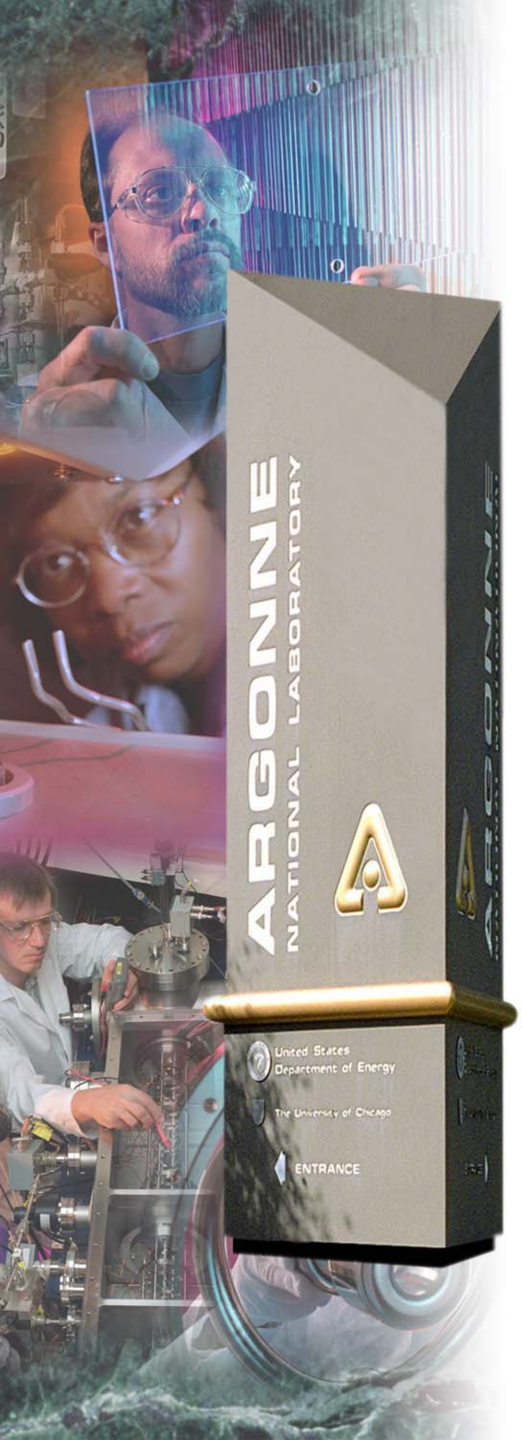


Modeling and Analysis of Nuclear Energy System Strategies in the US

The 25th USAEE/IAEE North American
September 21, 2005

A. Yacout and R. Hill

Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Objectives

- **Develop a policy informing-tool for the technical-economic assessment of nuclear energy systems in a macro-economic energy development context.**
- **Systems-Study Results are the appropriate language to communicate with Policy Makers – Who set R&D Funding Priorities**
  - They want to know outcomes given policy choices
  - They aren't interested in technical/engineering details
- **System studies as an integral element of our technology programs to exert INFLUENCE on DOE priority selections**

Objectives

- **Several goals motivate this analysis effort**
    - Frame quantitative goals for AFCI
    - Highlight urgency of the waste management issues
    - Compare diverse fuel cycle scenarios
- **Fuel cycle impact evaluated for limited set of scenarios**
    - Once-through and separations only
    - Single MOX recycle
    - Single and double tier transmutations systems
- **Dynamic analysis of fuel cycle performance**
    - Consider stable and growth scenarios
    - Estimate of infrastructure requirements
    - Impact of reprocessing on spent fuel characteristics
    - Tracking of material inventories throughout entire fuel cycle

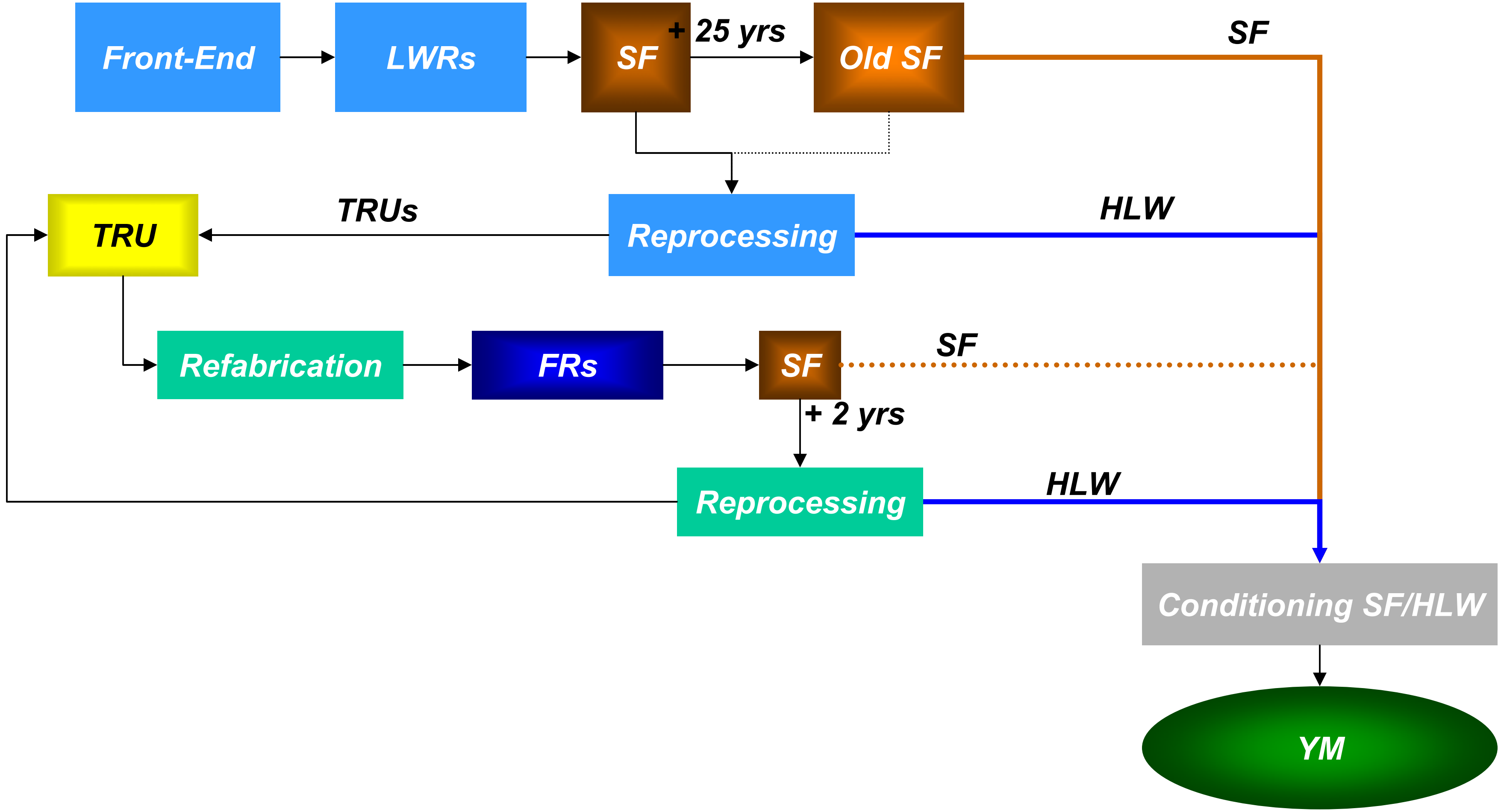
Approach

- **100-year nuclear futures dynamic simulations work was performed in prior years using a code, DYMOND, developed for that purpose (Gen-IV Initiative)**
  - ITHINK system dynamics modeling environment
  - Energy demand driven
  - Mass flow based
  - Dynamics of fuel cycle and reactor construction lag-times accounted for
- **An improved code, DANESS, has been produced**
  - Dynamic Analysis of Nuclear Energy System Strategies
  - Economic models; cost modeling development and evaluation
  - Cross flows of materials among reactor types
  - Validated data base of reactor attributes and fuel cycle processing attributes for ease of scenario construction

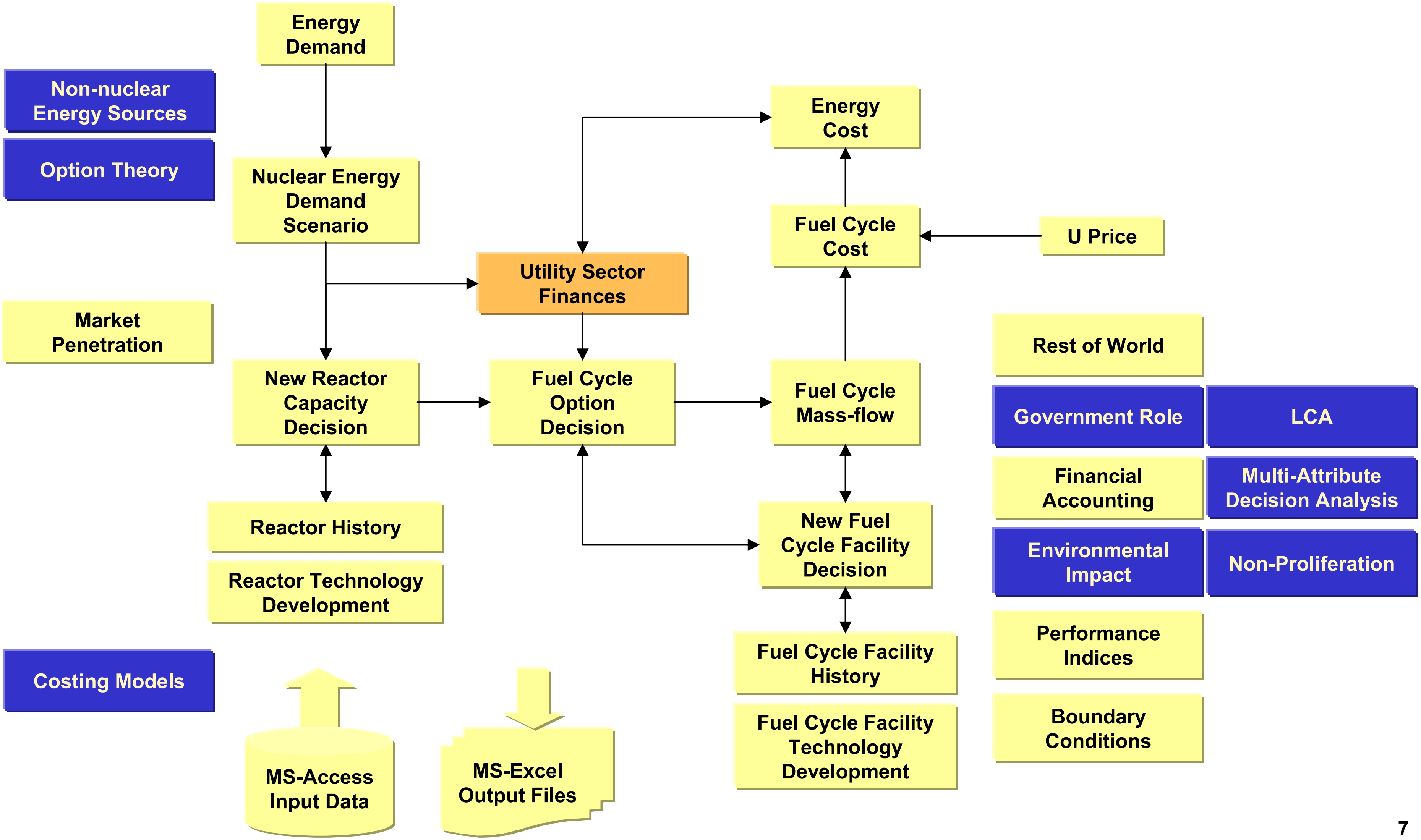
System Dynamics use in nuclear energy systems evaluation

- **DYMOND/DANESS**
  - Integrated Process Models simulating nuclear energy systems from U_{nat}-mining until final disposal taking into account:
    - *Timing of operations, i.e. including history of ordering, licensing, constructing, operating, decommissioning, … of facilities*
    - *Tracking primary mass flows but also secondary (waste) mass flows and, under development, LCA-related flows/emissions*
  - Scenario analysis tools as support to:
    - *Nuclear energy policy decision-making*
    - *R&D, e.g. impact of reactor/facility technology options*
    - *Nuclear energy economics*
    - *Educational use*
  - Quick and user-friendly, e.g.
    - *100 years 1 month time-step world simulation: < 4 min on PC*

Schematics of model

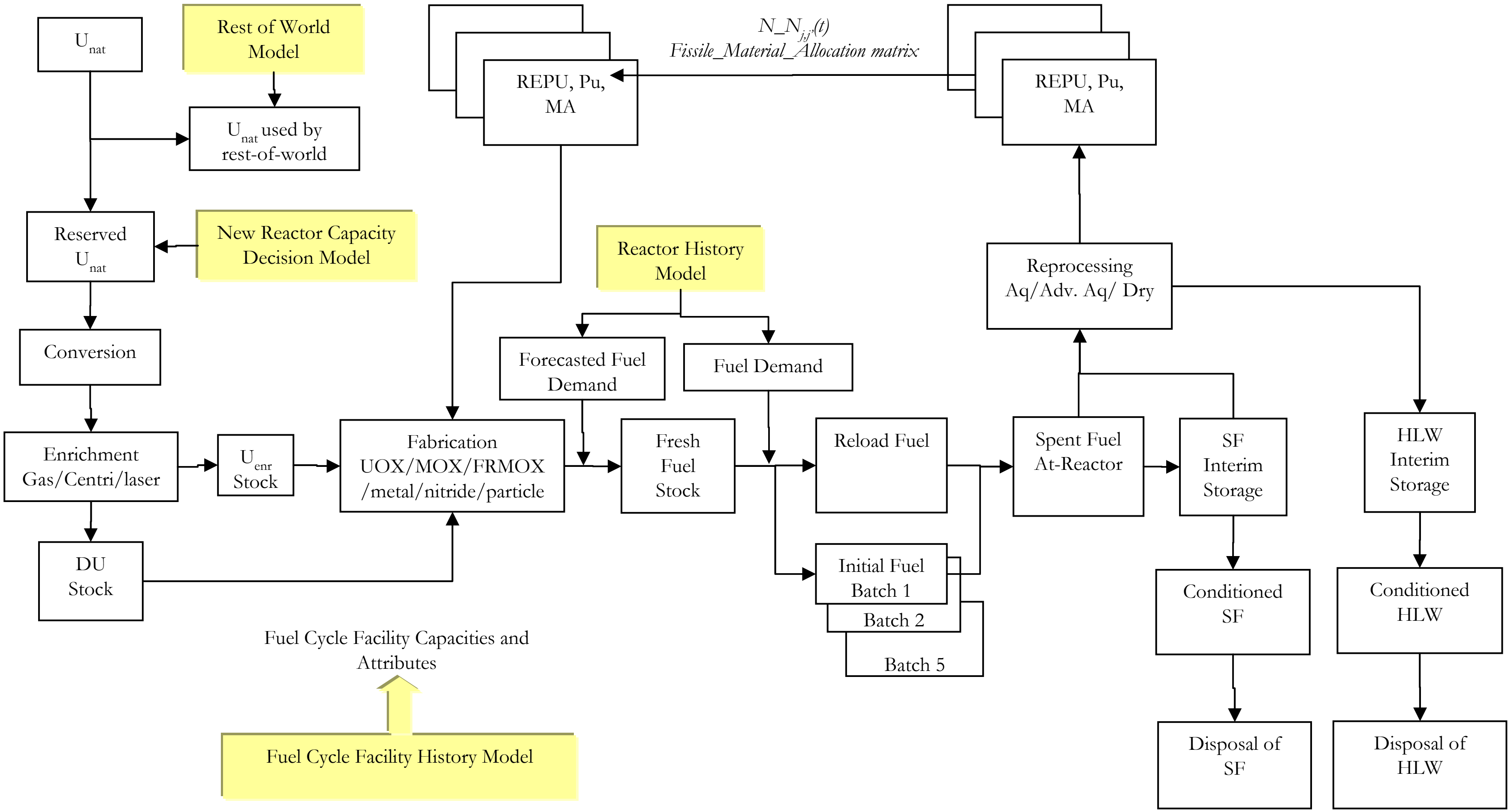


DANESS© v2.0



Energy Demand
Non-nuclear Energy Sources
Option Theory
Nuclear Energy Demand Scenario
Energy Cost
Fuel Cycle Cost
U Price
Utility Sector Finances
Market Penetration
Rest of World
New Reactor Capacity Decision
Fuel Cycle Option Decision
Fuel Cycle Mass-flow
Government Role
LCA
Financial Accounting
Multi-Attribute Decision Analysis
Reactor History
New Fuel Cycle Facility Decision
Environmental Impact
Non-Proliferation
Reactor Technology Development
Performance Indices
Fuel Cycle Facility History
Costing Models
Boundary Conditions
Fuel Cycle Facility Technology Development
MS-Access Input Data
MS-Excel Output Files

DANESS Overview Fuel Cycle Model



U_{nat}

Rest of World Model

U_{nat} used by rest-of-world

Reserved U_{nat}

New Reactor Capacity Decision Model

Conversion

Enrichment Gas/Centri/laser

U_{enr} Stock

DU Stock

REPU, Pu, MA

$N\_N_{j,j'}(t)$
Fissile_Material_Allocation matrix

REPU, Pu, MA

Fabrication UOX/MOX/FRMOX /metal/nitride/particle

Reactor History Model

Forecasted Fuel Demand

Fuel Demand

Fresh Fuel Stock

Reload Fuel

Initial Fuel Batch 1

Batch 2

Batch 5

Reprocessing Aq/Adv. Aq/ Dry

Spent Fuel At-Reactor

SF Interim Storage

HLW Interim Storage

Conditioned SF

Conditioned HLW

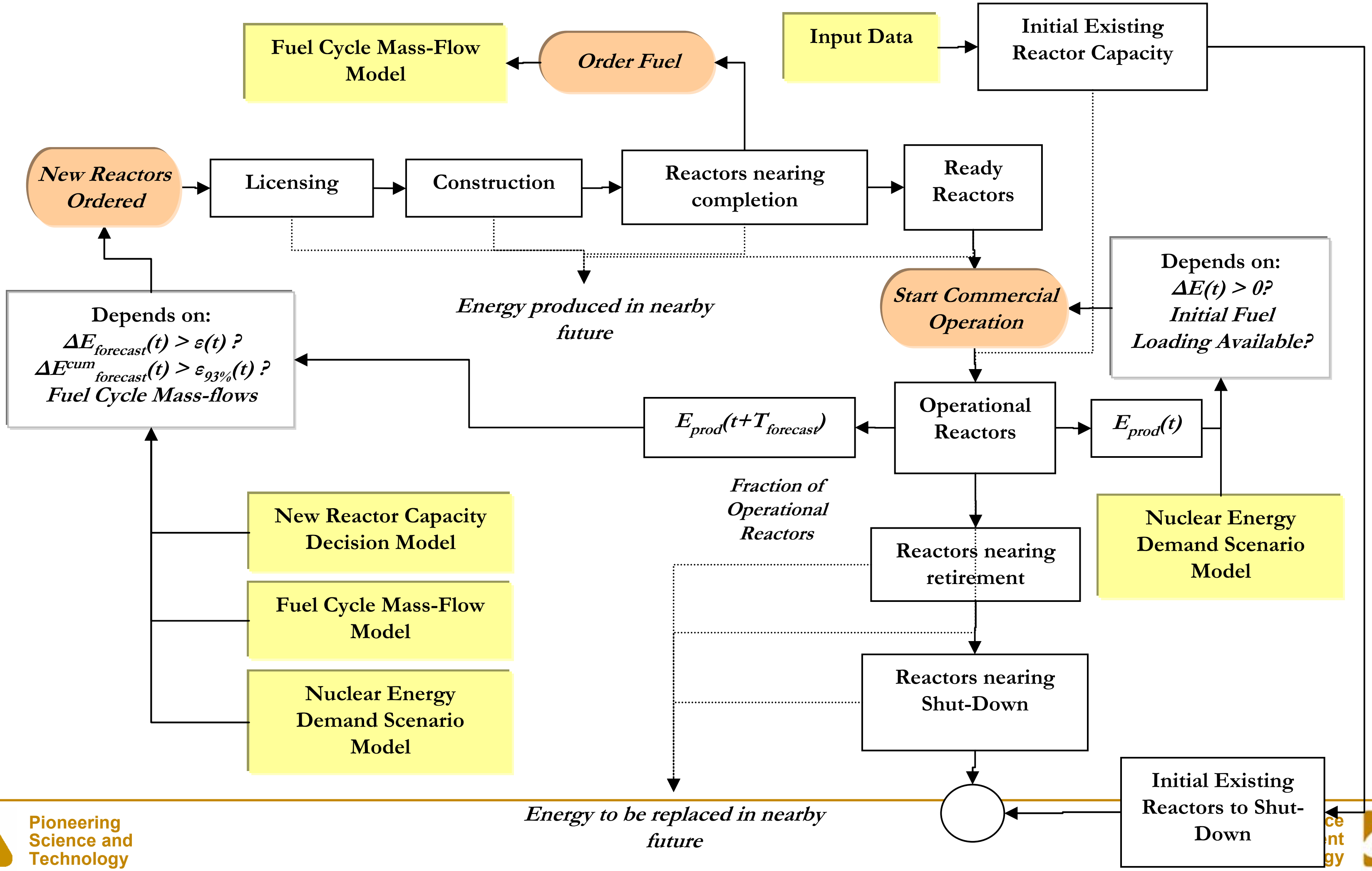
Disposal of SF

Disposal of HLW

Fuel Cycle Facility Capacities and Attributes

Fuel Cycle Facility History Model

DANESS: Reactors Follow a Life-path



Fuel Cycle Mass-Flow Model

Order Fuel

Input Data

Initial Existing Reactor Capacity

New Reactors Ordered

Licensing

Construction

Reactors nearing completion

Ready Reactors

Energy produced in nearby future

Start Commercial Operation

Depends on:
$\Delta E(t) > 0$?
Initial Fuel Loading Available?

Depends on:
$\Delta E_{forecast}(t) > \varepsilon(t)$?
$\Delta E^{cum}{}_{forecast}(t) > \varepsilon_{93\%}(t)$?
Fuel Cycle Mass-flows

$E_{prod}(t+T_{forecast})$

Operational Reactors

$E_{prod}(t)$

Fraction of Operational Reactors

New Reactor Capacity Decision Model

Fuel Cycle Mass-Flow Model

Nuclear Energy Demand Scenario Model

Reactors nearing retirement

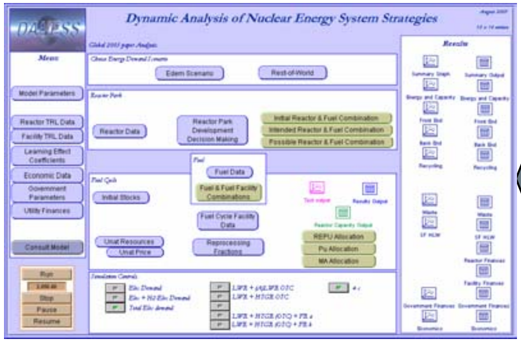
Nuclear Energy Demand Scenario Model

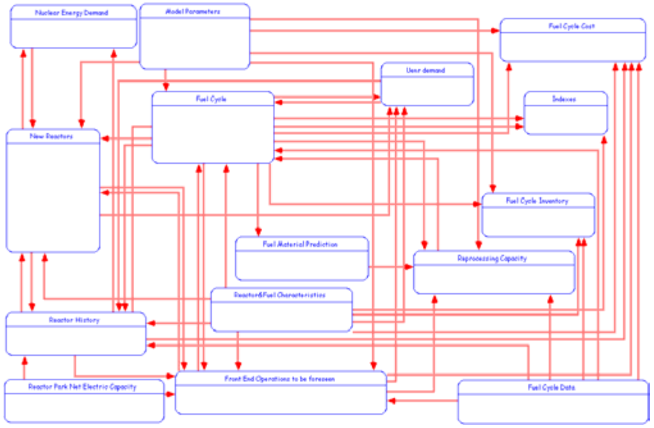
Reactors nearing Shut-Down

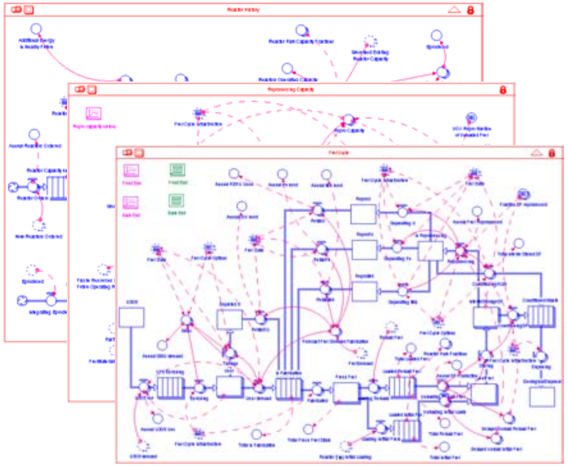
Initial Existing Reactors to Shut-Down

Energy to be replaced in nearby future

Ithink software



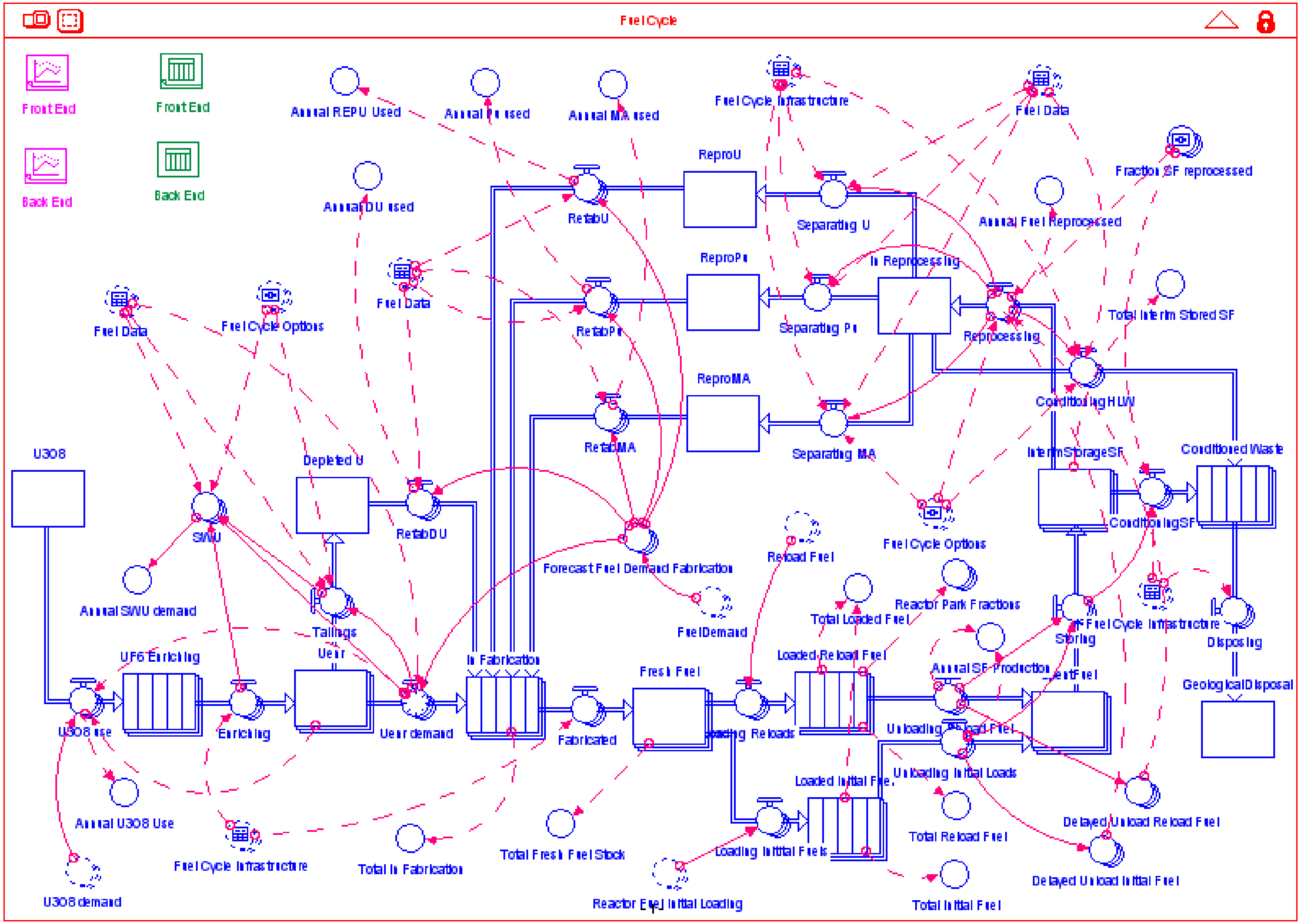




```
Reac_Licensing_Costs[Reactors](t) = Reac_Licensing_Costs[Reactors](t - dt) + (Reac_Start_Licensing_Costs[Reactors] - Reac_Licensing_Costs_Paid[Reactors]) * dt
INIT Reac_Licensing_Costs[Reactors] = 0
Reac_Start_Licensing_Costs[Reactors] = IF Economic_Parameters_Reactors[Reactors,LicTime]+Economic_Parameters_Reactors[Reactors,ConstrTime]=0 THEN 0 ELSE
IF Reactors data[Reactors,Pth]=0.99 THEN 0 ELSE
New_Reactor_Ordered[Reactors]/Reactorsdata[Reactors,Pe]*PMT(WACC/100,Economic_Parameters_Reactors[Reactors,EcLifetime],-
Reactor_Capital_Cost_Profile[Reactors,ReacCap_1]/100*(Economic_Parameters_Reactors[Reactors,Capital])*(1+ModelParameters[DiscountRate]/100)^(TIME-
ModelParameters[ReferenceTime])*0.5*(1+(1+ModelParameters[DiscountRate]/100)^Economic_Parameters_Reactors[Reactors,LicTime]),0)
```

Fortran

Model Topology



General Assumptions

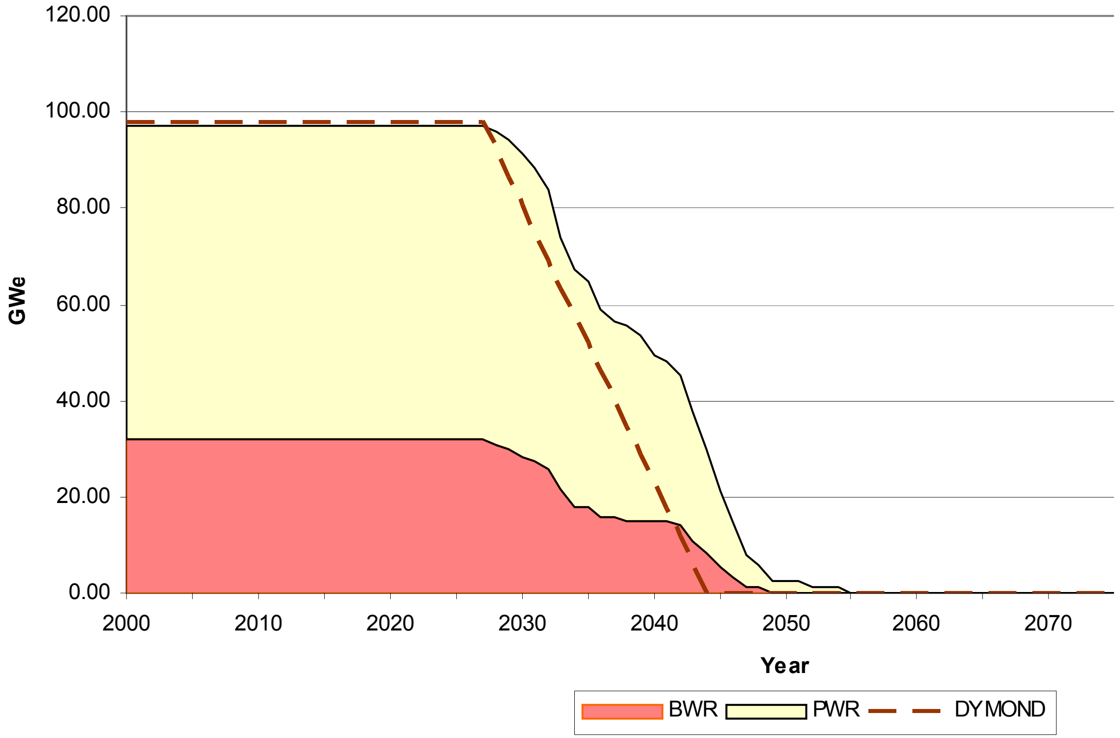
- **Front End**
  - Mining from unlimited source of natural uranium
  - Enrichment time is 1 year
  - Tail enrichment is 0.2%
  - Fabrication time is 1 year
- **Reactors**
  - Reactor licensing time = 2 years, Construction time = 5 years
  - Existing reactors and new reactors life time is 60 years.
- **Reprocessing and Fabrication Plants**
  - Lifetime is more than 65 years, i.e., built >= year 2025, and continue to operate to end of the century.
  - SF Reprocessing time = 1year, Fabrication time = 1 year
  - SF Cooling time = 5 years for LWR SF and 3 years for FR SF
  - Reprocessing Losses = 0.2% (0.1% Fabrication, 0.1% Separation) for all actinides and for all reprocessing technologies considered, i.e. PUREX, UREX and dry reprocessing
  - Dry reprocessing capacity for FR fuel will be made available according to the need for fabricating FR fuel (small fraction compared to needed LWR SF reprocessing capacity).

General Assumptions (Continue)

- **Legacy SF**
  - Legacy SF in year 2000:
    - *~ 14,700 MT UOX-33 (33GWd/t)*
    - *~ 29,700 MT UOX-51(50GWd/t)*
- **Repository**
  - Legacy SF generated up to year 2000 goes first to repository followed by SF cooled for at least 10 years
  - Reprocessing has higher priority than repository, so only >= 10 years old SF available after using the full reprocessing capacity is available for transfer to repository
  - Ramp up acceptance rate of SF to repository
    - *At 2012=400MT, 2013=600MT, 2014=1200MT, 2015=2000MT, 2016 and beyond 3000MT*
- **High Burnup Fuel**
  - 100 GWd/t High burnup fuel reduces the SF production rate by 50% as soon as it replaces lower 50 GWd/t fuel
  - However, **per MTHM** the integrated decay heat is **~1.6x** integrated decay heat from 1 MTHM of 50GWd/t burnup SF

General Assumptions (Continue)

- **Existing reactor park**
  - Assume life extension to 60 years
  - Total capacity in 2000 ~ 97.2 GWe (103 reactors , 0.95 GWe each, and has a capacity factor of 0.9, and 0.34 thermal efficiency)



Input Data

- Reactor Data
  - *MWth, MWe, BU%, Capacity factor, Lifetime, # batches*
  - *LWR, ALWR, FR*

- Fuel Data
  - *Fresh fuel composition*
  - *SF composition*
    - Pu, U, FP, MA, U enrichment
    - Decay heat for repository calculations:
      - Pu238, Pu239, Pu240, Pu241, Am241, Cs137, Sr90

Input Data (continue)

- **FR Data**
  - BOEC startup core consists of 4573 kg HM and 2515 kg TRU
  - BOEC recycle core consists of 4566 kg HM and 3110 kg TRU
  - For the startup core, the feed rate is 813 kg-TRU/year from conventional LWR SNF.
  - For the equilibrium recycle, the recycled TRU from fast reactors = 767 kg/year and the makeup TRU from conventional LWR SNF = 223 kg/year
  - The fast reactor power is **840 MWth** (thermal efficiency = 38%)
  - Fuel residence time in FR is about 3.5 years.
  - Burnup = 176 GWd/t

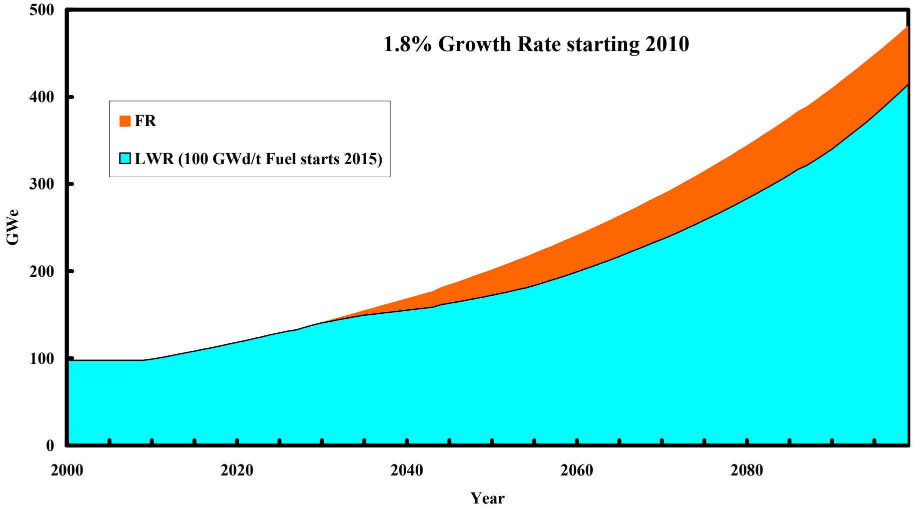
Scenario 1

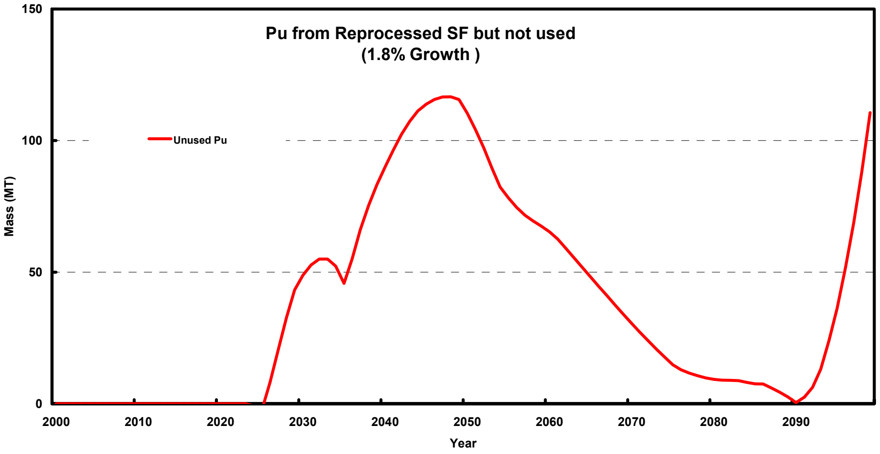
- **Timeline**
  - Starting 2010
    - *Demand growth (1.8%)*
  - Starting 2015
    - *Use high burnup, 100 GWd/t fuel in all reactors*
  - Starting 2025
    - *SF reprocessing*
      - First commercial plant (800 MT/yr) starts in 2025 followed by an upgrade to 2,000 MT/yr in 2035 and 3,000 MT/yr total capacities in 2055.
    - *FR deployment*
      - FOAK FR , followed by full deployment of FRs 5 years later, at a maximum rate of 1.6 GWe/yr (5 FR burners/yr)
  - Starting 2028
    - *Replace retiring LWRs with FRs to meet new energy demand if possible*
    - *If there is not enough TRU for FRs, build new ALWRs*

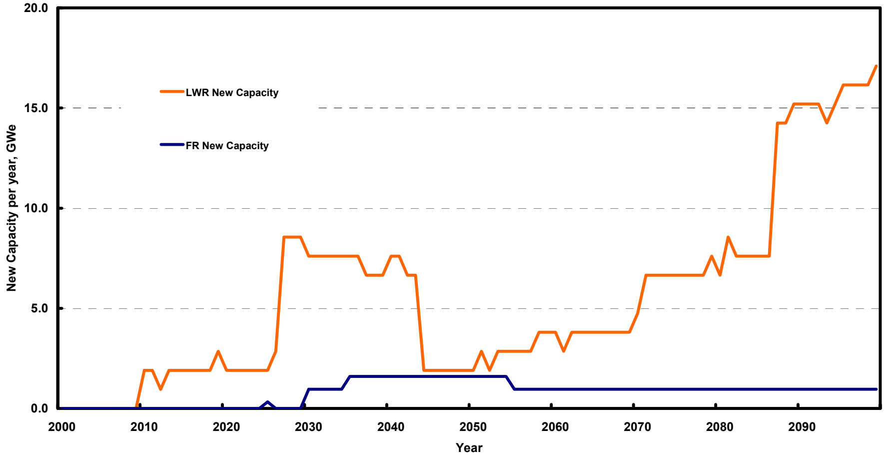
Scenario Assumptions

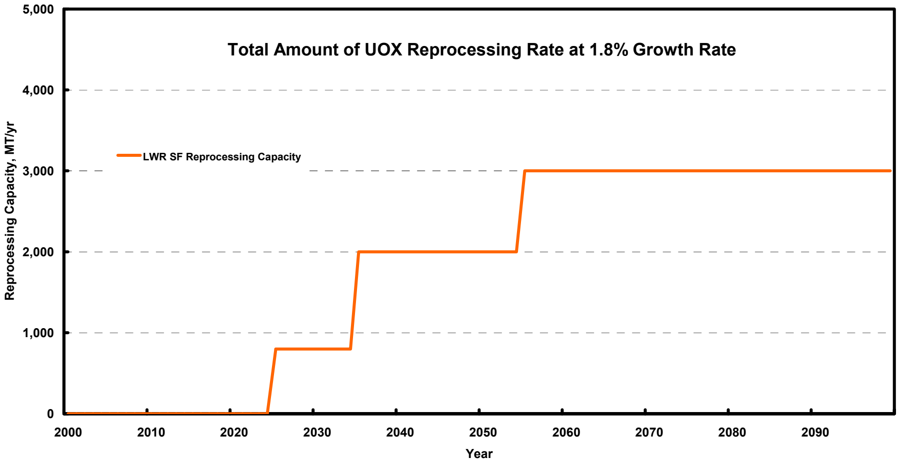
- **Assumptions**
  - Nuclear energy growth to maintain 20% market share (1.8% growth rate)
  - Military SNF to repository rate is 500 MT/y starting 2012 (total 7000 MT – also includes, as a surrogate, DOE SNF and HLW going to repository)
  - LWR SNF is initial 43,200 MT existing in year 2000, and it is sent first to repository
  - Fission Products are directly sent to repository following reprocessing
  - Deployment of FRs is limited to a maximum of about 1.6 GWe/y (correspond to 5 FR burners of about 3.2 GWe each), beyond 2030

Scenario 1 (Results)

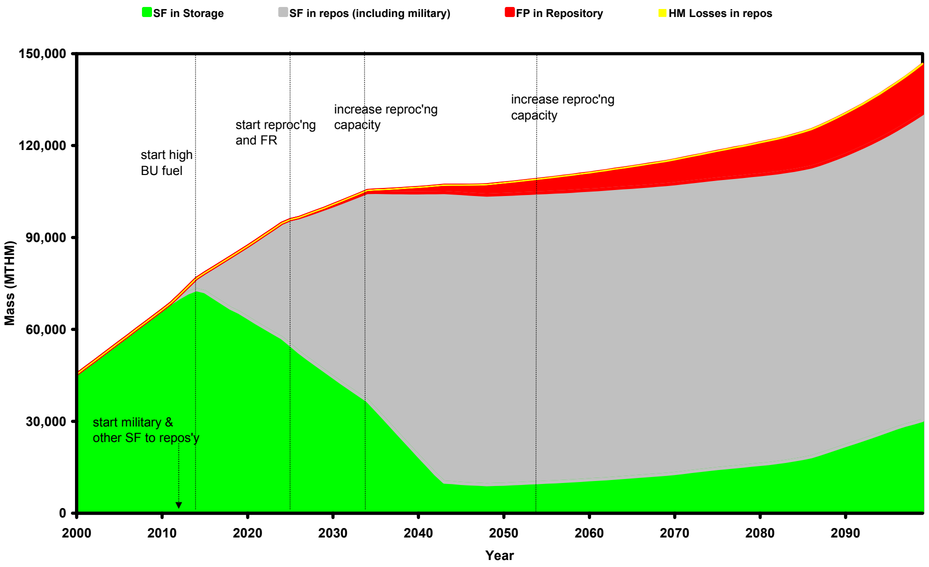


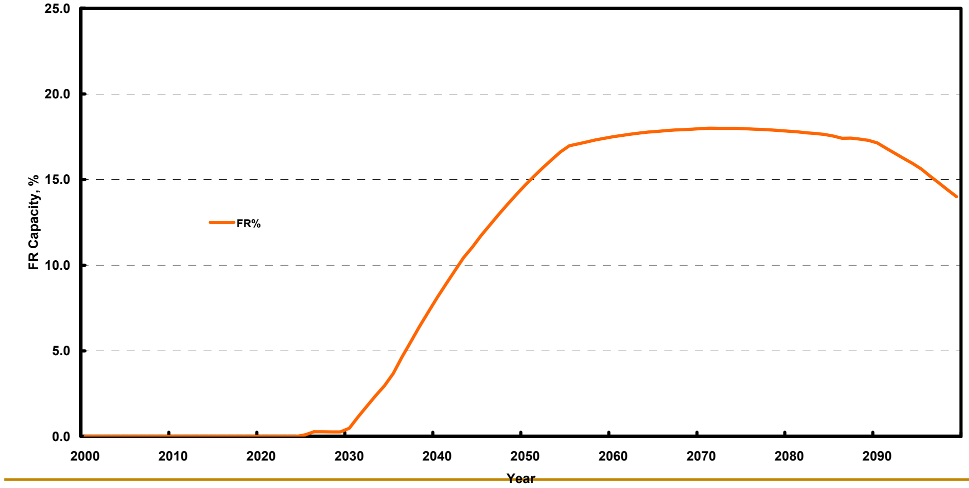




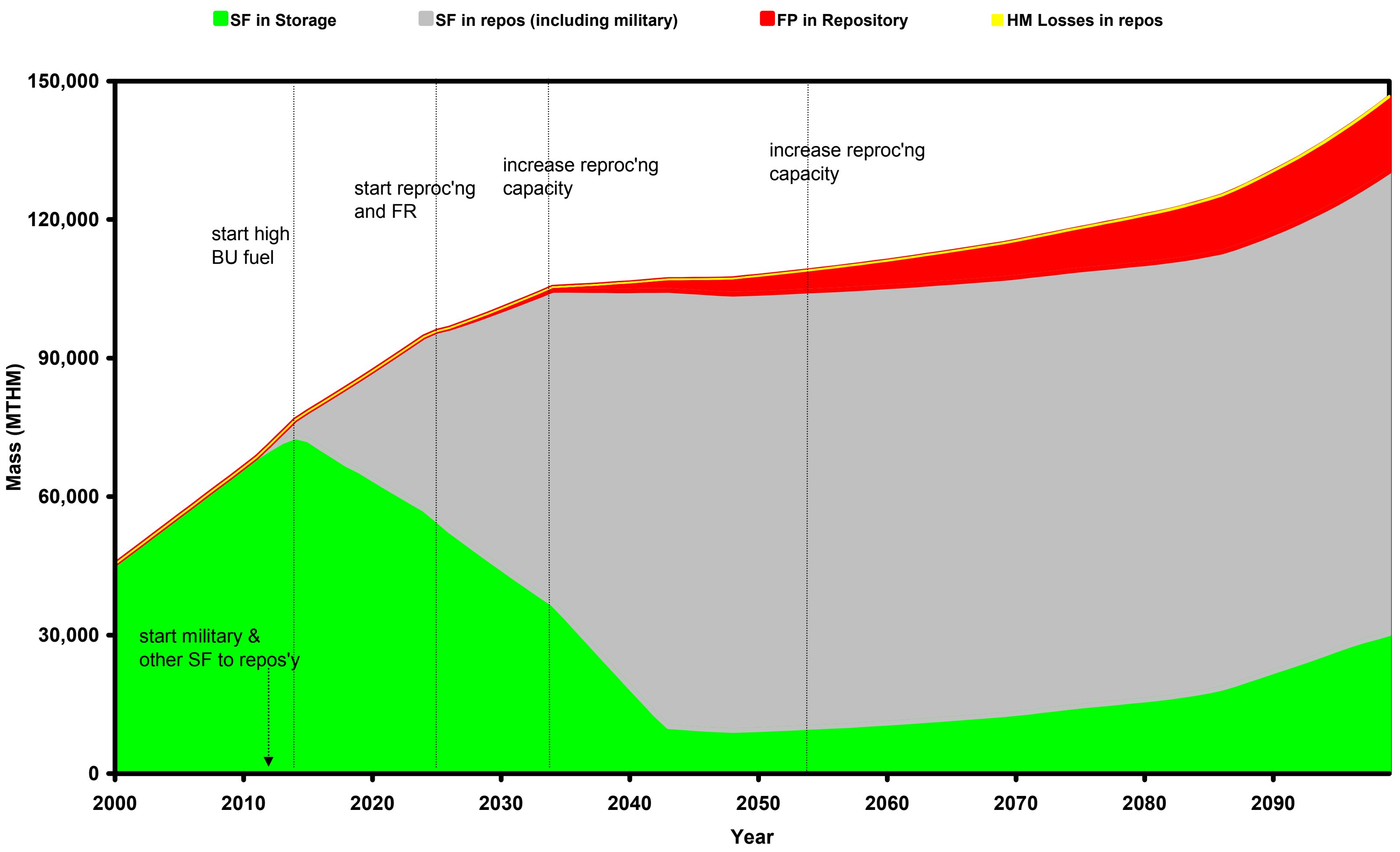


Scenario 1



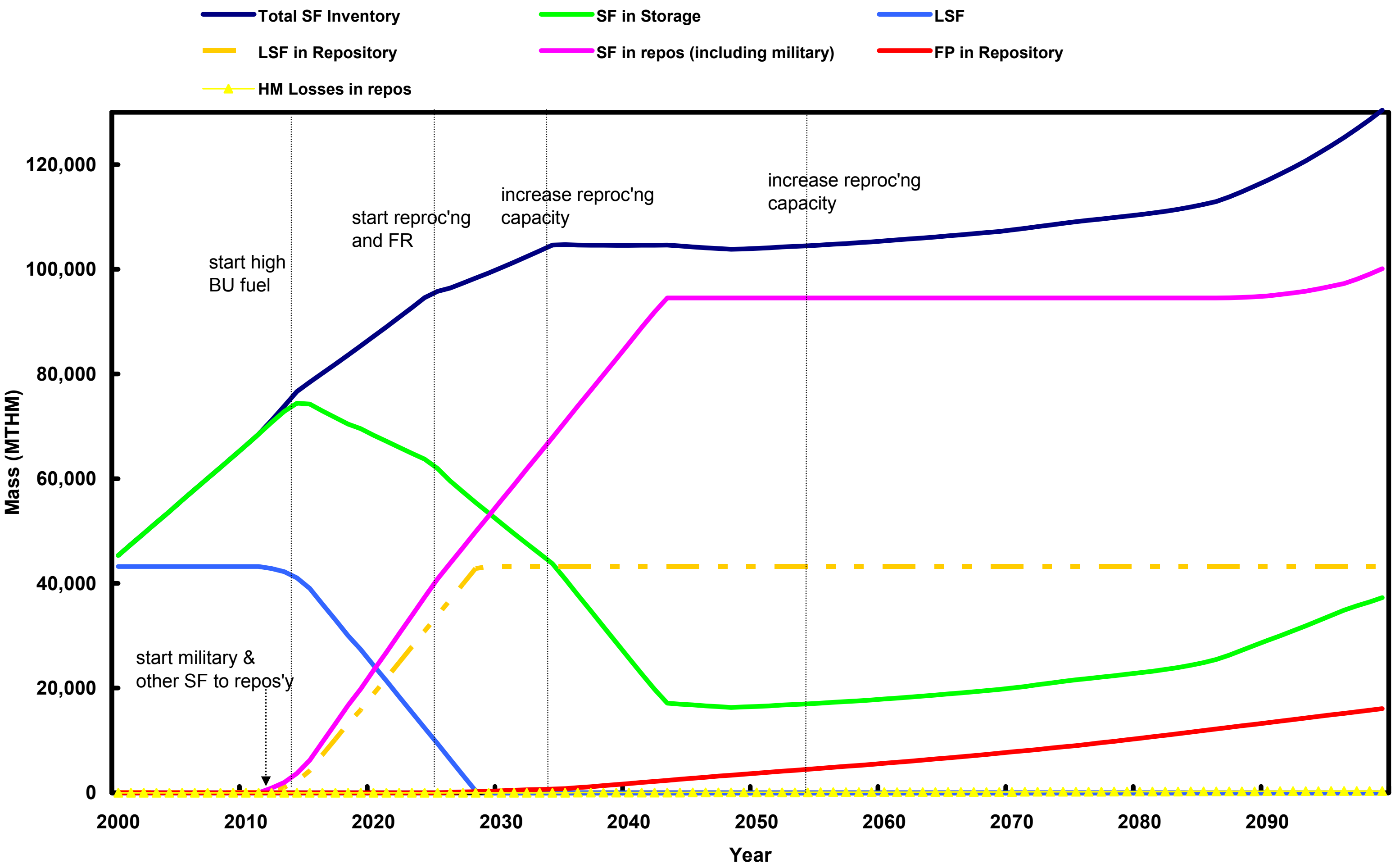


- SNF temporary storage requirements are minimized
  - *With reprocessing, storage requirement decline*
    - By about 2030, storage requirements are < storage requirements in 2000
    - Eventually storage requirements starts to increase after a 2043 minimum
- Direct disposal of large amounts of SNF in repository
  - *By 2028 all 2000 legacy SF is transferred to repository*
  - *By 2043, all SF production goes to reprocessing*
    - No more transfer to repository until ~ 2088 when SF available exceeds the reprocessing needs
    - SF in repository reach ~ 94,000 MT by 2043 (including military & DOE 7000 MT)
- FR% of total capacity increases gradually to reach about 18%, and large decline starts 2090 because of the retirement of FRs built in 2030, while TRU inventory is not large enough to make up for those reactors and also response to increase in demand
  - *This can be avoided by increasing the reprocessing capacity a few years earlier*
- Inventory of Pu (from reprocessed SF) at any point in time is < 150 tons



SF in Storage
SF in repos (including military)
FP in Repository
HM Losses in repos
150,000
120,000
90,000
60,000
30,000
0
Mass (MTHM)
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year
start high BU fuel
start reproc'ng and FR
increase reproc'ng capacity
increase reproc'ng capacity
start military & other SF to repos'y

Example Scenario Results



Possible Conclusions

- **Original goal to reduce the inventory of spent fuel *and* key waste species is difficult to achieve**
  - Mass of spent fuel is reduced by reprocessing
  - Inventory of plutonium and/or minor actinides can only be reduced by large infrastructure of transmuter (either advanced thermal or fast) systems
    - *Both reprocessing capacity and transmuter inventory requirements constrain the introduction rate*
  - Recommendation is to re-define goal to stabilization of the plutonium and/or minor actinide inventory
- **In contrast, significant reduction in key repository performance parameters can be achieved**
  - Large inventory is retained in the transmuter fuel cycle
  - Decay heat sent to waste can be drastically reduced

Achievements

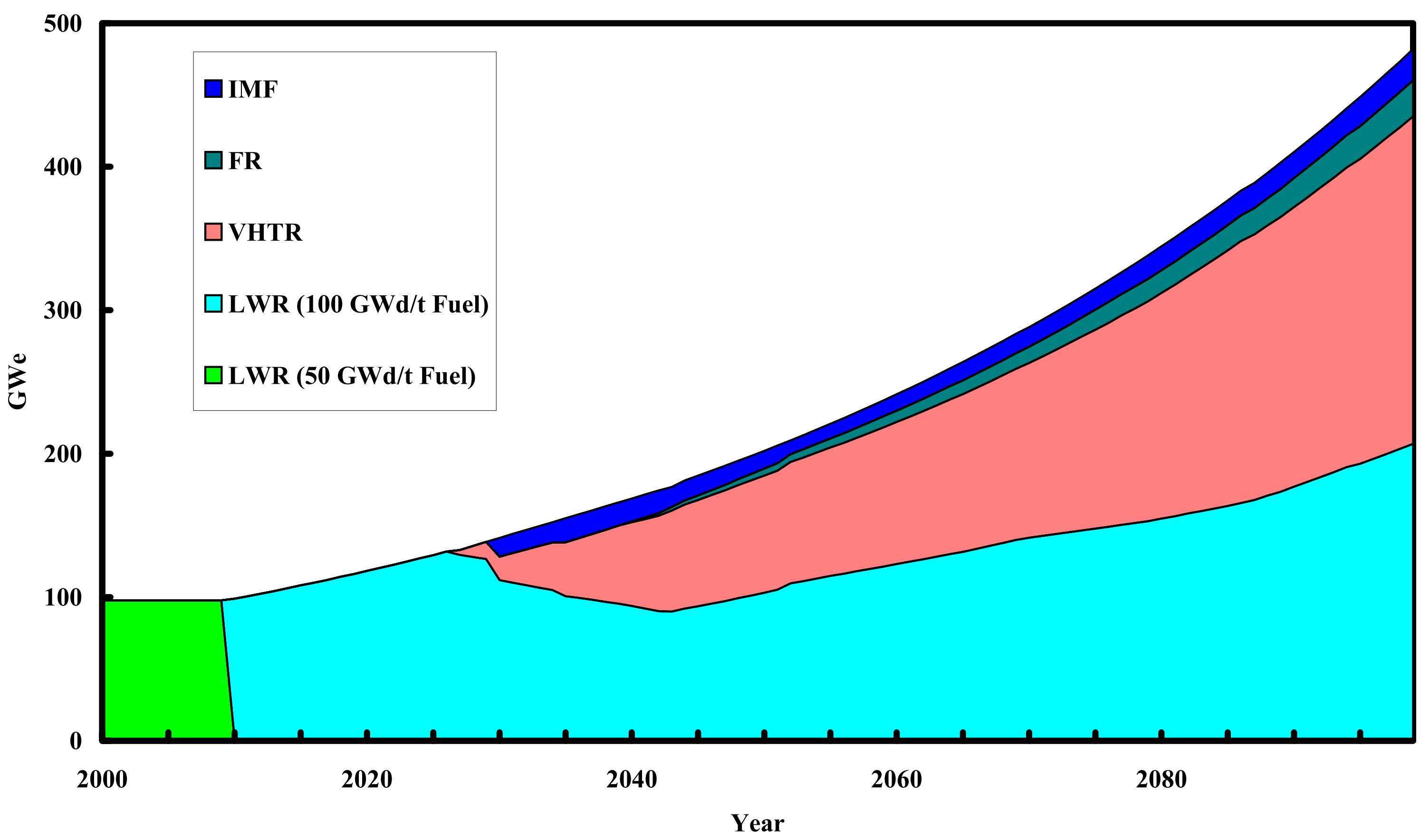
- **100-year nuclear futures dynamic simulations work was performed in prior years using a code, DYMOND, developed for that purpose**
  - Energy demand driven
  - Mass flow based
  - Dynamics of fuel cycle and reactor construction lag-times accounted for
- **An improved code, DANESS, has been produced**
  - Economic models
  - Cross flows of materials among reactor types
  - Validated data base of reactor attributes and fuel cycle processing attributes for ease of scenario construction
- **US-centric scenarios run for 6-Lab Report, AFCI Scenarios**
- **DANESS work on multi-regional fuel cycle, and other European scenarios**

Achievements

- **DANESS model development and verification**
- **Economic scenario studies**
  - 6-Lab directors report on nuclear energy
  - Dynamic analysis of nuclear energy system strategies for electricity and hydrogen production in the US
- **Support of AFCI (Advanced Fuel Cycle Initiative) scenarios**
  - Frame quantitative goals for the AFCI, to highlight the urgency of the waste management issues, and compare diverse scenarios.
  - Impact evaluated for a limited set of deployment scenarios
  - Impact on Yucca Mountain capacity extensions imparted as an outcome of various forms of partitioning and/or recycle
- **Publish Policy-Informing Scenario Outcomes**
  - Numerous publications in Global 03, ICAPP04, PHYSOR04
  - Organized energy futures session in Global03

- **Collaborations**
  - Paul Scherrer Institute (Switzerland)
    - *Renown worldwide expert on LCA*
    - *Very much interested in our nuclear dynamic systems modelling*
    - *ANL & PSI envisage development of more appropriate approaches to LCA*
    - *'Seed Money' proposal within PSI to support collaboration*
  - U-NERI with three universities
  - DANESS-Users: NRG (Netherlands), KAERI (Korea), …
- **Outreach activities**
  - DANESS Users
    - *Quest for LCI-data for new nuclear technologies*
  - Generation-IV International Forum
    - *Sustainability Assessment Working Group proposed*
  - IAEA, Department of State:
    - *Multi-regional fuel cycle and non-proliferation*

Example Scenario



Economics

- **Actual energy costs ($/kWh)**
- **(Net) Present Values**
- **Account of federal, state, local, sales taxes**

- **Capital**
  - *Construction*
  - *Capital charges*
  - *Other (overnight) costs*
  - *Decommissioning*
  - *Contingencies*
- **O&M**
- **Fuel Cycle**
  - *Owning or leasing fuel*
  - *Waste fees*

- **Financial Accounting keeps track of the revenues and expenses for each reactor, facility and owner**

Deployment Objectives

- **Only HLW emplaced in YM**
- **Reprocess SF such that**
  - Legacy SF worked down first
  - Allow realistic FR-deployment without
    - *Growing stock of separated TRUs*
    - *Keeping SF-storage needs reasonable*
- **Aim at**
  - Positive NPV
  - Negative cash-flows as small as possible

“BASE CASE” for cases 4 & 5

- **Base case for government consists of**
  - Constructing and operating all Repro/refab and FR plants
  - Selling electricity from FRs at average market price (3.5 c/kWhe)
    - *FR capital cost = 2500 $/kWe*
    - *O&M costs repro/refab = 6%/yr of initial investment*

File: /odin/ldurpel/DANESS/DANESS USA Results/BASE CASE.xls

Case A

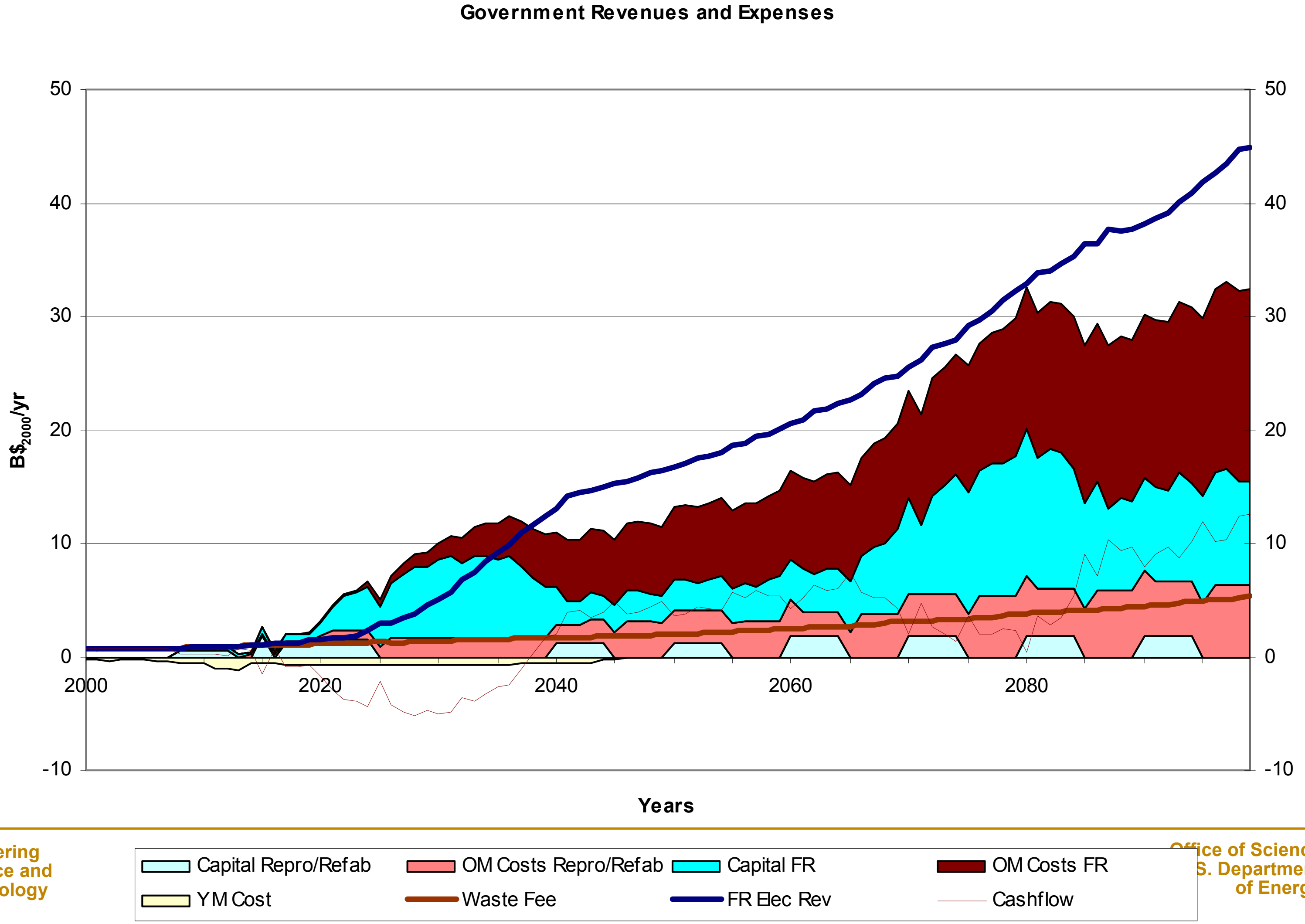
- **FR capacity, if possible, 25% of new reactors**
- **Repro/Refab Capacity**

Time of Ordering	Capacity (MtHM/yr)	Capital Cost (B$)	O&M Cost (B$/yr)
2010	**500**	**4.1715**	**0.206**
2015	**1500**	**8.236**	**0.62**
2020	**2000**	**9.862**	**0.825**
2065	**2000**	**9.862**	**0.825**
2085	**2000**	**9.862**	**0.825**

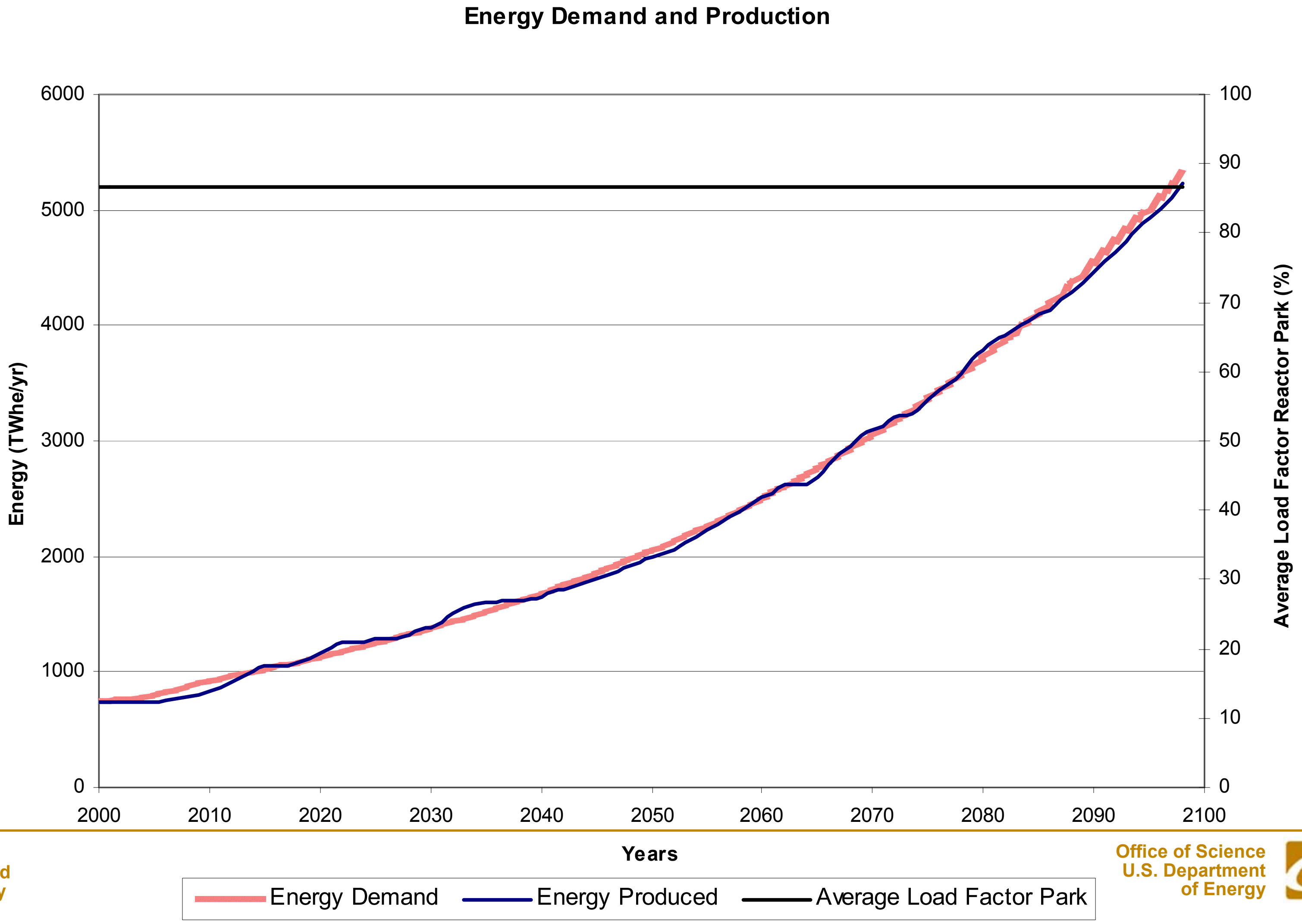
Results Case A

- **Total amount of SF in fuel cycle remains about YM <u>licensed</u> capacity**
- **No TRU build-up in fuel cycle**
- **NPV = 12.6 B$**
- **Cash-flow**
  - Most negative = -4.0 B$ in 2020
  - Becomes positive in 2030

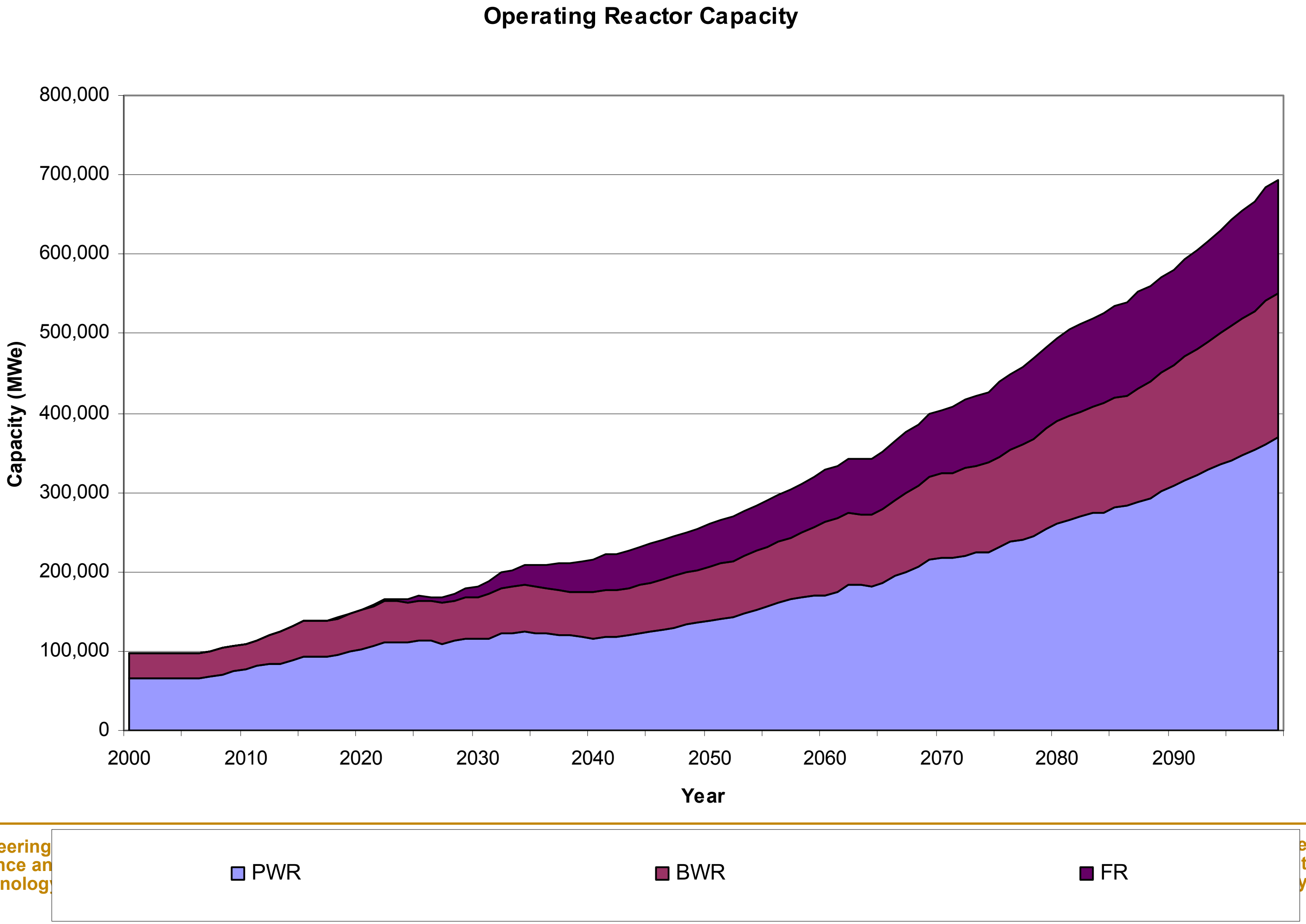
BASE CASE: Government Revenues and Expenses



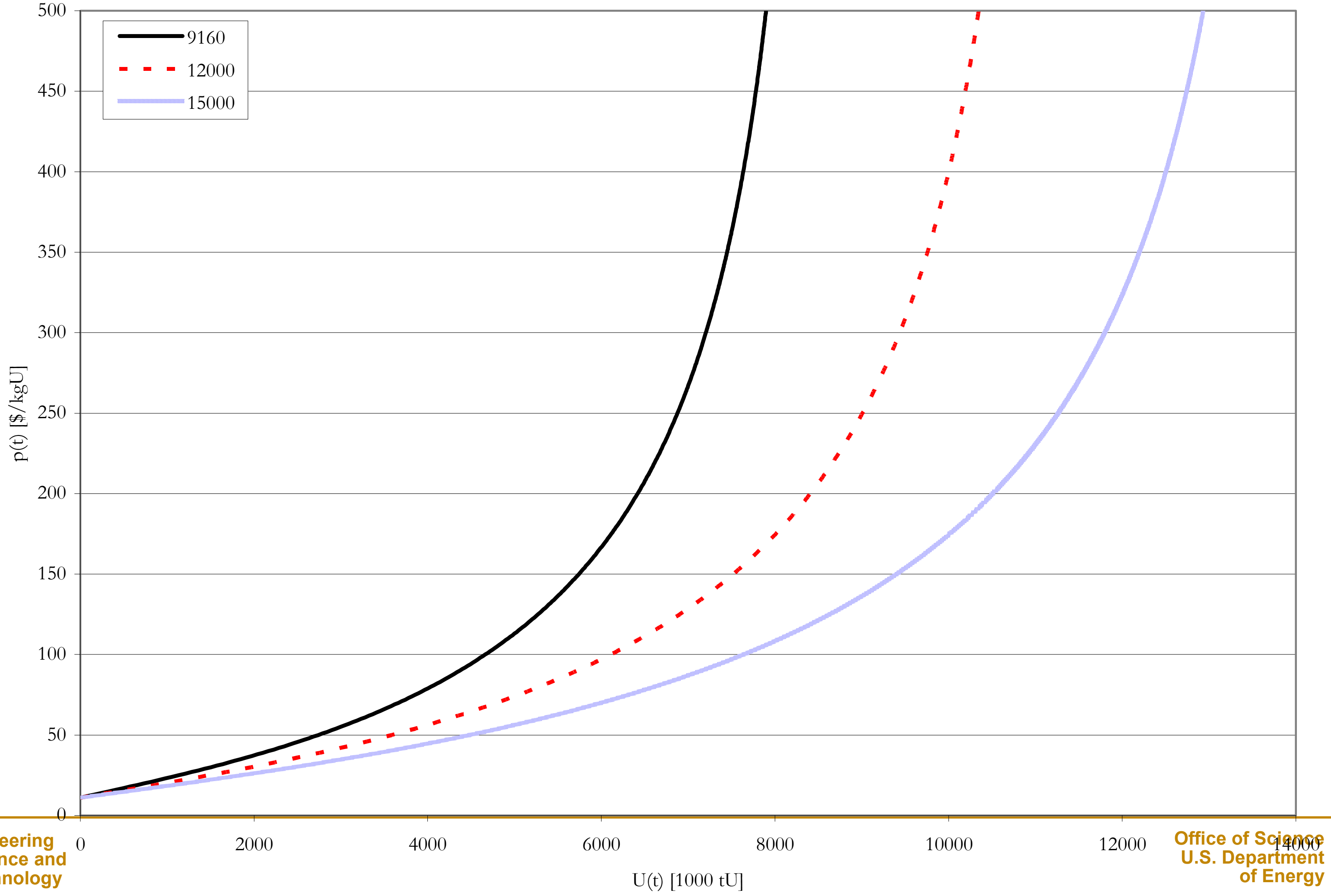
BASE CASE: Energy produced



BASE CASE: Operating Capacity



U Price Model



Economics

- **Revenuses**
  - Price for electricity = 3.5 c/kWhe
  - Waste Fee = 1 mills/kWhe collected for generated waste

- **Costs**
  - FR capital and O&M costs
  - Reprocessing Plants capital and O&M costs

Economics (continued)

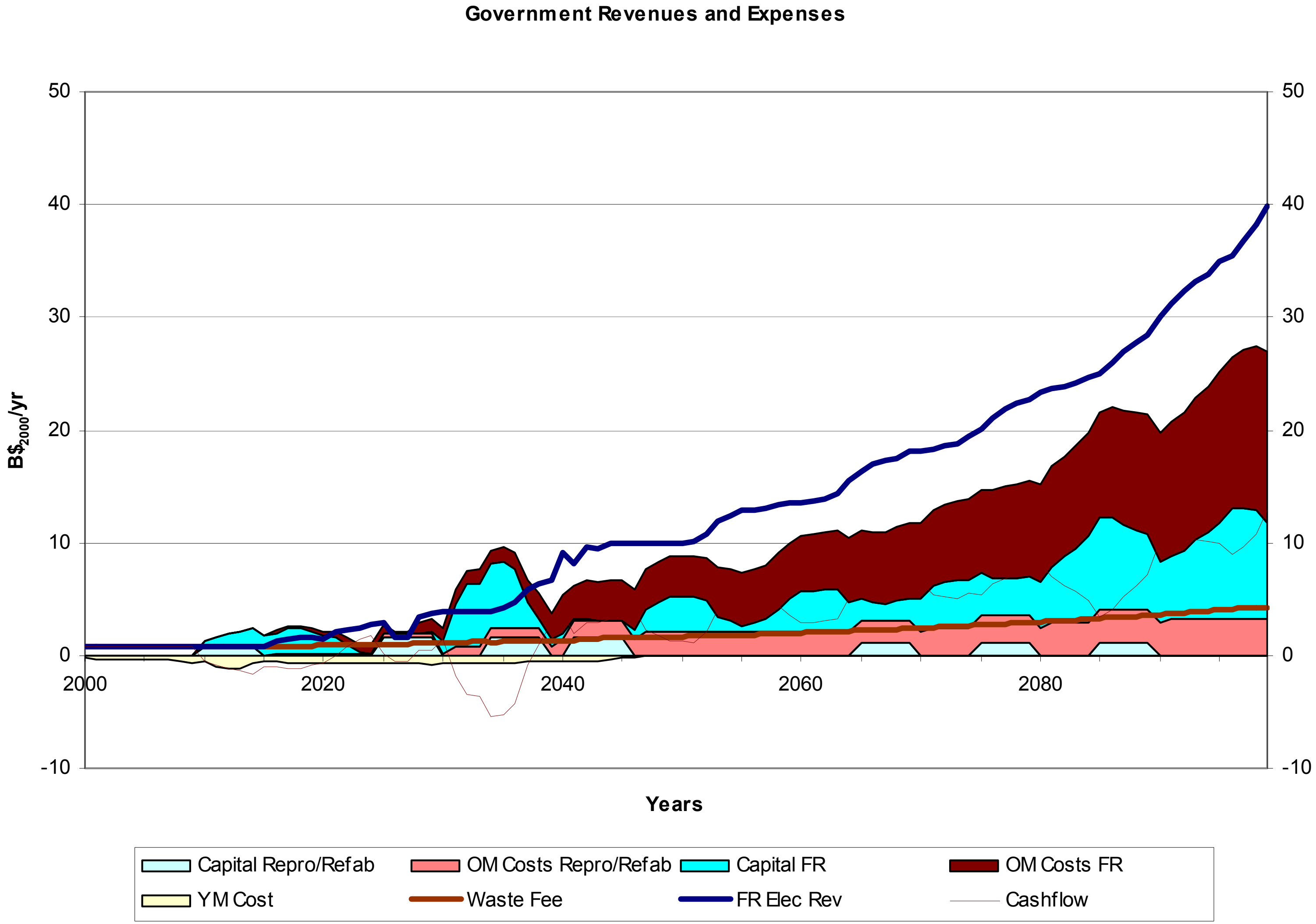
- **FR Costs**

Time	Capital Cost ($/kWe)	O&M Cost (c/kWhe)
FOAK	**1773**	**1.5**
NOAK (>= 5th FR)	**1492**	**1.5**

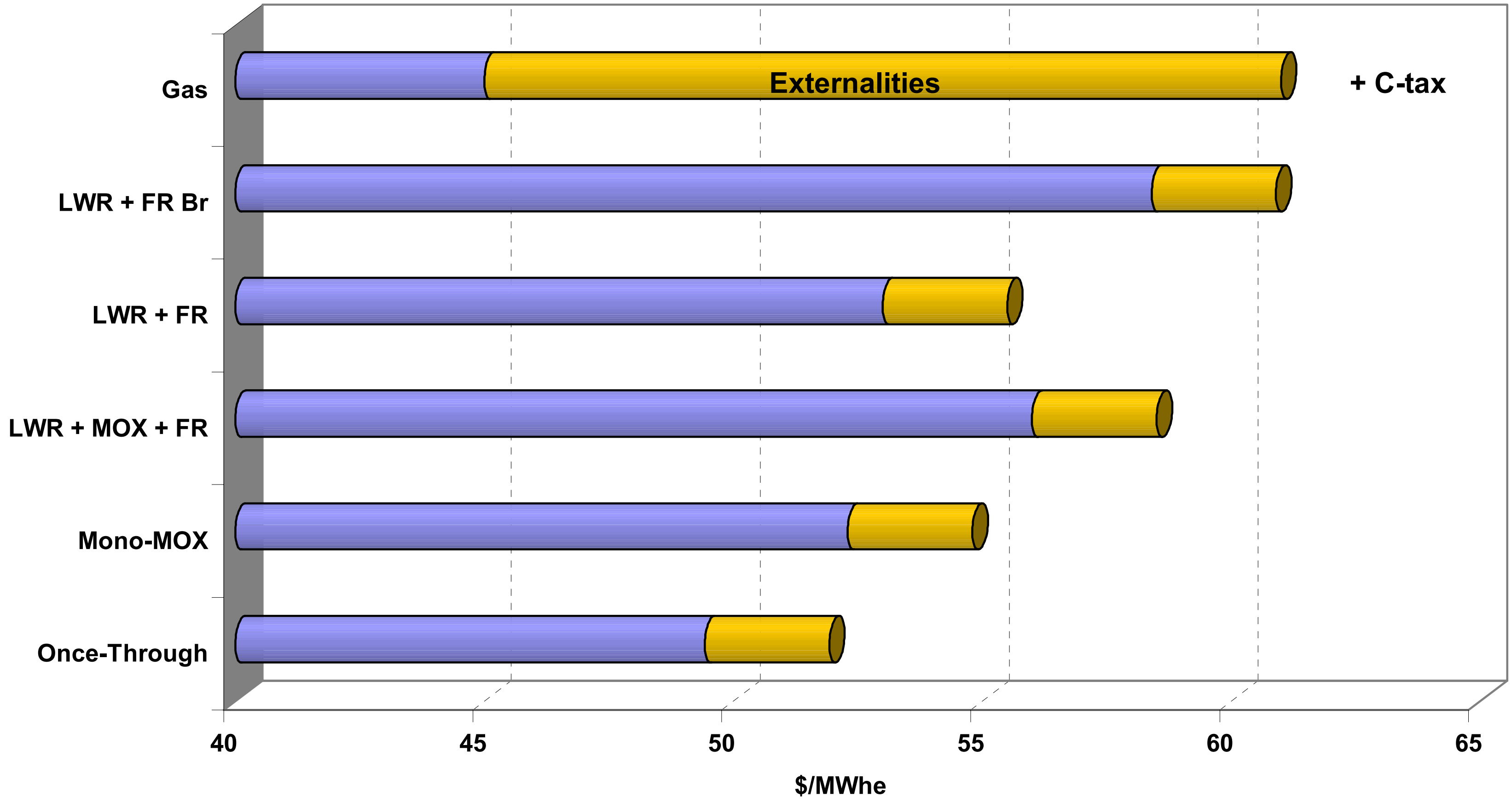
- **Reprocessing Costs**

Capacity, tHM/yr	Capital Cost (B$)	O&M Cost (B$/yr)
500	**4.1715**	**0.20625**
1500	**8.236**	**0.62**
2000	**9.862**	**0.825**

Economics


Government Revenues and Expenses
$B\$_{2000}$/yr
50
40
30
20
10
0
-10
2000
2020
2040
2060
2080
Years
Capital Repro/Refab
OM Costs Repro/Refab
Capital FR
OM Costs FR
YM Cost
Waste Fee
FR Elec Rev
Cashflow

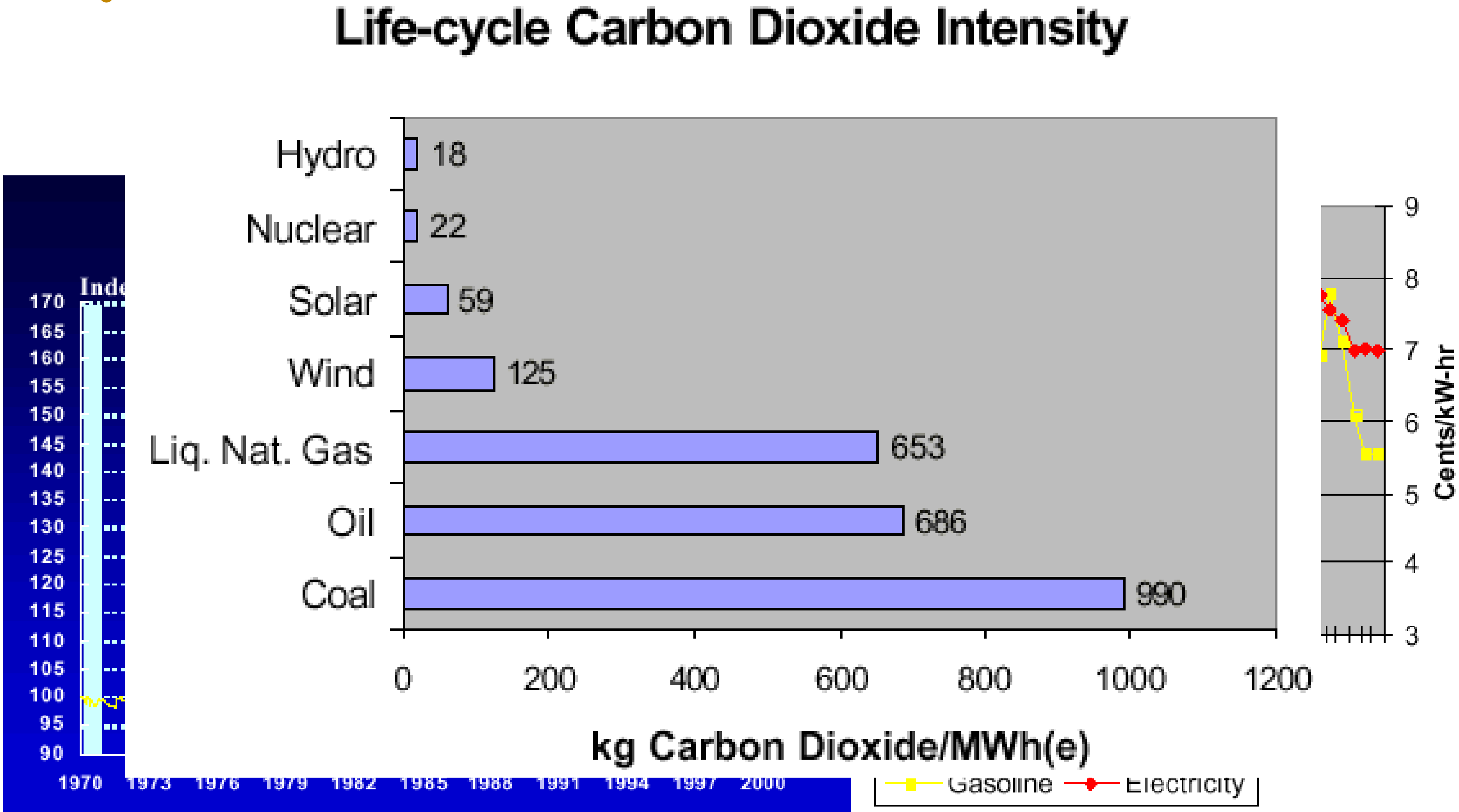
Economics



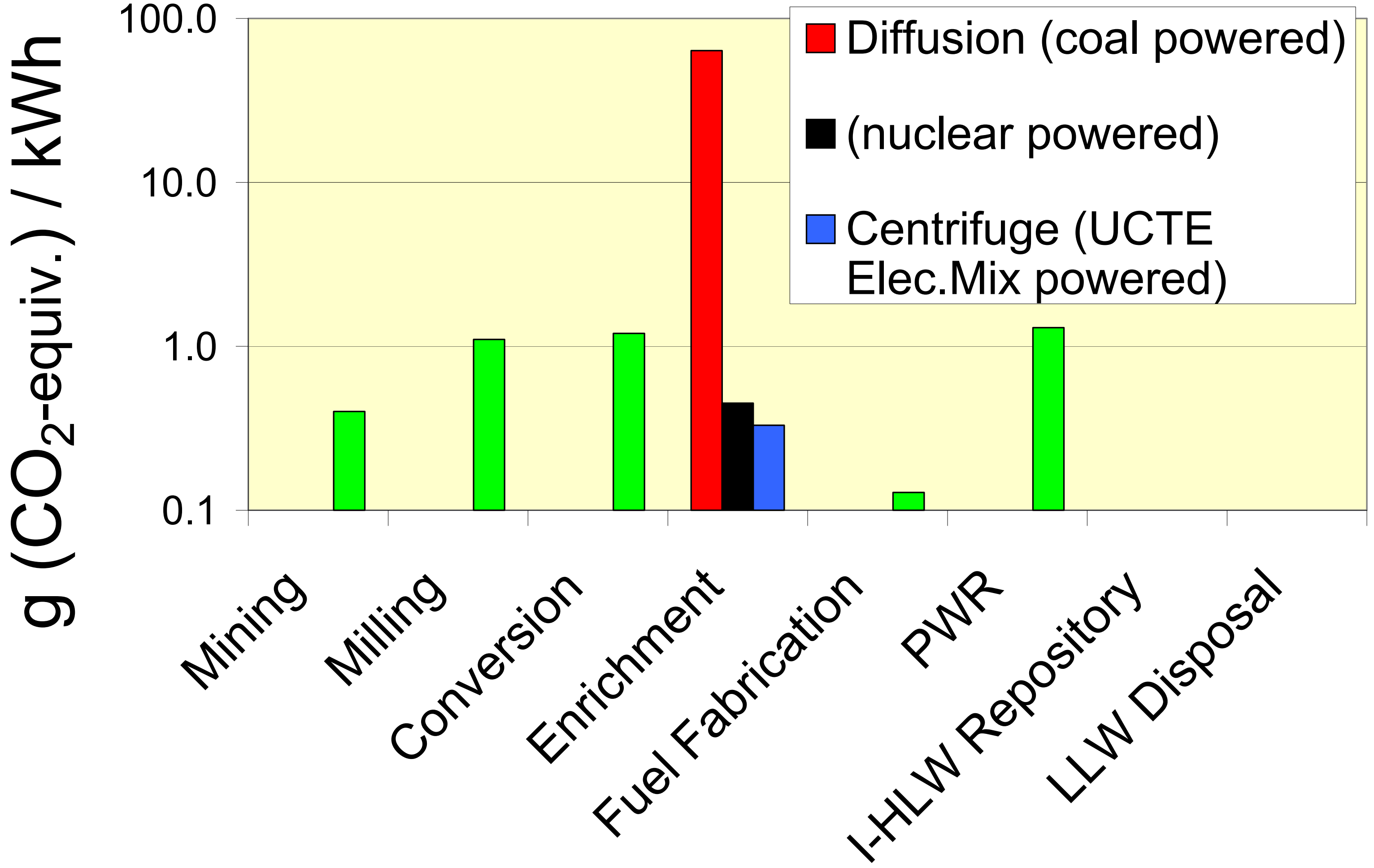
- Fuel cycle cost accounts for less than 1/5th of total cost
- Doubling of U-price results into a total cost increase by less than 5%

Macro-economic aspects

- **Carbon-tax**
-

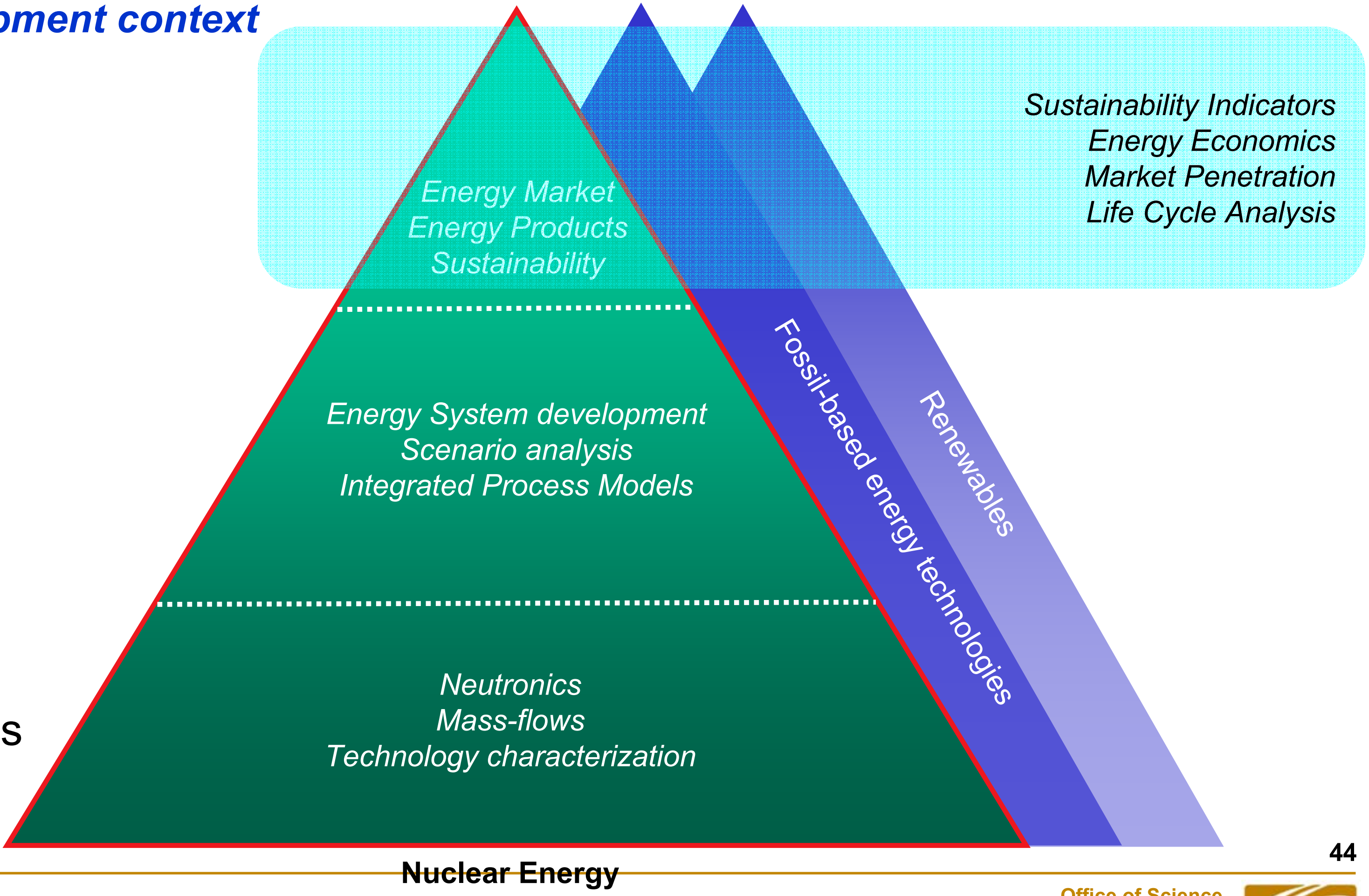


Examples of outcome using LCA



Objectives for DANESS

- *To be the standard for*
  - ***an easy-to-use and quick policy-informing tool for the technical-economic assessment of nuclear energy systems in a macro-economic energy development context***



Policy-Making

Energy Market
Energy Products
Sustainability

Sustainability Indicators
Energy Economics
Market Penetration
Life Cycle Analysis

R&D Portfolio

Energy System development
Scenario analysis
Integrated Process Models

Technical Analysis

Neutronics
Mass-flows
Technology characterization

Fossil-based energy technologies

Renewables

Nuclear Energy

General Assumptions (Continue)

- **Existing reactor park**

Operational Reactors in US, Year 2000

StationName	ReactorType	NetCapacity	CommercialOperation	Remaining years after 2000 before SD
OYSTER	BWR	650	01-Dec-69	29
NINE MILE	BWR	613	01-Dec-69	29
DRESDEN-2	BWR	784	09-Jun-70	30
DRESDEN-3	BWR	794	16-Nov-71	31
QUAD	BWR	789	18-Feb-73	33
BROWNS	BWR	1065	01-Aug-74	34
BROWNS	BWR	1065	01-Mar-75	35
MONTICELL	BWR	542	30-Jun-71	31
QUAD	BWR	789	10-Mar-73	33
VERMONT	BWR	522	30-Nov-72	32
PEACH	BWR	1055	05-Jul-74	34
PEACH	BWR	1035	23-Dec-74	34
PILGRIM-1	BWR	670	01-Dec-72	32
BROWNS	BWR	1065	01-Mar-77	37
COOPER	BWR	778	01-Jul-74	34
HATCH-1	BWR	797	31-Dec-75	35
BRUNSWICK-	BWR	821	03-Nov-75	35
BRUNSWICK-	BWR	821	18-Mar-77	37
DUANE	BWR	538	01-Feb-75	35
FITZPATRIC	BWR	820	28-Jul-75	35
ENRICO	BWR	1093	23-Jan-88	48
LIMERICK-1	BWR	1055	01-Feb-86	46
LIMERICK-2	BWR	1055	08-Jan-90	50
HOPE	BWR	1031	20-Dec-86	46
HATCH-2	BWR	806	05-Sep-79	39
LA SALLE-1	BWR	1078	01-Jan-84	44
LA SALLE-2	BWR	1078	19-Oct-84	44
SUSQUEHAN	BWR	1050	08-Jun-83	43
SUSQUEHAN	BWR	1050	12-Feb-85	45
COLUMBIA-2	BWR	1117	13-Dec-84	44
NINE MILE	BWR	1062	11-Mar-88	48
GRAND	BWR	1210	01-Jul-85	45
PERRY-1	BWR	1205	18-Nov-87	47
RIVER BEND-	BWR	936	16-Jun-86	46
CLINTON	BWR	950	24-Nov-87	47
R.E. GINNA	PWR	470	01-Jul-70	30
INDIAN	PWR	939	15-Aug-74	34
TURKEY	PWR	666	14-Dec-72	32
TURKEY	PWR	666	07-Sep-73	33
PALISADES-	PWR	805	31-Dec-71	31
H.B.	PWR	718	07-Mar-71	31
POINT	PWR	485	21-Dec-70	30
OCONEE-1	PWR	846	15-Jul-73	33
OCONEE-2	PWR	846	09-Sep-74	34
SALEM-1	PWR	1106	30-Jun-77	37
DIABLO	PWR	1073	07-May-85	45
SURRY-1	PWR	788	22-Dec-72	32
SURRY-2	PWR	788	01-May-73	33
PRAIRIE	PWR	536	16-Dec-73	33
FORT	PWR	476	20-Jun-74	34
INDIAN	PWR	965	30-Aug-76	36

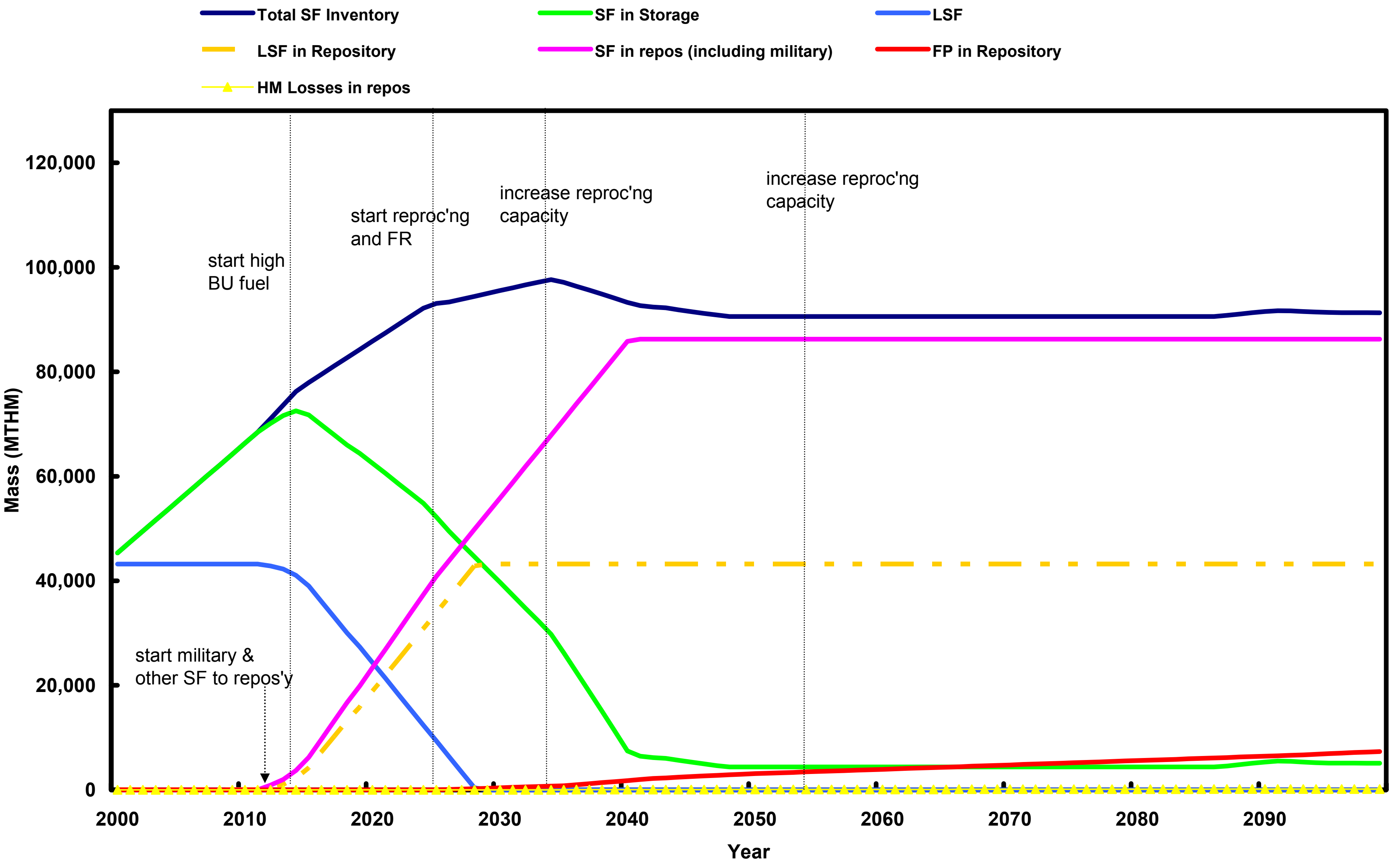
Operational Reactors in US, Year 2000

StationName	ReactorType	NetCapacity	CommercialOperation	Remaining years after 2000 before SD
OCONEE-3	PWR	846	16-Dec-74	34
THREE MILE	PWR	819	02-Sep-74	34
POINT	PWR	485	01-Oct-72	32
CRYSTAL	PWR	821	13-Mar-77	37
KEWAUNEE	PWR	540	16-Jun-74	34
PRAIRIE	PWR	536	21-Dec-74	34
SALEM-2	PWR	1106	13-Oct-81	41
ARKANSAS-1	PWR	836	19-Dec-74	34
DONALD	PWR	1020	27-Aug-75	35
DONALD	PWR	1060	01-Jul-78	38
CALVERT	PWR	865	08-May-75	35
CALVERT	PWR	865	01-Apr-77	37
DIABLO	PWR	1087	13-Mar-86	46
SEQUOYAH-	PWR	1141	01-Jul-81	41
SEQUOYAH-	PWR	1136	01-Jun-82	42
BEAVER	PWR	833	01-Oct-76	36
ST. LUCIE-1	PWR	839	21-Dec-76	36
MILLSTONE-	PWR	858	26-Dec-75	35
NORTH	PWR	907	06-Jun-78	38
NORTH	PWR	907	14-Dec-80	40
DAVIS	PWR	906	31-Jul-78	38
FARLEY-1	PWR	829	01-Dec-77	37
SAN	PWR	1070	08-Aug-83	43
SAN	PWR	1080	01-Apr-84	44
FARLEY-2	PWR	829	30-Jul-81	41
ARKANSAS-2	PWR	858	26-Mar-80	40
MCGUIRE-1	PWR	1129	01-Dec-81	41
MCGUIRE-2	PWR	1129	01-Mar-84	44
WATERFOR	PWR	1075	24-Sep-85	45
ST. LUCIE-2	PWR	839	08-Aug-83	43
WATTS BAR-	PWR	1154	05-May-96	56
VIRGIL C.	PWR	895	01-Jan-84	44
SHEARON	PWR	900	02-May-87	47
BEAVER	PWR	833	17-Nov-87	47
CATAWBA-1	PWR	1129	29-Jun-85	45
CATAWBA-2	PWR	1129	19-Aug-86	46
MILLSTONE-	PWR	1150	23-Apr-86	46
VOGTLE-1	PWR	1158	01-Jun-87	47
VOGTLE-2	PWR	1158	20-May-89	49
SEABROOK-	PWR	1161	19-Aug-90	50
COMANCHE	PWR	1150	13-Aug-90	50
COMANCHE	PWR	1150	03-Aug-93	53
BYRON-1	PWR	1120	16-Sep-85	45
BYRON-2	PWR	1120	21-Aug-87	47
BRAIDWOOD	PWR	1120	29-Jul-88	48
BRAIDWOOD	PWR	1120	17-Oct-88	48
WOLF	PWR	1150	03-Sep-85	45
CALLAWAY-	PWR	1143	19-Dec-84	44
SOUTH	PWR	1251	25-Aug-88	48
SOUTH	PWR	1250	19-Jun-89	49
PALO	PWR	1270	28-Jan-86	46
PALO	PWR	1270	19-Sep-86	46
PALO	PWR	1270	08-Jan-88	48

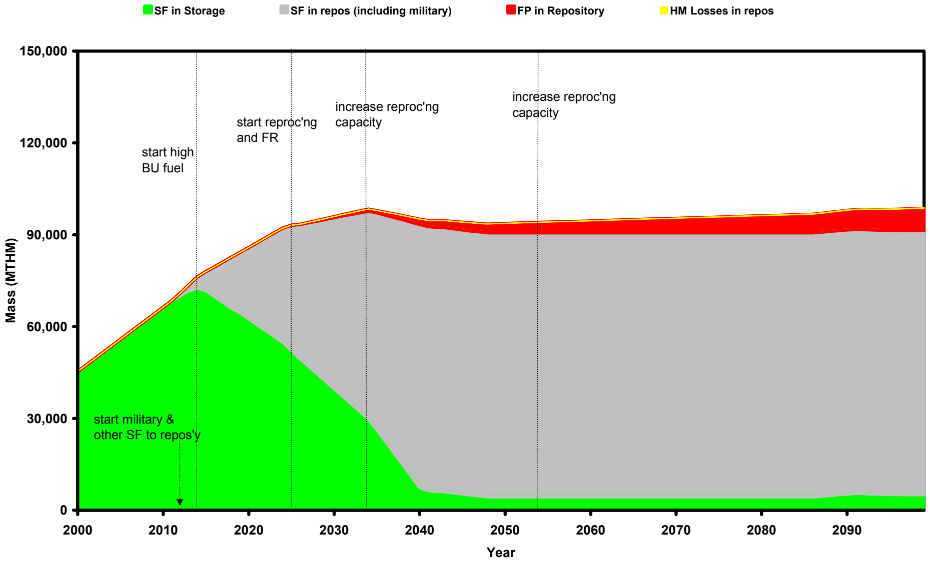
Scenario 1.a

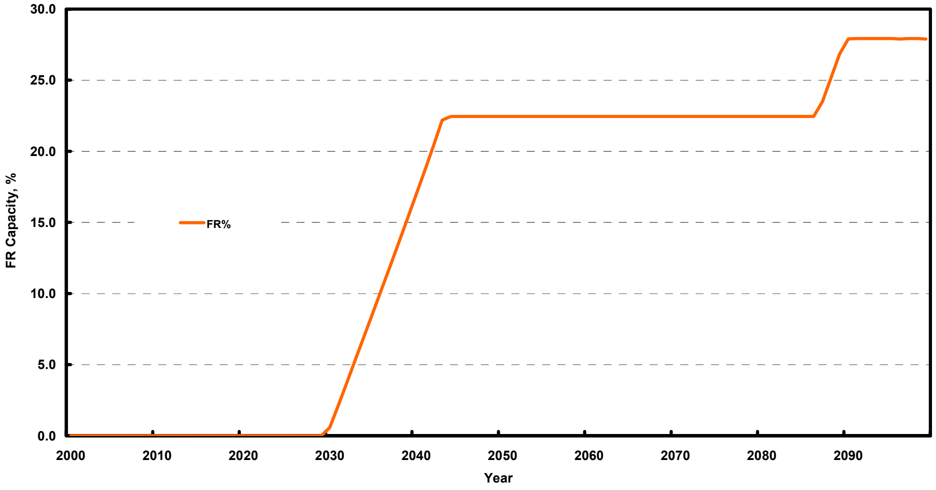
- **Timeline**
  - Similar to scenario 1
- **Assumptions**
  - Similar to scenario 1 except for the 0% demand growth rate

Scenario 1.a


Total SF Inventory
SF in Storage
LSF
LSF in Repository
SF in repos (including military)
FP in Repository
HM Losses in repos
Mass (MTHM)
120,000
100,000
80,000
60,000
40,000
20,000
0
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year
start high BU fuel
start reproc'ng and FR
increase reproc'ng capacity
increase reproc'ng capacity
start military & other SF to repos'y

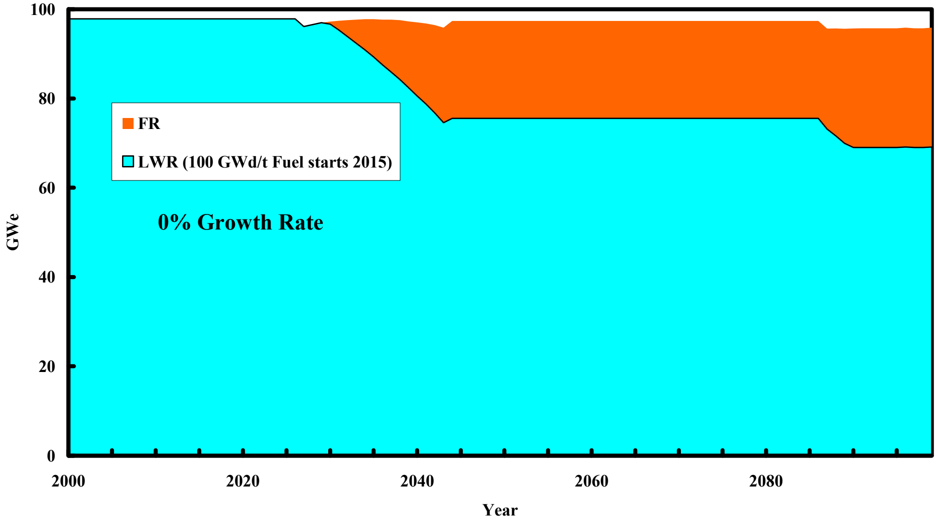
Scenario 1.a

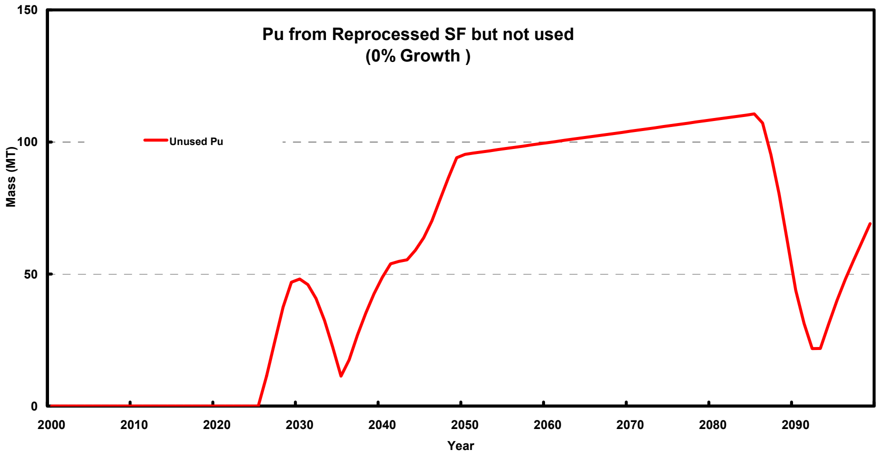


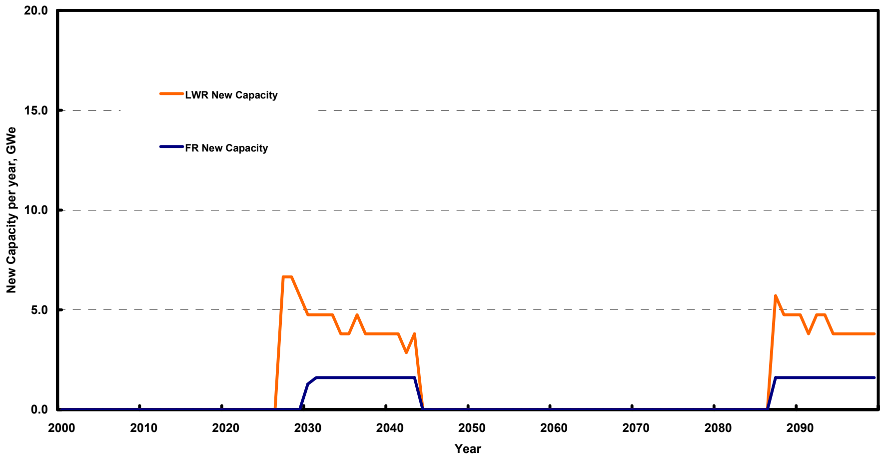


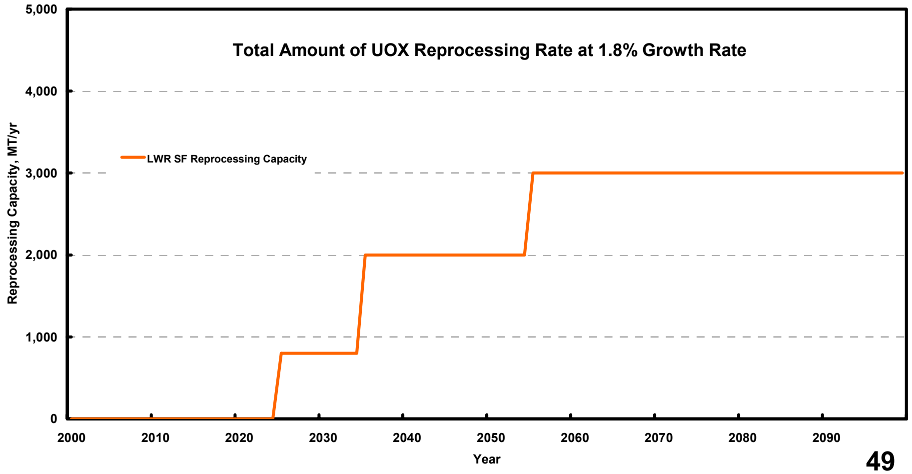
- SNF temporary storage requirements are minimal
  - *With reprocessing, storage requirement decline*
    - By about 2028, storage requirements are < storage requirements in 2000
- Direct disposal of large amounts of SNF in repository
  - *By 2028 all 2000 legacy SF is transferred to repository*
  - *By 2041, all SF production goes to reprocessing*
    - No more transfer to repository to 2100
    - SF in repository reach ~ 86,000 MT by 2041 (including military & DOE 7000 MT)
- By 2043, all existing reactor are retired and replaced by new LWRs and/or FRs, and no new reactors are built until 2087 when LWRs built in 2028 are retired
  - *Those ALWRs retired in 2087are replaced by FRs, which increase the FR% in capacity*
  - *By 2043, FR% in capacity reaches about 22.5%*
  - *Increase in FRs starting 2087 leads to FR% in capacity of about 28% by 2090*
- Inventory of Pu (from reprocessed SF) at any point in time is < 150 tons

Scenario 1.a


100
80
60
40
20
0
GWe
■ FR
□ LWR (100 GWd/t Fuel starts 2015)
0% Growth Rate
2000
2020
2040
2060
2080
Year


Pu from Reprocessed SF but not used
(0% Growth)
150
100
50
0
Mass (MT)
Unused Pu
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year

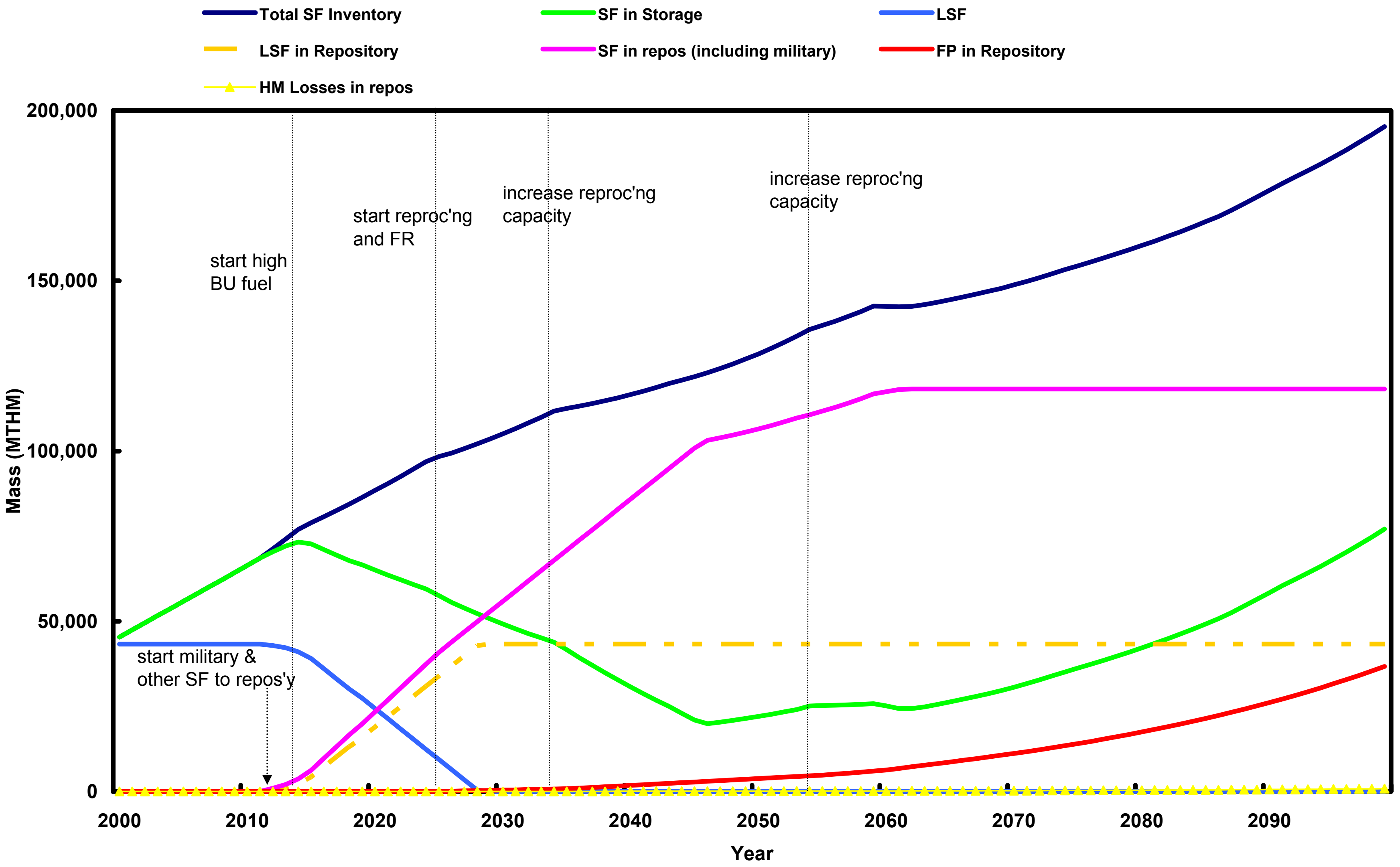

20.0
15.0
10.0
5.0
0.0
New Capacity per year, GWe
LWR New Capacity
FR New Capacity
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year


Total Amount of UOX Reprocessing Rate at 1.8% Growth Rate
5,000
4,000
3,000
2,000
1,000
0
Reprocessing Capacity, MT/yr
LWR SF Reprocessing Capacity
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year

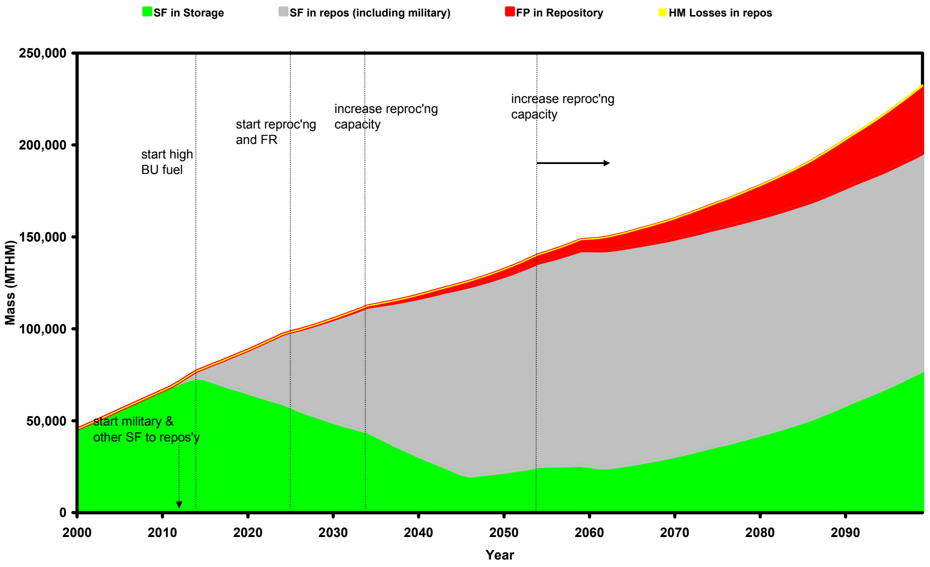
Scenario 1.b

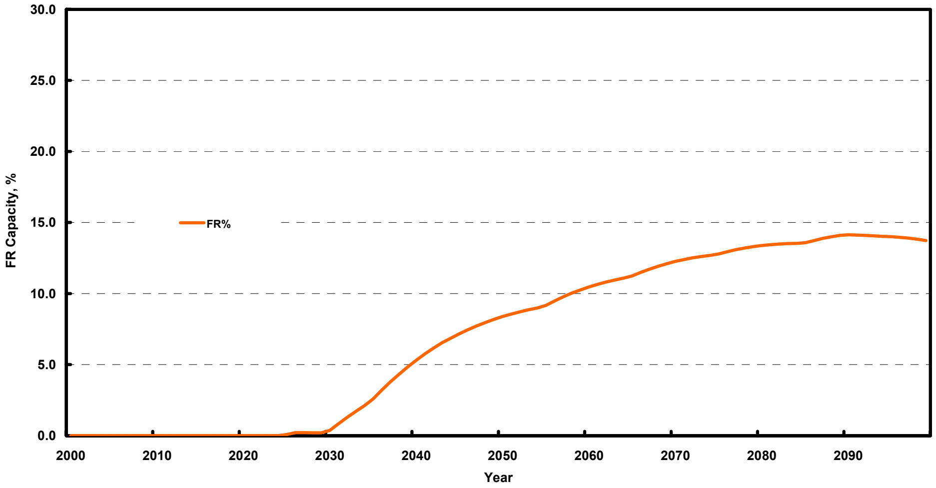
- **Timeline**
  - Similar to scenario 1 except for the need to deploy more reprocessing capacity to handle the extra waste (see figure)
- **Assumptions**
  - Similar to scenario 1 except for the higher demand growth rate of 3.2% per year

Scenario 1.b


Total SF Inventory
SF in Storage
LSF
LSF in Repository
SF in repos (including military)
FP in Repository
HM Losses in repos
200,000
150,000
100,000
50,000
0
Mass (MTHM)
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year
start high
BU fuel
start reproc'ng
and FR
increase reproc'ng
capacity
increase reproc'ng
capacity
start military &
other SF to repos'y

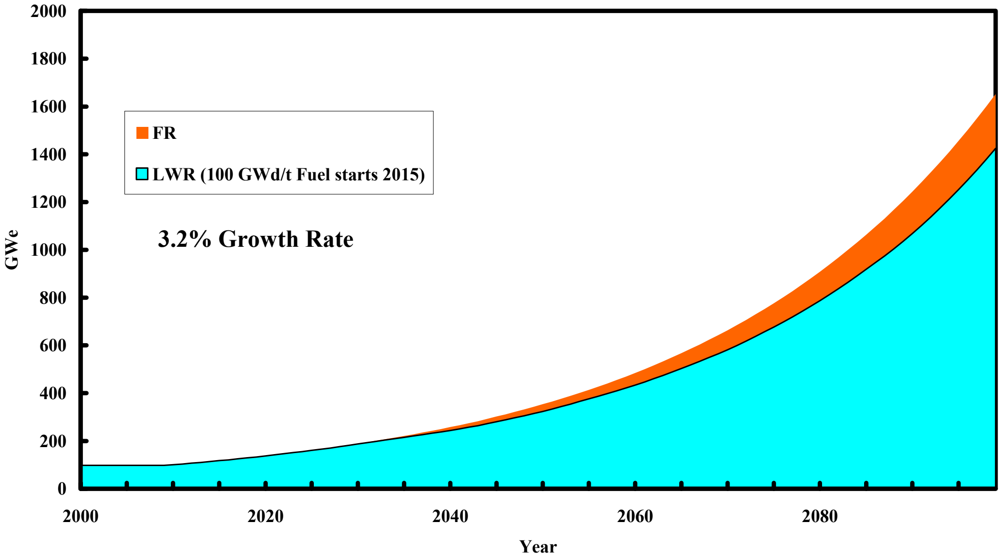
Scenario 1.b



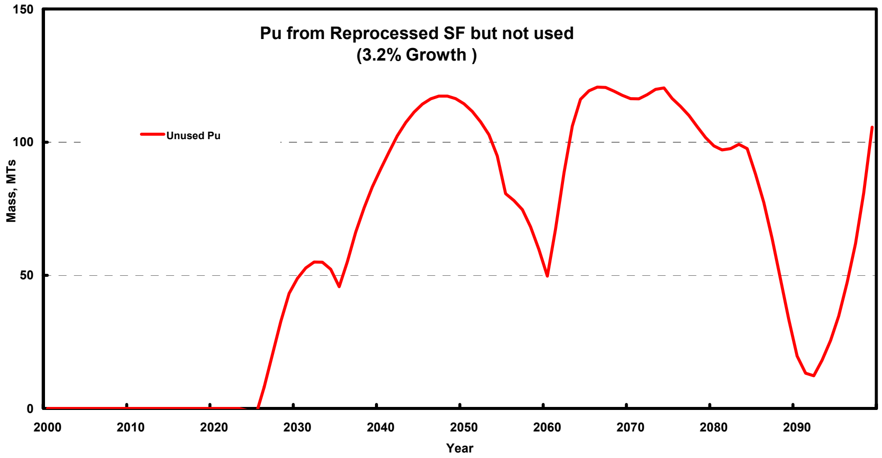


- SNF temporary storage requirements are minimized
  - *With reprocessing, storage requirement decline*
    - By about 2035, storage requirements are < storage requirements in 2000
    - Eventually storage requirements starts to increase after a 2045 minimum
- Direct disposal of large amounts of SNF in repository
  - *By 2028 all 2000 legacy SF is transferred to repository*
  - *By 2062, all SF production goes to reprocessing*
    - No more transfer to repository to 2100
    - SF in repository reach ~ 118,000 MT by 2062 (including military & DOE 7000 MT)
      - Most of it is high burnup fuel
- To 2055, reprocessing capacity is assumed to be the same as scenario 1, and beyond 2055 it is increased rapidly to catch up with the high SF production rate
  - *Buildup of FRs/year is allowed to go up gradually from 1.5 GWe/year in 2055 to about 7.3 GWe by 2095.*
  - *FR% reach about 14% (lower than the 1.8% growth rate because of the faster growth rate and the lake of enough TRU to build FR fast enough to respond to increased demand)*
- Inventory of Pu (from reprocessed SF) at any point in time is < 150 tons

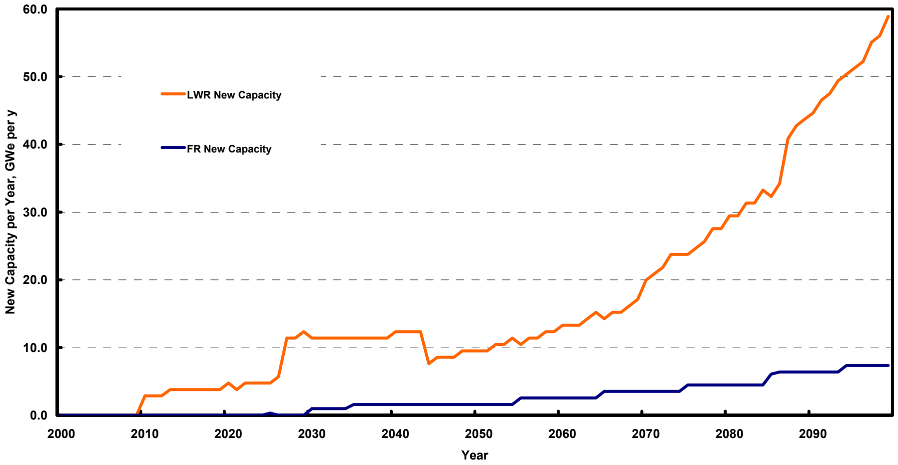
Scenario 1.b



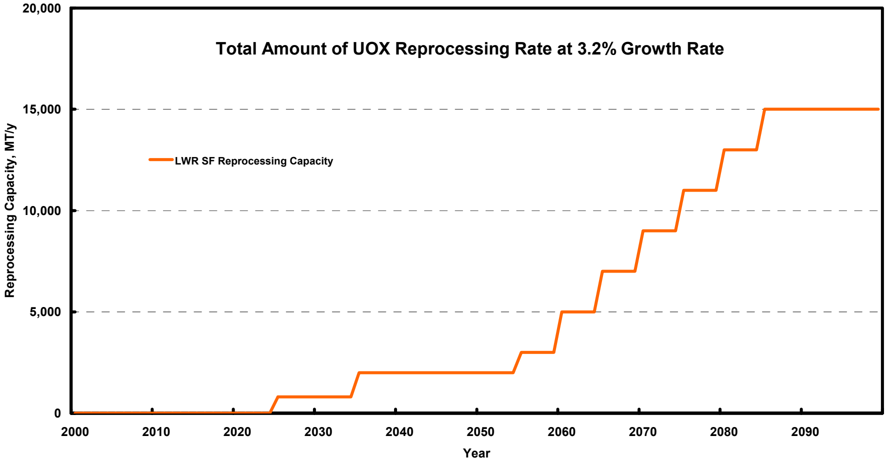
FR
LWR (100 GWd/t Fuel starts 2015)
3.2% Growth Rate
GWe
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2000
2020
2040
2060
2080
Year



Pu from Reprocessed SF but not used
(3.2% Growth)
Unused Pu
Mass, MTs
150
100
50
0
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year



LWR New Capacity
FR New Capacity
New Capacity per Year, GWe per y
60.0
50.0
40.0
30.0
20.0
10.0
0.0
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year

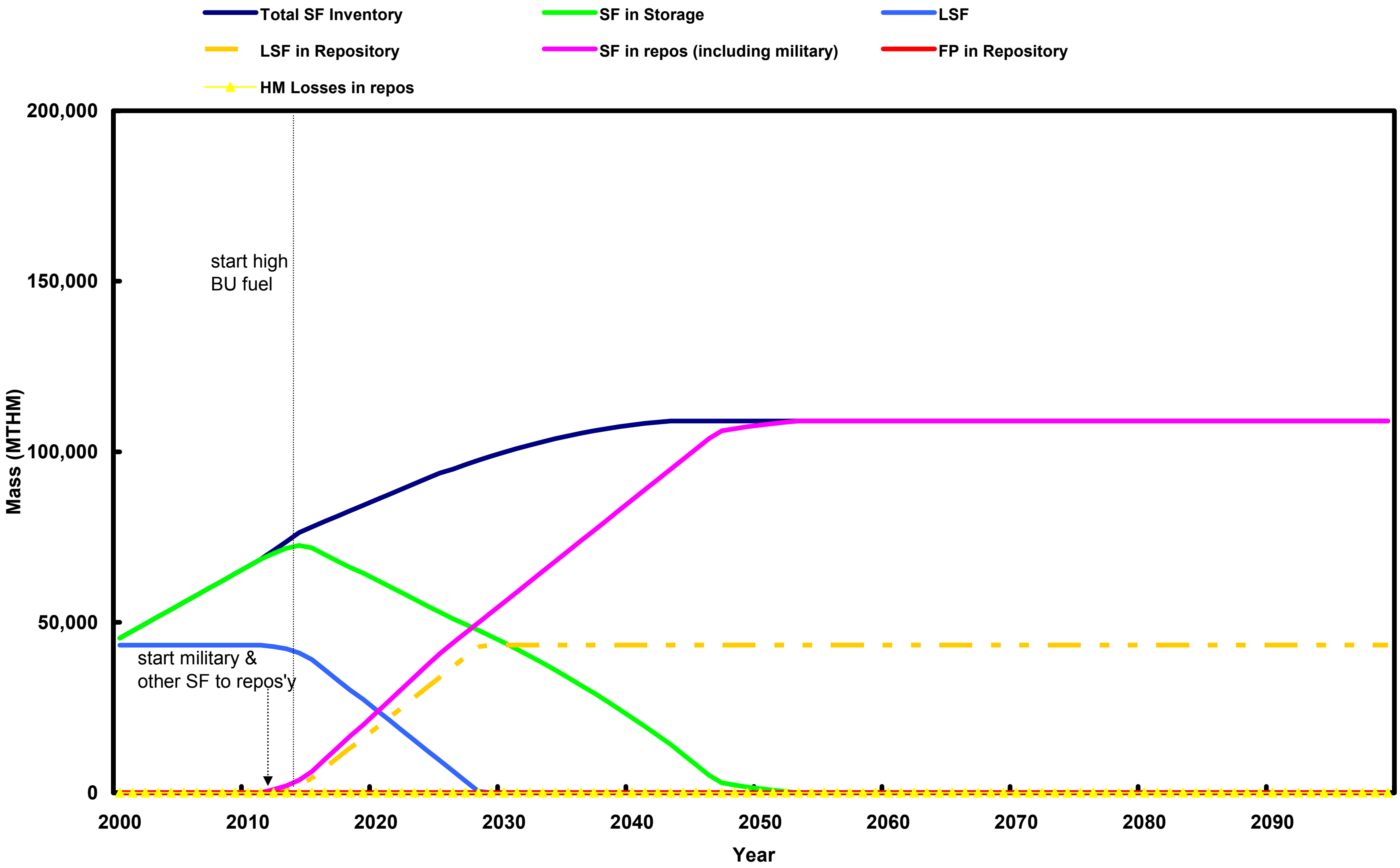


Total Amount of UOX Reprocessing Rate at 3.2% Growth Rate
LWR SF Reprocessing Capacity
Reprocessing Capacity, MT/y
20,000
15,000
10,000
5,000
0
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year

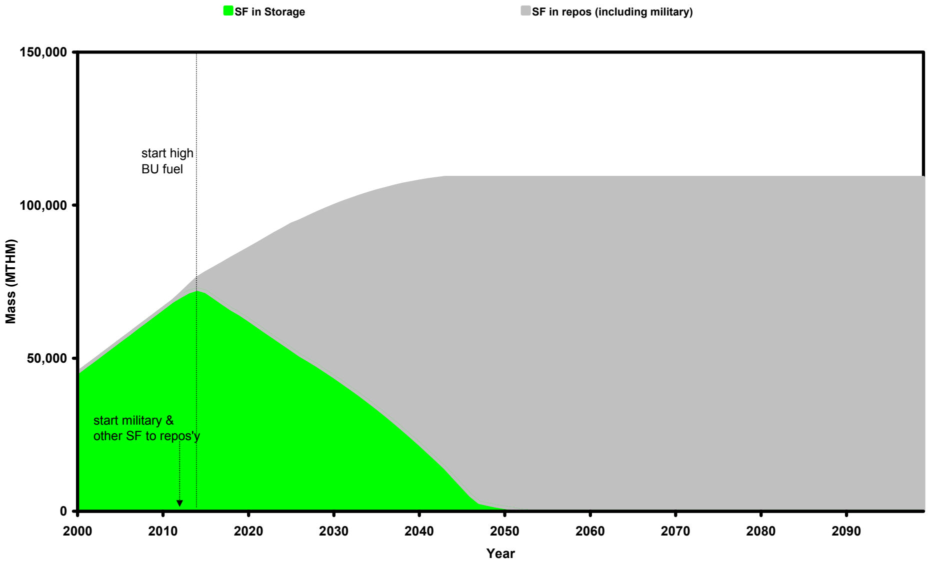
Scenario 1.c

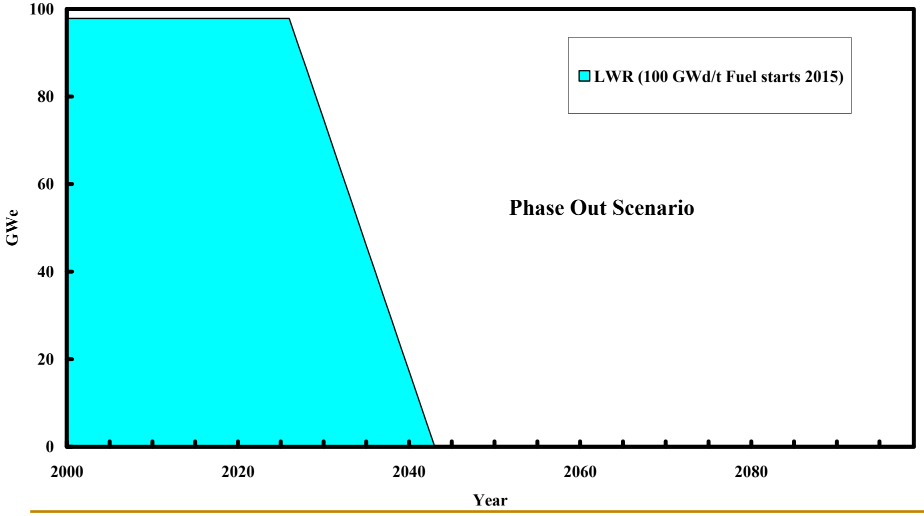
- **Timeline**
  - Phase out scenario where retired plants are not replaced
  - Still use high burnup fuel starting 2015
- **Assumptions**
  - Same assumptions as scenario 1 regarding repository timeline

Scenario 1.c


Total SF Inventory
SF in Storage
LSF
LSF in Repository
SF in repos (including military)
FP in Repository
HM Losses in repos
200,000
150,000
100,000
50,000
0
Mass (MTHM)
start high
BU fuel
start military &
other SF to repos'y
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year

Scenario 1.c



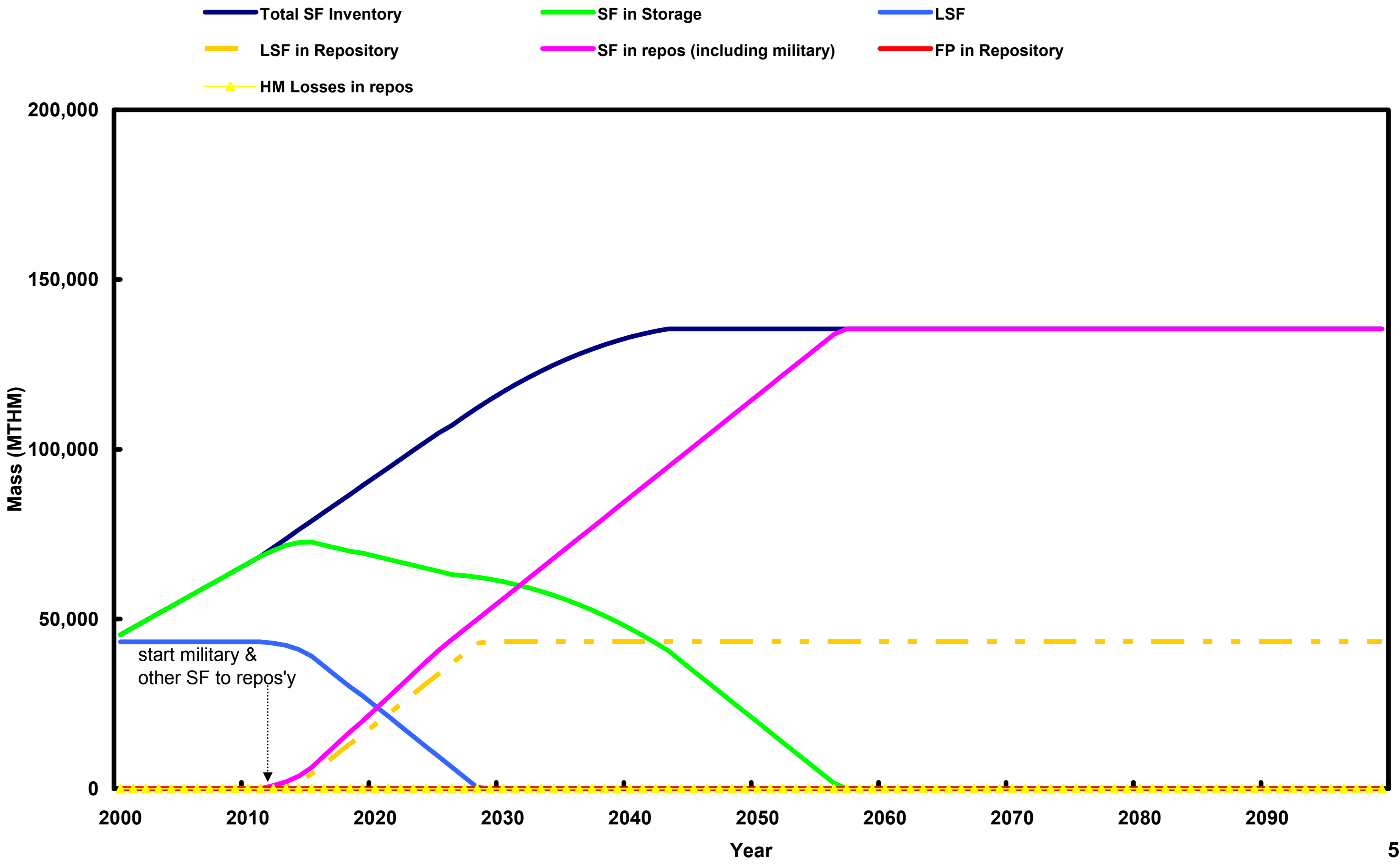


- SNF temporary storage requirements are eliminated by about 2050
- Direct disposal of large amounts of SNF in repository, that totals about 108,000 MT by 2050 (compared to about 118,000 MT for the 3.2% growth scenario)
- Majority of the SF in repository is high burnup SF

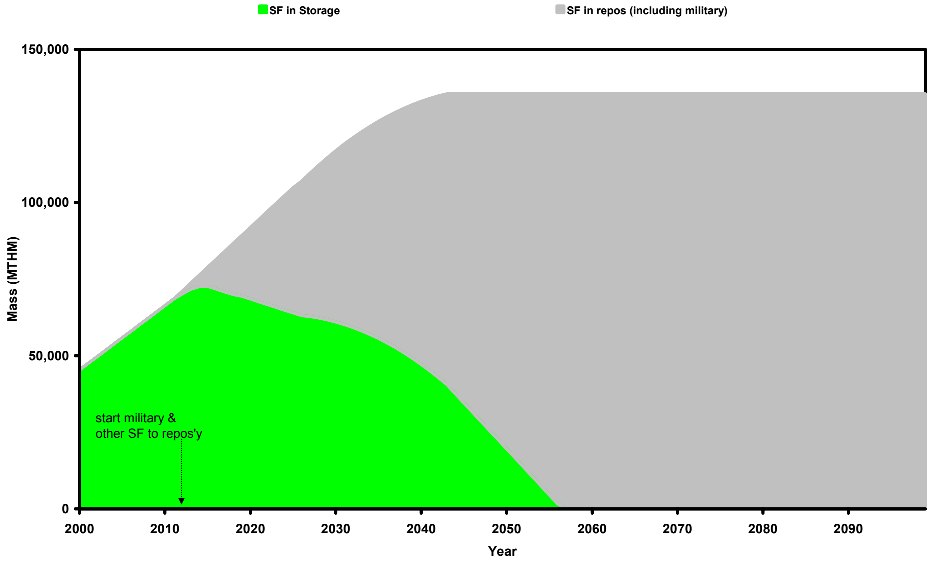
Scenario 1.c.1

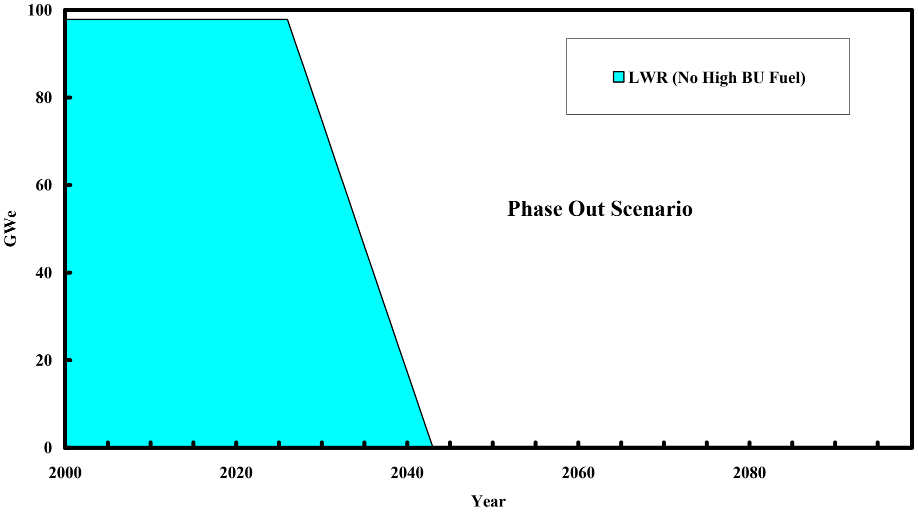
- **Timeline**
  - Phase out scenario where retired plants are not replaced
  - No use of high burnup fuel
- **Assumptions**
  - Same assumptions as scenario 1 regarding repository timeline

Scenario 1.c.1



Scenario 1.c.1





- SNF temporary storage requirements are eliminated by about 2057
- Direct disposal of large amounts of SNF in repository, that totals about 135,500 MT by 2057 (compared to about 118,000 MT for the 3.2% growth scenario)
- All of the SF in repository is lower burnup SF