A Comparison of SFR and PWR in View of the Core Design & Characteristics

October 28, 2015

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Presented at KNS 2015 Fall Meeting Workshop on the PGSFR, Gyungju, Korea

Outline

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  - Reactivity Control Systems
  - Fuel Management Scheme

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  - Neutron Spectrum and Economy
  - Excess Reactivity
  - Fuel Burnup and Compositions
  - Kinetic and Safety Parameters
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  - Accidental Reactivity Insertion
  - Fuel Cycle Considerations

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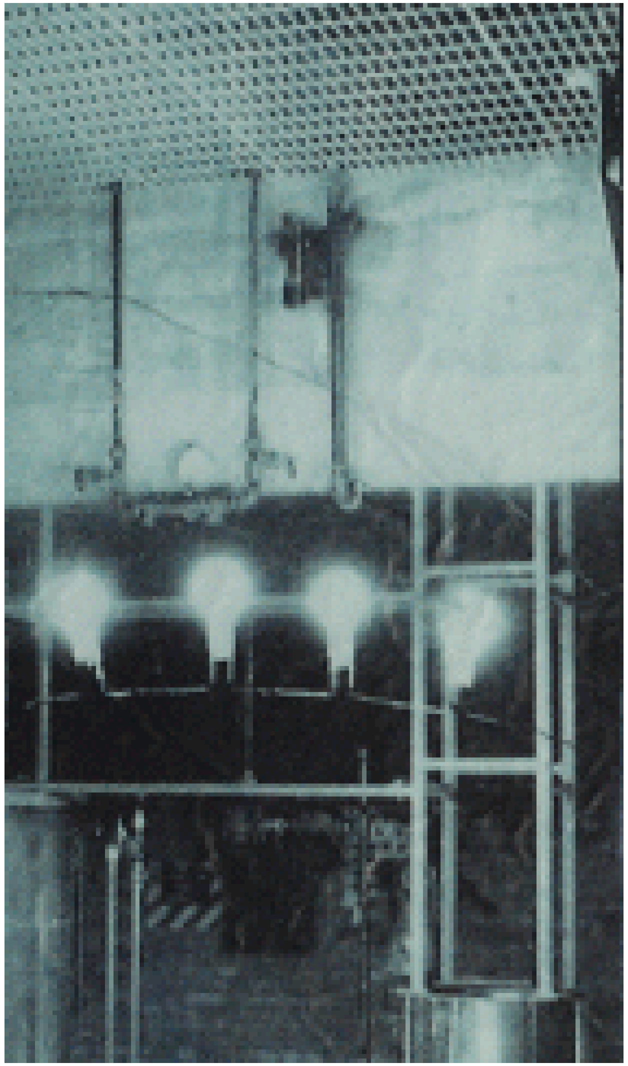
Introduction

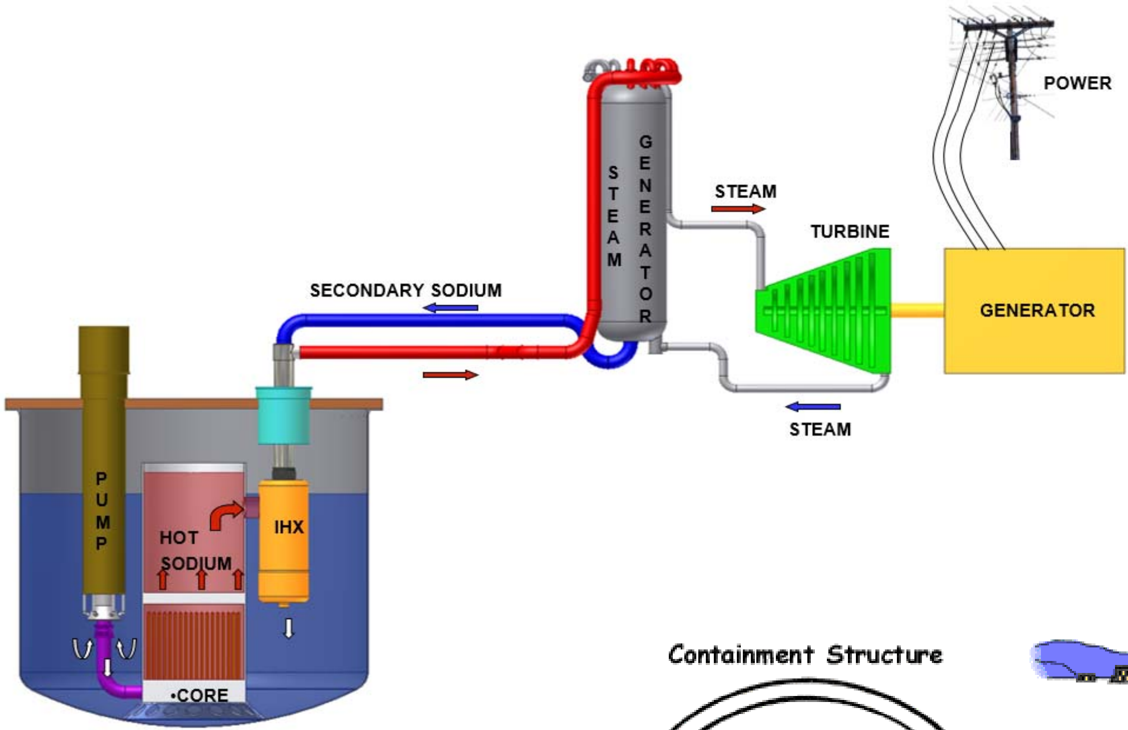
The 1st Nuclear Electricity

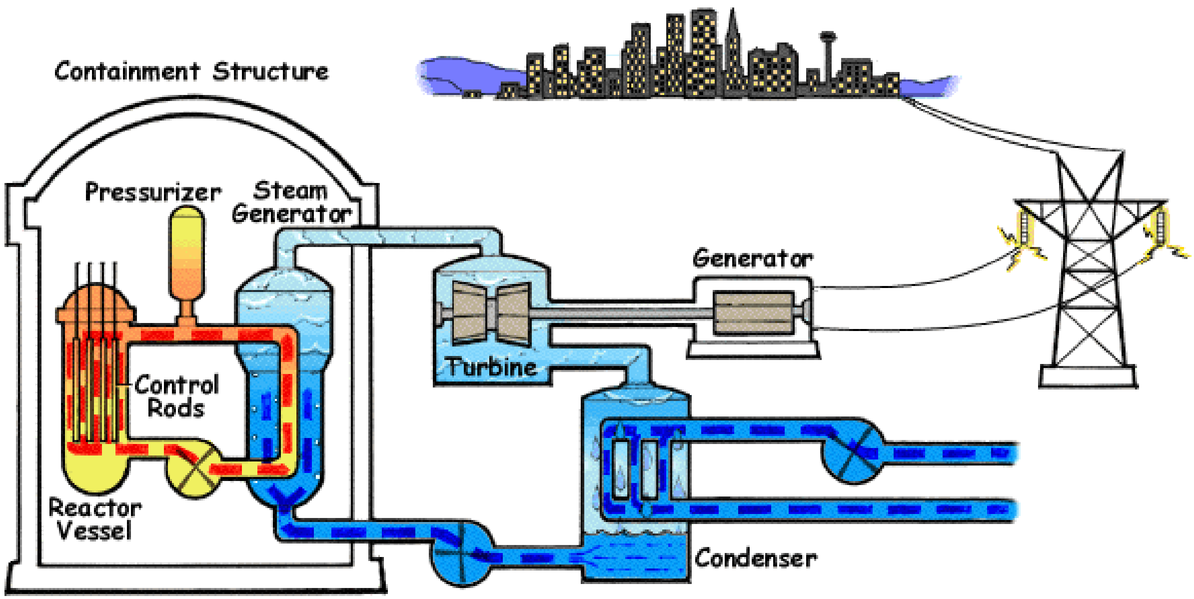
- In 1951, the 1st nuclear electricity was generated by EBR-1 (Experimental Breeder Reactor) in USA.
  EBR-1 was an SFR (sodium-cooled fast reactor) (Na-K coolant).



Introduction

- Layout of the SFR and PWR systems



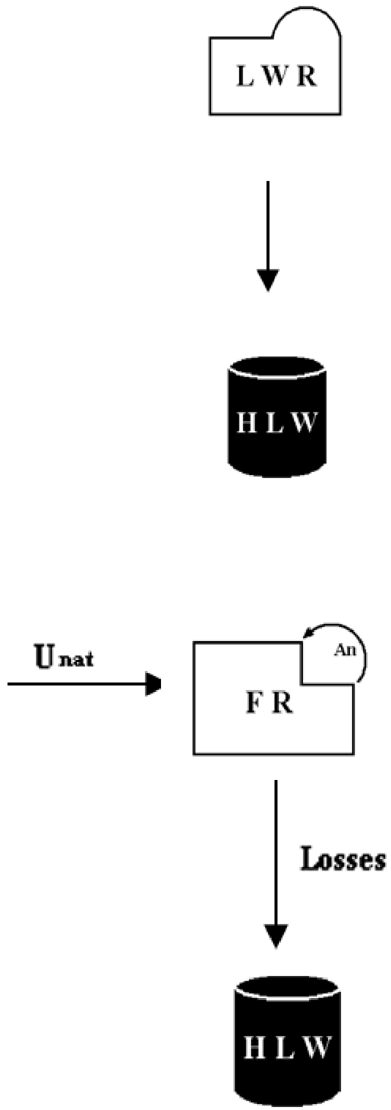


Introduction

- Scopes of comparison in this work
  - Reactor core design features
  - Core characteristics
  - Core safety parameters
  - Generic safety potential
  - Fuel cycle aspects

- What PWR and SFR are to be compared?
  - PWR
    : Standard commercial (~GWe) power reactor
    : UO_2 fueled core and open cycle
    : 18-month cycle

  - SFR
    : Standard big size (~GWe) power reactor
    : Closed U-Pu fuel cycle with a pyro-technology
    : U-Pu-10Zr metallic fuel
    : ~18-month cycle



Comparison of SFR and PWR Core Design Features

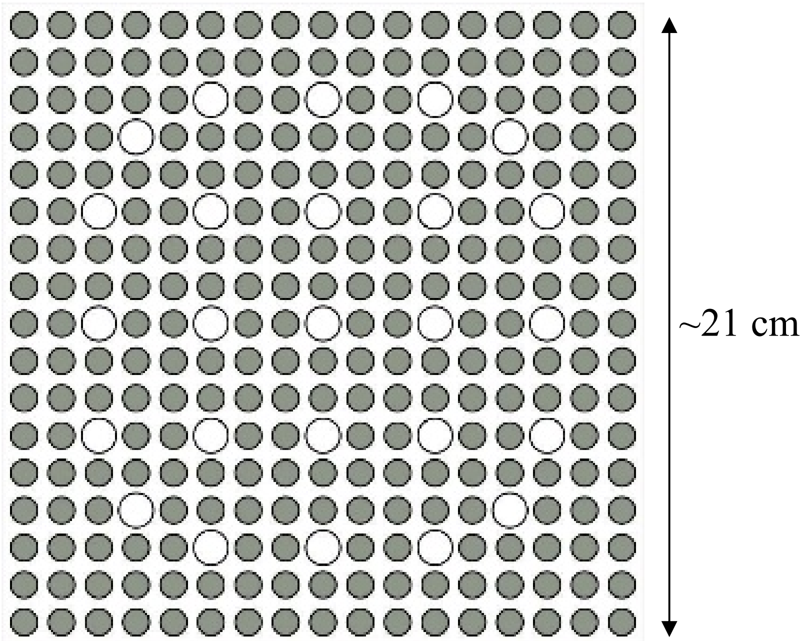
Na and Water Coolants

	Na	H_2O	Conditions
Melting temperature, ℃	97.8	0	STP
Boiling temperature , ℃	883	100	
Density, kg/m^3	880	713	~300 ℃ (2,000 psi for water)
Thermal conductivity, W/mK	76	0.54	
Viscosity	0.34	0.1	
Specific heat, J/kgK	1,300	5,600	
Heat capacity, MJ/m^{3}K	1.14	4.00	
Merit	Good material compatibility and heat transfer	Low melting T, Abundancy Good material compatibility	
Demerit	Na-water reaction Na fire	Low heat transfer High P	

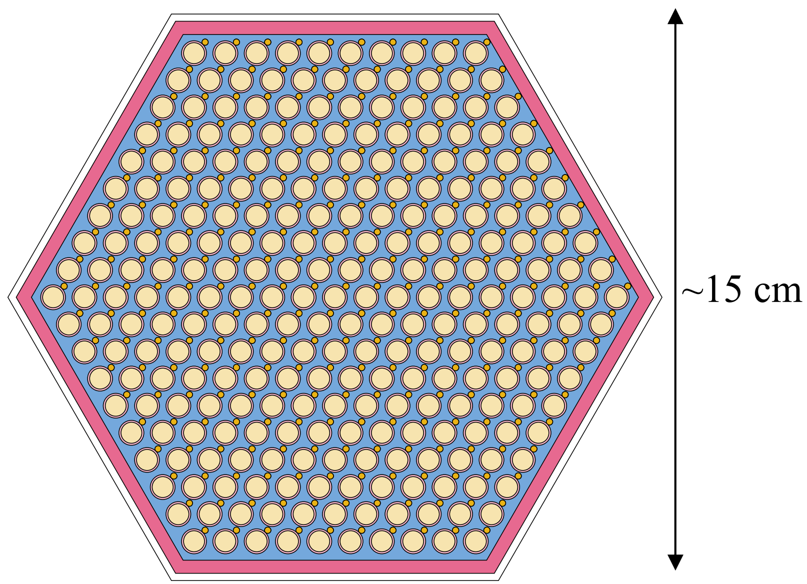
	SFR	PWR (2250 psi)
Inlet T, ℃	**~350**	**~300**
Exit T, ℃	**510~550**	**~300**
Boiling T, ℃	**> 892**	**345**

Fuel and Fuel Assembly Designs

- Ceramic (UO_2) fuel in PWR **vs.** Metallic (U-TRU-Zr) fuel in SFR
  - High fuel T, small gas plenum **vs.** Low fuel T, large gas plenum, low smear density
  - Zircaloy clad for PWR vs. HT9 clad for SFR
  - Good compatibility between fuel and coolant
- Fuel assembly (FA) design
  - Coarse rectangular array of fuel for PWR **vs.** Tight triangular array FA for SFR
  - ~50% water in PWR **vs.** 30~40% Na in SFR



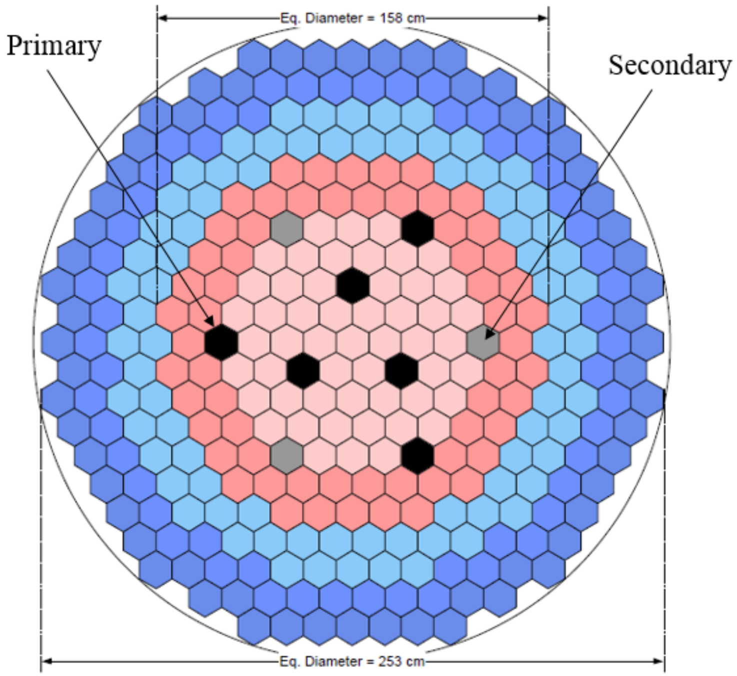
Fuel Assembly in PWR



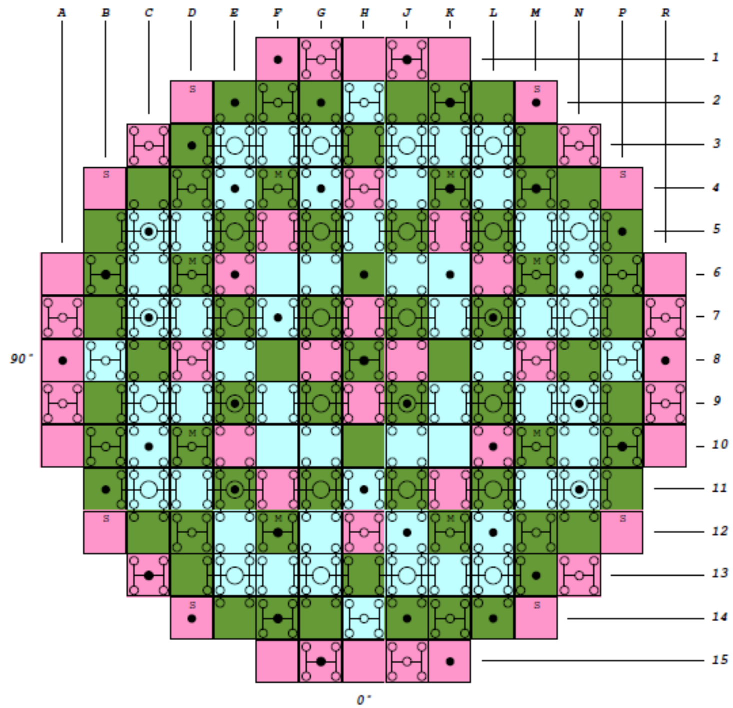
Fuel Assembly in SFR

Reactivity Control System

- Primary reactivity control system
  - Control rods in both SFR and PWR
  - Relatively small number of control rods in SFR
- Secondary reactivity control system
  - Independent control rods in SFR
  - Independent and diverse soluble boron (CVCS) in PWR



PGSFR Core

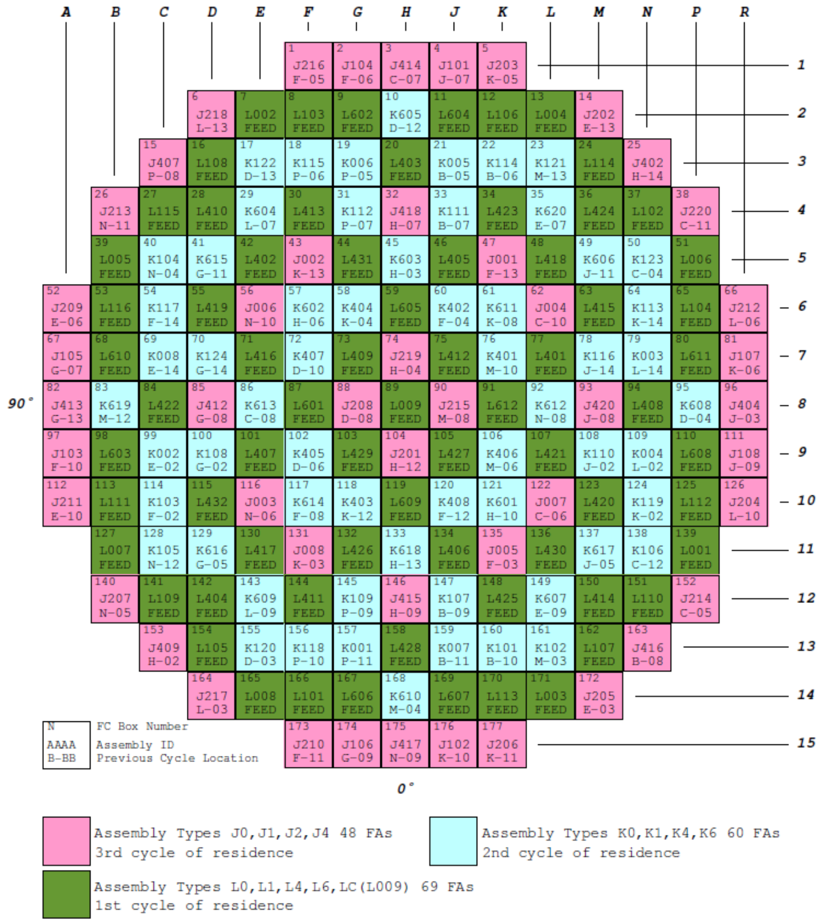


YGN Unit 6

Fuel Management Scheme

- Period fuel reloading in both SFR and PWR
  - Annual ~ 24-month cycle length (3~4 batch fuel management)
- Scattered reloading in SFR vs. Zone-wise fuel shuffling in PWR
  - Cycle-dependent loading pattern in SFR → only quasi equilibrium cycle
  - Batch-wise fixed loading pattern in PWR

    → Equilibrium cycle

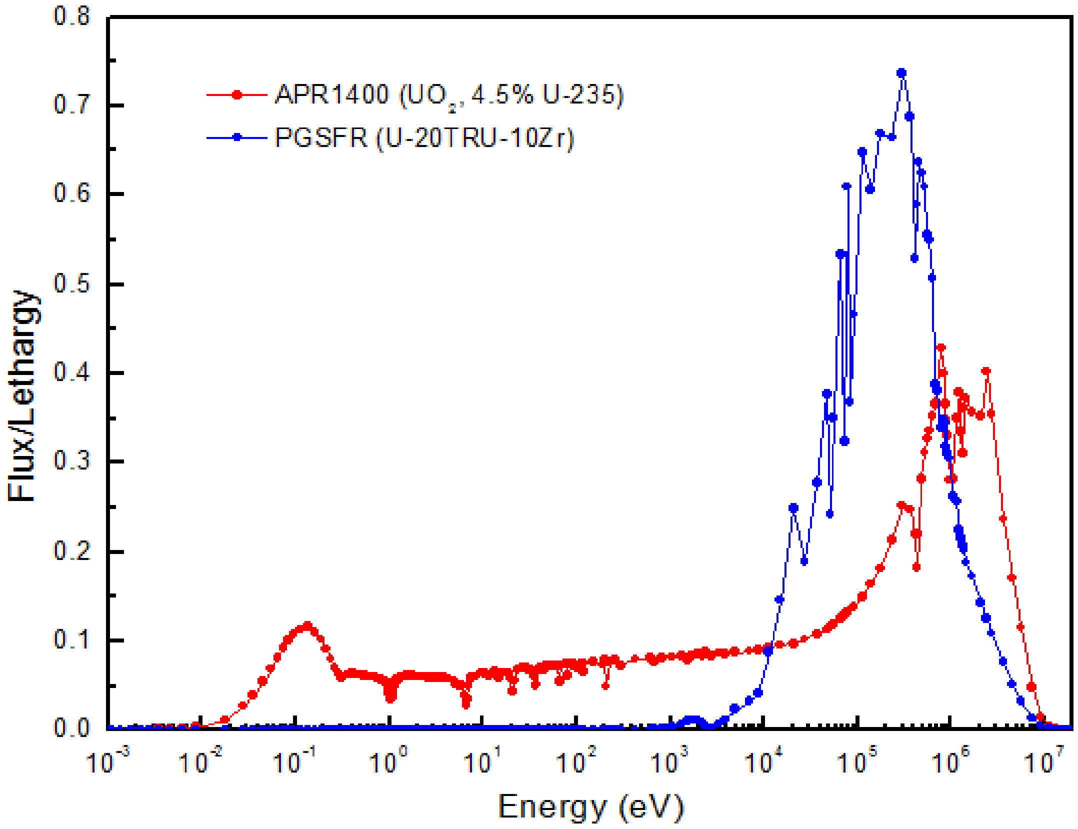


Loading pattern in YGN U6, Cycle 8

Neutronics Characteristics of the SFR and PWR Cores

Neutron Spectrum & Economy

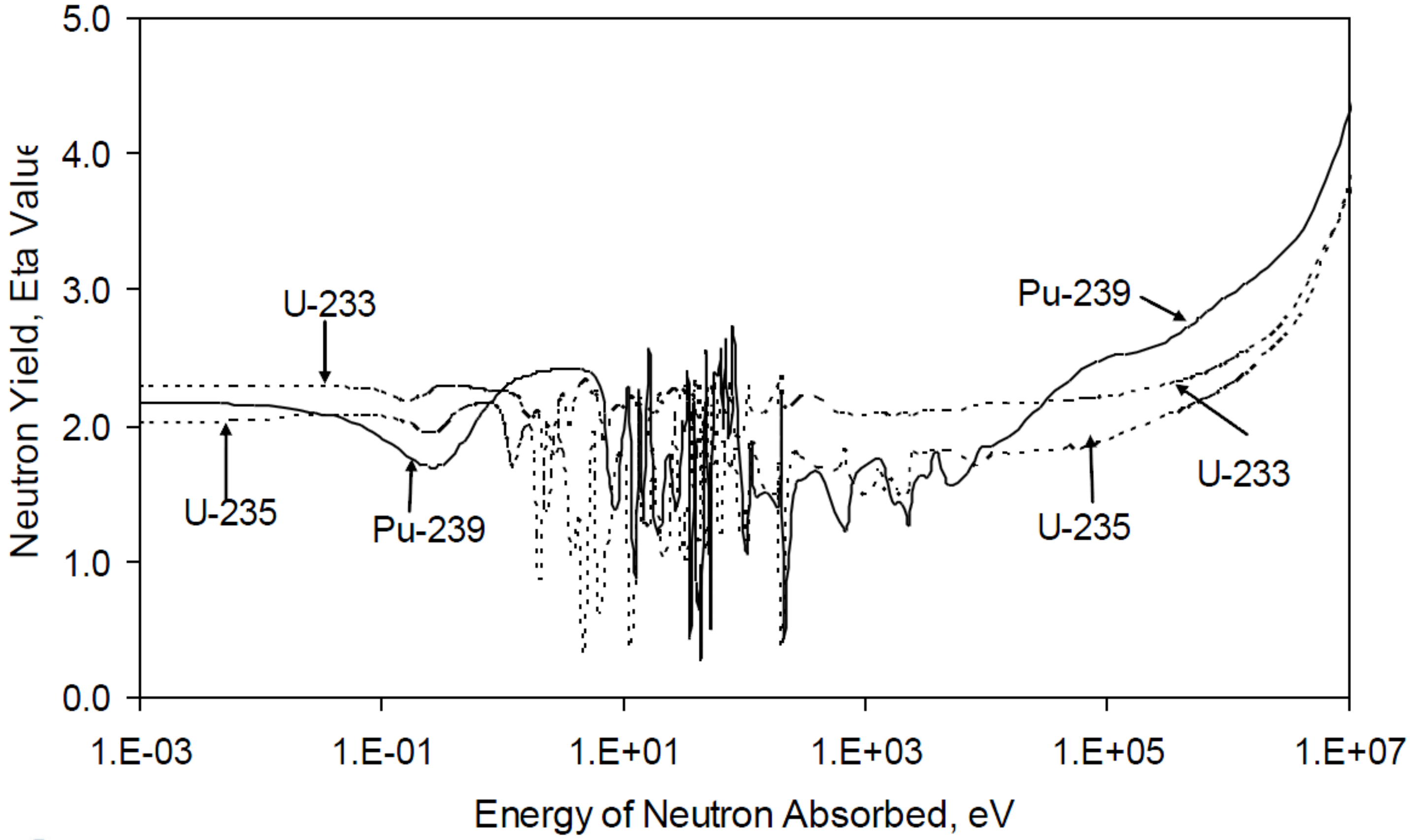
- Much harder spectrum in SFR → Higher neutron economy
  - Flexible core design in SFR (breeder, break-even, transmuter)
  - Rather flat power profile in SFR vs. Relatively high local peaking in PWR
  - Small fission product (FP) effects in SFR vs. High FP poisoning in PWR
  - More neutron E groups in SFR analysis (10~25)
  - More important inelastic scattering and unresolved resonances in SFR



  - A little higher fission neutron yield and energy release per fission in SFR

Neutron Spectrum & Economy

- Much harder spectrum in SFR → Higher neutron economy
- Conversion ratio (CR)
  - [Fissile Production] / [Fissile Destruction]
  - 0.2~1.3 in SFR vs. 0.5~0.6 in PWR



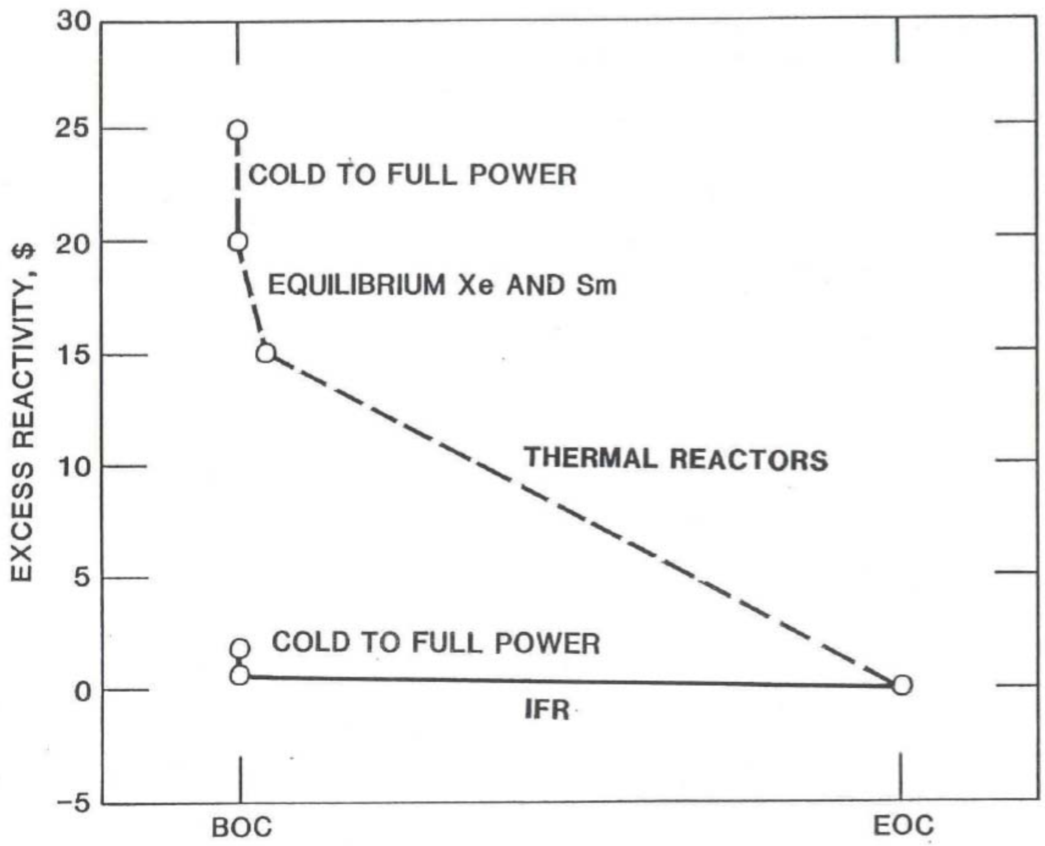
Neutron Spectrum & Economy

- CR = η + ε - 1 - A - L – D (normalized to a n absorption in fissile isotope)
  - η = no. of neutron by fission in fissile isotopes
  - ε = no. of neutrons by fission in fertile isotopes
  - A = parasitic capture; L = leakage; D = decay loss

	HWR	LWR	SFR
η	2.03	1.92	2.28
ε	0.02	0.09	0.36
η + ε -1	1.05	1.01	1.64
Losses: Structure	0.09	0.03	0.16
Coolant	0.03	0.08	0.01
Fis. Prod.	0.11	0.16	0.06
Leakage	0.08	0.15	0.05
Decay	-	-	0.03
Subtotal	0.31	0.42	0.31
Excess Neutrons (CR or BR)	0.74	0.59	1.33

Excess Reactivity During Operation

- High CR and small FP absorption in SFR vs. Low CR and Big FP absorption in PWR
  - In particular, large Xe worth (~3,000 pcm) in PWR
- Smaller temperature defects in SFR vs. relatively large T defects in PWR
- Small excess reactivity in SFR vs. Big excess in PWR
  - Smaller than a few dollars in SFR vs. Many dollars in PWR



Fuel Burnup and Composition

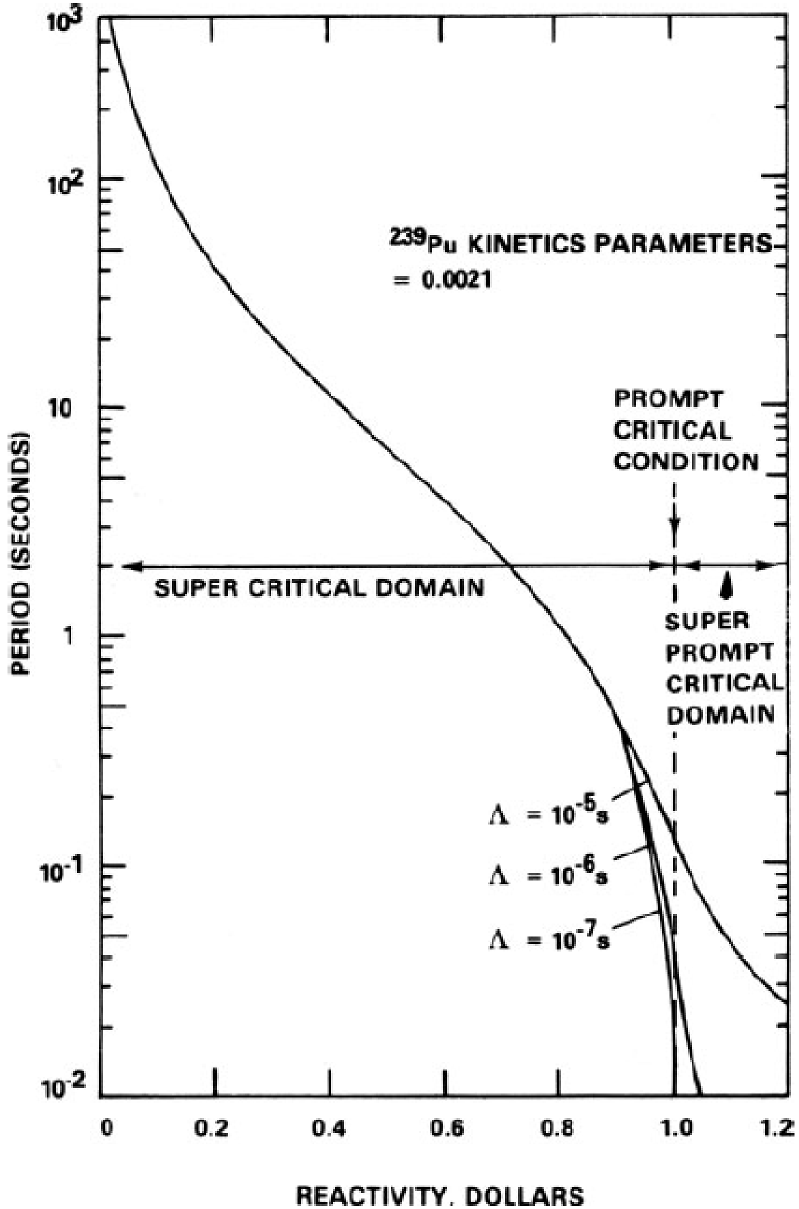
- Fuel discharge burnup
  - ~45 MWG/kgU in PWR vs. 100~150 GWD/kgHM in SFR
- Fuel compositions

Fuel Composition, %				
Reactor	PWR (APR1400, UO2, 4.5% U-235)		SFR (PGSFR, U-20Pu-10Zr)	
Condition	Fresh Fuel	Burnup (45 MWD/kgU)	Fresh Fuel	Burnup (150 MWD/kgHM)
U	100.00	98.68	77.90	79.32
Np	0.00	0.08	1.22	0.68
Pu	0.00	1.21	20.13	18.62
Am	0.00	0.02	0.53	1.05
Cm	0.00	0.01	0.22	0.34
Total	100.00	100.00	100.00	100.00

Pu Composition, %			
Reactor	PWR (APR1400, UO2, 4.5% U-235)	SFR (PGSFR, U-20Pu-10Zr)	
Condition	Burnup (45 MWD/kgU)	Fresh Fuel	Burnup (150 MWD/kgHM)
Pu-238	2.19	2.73	4.37
Pu-239	55.00	50.42	53.35
Pu-240	22.65	24.79	28.36
Pu-241	14.58	14.39	5.22
Pu-242	5.58	7.67	8.70
Total	100.00	100.00	100.00

Kinetic and Safety Parameters

- Neutron generation time
  - 0.2~0.4 μsec in SFR
  - 20~30 μsec in PWR
- Effective delayed neutron fraction
  - 300~400 pcm in SFR
  - 500~600 pcm in PWR
- Reactor period
  - Similar for ρ < 0.9 dollar



Kinetic and Safety Parameters

- Coolant void reactivity (CVR)

  - Clearly positive CVR (4~6 dollars) in SFR vs. Strongly negative CVR in PWR

- Reactivity coefficients

	SFR	PWR
Coolant temperature (density) coefficient	Clearly positive (0.1~0.2 cents/C; 0.3~0.6 pcm/C)	Strongly negative 0 ~ -60 pcm/C
Fuel temperature coefficient	Slightly negative (-0.05~-0.09 cents/C; -0.15~-0.24 pcm/C	Strongly negative -2~-4 pcm/C
Fuel axial expansion coefficient	Clearly negative (-0.06~-0.1 cents/C; -0.18~-0.33 pcm/C)	--
Core radial expansion coefficient	Strongly negative (-0.2~-0.3 cents/C; -0.66~-0.99 pcm/C)	--

- Positive Xe feedback coefficient in PWR?

Support of Passive Safety

- Passive reactivity shutdown in ATWS (Anticipated Transient without Scram) in SFR
  - Demonstration in EBR-II in 1986
  - Metallic fuel is more favorable due to the low Doppler reactivity.

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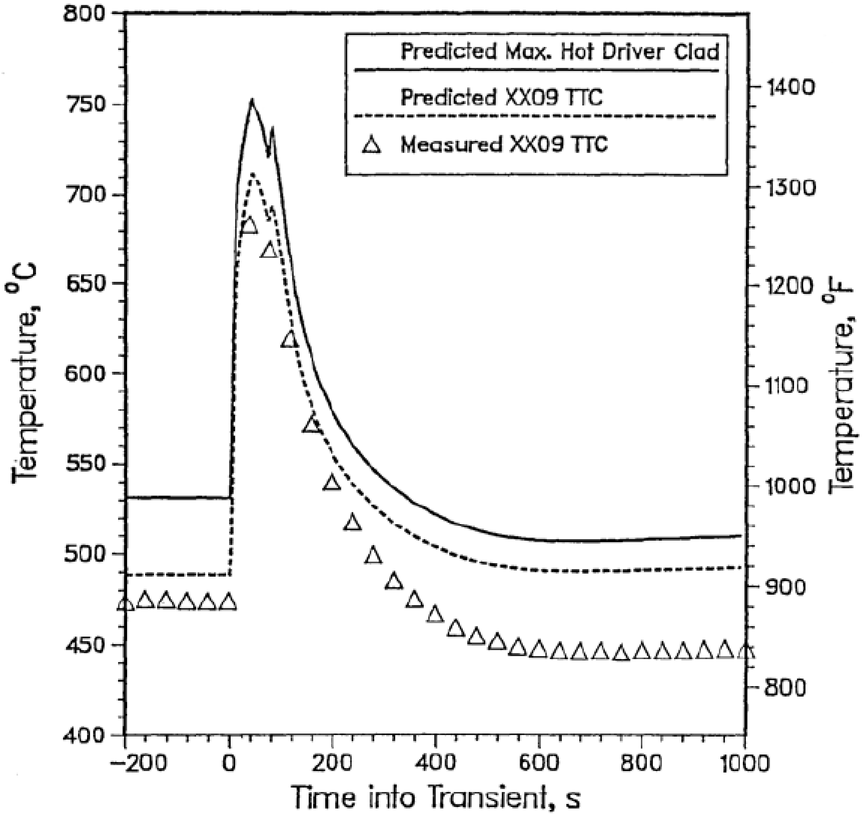
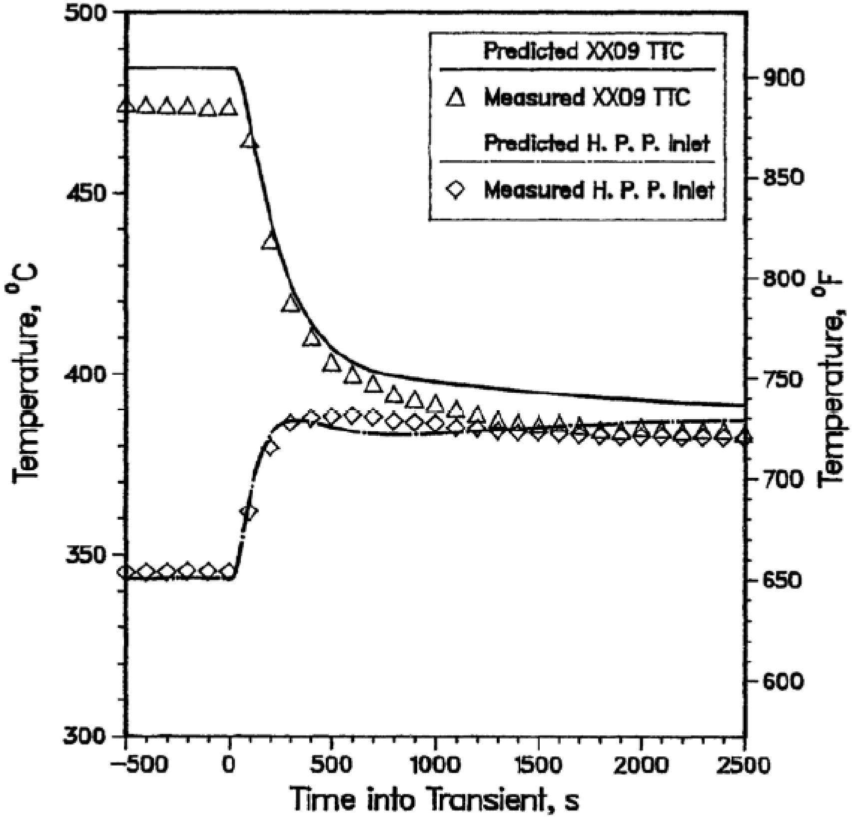
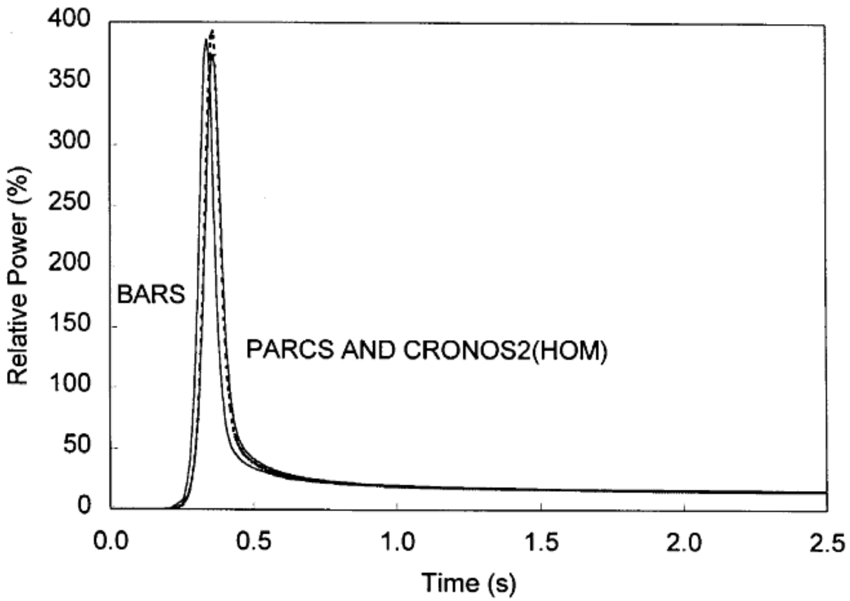


LOHS

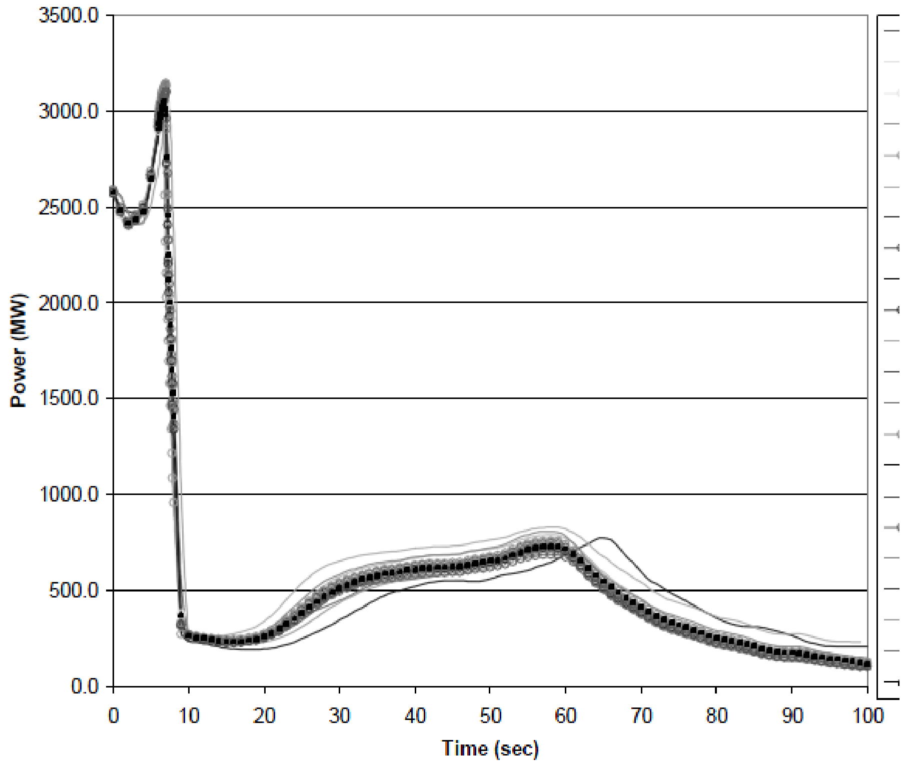


Accidental Reactivity Insertions

SFR	PWR
Coolant loss (impractical in pool-type?) Fuel slumping (impractical in metallic fuel?)	Rod ejection (self-controllable) Main steam-line break (uncontrollable)



Rod ejection in PWR

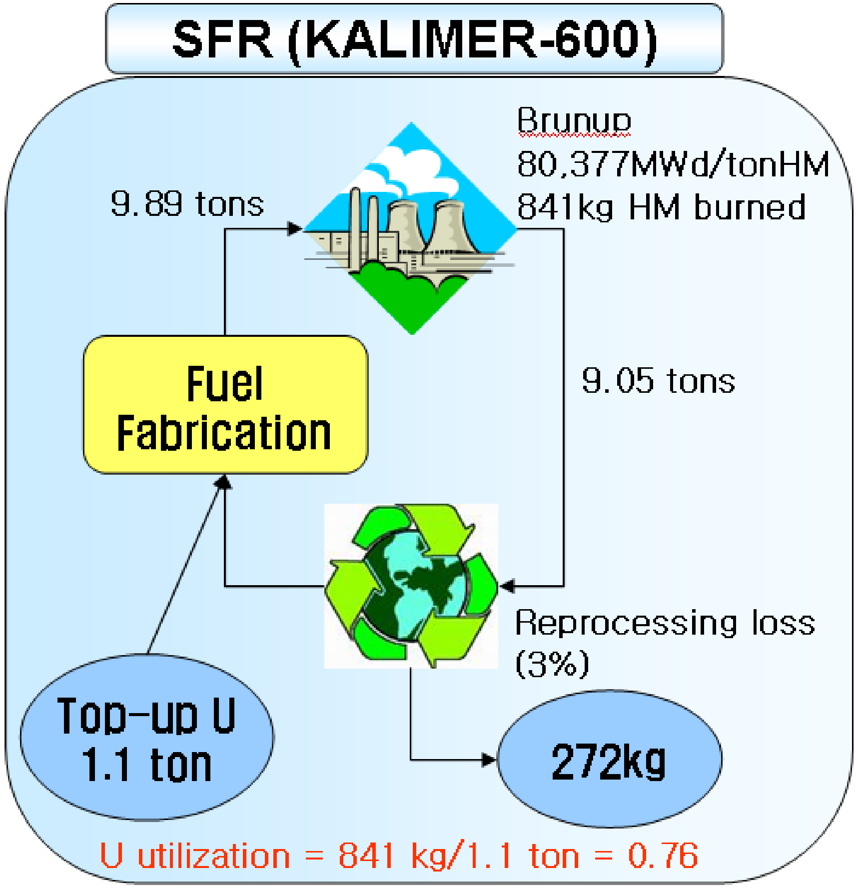


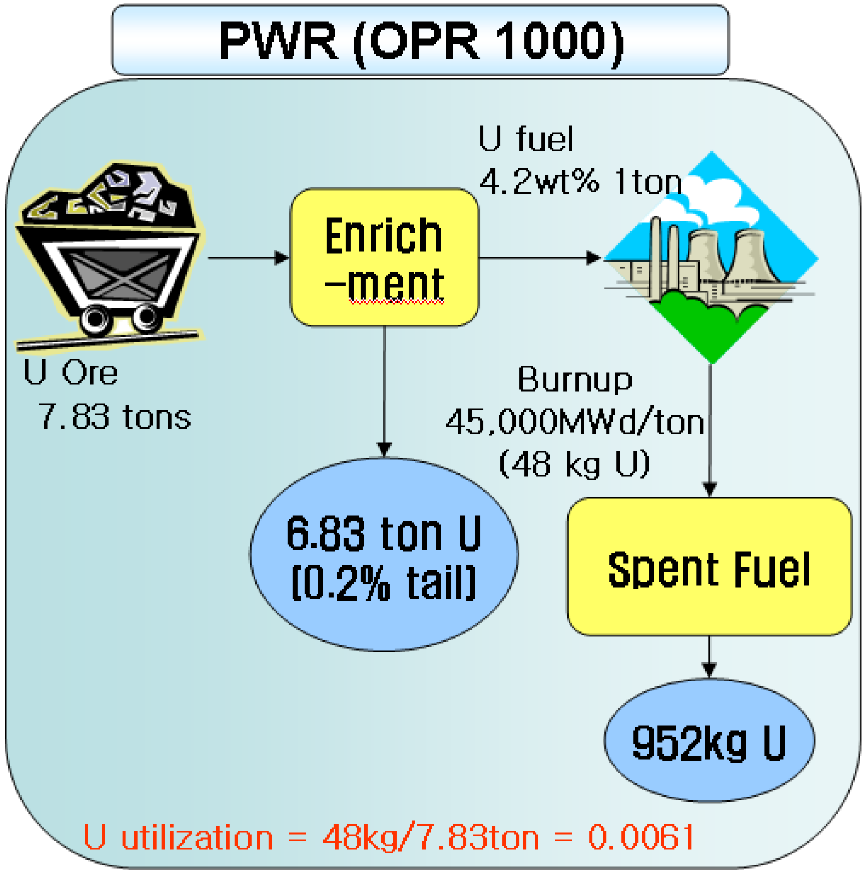
MSLB simulation TMI-2

- Too big negative feedback is not always good?
- Optimization is necessary for better transient responses in PWR.

Fuel Cycle Considerations

- About 100 times higher resource utilization in SFR with a closed fuel cycle
  - Efficient pyro-processing is a necessary condition for the favorable SFR performances.





Coolant Activations

- Sodium activation in SFR
  - Na-23 + n → Na-24 ($T_{1/2}$ = 15 hrs, gamma emitter)
    → Intermediate loop

- Estimated cool-down time to meet the IAEA "exemption" criteria (to be freely used for other industrial purposes)
  - Pure sodium: ~ 7 yrs
  - Sodium with impurities: 50~100 yrs

- Activation of water coolant in PWR
  - Tritium production due to boron and LiOH
    → Bulky liquid radioactive wastes

Summary and Concluding Remarks

- The spectral difference between SFR and PWR leads to fundamental and huge discrimination in the core performances, characteristics, and safety potentials.

- The fast-spectrum near-breakeven SFR is advantageous in terms of the resource utilization, and the passive reactor shutdown, although the coolant void reactivity is clearly positive.

- The CVR in SFR needs to be reduced further for a better generic safety and public acceptance. Or a reliable counter-measure may be introduced.

- A higher level of safety is expected, if the high excess reactivity in PWR can be substantially reduced.

- A strong negative reactivity feedback is not always favorable in nuclear reactors. An optimization of the negative feedbacks in PWR will be worthwhile.

Backup Slides

Neutron Economy

- No blanket in SFR

		PWR	SFR	
			CR=1.0	CR=0.5
U-235 or TRU enrichment, %		**4.2**	**13.9**	**33.3**
Source	fission	100.0%	99.8%	99.9%
	(n,2n)		0.2%	0.1%
Loss	leakage	3.5%	**22.9%**	**28.7%**
	radial	3.0%	12.3%	16.6%
	axial	0.4%	10.6%	12.1%
	absorption	96.5%	77.1%	71.3%
	fuel	76.7%	71.8%	62.2%
	(U-238 capture)	(27.2%)	(31.6%)	(17.1%)
	coolant	**3.4%**	0.1%	0.1%
	structure	0.6%	3.7%	3.7%
	fission product	**6.8%**	1.5%	2.4%
	control	9.0%	0.0%	2.9%

Metal vs. Oxide