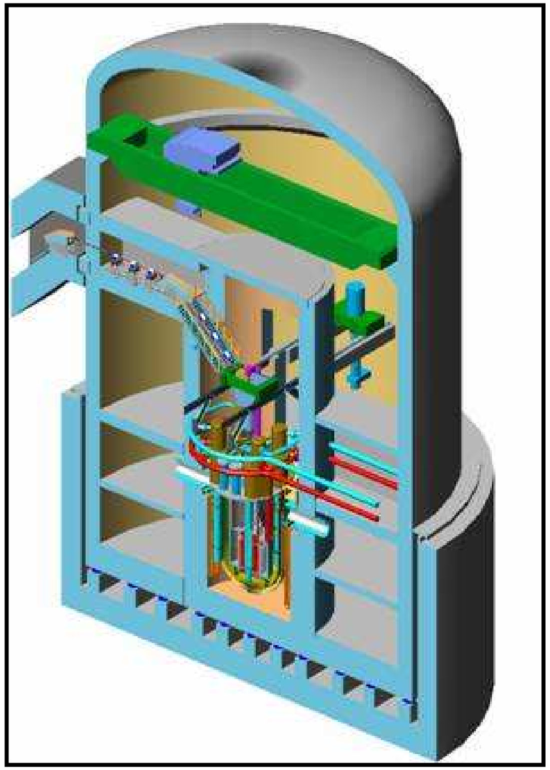

ASSESSMENT OF THE TRANSMUTATION CAPABILITY OF AN ACCELERATOR DRIVEN SYSTEM COOLED BY LEAD BISMUTH EUTECTIC ALLOY

Presented by

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OUTLINE

- **Why an ADT**
- **Studies at European Level**
- **ADT design constraints and hypotheses**
- **Neutronic analysis**
- **Fuel pin analysis**
- **Conclusions**

Why an ADT?

- **Reduction of LLFP and MA key point for public acceptability and nuclear energy economy.**
  - **Also a GEN IV sustainability-2 goal ➔ Gen IV will minimize and manage their nuclear waste, enabling them to significantly exceed current levels of protection for public health and the environment and notably reduce the long term stewardship burden in the future**

- **Fast reactors the best solution to transmute MA, but with limited amount**

  ➔ coolant void reactivity, Doppler effect, delayed neutron fraction

  ➔ dynamic behavior and control

- **XADT the best solution to transmute a large amount of MA in a double-strata scenario**

  ➔ plant control not rely on delayed neutron fraction

  ➔safe operation, no criticality risk due to keff < 1

Studies at European level on ADT

IV FP IABAT

- Studies on fuel cycles and ADS
- Nuclear Data
- Accelerator technologies

V FP

PDS-XADS

- To demonstrate the feasibility of the coupling among an accelerator, a target system and a subcritical system for the proposed solutions:
  - large LBE-cooled XADS (80 MWth)
  - Small LBE-cooled XADS (50 MWth)
  - Large Helium-cooled XADS (80 MWth)
- To preliminarily investigate the conditions to enhance the transmutation rate at values suitable for an industrial-scale transmuter

VI FP EUROTRANS IP

- To design an industrial-scale transmuter (EFIT)
- Development and studies MA-based SAs
- Development of related technologies

ADT design constraints and hypotheses

- Accelerator
  - **Reliability (limited number of beam trips)**
  - **Radioprotection (limited beam losses in normal and accidental conditions → limit beam current)**
  - **High value of I&E → high values of heat released in the small spallation volume (3.6 – 20 MWth) → issue for TARGET system**
  - **Proton beam current :**

$$I = \frac{P \cdot q \cdot (1 - K_{eff}) \cdot \nu}{\varphi * \cdot E_f \cdot K_{eff} \cdot Z}$$

32-34 n/p for LBE or Lead in the range of 1-2 GeV

  - **Design limits: (I≤ 20mA; E= 1 GeV)**

ADT design constraints and hypotheses

U-free MA-based fuels

▪ oxide composite fuel (Mo or MgO matrix)	- high thermal and chemical stability - simple handling and fabrication process - Matrix used to chemically linked MA and to increase thermal conductivity
▪ nitrite fuel	- better thermal properties - low stability of TRU nitrite (Nitrogen pressure build-up, actinide metal vaporization /redistribution) - fabrication more complicated (americium nitrite vaporization) - Production of ^{14}C by (n,p) reactions of ^{14}N (enrichment on ^{15}N)
▪ metal fuel	- easily reprocessing (pyro-chemical process) - poor properties (low melting temperature, thermal-conductivity), limited mutual solubility, significant swelling at low burn-up, etc

ADT design constraints and hypotheses

- **U-free MA-based fuels**
  - Fuel pin residence time (3-5 y)
  - Helium production (p≤ 50 bar)
  - Swelling (≤ 10%)
  - Fuel cladding damage (≤ 100 dpa)
  - decay heat (>30% MOX fuel➔ Curium)
  - Selected fuel: (Pu, Cm, Am)O_2 in MgO (CERCER) or

    Mo matrix (CERMET): enr. in Mo92 (92.7%)
    - Ratio matrix / fuel : ***40 / 60***
    - ***Design limits:***

Parameter	Unit	CERCER	CERMET
$Tmax_{fuel}$	**K**	**2350**	**2146**
$Tmax_{cladding}$	**K**	**823**	
Damage Function	**-**	**≤ 1**	
Burnup rate	**-**	**≤ 40% Heavy atoms**	
Power rating	**W/cm**	**≤250**	

ADT design constraints and hypotheses

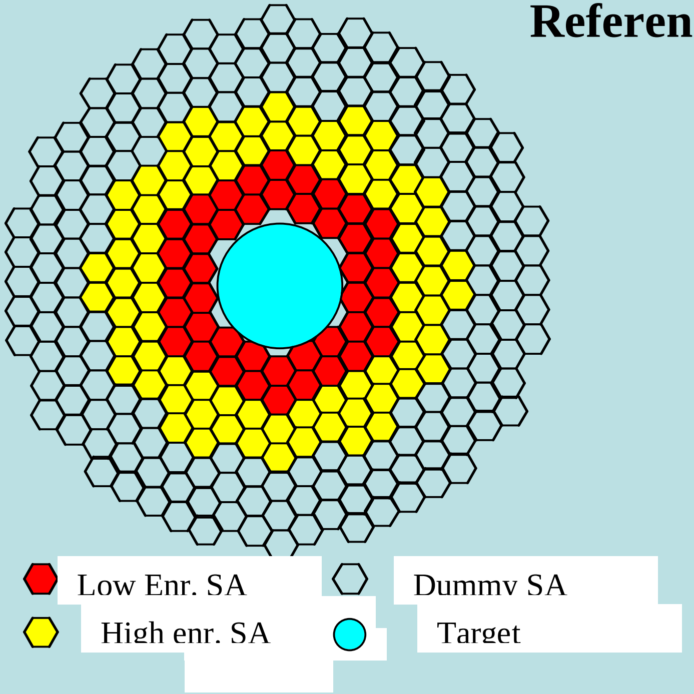
- **Double strata strategy (reprocessing loss rate: 0.1% for TRU and 1% for MA)**

Isotope	%	Isotope	%
U234	0.0040	**Pu242**	0.4362
U235	0.5973	**Am241**	27.8434
U236	0.0057	**Am242m**	0.2278
Np237	0.0067	**Am243**	25.0035
Pu238	0.0938	**Cm243**	0.0784
Pu239	23.7489	**Cm244**	10.9484
Pu240	8.3569	**Cm245**	1.6345
Pu241	0.8887	**Cm246**	0.1257

- **Multi-recycling scenario of 10 cycles (length equal to 930 days)**
- **k_{eff} = 0.97 at BOL of each cycle adjusting TRU and MA contents so that to obtain the same enrichment concentrations in the two core zones**
- **External neutron source was assumed equal to XADS-80 (14.98 neutrons per incident proton), as the source importance does not change significantly (multiplication factor for a 800 MeV proton beam is equal to 29.66, whereas for 600 MeV one is 29.65)**

Neutronic analysis

Reference core configuration



- central cavity for housing the target
- hexagonal wrapped fuel assembly (exploit FBRs experience).
- Fuel assembly same design of XADS MOX fuel assembly (material, dimension of pellets and pins)
- Reflecting region to reduce damage on fixed structures: wrapped assemblies filled –up by LBE

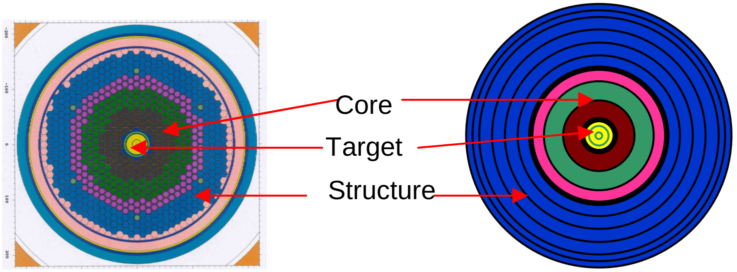
Fuel/Dummy SAs number: 120/168
Power rating: 82W/cm (max: 122 W/cm)
High enrichment: ~ 37 at% (~ 28.25 for XADS)
Number of fuel assemblies with high enr.: 78
Low enrichment: ~ 30 at% (~ 21.8 for XADS)
Number of fuel assemblies with low enr.: 42

Fuel SA: 90 pins
Fuel pin outer diameter: 8.5 mm
Fuel pin pitch: 13.4 mm
Fuel active length: 870 mm
Outline SA length: 3600 mm

Neutronic analysis
Computer code and models

- **ERANOS code vers. 2.0**
  - **ECCO code vers. 6 for cross-sections: heterogeneous geometrical description of SAs. Each set homogenized preserving the total reaction rates all over the assembly and collapsed in 33 energy groups**
  - **ERALIB1 for nuclear data: 279 nuclides, 1968 energy groups, different T and orders of scattering anisotropy (n = 4, 8, 16 - S4 adopted)**
  - **BISTRO for core calculations with transport equations (RZ core description adopted)**

- **MECONG procedure**
  - ➢ multi-recycling problem
  - ➢ Simplified calculation
    - **- geometrical cell description in homogenous way**
    - **- RZ cylindrical geometry (small effects on results)**
    - **- ECCO code vers.6 for cross-sections**
    - **- ERALIB1 for nuclear data: 279 nuclides, 1968 energy groups, different T and orders of scattering anisotropy**



Neutronic analysis

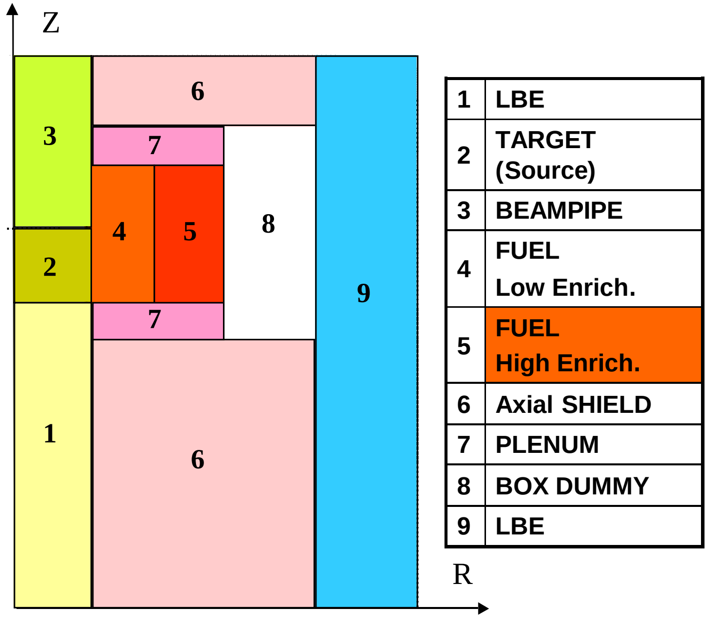
Codes and models

- **Performed calculations:**

❖ **Multi-recycling scenario analysis**

  ✓ **XADT-80**

  ✓ **Sensitivity analysis (density power, power size)**



1	LBE
2	TARGET (Source)
3	BEAMPIPE
4	FUEL Low Enrich.
5	FUEL High Enrich.
6	Axial SHIELD
7	PLENUM
8	BOX DUMMY
9	LBE

❖ **Detailed neutronic evaluation (300 MWth)**

❖ **For both:**

- **Cycle length divided in 6 steps of 155 EFPD**
- **cross-sections and main neutronic parameters (flux, burn-up, reactivity, etc.) calculated each time step**
- **Fission products simulated with 6 special pseudo nuclides (MECONG) or 75 pseudo nuclides (ERANOS)**

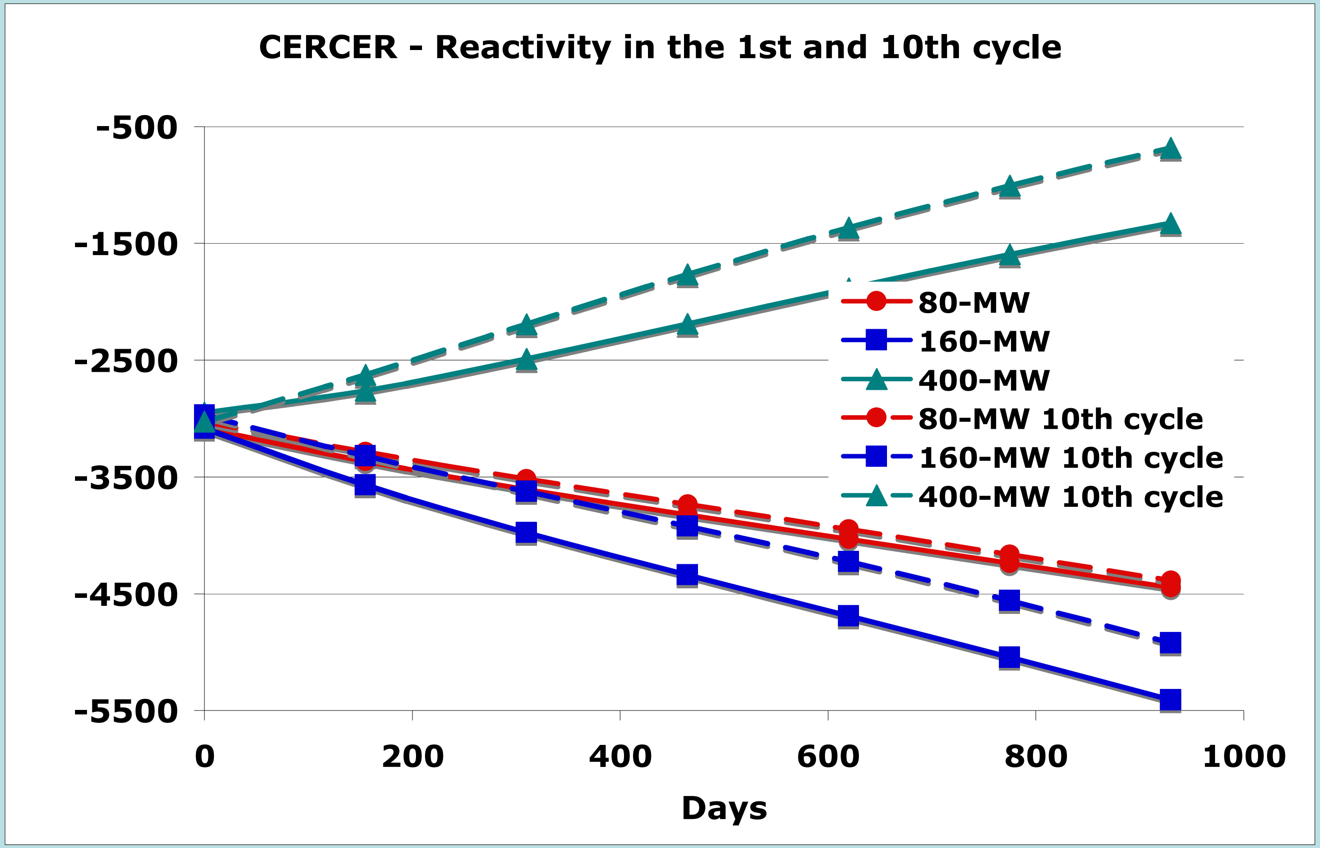
Neutronic analysis
MECONG Results

XADT-80

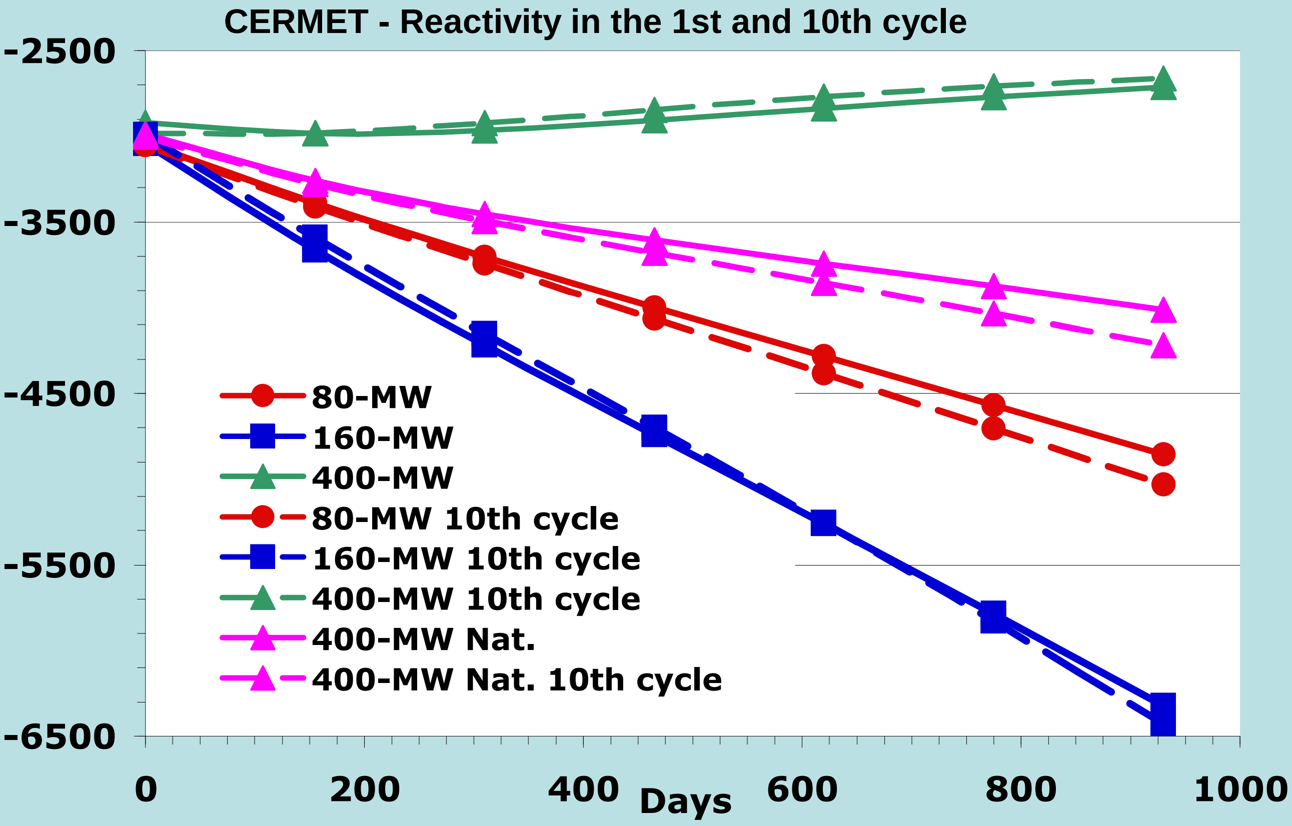
Parameters		**MgO**		**Mo92**	
		1st cycle	**10th cycle**	**1st cycle**	**10th cycle**
Inner core enrichment [%]		30.85	30.85	30.87	30.87
Outer core enrichment [%]		37.17	37.17	37.19	37.19
Reactivity loss per day [pcm/d]		1.46	1.46	1.95	2.13
Max density power [W/cm^3]	BOC	66.5	64.1	66.0	64.0
	EOC	71.1	69.2	71.8	70.6
Max power rating [W/cm]	BOC	122.0	117.6	121.0	117.4
	EOC	130.4	126.9	131.6	129.4
Average enrichment		34.96	34.96	34.98	34.98
Inner Core Flux *E14 [$n.cm^{-2}.s^{-1}$]	BOC	7.55	7.97	7.67	8.06
	EOC	8.09	8.49	8.28	8.70
Outer Core Flux *E14 [$n.cm^{-2}.s^{-1}$]	BOC	5.56	6.01	5.65	6.05
	EOC	5.70	6.11	5.79	6.17
Average Burnup [MWd/T]		37125	37086	37119	37085
Max Burnup [MWd/T]		55902	54071	55849	54485

Parameter	**MgO**	**Mo92**
β [pcm]	151.4	150.9
Fuel Doppler (pcm/K)	0.011	0.006
Coolant Void worth [pcm/dm^3]		
Fissile	2.0	1.7
LE Fissile	4.0	3.7
HE Fissile	0.7	0.39

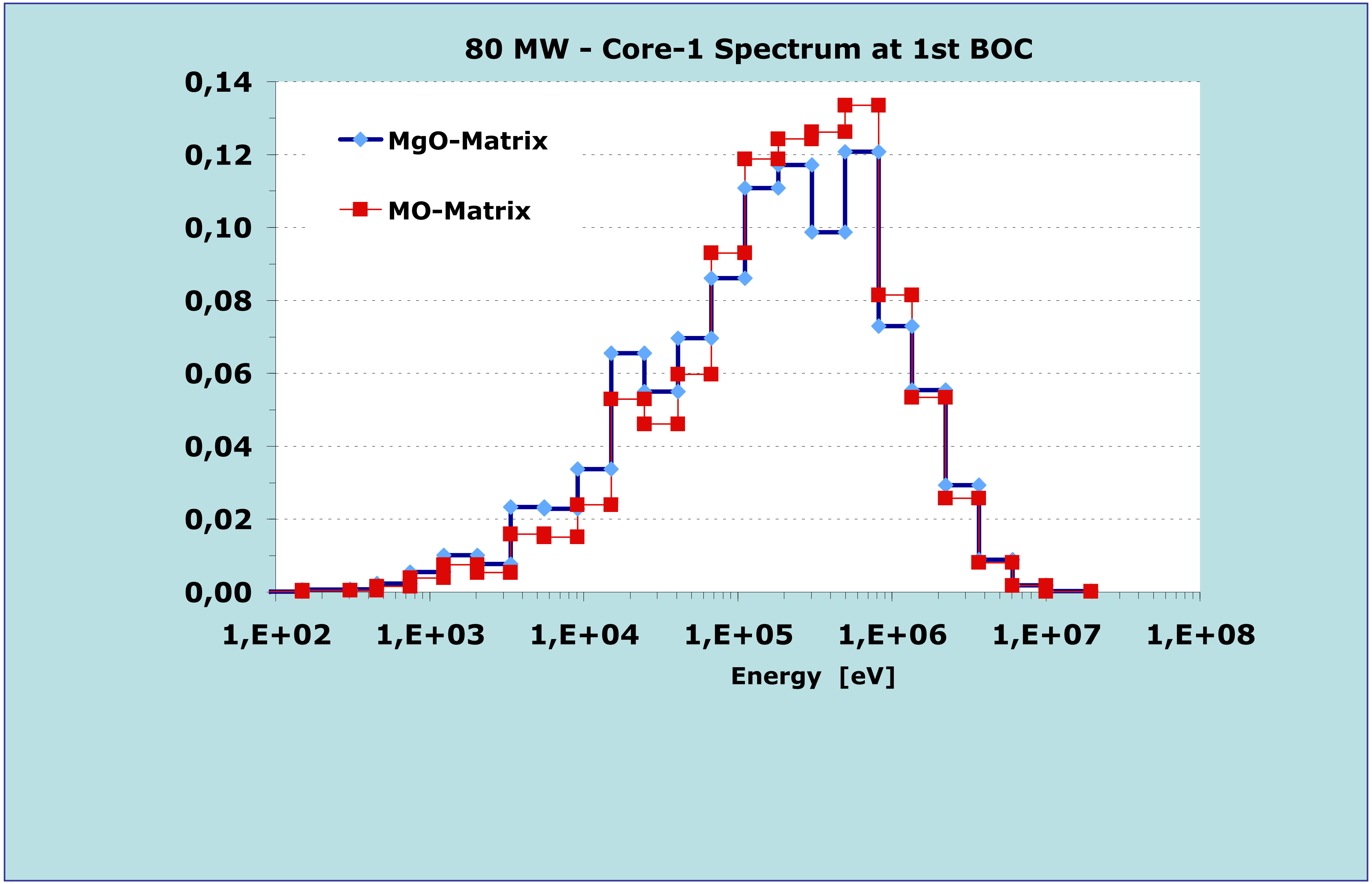
Neutronic analysis
MECONG Results



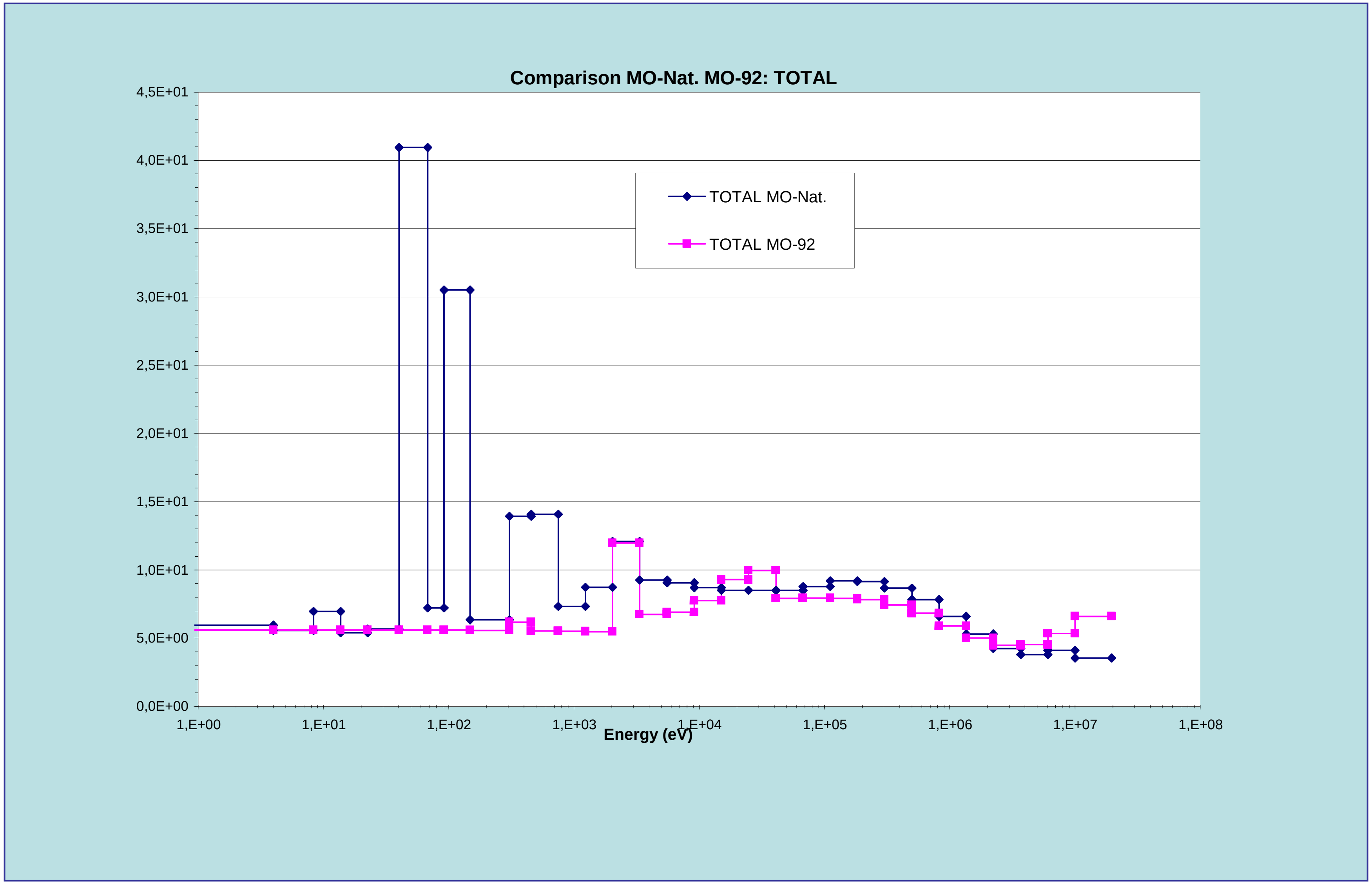
Neutronic analysis
MECONG Results



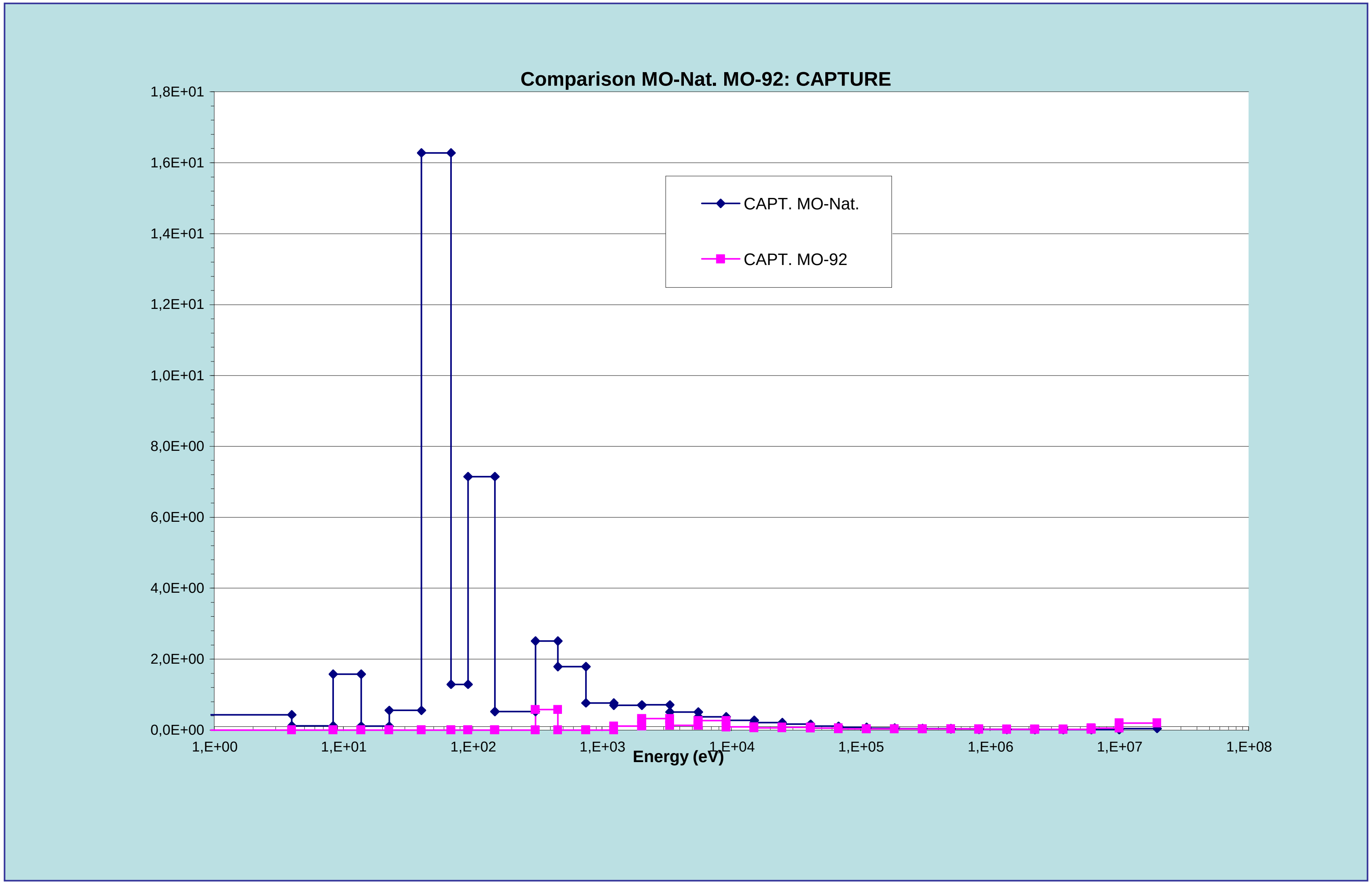
Neutronic analysis
MECONG Results



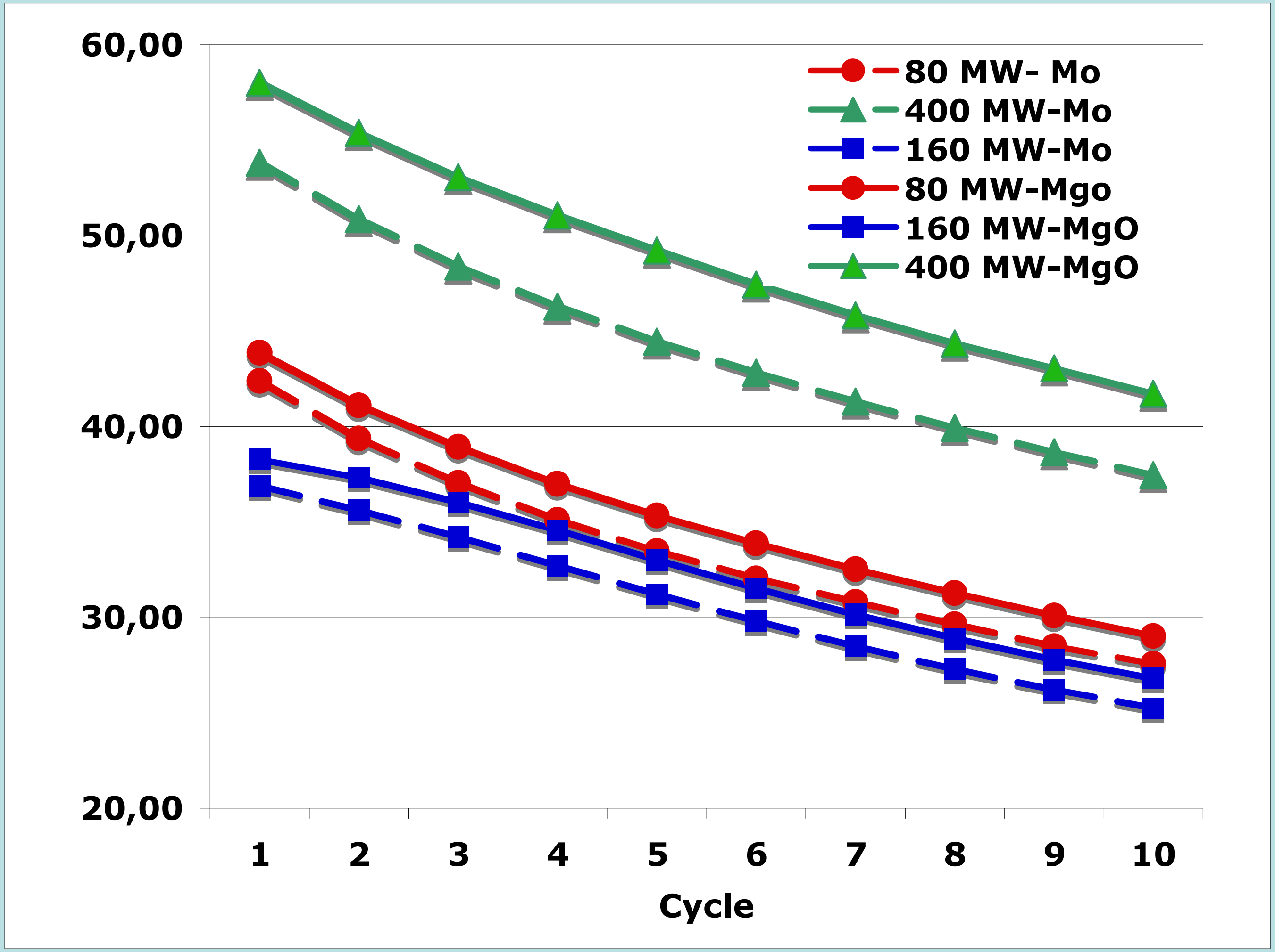
Neutronic analysis
MECONG Results



Neutronic analysis
MECONG Results

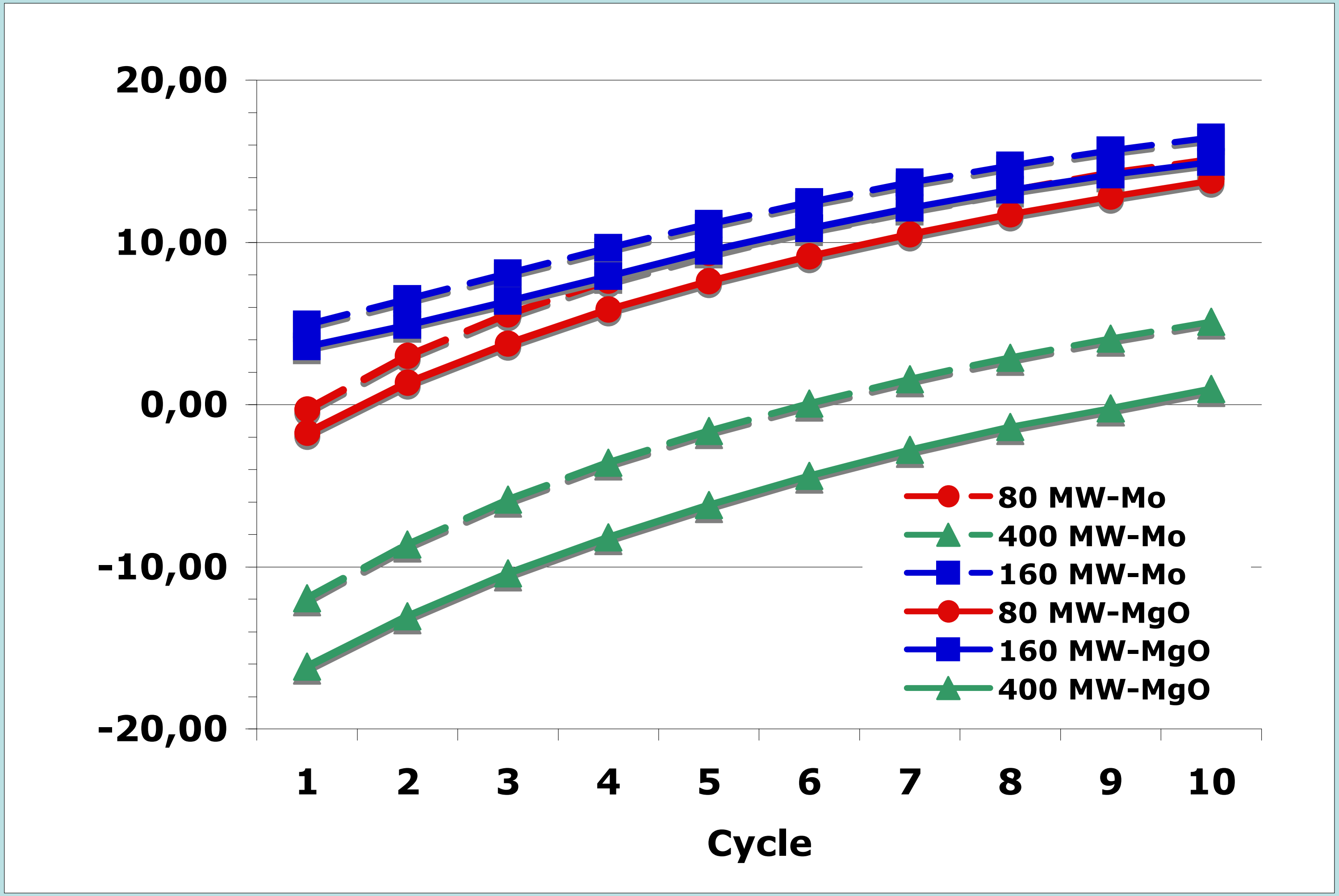


Neutronic analysis
MECONG Results



Neutronic analysis

MECONG Results



Neutronic analysis

ERANOS Results

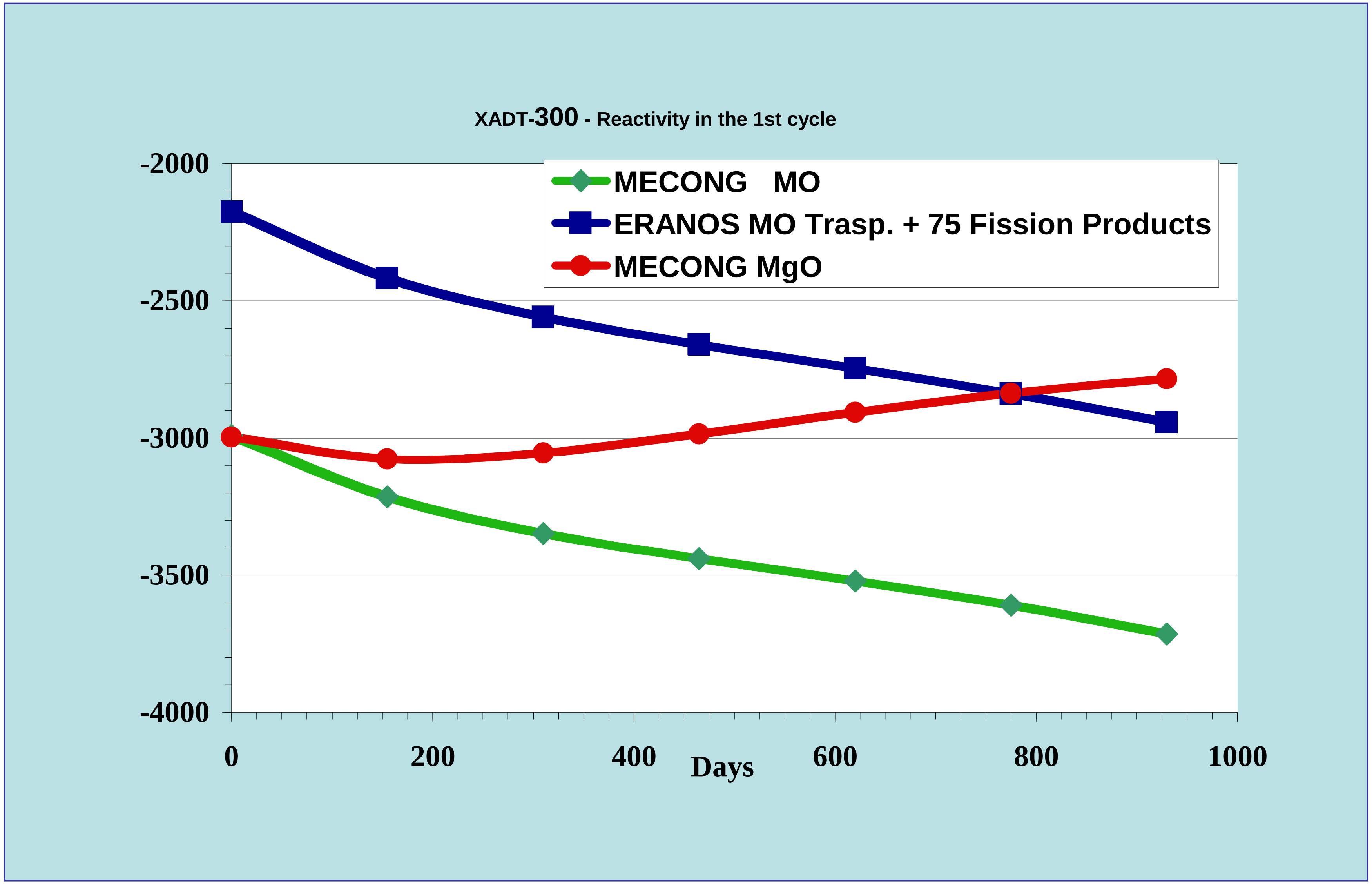
XADT-300

Parameters		1st cycle		
		ERANOS	MECONG	
		Mo92	Mo92	MgO
Inner core enrichment [%]		23.5	23.5	23.9
Outer core enrichment [%]		28.3	28.3	28.8
Reactivity loss per day [pcm/d]		0.82	0.78	
Max density power [W/cm^3]	BOC	121	136	137.3
	EOC	133	147.2	137.9
Max power rating [W/cm]	BOC	221.9	250	251.8
	EOC	244.1	269.9	252.8
Average enrichment		27.4	27.4	
Inner Core Flux *E14 [n.cm^{-2}.s^{-1}]	BOC	-	16.96	16.56
	EOC	-	19.04	17.84
Outer Core Flux *E14 [n.cm^{-2}.s^{-1}]	BOC	-	11.03	10.77
	EOC	-	11.53	11.21
Average Burnup [MWd/T]		-	63141	63151
Max Burnup [MWd/T]		-	115534	112878

Parameter	80 MWth	300 MWth
β [pcm]	150.9	135.6
Fuel Doppler (pcm/K]	0.006	0.006
Coolant Void worth [pcm/dm³]		
Fissile	1.7	1.4
LE Fissile	3.7	2.4
HE Fissile	0.39	1.2

Neutronic analysis

ERANOS Results



Neutronic analysis
ERANOS Results

Accelerator beam current analysis

Power [MW]	MgO				Mo92			
	1st cycle		10th cycle		1st cycle		10th cycle	
	BOC	**EOC**	**BOC**	**EOC**	**BOC**	**EOC**	**BOC**	**EOC**
80	2.45	3.53	4.37	3.44	2.37	3.80	2.39	3.93
160	4.89	8.59	4.69	7.74	4.82	10.0	4.7	10.1
400	11.9	5.36	12.1	2.72	11.7	10.9	11.8	10.5
300	9.02	8.41	9.01	5.53	9.00	11.2	-	-
300*	-	-	-	-	6.55	8.87	-	-

I ≤ Design limit

Fuel pin analysis
Code

TRANSURANUS (TU): Deterministic analysis
Statistical analysis

Modelling

TU standard

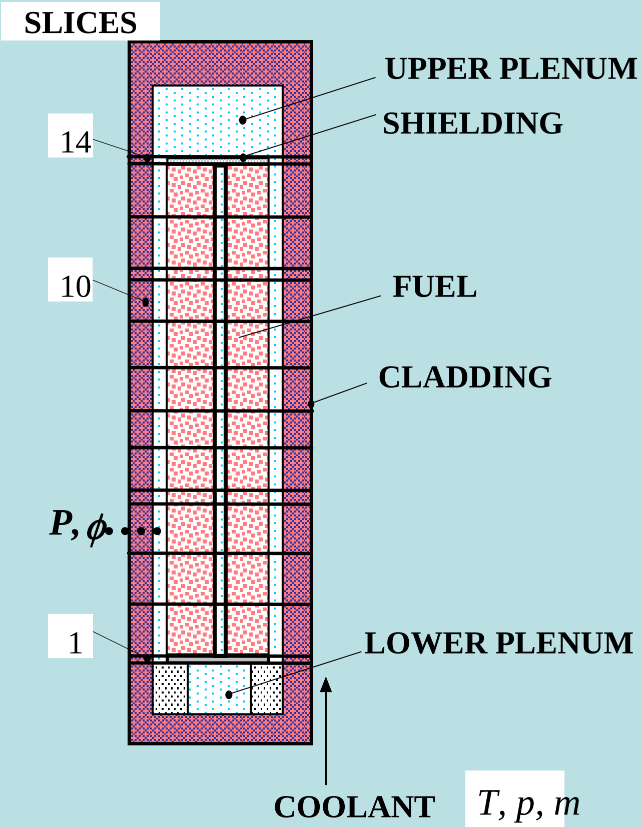
densification, relocation, restructuring, grain growth, FGR-Urgas, gap conductance-Urgap

TU modified

1. Thermo-physical and mechanical properties (density, specific heat, thermal conductivity, linear thermal expansion, Poisson ratio, Young modulus, yield stress)
2. LBE, T91, TRU, MgO, Mo, He

Hypotheses

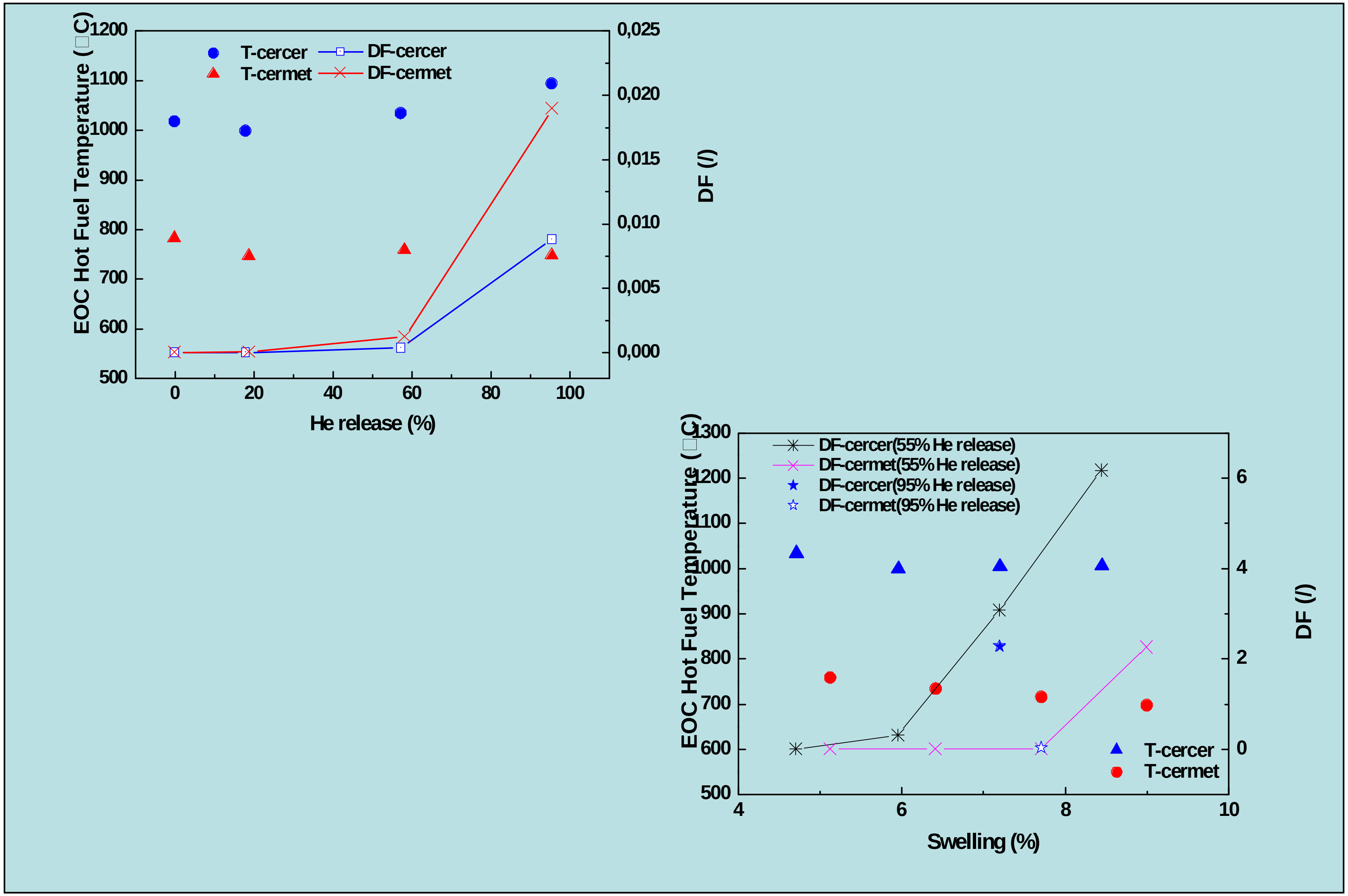
1. composites thermal cond. degradation due only to UO2-like MA oxide (matrix thermal conductivity degradation due to alpha and fission products neglected);
2. Swelling: matrix voids formation due to neutron flux considered only for CERMET, an annealing effect for CERCER. High Burnup Structure formation supposed for fuel phase with a modelling similar to LWR. Solid component of swelling changed by using an input factor. A 0.5 %/at% burnup solid fuel swelling was assumed.
3. gas release: diffusion modelling assumed for Xe-Kr and He in fuel phase, matrix effect represented by an input factor to increase the grain boundary saturation limit



14 axial slices
3 radial zones in the fuel
1 radial zone in the cladding

Fuel pin analysis

Results



Conclusions

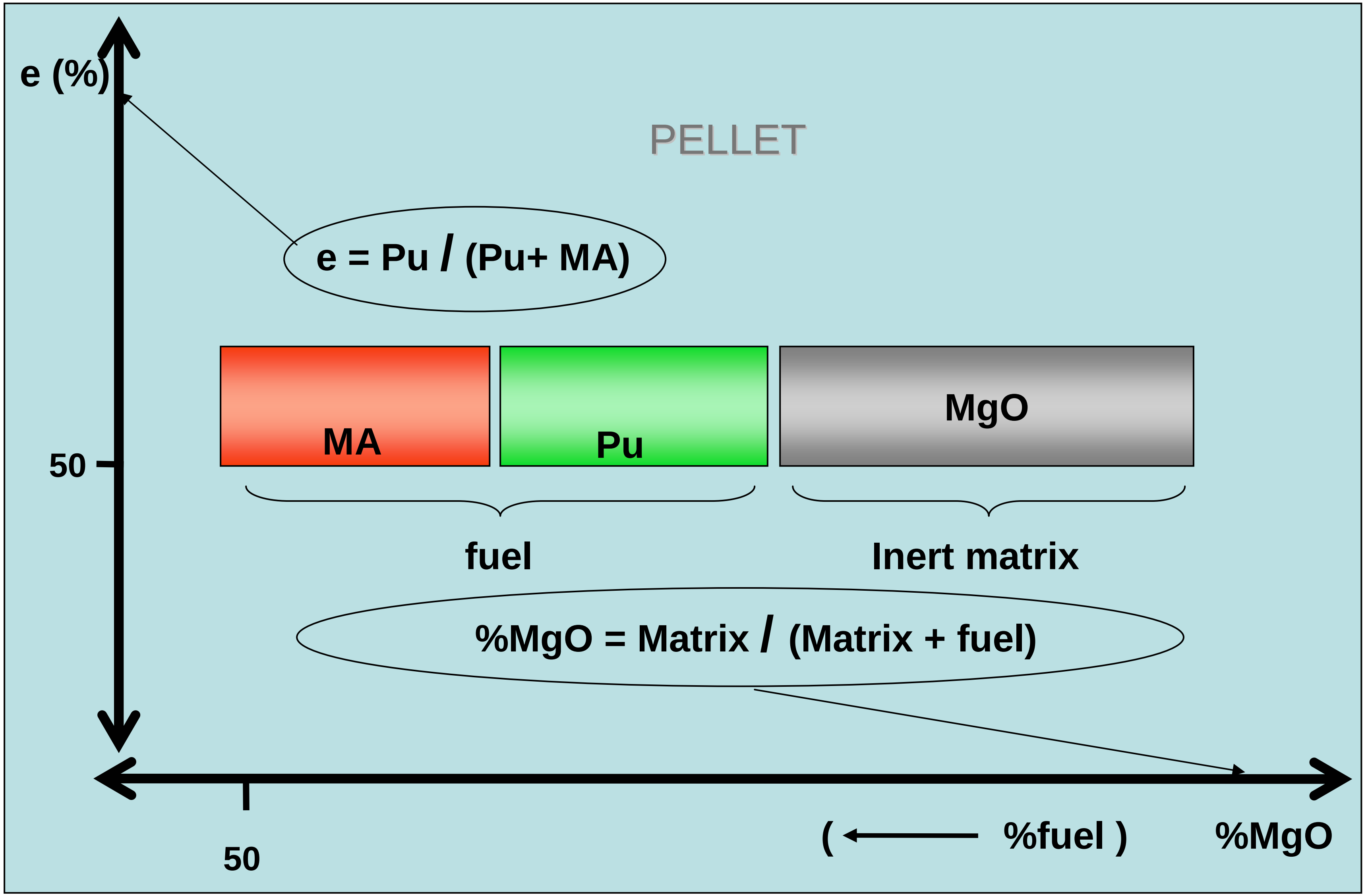
- **More efficient transmutation rates require larger cores, but suitable refuelling strategies or operation with proton beam current constant are needed to face up to the criticality risk:**

  keff constant or almost constant along the cycle with an appropriate choice of neutronic parameters, such as power rating, volume of different enrichment zones, core height and diameter, fuel isotopic vector, etc.)

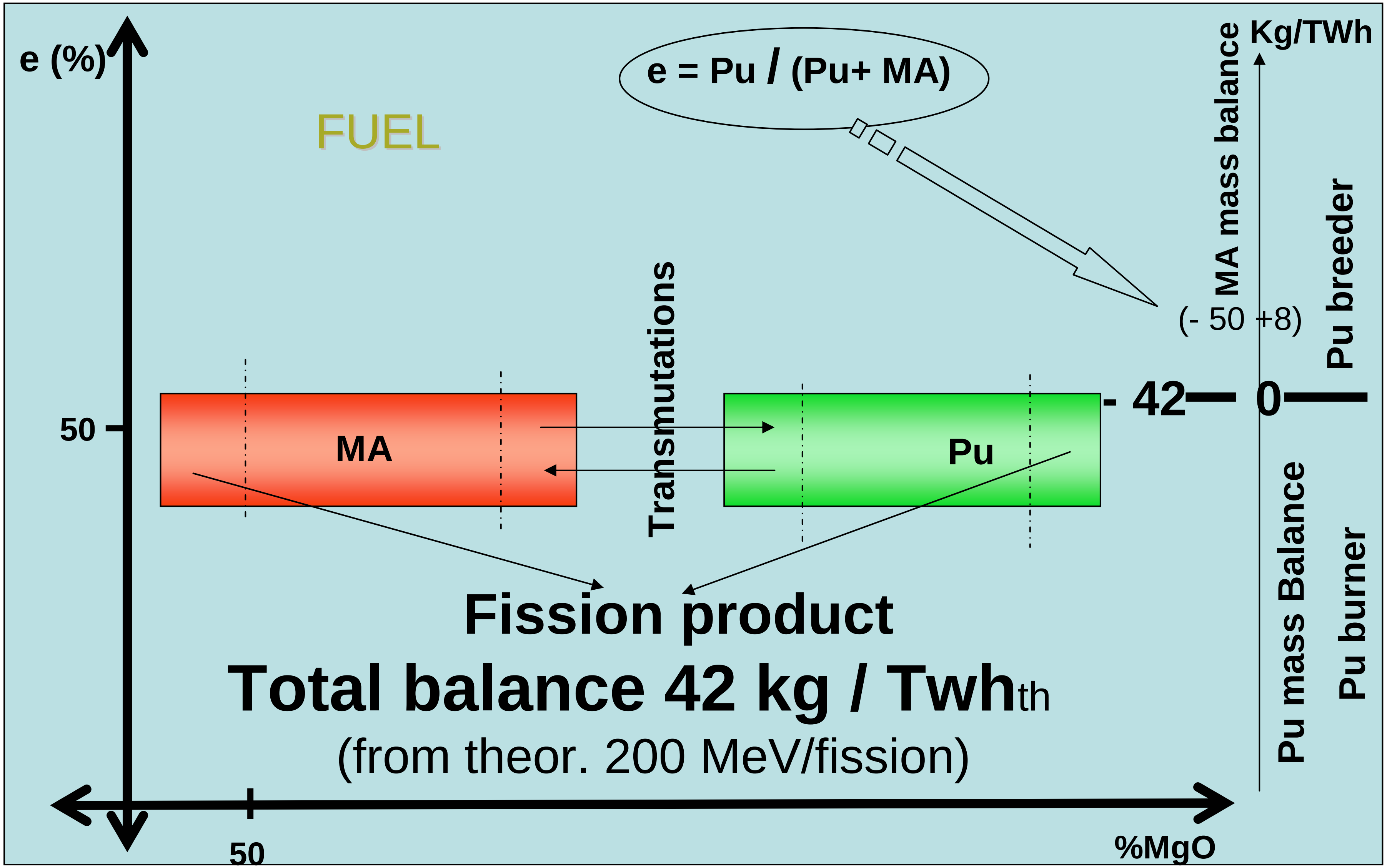
- **Supporting R&D research should be addressed to reduce the uncertainties on nuclear data and to develop new U-free fuels and new steel materials**

- **CERMET fuel is advisable**

MA+Pu


e (%)
PELLET
e = Pu / (Pu+ MA)
MA
Pu
MgO
50
fuel
Inert matrix
%MgO = Matrix / (Matrix + fuel)
50
(← %fuel)
%MgO

MA + Pu



Fission product

Total balance 42 kg / Twh$_{th}$

(from theor. 200 MeV/fission)

Fuel pin analysis

Cladding Damage Function **:**

$$\int \frac{d\varepsilon_{th,eq}}{\varepsilon_{th,\mathrm{lim}}} + \int \frac{d\varepsilon_{p,eq}}{\varepsilon_{p,\mathrm{lim}}} < 1$$

with:

$\boldsymbol{\varepsilon}_{\mathbf{th,lim}} = 0.2\%$ and $\varepsilon_{\mathrm{p,lim}} = 0.2\%$

Fuel pin analysis

- MgO matrix characteristics:
  - Density of the oxide = 11.46 g/cm^3
  - Density of MgO = 3.58 g/cm^3
  - Practical Density = 0.90 * Theoretical density
  - Filling Density = 0.81
  - Ratio matrix/fuel: = 40/60
- Mo matrix

Component	Mo92 matrix	Natural Mo matrix
Mo92	92.7	14.8
Mo94	6.23	9.3
Mo95	1.00	15.9
Mo96	0.07	16.7
Mo97	-	9.6
Mo98	-	24.1
Mo100	-	9.6

Fuel pin analysis

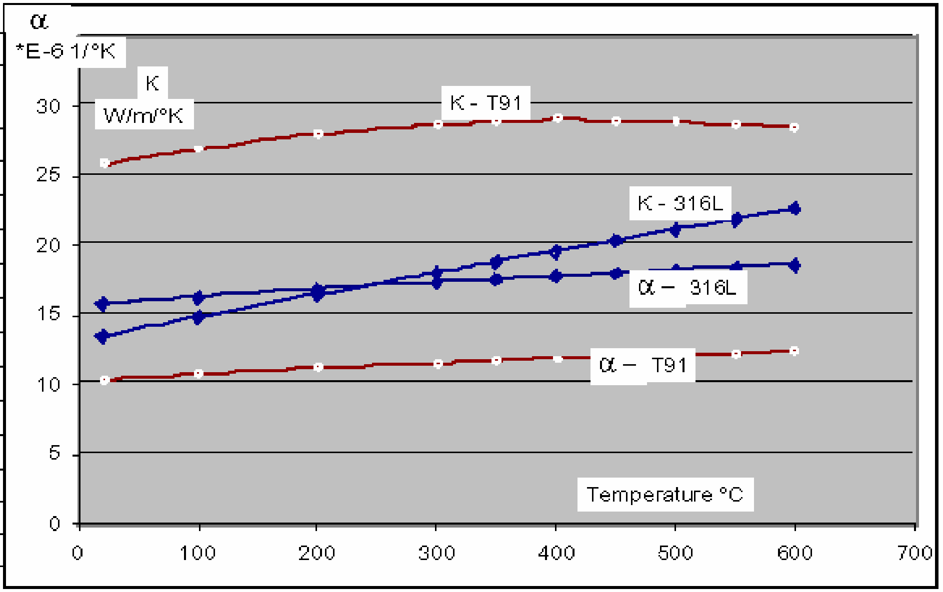
Analysis: deterministic

Nominal power: 300 MWth

Cycle length: 930 days (equal to ADT-80)

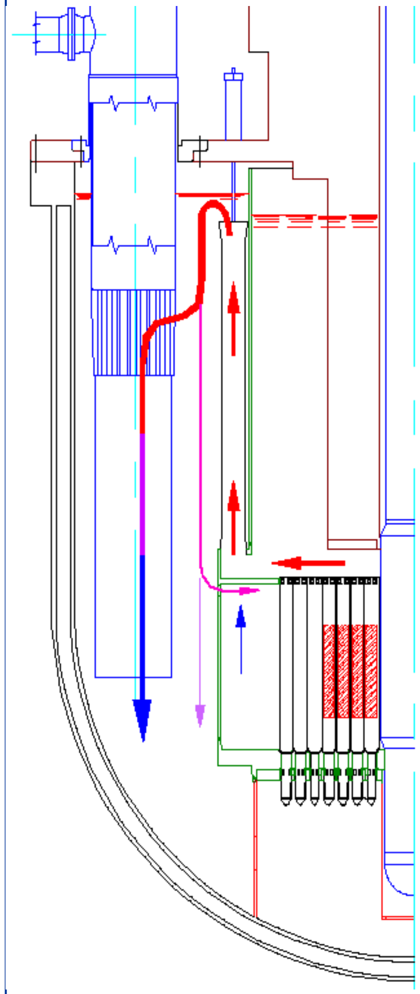
Cladding: 9Cr1Mo grade 91 (T91)

Element	Chemical Composition W%	
	AISI 316L by ASTM A240	T91 by ASME codeSA-213
Fe	balance	balance
Cr	16 ÷ 18	8 ÷ 9.5
Ni	10 ÷ 14	0.4 max
Mo	2÷3	0.85 ÷ 1.05
Nb	-	0.06 ÷ 0.1
Mn	2 max	0.3 ÷ 0.6
V	-	0.18 ÷ 0.25
C	0.03 max	0.08 ÷ 0.12
N	0.1 max	0.3 ÷ 0.7
Si	0.75 max	0.2 ÷ 0.5
S	0.03 max	0.01 max
P	0.045 max	0.02 max
Al	-	0.04 max

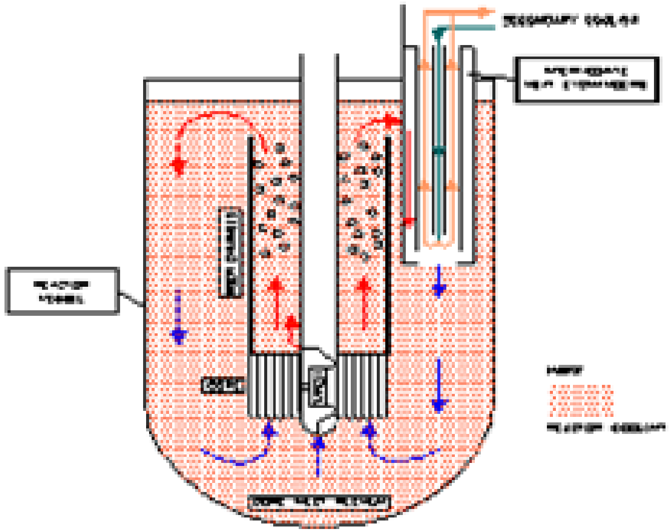


80MWth LBE-COOLED XADT

PRIMARY SYSTEM (1/3)



- Pool type design
- No pumps
- Enhanced natural circulation
- No separation between cold and hot plenum
- Decay heat removal by SCS and RVACS
- Low hydraulic resistance (≤0.3 bar)



80MWth LBE-COOLED XADT

TARGET UNIT (2/3)

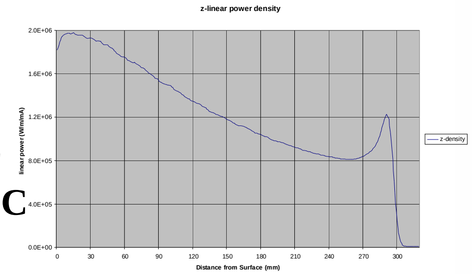
Functional and physical interface between Accel. and XADT core
To provide an external source to XADT core

Undesirable effects of spallation reaction:

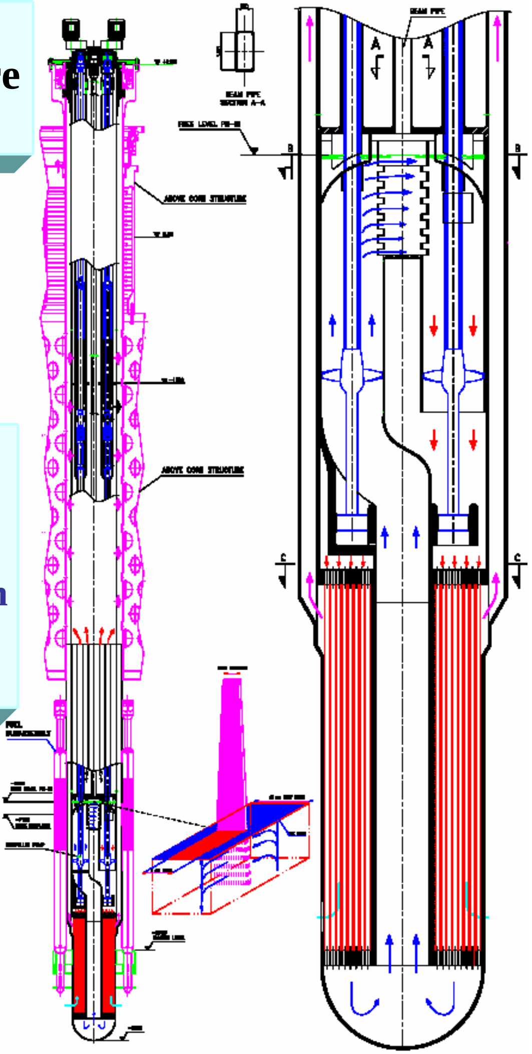
- **Large quantity of heat concentrated in a small volume**
- **Intense radiation damage in structural materials**

- **Windowless Target Unit**
- **LBE circulation by 2 propeller pumps (in-series)**
- **Proton beam footprint: 10 (‖flow) x80 (⊥flow) mm**
- **Spallation volume: 10 x80 x300 (⊥free surface) mm**
- **HX placed 1m beneath core region**
- **No natural circulation in case of the pumps loss**

- ☐ **Average power density: 12.5 KW/cm^3**
- ☐ **Beam/Target power: 3,6/2,6 MWth**
- ☐ **Inlet/outlet Target LBE temp.: 335/440 C**
- ☐ **Inlet/outlet primary LBE temp.: 300/380 C**
- ☐ **Target/primary flow rate: 188/256 Kg/s**
- ☐ **Target life: one fuel cycle**



Z-linear power density



80MWth LBE-COOLED XADT
SECONDARY SYSTEM (3/3)

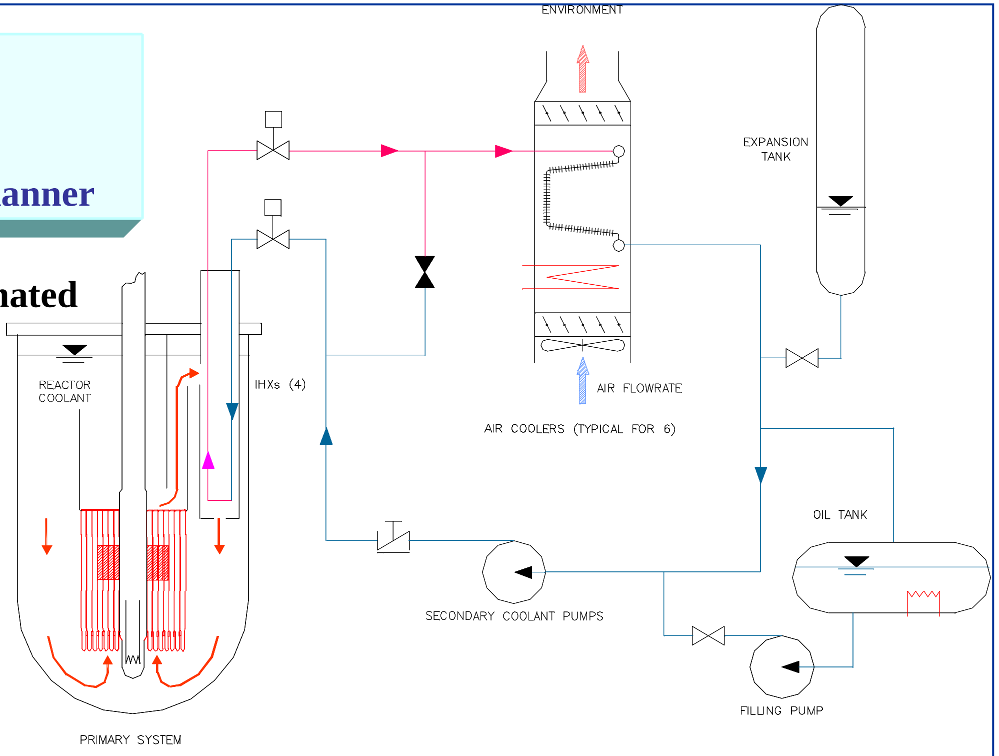
- ➢ Two loops operated at low pressure
- ➢No electricity production
- ➢Capable to remove decay heat in passive manner

Coolant: synthetic diathermic fluid (Hydrogenated Terphenyl Mixture)

Radiation stability
No chemical reaction with LBE and air
Low vapour pressure (<1 bar)

Each includes:

- one circulation pump
- three air coolers (in series)
 two IHX (in parallel)
- one expansion tank
- one natural circulation by-pass



Air coolers can work in forced or natural circulation (in case of fans failure)
Lay-out to avoid oil ingress into primary system
Upper oil temp.: 320 C (maximum bulk temp.: 345 C)
Inlet/outlet oil temp.: 270/312 C
IHX exchanged power: 20.75 MWth