

## ***Contribution to the NEA C5G7 MOX benchmark***

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### **ABSTRACT**

Results for the NEA C5G7 MOX benchmark are presented. The results were obtained with CRONOS diffusion and  $S_8$  finite elements and with the characteristic method of APOLLO2 for the 2D benchmark, and with CRONOS  $S_4$  finite elements for the 3D benchmark. Detailed results show the reliability and accuracy of the methods available in CRONOS and APOLLO2

### **1. INTRODUCTION**

The NEA C5G7 MOX benchmark [1] addresses the calculation of a MOX-UO2 interface in seven groups, either for a 2D or a 3D geometry comprising  $2 \times 2$  assemblies, two UO2 and two MOX surrounded by a moderator on the right and the left sides. The boundary conditions are specular on the top and the left sides and vacuum on the external surface of the moderator. For the 3D case there is a top layer of moderator and the boundary conditions are vacuum at top and specular reflection at the bottom. The aim of the benchmark is to test the ability of transport methods for this challenging problem with strong transport gradients at the MOX-UO2 interface.

We have performed three calculations with different methods for the 2D case and one calculation for the 3D case. We have also run a multigroup Monte Carlo reference calculation for the 2D case. All calculations were run in a DEC Alpha EV6 500MHz workstation. The relative precision on these calculations was of  $10^{-6}$  for the eigenvalue,  $10^{-5}$  for the fission source and  $10^{-5}$  for the fluxes in group iterations and acceleration.

In Sections 2 and 3 we present our 2D and 3D results. For each calculation we give the maximum and mean relative errors as well as parameters measuring the performance of the calculation. We have

observed that the maximum errors happen at the boundary assembly-reflector. We give two figures per calculation. The first gives the relative errors for the cells at the boundary with the reflector, while the second gives the relative errors along the row of cells that contain the cell with the maximum fission integral (hot cell). A brief conclusive discussion is given in Section 4. Appendices A, B and C give our detailed results.

## 2. 2D CALCULATIONS

A separate Monte Carlo calculation was run with  $9.2 \times 10^7$  particles, yielding a  $k_{\text{eff}}$  of 1.18648 with a standard deviation of  $\sigma = 17 \times 10^{-5}$ . This  $k_{\text{eff}}$  value is within error bands of the one obtained by the authors of the benchmark. All our comparisons in this paper are done taken as reference the Monte Carlo results proposed by the authors of the benchmark.

Two calculations, one transport and one diffusion, were run with the CRONOS2 code [2] using isoparametric finite elements (FE). The transport calculation was based on the even-parity form with a  $S_8$  (20 angles) angular discretization and linear triangular finite element with 36 triangles and 25 nodes per cell. The diffusion calculation used a parabolic triangular element with 36 triangles and 85 nodes per cell.

A third calculation was done with the method of characteristics (MOC) for unstructured meshes available in the APOLLO2 code [3]. The calculation was run for only half of the domain (using the diagonal symmetry) and with cyclic trajectories. The angular quadrature consisted of 8 nearly uniformly distributed azimuthal angles and 2 polar angles, obtained from an optimized Bickley-Naylor formula [4], with flat-flux approximation per region. A first run with 15579 regions showed large errors (max of 6.49%) near the moderator and it was decided to refine the discretization in that area, increasing the number of regions to 19188. With a distance between trajectories of  $\delta = 0.05$  the new calculation run in 1600 sec and gave  $k_{\text{eff}} = 1.18618$ . The final run was done with  $\delta = 0.02$  which resulted in 8234 trajectories with a total of 3073110 region intersections.

Table 1: Summary for 2D benchmark  
<sup>a</sup> Mean of absolute values for the relative errors

Method	Time (sec)	Number of points / group	Max error (%) (location)	Mean error <sup>a</sup> (%)	Eigenvalue ( $k_{\text{eff}}$ )
Monte Carlo					1.18655
CRONOS transport $S_8$	1100	$20 \times 24804$	4.98 (34,34)	0.77	1.18338
CRONOS diffusion	370	98737	5.96 (34,34)	1.42	1.18323

APOLLO2 characteristics	4228	19188	-3.2 (32,32)	0.50	1.18634
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The forms of the finite elements used for the CRONOS calculations are given in Fig. 1. Figures 2 and 3 show for the transport CRONOS calculation the relative errors for the cells at the boundary with the reflector and for the cells in the row that contains the cell with the maximum fission integral. Similar values are given for the MOC calculation in Figures 4 and 5.

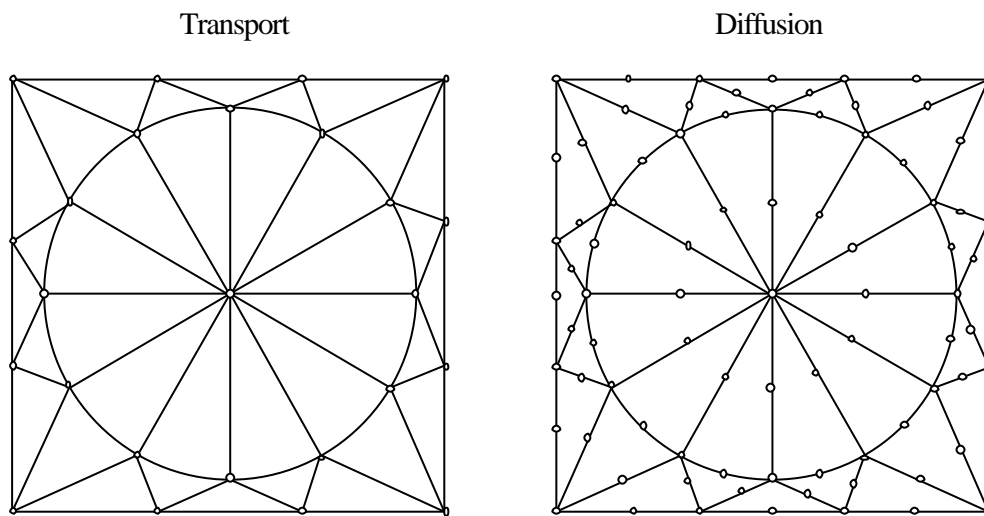


Figure 1: Isoparametric FE for CRONOS 2D calculations.

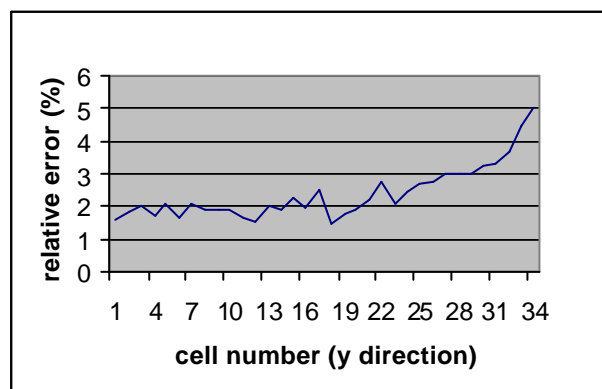


Figure 2: Relative percent errors along y cell column for x cell=34. CRONOS 2D  $S_8$  results.

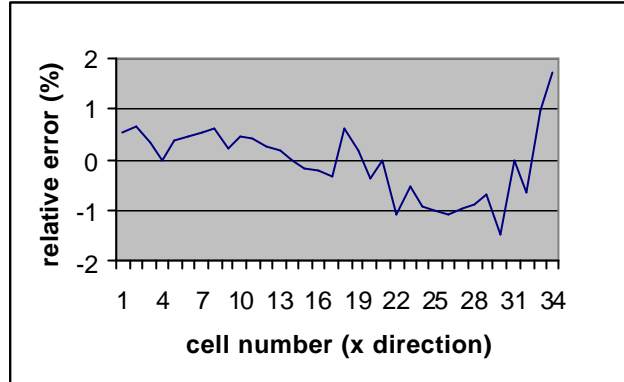


Figure 3: Relative percent errors along x cell column for y cell=4. CRONOS 2D S<sub>8</sub> results.

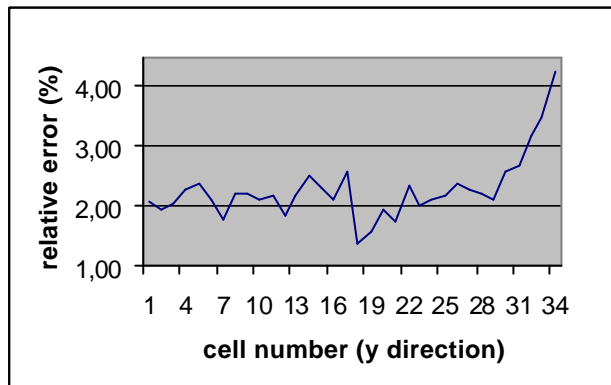


Figure 4: Relative percent errors along y cell column for x cell=34. MOC 2D results.

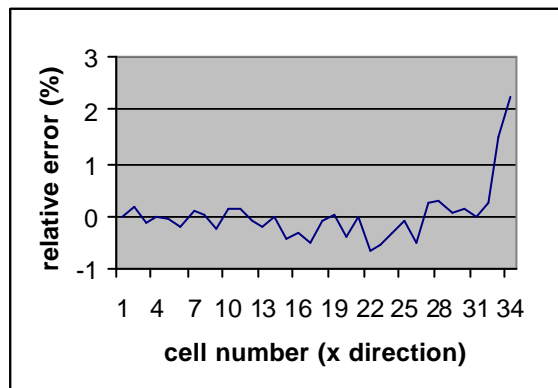


Figure 5: Relative percent errors along x cell column for y cell=4. MOC S<sub>8</sub> results.

### 3. 3D CALCULATION

A  $S_4$  (12 angles) even-parity transport calculation was run with CRONOS using isoparametric linear triangular FE with 20 triangles and 13 nodes per cell and 9 axial nodes for a total of  $12 \times 117972$  unknowns per group. The calculation required 8500 sec and gave an eigenvalue of 1.17723.

Table 2: Summary for 3D benchmark

<sup>a</sup> Mean of absolute values for the relative errors

Method	Time (sec)	Number of points / group	Max error (%) (location)	Mean error <sup>a</sup> (%)	Eigenvalue ( $k_{\text{eff}}$ )
Monte Carlo					1.18381
CRONOS transport $S_4$	8500	$12 \times 117972$	6.72 (34,34)	1.65	1.17723

The form of the finite elements used for the CRONOS calculation is given in Fig. 6. Figures 7 and 8 show for the CRONOS calculation the relative errors for the cells at the boundary with the reflector and for the cells in the row that contains the cell with the maximum fission integral.

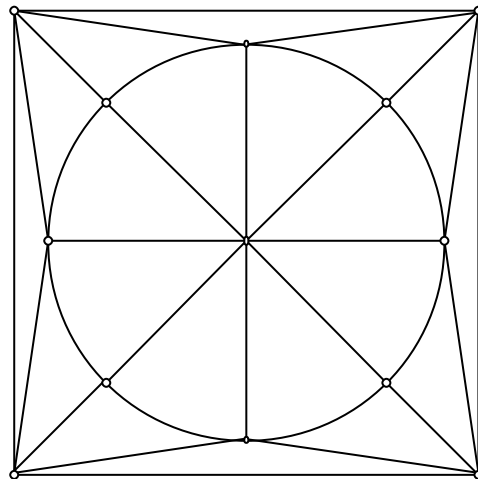


Figure 6: Isoparametric FE for CRONOS transport 3D calculations.

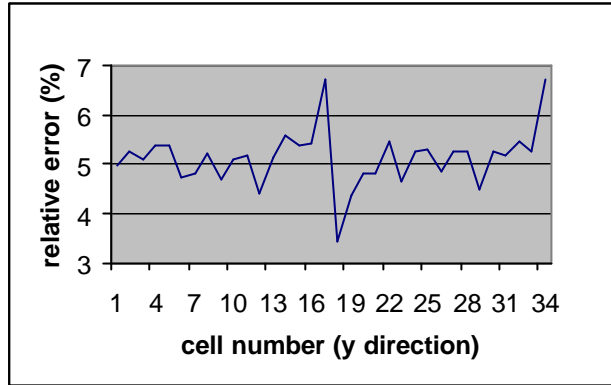


Figure 7: Relative percent errors along y cell column for x cell=34. CRONOS 3D  $S_4$  results.

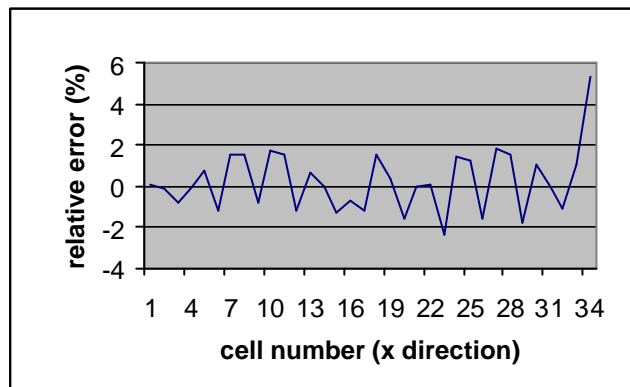


Figure 8: Relative percent errors along x cell column for y cell=4. CRONOS 3D  $S_4$  results.

#### 4. CONCLUSIONS

The spatial discretization of the 3D CRONOS transport FE calculation was limited by the available machine storage (this calculation used 1343 megawords). The other CRONOS calculations used 900 (2D transport) and 224 (2D diffusion) megawords, respectively. The geometrical mesh of the APOLLO2 MOC calculation could still be refined for fuel cells near the moderator in order to decrease the error in that area.

Although non shown here, the 2D results obtained with the MOC of APOLLO2 with a distance between trajectories of  $\delta=0.05$  was very close to that obtained with  $\delta=0.02$ . This means that the MOC can give very accurate results for this benchmark with 1600 sec computation time.

The detailed results show the reliability and accuracy of the methods available in CRONOS and APOLLO2. These results call for four comments: a) the use of diffusion for this type of transport problem gives acceptable precision for design purposes, b) errors observed in the MOC calculation for fluxes in the clad and moderator regions are much higher ( $\approx 9\%$ ) than those for the fission rates (these values, however, are not part of the benchmark), c) the precision on the eigenvalue of the MOC calculation is much better than the CRONOS, transport and diffusion, calculations, d) although this is an excellent 2D benchmark, the 3D problem is quite deceiving because the axial behavior is very regular and close to a cosine.

The spatial meshing used in the CRONOS calculations was the maximum that was possible with the available memory in the DEC Alpha EV6 workstation. Memory management is done with the in house ESOPE pre compiler whose addresses are 32 bit based, and this limits the total addressable memory to 2 Giga words. Note also that the present version of CRONOS cannot take into account axial symmetries and this doubles memory requirements for the cases treated here.

## REFERENCES

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**Appendix A: Detailed 2D  $S_8$  CRONOS results**

UO2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	2.21	2.22	2.22	2.24	2.24	2.24	2.20	2.16	2.13	2.07	2.01	1.96	1.86	1.76	1.63	1.48	1.28
2	2.22	2.23	2.25	2.29	2.32	2.38	2.27	2.23	2.26	2.13	2.07	2.08	1.93	1.80	1.66	1.49	1.28
3	2.22	2.25	2.33	2.45	2.48	0.00	2.39	2.34	0.00	2.24	2.18	0.00	2.06	1.93	1.71	1.51	1.28
4	2.24	2.29	2.45	0.00	2.51	2.47	2.31	2.26	2.30	2.16	2.11	2.15	2.08	0.00	1.81	1.54	1.29
5	2.24	2.32	2.48	2.51	2.41	2.44	2.29	2.24	2.29	2.15	2.09	2.13	2.01	1.97	1.83	1.56	1.29
6	2.24	2.38	0.00	2.47	2.44	0.00	2.36	2.31	0.00	2.21	2.15	0.00	2.03	1.94	0.00	1.61	1.30
7	2.20	2.27	2.39	2.31	2.29	2.36	2.23	2.19	2.23	2.10	2.04	2.06	1.91	1.82	1.77	1.53	1.27
8	2.16	2.23	2.34	2.26	2.24	2.31	2.19	2.15	2.19	2.06	2.01	2.02	1.87	1.78	1.73	1.50	1.25
9	2.13	2.26	0.00	2.30	2.29	0.00	2.23	2.19	0.00	2.10	2.05	0.00	1.91	1.82	0.00	1.53	1.24
10	2.07	2.13	2.24	2.16	2.15	2.21	2.10	2.06	2.10	1.98	1.92	1.94	1.80	1.71	1.67	1.45	1.21
11	2.01	2.07	2.18	2.11	2.09	2.15	2.04	2.01	2.05	1.92	1.87	1.89	1.76	1.68	1.63	1.42	1.18
12	1.96	2.08	0.00	2.15	2.13	0.00	2.06	2.02	0.00	1.94	1.89	0.00	1.79	1.72	0.00	1.43	1.16
13	1.86	1.93	2.06	2.08	2.01	2.03	1.91	1.87	1.91	1.80	1.76	1.79	1.69	1.67	1.56	1.33	1.11
14	1.76	1.80	1.93	0.00	1.97	1.94	1.82	1.78	1.82	1.71	1.68	1.72	1.67	0.00	1.47	1.26	1.06
15	1.63	1.66	1.71	1.81	1.83	0.00	1.77	1.73	0.00	1.67	1.63	0.00	1.56	1.47	1.31	1.17	1.01
16	1.48	1.49	1.51	1.54	1.56	1.61	1.53	1.50	1.53	1.45	1.42	1.43	1.33	1.26	1.17	1.07	0.95
17	1.28	1.28	1.28	1.29	1.29	1.30	1.27	1.25	1.24	1.21	1.18	1.16	1.11	1.06	1.01	0.95	0.87

%	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0.55	0.57	0.50	0.54	0.44	0.71	0.67	0.60	0.55	0.56	0.59	0.62	0.54	0.43	0.18	0.12	-0.43
2		0.69	0.57	0.69	0.60	0.40	0.52	0.53	0.38	0.49	0.41	0.24	0.46	0.26	0.04	-0.11	-0.36
3			0.56	0.33	0.30	0.00	0.35	0.35	0.00	0.16	0.29	0.00	0.19	0.07	0.08	0.00	-0.30
4				0.00	0.35	0.49	0.55	0.63	0.21	0.46	0.44	0.25	0.17	0.00	-0.17	-0.20	-0.33
5					0.63	0.44	0.62	0.67	0.43	0.49	0.43	0.23	0.41	0.03	-0.15	-0.14	-0.31
6						0.00	0.57	0.52	0.00	0.33	0.17	0.00	0.12	0.08	0.00	-0.51	-0.14
7							0.69	0.79	0.38	0.62	0.69	0.29	0.51	0.34	-0.02	-0.04	-0.41
8								0.58	0.41	0.68	0.60	0.33	0.49	0.39	0.01	-0.09	-0.24
9									0.00	0.31	0.42	0.00	0.41	0.30	0.00	-0.41	-0.28
10										0.54	0.41	0.17	0.41	0.37	-0.21	-0.18	-0.47
11											0.43	0.09	0.37	0.32	-0.13	-0.21	-0.49
12												0.00	0.03	0.00	0.00	-0.55	-0.61
13													0.26	-0.05	-0.38	-0.34	-0.56
14														0.00	-0.54	-0.28	-0.51
15															-0.29	-0.28	-0.75
16																-0.75	-0.96
17																	-1.13

Figure 9a: Detailed 2D  $S_8$  CRONOS results for the central UO2 assembly (top) and corresponding relative errors in % (bottom). The maximum fission rate for the entire problem happens in cell (4,5) for which the relative error is 0.35%. The two dark orange cells correspond to the maximum positive and negative relative errors for this assembly.



UO2	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
18	0.78	0.78	0.76	0.74	0.72	0.69	0.65	0.62	0.58	0.54	0.50	0.47	0.43	0.39	0.37	0.39	0.51
19	0.78	0.82	0.82	0.82	0.80	0.80	0.73	0.69	0.67	0.61	0.57	0.54	0.48	0.44	0.42	0.43	0.54
20	0.76	0.82	0.86	0.89	0.88	0.00	0.80	0.75	0.00	0.66	0.61	0.00	0.53	0.49	0.44	0.45	0.55
21	0.74	0.82	0.89	0.00	0.89	0.85	0.77	0.72	0.71	0.64	0.59	0.58	0.54	0.00	0.47	0.45	0.54
22	0.72	0.80	0.88	0.89	0.84	0.82	0.75	0.71	0.69	0.62	0.58	0.57	0.51	0.49	0.47	0.45	0.53
23	0.69	0.80	0.00	0.85	0.82	0.00	0.75	0.71	0.00	0.63	0.59	0.00	0.51	0.48	0.00	0.45	0.52
24	0.65	0.73	0.80	0.77	0.75	0.75	0.69	0.65	0.64	0.58	0.54	0.52	0.47	0.43	0.43	0.42	0.50
25	0.62	0.69	0.75	0.72	0.71	0.71	0.65	0.62	0.61	0.55	0.51	0.50	0.44	0.41	0.41	0.40	0.47
26	0.58	0.67	0.00	0.71	0.69	0.00	0.64	0.61	0.00	0.54	0.51	0.00	0.44	0.41	0.00	0.39	0.45
27	0.54	0.61	0.66	0.64	0.62	0.63	0.58	0.55	0.54	0.49	0.46	0.44	0.40	0.37	0.37	0.36	0.42
28	0.50	0.57	0.61	0.59	0.58	0.59	0.54	0.51	0.51	0.46	0.43	0.41	0.37	0.35	0.34	0.33	0.40
29	0.47	0.54	0.00	0.58	0.57	0.00	0.52	0.50	0.00	0.44	0.41	0.00	0.36	0.34	0.00	0.32	0.37
30	0.43	0.48	0.53	0.54	0.51	0.51	0.47	0.44	0.44	0.40	0.37	0.36	0.33	0.32	0.30	0.29	0.34
31	0.39	0.44	0.49	0.00	0.49	0.48	0.43	0.41	0.41	0.37	0.35	0.34	0.32	0.00	0.28	0.26	0.31
32	0.37	0.42	0.44	0.47	0.47	0.00	0.43	0.41	0.00	0.37	0.34	0.00	0.30	0.28	0.25	0.24	0.29
33	0.39	0.43	0.45	0.45	0.45	0.45	0.42	0.40	0.39	0.36	0.33	0.32	0.29	0.26	0.24	0.24	0.28
34	0.51	0.54	0.55	0.54	0.53	0.52	0.50	0.47	0.45	0.42	0.40	0.37	0.34	0.31	0.29	0.28	0.30

%	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
18	-1.42	-1.32	-1.28	-1.12	-1.23	-1.16	-1.33	-1.25	-0.98	-1.05	-1.11	-1.15	-1.10	-0.61	-0.41	0.58	1.50
19		-1.07	-0.89	-1.03	-0.89	-0.86	-0.79	-0.65	-0.87	-0.68	-1.12	-0.82	-0.39	-0.29	0.48	1.43	1.79
20			-0.92	-1.09	-0.89	0.00	-0.56	-0.60	0.00	-0.61	-0.71	0.00	-0.49	-0.34	0.64	1.81	1.92
21				0.00	-0.60	-0.55	-0.18	-0.11	-0.24	-0.23	-0.11	-0.34	-0.33	0.00	0.62	1.90	2.23
22					-0.29	-0.24	-0.28	-0.33	-0.06	0.07	-0.07	-0.41	0.07	0.01	0.81	1.67	2.73
23						0.00	-0.31	-0.47	0.00	-0.10	-0.03	0.00	0.00	0.34	0.00	1.44	2.07
24							-0.14	-0.06	-0.23	0.08	0.45	-0.15	0.25	0.75	0.98	1.88	2.44
25								-0.18	-0.04	0.01	0.19	-0.12	0.43	0.35	0.95	1.88	2.67
26									0.00	-0.08	-0.09	0.00	0.22	0.25	0.00	1.70	2.73
27										0.34	0.27	-0.08	0.65	0.88	1.12	2.13	2.95
28											0.31	0.14	0.53	0.90	1.65	2.18	2.97
29												0.00	0.68	1.02	0.00	2.19	2.95
30													1.23	1.41	1.96	2.47	3.27
31														0.00	1.88	2.42	3.32
32															1.97	2.66	3.70
33																4.01	4.46
34																	4.98

Figure 9b: Detailed 2D  $S_8$  CRONOS results for the external UO2 assembly (top) and corresponding relative errors in % (bottom). The two dark orange cells correspond to the maximum positive and negative relative errors for this assembly.

MOX	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	1.32	1.06	0.93	0.86	0.80	0.76	0.70	0.66	0.61	0.56	0.52	0.48	0.43	0.39	0.38	0.41	0.61
2	1.30	1.35	1.17	1.09	1.04	1.04	0.91	0.84	0.83	0.73	0.67	0.65	0.56	0.50	0.47	0.52	0.60
3	1.30	1.32	1.17	1.17	1.11	0.00	0.94	0.86	0.00	0.75	0.68	0.00	0.60	0.54	0.47	0.51	0.60
4	1.30	1.34	1.26	0.00	1.10	1.12	0.95	0.87	0.87	0.75	0.69	0.70	0.58	0.00	0.51	0.52	0.60
5	1.30	1.36	1.28	1.17	1.14	1.08	0.92	0.85	0.85	0.73	0.67	0.67	0.60	0.53	0.52	0.53	0.60
6	1.30	1.43	0.00	1.28	1.14	0.00	0.98	0.89	0.00	0.78	0.71	0.00	0.62	0.57	0.00	0.55	0.60
7	1.28	1.33	1.22	1.14	1.03	1.03	0.89	0.82	0.83	0.71	0.65	0.65	0.55	0.52	0.49	0.52	0.59
8	1.26	1.31	1.19	1.12	1.01	1.01	0.88	0.81	0.81	0.70	0.64	0.64	0.55	0.51	0.48	0.51	0.59
9	1.25	1.36	0.00	1.18	1.07	0.00	0.94	0.86	0.00	0.75	0.68	0.00	0.58	0.54	0.00	0.54	0.58
10	1.22	1.27	1.16	1.08	0.98	0.98	0.85	0.79	0.79	0.69	0.63	0.62	0.53	0.50	0.47	0.50	0.57
11	1.19	1.24	1.14	1.07	0.97	0.97	0.84	0.78	0.78	0.68	0.62	0.62	0.53	0.49	0.46	0.50	0.57
12	1.17	1.29	0.00	1.16	1.04	0.00	0.90	0.82	0.00	0.72	0.66	0.00	0.57	0.54	0.00	0.52	0.56
13	1.13	1.19	1.13	1.03	1.01	0.96	0.82	0.76	0.77	0.66	0.61	0.61	0.55	0.49	0.48	0.49	0.55
14	1.08	1.13	1.07	0.00	0.95	0.98	0.83	0.77	0.77	0.67	0.62	0.63	0.52	0.00	0.46	0.47	0.54
15	1.04	1.09	0.98	0.99	0.95	0.00	0.82	0.76	0.00	0.66	0.61	0.00	0.54	0.49	0.43	0.46	0.54
16	1.01	1.10	0.99	0.94	0.91	0.92	0.82	0.76	0.76	0.67	0.62	0.60	0.53	0.47	0.44	0.49	0.55
17	1.02	0.91	0.85	0.82	0.79	0.76	0.71	0.67	0.63	0.58	0.54	0.50	0.46	0.42	0.40	0.43	0.59

%	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	0.66	-0.06	-0.72	-0.85	-1.27	-1.05	-1.17	-1.46	-1.33	-1.35	-1.71	-1.36	-1.22	-1.03	-0.66	-0.09	1.58
2	0.59	0.41	-0.10	-0.36	-0.69	-0.79	-0.87	-0.92	-0.79	-0.85	-0.87	-0.94	-0.92	-0.56	-0.19	0.95	1.82
3	0.68	0.46	-0.06	-0.54	-1.02	0.00	-0.69	-1.11	0.00	-0.95	-0.94	0.00	-1.01	-0.76	-0.56	0.95	2.00
4	0.62	0.19	-0.35	0.00	-1.10	-0.53	-0.93	-1.00	-1.07	-0.96	-0.88	-0.65	-1.46	0.00	-0.64	0.96	1.74
5	0.65	0.33	-0.39	-0.66	-0.48	-0.71	-0.76	-1.11	-1.09	-1.09	-0.99	-0.64	-0.98	-1.26	-1.17	1.21	2.06
6	0.83	0.32	0.00	-0.45	-0.59	0.00	-0.65	-0.93	0.00	-0.97	-0.79	0.00	-0.75	-0.72	0.00	1.17	1.68
7	0.59	0.19	-0.53	-0.49	-0.87	-0.79	-1.02	-1.09	-1.03	-1.59	-1.37	-1.10	-1.25	-0.91	-0.46	1.00	2.09
8	0.67	0.20	-0.32	-0.65	-0.88	-0.86	-1.31	-1.16	-1.04	-1.30	-1.43	-1.15	-0.92	-1.09	-0.41	0.57	1.88
9	0.51	0.41	0.00	-0.34	-0.63	0.00	-0.89	-1.31	0.00	-0.91	-1.26	0.00	-0.94	-0.73	0.00	1.00	1.90
10	0.64	0.24	-0.33	-0.63	-0.79	-0.69	-1.09	-1.25	-1.10	-1.53	-1.42	-0.95	-1.18	-0.80	-0.37	1.11	1.90
11	0.56	0.14	-0.56	-0.35	-0.82	-0.56	-0.89	-1.14	-1.01	-0.92	-1.33	-0.99	-1.06	-0.93	-0.68	0.93	1.68
12	0.28	-0.01	0.00	-0.15	-0.72	0.00	-0.86	-0.79	0.00	-0.71	-1.19	0.00	-1.06	-0.57	0.00	0.70	1.55
13	0.46	0.24	-0.50	-1.00	-0.79	-0.78	-0.99	-0.92	-0.73	-1.30	-1.16	-1.14	-1.11	-1.45	-0.50	1.09	1.99
14	0.65	0.30	-0.11	0.00	-1.16	-0.78	-0.65	-0.68	-0.44	-0.60	-1.02	-1.02	-1.43	0.00	-0.51	0.77	1.88
15	0.56	0.26	-0.10	-0.72	-0.98	0.00	-0.71	-0.59	0.00	-0.67	-0.77	0.00	-0.97	-0.47	-0.27	1.23	2.27
16	0.43	0.71	0.10	-0.30	-0.25	-0.40	-0.22	-0.30	-0.29	-0.26	-0.28	-0.35	-0.45	-0.10	0.46	1.84	1.95
17	0.03	-0.08	0.10	-0.18	-0.14	-0.02	0.04	0.05	0.00	0.05	0.03	-0.33	-0.24	0.21	0.99	1.35	2.48

Figure 9c: Detailed 2D  $S_g$  CRONOS results for the MOX assembly (top) and corresponding relative errors in % (bottom). The two dark orange cells correspond to the maximum positive and negative relative errors for this assembly. Colors are used to indicate MOX zoning.

**Appendix B: Detailed 2D MOC results**

UO2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	2,19	2,20	2,21	2,22	2,23	2,23	2,19	2,15	2,12	2,06	2,00	1,95	1,85	1,75	1,63	1,48	1,27
2	2,20	2,22	2,24	2,28	2,31	2,37	2,26	2,22	2,25	2,12	2,06	2,07	1,92	1,79	1,65	1,49	1,27
3	2,21	2,24	2,31	2,44	2,47	0,00	2,38	2,33	0,00	2,23	2,17	0,00	2,06	1,92	1,71	1,51	1,28
4	2,22	2,28	2,44	0,00	2,50	2,45	2,30	2,25	2,29	2,15	2,10	2,14	2,08	0,00	1,81	1,53	1,29
5	2,23	2,31	2,47	2,50	2,41	2,43	2,28	2,24	2,28	2,14	2,09	2,12	2,00	1,97	1,83	1,56	1,29
6	2,23	2,37	0,00	2,45	2,43	0,00	2,34	2,30	0,00	2,20	2,14	0,00	2,02	1,93	0,00	1,60	1,29
7	2,19	2,26	2,38	2,30	2,28	2,34	2,22	2,18	2,22	2,09	2,03	2,05	1,91	1,81	1,76	1,53	1,27
8	2,15	2,22	2,33	2,25	2,24	2,30	2,18	2,14	2,18	2,05	2,00	2,01	1,87	1,78	1,73	1,50	1,25
9	2,12	2,25	0,00	2,29	2,28	0,00	2,22	2,18	0,00	2,09	2,04	0,00	1,91	1,81	0,00	1,53	1,24
10	2,06	2,12	2,23	2,15	2,14	2,20	2,09	2,05	2,09	1,97	1,92	1,93	1,79	1,71	1,66	1,45	1,21
11	2,00	2,06	2,17	2,10	2,09	2,14	2,03	2,00	2,04	1,92	1,87	1,89	1,75	1,67	1,63	1,41	1,18
12	1,95	2,07	0,00	2,14	2,12	0,00	2,05	2,01	0,00	1,93	1,89	0,00	1,78	1,71	0,00	1,43	1,16
13	1,85	1,92	2,06	2,08	2,00	2,02	1,91	1,87	1,91	1,79	1,75	1,78	1,69	1,67	1,56	1,33	1,11
14	1,75	1,79	1,92	0,00	1,97	1,93	1,81	1,78	1,81	1,71	1,67	1,71	1,67	0,00	1,47	1,26	1,06
15	1,63	1,65	1,71	1,81	1,83	0,00	1,76	1,73	0,00	1,66	1,63	0,00	1,56	1,47	1,31	1,17	1,01
16	1,48	1,49	1,51	1,53	1,56	1,60	1,53	1,50	1,53	1,45	1,41	1,43	1,33	1,26	1,17	1,08	0,95
17	1,27	1,27	1,28	1,29	1,29	1,29	1,27	1,25	1,24	1,21	1,18	1,16	1,11	1,06	1,01	0,95	0,87

%	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	-0,39	0,06	-0,02	-0,15	0,16	-0,01	-0,06	0,20	0,00	-0,09	0,20	0,01	-0,07	-0,28	-0,15	-0,38	-0,57
2		0,10	0,19	0,08	0,30	-0,13	0,07	0,32	-0,10	0,11	0,19	-0,08	0,11	-0,10	-0,12	-0,20	-0,63
3			-0,13	-0,19	-0,07	0,00	-0,23	-0,21	0,00	-0,08	-0,03	0,00	-0,04	-0,34	-0,08	-0,24	-0,56
4				0,00	-0,05	-0,19	0,11	0,04	-0,24	0,14	0,14	-0,10	-0,19	0,00	-0,46	-0,32	-0,52
5					0,10	-0,06	0,17	0,17	-0,10	0,11	0,20	-0,13	0,17	-0,19	-0,30	-0,29	-0,46
6						0,00	-0,15	-0,23	0,00	0,03	-0,03	0,00	-0,23	-0,24	0,00	-0,56	-0,67
7							0,05	0,13	-0,08	0,06	0,03	-0,20	0,18	0,07	-0,45	-0,26	-0,47
8								0,15	-0,14	0,11	0,16	-0,28	0,11	-0,11	-0,46	-0,16	-0,54
9									0,00	-0,10	-0,03	0,00	-0,13	-0,26	0,00	-0,43	-0,63
10										0,29	0,15	-0,31	-0,03	-0,28	-0,48	-0,41	-0,59
11											0,16	-0,22	0,03	0,04	-0,39	-0,33	-0,62
12												0,00	-0,25	-0,34	0,00	-0,57	-0,57
13													-0,03	-0,21	-0,46	-0,19	-0,49
14														0,00	-0,51	-0,36	-0,39
15															-0,51	-0,22	-0,33
16																-0,52	-0,78
17																	-0,81

Figure 10a: Detailed 2D APOLLO2 MOC results for the central UO2 assembly (top) and corresponding relative errors in % (bottom). The maximum fission rate for the entire problem happens in cell (4,5) for which the relative error is -0.05%. The two dark orange cells correspond to the maximum positive and negative relative errors for this assembly.

UO2	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
18	0,79	0,78	0,77	0,75	0,72	0,70	0,66	0,62	0,59	0,54	0,50	0,47	0,43	0,39	0,38	0,39	0,51
19	0,78	0,82	0,83	0,82	0,81	0,80	0,74	0,70	0,68	0,61	0,57	0,55	0,49	0,44	0,42	0,43	0,54
20	0,77	0,83	0,86	0,90	0,88		0,80	0,75		0,66	0,62		0,54	0,49	0,44	0,44	0,54
21	0,75	0,82	0,90		0,89	0,85	0,77	0,72	0,71	0,64	0,60	0,58	0,54		0,47	0,45	0,54
22	0,72	0,81	0,88	0,89	0,84	0,82	0,75	0,71	0,69	0,63	0,58	0,57	0,52	0,50	0,47	0,45	0,53
23	0,70	0,80		0,85	0,82		0,75	0,71		0,63	0,59		0,51	0,48		0,45	0,52
24	0,66	0,74	0,80	0,77	0,75	0,75	0,69	0,65	0,64	0,58	0,54	0,52	0,47	0,43	0,43	0,42	0,49
25	0,62	0,70	0,75	0,72	0,71	0,71	0,65	0,62	0,61	0,55	0,51	0,50	0,44	0,41	0,41	0,40	0,47
26	0,59	0,68		0,71	0,69		0,64	0,61		0,54	0,51		0,44	0,41		0,39	0,45
27	0,54	0,61	0,66	0,64	0,63	0,63	0,58	0,55	0,54	0,49	0,46	0,44	0,40	0,37	0,36	0,36	0,42
28	0,50	0,57	0,62	0,60	0,58	0,59	0,54	0,51	0,51	0,46	0,43	0,42	0,37	0,35	0,34	0,33	0,39
29	0,47	0,55		0,58	0,57		0,52	0,50		0,44	0,42		0,36	0,34		0,32	0,37
30	0,43	0,49	0,54	0,54	0,52	0,51	0,47	0,44	0,44	0,40	0,37	0,36	0,33	0,32	0,30	0,29	0,34
31	0,39	0,44	0,49		0,50	0,48	0,43	0,41	0,41	0,37	0,35	0,34	0,32		0,27	0,26	0,31
32	0,38	0,42	0,44	0,47	0,47		0,43	0,41		0,36	0,34		0,30	0,27	0,25	0,24	0,29
33	0,39	0,43	0,44	0,45	0,45	0,45	0,42	0,40	0,39	0,36	0,33	0,32	0,29	0,26	0,24	0,24	0,28
34	0,51	0,54	0,54	0,54	0,53	0,52	0,49	0,47	0,45	0,42	0,39	0,37	0,34	0,31	0,29	0,28	0,30

%	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
18	-0,97	-1,06	-0,86	-0,65	-0,39	-0,46	-0,63	-0,60	-0,44	-0,38	-0,39	-0,18	-0,30	0,03	0,48	1,01	1,38
19		-0,65	-0,62	-0,43	-0,27	-0,63	-0,15	-0,07	-0,30	-0,12	0,13	-0,40	0,15	0,25	0,59	1,01	1,58
20			-0,18	-0,60	-0,24	0,00	-0,39	-0,36	0,00	0,14	0,16	0,00	0,53	0,25	0,96	1,46	1,94
21				0,00	-0,17	-0,30	0,07	0,31	-0,09	0,23	0,09	0,12	0,16	0,00	0,93	1,30	1,74
22					0,03	-0,06	0,28	0,33	0,00	0,30	0,40	0,35	0,71	0,64	1,08	1,52	2,36
23						0,00	0,05	-0,04	0,00	0,27	0,18	0,00	0,13	0,50	0,00	1,26	2,01
24							0,21	0,52	0,39	0,63	0,53	0,39	0,69	0,52	0,76	1,62	2,14
25								0,68	0,27	0,48	0,87	0,65	1,05	0,84	1,18	1,64	2,19
26									0,00	0,64	0,41	0,00	0,73	0,76	0,00	1,46	2,39
27										0,93	0,46	0,51	1,04	0,97	0,94	1,71	2,29
28											0,79	0,35	0,77	1,20	1,09	1,66	2,25
29												0,00	0,74	0,60	0,00	1,50	2,15
30													1,07	0,72	1,17	1,83	2,59
31														0,00	1,20	2,52	2,70
32															2,26	2,58	3,19
33																3,36	3,49
34																	4,29

Figure 10b: Detailed 2D APOLLO2 MOC results for the external UO2 assembly (top) and corresponding relative errors in % (bottom). The two dark orange cells correspond to the maximum positive and negative relative errors for this assembly.

MOX	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	1,31	1,06	0,93	0,86	0,81	0,76	0,71	0,66	0,62	0,57	0,52	0,48	0,44	0,40	0,38	0,41	0,61
2	1,29	1,34	1,17	1,09	1,05	1,04	0,92	0,85	0,83	0,73	0,67	0,66	0,57	0,51	0,47	0,52	0,60
3	1,29	1,32	1,18	1,17	1,11	0,00	0,94	0,86	0,00	0,75	0,69	0,00	0,61	0,54	0,48	0,52	0,60
4	1,29	1,33	1,26	0,00	1,10	1,12	0,96	0,88	0,87	0,76	0,70	0,70	0,59	0,00	0,52	0,52	0,60
5	1,29	1,36	1,28	1,17	1,14	1,08	0,93	0,86	0,85	0,74	0,68	0,68	0,61	0,54	0,52	0,53	0,60
6	1,30	1,42	0,00	1,27	1,14	0,00	0,98	0,90	0,00	0,78	0,71	0,00	0,62	0,58	0,00	0,56	0,60
7	1,27	1,33	1,21	1,15	1,04	1,03	0,90	0,83	0,83	0,72	0,66	0,65	0,56	0,53	0,49	0,52	0,59
8	1,26	1,31	1,19	1,12	1,02	1,01	0,89	0,82	0,82	0,71	0,65	0,64	0,56	0,52	0,48	0,52	0,59
9	1,24	1,36	0,00	1,18	1,07	0,00	0,94	0,86	0,00	0,75	0,69	0,00	0,59	0,54	0,00	0,54	0,59
10	1,21	1,27	1,15	1,09	0,99	0,98	0,86	0,80	0,80	0,69	0,64	0,63	0,54	0,51	0,47	0,51	0,58
11	1,19	1,24	1,13	1,07	0,97	0,97	0,85	0,79	0,79	0,68	0,63	0,62	0,54	0,50	0,47	0,50	0,57
12	1,16	1,28	0,00	1,16	1,04	0,00	0,90	0,83	0,00	0,73	0,66	0,00	0,58	0,54	0,00	0,52	0,56
13	1,12	1,19	1,13	1,03	1,01	0,96	0,83	0,77	0,77	0,67	0,62	0,62	0,56	0,49	0,48	0,49	0,55
14	1,08	1,13	1,08	0,00	0,96	0,98	0,84	0,78	0,77	0,68	0,63	0,63	0,53	0,00	0,47	0,47	0,54
15	1,03	1,08	0,99	0,99	0,95	0,00	0,82	0,76	0,00	0,67	0,61	0,00	0,55	0,49	0,43	0,47	0,54
16	1,01	1,09	0,99	0,94	0,92	0,92	0,82	0,77	0,76	0,67	0,62	0,61	0,53	0,47	0,44	0,49	0,55
17	1,01	0,91	0,86	0,82	0,79	0,76	0,71	0,67	0,63	0,59	0,54	0,51	0,46	0,42	0,40	0,43	0,59

%	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	0,17	-0,32	-0,39	-0,64	-0,90	-0,60	-0,67	-1,03	-0,85	-0,81	-0,61	-0,59	-0,85	-0,45	0,34	0,98	2,06
2	-0,07	0,17	0,06	-0,21	-0,53	-0,77	-0,39	-0,14	-0,71	-0,19	-0,08	-0,66	0,04	0,25	0,66	1,41	1,94
3	0,04	0,18	-0,30	-0,79	-0,83	0,00	-0,65	-0,71	0,00	-0,76	-0,52	0,00	-0,57	0,09	0,76	1,22	2,04
4	-0,09	0,02	-0,37	0,00	-0,68	-0,56	-0,28	-0,09	-0,51	0,23	0,30	0,07	0,15	0,00	0,26	1,49	2,28
5	-0,04	0,27	-0,53	-0,72	-0,38	-0,95	-0,14	0,07	-0,47	0,12	0,24	0,05	0,19	0,36	0,53	1,77	2,40
6	0,06	-0,55	0,00	-0,77	-0,60	0,00	-0,84	-0,78	0,00	-0,47	-0,47	0,00	-0,08	0,45	0,00	1,31	2,11
7	-0,08	-0,10	-0,90	-0,35	-0,03	-0,61	-0,25	-0,45	-0,50	0,01	0,14	-0,06	0,44	1,15	0,81	1,64	1,79
8	0,04	0,01	-0,90	-0,24	-0,27	-0,87	-0,29	0,15	-0,17	-0,27	0,16	-0,37	0,35	1,04	0,33	1,87	2,23
9	-0,06	-0,71	0,00	-0,78	-0,33	0,00	-0,94	-0,75	0,00	-0,60	-0,34	0,00	-0,23	0,48	0,00	1,46	2,22
10	-0,25	-0,30	-0,66	-0,09	-0,13	-0,68	-0,26	-0,55	-0,67	-0,12	-0,08	-0,33	0,16	1,03	0,87	1,38	2,13
11	0,08	0,17	-0,71	-0,05	-0,21	-0,80	0,11	0,37	-0,50	0,28	0,15	-0,29	0,43	1,09	0,64	1,09	2,19
12	0,04	-0,37	0,00	-0,57	-0,55	0,00	-0,80	-0,73	0,00	-0,50	-0,18	0,00	-0,16	0,70	0,00	1,29	1,84
13	-0,10	0,11	-0,59	-0,66	-0,06	-0,55	0,14	-0,12	-0,57	0,10	0,11	0,01	0,60	0,47	1,00	1,77	2,21
14	-0,15	0,02	-0,44	0,00	-0,42	-0,46	0,29	0,36	-0,08	0,01	0,59	0,11	0,13	0,00	0,57	1,54	2,51
15	0,05	0,03	-0,06	-0,43	-0,50	0,00	-0,60	-0,43	0,00	-0,51	-0,17	0,00	0,00	0,14	0,69	1,62	2,33
16	-0,12	0,04	0,12	0,00	-0,15	-0,15	0,25	0,16	-0,11	0,10	0,10	-0,10	0,70	0,67	0,91	2,03	2,10
17	-0,10	-0,01	0,08	-0,06	-0,08	0,19	0,16	0,12	0,26	-0,12	-0,12	0,44	0,46	0,66	1,39	1,52	2,58

Figure 10c: Detailed 2D APOLLO2 MOC results for the MOX assembly (top) and corresponding relative errors in % (bottom). The two dark orange cells correspond to the maximum positive and negative relative errors for this assembly. Colors are used to indicate MOX zoning.

Appendix C: Detailed 3D S<sub>4</sub> CRONOS results

UO2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	2.20	2.21	2.22	2.23	2.23	2.22	2.19	2.15	2.11	2.06	2.00	1.94	1.86	1.75	1.63	1.48	1.26
2	2.21	2.22	2.25	2.27	2.34	2.36	2.29	2.24	2.24	2.15	2.09	2.06	1.94	1.79	1.65	1.49	1.26
3	2.22	2.25	2.34	2.42	2.49	0.00	2.37	2.32	0.00	2.22	2.16	0.00	2.07	1.91	1.73	1.51	1.27
4	2.24	2.28	2.42	0.00	2.52	2.43	2.33	2.28	2.27	2.18	2.13	2.12	2.09	0.00	1.79	1.53	1.28
5	2.24	2.34	2.49	2.52	2.46	2.41	2.32	2.27	2.26	2.17	2.12	2.11	2.05	1.98	1.84	1.58	1.28
6	2.23	2.37	0.00	2.43	2.41	0.00	2.33	2.29	0.00	2.19	2.13	0.00	2.01	1.91	0.00	1.60	1.28
7	2.20	2.29	2.37	2.33	2.32	2.33	2.26	2.22	2.21	2.12	2.07	2.04	1.93	1.84	1.75	1.55	1.26
8	2.16	2.25	2.32	2.28	2.27	2.29	2.22	2.18	2.17	2.09	2.03	2.00	1.90	1.80	1.72	1.52	1.24
9	2.12	2.24	0.00	2.28	2.26	0.00	2.21	2.17	0.00	2.08	2.03	0.00	1.89	1.80	0.00	1.52	1.22
10	2.07	2.15	2.22	2.18	2.17	2.19	2.12	2.08	2.08	2.00	1.95	1.92	1.82	1.73	1.65	1.46	1.20
11	2.01	2.09	2.16	2.13	2.12	2.13	2.06	2.03	2.02	1.95	1.89	1.87	1.78	1.69	1.61	1.43	1.17
12	1.95	2.07	0.00	2.12	2.10	0.00	2.04	2.00	0.00	1.92	1.87	0.00	1.77	1.69	0.00	1.42	1.14
13	1.86	1.94	2.07	2.09	2.05	2.01	1.93	1.89	1.89	1.82	1.78	1.77	1.73	1.68	1.56	1.35	1.10
14	1.76	1.79	1.91	0.00	1.98	1.91	1.84	1.80	1.80	1.73	1.69	1.69	1.68	0.00	1.45	1.25	1.05
15	1.63	1.65	1.72	1.79	1.83	0.00	1.74	1.71	0.00	1.65	1.61	0.00	1.56	1.45	1.32	1.17	1.00
16	1.48	1.49	1.50	1.52	1.57	1.59	1.54	1.52	1.52	1.46	1.43	1.42	1.34	1.25	1.17	1.07	0.94
17	1.26	1.26	1.27	1.27	1.28	1.27	1.26	1.24	1.22	1.19	1.17	1.14	1.10	1.05	1.00	0.94	0.86

%	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0.14	0.23	0.11	0.09	0.36	-0.42	0.26	0.42	-0.36	0.24	0.42	-0.43	0.10	-0.21	-0.28	-0.54	-1.59
2		0.49	0.45	-0.15	1.48	-0.38	1.37	1.53	-0.40	1.43	1.38	-0.37	1.26	-0.45	-0.06	-0.15	-1.35
3			1.17	-0.80	0.64	0.00	-0.83	-0.91	0.00	-0.76	-0.74	0.00	0.63	-1.23	0.94	-0.26	-1.34
4				0.00	0.78	-1.18	1.56	1.52	-0.82	1.68	1.56	-1.20	0.66	0.00	-1.33	-0.76	-1.19
5					2.48	-0.60	1.71	1.65	-0.72	1.66	1.72	-0.74	2.59	0.54	0.32	0.82	-1.16
6						0.00	-0.64	-0.74	0.00	-0.47	-0.63	0.00	-0.79	-1.42	0.00	-0.95	-1.98
7							1.71	1.78	-0.57	1.68	1.61	-0.78	1.69	1.41	-1.20	0.95	-1.02
8								1.63	-0.73	1.67	1.71	-0.78	1.59	1.23	-1.23	0.92	-1.13
9									0.00	-0.59	-0.62	0.00	-0.76	-0.95	0.00	-0.96	-1.95
10										1.78	1.68	-0.87	1.46	1.05	-1.30	0.74	-1.15
11											1.60	-0.93	1.52	1.22	-1.29	0.70	-1.26
12												0.00	-0.94	-1.64	0.00	-1.11	-2.04
13													2.17	0.38	-0.04	0.77	-1.41
14														0.00	-1.75	-1.06	-1.35
15															0.10	-0.58	-1.43
16																-0.84	-1.88
17																	-2.28

Figure 11a: Detailed 3D S<sub>4</sub> CRONOS results for the central UO2 assembly (top) and corresponding relative errors in % (bottom). The maximum fission rate for the entire problem happens in cell (4,5) for which the relative error is 0.78%. The two dark orange cells correspond to the maximum positive and negative relative errors for this assembly.

UO2	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
18	0.78	0.77	0.75	0.73	0.71	0.68	0.65	0.61	0.57	0.54	0.50	0.46	0.43	0.39	0.37	0.39	0.52
19	0.77	0.82	0.82	0.81	0.81	0.79	0.74	0.70	0.67	0.62	0.57	0.54	0.49	0.44	0.42	0.43	0.55
20	0.75	0.82	0.86	0.88	0.88	0.00	0.79	0.74	0.00	0.65	0.61	0.00	0.54	0.49	0.45	0.45	0.56
21	0.73	0.81	0.88	0.00	0.89	0.83	0.77	0.73	0.70	0.64	0.60	0.57	0.55	0.00	0.47	0.45	0.56
22	0.71	0.81	0.88	0.89	0.85	0.81	0.75	0.71	0.68	0.63	0.59	0.56	0.53	0.50	0.47	0.46	0.55
23	0.68	0.79	0.00	0.83	0.81	0.00	0.74	0.70	0.00	0.62	0.58	0.00	0.51	0.47	0.00	0.45	0.53
24	0.64	0.74	0.78	0.77	0.75	0.74	0.70	0.66	0.63	0.59	0.55	0.52	0.47	0.44	0.43	0.43	0.51
25	0.61	0.69	0.74	0.73	0.71	0.70	0.66	0.63	0.60	0.56	0.52	0.49	0.45	0.42	0.41	0.41	0.48
26	0.57	0.66	0.00	0.70	0.68	0.00	0.63	0.60	0.00	0.54	0.50	0.00	0.43	0.40	0.00	0.39	0.46
27	0.53	0.61	0.65	0.64	0.63	0.62	0.58	0.56	0.54	0.50	0.46	0.44	0.40	0.37	0.36	0.36	0.43
28	0.49	0.57	0.60	0.60	0.59	0.58	0.54	0.52	0.50	0.46	0.43	0.41	0.38	0.35	0.34	0.34	0.40
29	0.46	0.54	0.00	0.57	0.56	0.00	0.52	0.49	0.00	0.44	0.41	0.00	0.36	0.33	0.00	0.32	0.38
30	0.42	0.49	0.53	0.54	0.52	0.50	0.47	0.45	0.43	0.40	0.38	0.36	0.34	0.32	0.30	0.29	0.35
31	0.39	0.44	0.48	0.00	0.49	0.47	0.44	0.42	0.40	0.37	0.35	0.33	0.32	0.00	0.27	0.26	0.32
32	0.37	0.41	0.44	0.46	0.47	0.00	0.42	0.40	0.00	0.36	0.34	0.00	0.30	0.27	0.25	0.24	0.29
33	0.39	0.43	0.44	0.44	0.45	0.45	0.42	0.40	0.39	0.36	0.34	0.32	0.29	0.26	0.24	0.24	0.28
34	0.51	0.54	0.55	0.55	0.54	0.52	0.50	0.48	0.45	0.43	0.40	0.37	0.34	0.31	0.29	0.28	0.31

%	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	
18	-2.62	-2.51	-2.54	-2.26	-1.92	-2.65	-2.06	-2.01	-2.54	-1.63	-1.52	-1.91	-1.23	-0.68	-0.01	0.48	3.42	
19		-1.42	-1.54	-1.74	-0.11	-1.91	0.19	0.21	-1.56	0.36	0.70	-1.27	1.05	-0.04	1.25	1.89	4.37	
20			-0.29	-2.37	-0.57	0.00	-2.00	-1.90	0.00	-1.38	-1.16	0.00	0.79	-0.57	2.57	2.38	4.83	
21				0.00	-0.41	-2.39	0.63	0.95	-1.53	1.03	0.99	-1.34	0.90	0.00	0.74	1.83	4.83	
22					1.33	-1.61	0.95	1.00	-1.36	1.17	1.40	-0.64	2.91	1.57	2.46	3.55	5.45	
23						0.00	-1.50	-1.50	0.00	-0.97	-0.95	0.00	-0.60	-0.44	0.00	1.76	4.66	
24							0.93	1.25	-0.98	1.52	1.44	-0.61	2.11	2.15	0.79	3.67	5.25	
25								1.26	-1.11	1.37	1.78	-0.28	2.40	2.35	1.06	3.67	5.29	
26									0.00	-0.68	-0.75	0.00	-0.04	0.28	0.00	1.87	4.87	
27										1.75	1.42	-0.56	2.43	2.61	0.85	3.71	5.25	
28											1.71	-0.71	2.11	2.70	0.96	3.61	5.24	
29												0.00	-0.02	-0.26	0.00	1.89	4.48	
30													3.32	1.76	2.29	3.74	5.24	
31														0.00	1.03	2.93	5.16	
32																4.03	3.38	5.45
33																	4.05	5.24
34																		6.71

Figure 11b: Detailed 3D  $S_4$  CRONOS results for the external UO2 assembly (top) and corresponding relative errors in % (bottom). The two dark orange cells correspond to the maximum positive and negative relative errors for this assembly.

MOX	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	1.33	1.06	0.92	0.85	0.80	0.75	0.70	0.65	0.60	0.56	0.52	0.47	0.43	0.39	0.38	0.41	0.63
2	1.32	1.36	1.17	1.09	1.07	1.04	0.94	0.87	0.83	0.75	0.68	0.66	0.58	0.50	0.48	0.53	0.62
3	1.31	1.33	1.19	1.15	1.12	0.00	0.93	0.85	0.00	0.74	0.67	0.00	0.61	0.53	0.49	0.52	0.62
4	1.31	1.34	1.24	0.00	1.11	1.10	0.97	0.89	0.86	0.77	0.71	0.69	0.59	0.00	0.51	0.52	0.62
5	1.32	1.39	1.30	1.19	1.18	1.06	0.94	0.86	0.84	0.75	0.68	0.67	0.63	0.54	0.53	0.54	0.62
6	1.31	1.43	0.00	1.25	1.12	0.00	0.96	0.88	0.00	0.77	0.70	0.00	0.61	0.57	0.00	0.56	0.62
7	1.29	1.37	1.20	1.17	1.05	1.02	0.91	0.84	0.82	0.73	0.67	0.64	0.57	0.53	0.48	0.53	0.61
8	1.28	1.35	1.17	1.14	1.03	1.00	0.90	0.83	0.80	0.72	0.66	0.63	0.56	0.52	0.47	0.53	0.61
9	1.25	1.37	0.00	1.17	1.05	0.00	0.92	0.85	0.00	0.74	0.67	0.00	0.58	0.54	0.00	0.54	0.60
10	1.23	1.30	1.14	1.11	1.00	0.97	0.87	0.81	0.79	0.70	0.64	0.62	0.55	0.51	0.46	0.52	0.59
11	1.20	1.27	1.12	1.09	0.98	0.95	0.86	0.79	0.77	0.69	0.63	0.61	0.54	0.51	0.46	0.51	0.59
12	1.17	1.29	0.00	1.14	1.02	0.00	0.89	0.81	0.00	0.71	0.65	0.00	0.57	0.53	0.00	0.52	0.58
13	1.14	1.22	1.14	1.05	1.05	0.95	0.84	0.78	0.76	0.68	0.62	0.61	0.58	0.50	0.48	0.50	0.57
14	1.09	1.13	1.06	0.00	0.96	0.96	0.85	0.79	0.76	0.69	0.63	0.62	0.53	0.00	0.46	0.47	0.56
15	1.05	1.09	1.00	0.98	0.96	0.00	0.80	0.74	0.00	0.65	0.60	0.00	0.55	0.48	0.44	0.47	0.56
16	1.02	1.10	0.99	0.94	0.93	0.92	0.84	0.78	0.76	0.69	0.63	0.61	0.54	0.47	0.45	0.49	0.57
17	1.02	0.92	0.86	0.82	0.79	0.76	0.72	0.67	0.63	0.59	0.55	0.51	0.47	0.43	0.41	0.43	0.61

%	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	1.56	-0.64	-1.36	-1.79	-2.10	-2.72	-2.12	-2.32	-2.97	-2.16	-2.00	-2.54	-1.97	-1.45	-0.71	-0.18	4.97
2	1.89	1.51	0.40	-0.52	1.54	-0.78	1.84	1.78	-0.81	2.00	1.80	-0.75	2.30	-0.03	1.30	2.25	5.25
3	1.63	1.08	1.25	-1.93	0.33	0.00	-2.37	-2.68	0.00	-2.58	-2.52	0.00	0.07	-1.44	2.44	1.37	5.08
4	1.57	0.41	-1.57	0.00	0.03	-2.40	1.44	1.22	-1.61	1.87	1.56	-1.82	1.10	0.00	-1.14	1.09	5.38
5	1.62	2.81	0.53	0.43	3.10	-2.36	1.14	0.87	-2.07	1.27	1.13	-1.51	3.37	0.85	1.57	3.71	5.40
6	1.05	0.22	0.00	-2.20	-2.18	0.00	-2.21	-2.43	0.00	-1.81	-2.19	0.00	-1.52	-1.73	0.00	1.27	4.75
7	1.60	2.69	-2.25	1.57	1.08	-2.03	1.11	0.58	-2.12	1.30	1.03	-1.69	1.64	2.33	-1.00	3.58	4.80
8	1.51	2.61	-2.30	1.73	0.57	-2.35	0.97	0.79	-1.84	1.10	0.94	-1.84	1.48	2.04	-1.59	3.69	5.23
9	0.89	0.00	0.00	-1.72	-2.18	0.00	-2.23	-2.45	0.00	-1.97	-2.28	0.00	-1.65	-1.14	0.00	1.16	4.69
10	1.33	2.40	-2.09	1.84	0.86	-2.26	0.94	0.38	-2.28	1.10	0.82	-1.95	1.32	2.05	-1.11	3.31	5.11
11	1.54	2.61	-2.31	1.70	0.64	-2.44	1.14	1.00	-2.24	1.35	0.96	-2.04	1.56	2.10	-1.40	2.93	5.17
12	0.91	0.18	0.00	-2.17	-2.44	0.00	-2.26	-2.40	0.00	-2.08	-2.16	0.00	-1.73	-1.53	0.00	1.14	4.40
13	1.31	2.45	0.13	0.36	3.19	-2.17	1.10	0.53	-2.35	1.16	0.79	-1.76	3.78	0.90	1.73	3.59	5.14
14	1.25	0.03	-1.99	0.00	-0.06	-2.65	1.50	1.23	-1.52	1.40	1.50	-2.02	0.81	0.00	-0.93	1.11	5.57
15	1.32	0.71	1.23	-1.83	0.38	0.00	-2.53	-2.52	0.00	-2.50	-2.34	0.00	0.59	-1.40	2.50	1.80	5.38
16	1.06	1.12	0.39	-0.38	1.89	-0.28	2.43	2.10	-0.18	2.35	2.14	0.04	3.23	0.77	1.88	3.10	5.42
17	0.59	0.74	0.54	0.42	0.56	0.04	0.74	0.82	0.25	0.62	0.71	0.61	1.53	2.10	3.07	3.30	6.72

Figure 11c: Detailed 3D  $S_4$  CRONOS results for the MOX assembly (top) and corresponding relative errors in % (bottom). The two dark orange cells correspond to the maximum positive and negative relative errors for this assembly. Colors are used to indicate MOX zoning.