The GAINS Framework – A Platform for Exploring Deployment of Multi-National Sustainable Nuclear Energy Systems

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Introduction-1

- Building or expanding a Nuclear Energy System (NES) involves more than construction of reactors
  - Must secure fuel supplies
  - Must develop a spent fuel management strategy
  - Must arrange for the supporting infrastructure
- Often there are different options on how to proceed
- Scenario analyses of potential options can help with decision making by identifying:
  - Which options best achieve goals
  - Which are most flexible, in case plans need to change
  - What issues may arise during deployment or operations

Introduction-2

- Fuel cycle simulators are powerful tools for conducting scenario analyses
- The GAINS Framework is a collection of data, utilities, and base cases for use with fuel cycle simulators to perform scenario analyses
- Together with a simulator, the Framework can be used to analyze and compare different strategies and schedules for deploying reactors and supporting fuel cycle facilities
  - As a standalone system contained within a single country
  - As a collaborative system shared with other countries

Introduction-3

This presentation will provide information on how to conduct scenario analyses using the GAINS Framework, including:

- Fuel Cycle Simulator Overview
- GAINS Framework Components
- Framework Base Cases
- Sensitivity Analyses

Outline of Presentation

- Fuel Cycle Simulator Overview
- GAINS Framework Components
- Framework Base Cases
- Sensitivity Analyses

Fuel Cycle Simulator Overview

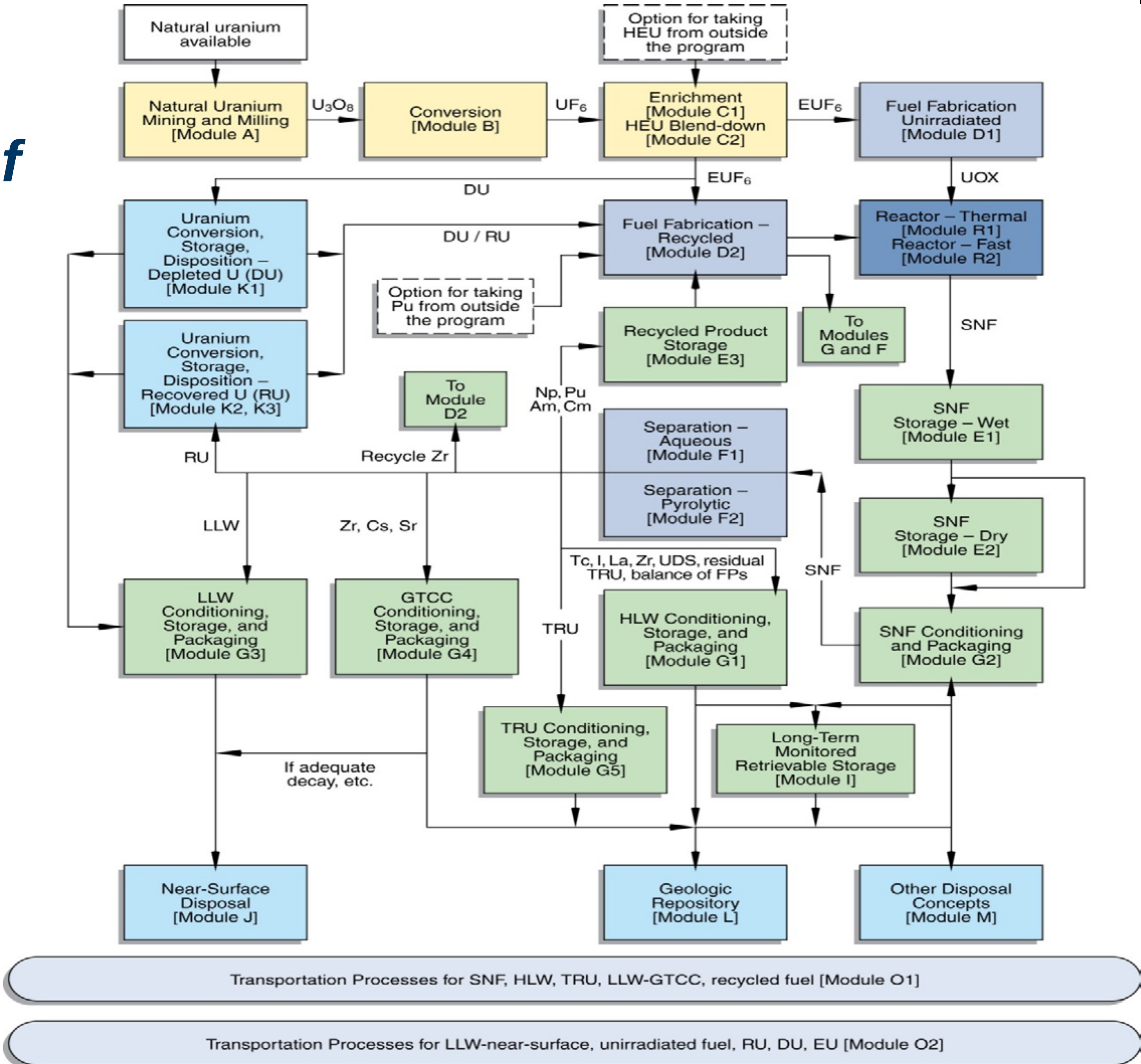
- Fuel Cycle Simulators are used to model the operation and evolution of a nuclear energy system
  - Construction, operation and retirement of reactors and fuel cycle facilities
  - Generation of electricity and heat
  - Flow of fuel materials and associated products and wastes

- Simulators provide multiple useful outputs:
  - Show inventories of materials and wastes
    - Indicate when materials are insufficient to operate facilities
  - Show production rates of facilities
    - Show transportation requirements
    - Indicate when energy demands can or can't be met
    - Indicate impacts of facility outages
  - Provide multiple indicators
    - Uranium utilization, SWUs used, waste generation, waste radiotoxicity, attractive material inventories, etc.

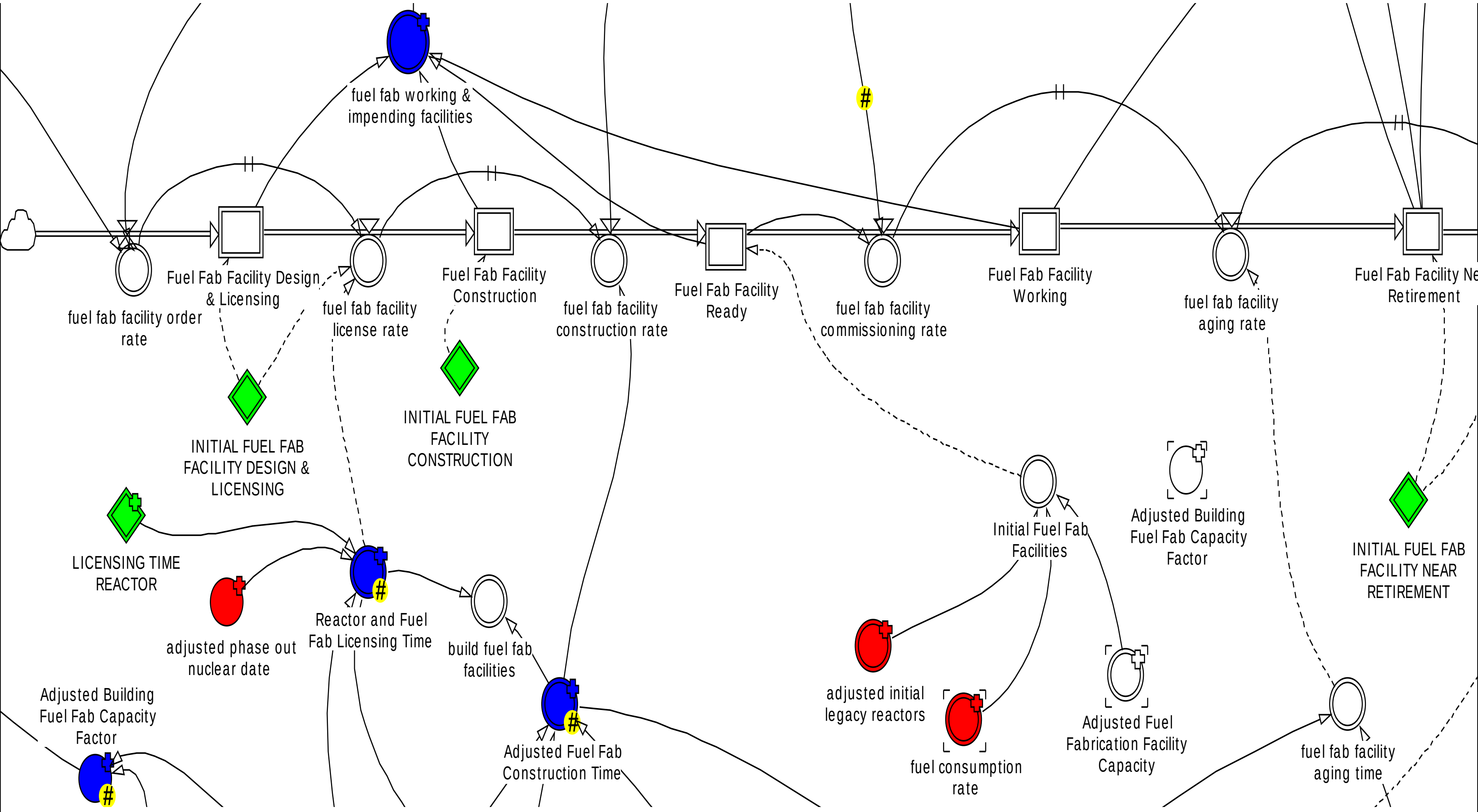
Fuel Cycle Simulator Overview

- There are several types of simulators
  - Everything from simple spreadsheets to very involved codes
- Main differentiators
  - What is modeled
    - Types of reactors, types of fuels, other facilities, etc.
    - Costs, waste forms, etc.
    - How much detail included (fuel cycle steps, facilities, isotopes)
  - What is output
    - Inventories and mass flows
    - Indicators, graphics
  - Whether there are intelligent algorithms
    - Automatically manage facilities, ordering, checking for constraints, ensuring no negative inventories, etc.

Example of Simulator Modules (VISION)



Example of Code Internals (VISION)



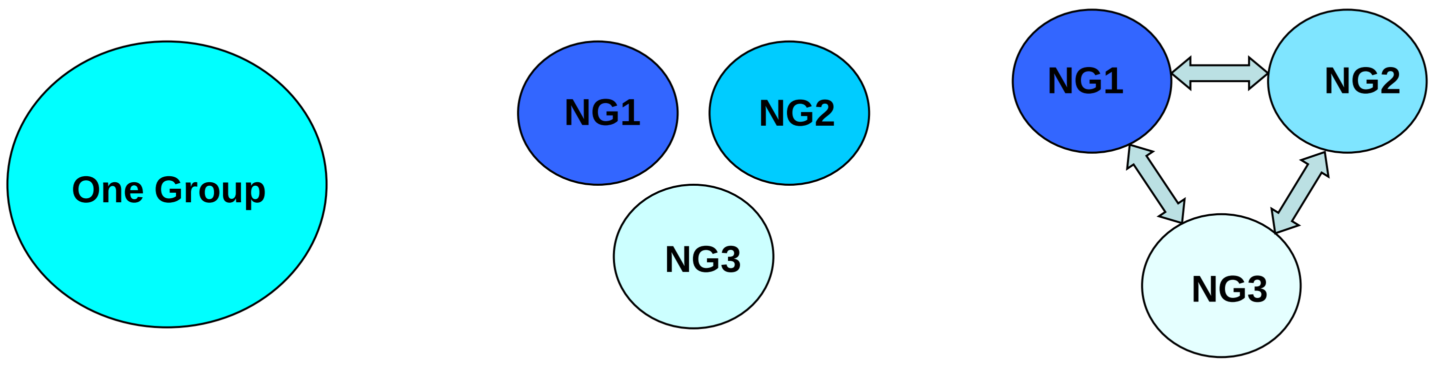
Examples of Fuel Cycle Simulation Tools

- IAEA codes
  - NFCSS
  - MESSAGE
  - DESAE
- Country codes
  - COSI – France
  - DANESS – U.S.
  - FAMILY – Japan
  - TEPS – India
  - VISION – U.S.
- University codes
  - CAFCA – MIT
  - CYCLUS – UW-Madison

Outline of Presentation

- Fuel Cycle Simulator Overview
- GAINS Framework Components
  - Storylines for Homogeneous and Heterogeneous World Scenarios
  - Key Indicators and Evaluation Parameters
  - Global Growth Curves
  - Reactor/Fuels Template
  - Key Indicators Template
  - Framework Base Cases
- Framework Base Cases
- Sensitivity Analyses

Homogeneous and Heterogeneous World Scenarios



(a) Homogeneous

(b1) Heterogeneous Non-Synergistic

(b2) Heterogeneous Synergistic

- Most analyses treat world as single technology group
  - Assumes all follow the same strategy and use the same facilities
- GAINS Framework also supports breaking world into three separate nuclear strategy groups following different fuel cycle strategies
  - NG1 starts with LWRs, transitions to a closed fuel cycle with fast reactors
  - NG2 maintains an open fuel cycle with LWRs and HWRs
  - NG2 starts with no reactors, develops LWRs & minimal fuel cycle infrastructure

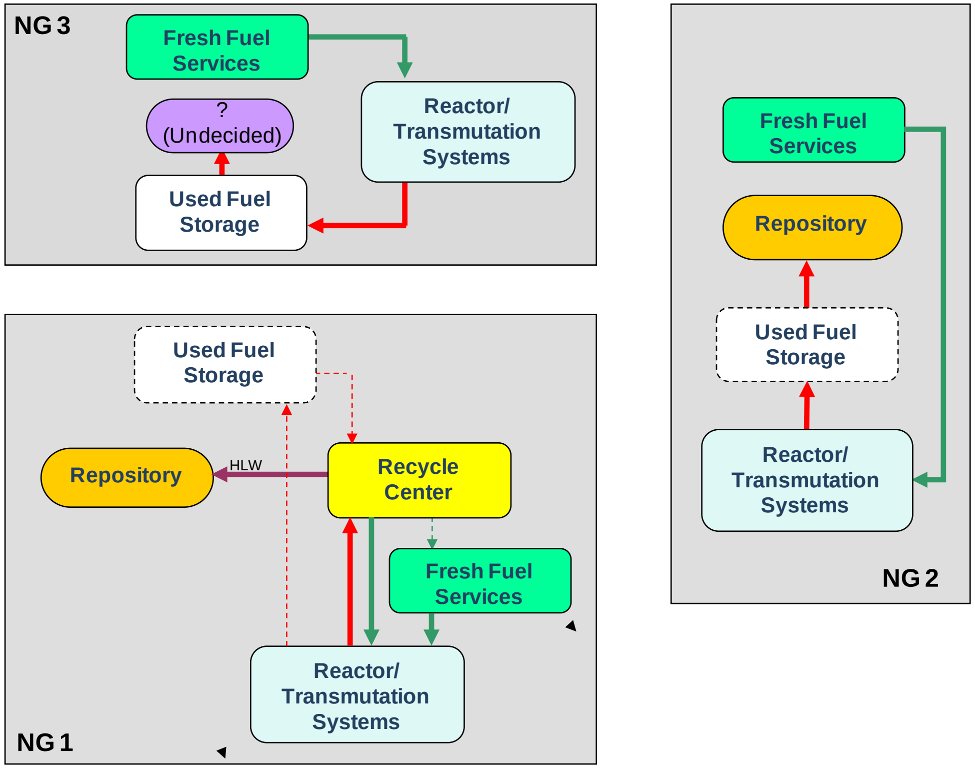
Fuel Cycle Strategies of the NG groups

- ***NG1: General strategy is to recycle used fuel* —** The group plans to build, operate, and manage used fuel recycling facilities and permanent geologic disposal facilities for highly radioactive waste.

- ***NG2: General strategy is to either directly dispose of used fuel, or reprocess used fuel abroad* —** The group plans to build, operate, and manage permanent geologic disposal facilities for highly radioactive waste (in the form of used fuel and/or reprocessing waste) and/or it works synergistically with another group to have it's fuel recycled.

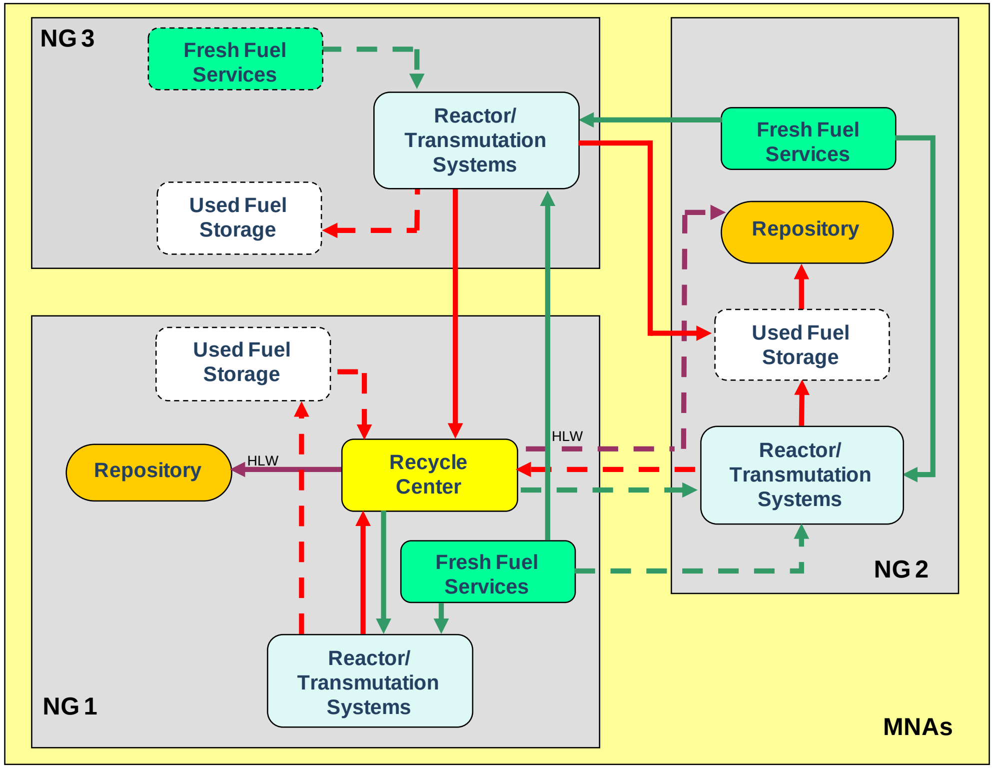
- ***NG3: General strategy is to use fresh fuel, and send used fuel abroad for either recycle or disposal, or the back-end strategy is undecided*** — The group has no plans to build, operate, and manage used fuel recycling facilities or permanent geologic disposal facilities for highly radioactive waste. They may obtain fabricated fuel from abroad and may arrange for export of their used fuel.

Heterogeneous Non-Synergistic Storyline



- *No interactions between groups*
  - *NG1: General strategy is to recycle used fuel*
  - *NG2: General strategy is to directly dispose of used fuel*
  - *NG3: General strategy is to use fresh fuel, the back-end strategy is undecided*

Heterogeneous Synergistic Storyline



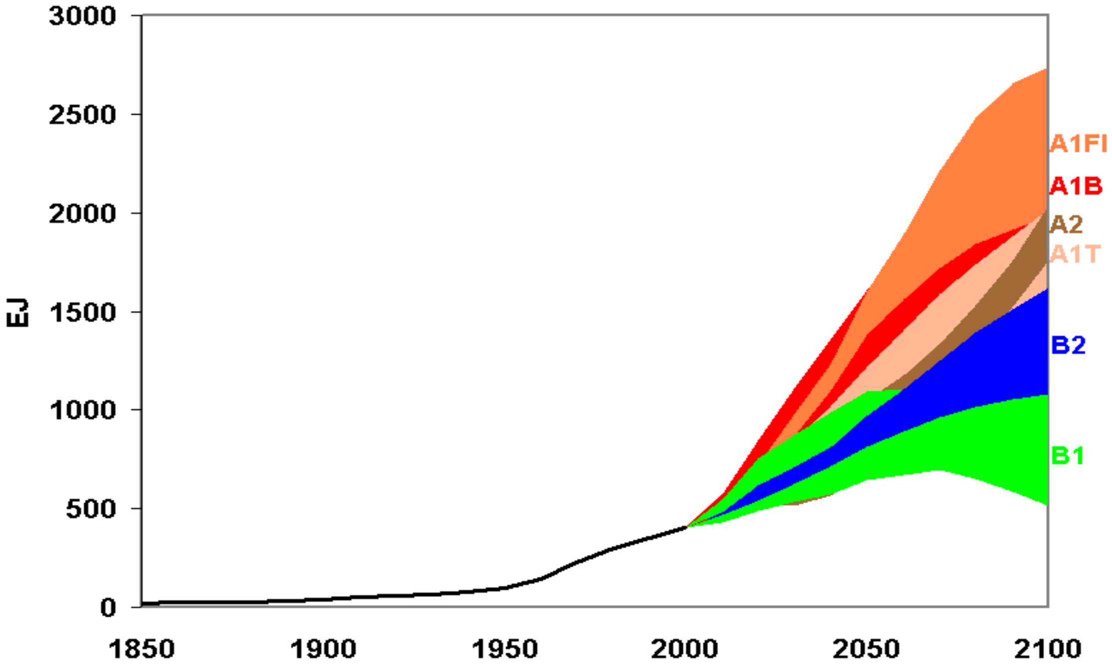
- *Synergistic interactions*
  - *NG1: General strategy is to recycle used fuel*
  - *NG2: General strategy is to directly dispose of used fuel, or reprocess used fuel abroad*
  - *NG3: General strategy is to use fresh fuel, and send used fuel abroad for either recycle or disposal*
- *May include Multi-lateral Nuclear Approaches (MNAs)*

Scenarios and Assumptions

- Evaluation of different story lines involves development of scenarios
  - Scenarios assume an initial strategy and how that strategy may evolve over a period of 50-100 years or more
- Each scenario requires multiple analysis assumptions
  - Initial conditions
  - Overall energy demand changes
  - Reactor characteristics
  - Introduction rates for reactors and fuel cycle facilities
  - Uranium limits
  - Enrichment tail assays
  - Etc.

Overall Energy Demand is the Primary Scenario Driver

- Many studies have generated multiple future energy demand scenarios
- GAINS decided to develop two simplified scenarios for use in the Base Cases

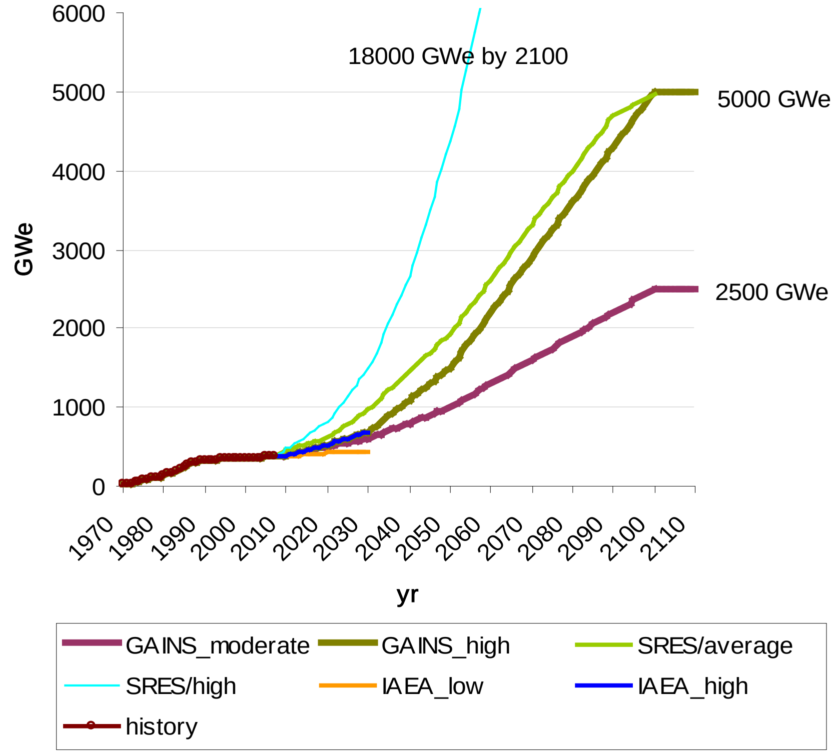


Energy demand growth scenarios from the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (SRES)

Global Growth Curves

- Established two growth curves for GAINS
  - Considered multiple global growth projections
  - High case climbs to 5000 GWe
  - Moderate climbs to 2500 GWe

- Similar forms
  - Start with history (1970-2008)
  - Add 3 growth periods
    - 2008-2030
    - 2031-2050
    - 2051-2100
  - Flat after 2100 (to let codes stabilize)



Global Growth Curves – Heterogeneous World

- Historic growth
  - Split equally between NG1, NG2
  - Assumes 6% HWRs, 94% LWRs
  - All HWRs in NG2
- Projected growth
  - NG3 starts at zero, has growing share
  - Final split:
    - 40% NG1
    - 40% NG2
    - 20% NG3

5000 Gwe in 2100 Case

Nominal Case (40%, 40%, 20% in 2100)

Year	NG1	NG2	NG3	Total
2008	149	149	0	298
2030	333	333	33	700
2050	682	682	137	1500
2100	2000	2000	1000	5000

Reactor/Fuel Data Template – Reactor characteristics

Reactor net electric output	MW	870		
Reactor thermal output	MW	2100		
Thermal efficiency	%	41.43		
Average load factor	%	85		
Operation cycle length	EFPD	140		
		Core	Axial blanket	Radial blanket
Power share of each region*	%	94.5	3.0	2.5
No. of refuelling batches**		3	3	3.5
Fuel residence time**	EFPD	420	420	490
Specific power density*	MW/t	157.00	11.465	8.532
Average discharged burnup*	MWd/t	65939	4815	4181
Thermal power of each region*	MW	1984.5	63.0	52.5
Heavy metal weight share				
Intial core and full core discharge	%	52.0	22.6	25.4
Equilibrium refueling	%	54.0	23.5	22.5
Average burnup of whole core*	MWd/t	37677		
Average residence time of whole core*	EFPD	435.771		
Average power density of whole core*	MW/t	86.462		
Initial core inventory	tHM	24.288		
Equilibrium Loading	tHM / y	17.292		

- Excel Template
  - Used to document all types of reactors
  - Data used by simulation codes
  - Dozens of completed templates in library
  - Example is break-even FR

Reactor/Fuel Data Template – Isotopic Charge/Discharge

Refueling Data	**(Attention!! Reload and discharge are as of one refueling in equilibrium cycle.)**						
Isotopes	Initial loading (kg)		Reload (kg)		Discharge (kg)		Full core discharge (kg)
	Weight (kg)	(%)	Weight (kg)	(%)	Weight (kg)	(%)	Weight (kg)
U-234					3.863E-03	4.951E-05	7.944E-03
U-235	6.458E+01	2.659E-01	2.065E+01	2.646E-01	1.932E+01	2.476E-01	6.668E+01
U-236					1.695E+00	2.173E-02	4.017E+00
U-238	2.146E+04	8.836E+01	6.862E+03	8.794E+01	6.537E+03	8.377E+01	2.073E+04
Np-237					1.037E+00	1.329E-02	2.262E+00
Pu-238	1.381E+01	5.685E-02	4.602E+00	5.898E-02	3.522E-01	4.514E-03	5.661E-01
Pu-239	1.657E+03	6.822E+00	5.523E+02	7.078E+00	5.767E+02	7.390E+00	1.762E+03
Pu-240	6.766E+02	2.786E+00	2.255E+02	2.890E+00	2.459E+02	3.151E+00	7.280E+02
Pu-241	3.010E+02	1.239E+00	1.003E+02	1.286E+00	7.410E+01	9.496E-01	2.463E+02
Pu-242	1.132E+02	4.662E-01	3.774E+01	4.837E-01	4.006E+01	5.134E-01	1.193E+02
Am-241					3.926E+00	5.031E-02	8.531E+00
Am-242m					8.594E-02	1.101E-03	1.455E-01
Am-243					2.960E+00	3.793E-02	6.071E+00
Cm-242					2.694E-01	3.452E-03	4.793E-01
Cm-244					3.094E-01	3.966E-03	4.930E-01
Cm-245					1.039E-02	1.331E-04	1.425E-02
Total FP					2.997E+02	3.841E+00	6.166E+02
Total HM&FP	24288.257	100.000	7803.086	100.000	7803.086	100.000	24288.257
Total U	21526.758	88.630	6882.586	88.203	6557.715	84.040	20797.868
Total Pu	2761.499	11.370	920.500	11.797	937.062	12.009	2855.758
Total MA (Np+Am+Cm)	13.807	0.057	0.000	0.000	8.598	0.110	17.996

Key Indicators and Evaluation Parameters

- Based on INPRO methodology (TECDOCs 1434, 1575)
  - INPRO methodology supports a detailed evaluation for use by an individual nation
  - GAINS approach simplifies the methodology to be suitable for comparing different options or scenarios

- GAINS Approach
  - 10 Key Indicators + 11 Evaluation Parameters screened for relevance to GAINS Objectives
  - Comparison only - No Acceptance Limits
  - Most KI and EP are normalized per unit of energy produced to remove growth bias (all indicators growing exponentially)

- Future analyses may expand on or modify this list of indicators
  - Include additional parameters of interest

GAINS Key Indicators and Evaluation Parameters

No.	KI or EP	Units
Power Production		
KI-1	Nuclear power production capacity by reactor type	GW(e)
EP-1.1	(a) Commissioning and (b) decommissioning rates	GW(e)/a
Nuclear Material Resources		
KI-2	Average net energy produced per unit mass of natural uranium	GWa/ktHM
EP-2.1	Cumulative demand of natural nuclear material	ktHM
KI-3	Direct use material inventories per unit energy generated	kg/GWa
Discharged Fuel		
KI-4	Discharged fuel inventories per unit energy generated	tHM/GWa and m^3/GWa
Radioactive Waste and Minor Actinides		
KI-5	Radioactive waste inventories per unit energy generation	m^3/GWa (or kt/GWa)
EP-5.1	Radiotoxicity and decay heat of waste, including discharged fuel destined for disposal	Sv/kWh; or kWt/t
EP-5.2	Minor actinide inventories per unit energy generated	kg/GWa

GAINS Key Indicators and Evaluation Parameters

Fuel Cycle Services		
KI-6	(a) Uranium enrichment and (b) fuel reprocessing capacity, per unit of nuclear power production capacity	(SWU/a) / GW(e); and (tDM/a) / GW(e)
KI-7	Annual quantities of fuel and waste material transported between groups	ktiHM/a
EP-7.1	Category of nuclear material transported between groups	Category (I, II, or III)
System Safety		
KI-8	Annual collective risk per unit energy generation	Risk/MWh; or qualitative discussion
Costs and Investment		
KI-9	Levelized unit of electricity cost (LUEC)	US$/MWh
EP-9.1	Overnight cost for Nth-of-a-kind reactor	billion US$; US$/kWe
KI-10	Estimated R&D investment in Nth-of-a-kind deployment	billion US$
EP-10.1	Additional functions or benefits	Text providing qualitative description

Output Template – Key Indicators

- Excel Template
- Used to document analysis results in standard format
  - Link to simulation code output
- Two versions
  - Homogeneous world
  - Heterogeneous world – sheets by group and global total
- Includes 36 built-in graphs
  - 20 Key Indicators and Evaluation Parameter graphs
  - 16 Additional graphs to document mass flows, etc.
- Framework Base Case Presentation Graphs from Template

Outline

- Fuel Cycle Simulator Overview
- GAINS Framework Components
- Framework Base Cases
  - Homogeneous World
    - Business as Usual Scenario
    - Fast Reactor Introduction Scenario
  - Heterogeneous World
    - Non-Synergistic World Scenario
    - Synergistic World Scenario
- Sensitivity Analyses

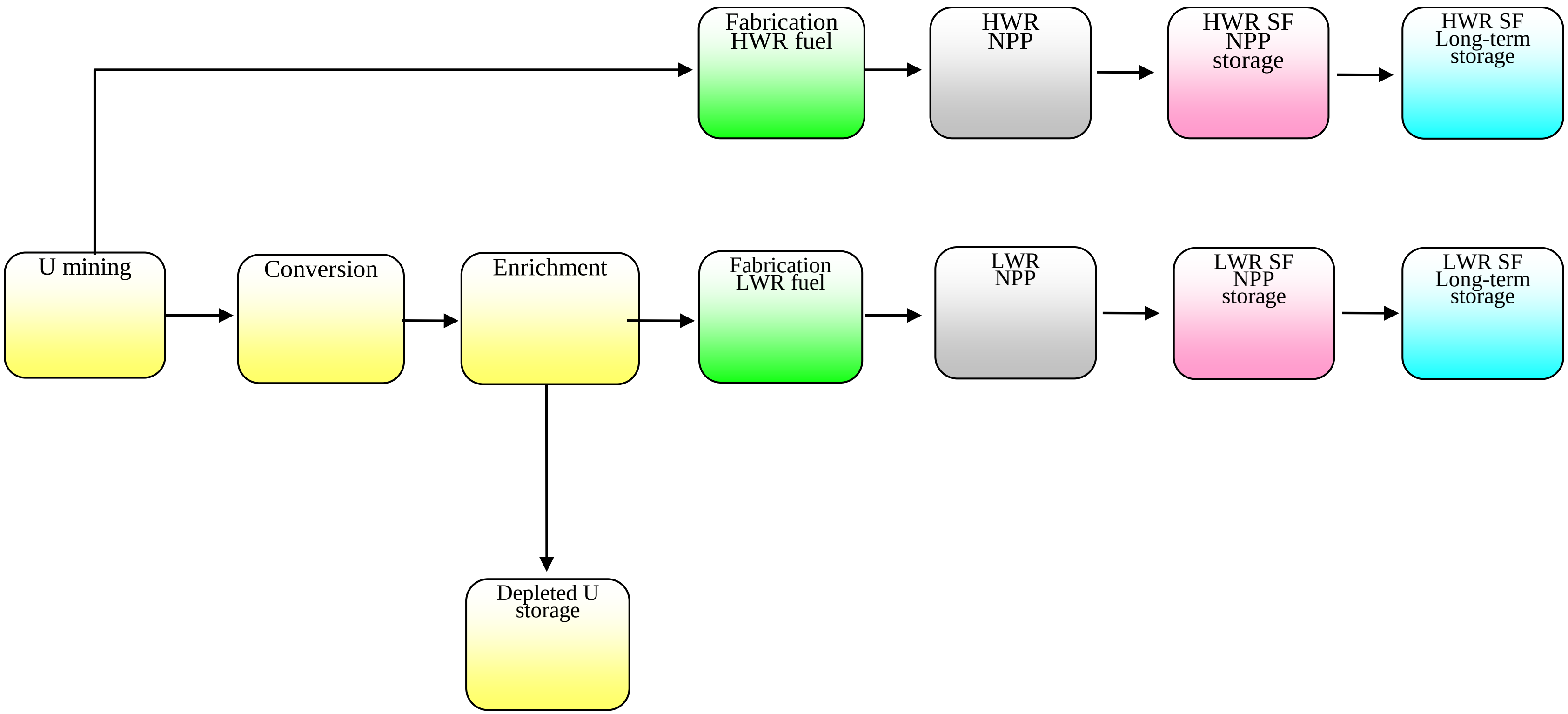
The Eight Framework Base Cases

- The Base Cases are illustrative examples
  - Also can be modified to create custom scenarios

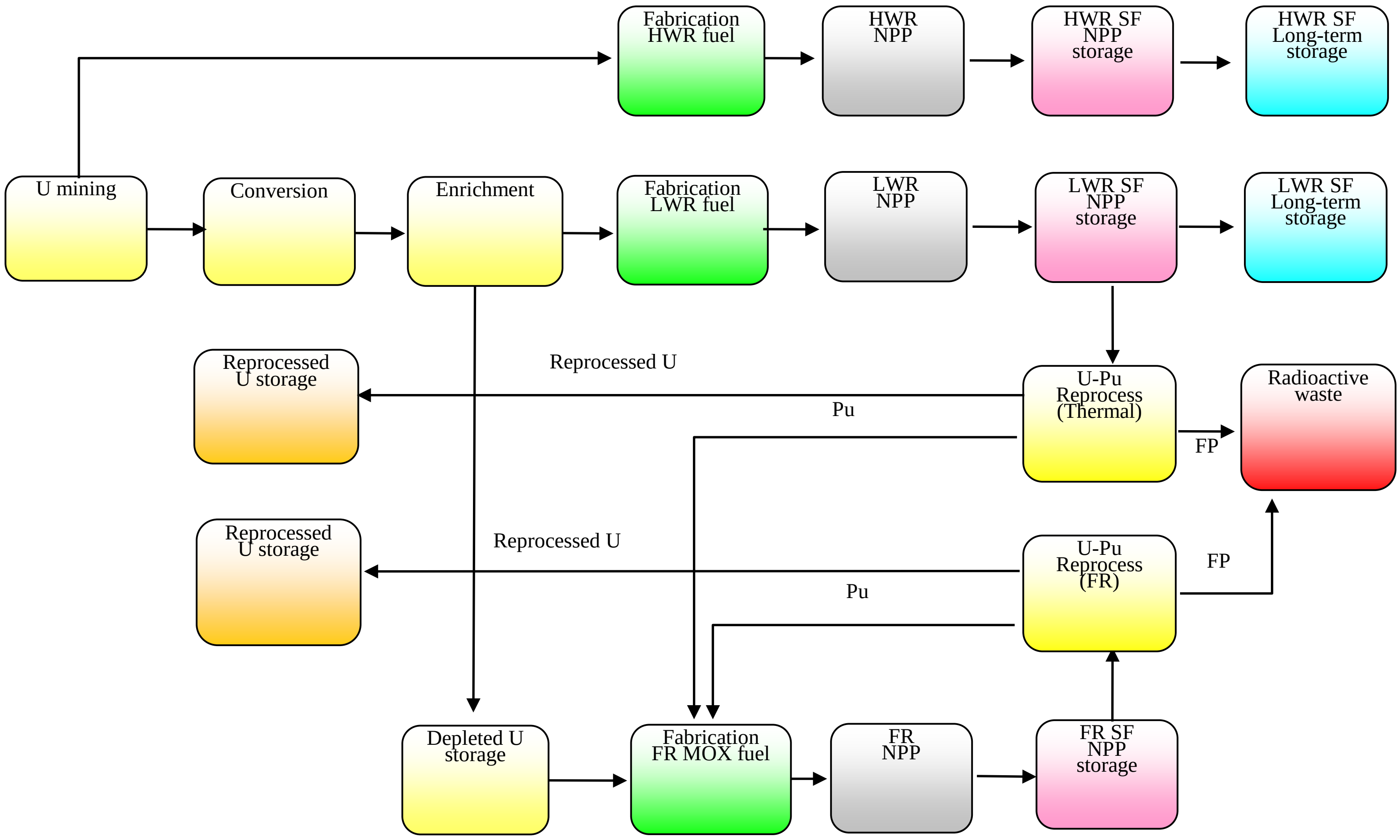
- Homogeneous world
  - Business-as-usual (BAU) scenario
    - Moderate growth case
    - High growth case
  - BAU with fast reactor (BAU-FR) scenario
    - Moderate growth case
    - High growth case
- Heterogeneous world for BAU with fast reactor scenario
  - Non-synergistic
    - Moderate growth case
    - High growth case
  - Synergistic
    - Moderate growth case
    - High growth case

Components of the Business as Usual (BAU) Case

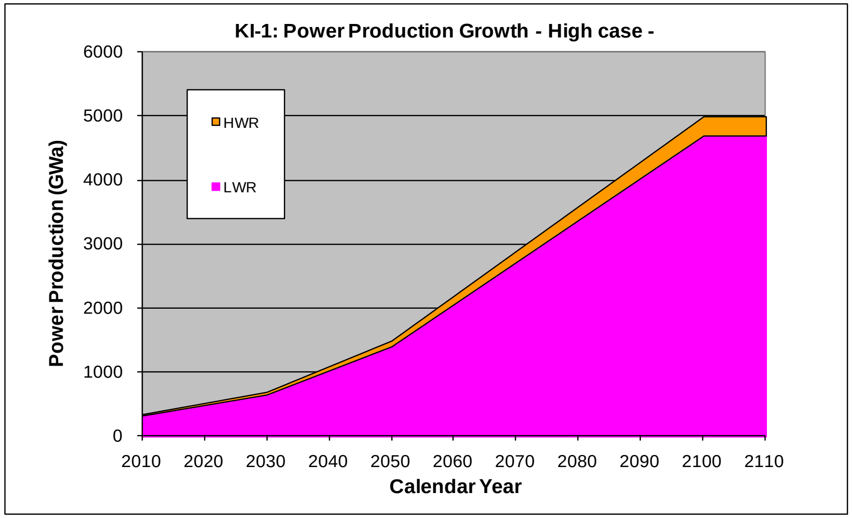
- To make this Base Case easier to model
  - Only 2 types of reactors (LWR, HWR)
  - All reactors of the same type use the same load factor, operating life, fuel burn-up, etc.

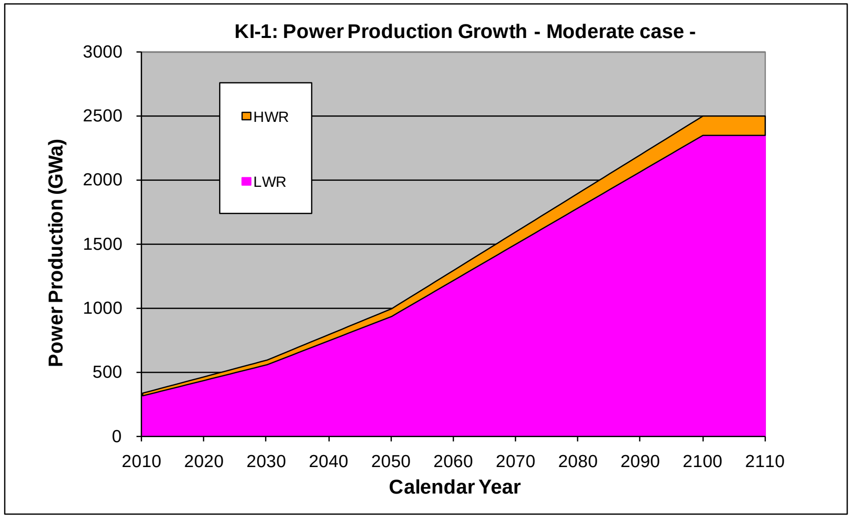


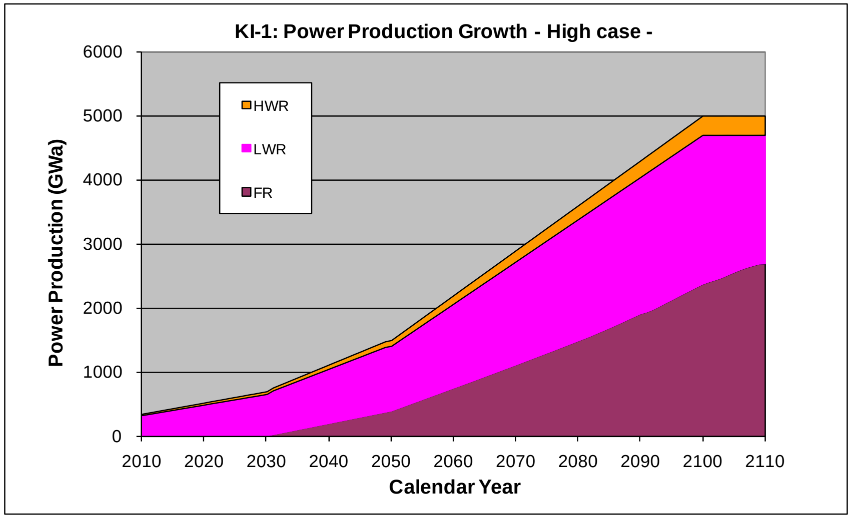
Components of the BAU with Fast Reactors Case

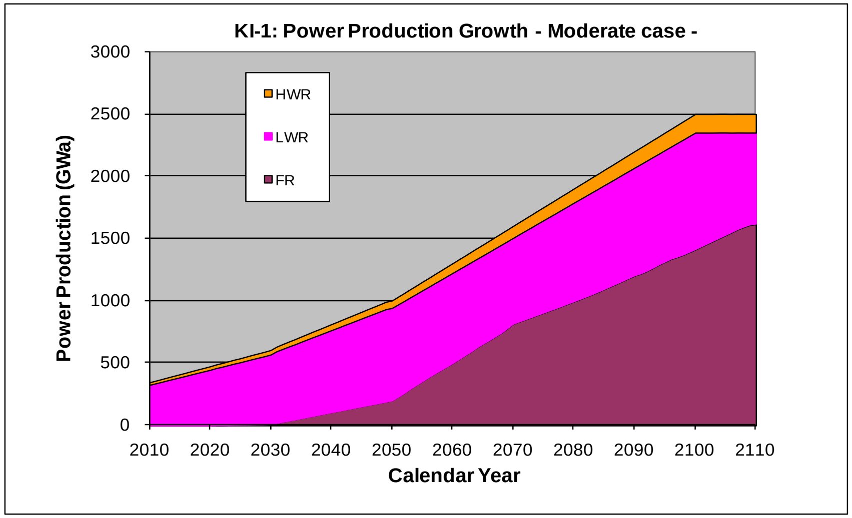


High and Moderate Growth Rates – BAU and BAU-FR cases

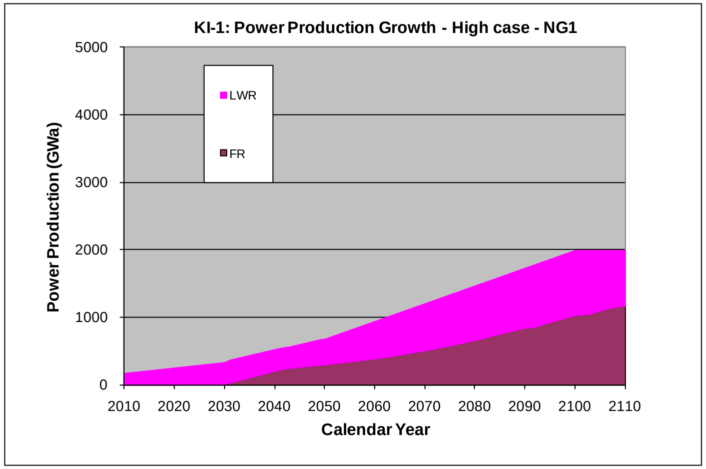


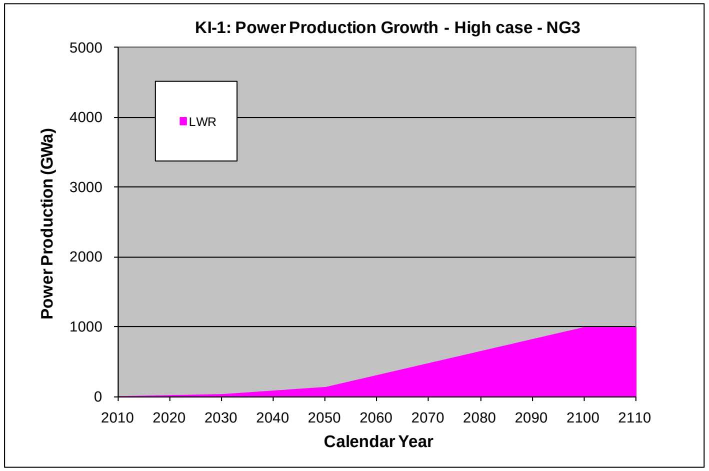


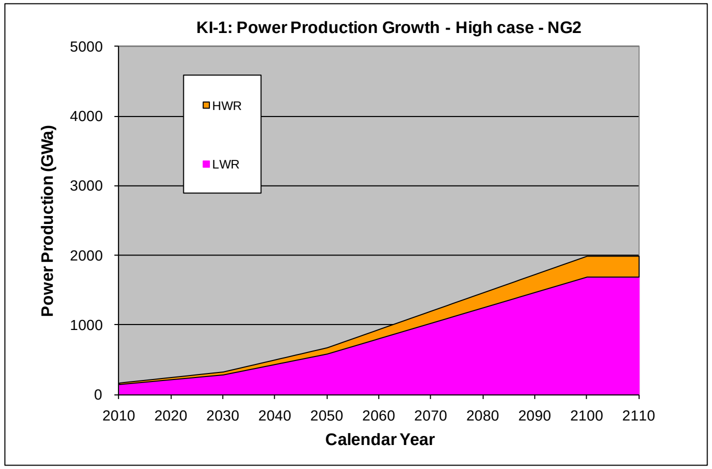


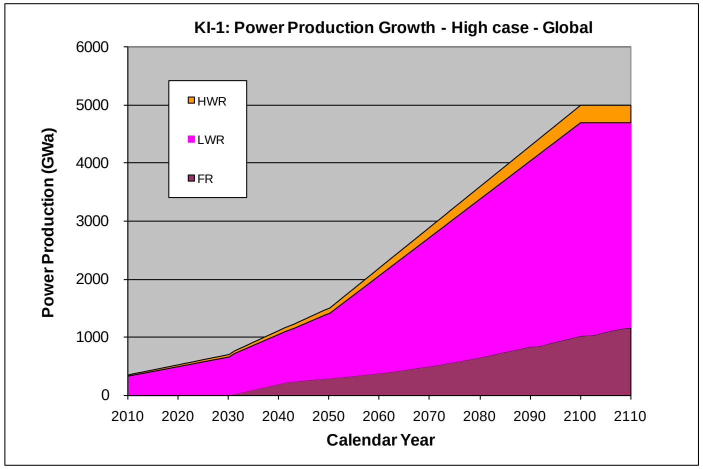


KI-1 Nuclear Power Production by NG Heterogeneous Non-Synergistic Case

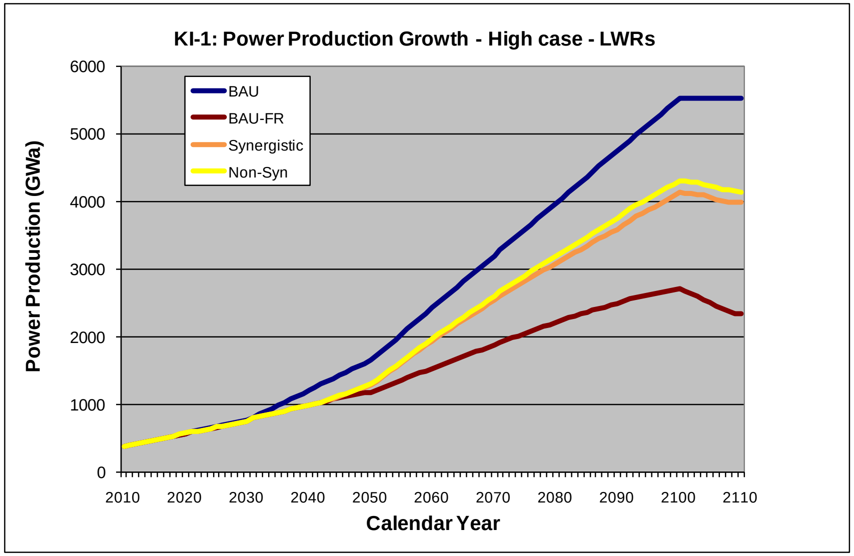


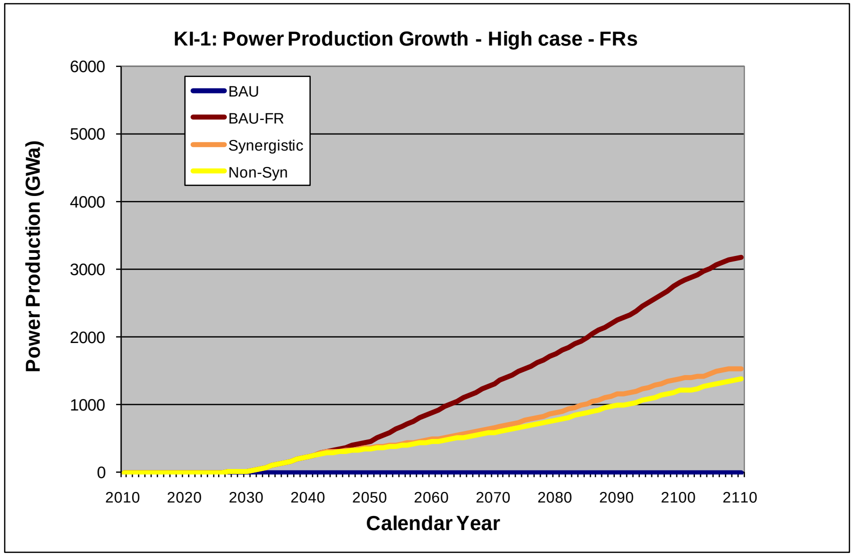




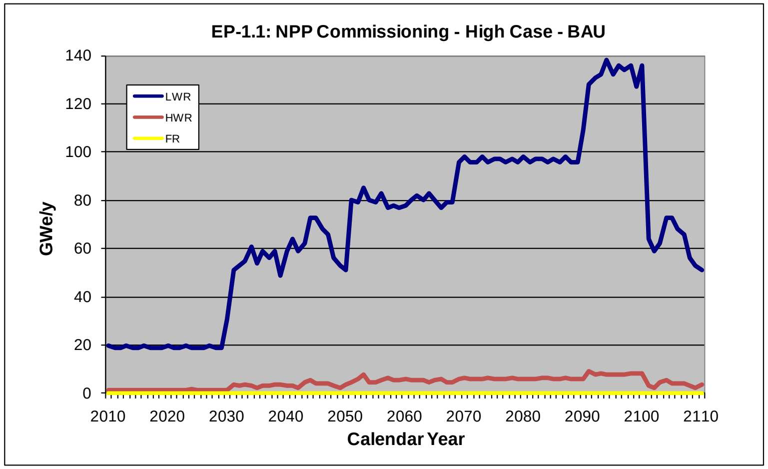


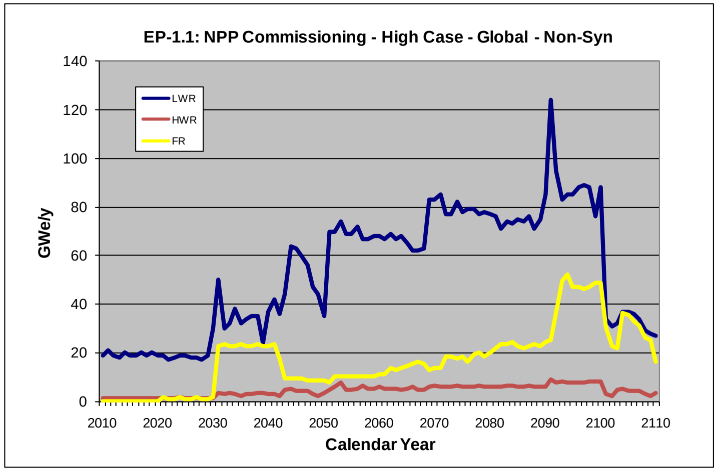
KI-1 LWR and FR Production Comparison

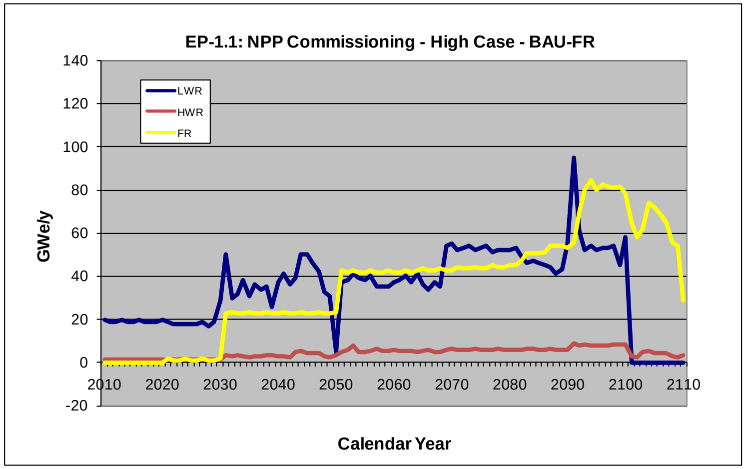


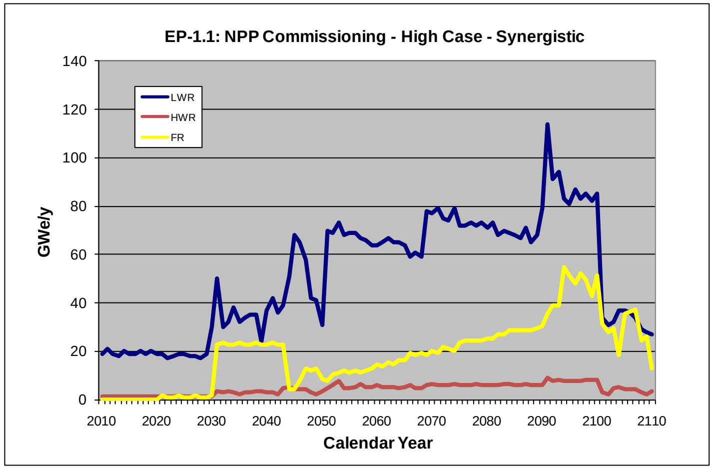


EP-1.1 NPP Commissioning Rates

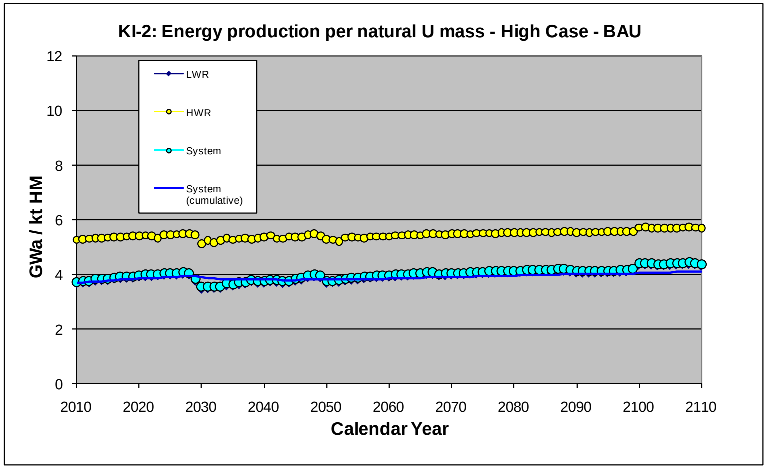


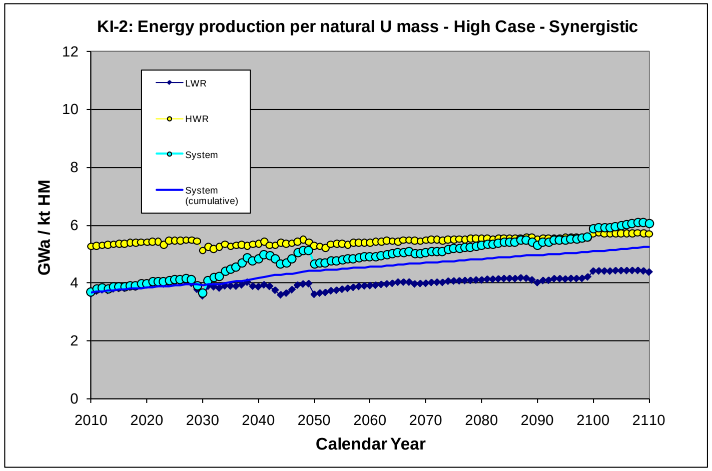


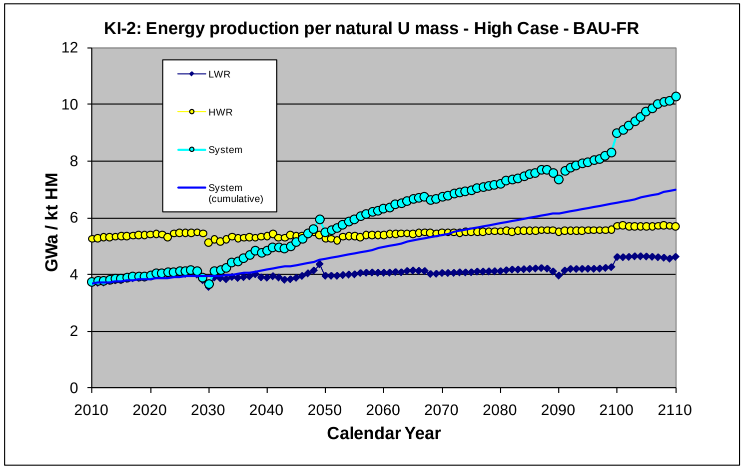


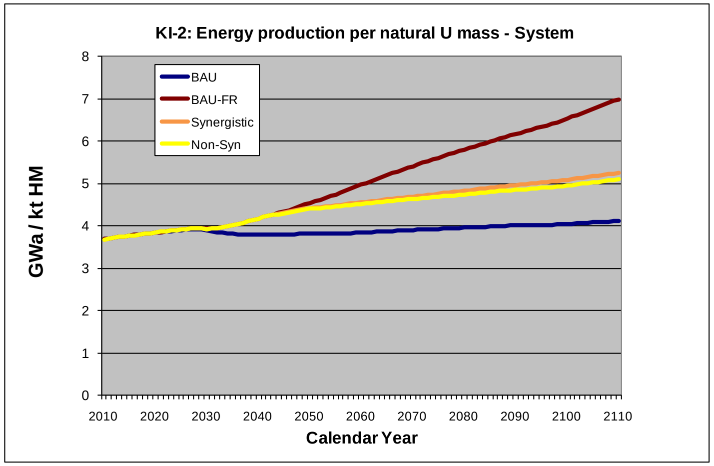


KI-2 Energy Production / MT Unat

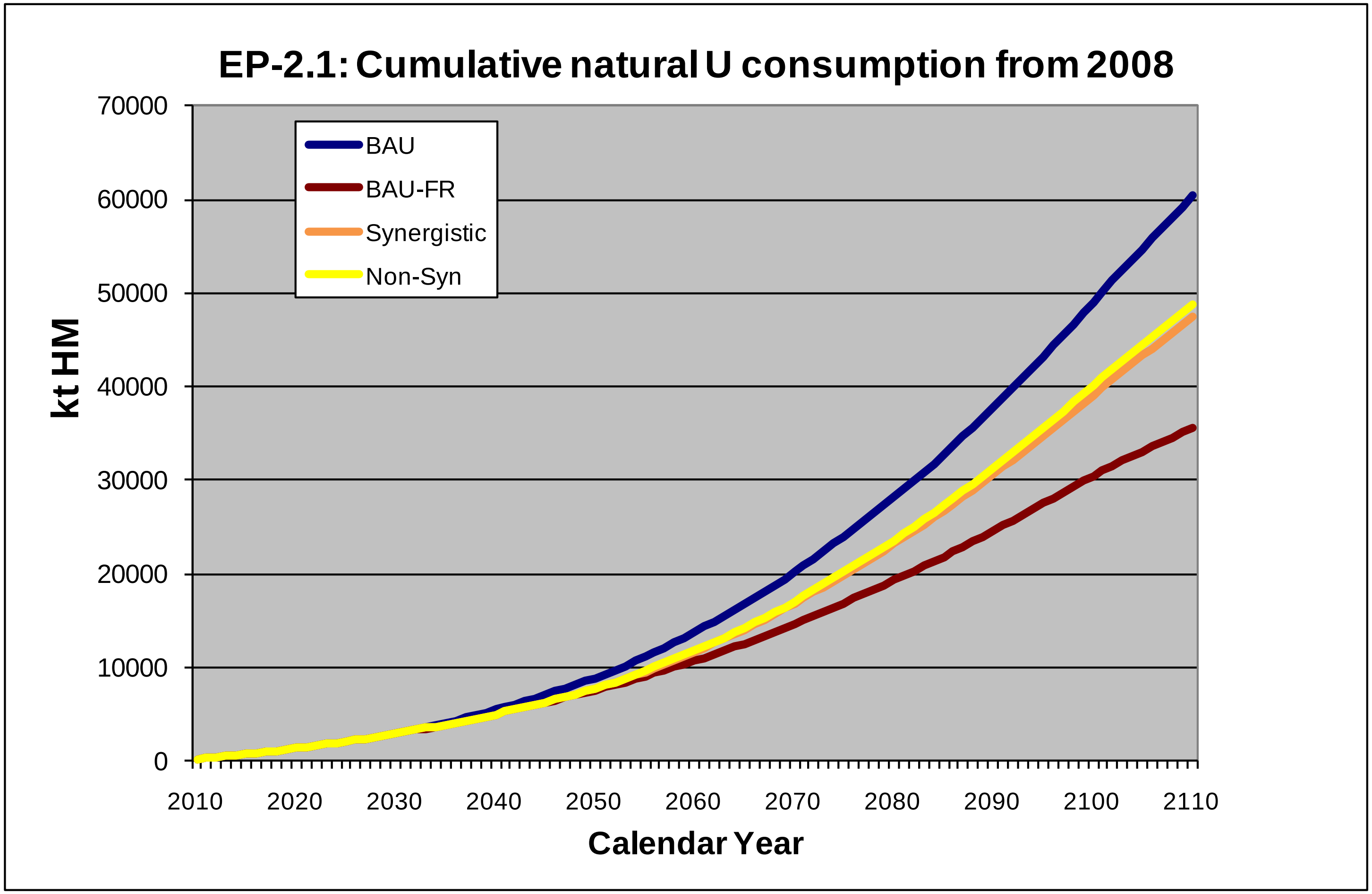




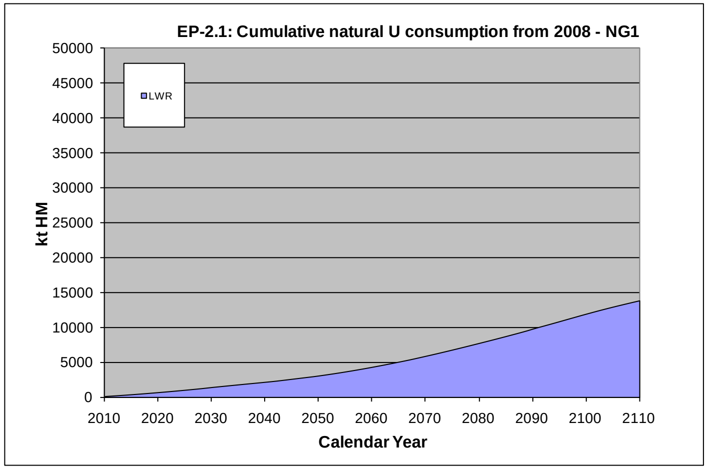


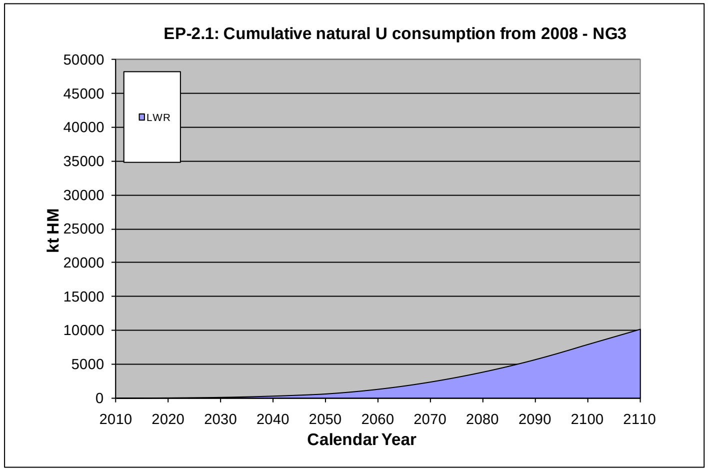


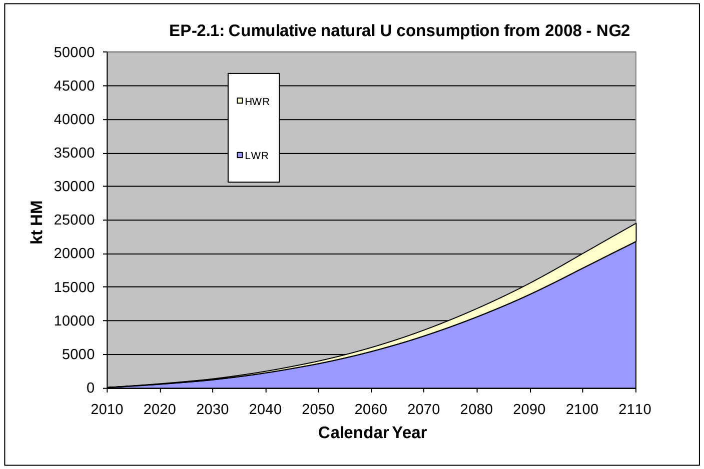
EP-2.1 Cumulative Natural Uranium Used – All Cases

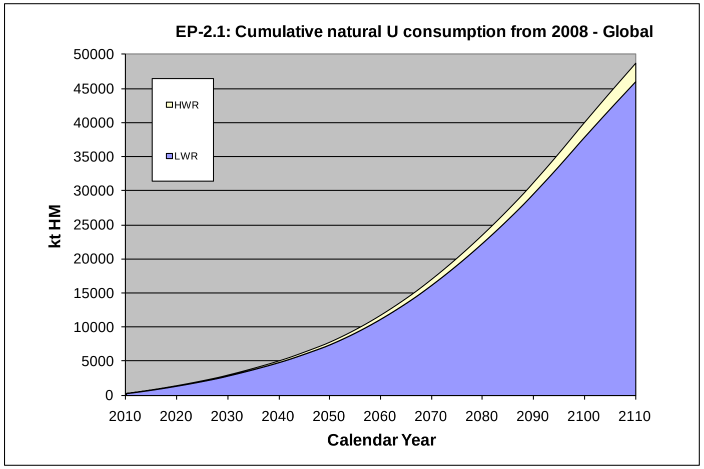


EP-2.1 Cumulative Unat Used – Non-Synergistic Case

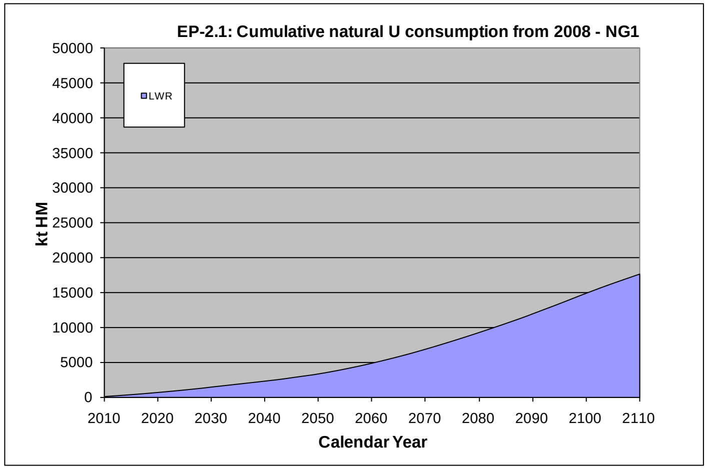


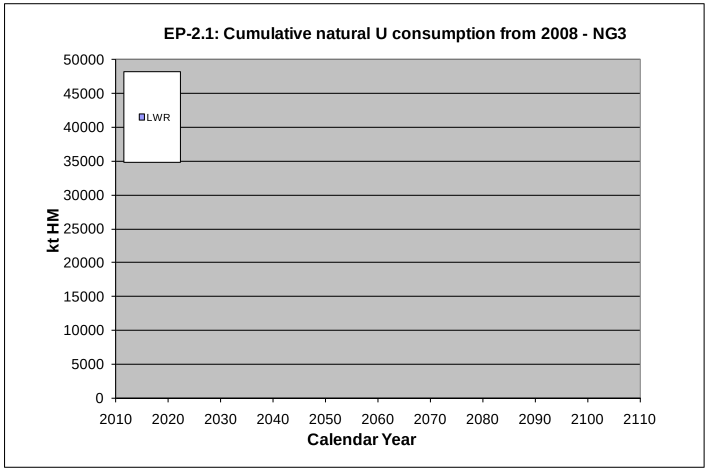


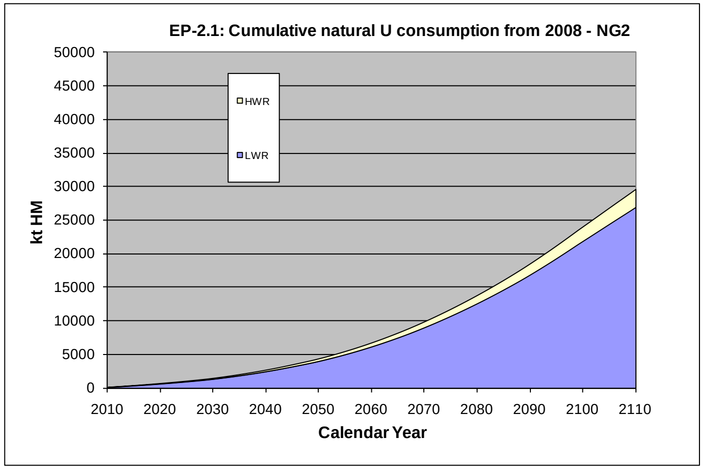


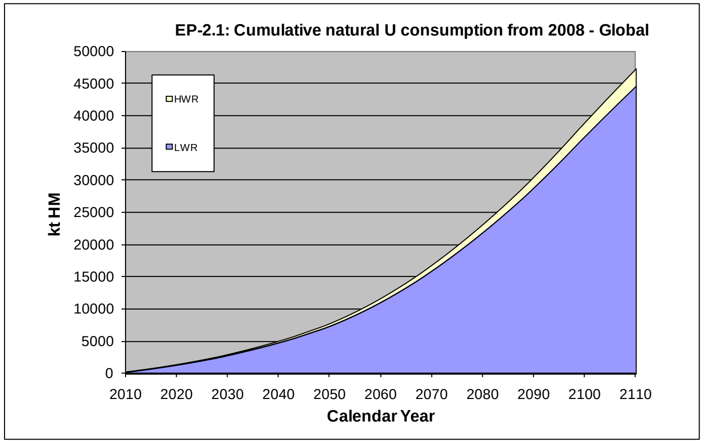


EP-2.1 Cumulative Unat Used –Synergistic Case

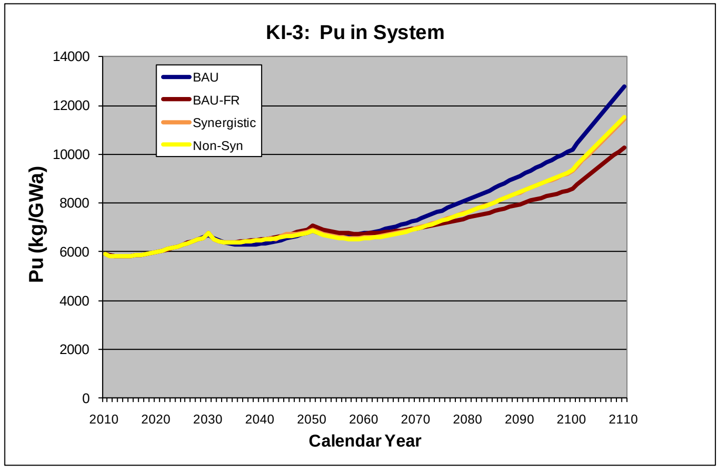


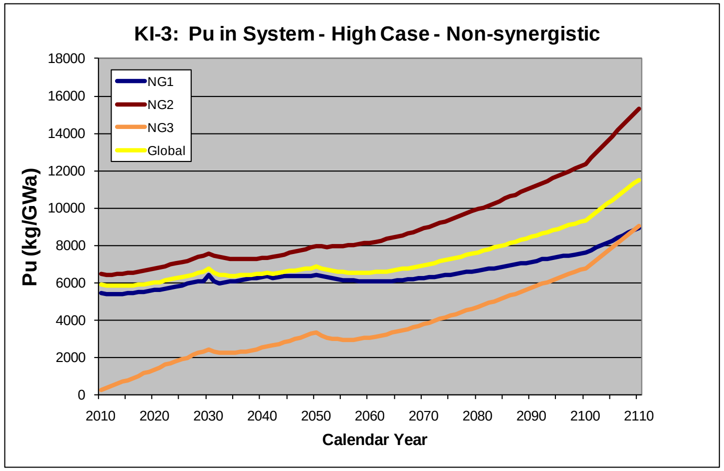




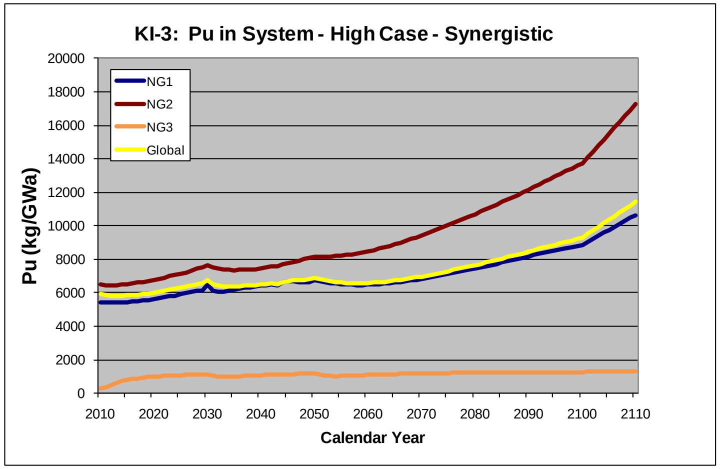


KI-3: Direct Use Material in System



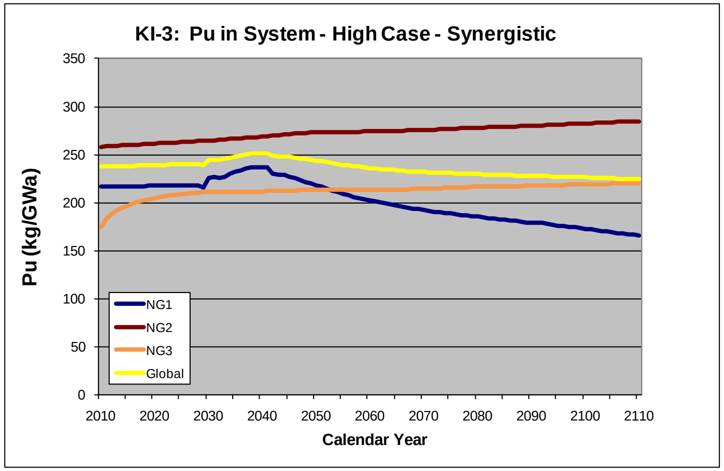


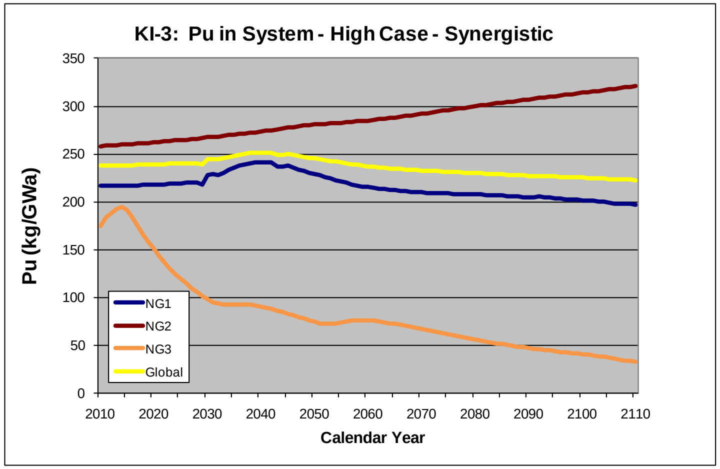
- Pu in system includes:
  - Fuel in reactors
  - Used fuel in cooling pools
  - Used fuel in long-term storage/disposal
  - Inventories at reprocessing and fuel fabrication facilities
  - Separated Pu in other storage



KI-3: Direct Use Material in System

- Different normalization approaches reveal different behavior
  - Previous slide was current inventory normalized by current year energy generation
    - Reflects Pu inventory build-ups
  - Slides on right are normalized by cumulative energy generation
    - Reflects long-term trends of Pu generation/consumption

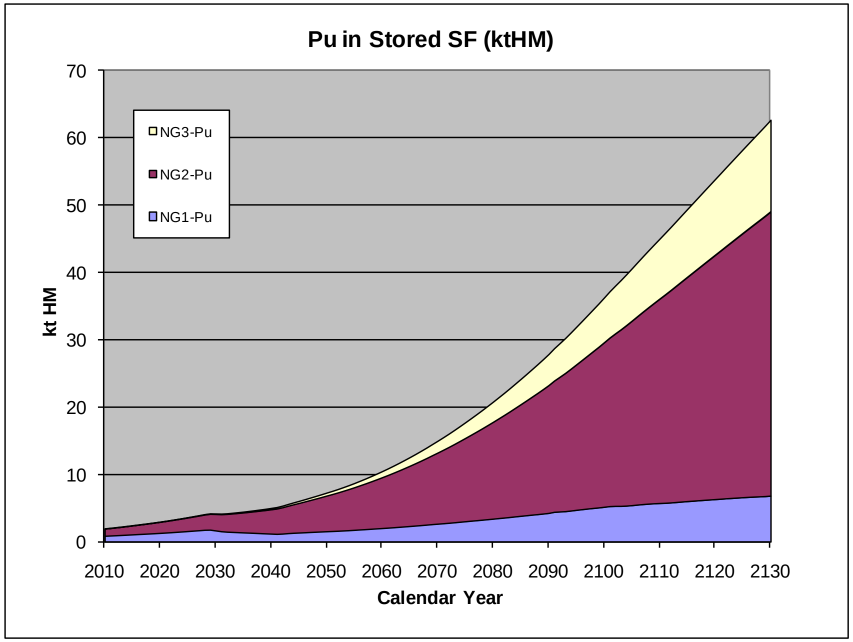




Pu Inventory Comparison by Group

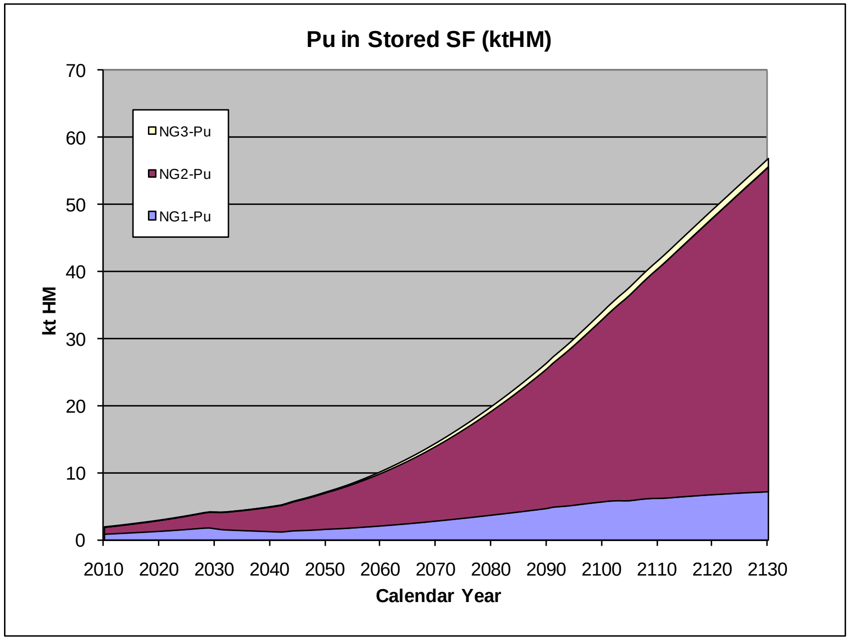
Non-Synergistic Case –

Inventory of Pu in NG3 continues to grow



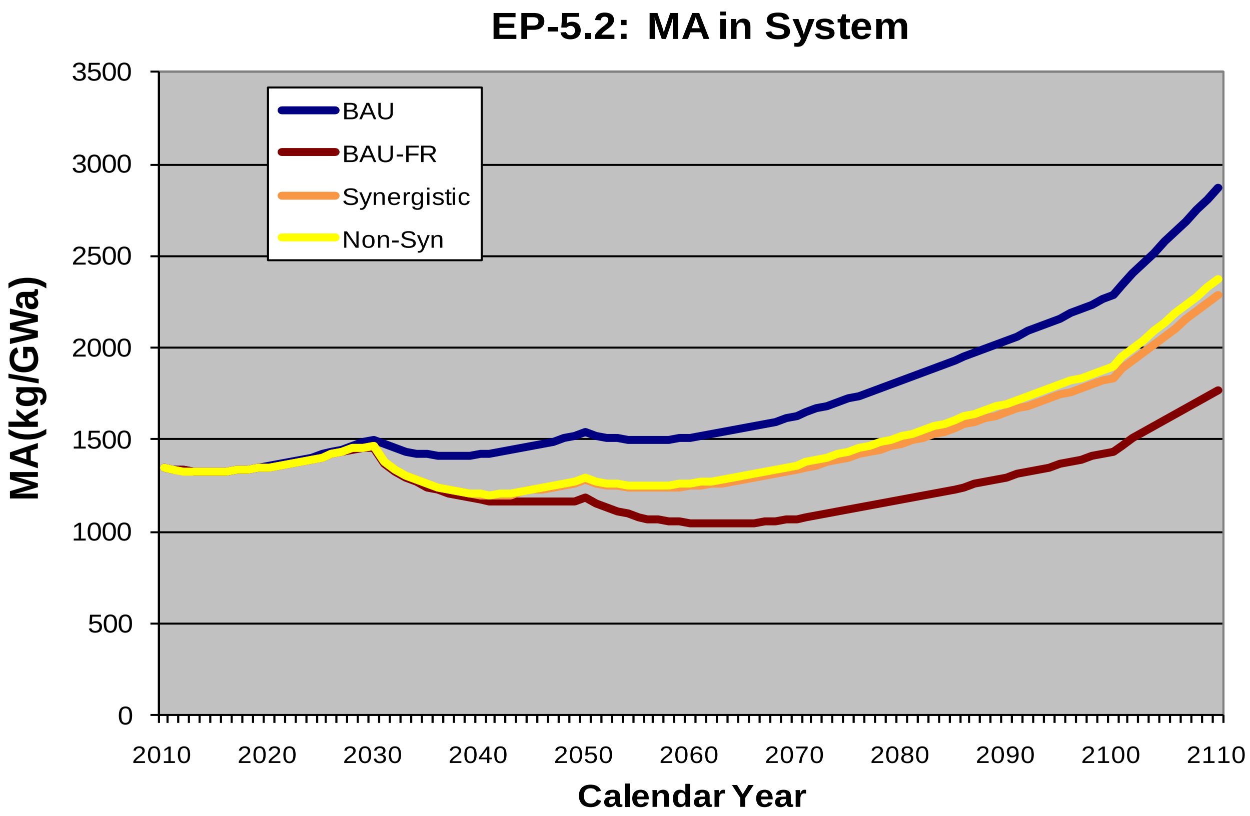
Synergistic Case –

Pu transferred out of NG3

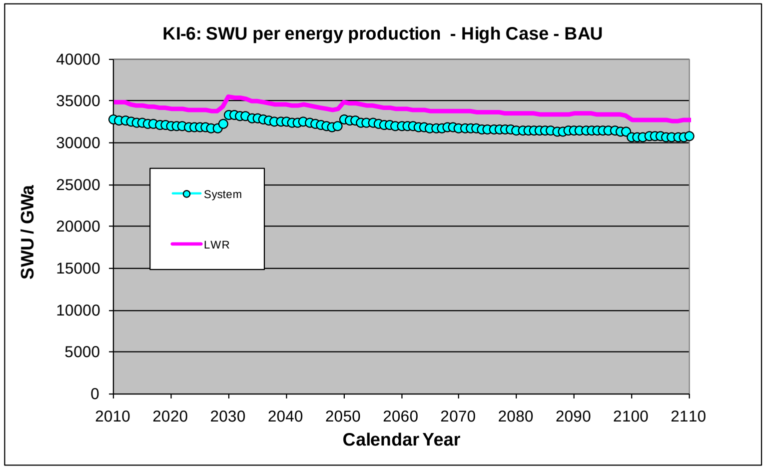


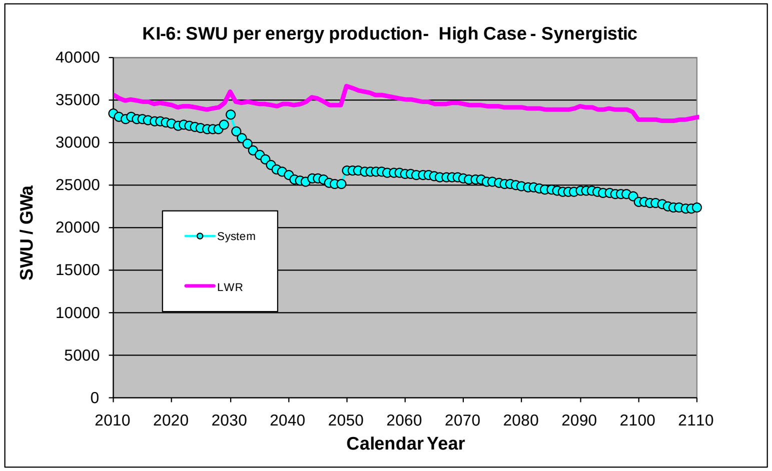
EP-5.2: Minor Actinides in System

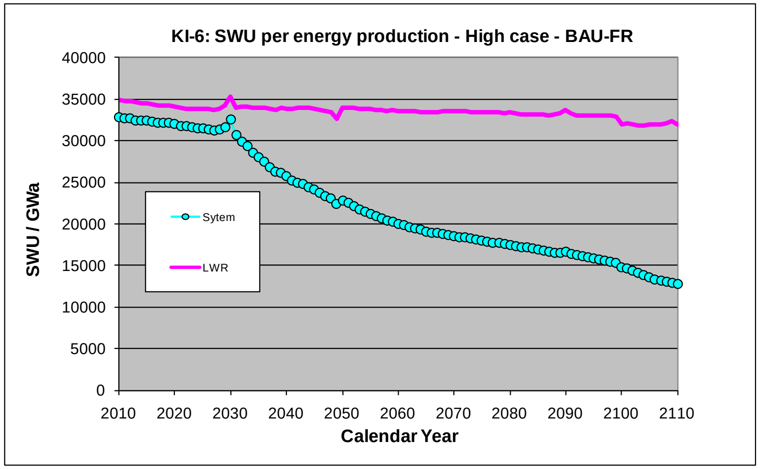
- The GAINS Base Cases assume all MA are disposed
  - Optionally, recycle of MA in fast reactors may result in MA reductions

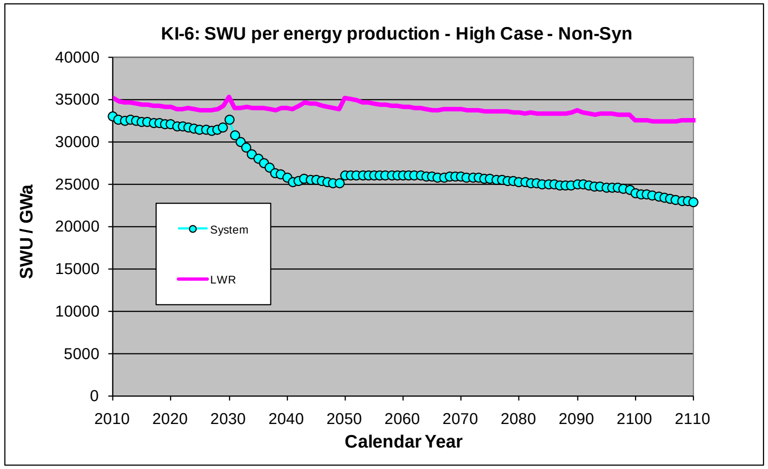


KI-6: Uranium Enrichment

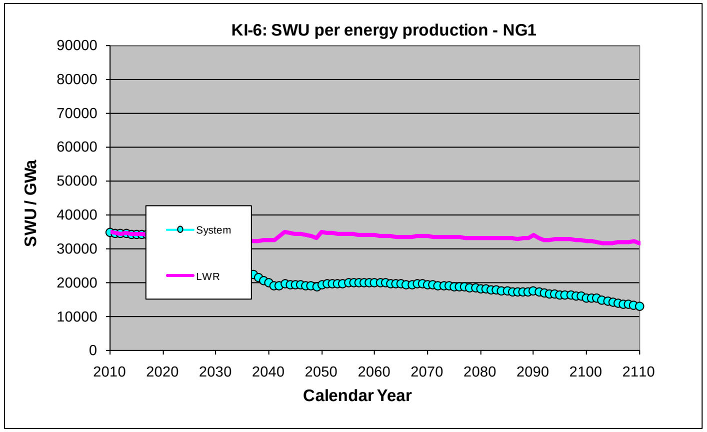


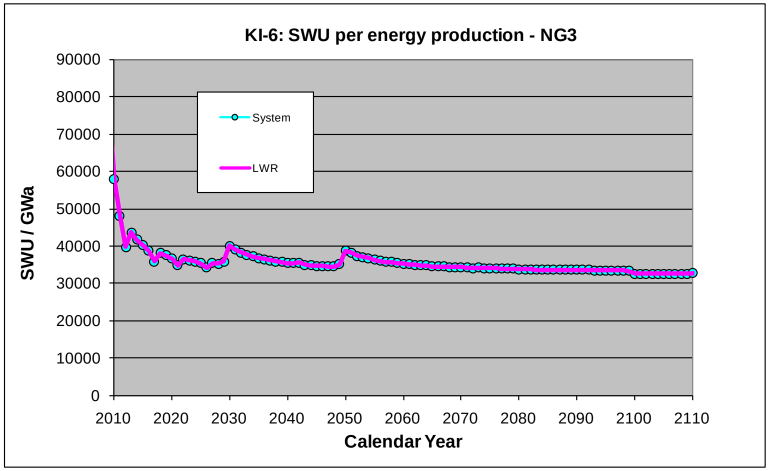


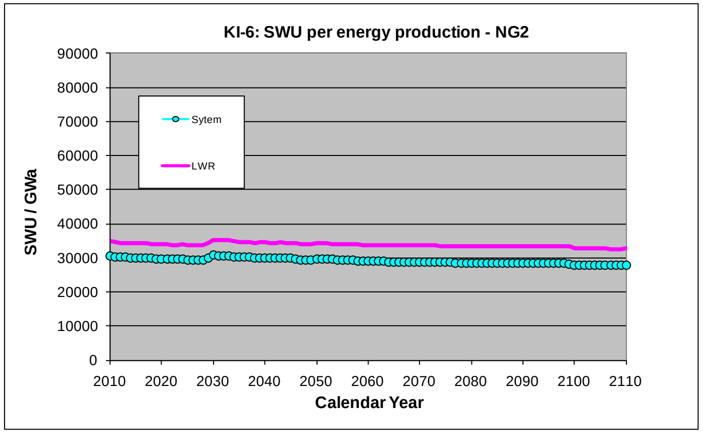


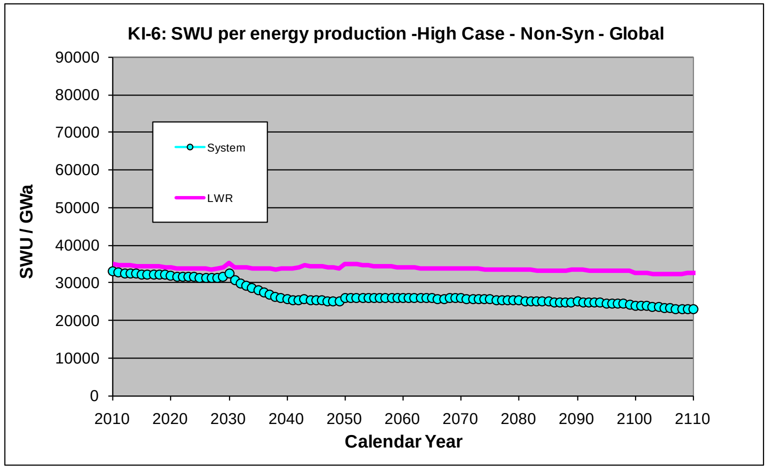


KI-6: Uranium Enrichment – Non-synergistic Case

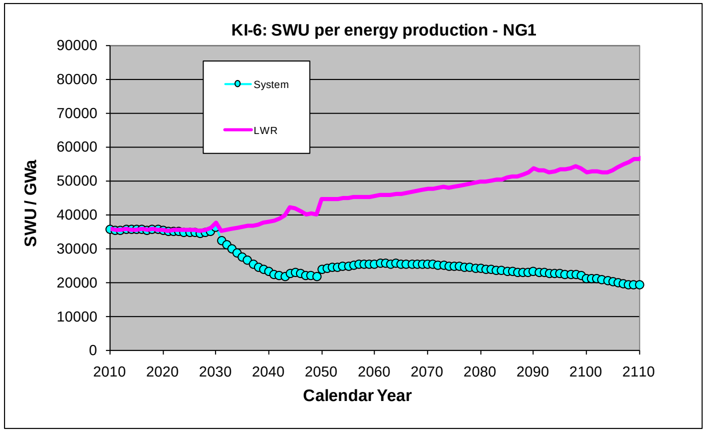


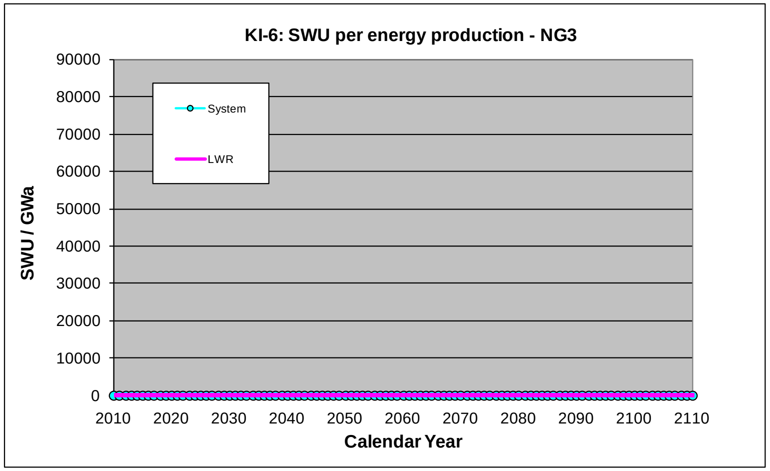


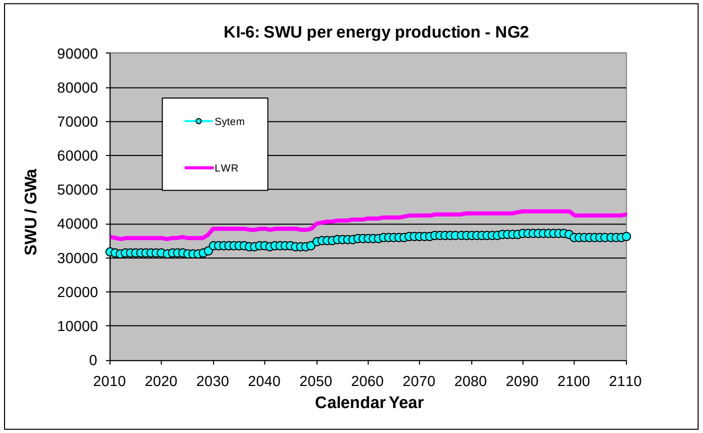


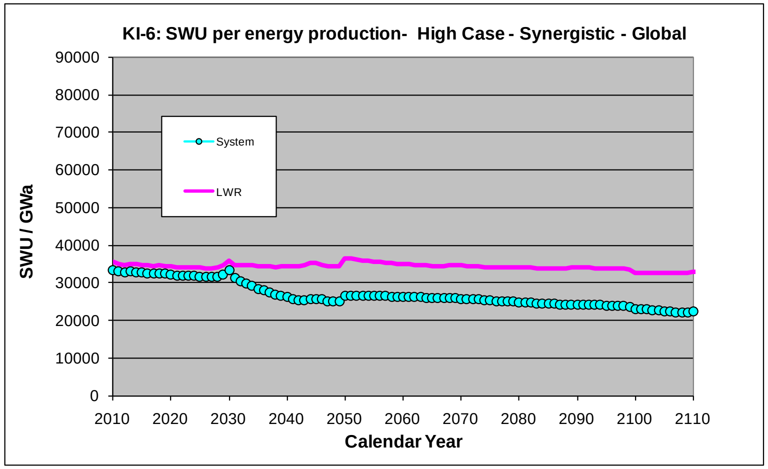


KI-6: Uranium Enrichment – Synergistic Case

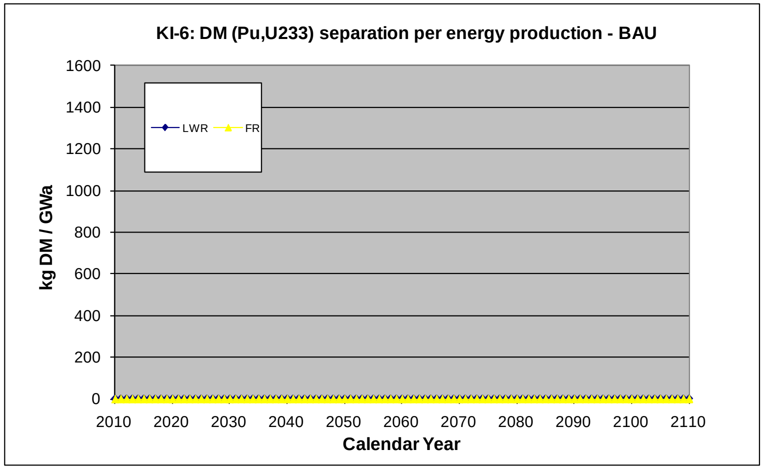


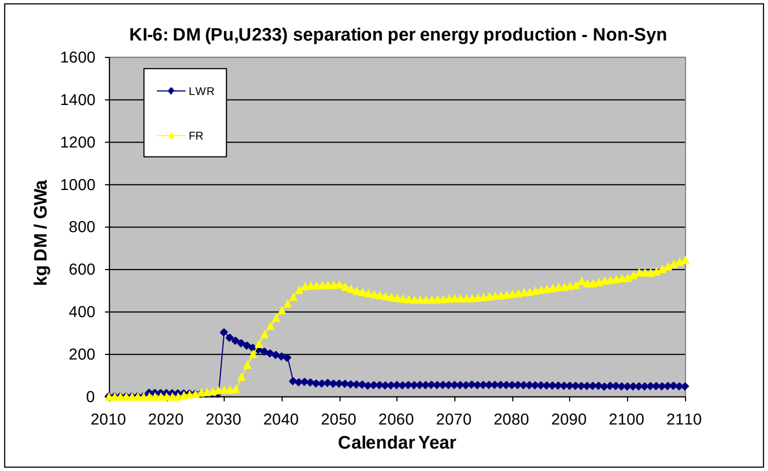


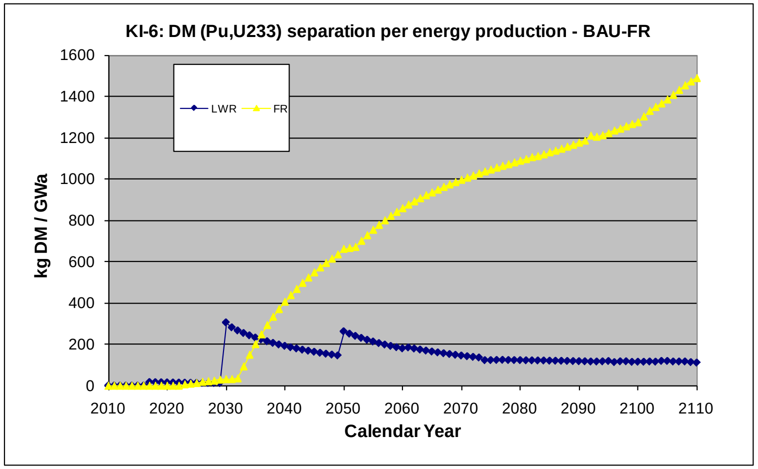


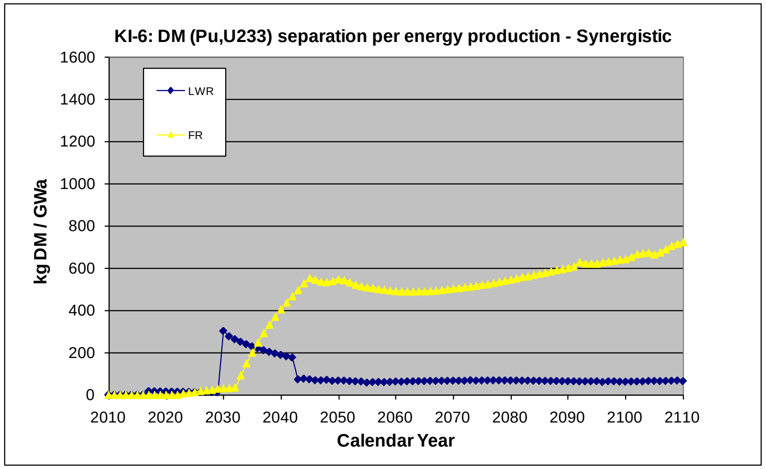


KI-6: Fuel Reprocessing

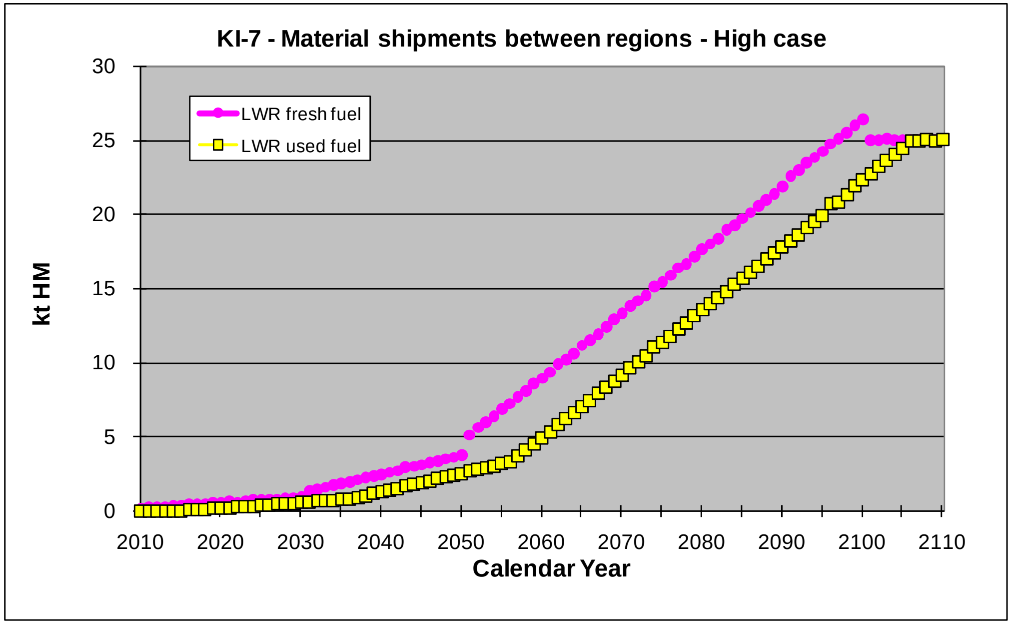








KI-7: Material Transported Between Groups – Synergistic Case Only



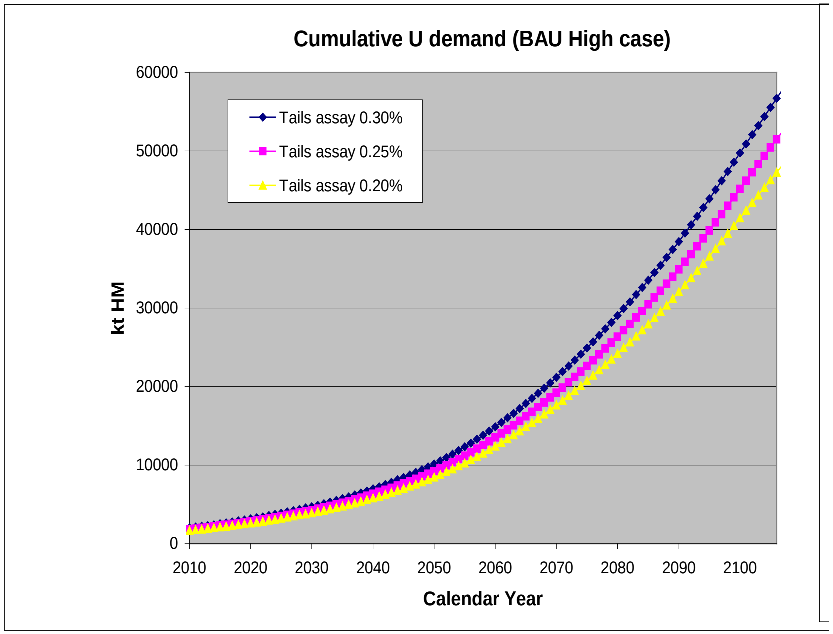
- Graph shows imports (fresh fuel) and exports (used fuel) from NG3
  - The corresponding exports/imports are split equally between NG1, NG2
- EP-7.1: Category of nuclear material transported between groups
  - All material is Cat-3. Fresh fuel only contains LEU, used fuel is self-protecting

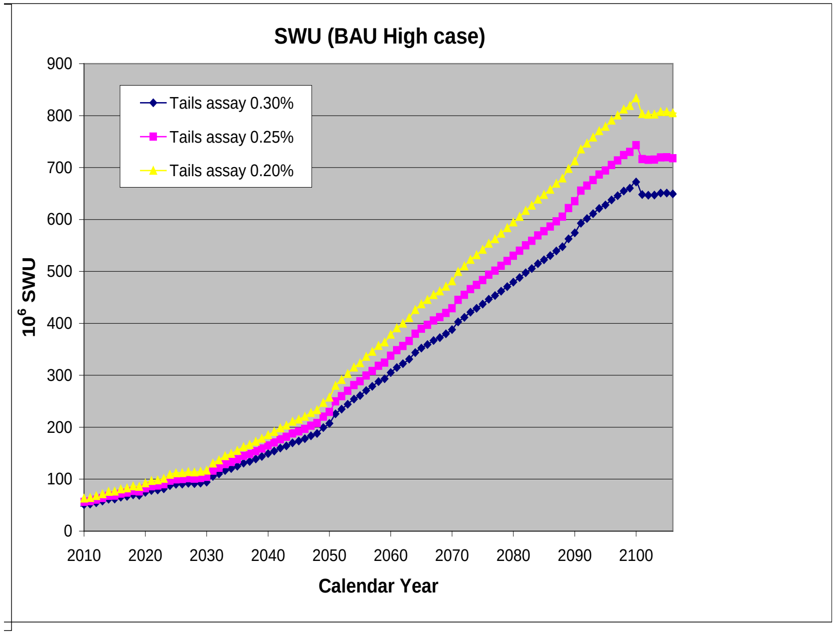
Outline

- Fuel Cycle Simulator Overview
- GAINS Framework Components
- Framework Base Cases
- Sensitivity Analyses

Tails Assay Sensitivity Study – BAU case

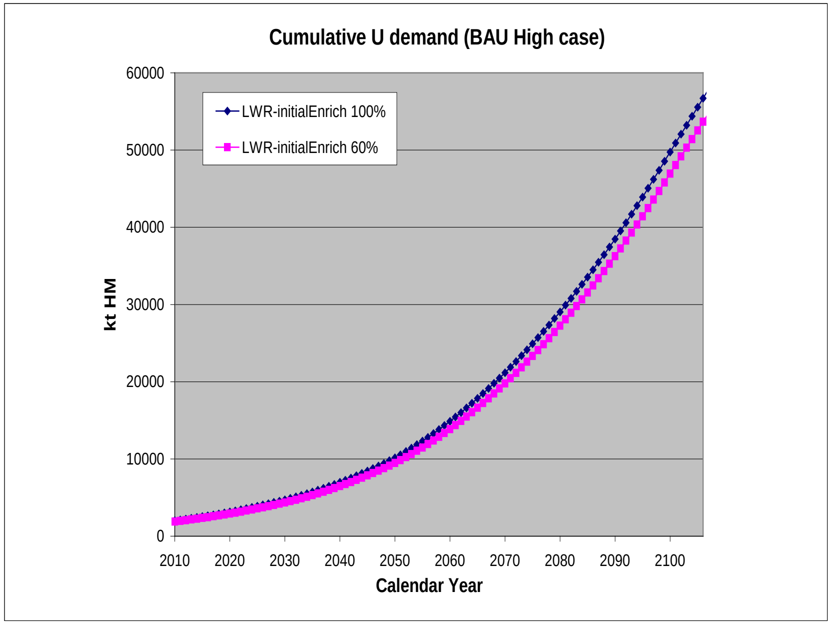
- Sensitivity analysis of impact of ranging tails assay from 0.3% to 0.2%
- Higher assay results in higher uranium demand but lower SWU demand

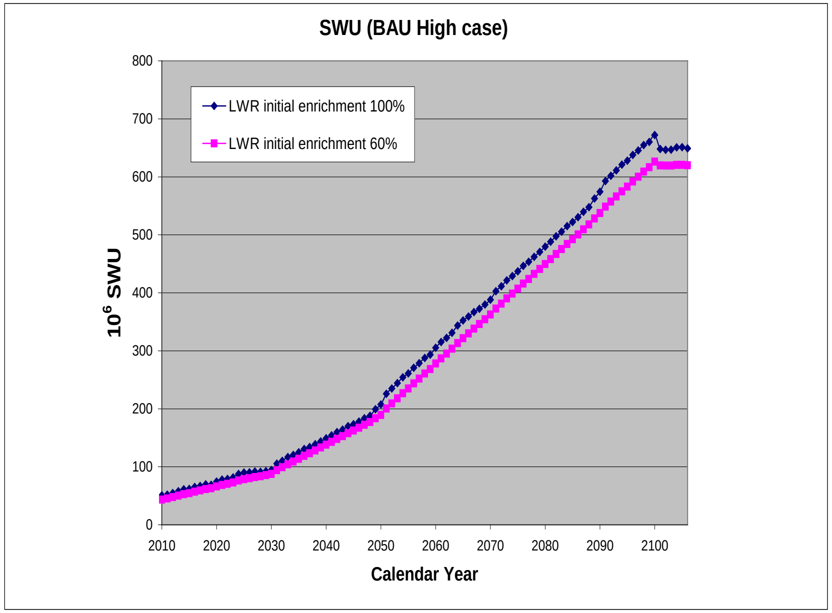




Modeling Initial Core Sensitivity Study – BAU case

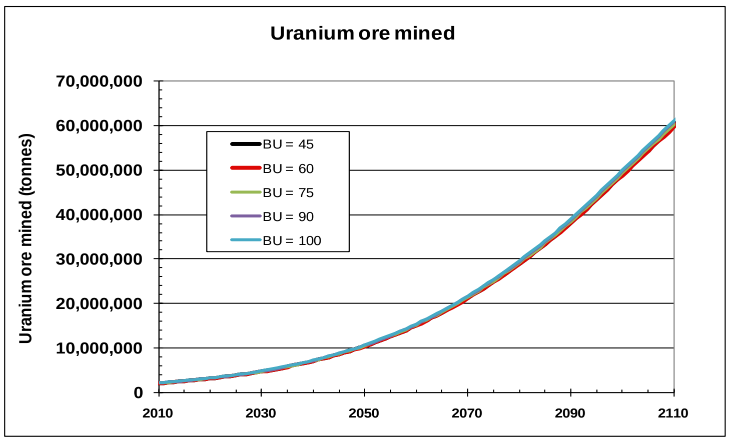
- Shows the impact of modeling the initial full core at a lower enrichment
  - Portions of the initial core are discharged at lower burnup to start fuel cycling
- Impact becomes smaller with longer reactor life

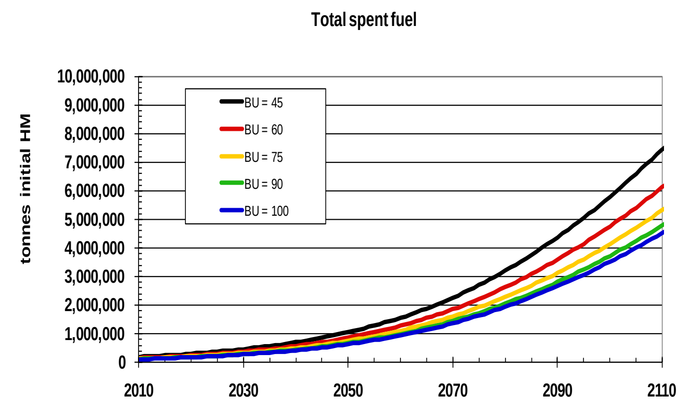


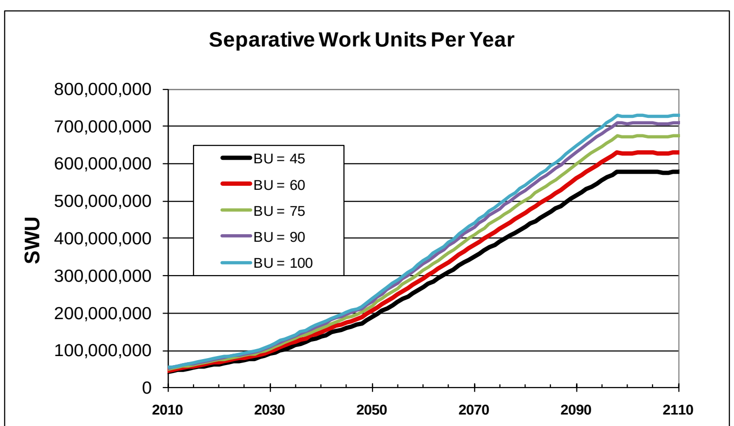


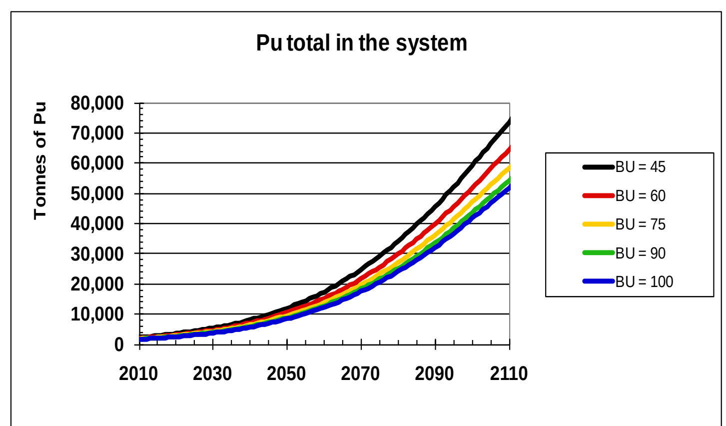
LWR Burnup Sensitivity Study – BAU Case

- Higher burnup increases enrichment needs, but decreases spent fuel and Pu in system. Little impact on U needs



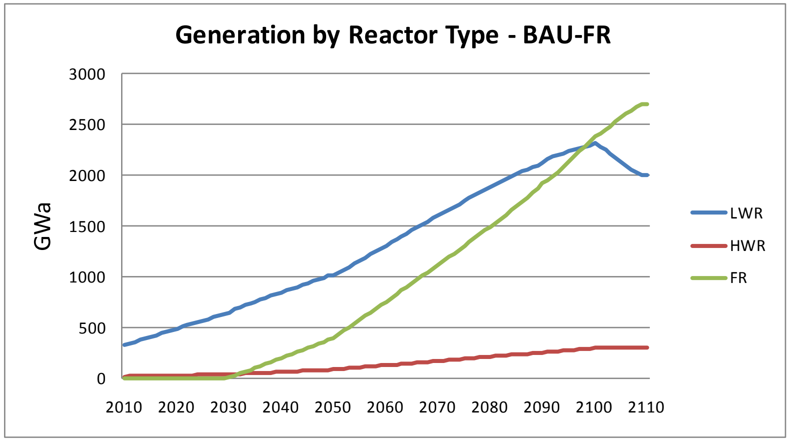


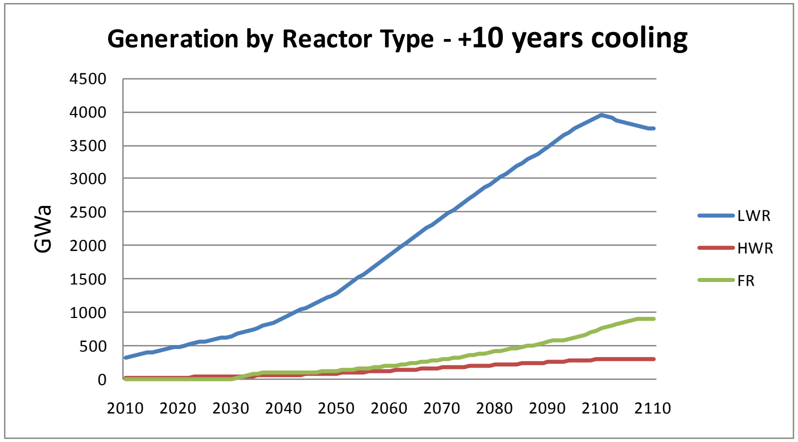


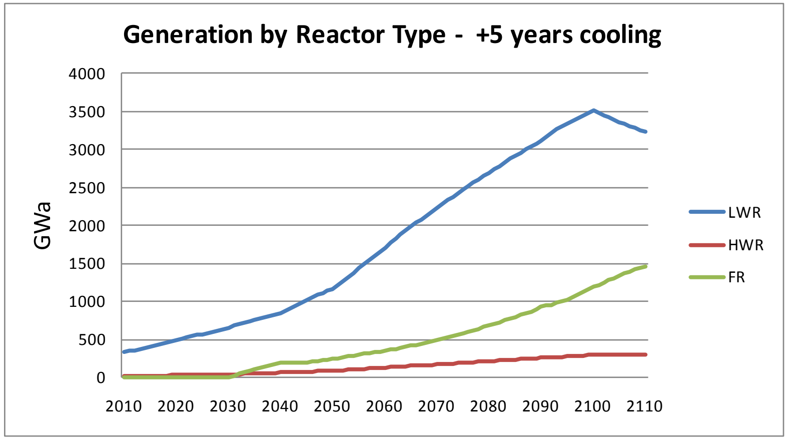


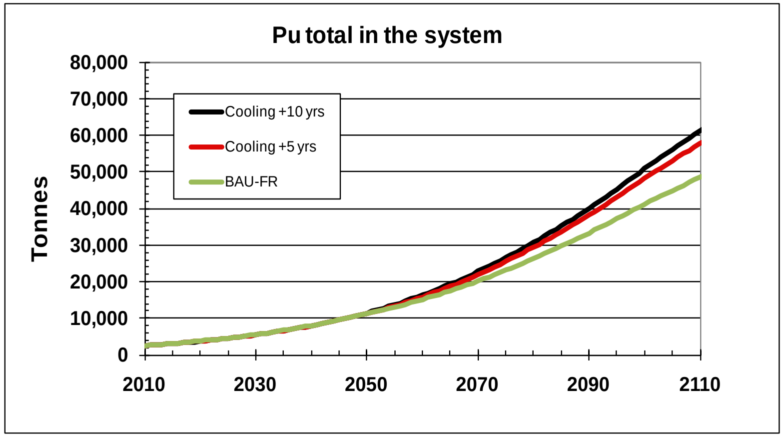
Cooling Time Sensitivity Study – BAU-FR Case

- Longer cooling time before reprocessing fuel results in significantly fewer fast reactors and more Pu in the system.



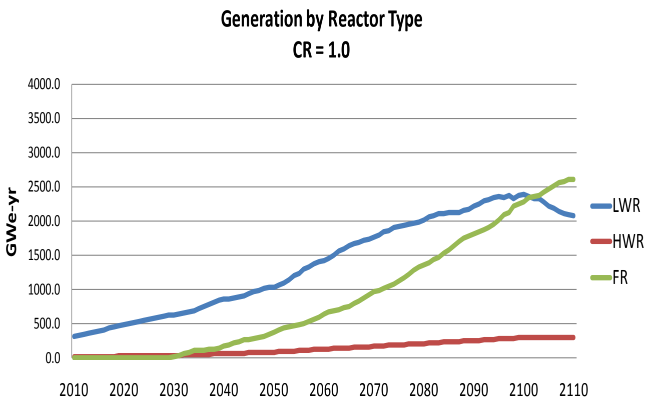


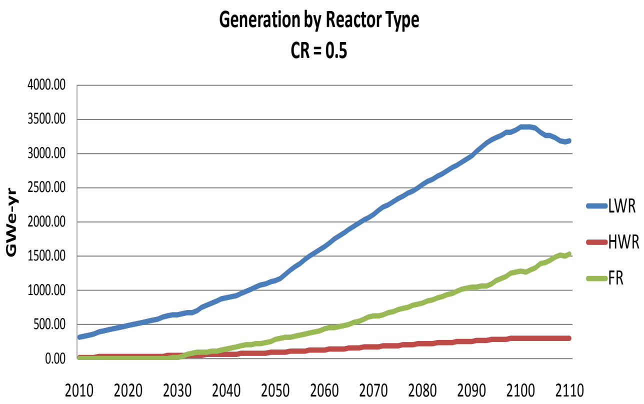


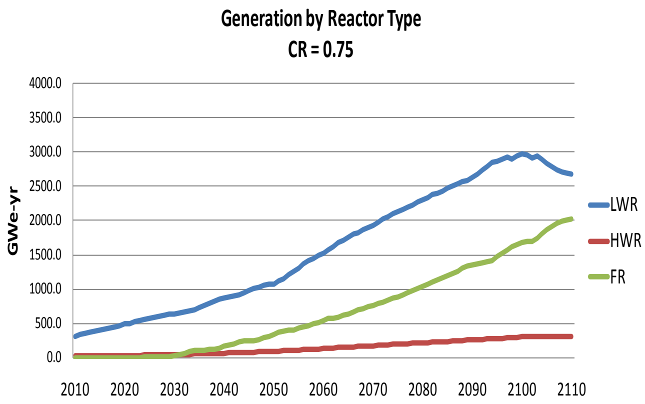


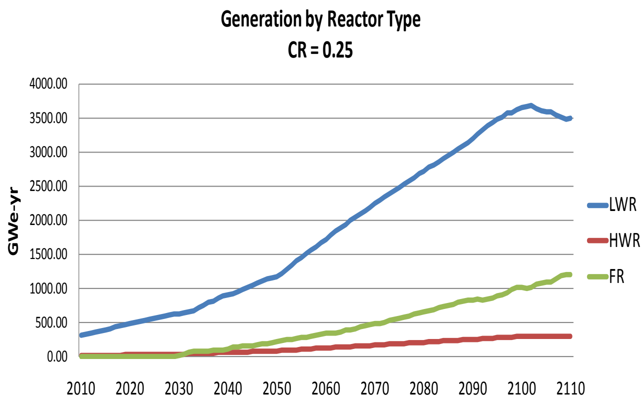
Burner FR Sensitivity Study

- If fast reactors burn more transuranics that they make, it decreases the number of fast reactors



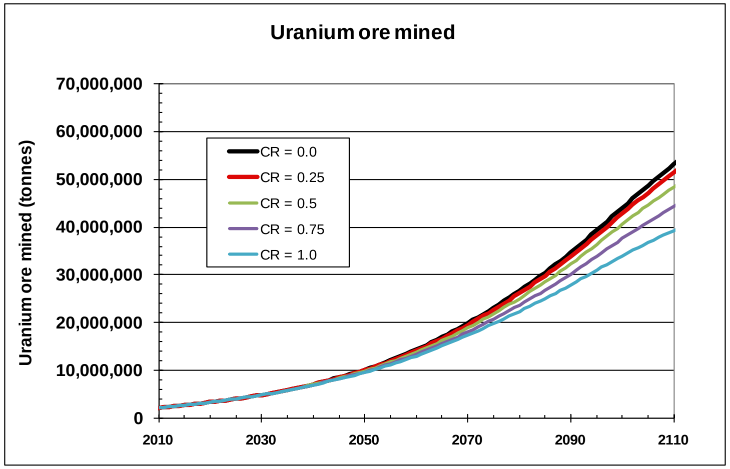


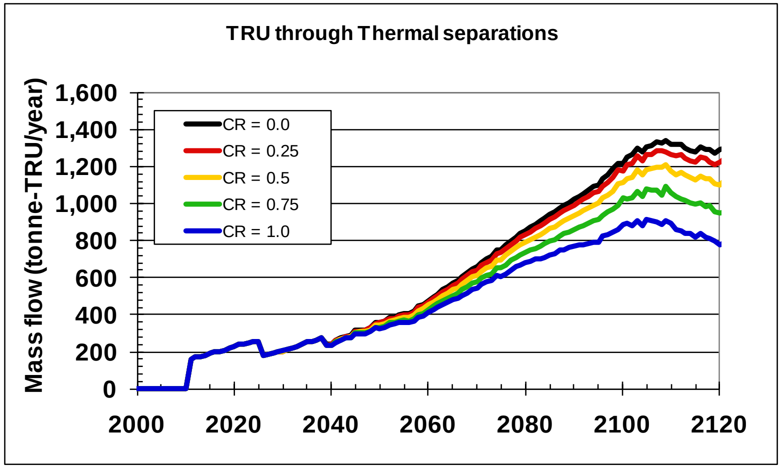


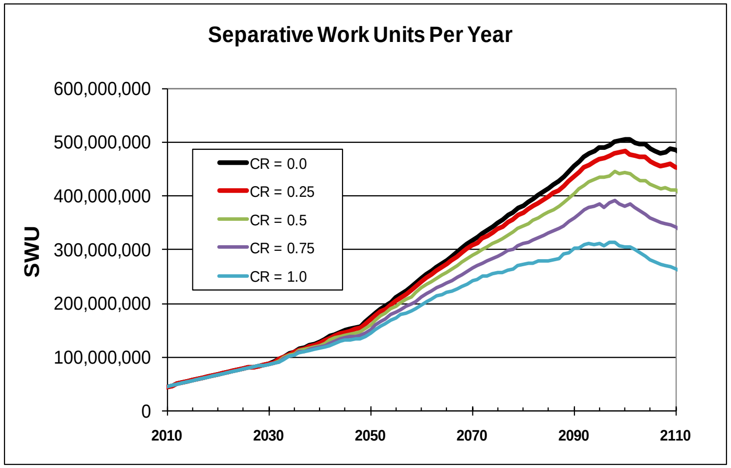


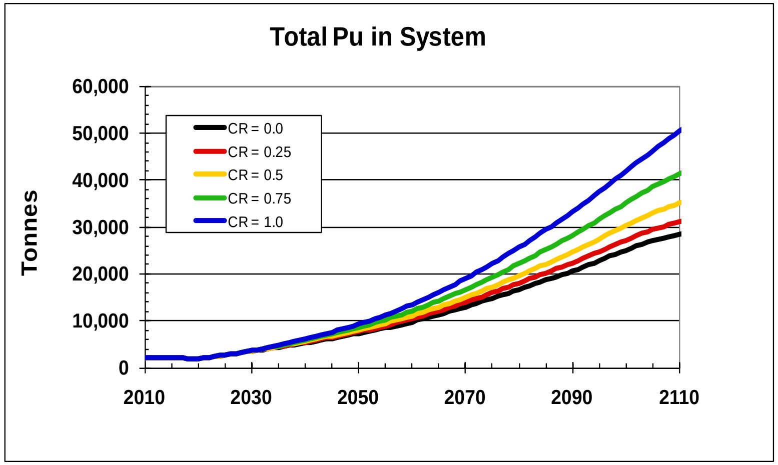
Burner FR Sensitivity Study (Continued)

- Lower net TRU also increases U needs, enrichment needs, and reprocessing needs, but decreases the amount of Pu in the system

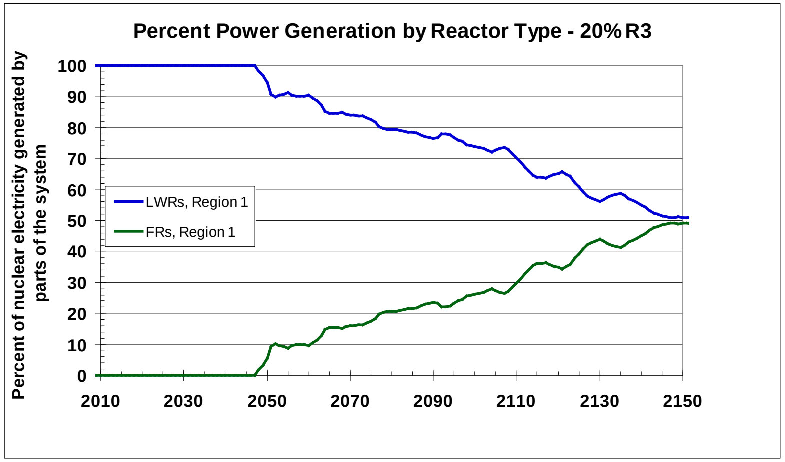


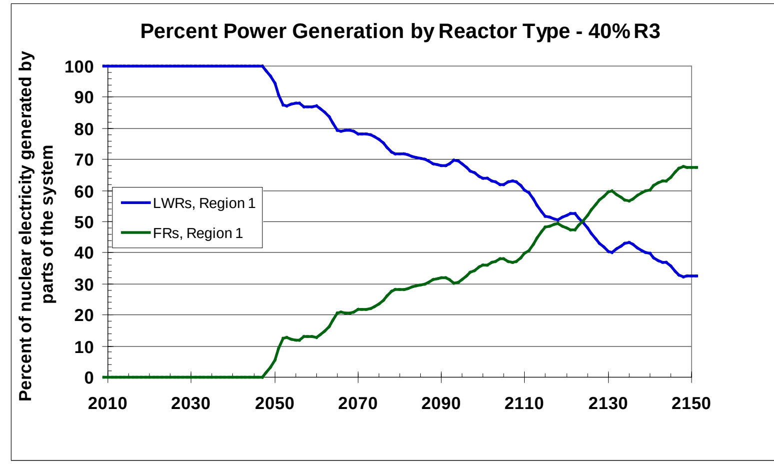






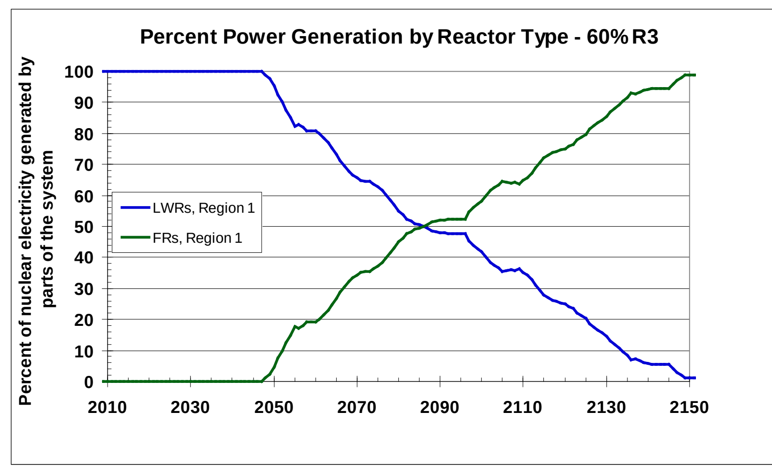
NG3 market share sensitivity study





(Based on older assumptions)

- As market share of NG3 increases:
  - More fast reactors built in NG1
  - Eventually, NG1 is 100% FR
  - At that point, new strategy will be needed



Conclusions

- The GAINS Framework is a collection of data, utilities, and base cases for use with fuel cycle simulators to perform scenario analyses
- Key Features
  - Assessment of interactions between 2-3 different entities/groups
    - Could be countries, consortiums, companies, etc.
    - Analysis of nuclear infrastructure
  - Focus on dynamics
    - Infrastructure evolution, including investments
    - Transportation, material inventories, other operational parameters
  - Full suite of performance indicators
- Together with a simulator, the Framework can be used to analyze and compare different strategies and schedules for deploying reactors and supporting fuel cycle facilities
  - As a standalone system contained within a single country
  - As a collaborative system shared with other countries