TOSHIBA

東芝核燃料サイクルシミュレータ ATRUNCYSの開発

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01

背景-コンセプト

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ATRUNCYS開発　背景

新型炉や新燃料概念を検討するにあたり、その概念が核燃料サイクルに与える影響や貢献を評価するために、核燃料サイクルシミュレータが必要

＜要求性能＞
- 自由なプラント選択（炉型や新概念燃料）
- 運転プラント数の上限を設けない（50基程度の運転を解析可能）
- 自由な核種の選択（必要核種を扱いつつ、不要なデータを出さない）

公開コードでは自由な炉心選択が困難であったことから、ATRUNCYSを開発
※ORIGEN2用ライブラリの範囲を超えた炉心を取扱いたい

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ATRUNCYS開発　コンセプト

- ATRUNCYS Code
  - Advanced TRU Nuclear fuel Cycle Simulator

- コンセプト
  - 各プラントタイプや核種に対してコード仕様上の上限を設けない
    - プラントタイプ: 鉱山, 燃料加工工場, 原子炉, 再処理工場, 貯蔵施設（中間・最終）.
    - 原子炉タイプ: LWR, FR, ADS, HTGR, Fusion Reactor, etc.
    - 燃料タイプ: UOX, MOX, Blanket fuel, etc.
  - データライブラリ、シナリオ入力、解析モジュールの切り離し
    - データライブラリ: decay matrix, burn-up tables, factors, plant schedule
    - 解析モジュール: mass and demand analysis



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ATRUNCYS モデル

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モデル

- 崩壊計算
  - ORIGEN2*による事前計算でDecay Matrixを作成し計算
- 燃焼計算
  - 事前評価でBurnup Tableを作成し、作成燃焼度点以外は線形内挿
    - モンテカルロ燃焼計算コード、ORIGEN2、集合体核設計コードで作成実績あり
      ⇒　ADSや核融合などの核変換施設、スペクトルシフト等も評価可能
  - 簡易フォーマットでユーザーが自由に作成可能

BU	0.00e+00	2.00e+02	5.00e+02	1.00e+03	2.00e+03	3.00e+03	4.00e+03	5.
TH232	0.00E+00	2.41E-15	1.50E-14	6.01E-14	2.38E-13	5.32E-13	9.37E-13	1.
TH234	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.
PA231	0.00E+00	7.22E-20	7.80E-20	1.24E-19	5.12E-19	1.56E-18	3.58E-18	6.
PA233	0.00E+00	2.78E-19	3.26E-18	2.30E-17	1.49E-16	4.21E-16	8.54E-16	1.
U233	0.00E+00	9.18E-12	2.30E-11	4.59E-11	9.21E-11	1.36E-10	1.79E-10	2.
U234	1.11E-04	1.11E-04	1.10E-04	1.10E-04	1.09E-04	1.08E-04	1.07E-04	1.
U235	7.39E-03	7.35E-03	7.29E-03	7.19E-03	7.00E-03	6.81E-03	6.62E-03	6.
U236	0.00E+00	7.43E-06	1.85E-05	3.68E-05	7.28E-05	1.07E-04	1.42E-04	1.
U237	0.00E+00	5.24E-08	8.96E-08	1.17E-07	1.58E-07	1.93E-07	2.26E-07	2.
U238	1.64E-01	1.64E-01	1.64E-01	1.64E-01	1.64E-01	1.64E-01	1.64E-01	1.

燃焼度

核種組成

Burnup Table例

```
ReactorParams{
 Name        [ CurUBWR   ] #
 Capacity    [ 872       ] # Assembly
 ThPow       [ 3926      ] # MWth
 ElPow       [ 1350      ] # MWe
 CyBu        [  8436.03  ] # MWd/tHM
}
```

Reactor Parameter例

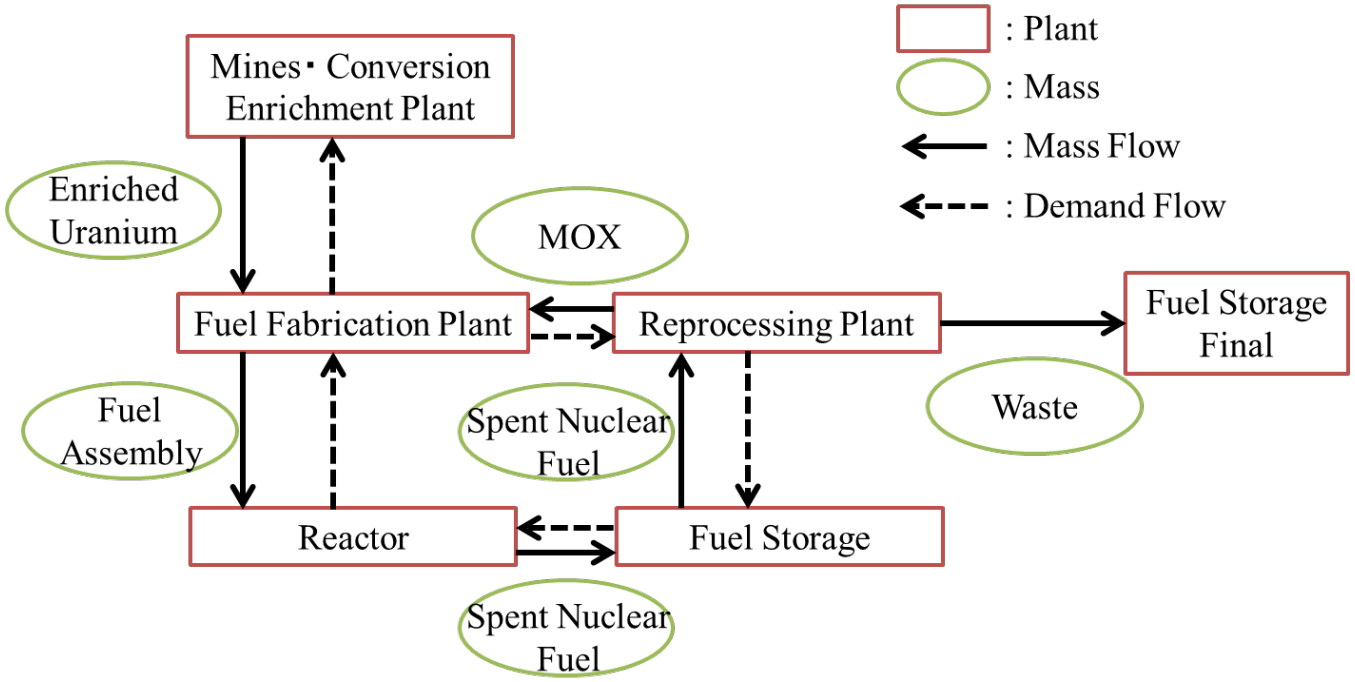
＊：A. G. Croff “ORIGEN2: A Versatile Computer Code for Calculating the Nuclide Compositions and Characteristics of Nuclear Materials”, *Nucl.Technol.*, **62**, P.335 (1983).

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モデル

- 入力データ: 核燃料シナリオ(各Reactor 運開時期, 解析対象期間)
- ライブラリデータ: Plant data, Decay matrix, Burn-up tables, etc.

->Output data:
核施設における核種量
発電量(We)、熱出力(Wth)、天然ウラン必要量(t)、SWU(t)、DepU(t)、RepU(t)、発熱量(Wat)、
放射能(Bq)、放射性毒性(Sv)、燃料体数、マスフロー



The model of ATRUNCYS

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コード比較

	ATRUNCYS	MNB4.0[1)]	COSI7[2)]
機関（国）	東芝エネルギーシステムズ (Japan)	東工大/JAEA(Japan)	CEA(France)
開発言語	C#	VBA	C++
核種数	無制限 (現在は100核種・燃焼計算依存)	179	~300
燃焼計算手法	燃焼Lookup Table (事前にライブラリ整備)	OEM (Okamura Explicit Method)	CESAR5.3 Matrix method
廃棄物計算	Yes	Yes	Yes
処分場計算	No	Yes	Yes
経済性評価	No	Yes	Yes
公開	No	Yes	No

1: Tomohiro Okamura, Ryota Katano, et al., “NMB4.0: development of integrated nuclear fuel cycle simulator from the front to back-end”, EPJ Nuclear Science and Technology., 7, 19, (2021). https://doi.org/10.1051/epjn/2021019

2: G. Krivtchik, EPJ Web Conf. 247 13001 (2021), https://doi.org/10.1051/epjconf/202124713001

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検証（ATRUNCYS 妥当性確認）

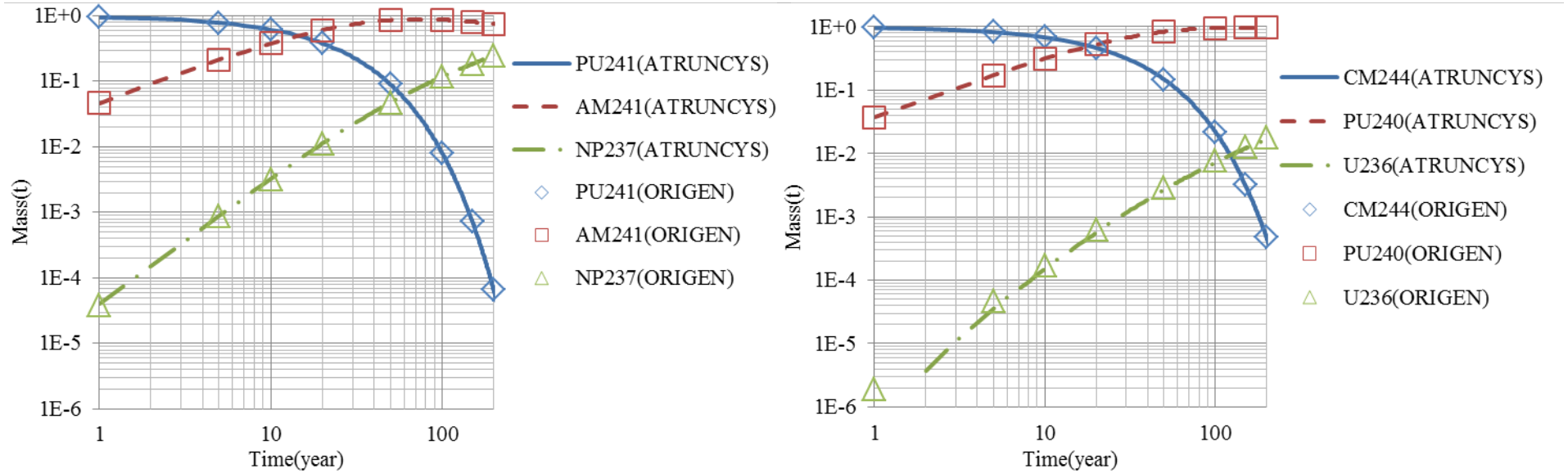
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モデル検証 –崩壊Matrix –

In order to validate the decay model, the time-dependent composition rates of TRUs are compared to ORIGEN2 in a nominal case.

The masses of all nuclides are in good agreement with those obtained by ORIGEN2.

-> ATRUNCYS is accurate for predicting the time-dependent masses caused by the decay.



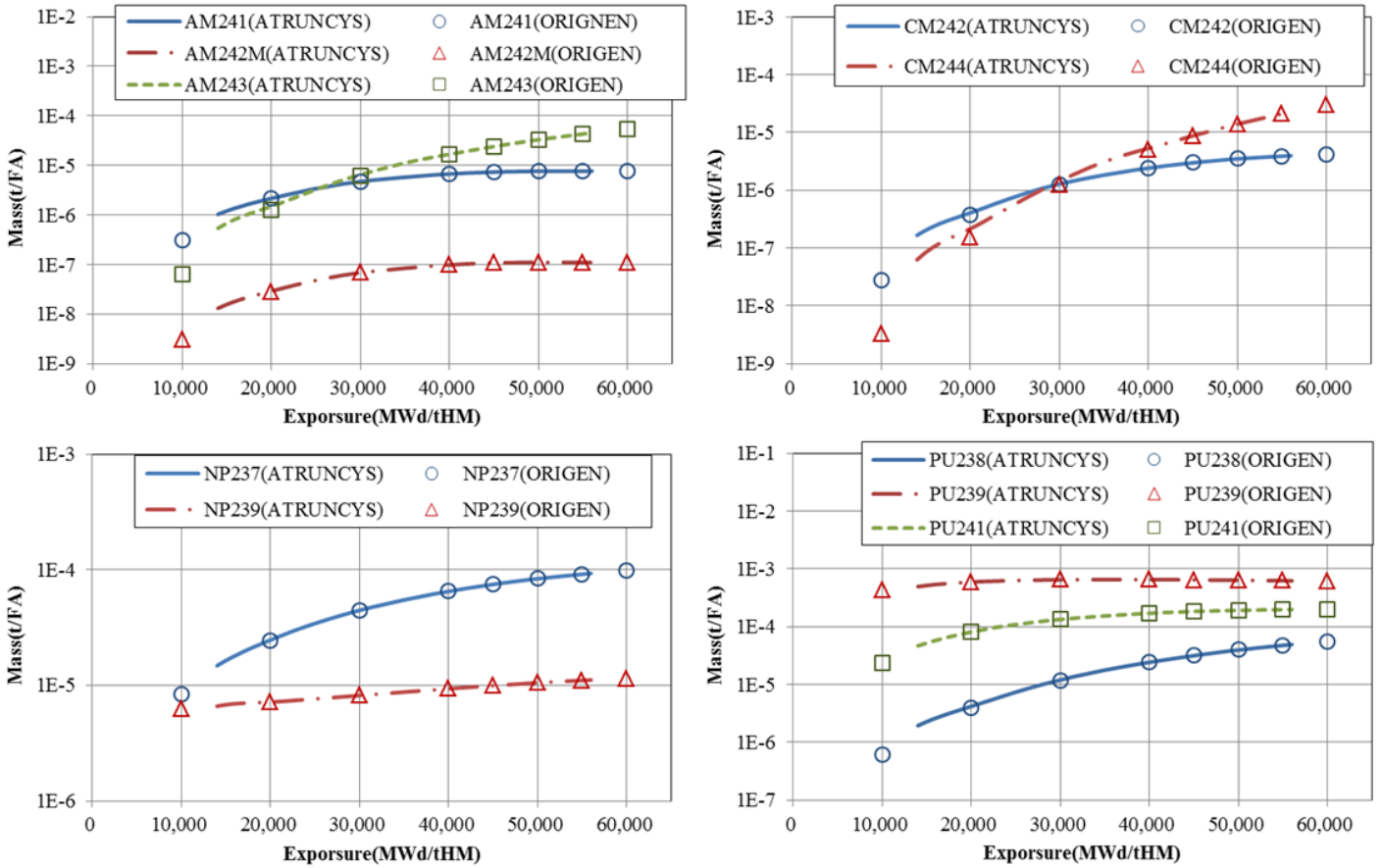
Comparison of mass from decay between ATRUNCYS and ORIGEN2

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モデル検証 –燃焼Table –

In order to validate the burn-up model, the exposure-dependent composition rates of TRUs are compared to ORIGEN2 in a nominal case*.

-> The burn-up calculation in ATRUNCYS seems to be adequate.



Comparison of mass from burn-up between ATRUNCYS and ORIGEN2

*The fuel specific of the case is 3.8wt% enriched BWR UO2 fuel.

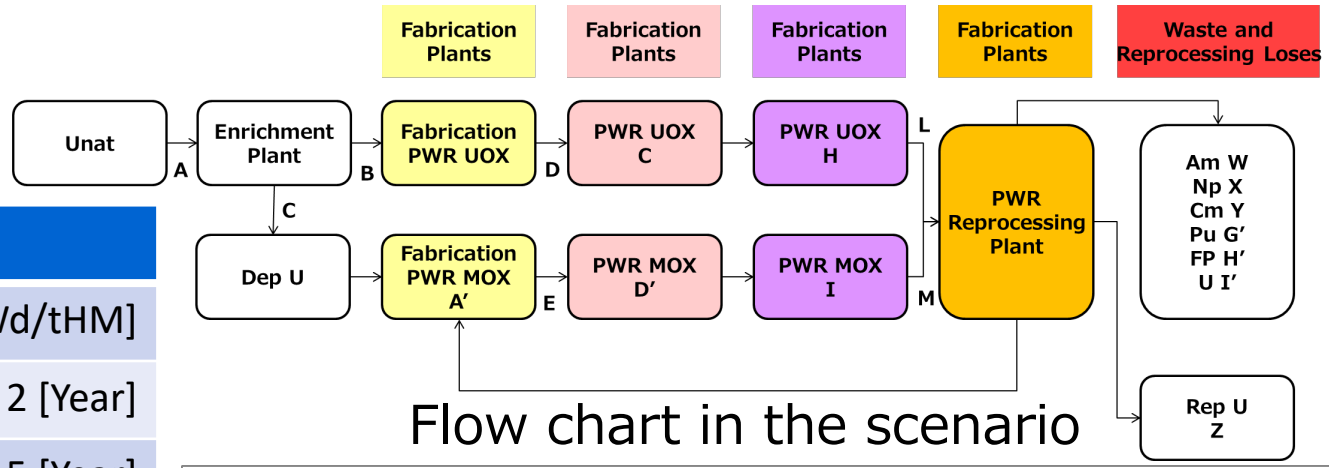
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OECD/NEA Benchmarkによる検証 –ベンチマーク問題概要–

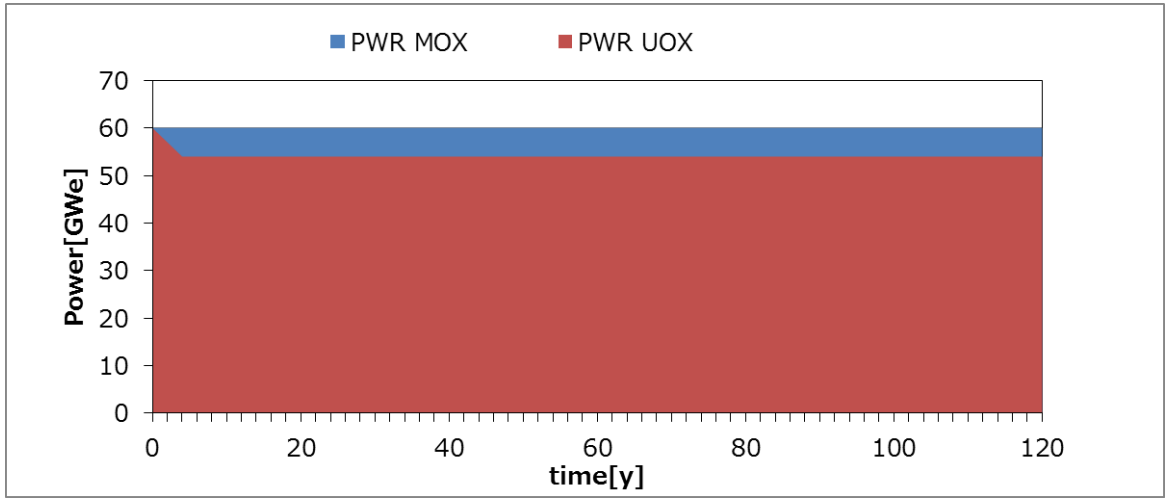
In order to validate the system of ATRUNCYS™ code, the OECD/NEA benchmark study* was adopted.

Fuel & Core Specific	
Fuel burn-up	60 [GWd/tHM]
Fabrication time	2 [Year]
Min. cooling time	5 [Year]
Power (/Plant)	1.5 [GWe]
Load factor	0.8176
Loss rate	0.1 [%]
EFPD**	410 [day]
Core fraction (fuel)	1/4

**EFPD: Effective Full Power Day



Flow chart in the scenario

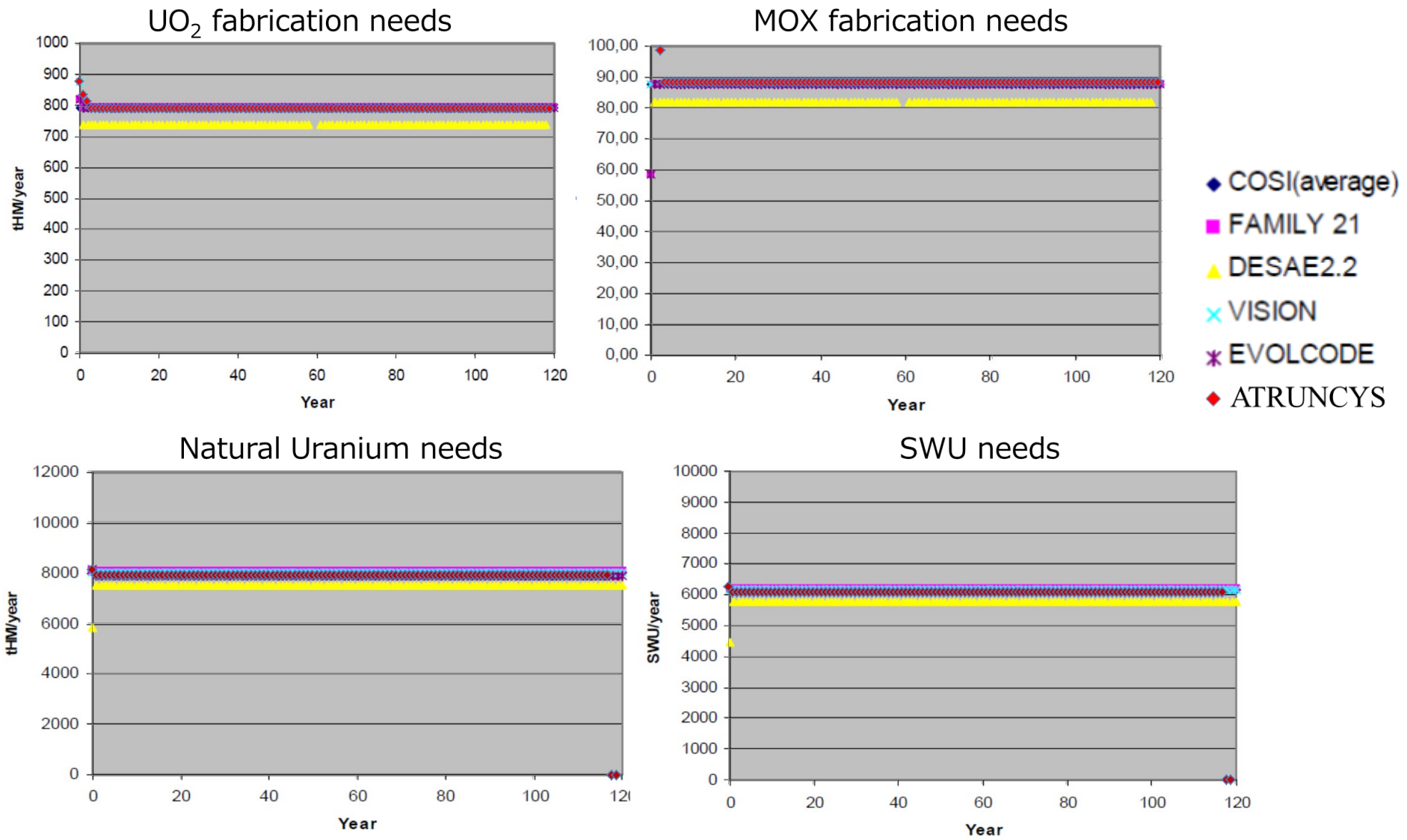


Installed capacity in the scenario

*NEA/NSC/WPFC/DOC(2012)16
"Benchmark Study on Nuclear Fuel Cycle Transition Scenarios Analysis Codes"

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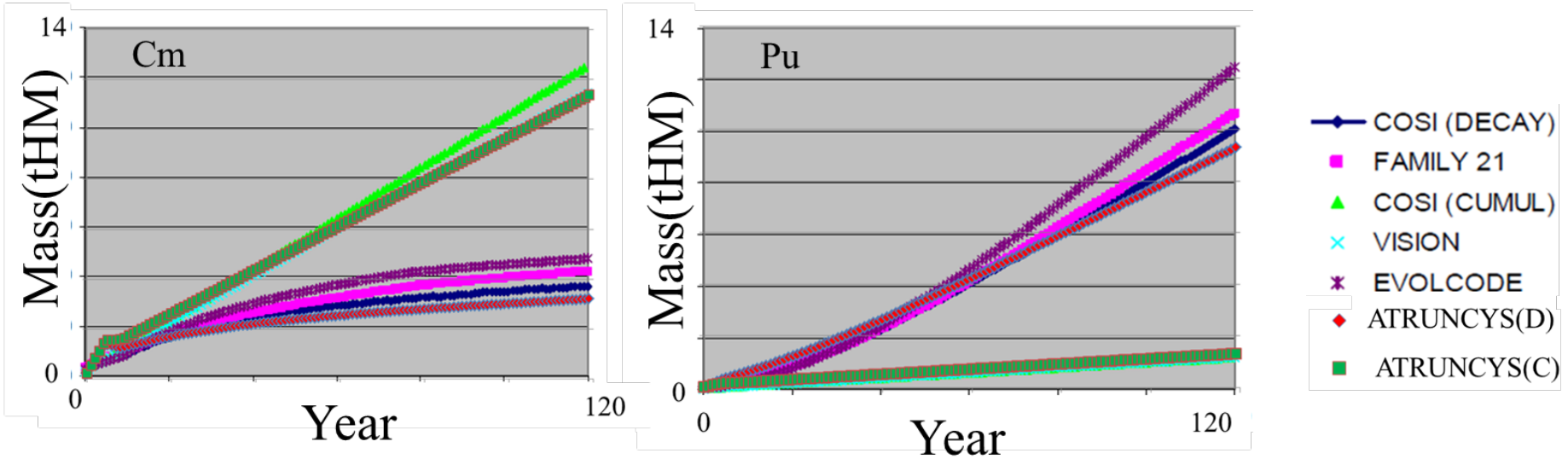
OECD/NEA Benchmarkによる検証 –他コードとの比較結果各燃料体数、NU, SWU–



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OECD/NEA Benchmarkによる検証 –他コードとの比較結果Pu, Cm–

- Cm & Pu losses are in good agreement between ATRUNCYS and COSI.
- There are two type of results,
  - on the one hand, codes are not considering the decay
    ; COSI(CUMUL), ATRUNCYS(C), and VISION,
  - on the other hand, codes are considering the decay
    ; COSI(DECAY), FAMILY21, EVOLCODE, and ATRUNCYS(D).
- Pu-238, -240 are produced by the decay of Cm-242, -244.
  - Cm-242 -> Pu-238 (alpha-decay)
  - Cm-244 -> Pu-240 (alpha-decay)

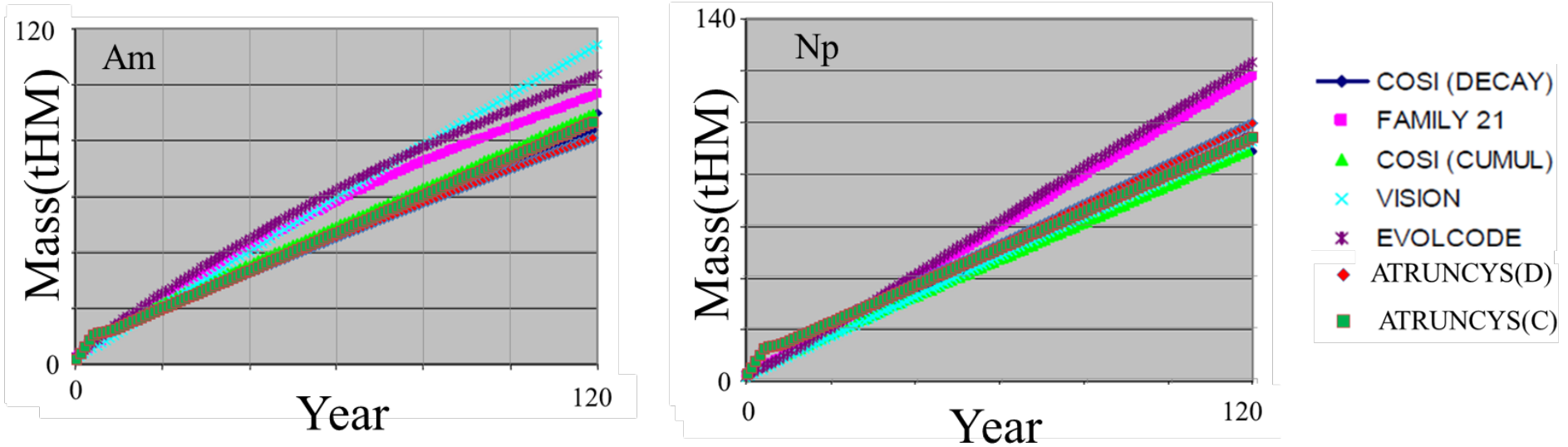


Accumulated Cm and Pu losses in reprocessing plant in the scenario

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OECD/NEA Benchmarkによる検証 –他コードとの比較結果Am, Np–

- Am & Np losses are in good agreement between ATRUNCYS and COSI.
- FAMILY21 & EVOLCODE are different from ATRUNCYS and COSI.
  - FAMILY21 & EVOLCODE have a larger cooling time than COSI.
  - Am-241 is produced by the beta-decay of Pu-241(14y).
  - Np-237 is produced by the alpha-decay of Am-241(432y).
- The first period of the scenario, Am & Np losses obtained by ATRUNCYS are larger than other codes.
  - ATRUNCYS has larger initial spent fuel in spent fuel pool than other codes, because spent fuels loaded in first year are not be reprocessed in ATRUNCYS.



Accumulated Am and Np losses in reprocessing plant in the scenario

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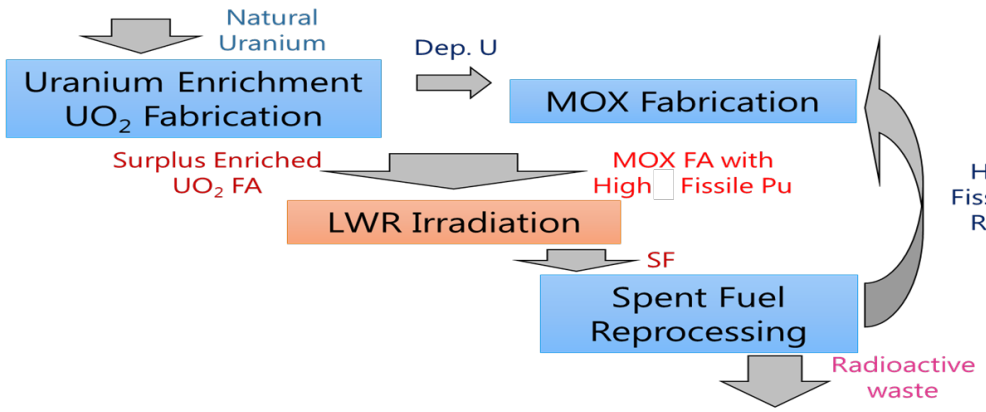
解析例

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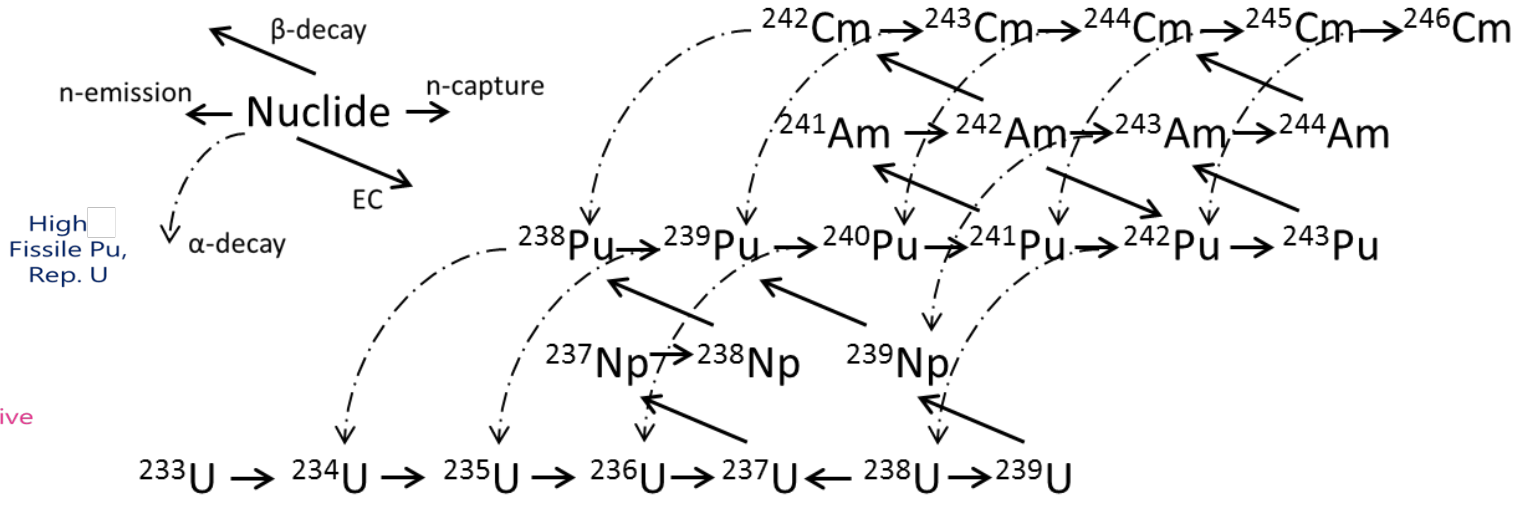
ATRUNCYS を用いたFORSETIの概念検証（FORSETI概念*）

FORSETI: **F**uel Cycle based **o**n Light-Water-**R**eactor with **S**urplus **E**nriched Uranium for **T**RU-production **I**nhibition

- Use UO_2 fuels with HALEU in the LWR,
- Discharge the UO_2 fuels before burned out,
- Reprocess the spent-UO_2 fuels and extract Pu with high ^{239}Pu composition ratio,
- Fabricate MOX fuels with the reprocessed Pu,
- Use the MOX fuels in the LWR,
- Multi-recycle the MOX fuels.



FORSETI Concept



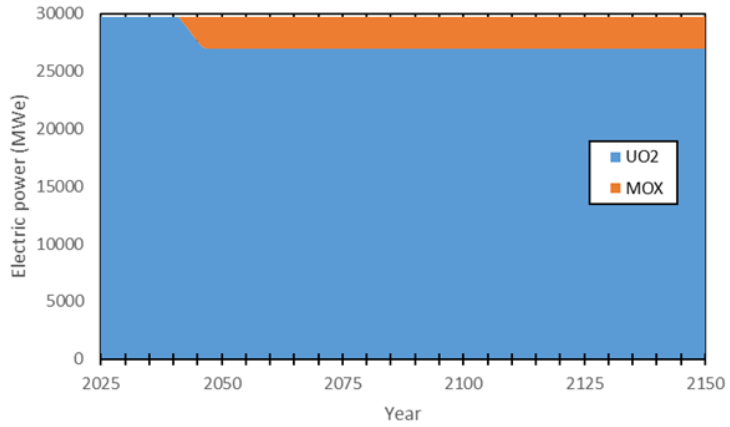
Burnup chain

*Wada, Satoshi, et al. "Fuel-Cycle Scenario to Reduce Radioactive Waste from Light-Water Reactor." EPJ Web of Conferences. Vol. 247. EDP Sciences, 2021.

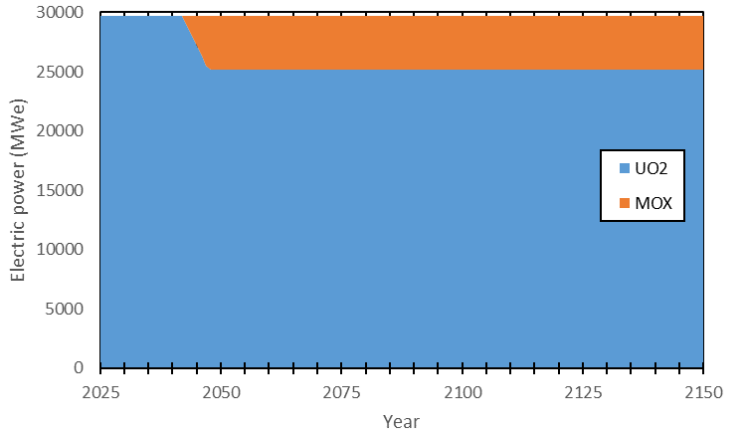
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ATRUNCYS を用いたFORSETIの概念検証（検証シナリオ）

Parameter		Current		FORSETI	
		UO_2	MOX	UO_2	MOX
EFPM[1] [month]		15.0	15.0	15.0	15.0
Discharge exposure [GWd/tHM]		45.0	45.0	45.0	45.0
Thermal Power [MWt]		3,900	3,900	3,900	3,900
Power density [kW/l]		50	50	50	50
Fabrication time [year]		2	2	2	2
Minimum cooling time [year]		15	15	15	15
Composition rate[wt%]	^{235}U	3.9	1.2	9.0	1.2
	^{238}U	96.1	91.9	91.0	94.7
	^{238}Pu	-	0.2	-	0.1
	^{239}Pu	-	3.6	-	2.9
	^{240}Pu	-	2.1	-	0.8
	^{241}Pu	-	0.4	-	0.2
	^{242}Pu	-	0.6	-	0.1



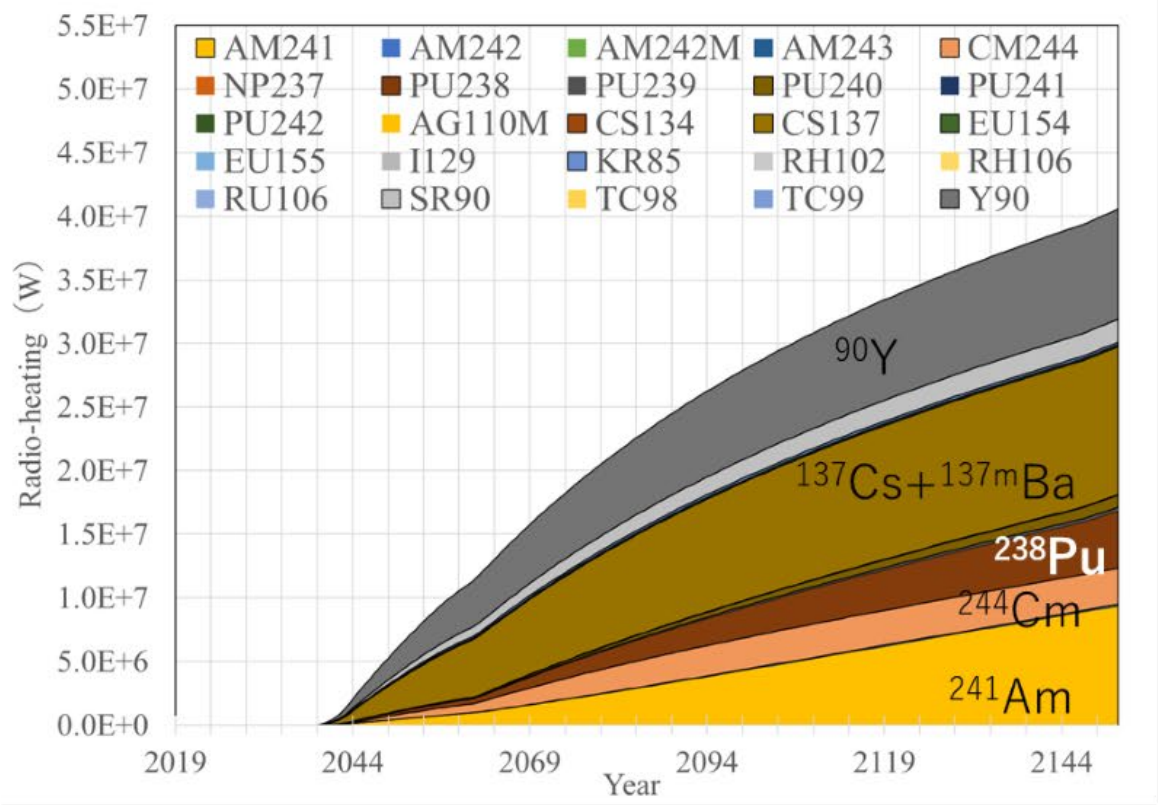
Current type Scenario



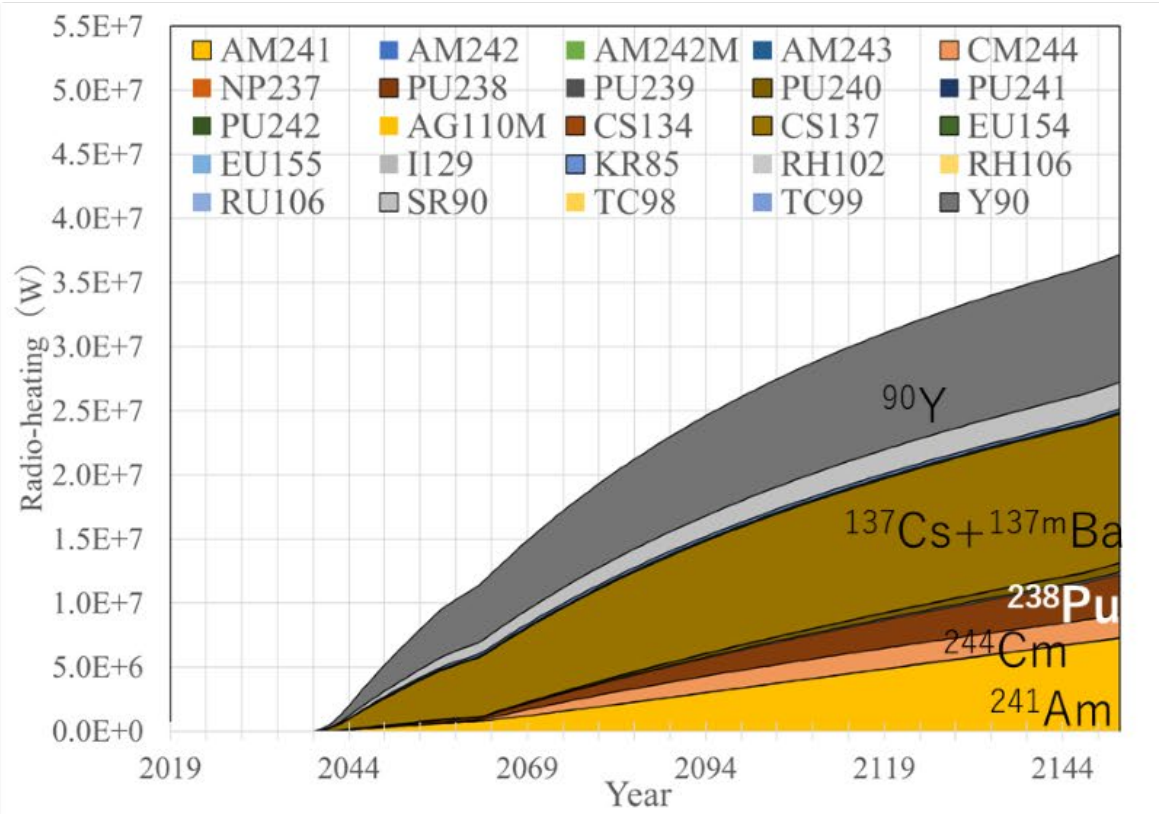
FORSETI concept Scenario

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ATRUNCYS を用いたFORSETIの概念検証（評価結果）



Current type Scenario



FORSETI concept Scenario

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05

まとめ

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まとめ

- ✓ 新型炉や新燃料概念を検討するにあたり、その概念が核燃料サイクルに与える影響や貢献を評価するために、ATRUNCYSを開発
- ✓ ATRUNCYSでは、任意のスペクトルの炉型の燃焼テーブルをユーザが作ることが可能で、様々な核燃料サイクル評価が可能
- ✓ コード動作の妥当性をノミナルケース、OECD/NEA Benchmarkにより確認
- ✓ ATRUNCYSを用いた新燃料概念の核燃料サイクル評価を実施

- ✓ 今後、経済性評価の実装や燃焼計算手法の高度化開発の実施を検討中

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