SCK•CEN

STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

ANICCA CODE AND THE BELGIAN NUCLEAR FUEL CYCLE

TECHNICAL WORKSHOP : DYNAMIC NUCLEAR FUEL CYCLE
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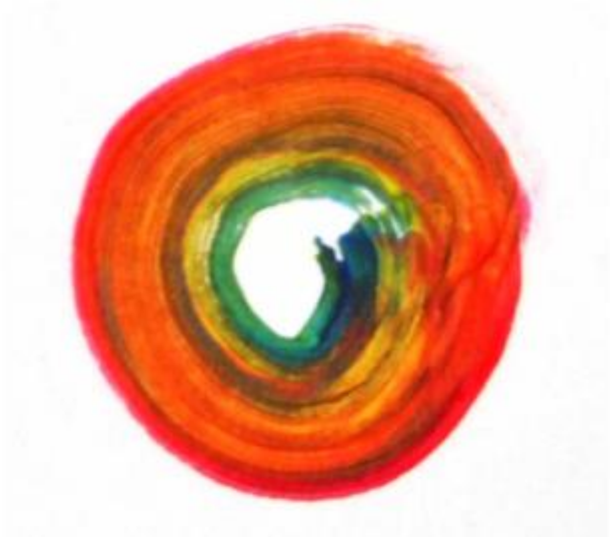
Contents

ANICCA

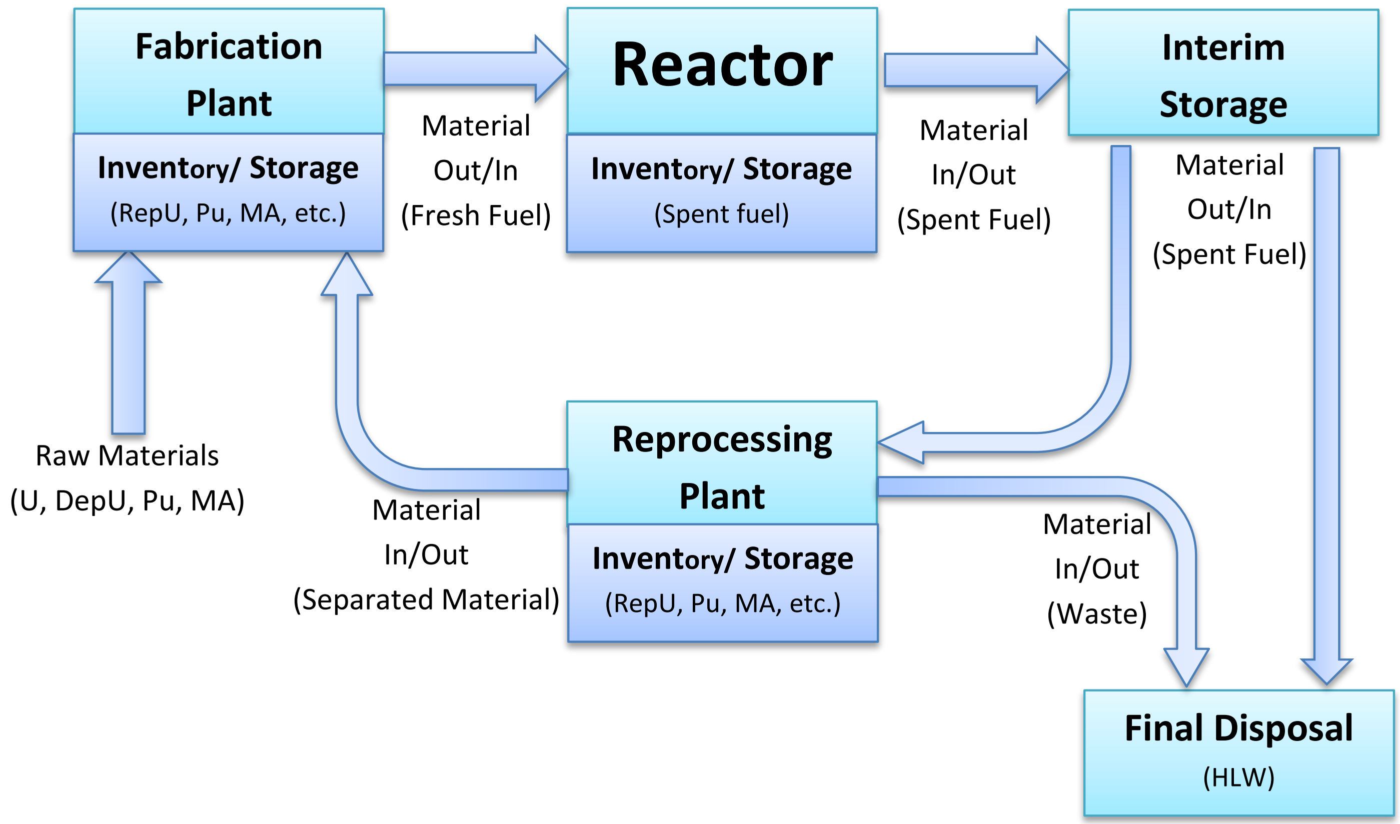
ANICCA: Introduction

- A SCK-CEN code in collaboration with an industrial partner.
- A flexible tool to simulate nuclear fuel cycle scenarios
- Material flows as “packages” between facilities.
- Each package contains:
  - Isotopic vector
  - Amount
  - Name
- Written in Python 3



ANICCA: Introduction

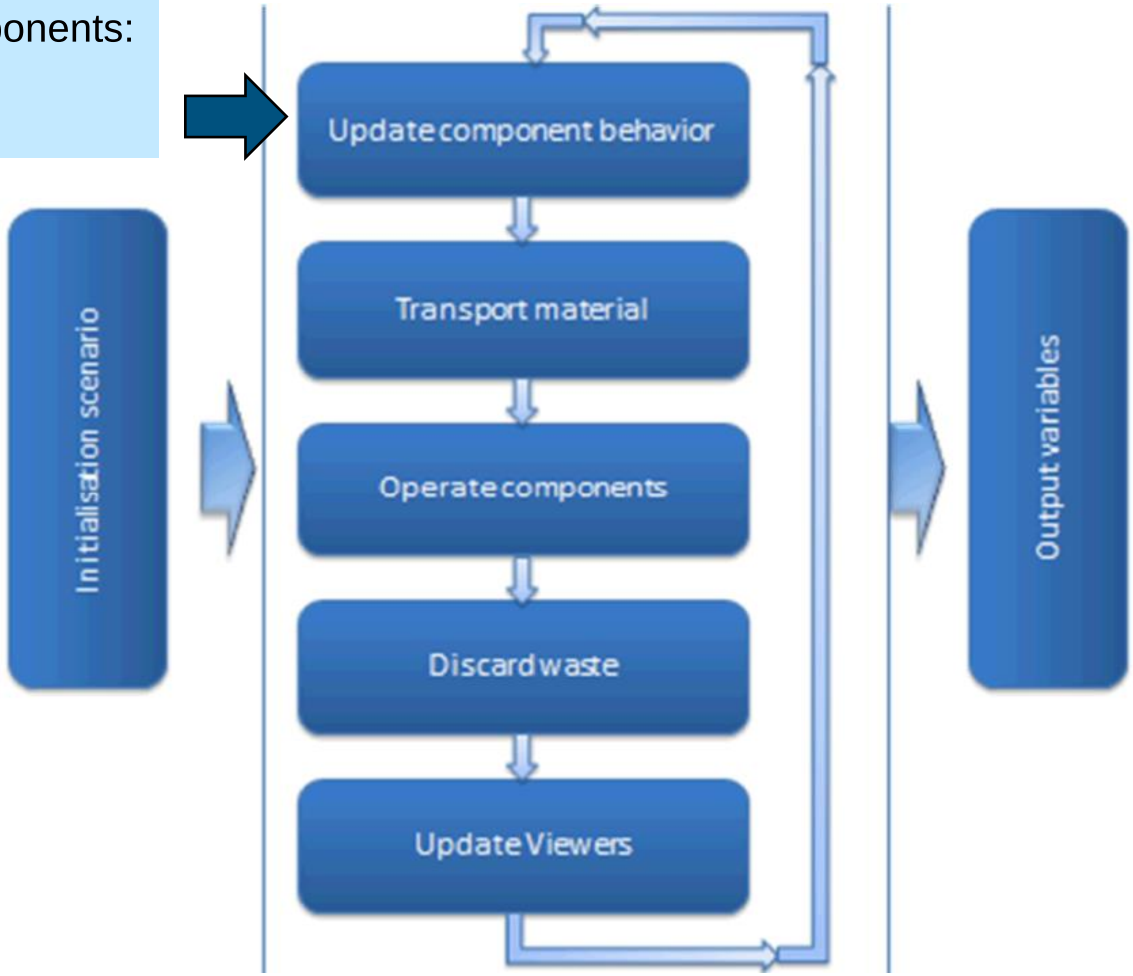
The Nuclear fuel Cycle



ANICCA: Structure

Inputs for components:
- Libraries
- Fuels

1. General Input
2. Nuclide Data (JEFF data)



ANICCA: General Input

1. Scenario Definition
   - Reactor history (input)
   - Time steps
   - Isotopes to track, etc.
2. Components
   - Mine, Reactors, Fabrication Plan, Storage, etc.
3. Connections
   - From -> To
4. Viewers
   - Package masses
   - Elements/Isotopes (Facilities, Group of Facilities)
   - Radiotoxicity, Decay heat

General input: Scenario definition

```
Scenario:
    title: Belgium
    start date: 1970
    file: HistoryBelgium.xls
    time steps:
        - 150x 1 year
        - 50x 10 year
        - 10x 100 year
        - 10x 1000 year
        - 10x 10000 year
        - 10x 100000 year
    nuclide data:
        decay: True
        spontaneous fission: true
        cut_off_decay_time:  2 min
#       specified_isotopes: origen
```

→ Input file for the reactor irradiation history

} Numbers of steps

} Isotopes to track and options

ANICCA: Reactor Inputs

The reactor history input includes:

- Year of irradiation
- Net Power
- Burnup
- Load Factor
- Reactors commissioned
- Reactors decommissioned

This information allows an accurate estimation of:

- Fuel mass requirement
- Waste generated

Year	NetPower	Burnup	LoadFactor	ReactorIN	ReactorOut
1975	0.392	40	0.758	1	0
1976	0.395	40	0.769	0	0
1977	0.395	40	0.818	0	0
1978	0.395	40	0.789	0	0
1979	0.395	40	0.878	0	0
1980	0.395	40	0.836	0	0
1981	0.395	40	0.851	0	0
1982	0.395	40	0.92	0	0
1983	0.393	40	0.82	0	0
1984	0.393	40	0.906	0	0
1985	0.392	40	0.843	0	0
1986	0.392	40	0.782	0	0
1987	0.4	40	0.836	0	0
1988	0.4	40	0.767	0	0
1989	0.4	40	0.717	0	0
1990	0.4	40	0.816	0	0
1991	0.4	40	0.874	0	0
1992	0.4	40	0.851	0	0
1993	0.4	40	0.83	0	0
1994	0.4	40	0.834	0	0
1995	0.392	40	0.813	0	0
1996	0.392	40	0.92	0	0
1997	0.392	40	0.907	0	0
1998	0.392	40	0.959	0	0
1999	0.392	40	0.931	0	0
2000	0.392	40	0.948	0	0
2001	0.392	40	0.919	0	0
2002	0.392	40	0.95	0	0
2003	0.392	40	0.881	0	0
2004	0.392	40	0.868	0	0
2005	0.392	40	0.892	0	0
2006	0.392	40	0.903	0	0
2007	0.392	40	0.882	0	0
2008	0.392	40	0.781	0	0
2009	0.392	40	0.837	0	0
2010	0.433	40	0.897	0	0
2011	0.433	40	0.878	0	0
2012	0.433	40	0.906	0	0
2013	0.433	40	0.978	0	0
2014	0.433	40	0.938	0	1

D1 D2 D3 D4 T1 T2 T3

General input: Components

- Components = Nuclear facilities

- They execute their activities in states
  - State 1: Burning UOX for 10 years
  - State 2 : Burning UOX (70%) and MOX (30%) for 20 years
  - Decommissioning

- States can perform different processes at the same time
  - Process 1: UOX irradiation
  - Process 2: MOX irradiation

General input: Components

```
# D1 general input
time: 1970
initial_electricity : 0
electric_power : 0.433  GW
thermal_power : 1.311  GW
reactor_core_mass:
    UOX_33: 40
state_order:
    - UOX_state1
UOX_state1:
     type: state
     duration: 45 year
     residence_times:
         UOX_33_SPENT: 5 year
         UOX_33: 45 year
     processes:
         UOX1:
             type: Irradiation
             delay: 2 years
             library: thermalUOX40
             material_in:
                 UOX_33: 1
             material_out:
                 UOX_33_SPENT: 1
             cycle: 1.0 year
tags:
    - D1
    - REACTOR
    - BELGIUM
```

General input for a reactor (line 1)

Reactor (fleet) details (lines 2–7)

State of the reactor (line 10)

Process for the fuel types (line 16)

Reactor libraries (Taken from Aleph) (line 20)

Fractions of Material In/Out (lines 21–25)

Identifiers for the component (lines 26–29)

General input: Components

```yaml
Fabrication:
    type: Facility
    time: 1970
    state_order:
        - Fab
        - decommission
    Fab:
        type: state
        duration: 60 year
        processes:
            UOX_45:
                type: Enrichment
                Material_in:
                    NAT: x
                Material_out:
                    UOX_45: 0.045
                    DepU: 0.002
                cycle: on demand
            MOX:
                type: MoxCombine
                Material_in:
                    DepU: 0.923
                    PU: 0.077
                Material_out:
                    MOX: 1
                cycle: on demand
                pu_equivalent: thermalMOX50
                delay: 2 years
        residence_times:
            DepU: 60
            PU: 60
    decommission:
        type: state
        duration: 0 years
    tags:
        - Fabrication
        - BELGIUM
```

Fabrication Plant

UOX fuel definition

MOX, ADS (+MA) definition

Reactor Library

General input: Components

```yaml
ReproPlant:
    type: Facility
    time: 1990
    state_order:
        - reproformox
        - decommission
    reproformox:
        type: state
        duration: 10 years
        processes:
            UOX:
                type: Reprocess
                process_order: 'LIFO'
                releases: purex
                Material_in:
                    UOX_33_SPENT: 68
                Material_out:
                    U:
                        92: 0.999
                    PU:
                        94: 0.999
                    WASTE_UOX1: x
                    SM_UOX1: structural_material
                cycle: 1 year
        residence_times:
            U: 0 year
            PU: 0 year
            WASTE_UOX1: 0 year
            SM_UOX1: 0 year
    decommission:
        type: state
        duration: 0 years
    tags:
        - ReproPlant
        - BELGIUM
```

Reprocessing Plant

Reprocessing strategies

Material to reprocess and mass(es)

Material-Out and efficiencies

General input: Viewers

```
Viewers:
    Packages:
        type: TxtFile
        outputfile: PhaseOut_Output_Packages.xls
        variables: [Packages]
        observables:
            - U_mine
            - Fabrication
            - NIRAS
            - RepU_Repository
            - REACTOR
            - ReproPlant
            - BELGIUM

    HM:
        type: TxtFile
        outputfile: PhaseOut_Result_HM_elem.xls
        variables: [92, 93, 94, 95, 96, Total_weight,Fission_product]
        observables:
            - NIRAS
            - RepU_Repository
            - Fabrication
            - Reactor
            - BELGIUM

    Fab_flow:
        type: TxtFile
        outputfile: PhaseOut_Flow.xls
        variables: [Packages]
        observables: [Fabrication to all, ReproPlant to all, U_mine to all]

    Raditoxicity:
        type: TxtFile
        outputfile: PhaseOut_Radiot.xls
        variables: [Radio_toxicity, Total_weight, heat, alpha_heat]
        observables: [ NIRAS, RepU_Repository, Fabrication, BELGIUM]
```

Packages and amounts in components

Elements/Isotopes in components

Material flowing between components

Parameters

Viewers output: Packages

Example: Packages and amounts in components

	A	B	C	D	E	F	G	H	I	J	K	L	M
1		Depu (tons)	Mox (tons)	Mox_spent (tons)	Nat (tons)	Pu (tons)	Sm_uox1 (tons)	U (tons)	Uox_33 (tons)	Uox_33_spent (tons)	Uox_45 (tons)	Uox_45_spent (tons)	Waste_uox1 (tons)
2	**1971**	0	0	0	0	0	0	0	0	0	0	0	0
3	**1972**	0	0	0	0	0	0	0	0	0	0	0	0
4	**1973**	0	0	0	0	0	0	0	0	0	0	0	0
5	**1974**	1390.3	0	0	0	0	0	0	151.2	0	0	0	0
6	**1975**	1664.7	0	0	0	0	0	0	181.0	0	0	0	0
7	**1976**	1989.0	0	0	0	0	0	0	180.1	36.2	0	0	0
8	**1977**	2330.4	0	0	0	0	0	0	187.4	66.0	0	0	0
9	**1978**	2641.6	0	0	0	0	0	0	186.0	101.3	0	0	0
10	**1979**	2982.3	0	0	0	0	0	0	185.9	138.4	0	0	0
11	**1980**	3333.9	0	0	0	0	0	0	190.3	172.3	0	0	0
12	**1981**	4243.5	0	0	0	0	0	0	190.6	209.3	72.7	0	0
13	**1982**	5264.1	0	0	0	0	0	0	185.9	247.6	164.2	0	0
14	**1983**	5925.5	0	0	0	0	0	0	187.3	284.9	183.6	19.7	0
15	**1984**	7128.7	0	0	0	0	0	0	190.7	318.4	256.4	57.9	0
16	**1985**	8414.6	0	0	0	0	0	0	180.1	357.2	349.2	97.0	0
17	**1986**	9359.2	0	0	0	0	0	0	183.5	394.1	366.9	153.0	0
18	**1987**	10316.4	0	0	0	0	0	0	192.6	422.3	368.4	230.5	0
19	**1988**	11235.8	0	0	0	0	0	0	188.3	462.7	370.3	304.1	0
20	**1989**	12187.1	0	0	0	0	0	0	187.1	499.9	370.9	383.1	0
21	**1990**	13144.1	0	0	0	0	0	0	188.7	535.9	373.8	458.7	0
22	**1991**	14110.6	0	0	0	0	0	0	190.2	572.0	374.0	538.2	0
23	**1992**	15057.4	0	0	0	0	0	0	193.9	609.6	368.4	616.7	0
24	**1993**	15978.7	0	0	0	0.721	20.01	63.30	195.9	580.2	360.2	696.5	0.2
25	**1994**	16859.2	5.89	0	0	0.988	40.01	126.60	190.3	554.5	358.9	769.3	0.4
26	**1995**	17786.0	12.10	0	0	1.236	60.02	189.91	192.2	527.1	358.1	840.9	0.6
27	**1996**	18792.1	12.53	5.89	0	1.476	80.02	253.21	200.3	495.8	364.8	912.5	0.8
28	**1997**	19775.9	12.93	12.10	0	1.694	100.03	316.51	201.7	470.3	370.4	983.3	1.0
29	**1998**	20813.7	13.52	18.42	0	1.895	120.03	379.81	200.4	447.1	376.1	1061.6	1.1
30	**1999**	21842.9	13.37	25.04	0	2.135	140.04	443.11	203.9	423.0	377.8	1138.0	1.3
31	**2000**	22827.5	12.79	31.94	0	2.382	160.04	506.42	203.0	398.5	372.0	1221.9	1.5
32	**2001**	23832.1	12.86	38.41	0	2.620	180.05	569.72	198.6	377.9	374.0	1300.1	1.7
33	**2002**	24843.0	13.07	44.73	0	2.861	200.05	633.02	201.4	352.5	374.2	1378.2	1.8
34	**2003**	25842.4	13.48	51.26	0	2.326	200.05	633.02	200.6	394.5	374.5	1458.4	1.8
35	**2004**	26851.5	13.65	57.80	0	1.810	200.05	633.02	198.1	438.9	377.2	1536.6	1.8
36	**2005**	27852.4	13.00	64.75	0	1.324	200.05	633.02	202.9	480.1	371.6	1617.1	1.8

BELGIUM / Fabrication / NIRAS / REACTOR / ReproPlant / U_NIRAS / U_mine

THE BELGIAN NUCLEAR FUEL CYCLE

Belgian Fuel Cycle: Introduction

- 7 commercial PWR
- Operating since 1975
- Reactors will be working until 2025.
- The different fuels involved in the cycle so far have been grouped into three representative PWR types: UO2_40, UO2_50 and MOX.

Reactor Features

NPP	Operation time		Power (MWe)	Power (MWth)
Doel 1	1975	2015	433	1311
Doel 2	1975	2015	433	1311
Doel 3	1982	2022	1006	3054
Doel 4	1985	2025	1033	2988
Tihange 1	1975	2015	962	2873
Tihange 2	1982	2022	1008	3065
Tihange 3	1985	2025	1046	3000
EFIT	2045	2093	128	400

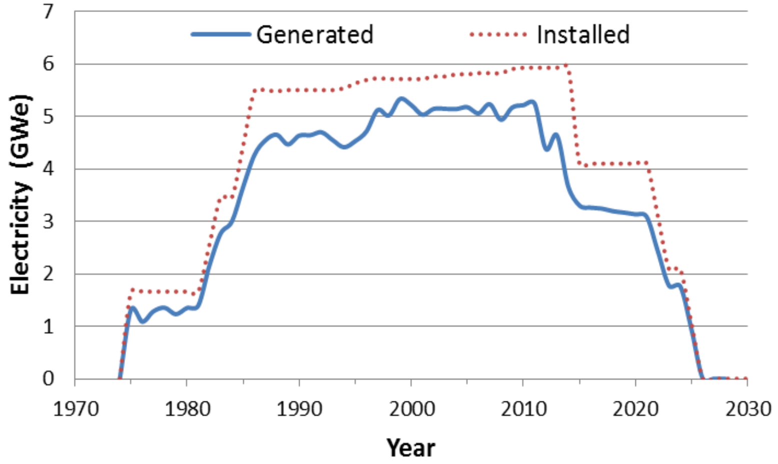
Fuels

NPP	Average Burnup (GWd/tHM)	Fuel type
Doel 1	40	UO_2
Doel 2	40	UO_2
Doel 3	50	UO_2/MOX
Doel 4	50	UO_2
Tihange 1	40	UO_2
Tihange 2	50	UO_2/MOX
Tihange 3	50	UO_2
EFIT	130	Pu+MA

Belgian Fuel Cycle: Scenarios

1. Phase-out scenario (P-O):

- All reactors will operate for a lifespan of 40 years
- No new nuclear power plants.
- The total electricity generated will be 1664 TWhe.
- 670 tHM of SF are reprocessed .



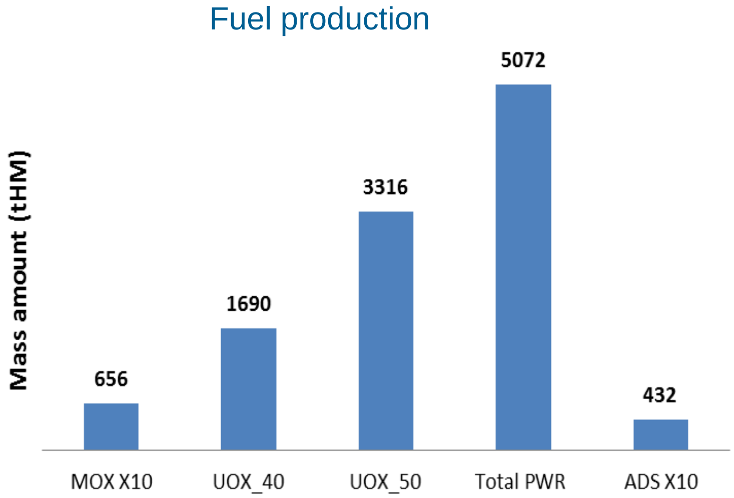
2. ADS scenario (EFIT):

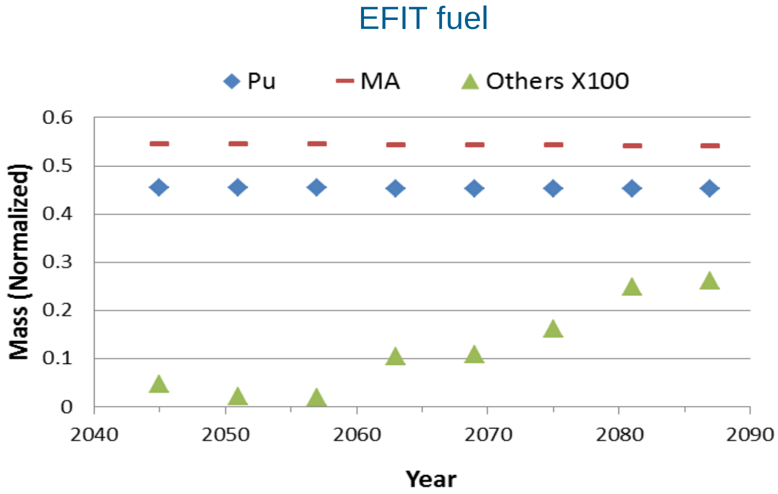
- Extension of the P-O scenario.
- It includes an ADS (20 years after the shutdown of all the PWRs)
- The total electricity generated will be around 1718 TWhe.

Belgian Fuel Cycle: Results

FRONT-END

- P-O: 5100 t of fuel
  - 670 reprocessed to produce MOX
  - Similar masses compared to reference studio (*)
- ADS: 43 t for EFIT fuel
  - 55 % MA, 45% Pu





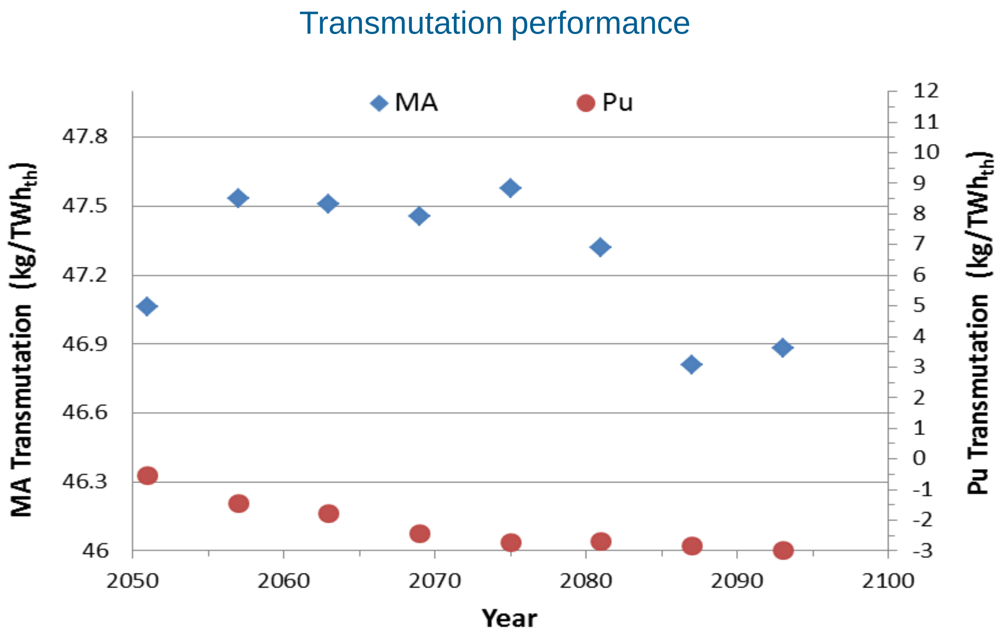
PWR MOX fuel

Year	PU	DepU
1996	7.40%	92.60%
1997	7.56%	92.44%
1998	7.70%	92.30%
1999	7.82%	92.18%
2000	7.91%	92.09%
2001	8.00%	92.00%
2002	8.10%	91.90%
2003	8.16%	91.84%
2004	8.22%	91.78%
2005	8.28%	91.72%

(*) Second meeting of the Contracting Parties to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. Belgium, May 2006

Results: EFIT Transmutation Performance

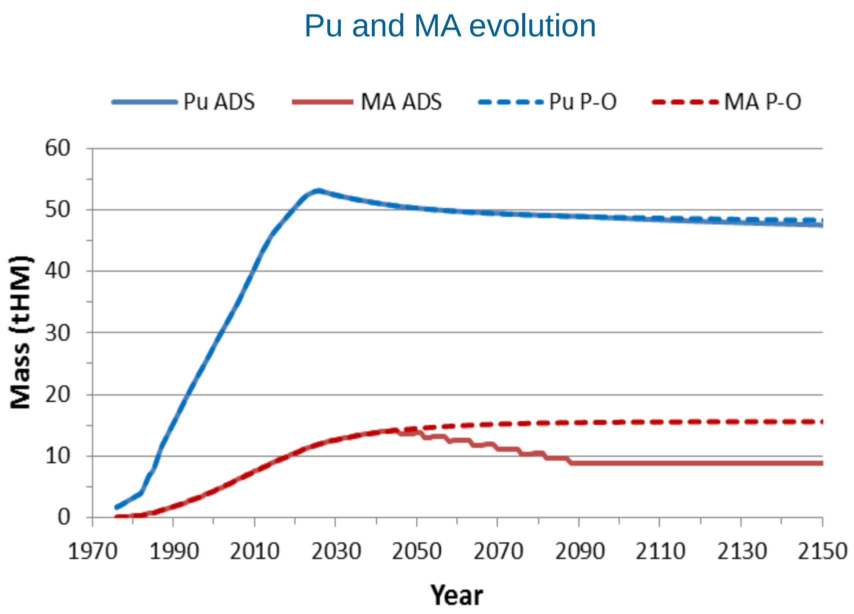
- Full core discharged every 6 years (8 cycles)
- MA burning according to the reference (*)
- No Pu consumption (small production)

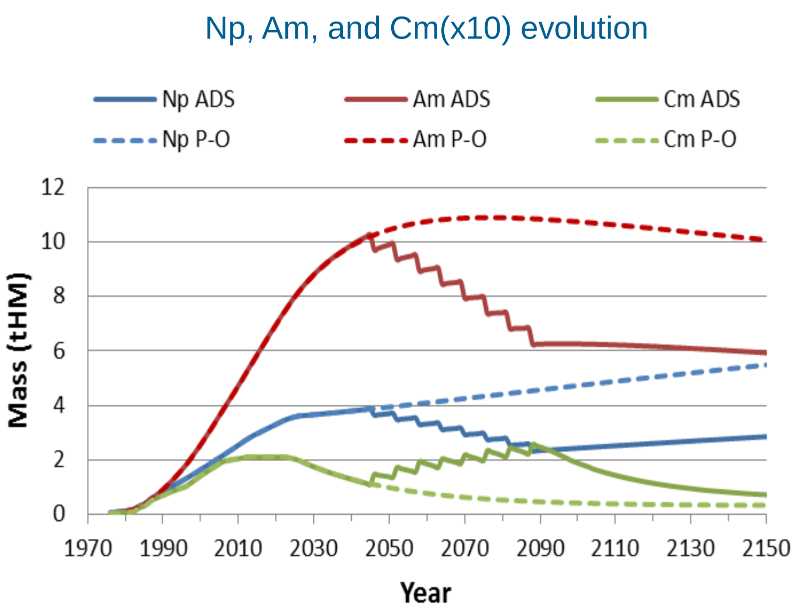


(*) C. Artioli et all, *"Optimization of the Minor Actinides transmutation in ADS: The European Facility for Industrial Transmutation EFIT-Pb Concept" .* Eighth International Topical Meeting on Nuclear Applications and Utilization of Accelerators. Idhao, USA, July 2007

Results: TRU Evolution

- A MA reduction of about 45% is reached by transmutation
- Pu amount “constant”





Results: Back-End

- Separated Material at EOC is not considered waste.
- Number of canisters by post processing based on Red Impact (*).
  - 4 SF-UOX
  - 1 SF-MOX
  - 3 Glasses (FP+ losses = 60 kg each)

Separated material at EOC

Material	P-O	ADS
DepU	39988	39988
RepU	650	4785
Pu	2.1 **	50.6
MA	-	6.3

(**) Pu available = 0

Material to store in the Final Disposal

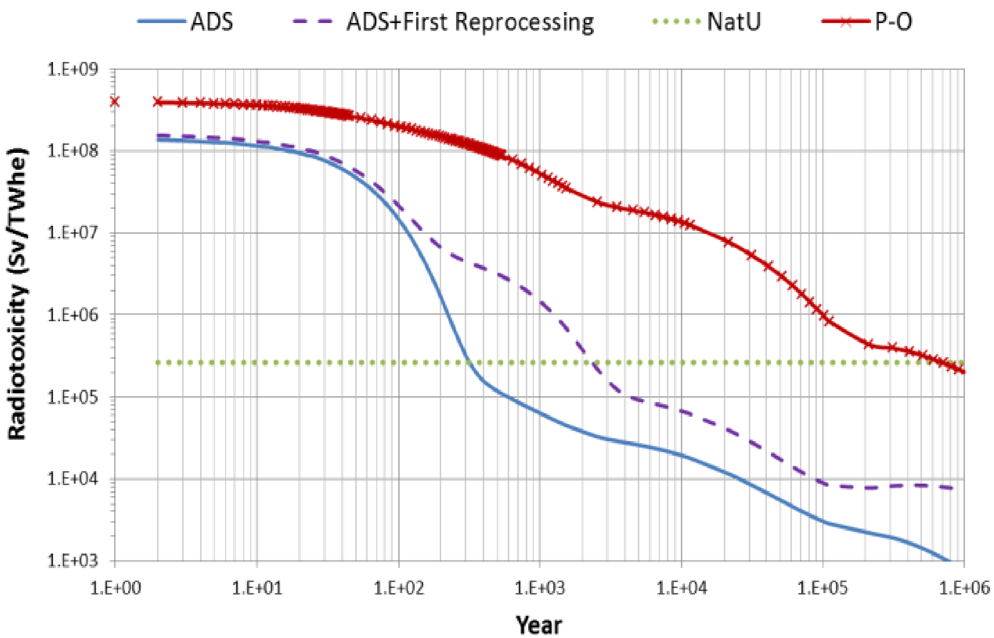
Scenario	P-O	ADS
Spent Fuel		
ADS SF (t)	-	-
MOX SF (t)	66	-
UOX_40 SF (t)	1020	-
UOX_50 SF (t)	3315	-
HLW		
ADS HLW (t)	-	5.1
MOX HLW (t)	-	2.5
UOX HLW (t)	17.2	154.5
Packages to manage		
SF (assemblies)	9560	-
HLW (vitrified waste)	292	2700
Structural Material (canisters)	500	3888
Final Disposal		
Volume for SF & HLW (m3)	6930	2610
Volume Structural Material (m3)	100	778

(*)*RED-IMPACT Synthesis Report*. ISBN 978-3-89336-538-8. FZJ, Germany (2008).

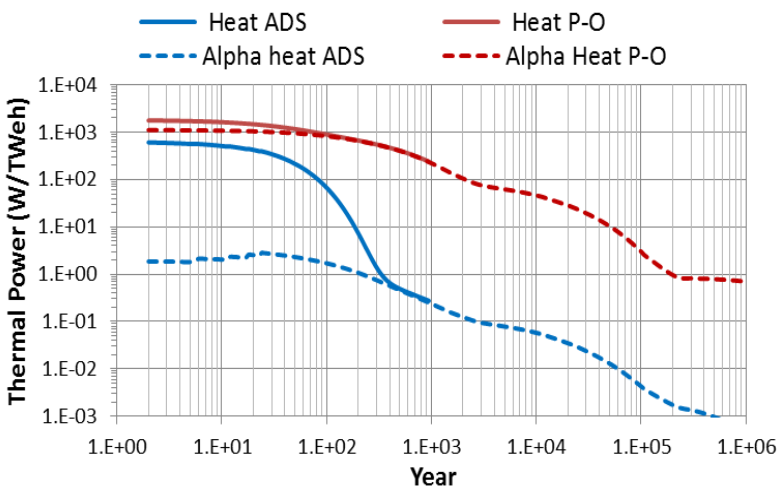
Results: Radiotoxicity and Decay Heat

- Radiotoxicity and decay heat results show consistencies between values and tendencies compared to related studies [Red-Impact]
- The impact of applying a reprocessing strategy without a MA separation in the past increased the radiotoxicity of the final repository

Radiotoxicity in the Final Disposal



Decay heat in the Final Disposal



Conclusions for the Belgian Nuclear Fuel Cycle

- ANICCA has provided answers to questions that can arise when studying a nuclear fuel cycle.
- ANICCA obtained reliable results in regards to the estimation of fuel mass and nuclear material required in the cycle (when the right assumptions are taken).
- Concerning the EFIT facility, the transmutation behaviour results are compatible with reference studies for this ADS.
- For the back-end, by applying the ADS strategy gives an important reduction (of more than 60%) of the volume compared to the reference scenario (P-O).
- Regarding the radiotoxicity and decay heat, results are also consistent with the bibliography .

Thank you for your attention