Benchmark analyses for BN-600 MOX core with minor actinides

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OUTLINE

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- **TRU isotopic composition for MOX with MAs**

- **Benchmark description**

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- **Burnup simulation**

- **Energy and isotopic contributions to reactivity effects**

- **Sensitivity to variations in nuclear data**

- **Transient simulations**

- **Conclusions**

BN-600 core benchmarks with UOX/MOX and MOX fuel (1)

➢ **IAEA CRP on "Updated Codes and Methods to Reduce the Calculational Uncertainties of the LMFR Reactivity Effects" started in 1999**

➢ **Validate, verify and improve methodologies& codes for calculation of reactivity coefficients in fast reactors**

➢ **Calculations models based on the BN-600 core, partly or fully with MOX, provided by IPPE, Phases 1 to 6**

➢ **10 organizations, 9 countries (all or some Phases)**

➢ **Compute integral values and spatial distributions of power and safety-relevant reactivity coefficients**

➢ **Compare results of transient simulations with potentially different reactor physics parameters**

- ➢ „Hybrid" core: partially (about 20%) with MOX, weapons- grade Pu, steel shielding SAs instead of radial blanket, axial blankets remain:

  - ➢ RZ homogeneous benchmark (Phase 1),

  - ➢ HEX-Z homogeneous benchmark (Phase 2),

  - ➢ HEX-Z heterogeneous and burnup benchmark (Phase 3).

- ➢ Diffusion approximation found to be reasonably accurate

- ➢ Appreciable spread in calculated parameters (data, tools)

- ➢ Minor influence of deviations in reactor physics parameters on ULOF before sodium boiling, but significant divergence in accident progression after
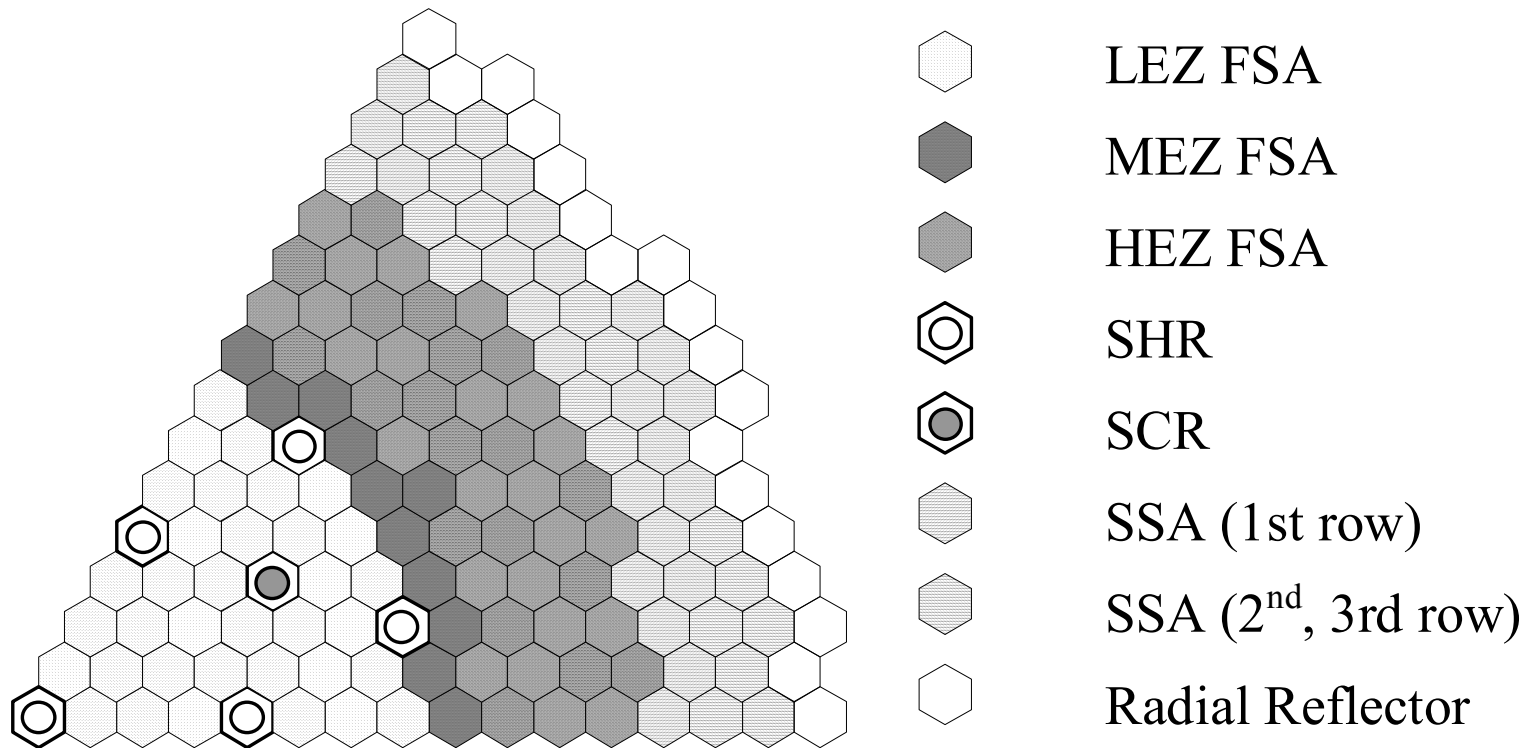
- ➢ PHYSOR 2002 paper by Y.I. Kim et al.

- **Full MOX core (Phase 4)**

  - **upper sodium plenum instead of axial blanket**

  - **internal breeding zone (ca. 5 cm) in the inner core**

  - **reduced fissile height, extra row of fuel SAs**

- **Larger differences in spatial distributions of reactivity coefficients =>larger effect on prediction of maximal values of parameters of the UTOP and ULOF**

- **Sodium plenum modeling: a particular source of uncertainties**

- **Uncertainty due to choice of geometry approximations (RZ, HEX-Z) higher than of those due to choice of heterogeneous/ homogeneous or diffusion/transport calculation options**

- **Heterogeneous and transport corrections of similar magnitude, but different sign for sodium density coefficient; small for Doppler**

- **PHYSOR 2004 paper by Y.I. Kim et al.**

➢ **Phase 5: validation of tools for criticality values and sodium void distribution with results of BFS-62 critical facility**

>   ➢**3rd in series to study changes in physics of the BN-600 reactor from UOX to hybrid**

>   ➢**A homogenized model and "adjusted" experimental data provided by IPPE**

➢ **Applicabity of tools and data confirmed in general**

➢ **Issues related to steel reflectors instead of fertile blankets**

➢ **Phase 6 (last): fully MOX with MAs, presented in the following**

➢ **IAEA TECDOC on Phases 1, 2, 3, and 5 in print**

➢ **IAEA TECDOC on Phases 4 and 6: next year**

TRU isotopic composition for MOX with MAs

- ➢ **Phases 1 to 5:utilization of weapons-grade plutonium in BN-600**

- ➢ **Phase 6: TRU from spent LWR fuel**

- ➢ **"Envelope" case: 60 GWd/t, cooling for 50 years, no separation of Pu and MAs**

  - ➢ **More than 5% of TRUs if 25% or more enriched**

  - ➢ **Lower burnup (e.g. 45 GWd/t) and/or short cooling times not considered due to lower MA content**

  - ➢ **2.5% to 5% of MAs: a possible limit for some designs**

- ➢ **TRU isotopic compostion provided by CEA under the above mentioned assumptions**

➢ **The same geometry as for Phase 4:**

> ➢ **three enrichment zones: inner LEZ, middle MEZ, outer HEZ**
>
> ➢ **internal axial blanket in LEZ**
>
> ➢ **sodium plenum above the fissile core**
>
> ➢ **shim rods near mid-plane**
>
> ➢ **scram rods just above the fissile core**
>
> ➢ **HEX pitch ca. 10 cm**
>
> ➢ **127 pins per SA**

LEZ FSA

MEZ FSA

HEZ FSA

SHR

SCR

SSA (1st row)

SSA (2nd, 3rd row)

Radial Reflector

Layout of the BN-600 model (60-degree sector, rotational symmetry).

Reflector	30.0	30.0		22	22	22	22	22	22	22	21
Cones	4.5	4.5		12	12	12	14	16	19	20	21
Upper Boron Shield	15.0	5.0 / 5.0 / 5.0		13	13	13	14	16 SCR	19	20	21
Cones	4.5	4.5		12	12	12	14	17	19	20	21
Sodium Plenum	23.0	8.0 / 8.0 / 7.0		11	11	11	14	17	19	20	21
Plugs	5.3	5.3		10	10	10	14	17	19	20	21
Core	41.15	8.23 / 8.23 / 8.23 / 8.23 / 8.23		1 LEZ	2 MEZ	3 HEZ	14 SHR	17	19 SSA1	20 SSA2, 3	21 Radial Reflector
IBZ	5.1	5.1		23 IBZ	2	3	15	18	19	20	21
Core	41.15	8.23 / 8.23 / 8.23 / 8.23 / 8.23		1 LEZ	2 MEZ	3 HEZ	15	18	19 SSA1	20 SSA2, 3	21 Radial Reflector
A. Blanket 1	5.5	5.5		7	8	9	15	18	19	20	21
Axial Blanket 2	29.7	9.7 / 10.0 / 10.0		4	5	6	15	18	19	20	21
Reflector	30.0	30.0		22	22	22	22	22	22	22	21

RZ core arrangement

Parameters to calculate at BOC:

- **K-effective**
- **Beta-effective**
- **Fuel Doppler coefficient (1500K->2100K)**
- **Steel Doppler coefficient (600K->900K)**
- **Sodium density coefficient (integral and spatial by 1st order PT)**
- **Fuel density coefficient (integral and spatial by 1st order PT)**
- **Steel density coefficient (integral and spatial by 1st order PT)**
- **Radial expansion coefficient**
- **Axial expansion coefficient**

Burnup simulation for 140 EFPDS: reactivity loss, nuclear densities, reactivity coefficients at EOC

Results at BOC (1)

Parameters for BN-600 with MOX, Phase 6 (Phase 4)

	CEA& SERCO, JEF 2.2/ JEFF3.1 1968→33 gr. (Phase4)	FZK, JEFF 3.0, 30→21gr. / 560→21 gr. (Phase4)	IPPE, ABBN-93 26→18gr. /FOPT (Phase4)	IGCAR, XSET 98, 26 gr. (Phase4)	JAEA, JENDL 3.2, 70→18 gr. (Phase4)	KAERI, JEFF3.1 150→25gr. / JEF 2.2 80→9 gr. (Phase4)
k-eff	0.98829/ 1.00386	0.99069	0.99517*	1.00238	0.99194	1.00658/ 0.99022
Fuel Doppler coefficient (pcm)	-401/-408 (-789/-794)	-351/-379 (-698/ -766)	-337*/ -341* (-684)	-371 (-732)	-371 (-770)	-424/-438 (/888)
Sodium density coefficient (pcm)	-1680/ -1489 (-199)	-1124	/-1140 (139)	-1392 (-15)	-1571 (84)	-1133/ -1324 (223)

Results at BOC (2)

- **Fuel Doppler constant for Phase 6: ca 50% or more lower by magnitude compared to Phase 4 (e.g. -400 pcm vs. -800 pcm)**

- **Sodium density coefficient (SDC) appreciably lower (e.g. -1500 pcm vs. ca. -200 pcm): higher sodium void**

- **Leakage and non-leakage contributions for SDC:**
  - **2664 and – 4056 pcm: Phase 6**
  - **2989 pcm and -2974 pcm: Phase 4**
  - **Similar leakage component, lower spectral one for Phase 6**

- **Highest/lowest criticality values: JEFF 3.1/JEF 2.2, the deviation for Phase 6 (1500 to 1900 pcm) higher than for Phase 4 (ca. 200 pcm): indication on higher uncertainty due to data for Phase 6**

Results at BOC (3): fuel Doppler

- **The lowest by magnitude fuel Doppler coefficients were obtained by FZK (in case of using the 30-group library) and IPPE.**
    - **Related to a relatively low number of energy groups in the basic data library in the FZK case (560 group instead of 30 -> higher by magnitude Doppler coefficient by ca. 10%).**
- **Highest value (by magnitude): KAERI**

Results at BOC (4): Sodium density

- **The lowest by magnitude sodium density coefficients by FZK, IPPE and KAERI (with JEFF 3.1), the highest ones by CEA&SERCO (JEF 2.2) and JAEA.**

- **Newly evaluated Na cross-sections (as concerns the contribution of elastic and inelastic scattering to the total neutron scattering) available from JEFF 3.0 and JEFF 3.1.**

- **Using of JEFF 3.1 data - as compared to JEF 2.2 - yields a lower by ca. 200 pcm absolute value of the density coefficient (lower positive void effect).**

Results at BOC (5): Fuel/steel, other

- **The highest values for the fuel density and (by magnitude) for the steel density coefficients by CEA&SERCO (JEF 2.2)**

- **Exceed the results of the other participants by about 10% or more.**

- **Further analyses are needed to understand whether using of a much finer (as compared to other participants) basic data library is the reason for the observed deviations or this is due to data.**

- **Expansion coefficients and kinetics parameters: reasonable agreement between participants**

Reactivity loss and Nuclear density variations after 140 EFPDs.

|	CEA&SERCO	FZK	JAEA
Reactivity loss, pcm	456	594	541

Branching ratio Am241 (to Am242): 0.85 (CEA, JAEA), ca. 0.90 (FZK), high branching ratio -> higher reactivity loss, lower Am242m content

	Nuclear density at BOC, at/barn/cm	Average variation after 140 EFPDs, at/barn/cm	Ratio to the average by CEA	Ratio to the average by FZK	Ratio to the average by JAEA	Ratio to the average by KAERI
U238	5.823E-03	-0.000122	0.98	1.02	1.00	1.00
Np237	1.321E-04	-0.000014	0.97	0.99	1.05	1.00
Pu238	8.871E-05	0.000013	1.05	1.00	1.00	0.95
Pu239	9.959E-04	-0.000039	1.00	1.02	1.03	0.95
Pu240	5.179E-04	-0.000001	1.68	0.78	2.13	-0.59
Pu241	2.341E-05	0.000011	1.06	0.94	1.12	0.88
Pu242	6.243E-06	0.000005	0.99	1.09	0.97	0.95
Am241	2.827E-04	-0.000035	1.01	1.05	0.96	0.98
Am242m	4.353E-06	0.000003	1.08	0.49	0.97	1.46
Am243	4.118E-05	-0.000004	1.01	1.06	0.95	0.98
Cm242	1.494E-05	0.000008	1.06	1.24	0.87	0.83

➢ **Spectra in the MEZ region: slightly harder neutron spectra, appreciably harder adjoint spectra for Phase 6: larger contribution from threshold fission to the total fission rate**
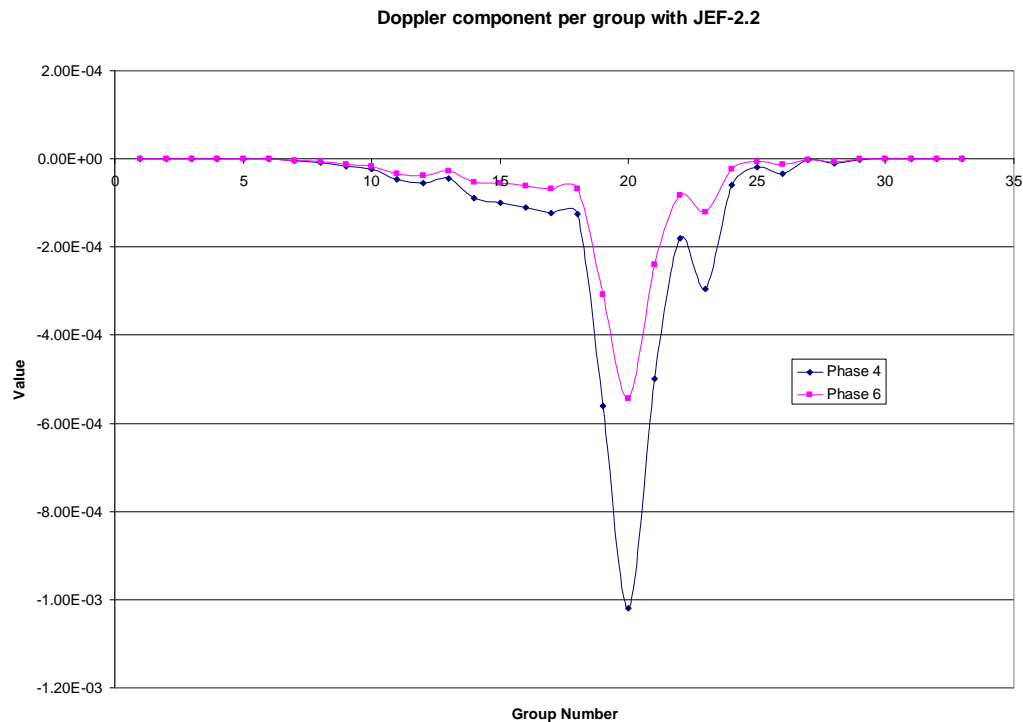

Direct flux normalized (Phase 4 & Phase 6)
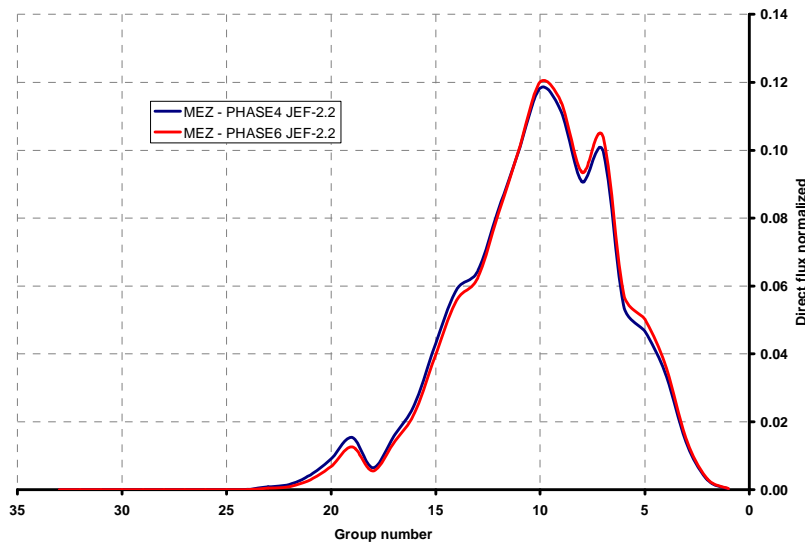

Adjoint flux normalized (Phase 4 & Phase 6)
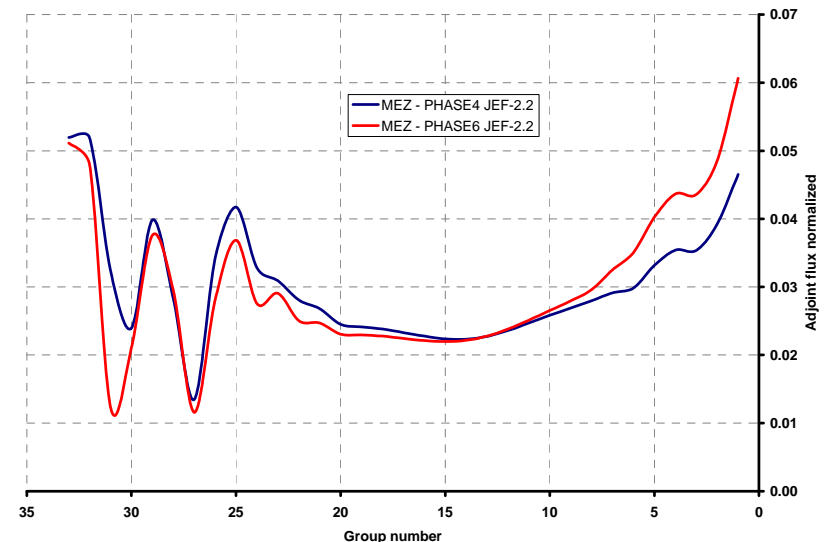
> **Energy contributions to fuel Doppler Effect: mainly from energies near 1 keV (group 20: 0.749-1.23 keV, group 10: 111-182 kev): lower importance of lower energy neutrons -> lower fuel Doppler effect**

Doppler component per group with JEF-2.2

➢ The differences are affected by a large cancellation of contributions from reactions, especially, U238 inelastic, Pu239 FP capture, Pu239 fission (due to its large sensitivity), Am241 capture (need to be investigated), Pu238 fission, Pu240 nu-bar value, oxygen capture, nickel capture, etc..
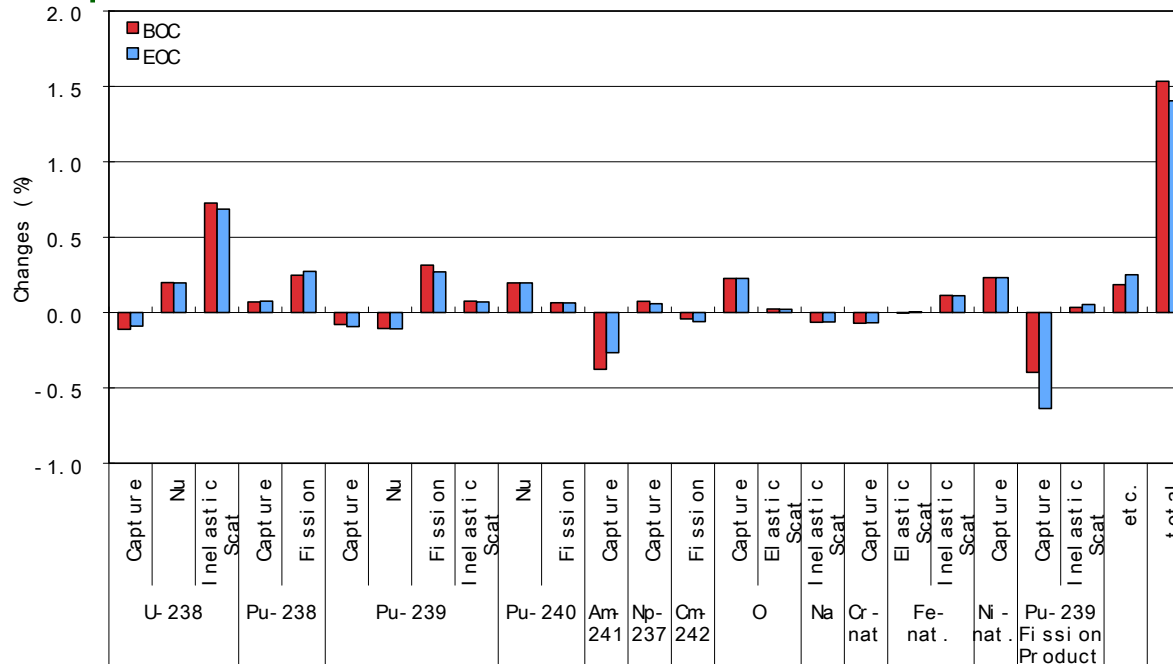
➢ Sensitivity approach is reasonably accurate and may help to identify main contributions from particular nuclides and nuclear reactions as concerns the criticality and the reactivity coefficients.

➢ For the burnup results, this approach is less accurate due to non-linear effects.

	Sensitivity	Direct
Criticality, BOC	1.53	1.48
Criticality, EOC	1.41	1.68
Sodium density coefficient, BOC	-38.5	-27.9
Sodium density coefficient, EOC	-42.4	-34.1
Burnup reactivity loss	23.5	-37.5
Atomic Number Density of LEZ region at EOC		
Pu-239	-0.2	0.3
Pu-241	-4.0	-7.2
Am-241	-1.2	-0.3
Np-237	0.0	0.7
Cm-242	6.2	-1.4
Cm-245	1.9	2.2

- ULOF transient simulations were performed at IPPE by employing preliminary results of IPPE, JAEA and KAERI, so that the fuel Doppler coefficient varied from -114 (IPPE) pcm to -424 pcm (KAERI). For Phase 4, parameters computed by seven participants were considered.

- For Phase 6, using of the IPPE parameters led to lower sodium outlet temperatures compared to those of KAERI and JAEA

- The reactivity variations in Phase 4 were mainly affected by positive fuel Doppler and negative radial expansion contributions. The positive sodium density effects and negative axial expansion effects were much smaller and compensated partly each other.

- Phase 6 results show a certain similarity, but they are different due to lower (by magnitude) fuel Doppler and higher (by magnitude) sodium density coefficients.

- As earlier, one may observe that deviations in the reactivity coefficients may not lead to substantial variations in transient results at the beginning of the initial phase of the ULOF transient.

ULOF transient results for BN-600, MOX fuel with MAs of Phase 6, BOC

Time (s)	0	20	40	100
Power (relative to t=0)	1	0.75(±0.01)	0.68 (±0.02)	0.66 (±0.03)
Net reactivity, pcm	0	-325(±30)	-150(±20)	-40(±5)
Sodium outlet Temperature, °C	500	710 (±2)	720 (±5)	730 (±12)

ULOF transient results for BN-600, MOX fuel of Phase 4, BOC.

Time (s)	0	20	40	100
Net reactivity, pcm	0	-500(±100)	-210(±50)	-60(±10)
Sodium outlet temperature, °C	500	780 (±20)	770 (±20)	760 (±20)
Power (relative to t=0), IPPE	1	0.65	0.63	0.62
Maximal fuel temperature, IPPE, °C	2300	1800	1750	1700

Conclusions (1)

- **A BN-600 core model with MOX fuel containing more than 5% of minor actinides in the fresh fuel, was investigated in Phase 6**
- **TRUs come from spent LWR fuel with burnup of 60 GWd/t and cooling time of 50 years: envelope case**
- **The obtained values for criticality, reactivity coefficients, burnup reactivity loss and variations in the fuel composition are in qualitative agreement**
- **Transient results show a certain similarity, but differ due to other fuel Doppler and sodium density coefficients**
- **The absolute value of the fuel Doppler constant is lower by about 50% or more, the sodium density coefficient increased appreciably (by magnitude), the effective delayed neutron fraction and neutron life-time become smaller, in line with commonly observed trends**
- **Higher MA content leads to higher deviations in criticality due to using of JEFF 3.1 instead of JEF 2.2 data, an indication of potentially higher uncertainties in computed parameters compared to Phase 4**

Conclusions (2)

- **Using of a relatively small (about 30) number of energy groups may lead to an underestimation of the absolute value of the fuel Doppler coefficient by a value of the order of 10%.**

- **A limited set of transient results was provided by IPPE for the beginning of the ULOF initiation phase, while employing a few different sets of reactor physics parameters.**

- **The results confirm an earlier observation on a substantial effect of compensations of deviations between the parameters with respect to their influence on transient progression at the considered transient phase**

- **With the limited amount of results available, no definite conclusion on the reactor safety can be made.**

- **On the other hand, the available results do not give any particular reason that would prevent utilization of weapons-grade plutonium or TRUs from LWR spent fuel in a BN-600 type reactor.**