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Trends in Transmutation Performance and Safety Parameters Versus TRU Conversion Ratio of Sodium-Cooled Fast Reactors

The Tenth OECD Nuclear Energy Agency Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation

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Outline

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  - Advanced Burner Reactor
- **Core Designs**
  - Design Approaches
  - Oxide and Metal Fuel Cores
- **Performance Parameters**
  - TRU Charge and Consumption Rates
- **Safety Parameters**
  - Reactivity Feedback Coefficients
- **Summary**

GNEP Fast Reactor Campaign

- **Develop and demonstrate advanced recycle fast reactor technology (for the GNEP closed fuel cycle)**

- **Key technology needs identified in Technology Development Plan**
  - Closed fuel cycle demonstration
    - *By prototype in conjunction with separations and fuel facilities*
  - Establishment of domestic infrastructure
  - Fast reactor capital cost reduction
  - Reactor safety validation

- **Campaign structured in three elements**
  - Near-term technology development *(prototype design needs)*
  - Long-term reactor research *(cost reduction features)*
  - Reactor simulation *(new tools for design optimization)*

Advanced Burner Reactor

- **ABR is one of the major technologies to be developed in GNEP**
  - Primary mission of ABR is to demonstrate the transmutation of TRU recovered from LWR spent fuel, and hence the benefits of the fuel cycle closure to nuclear waste management
- **Potential design objectives**
  - Small core size (i.e., high power density) is desirable to reduce the construction cost
  - Longer cycle length is desirable to increase the capacity factor
  - Low TRU conversion ratio is desirable to increase the TRU consumption rate
- **However, a low conversion ratio**
  - Requires a high TRU fraction in heavy metal, which is far beyond the current irradiation experience with plutonium-based fast reactor fuels
  - Increase the burnup reactivity swing
    - *To compensate the reactivity control requirement, more control assemblies must be employed or cycle length needs to be reduced*

Overview of Parametric Study

- **A systematic study was performed on the trends in transmutation performance and safety parameters versus TRU conversion ratio for sodium-cooled recycle reactors**
- **Twenty ABR core concepts of 1000 MWt power rating were developed, starting from the SuperPRISM core designs**
  - Both metal and oxide core designs were developed for target TRU conversion ratios of 1.0, 0.75, 0.50, 0.25, and 0.0 at an equilibrium cycle
    - *Ternary metal fuel form of U-TRU-Zr*
    - *Mixed oxide form of (U-TRU)O2*
  - TRU recovered from ABR spent fuel was used as the primary feed and the TRU from an external supply was used for makeup
  - Two makeup TRU feeds were considered with different MA to Pu ratio
    - *TRU recovered from 5-year cooled LWR spent fuel with average discharge burnup of 50 MWd/kg (MA/Pu≈0.1)*
    - *TRU from multi-recycled Pu fuel (MA/Pu≈1.0)*

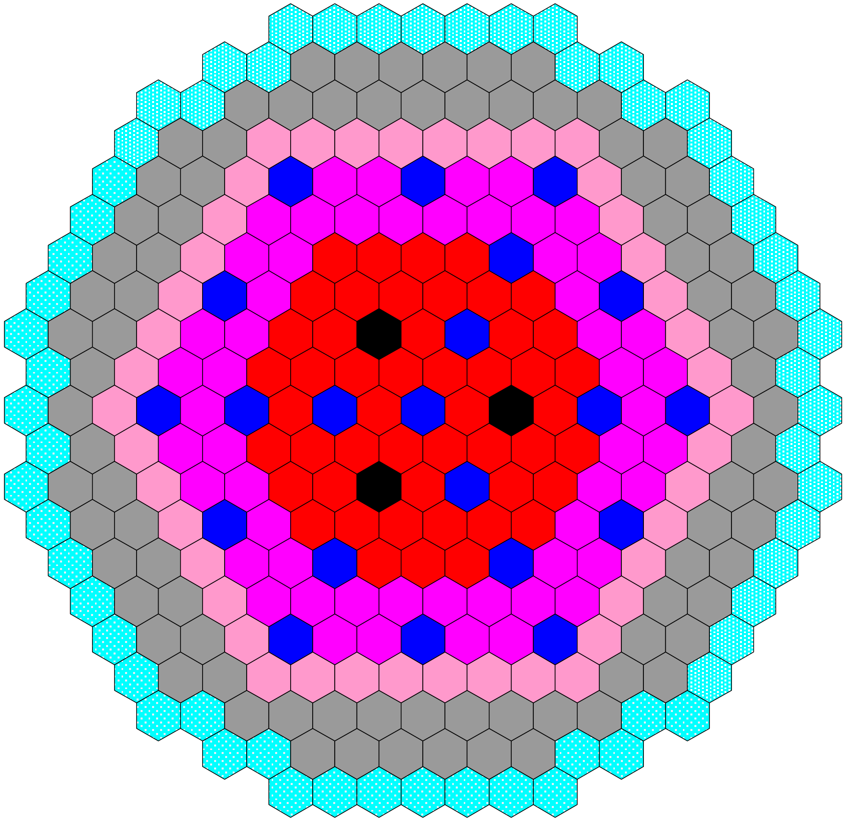
Makeup TRU Feeds

TRU from LWR Spent Fuel				TRU from Multi-Recycled Pu Fuel			
Np-237	4.8	Am-241	3.4	Np-237	7.3	Am-241	18.8
Pu-236	0.0	Am-242	0.0	Pu-236	0.0	Am-242	0.1
Pu-238	2.3	Am-243	1.5	Pu2-38	2.0	Am-243	15.9
Pu-239	47.9	Cm-242	0.0	Pu-239	18.2	Cm-242	0.0
Pu-240	22.5	Cm-243	0.0	Pu-240	13.4	Cm-243	0.1
Pu-241	10.6	Cm-244	0.5	Pu-241	5.9	Cm-244	7.0
Pu-242	6.5	Cm-245	0.0	Pu-242	10.6	Cm-245	0.9
Pu	89.8	MA	10.2	Pu	50.0	MA	50.0

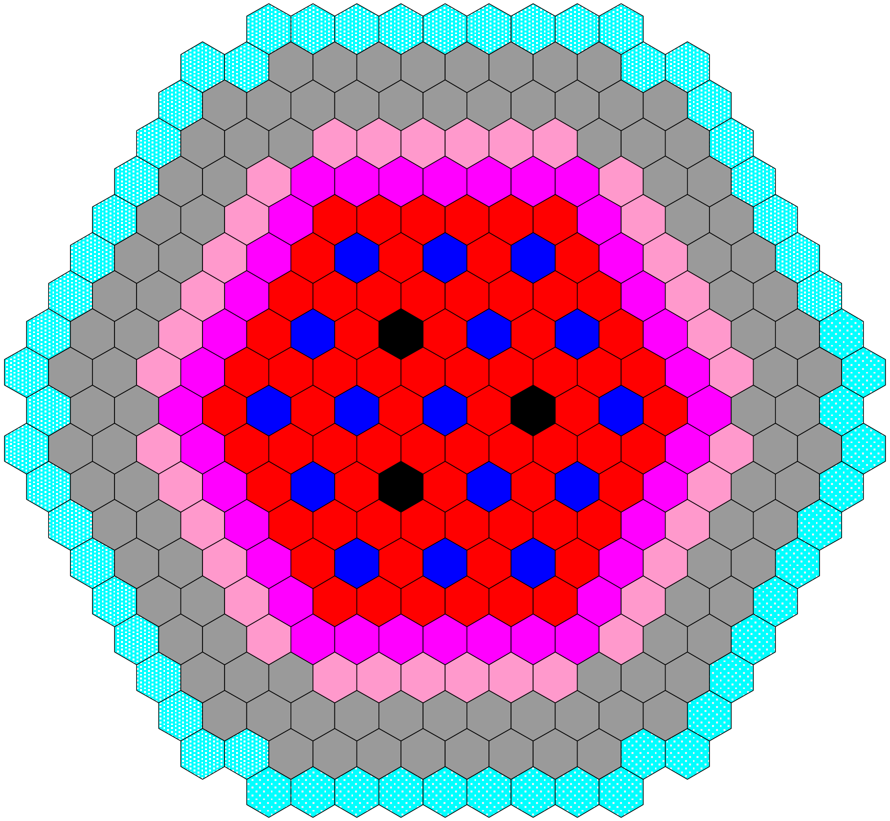
Design Approaches

- **Conventional design approaches were adopted to stay within current fast reactor technology bases as much as possible, since TRU transmutation fuels are not fully developed**
  - Fuel smeared density was assumed 75% for the ternary metal fuel and 85% theoretical density for the oxide fuel
  - Low-swelling ferritic stainless steel (HT9) cladding was selected as structural material (cladding and duct)
- **Compact cores were developed to maximize the linear power within the thermal design limits**
- **Discharge burnup was maximized within the fast fluence limit of assumed cladding material**
  - To stay within the current database, a cladding fast fluence limit was assumed to be about 4×10^{23} n/cm^2
- **Fuel volume fraction was iteratively determined to yield the target conversion ratio that is primarily determined by the TRU enrichment**
  - Fuel pin size and the number of fuel pins per assembly were adjusted to yield the appropriate fuel volume fraction and satisfy the linear power limit

Example Core Layouts (CR=0.25)



Metal Fuel Core



Oxide Fuel Core

Inner core
Middle core
Outer core
Reflector
Primary control
Ultimate shutdown
Shield

Key Design Parameters of Metal Cores

Target TRU CR		1.0	0.75	0.5	0.25	0.0	
						MA/Pu≈0.1	MA/Pu≈1.0
Fuel assemblies		19/66/66[a]	30/42/72	42/66/36	48/54/42	78/24/42	78/24/42
Control assemblies		9/3[b]	16/3	16/3	22/3	22/3	22/3
Fuel pins per assembly		271	271	324	540	540/540/547	540/540/547
Fuel pin diameter (cm)		0.81	0.76	0.62	0.46	0.45/0.49/0.54	0.49/0.54/0.59
Volume fraction (%)	Fuel	34.26	29.30	22.08	17.44	16.0/20.6/26.1	20.4/26.2/33.3
	Bond	11.42	9.77	7.36	5.81	5.3/ 6.9/ 8.7	6.8/ 8.7/11.1
	Structure	25.73	25.68	26.41	29.15	28.5/30.4/31.4	31.4/31.4/32.4
	Coolant	28.59	35.25	44.15	47.60	50.1/42.1/33.9	41.4/33.6/23.2

[a] Inner core (IC)/Middle Core (MC)/Outer Core (OC); [b] Primary/Secondary control assemblies

Key Design Parameters of Oxide Cores

Target TRU CR		1.0	0.75	0.5	0.25	0.0	
						MA/Pu≈0.1	MA/Pu≈1.0
Fuel assemblies		19/66/66[a]	72/36/36	72/36/36	72/36/36	78/24/42	78/24/42
Control assemblies		9/3[b]	16/3	16/3	22/3	22/3	22/3
Fuel pins per assembly		271	271	324	324	324/324/324	324/324/324
Fuel pin diameter (cm)		0.87	0.81	0.66	0.56	0.44/0.46/0.48	0.48/0.50/0.53
Volume fraction (%)	Fuel	49.29	41.65	30.22	19.73	10.4/11.9/13.5	13.2/15.1/17.2
	Bond	2.55	2.16	1.56	1.02	0.54/0.62/0.70	0.68/0.78/0.89
	Structure	28.58	27.71	29.22	26.22	22.8/23.4/24.0	23.9/24.7/25.4
	Coolant	19.58	28.48	39.00	53.02	66.4/64.1/61.8	62.2/59.4/56.5

[a] Inner core (IC)/Middle Core (MC)/Outer Core (OC); [b] Primary/Secondary control assemblies

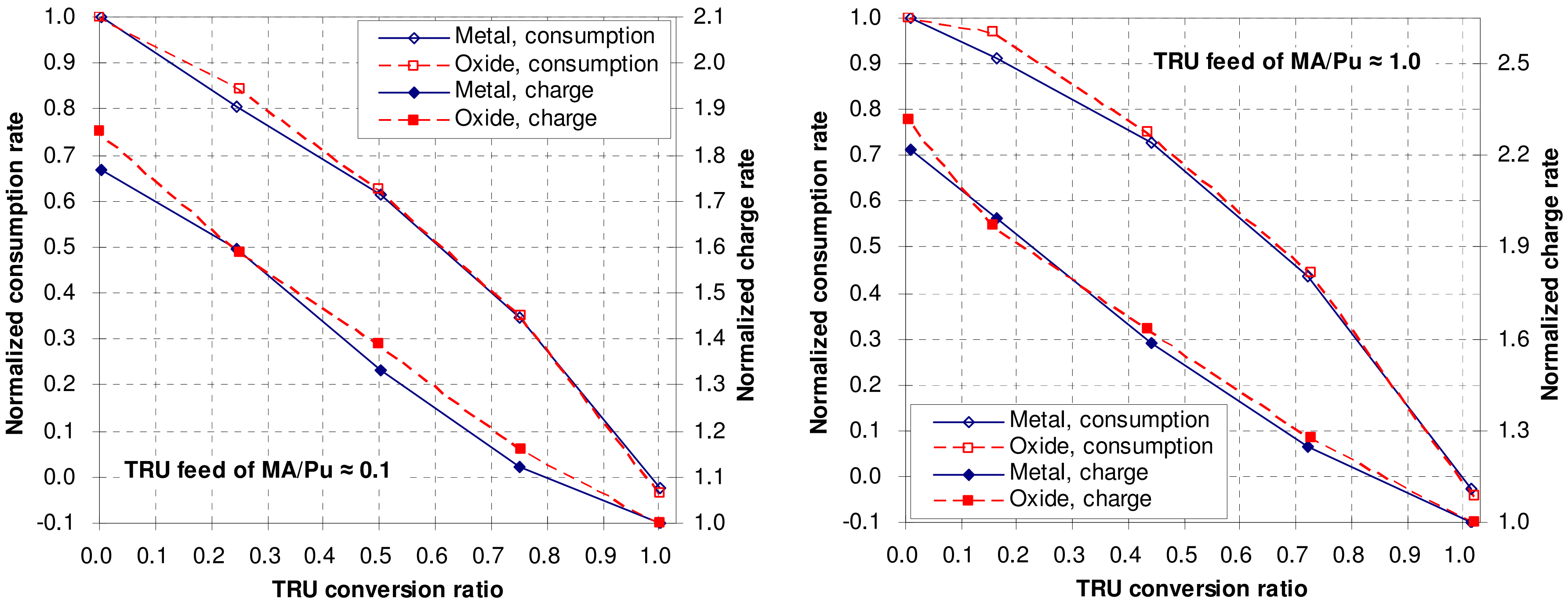
Equilibrium Cycle Core Performance Parameters
for Makeup TRU Feed of MA/Pu≈0.1

Target TRU CR		1.0	0.75	0.5	0.25	0.0
Metal fuel core	Cycle length, days	370	232	221	158	132
	Average fuel residence time, days	1351	1448	1380	1293	1284
	Average TRU enrichment, %	13.9	21.2	33.3	55.5	98.6
	TRU conversion ratio	1.001	0.749	0.502	0.245	0.004
	HM inventory at BOC, MT	16.75	13.44	9.45	5.86	3.62
	TRU inventory at BOC, MT	2.45	2.86	3.08	3.22	3.57
	Ave. discharge burnup, MWd/kg	73	100	132	183	294
	Burnup reactivity loss, %Δk	-0.06	1.49	2.98	3.78	4.35
Oxide fuel core	Cycle length, days	607	353	326	165	124
	Average fuel residence time, days	2216	2204	2039	1851	1582
	Average TRU enrichment, %	16.9	25.1	38.0	59.9	99.9
	TRU conversion ratio	1.001	0.753	0.499	0.250	0.001
	HM inventory at BOC, MT	19.28	15.25	10.91	6.86	3.82
	TRU inventory at BOC, MT	3.49	3.88	4.08	4.00	3.81
	Ave. discharge burnup, MWd/kg	103	131	166	229	328
	Burnup reactivity loss, %Δk	0.20	1.80	3.57	3.02	4.06

Equilibrium Cycle Core Performance Parameters
for Makeup TRU Feed of MA/Pu≈1.0

Target TRU CR		1.0	0.75	0.5	0.25	0.0
Metal fuel core	Cycle length, days	370	232	221	158	132
	Average fuel residence time, days	1351	1448	1380	1293	1284
	Average TRU enrichment, %	13.9	23.6	39.7	69.4	97.4
	TRU conversion ratio	1.015	0.722	0.442	0.163	0.008
	HM inventory at BOC, MT	16.75	13.44	9.46	5.88	4.82
	TRU inventory at BOC, MT	2.45	3.19	3.71	4.11	4.68
	Ave. discharge burnup, MWd/kg	73	100	132	183	230
	Burnup reactivity loss, %Δk	-0.06	1.03	1.93	2.36	2.23
Oxide fuel core	Cycle length, days	607	353	326	165	124
	Average fuel residence time, days	2216	2204	2039	1851	1582
	Average TRU enrichment, %	16.9	27.5	44.7	74.3	97.9
	TRU conversion ratio	1.022	0.727	0.435	0.156	0.007
	HM inventory at BOC, MT	19.28	15.26	10.93	6.88	5.12
	TRU inventory at BOC, MT	3.49	4.27	4.85	5.07	5.01
	Ave. discharge burnup, MWd/kg	103	131	166	228	257
	Burnup reactivity loss, %Δk	0.20	1.30	2.30	1.86	2.00

Normalized TRU Charge and Consumption Rates

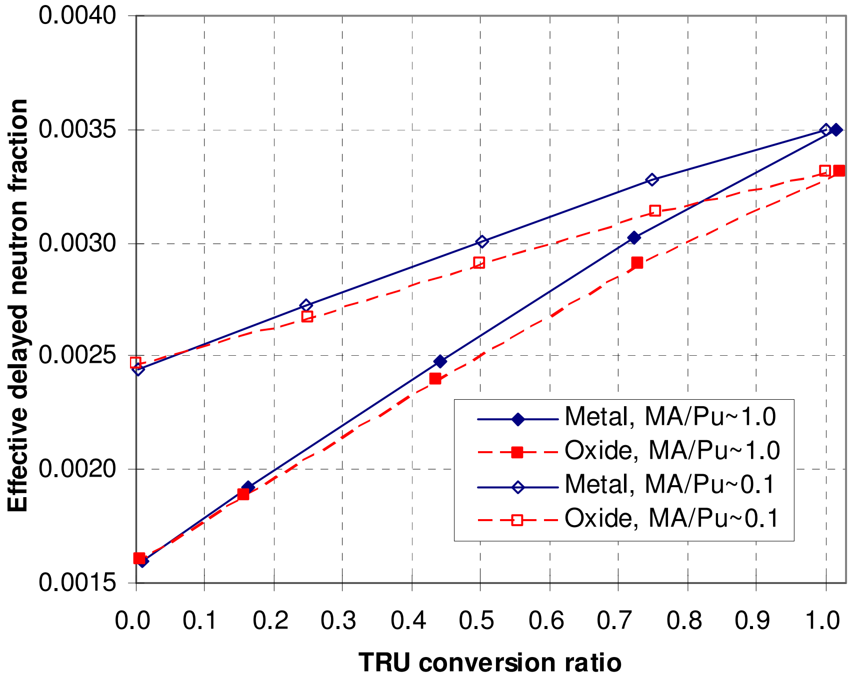


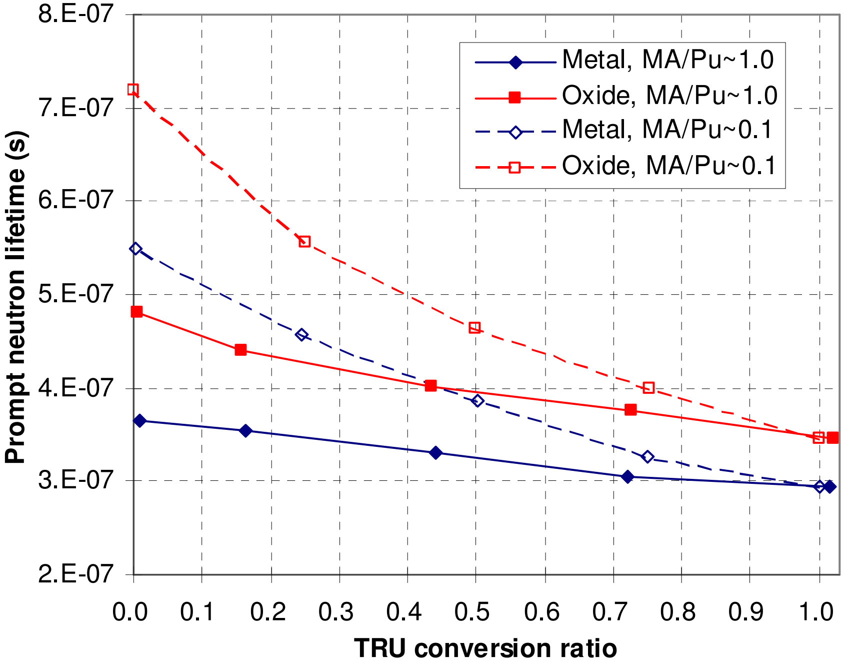
- TRU consumption rate (relative to the maximum theoretical value of uranium-free fuel) reaches ~80% of the maximum theoretical value when TRU CR is in the range of 0.25-0.35
- TRU charge rate (relative to the breakeven core) increases with decreasing TRU CR

TRU Charge and Consumption Rates

- **In order to reduce the legacy TRU inventory or to increase the support ratio to optimize the LWR to ABR ratio in the total nuclear fleet (under the assumption that ABR is less economical than LWR),**
  - It is desirable to reduce the TRU conversion ratio as low as practically possible within the safety and TRU fuel related constraints
  - With a low TRU conversion ratio, the amount of spent ABR fuel to be reprocessed is also reduced significantly due to the significantly smaller HM charge rate
- **On the other hand, the initial TRU inventory required to start the ABR and the TRU charge rate to produce the same amount of energy increase with decreasing TRU conversion ratio**
  - If the fractional reprocessing loss is constant, the increase in the required amount of TRU would increase the reprocessing loss of TRU to the geological repository
- **If two design objectives of maximizing the TRU consumption rate and minimizing the reprocessing loss of TRU to the geological repository are pursued, a compromised TRU conversion ratio would be in the range of 0.2 to 0.4**

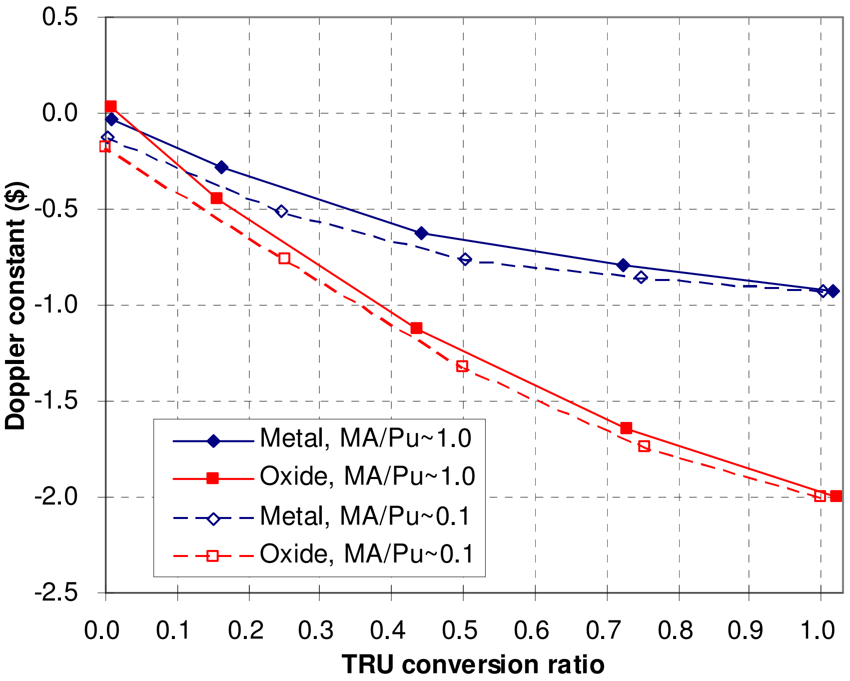
Reactivity Feedback Coefficients

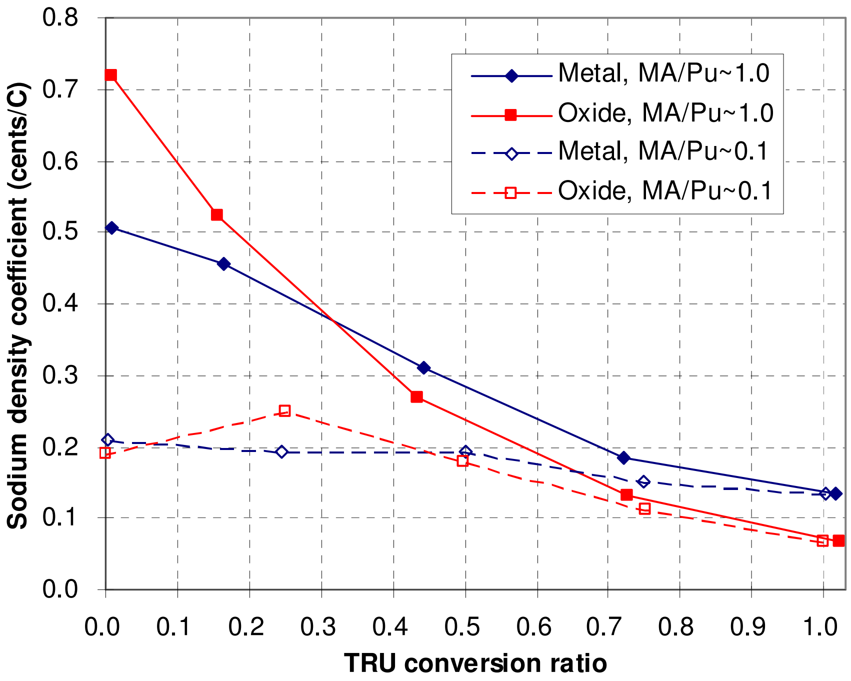




- **Heavy metal loading and the TRU fraction in HM increases with decreasing TRU conversion ratio**
  - Effective delayed neutron fraction decreases monotonically due to reduced U-238 fission
  - The reduced absorption in HM increases the prompt neutron lifetime

Reactivity Feedback Coefficients





- **Reduced U-238 fraction makes the Doppler constant less negative**
  - Doppler constant of the uranium-free core (i.e., CR~1.0) fueled with TRU feed of MA/Pu≈1 is almost zero
- **Sodium density coefficient generally becomes more positive with decreasing TRU conversion**
  - But it does not show a monotonic behavior because of the variations in the core configuration, material volume fractions, and TRU inventory

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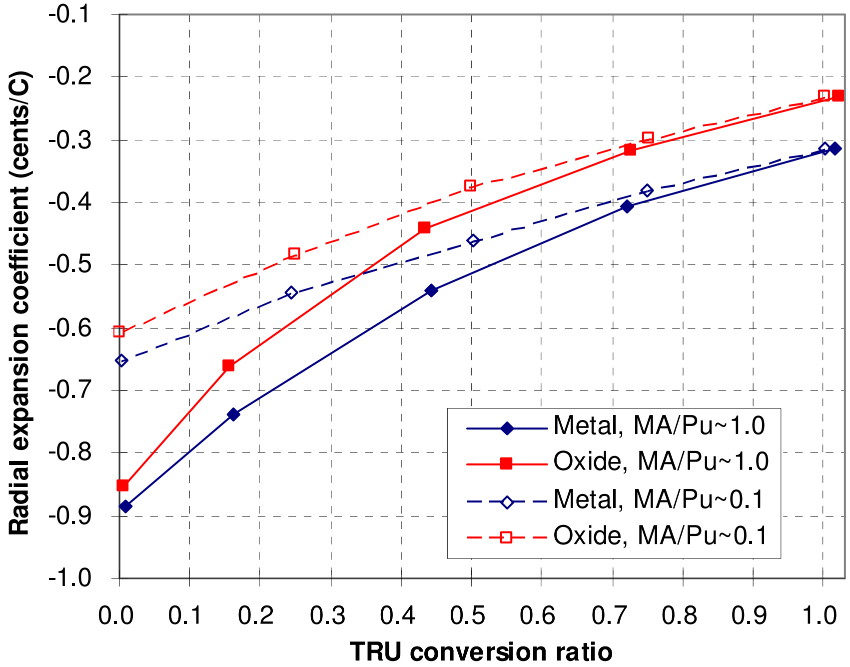
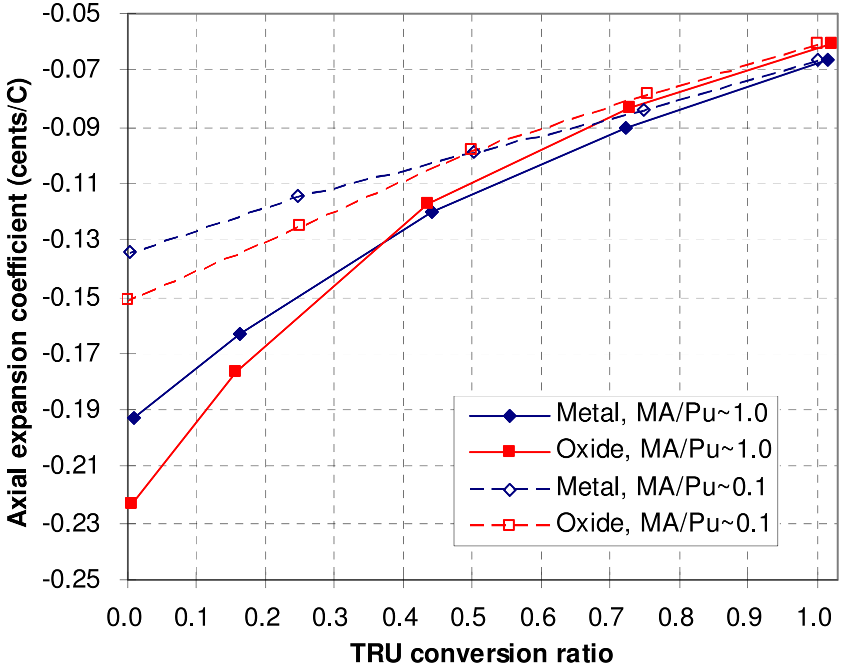
Reactivity Feedback Coefficients





- **Reduced absorption in HM makes both the radial and axial expansion coefficients more negative by increasing the leakage fraction**
  - Enhanced leakage to reduces the neutron absorption in the core

Passive Safety Behavior

- **Inherent safety trends and general criteria are explained in Wade and Fujita, *Trends versus Reactor Size of Passive Reactivity Shutdown and Control Performance, Nuclear Science and Engineering*, 103 (1989)**
- **The quasi-static fast reactor reactivity balance can be written as follows:**

$$\delta\rho = \mathbf{A}[P(t)-1] + \mathbf{B}[P(t)/F(t)-1] + \mathbf{C}\,\delta T_{in}(t) + \delta\rho_{ext}$$

- **The relative importance of each of these terms is determined by the integral reactivity feedback parameters, A, B, and C**
  - The integral reactivity parameters A, B, and C are measurable
  - The reactivity feedback coefficients that form the three parameters A, B, and C are associated with the reactor core, and depend on fuel type, fuel volume fraction, coolant volume fraction, etc.

$$\mathbf{A} = \alpha_{Dop}\Delta T_{fc}$$

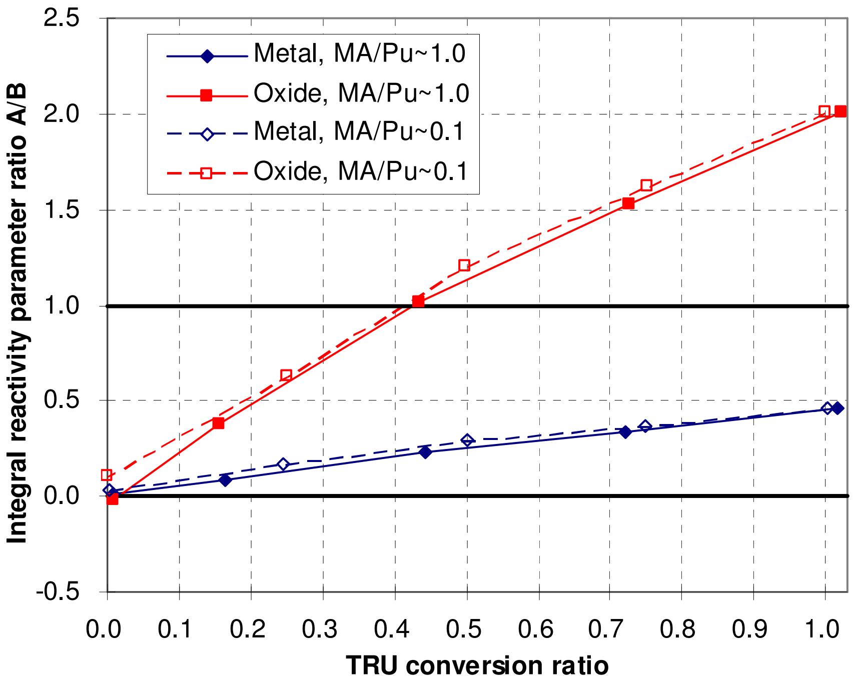
$$\mathbf{B} = [\alpha_{Dop} + \alpha_{Na} + \alpha_{ax} + a_1\alpha_{rad} + a_2\alpha_{CR}]\Delta T_c / 2$$

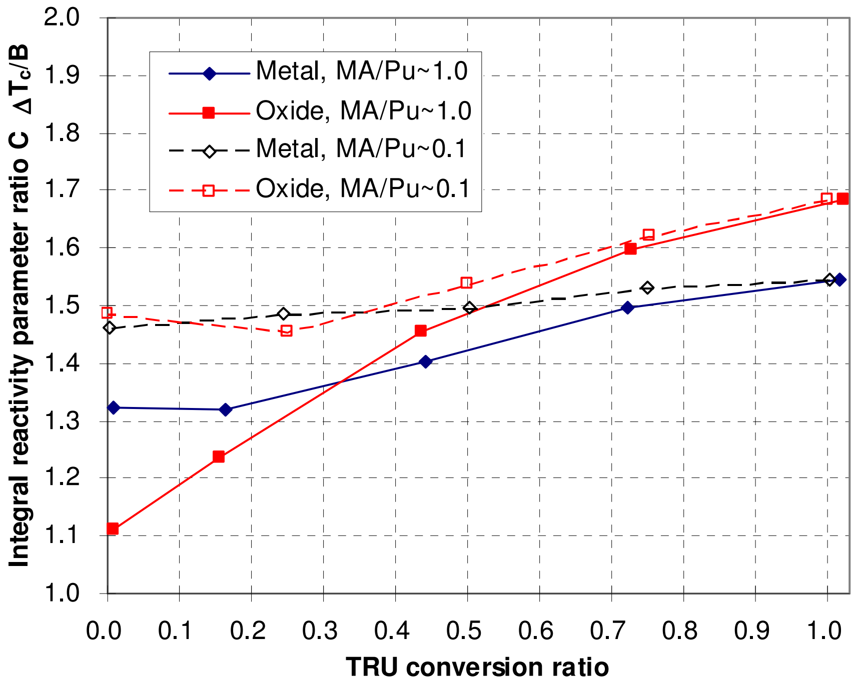
$$\mathbf{C} = [\alpha_{Dop} + \alpha_{Na} + \alpha_{ax} + b_1\alpha_{rad} + b_2\alpha_{CR}]$$

Passive Safety Criteria

- **For possible unprotected accident scenarios**
  - Primary pump induced events (changes in flow)
    - *LOF, pump over-speed*
  - BOP induced events (changes in inlet temperature)
    - *LOHS, chilled inlet temperature*
  - Control rod induced events (changes in external reactivity)
    - *"slow" TOP*
- **Sufficient conditions were established in such a way that the increase in the asymptotic core outlet temperature above its normal full-power, full-flow condition never exceeds one ΔT_c**
  - A, B, and C are all negative
  - $\mathbf{A}/\mathbf{B} < 1, \quad 1 < \mathbf{C}\Delta T_c/\mathbf{B} < 2, \quad \delta\rho_{ext}/\mathbf{B} < 1$
- **Comparison of the whole-core reactivity coefficients to these criteria gives indication for favorable passive safety features of design concept**
  - Detailed safety analyses are required to confirm performance and margins

Integral Reactivity Parameter Ratios





- **The ratio $C\Delta T_c/B$ satisfies the sufficient condition for all the core designs of TRU conversion ratios from 1.0 to 0.0**
- **For very small TRU conversion ratios, however, the ratio becomes too small to satisfy the sufficient condition, mainly because of the diminished Doppler effects**
  - Oxide cores do not satisfy this sufficient condition for conversion ratios higher than ~0.45, because of the large power coefficient A due to high fuel temperature and large Doppler coefficient

Summary

- **A systematic study was performed on the trends in transmutation performance and safety parameters versus TRU conversion ratio for sodium-cooled recycle reactors**
- **As the TRU conversion ratio decreases**
  - Initial heavy metal inventory and charge rate decrease by a factor of 3 to 5
  - On the other hand, the TRU inventory and charge rate increases, but to a less extent
- **TRU consumption rate reaches ~80% of the maximum theoretical value when the TRU conversion ratio is in the range of 0.25-0.35**
  - If two design objectives of maximizing the TRU consumption rate and minimizing the reprocessing loss of TRU to the geological repository are pursued, a compromised TRU conversion ratio would be in the range of 0.2 to 0.4
- **Estimated safety parameters indicate that the metal and oxide cores of TRU conversion ratio in the range of 0.25-0.40 are feasible with favorable passive safety features**
  - The safety parameters of these cores are comparable to those of conventional fast reactor cores, and the sufficient conditions for acceptable asymptotic core outlet temperatures for possible unprotected accident scenarios are satisfied