through fuel cycle - current practice in the U.S.
Environmental Friendliness
Public Safety
Minin, milling, enrichment, fuel fabrication
Transport of spent and recycled fuel
Reactor operation and decomissioning period
Spent fuel storage – 50 years on top of PAL
Final disposal of SF and other waste–between 50 and up to 1 million y.
GENERATION 1
GENERATION 2
GEN n



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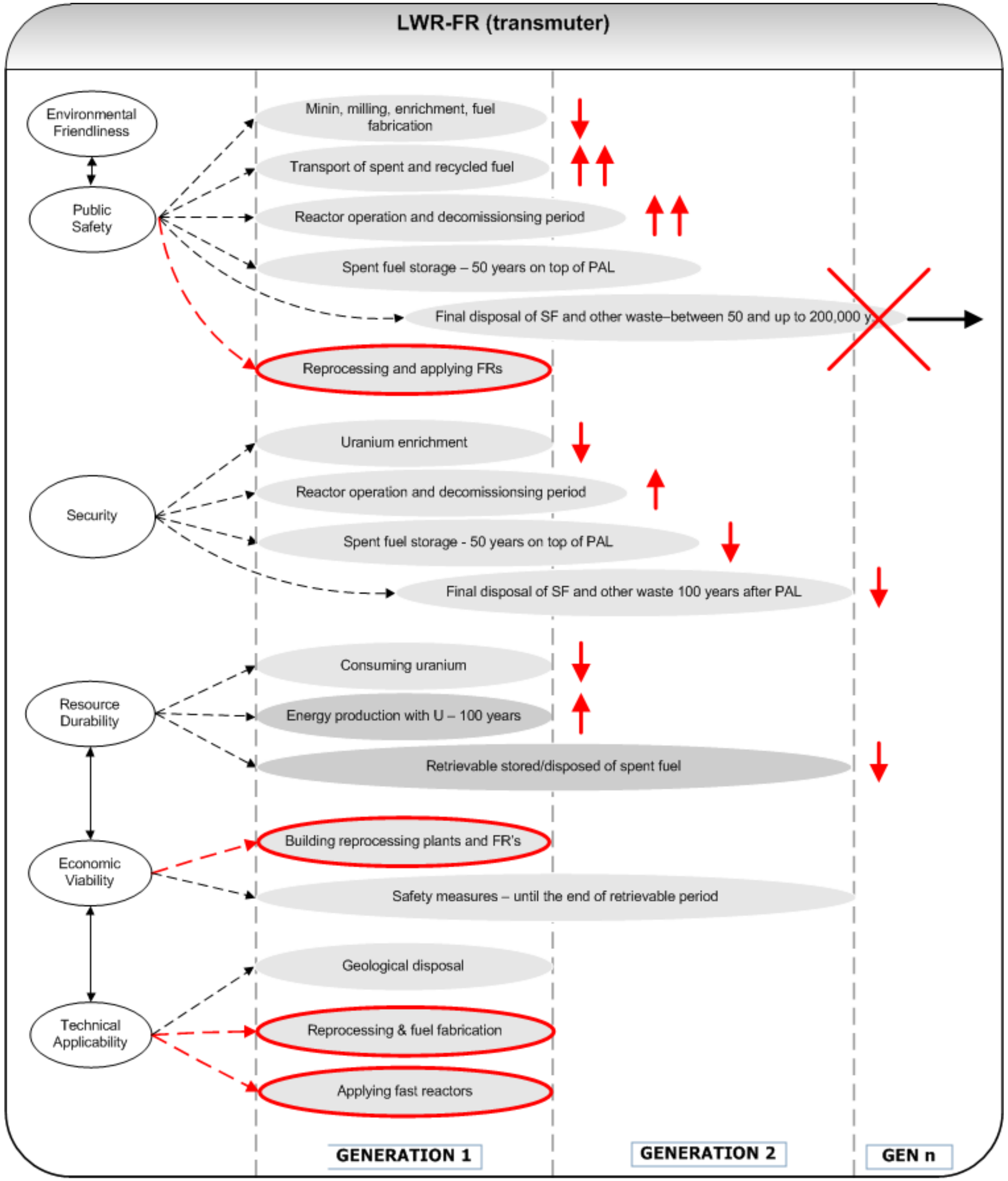
Security
Uranium enrichment
Reactor operation and decomissionsing period
Spent fuel storage - 50 years on top of PAL
Final disposal of SF and other waste 100 years after PAL
Resource Durability
Consuming uranium
Energy production with U – 100 years
Retrievable stored/disposed of spent fuel
Economic Viability
Safety measures – until the end of retrieval period
Technical Applicability
Geological disposal
GENERATION 1
GENERATION 2
GEN n


LWR-FR (transmuter)
Environmental Friendliness
Public Safety
Minin, milling, enrichment, fuel fabrication
Transport of spent and recycled fuel
Reactor operation and decomissionsing period
Spent fuel storage – 50 years on top of PAL
Final disposal of SF and other waste–between 50 and up to 200,000 y
Reprocessing and applying FRs
Security
Uranium enrichment
Reactor operation and decomissionsing period
Spent fuel storage - 50 years on top of PAL
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Resource Durability
Consuming uranium
Energy production with U – 100 years
Retrievable stored/disposed of spent fuel
Economic Viability
Building reprocessing plants and FR's
Safety measures – until the end of retrievable period
Technical Applicability
Geological disposal
Reprocessing & fuel fabrication
Applying fast reactors
GENERATION 1
GENERATION 2
GEN n

Impact table and scorecard

- Scorecard is a disaggregate policy analysis method
  - …that presents impacts for each alternative separately
- An impact table for mapping the impacts
  - Each column represents an alternative
  - Each row a particular impact for all alternatives
- In order to reveal patterns and trade-offs
  - We add colors to the impact table (Green, Amber, Red)

Score card for three fuel cycles

IMPACTS	ALTERNATIVES					
	Current Practice		LWR-FR (Burner)		LWR-FR (Breeders)	
	Gen 1	Gen 2-n	Gen 1	Gen 2-n	Gen 1	Gen 2-n
Environmental Friendliness/Public Safety						
Mining, milling, enrichment, fuel fabrication	High		High		Low	
Transport of fresh and spent fuel	Low		Low		Low	
Reactor operation and decommissioning period	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent
Spent fuel storage	High	High	High	High	High	High
Final disposal of spent fuel and other waste	Medium	High	Medium	Low	Medium	Medium
Reprocessing – applying breeders	None		Minor		Major	
Security						
Uranium enrichment	High		Medium		Low	
Reactor operation and decommissioning period	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent
Spent fuel storage	High	High	High	High	High	High
Final disposal of spent fuel and other waste	High	High	Low	Low	Medium	Medium
Reprocessing and Pu in breeders	None		None		Major	
Resourse durability						
Consuming uranium	High		Medium		Low	
Energy production with uranium	Worst	Worst	Worst	Middle	Best	Best
Stored and disposed of spent fuel	Best	Best	Worst	Worst	Worst	Worst
Economic Viability						
Deployment of current technology	Indifferent		Indifferent		Indifferent	
Safety measures until the end of retrieval period	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent
Building reprocessing plants and fast reactors	None		Minor		Major	
Technological Applicability						
Applying LWR and geological disposal	High		Medium		Low	
Applying reprocessing technology	None		Major		Major	
Applying fast breeders	None		Minor		Major	

Spatial trade-offs

IMPACTS	ALTERNATIVES					
	Current Practice		LWR-FR (Burner)		LWR-FR (Breeders)	
	Gen 1	Gen 2-n	Gen 1	Gen 2-n	Gen 1	Gen 2-n
Environmental Friendliness/Public Safety						
Mining, milling, enrichment, fuel fabrication	High		High		Low	
Transport of fresh and spent fuel	Low		Low		Low	
Reactor operation and decommissioning period	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent
Spent fuel storage	High	High	High	High	High	High
Final disposal of spent fuel and other waste	Medium	High	Medium	Low	Medium	Medium
Reprocessing – applying breeders	None		Minor		Major	
Security						
Uranium enrichment	High		Medium		Low	
Reactor operation and decommissioning period	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent
Spent fuel storage	High	High	High	High	High	High
Final disposal of spent fuel and other waste	High	High	Low	Low	Medium	Medium
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Safety measures until the end of retrieval period	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent	Indifferent
Building reprocessing plants and fast reactors	None		Minor		Major	
Technological Applicability						
Applying LWR and geological disposal	High		Medium		Low	
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Applying fast breeders	None		Minor		Major	

Trade-offs in opting for a fuel cycle

- In opting for fuel cycles, policy-makers make (implicit) trade-offs
  - We just saw examples of spatial trade-offs

- There are also temporal trade-offs

1) To what extent are additional current burdens justifiable?
   - GNEP and the Breeder Cycle bring current safety, security, and economic burdens for the benefit of future generations

2) To what extent are long-term transferring of risk justifiable?
   - Under what conditions could the current generation consent to risks being imposed on future people? (open fuel cycle)

Part II:

conflicting values in nuclear reactor design

Values as assessment criteria

- In an ex-post analysis and for choosing a fuel cycle
  - Open cycle: US, Sweden etc.
  - Closed cycle: many European countries, Japan, etc.

- In an ex-ante analysis and for opting for a new fuel cycle
  - Discussions on value trade-offs should lead development trajectories for a new fuel cycle

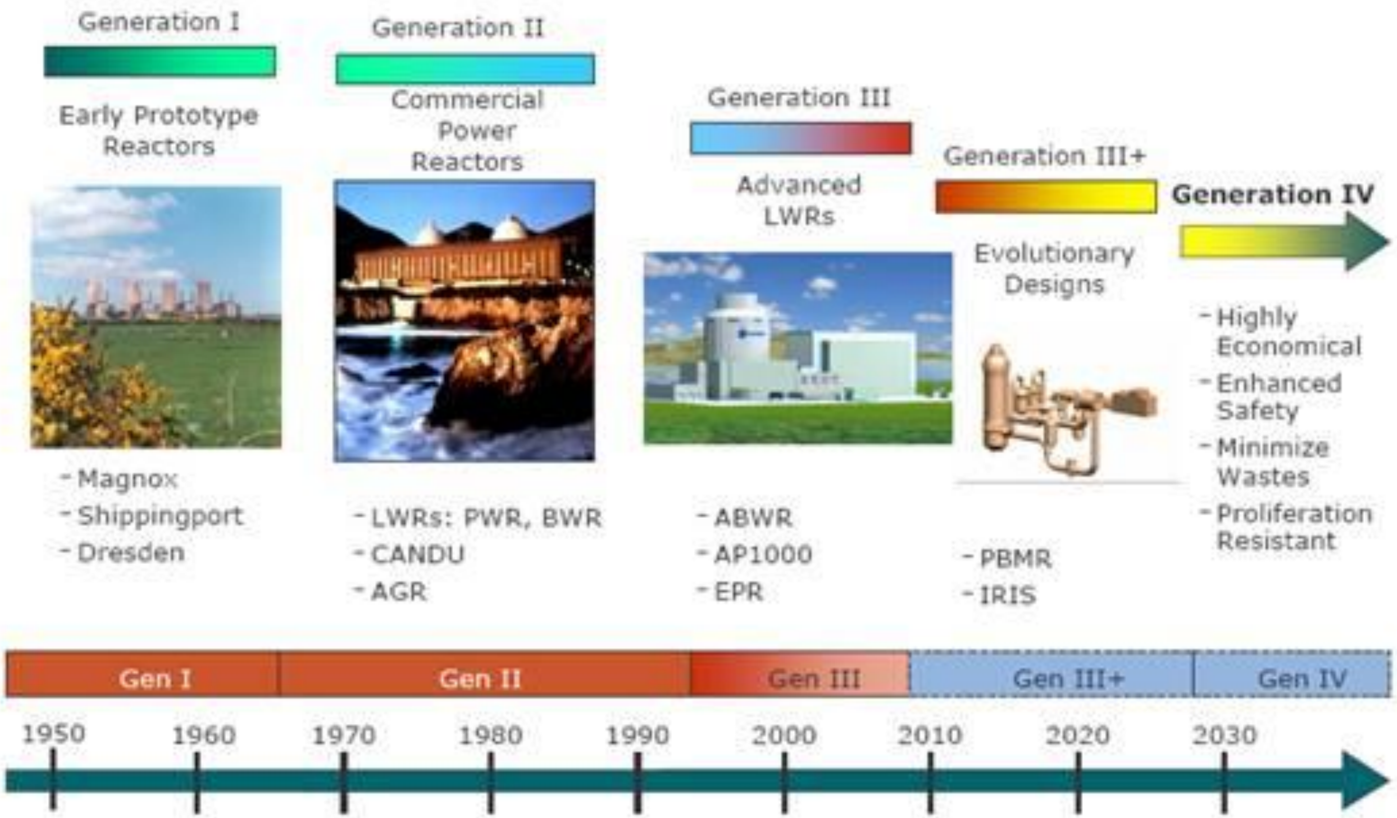
- Value trade-offs in designing new reactors (ex-ante)
  - The Best Achievable Nuclear Reactor is designed for safety, security, resource durability and economic viability

Two approaches to safer reactors

- Safety has been the leading notion in reactor design for decades
  - The Probabilistic Risk Assessments proposed by Rasmussen in 1975
  - Mapping all events that could go wrong and assigning probabilities
  - Making reactors more resistant to **melt-down**

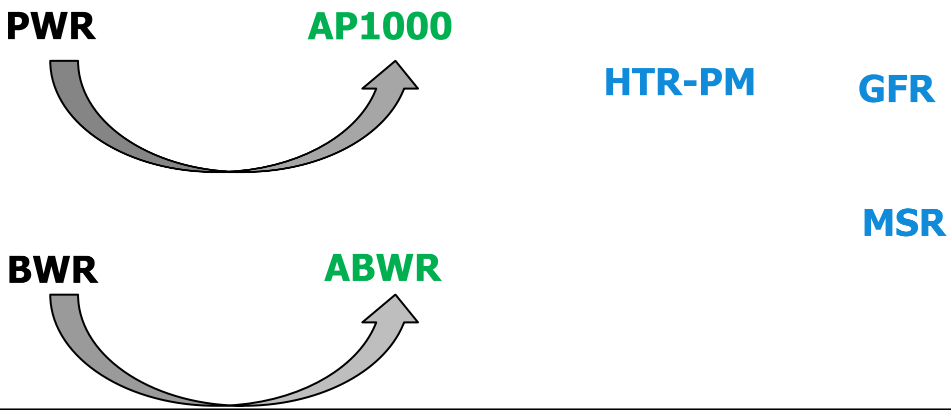
1) **Incremental** changes in the safety
- Taking current designs as the departing point
- And adding safety features (or removing reasons of accidents)

2) Taking a **radical** approach to design
- Starting from scratch with safety as a leading design criterion



Green: incremental improvements

Blue: radical design change



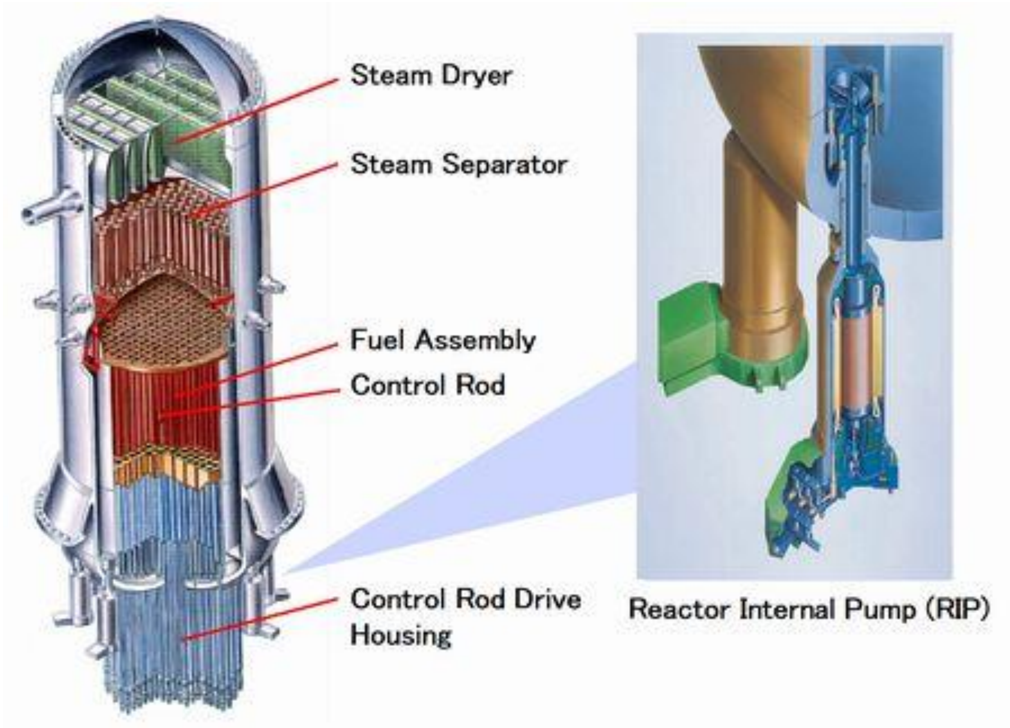
BWR & PWR

- These are Light Water Reactors (LWR)
  - They form the basic design for many later designs
- These Gen II reactors comprise the majority of operable reactors
  - 75% are PWR and 25% BWR
- Pressurized Water Reactor were originally designed for submarines
  - With leading design criteria compactness and simplicity
- PWR was later proposed for bigger commercial reactors
  - Being bigger in size made them less safe
  - Hence many safety features were added to the design: valves, pumps etc.
  - These features made the system immensely complicated (hence unsafe)

Gen III: ABWR

- The only operable Gen III is Advanced Boiling Water Reactor
- ABWR is based on a BWR with **advanced safety features**
  - Ten separate internal pumps at the bottom of the reactor vessel
  - Thick fiber reinforced concrete containment, etc.
- **Simplified design**, hence improved performance
  - Pumps in the rector make complex piping structure unnecessary
  - Cooling is simple &redundant; failure of a pump is not disastrous
- ABWR substantially reduces the melt-down probability
  - Compared to BWR

Reactor vessel of ABWR

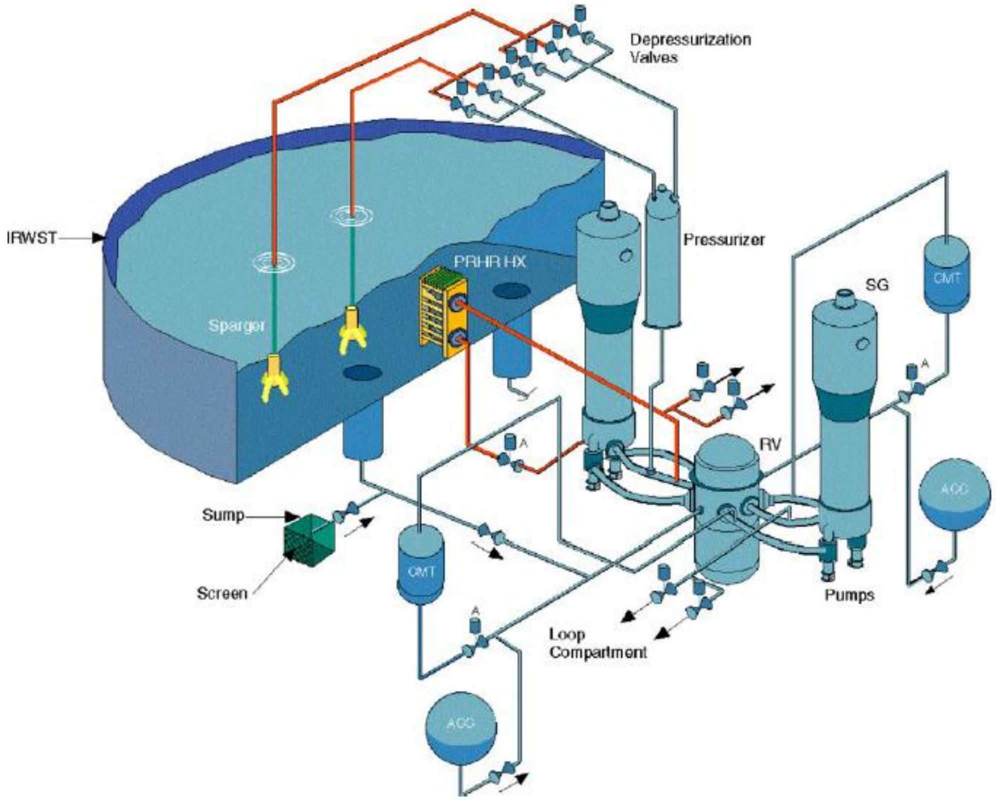


Source: http://nuclearstreet.com/nuclear-power-plants/w/nuclear_power_plants/abwr-ge-hitachi.aspx

GEN III+: AP1000

- AP1000 is an **evolutionary** design of PWR
  - Incremental change in design
- AP1000 is a substantially **simplified** version of PWR
  - 51% less valves, 34% less pumps, 83% less piping and 87% less cables
- Furthermore, It moves towards **passively safe** systems
  - Using a passive core cooling system with three sources of water to maintain cooling through safety injections
  - Based on **gravity** and natural circulation and containment cooling

Passive core cooling system of AP1000



Gen III+: HTR-PM

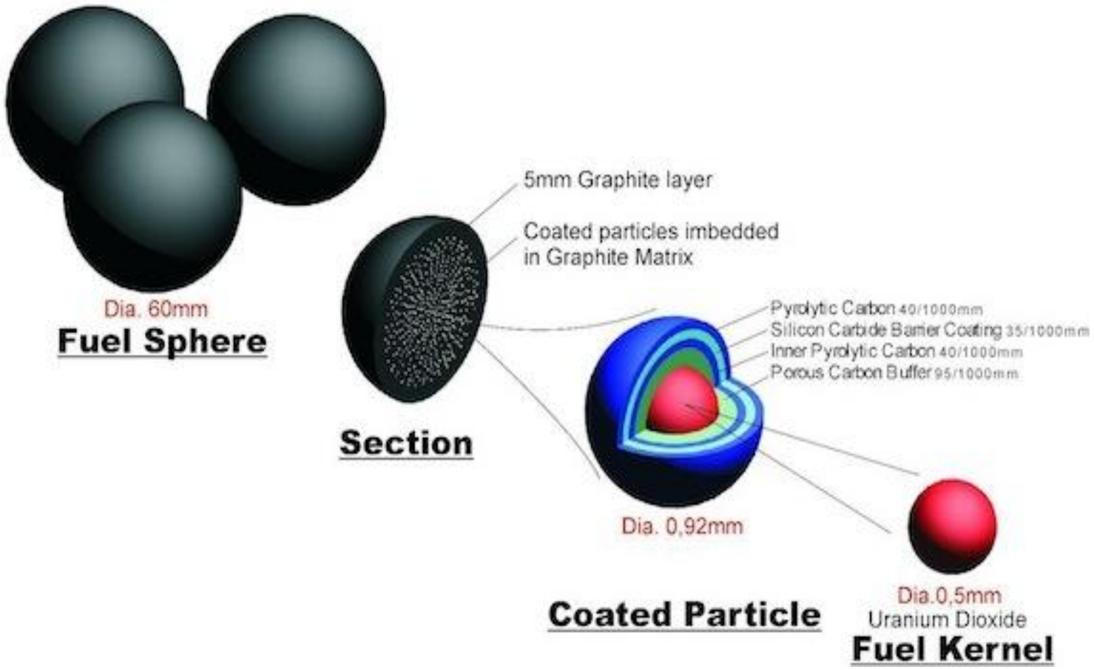
- Pebble Bed Modular Reactor presents a **radical** design change

- **Safety and economic** as primary design criteria
  - It should never require evacuation in case of internal accident
  - It should not need a large exclusion zone: beneficial for licensing and electricity transport to densely populated areas
  - Higher levels of radiation safety for workers

- PBMR moves towards **inherently safe** reactors
  - Cylindrical shape of reactor vessel: natural cooling
  - Type of the fuel: melt-down risk physically impossible

Pebble fuel in HTR-PM

- A melt-down could not occur in a PBMR
  - In PRA, one looks rather at the possibility of radionuclides release into the environment, du to Sic coating damage (>1200°C)



Gen IV: GFR & plutonium economy

- Gas-cooled Fast Reactor

- Leading design criterion is **resource durability**
  - Efficient use of major uranium isotope (^{238}U)
  - By first converting it to Pu (plutonium economy)
  - It can also get rid of long-lived waste after reprocessing
  - Hence, applicable in an **extended** closed fuel cycle

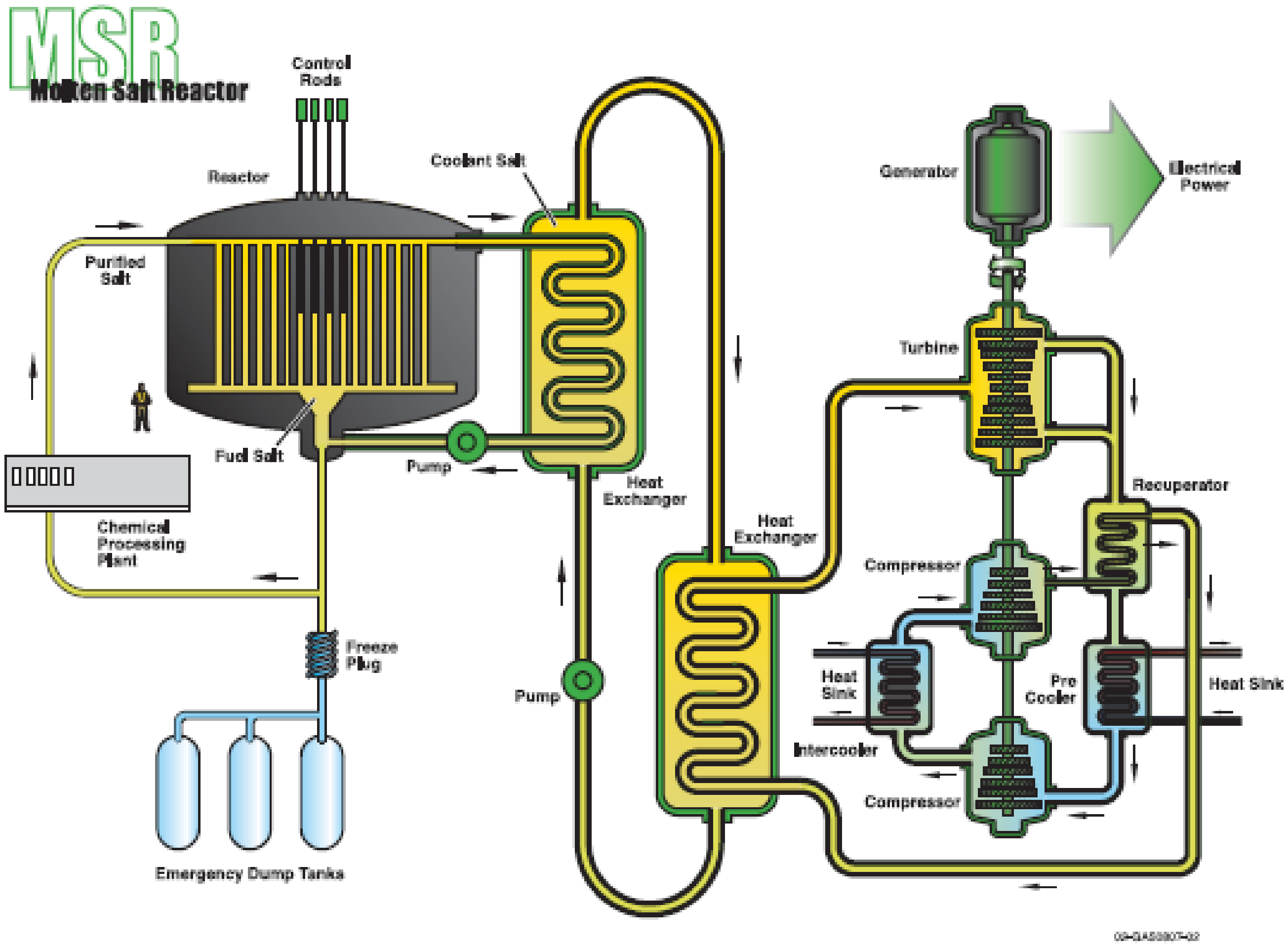
- Drawbacks
  - Reprocessing technologies for FR spent fuel must be developed
  - Pu brings about serious proliferation risks
  - Best waste life-time reduction only achieved after multiple recycling

Gen IV: MSR - radical new design

- Molten Salt Reactors is a FR with **radically** new design philosophy
  - Driving force is (again) **resource durability**
  - It was first proposed as aircraft propeller in the US

- Features of MSR
  - One of the few reactors that can use (abundantly available) **thorium**
  - The fuel circulates and serves also as the coolant
  - Continuous (re)fueling: fresh fuel will be added during operation
  - In case of accident, the fuel can be drained (dumped in tanks)

- Serious R&D investments needed
  - The fuel is highly radioactive and corrosive
  - Fuel development, salt chemistry control, corrosion studies etc.



Source: DOE (2002) A Technology Roadmap for Generation IV Nuclear Energy Systems. GIF-002-00 (Washington D.C.: U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum), p 33.

Overview of the reactors and their core damage probabilities

Generation	II	III	III+	III+	IV	IV
Reactor type - acronym	PWR & BWR	ABWR	AP1000	HTR-PM	GFR	MSR
Core damage frequency (per reactor-year)	10^{-4} to 10^{-5}	1,6 X 10^{-7}	4,2 X 10^{-7}	5 x 10^{-7}	tbd	tbd
Type of change in design	Default design	Small & incremental compared to BWR	Medium & incremental compared to PWR	Radical	Medium to radical	Very radical change in reactor technology

Comparison of promising reactors

- HTR-PM designed with safety as primary criterion
  - Good on security: no enrichment and Pu separation difficult

- GFR was designed with resource durability as leading criterion
  - It scores less on safety and security because of Pu

- MSR uses Th and is designed with resource durability in mind
  - It scores bad on security because of proliferation-sensitive ^{233}U

	HTR-PM	GFR	MSR
Safety	++	-	0
Security	+	- -	-
Resource durability	-	+	+ +
Economic viability	+	0	-

- These trade-offs should better be made prior to development
  - Different design criteria will lead to different reactor types

Thank you for your attention

- Questions and remarks are highly appreciated. Now or later.

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