

Quantification of geometrical and material data uncertainties in TRISO fuel performance analysis



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New reactor concepts and safety analyses for the Polish Nuclear Energy Program
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Introduction

What is covered in fuel performance analysis[1]:

- Pressure build-up in buffer layer
- Heat generation and transfer from the kernel
- Anisotropy effects and kernel migration
- Fission product build-up and release
- Chemical effects
- Thermomechanical behavior (irradiation induced)
- Fuel failure mechanisms and failure fraction

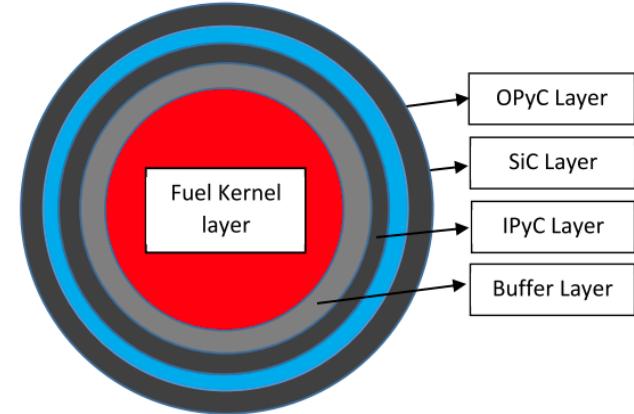


Fig. 1. The geometry of the TRISO fuel particle.

Why quantifying uncertainties is important?

- Manufacturing source of uncertainties (geometry and materials)
- Model based uncertainties [2]
- Small uncertainty in one model can impact on the accuracy of another model
- Is current design of TRISO the most optimal?



Case description-1

Irradiation conditions of AGR-2 compacts [3]

Compact	Fuel Type	Fluence (10^{25} n/m 2) [E>0.18 MeV]	Burnup (%FIMA)	Avg. Temp. (°C)	Compact	Fuel Type	Fluence (10^{25} n/m 2) [E>0.18 MeV]	Burnup (%FIMA)	Avg. Temp. (°C)
Capsule 2					Capsule 5				
2-1-1	UCO	3.21	12.55	1218	5-1-1	UCO	3.41	12.82	1108
2-1-2	UCO	3.25	12.64	1219	5-1-2	UCO	3.43	12.90	1109
2-1-3	UCO	2.88	10.96	1194	5-1-3	UCO	3.03	11.10	1078
2-2-1	UCO	3.35	12.49	1287	5-2-1	UCO	3.38	12.30	1141
2-2-2	UCO	3.39	12.57	1287	5-2-2	UCO	3.39	12.36	1141
2-2-3	UCO	2.99	10.82	1261	5-2-3	UCO	3.00	10.44	1108
2-3-1	UCO	3.42	12.65	1296	5-3-1	UCO	3.28	12.05	1126
2-3-2	UCO	3.46	12.07	1296	5-3-2	UCO	3.29	12.10	1126
2-3-3	UCO	3.06	11.02	1270	5-3-3	UCO	2.91	10.08	1093
2-4-1	UCO	3.44	13.14	1240	5-4-1	UCO	3.13	12.07	1071
2-4-2	UCO	3.47	13.17	1240	5-4-2	UCO	3.14	12.05	1071
2-4-3	UCO	3.08	11.53	1216	5-4-3	UCO	2.78	10.09	1040
Capsule 3					Capsule 6				
3-1-1	UO ₂	3.41	10.62	1011	6-1-1	UCO	2.73	10.79	1100
3-1-2	UO ₂	3.45	10.69	1012	6-1-2	UCO	2.73	10.83	1100
3-1-3	UO ₂	3.05	9.27	996	6-1-3	UCO	2.42	9.10	1069
3-2-1	UO ₂	3.47	10.45	1061	6-2-1	UCO	2.60	10.18	1129
3-2-2	UO ₂	3.51	10.54	1062	6-2-2	UCO	2.61	10.20	1129
3-2-3	UO ₂	3.09	9.03	1045	6-2-3	UCO	2.30	8.23	1095
3-3-1	UO ₂	3.49	10.49	1062	6-3-1	UCO	2.42	9.60	1094
3-3-2	UO ₂	3.53	10.56	1062	6-3-2	UCO	2.43	9.61	1094
3-3-3	UO ₂	3.11	9.09	1046	6-3-3	UCO	2.14	7.47	1060
3-4-1	UO ₂	3.47	10.65	1013	6-4-1	UCO	2.20	9.25	1018
3-4-2	UO ₂	3.50	10.71	1013	6-4-2	UCO	2.21	9.27	1018
3-4-3	UO ₂	3.10	9.33	998	6-4-3	UCO	1.94	7.27	987



Case description-2

Objective parameters and reference values

Selected parameter	Min value	Max value
Gas pressure	833.3486	4149459
Pd penetration	1.12E-08	5.09E-06
SiC stress radial	-2.5E+07	-3741415
SiC stress tangential	-3.4E+08	-4.8E+07
IPyC failure probability	9.24E-10	0.270195
SiC failure probability	6.52E-14	1.44E-08

Results are performed for 5 equal groups over neutron irradiation time.

Characteristics of AGR-2 TRISO fuel particles [3]

Property	Mean Value ± Standard Deviation	
	UCO	UO ₂
Kernel diameter (μm)	426.7 ± 8.8	507.7 ± 11.9
Kernel density (Mg/m ³)	10.966 ± 0.033	10.858 ± 0.082
U-235 enrichment (wt%)	14.029 ± 0.026	9.600 ± 0.010
Carbon/uranium (atomic ratio)	0.392 ± 0.002	not applicable
Oxygen/uranium (atomic ratio)	1.428 ± 0.005	2.003 ± 0.005
Buffer thickness (μm)	98.9 ± 8.4	97.7 ± 9.9
Buffer density (Mg/m ³)	not measured	0.99
IPyC thickness (μm)	40.4 ± 2.5	41.9 ± 3.2
IPyC density (Mg/m ³)	1.890 ± 0.011	not measured
SiC thickness (μm)	35.2 ± 1.2	37.5 ± 1.2
SiC density (Mg/m ³)	3.197 ± 0.004	3.200 ± 0.002
OPyC thickness (μm)	43.4 ± 2.9	45.6 ± 2.4
OPyC density (Mg/m ³)	1.907 ± 0.007	1.884 ± 0.004
Compact diameter (mm)	12.286 ± 0.005	12.269 ± 0.007
Compact length (mm)	25.141 ± 0.017	25.134 ± 0.018
Compact matrix density (Mg/m ³)	1.589 ± 0.005	1.667 ± 0.006



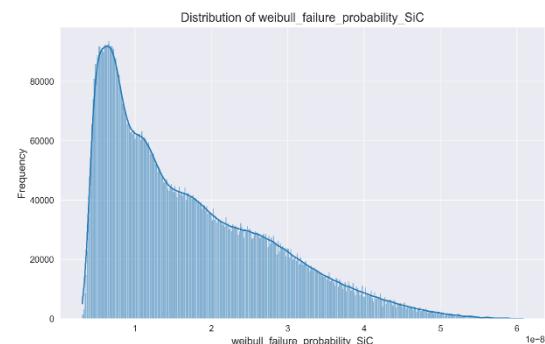
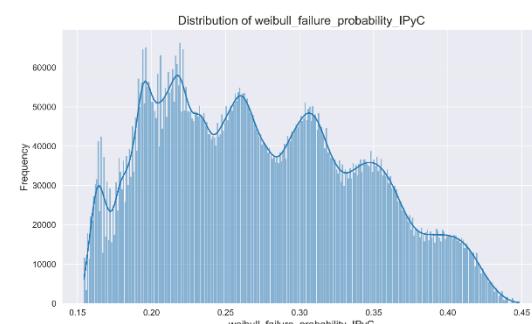
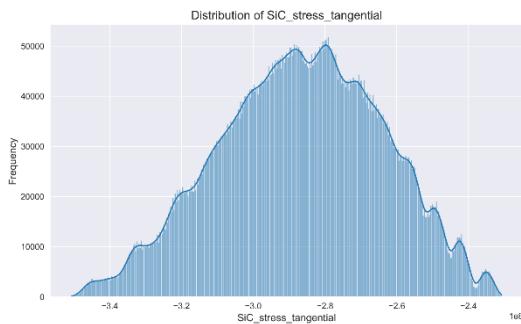
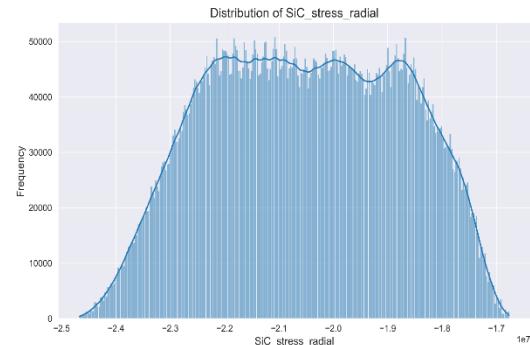
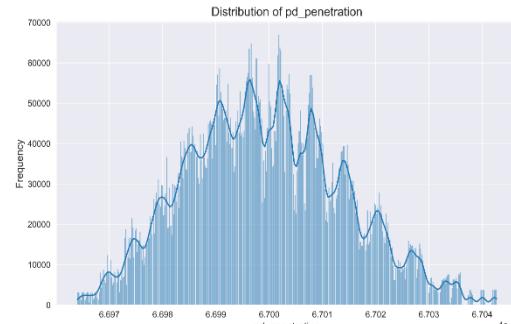
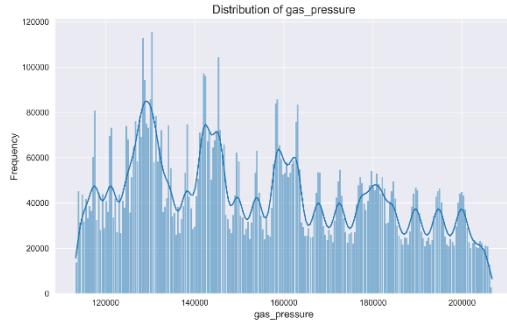
Case description -3

Selected values for uncertainty quantification

	x	ref	ref-x	ref+x	ref-2x	ref+2x
Parameter	uncertainty range (+-)	case0	case1	case2	case3	case4
Kernel radius (mm)	4.4	213.35	208.95	217.75	204.55	222.15
Buffer thickness (mm)	8.4	98.9	90.5	107.3	82.1	115.7
IPyC thickness (mm)	2.5	40.4	37.9	42.9	35.4	45.4
SiC thickness (mm)	1.2	35.2	34	36.4	32.8	37.6
OPyC thickness (mm)	2.9	43.4	40.5	46.3	37.6	49.2
Kernel density (g/cm3)	0.033	10.966	10.933	10.999	10.9	11.032
Buffer density (g/cm3)	0.01	1.05	1.04	1.06	1.03	1.07
IPyC density (g/cm3)	0.011	1.89	1.879	1.901	1.868	1.912
SiC density (g/cm3)	0.004	3.197	3.193	3.201	3.189	3.205
OPyC density (g/cm3)	0.007	1.907	1.9	1.914	1.893	1.921

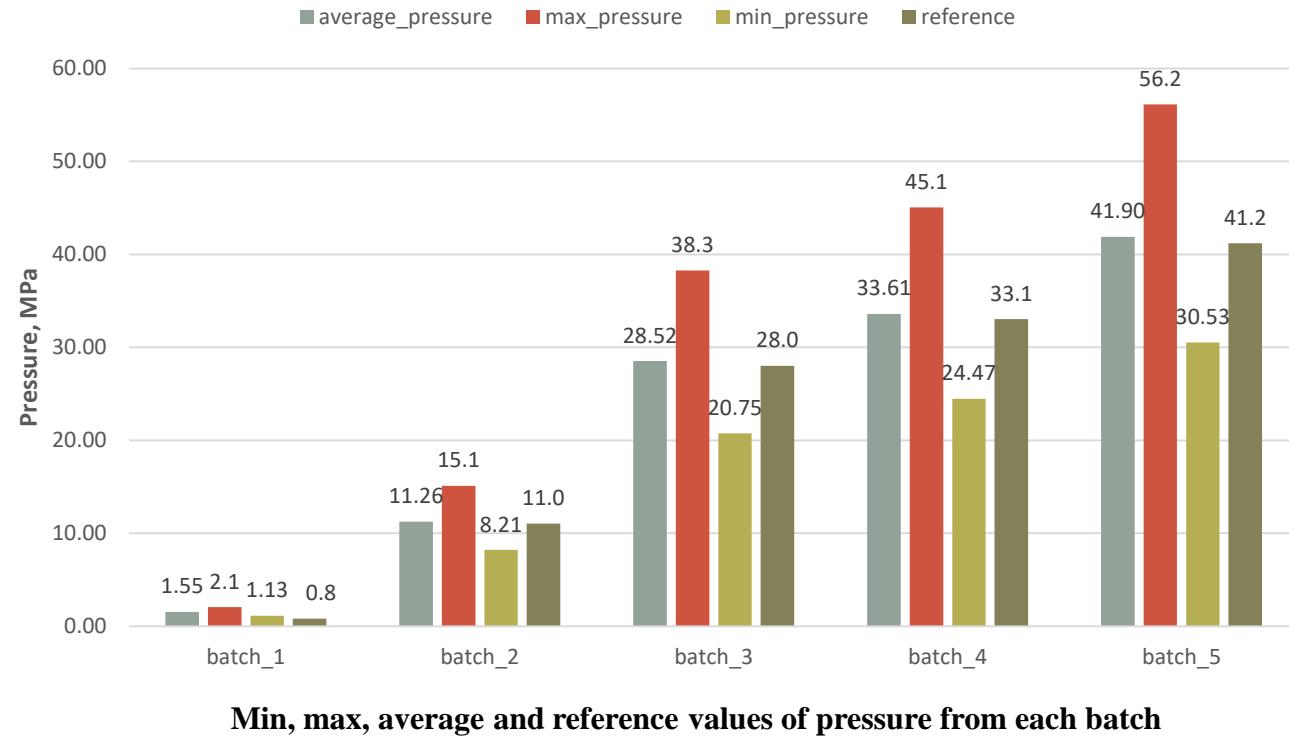


Results - distributions





Results: pressure





Results: pressure

Min and max cases for the pressure for each batch

pressure results	b1_min	b1_max	b2_min	b2_max	b3_min	b3_max	b4_min	b4_max	b5_min	b5_max
kernel_radius	0.22215	0.20455	0.22215	0.20455	0.22215	0.20455	0.22215	0.20455	0.22215	0.20455
buffer_thickness	0.0821	0.1157	0.0821	0.1157	0.0821	0.1157	0.0821	0.1157	0.0821	0.1157
IPyC_thickness	0.0354	0.0454	0.0354	0.0454	0.0354	0.0454	0.0354	0.0454	0.0354	0.0454
SiC_thickness	0.0328	0.0376	0.0328	0.0376	0.0328	0.0376	0.0328	0.0376	0.0328	0.0376
OPyC_thickness	0.0492	0.0376	0.0492	0.0376	0.0492	0.0376	0.0492	0.0376	0.0492	0.0376
kernel_density	10.9	11.032	10.9	11.032	10.9	11.032	10.9	11.032	10.9	11.032
buffer_density	1.07	1.03	1.07	1.03	1.07	1.03	1.07	1.03	1.07	1.03
ipyc_density	1.912	1.868	1.912	1.868	1.912	1.868	1.912	1.868	1.912	1.868
sic_density	3.189	3.205	3.197	3.205	3.197	3.193	3.189	3.205	3.189	3.205
opyc_density	1.893	1.921	1.921	1.893	1.921	1.893	1.921	1.893	1.921	1.893



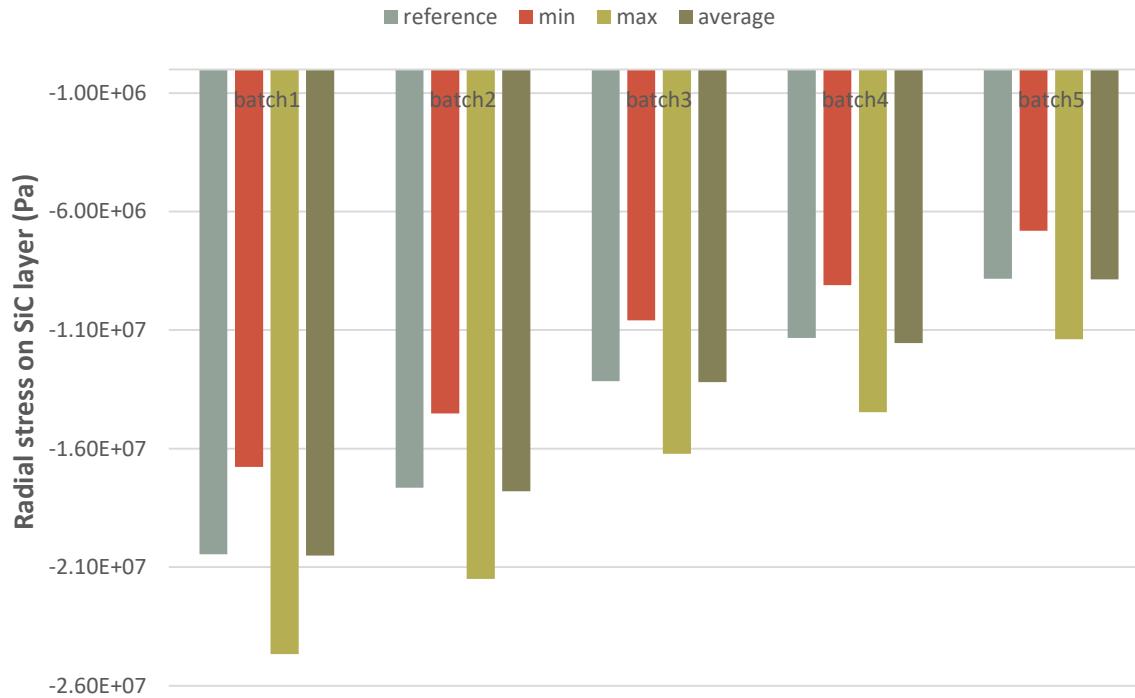
Results: Pd penetration

Min and max cases for the Pd penetration for each batch

pd_penetration	b1_max	b1_min	b2_max	b2_min	b3_max	b3_min	b4_max	b4_min	b5_max	b5_min
kernel_radius	0.22215	0.20455	0.22215	0.20455	0.22215	0.20455	0.22215	0.20455	0.22215	0.20455
buffer_thickness	0.0821	0.1157	0.0821	0.1157	0.0821	0.1157	0.0821	0.1157	0.0821	0.1157
IPyC_thickness	0.0354	0.0454	0.0354	0.0454	0.0354	0.0454	0.0354	0.0454	0.0354	0.0454
SiC_thickness	0.0376	0.0328	0.0376	0.0328	0.0376	0.0328	0.0376	0.0328	0.0376	0.0328
OPyC_thickness	0.0492	0.0376	0.0492	0.0376	0.0492	0.0376	0.0492	0.0376	0.0492	0.0376
kernel_density	11.032	10.9	11.032	10.9	11.032	10.9	11.032	10.9	11.032	10.9
buffer_density	1.03	1.07	1.03	1.07	1.03	1.07	1.03	1.07	1.03	1.07
ipyc_density	1.868	1.912	1.868	1.912	1.912	1.868	1.912	1.868	1.912	1.868
sic_density	3.189	3.205	3.189	3.201	3.189	3.201	3.197	3.205	3.197	3.205
opyc_density	1.921	1.893	1.921	1.893	1.921	1.893	1.921	1.893	1.921	1.893



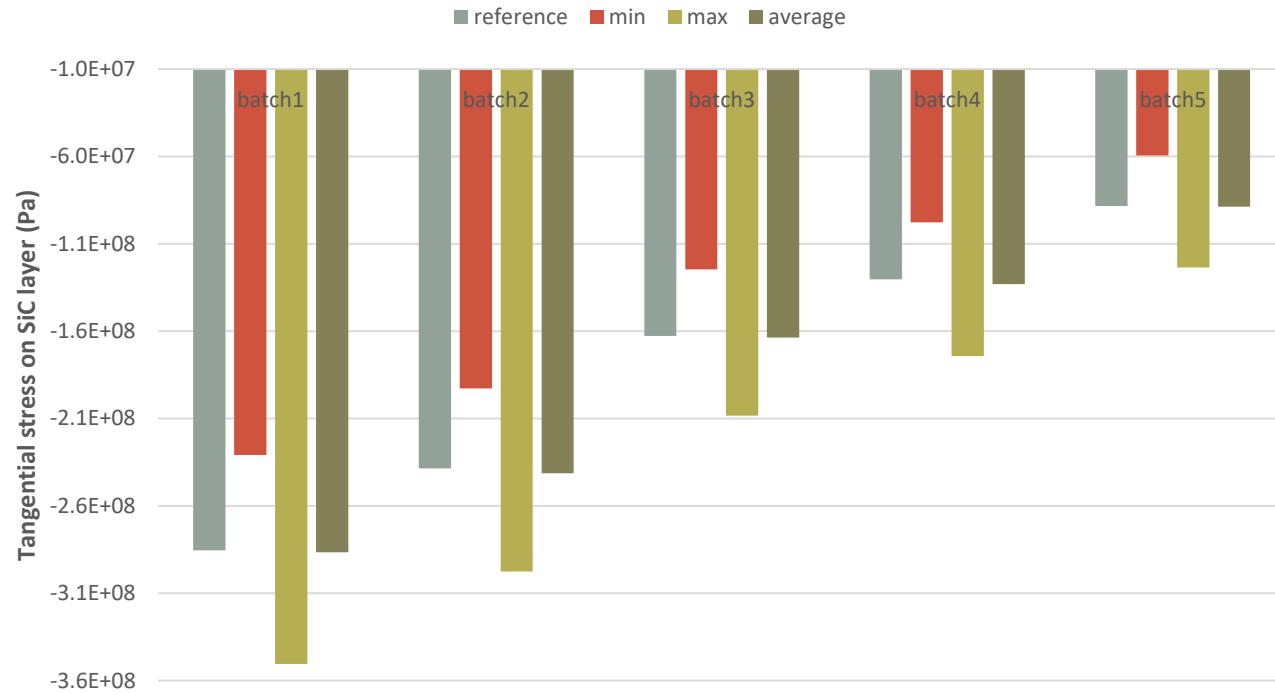
Results - radial stress



Results of analysis of the tangential stress on SiC layer



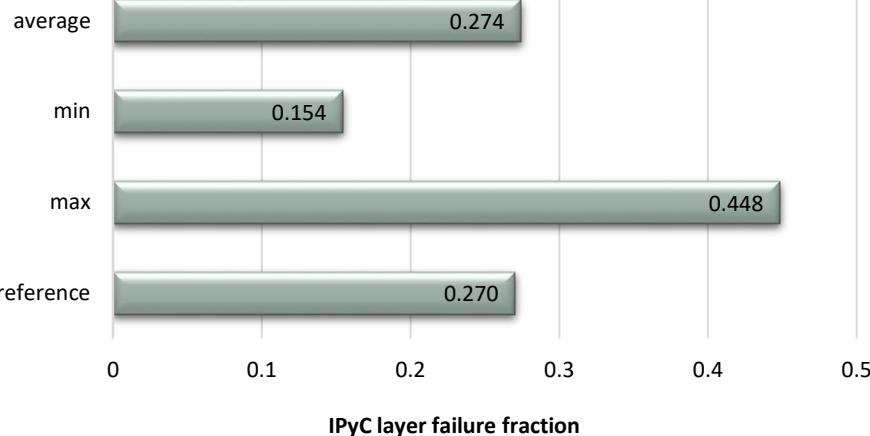
Results-tangential stress



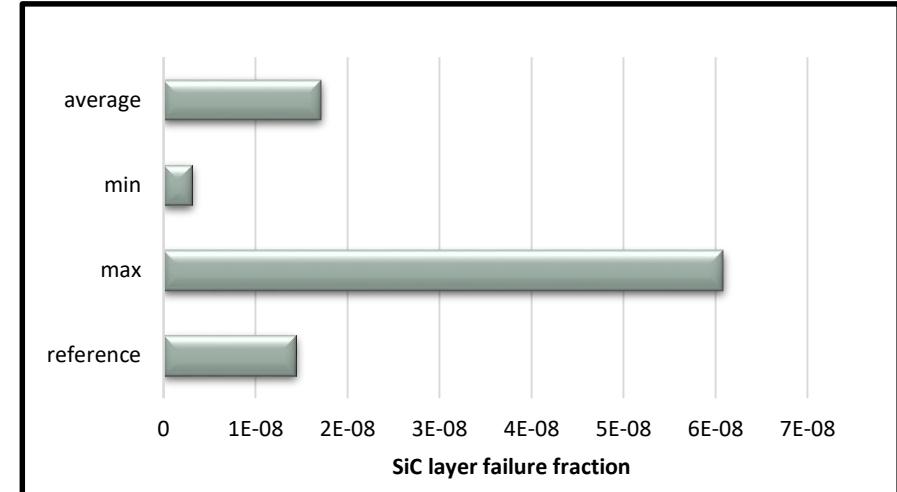
Results of analysis of the tangential stress on SiC layer



Results - failure fraction



Min, max, average and reference values of IPyC layer failure fraction



Min, max, average and reference values of SiC layer failure fraction



Summary



- Fuel performance analysis of TRISO fuel are important for safety and licensing perspectives
- Uncertainty quantification in fuel performance analysis is complex but very important
- Even small uncertainties in TRISO geometry can cause an important impact on buffer pressure and SiC max tangential stress values
- The results can be used for TRISO fuel optimization analysis for high burnup values
- For the overall quantification of the uncertainty impact and optimization analysis one should consider also the neutrons, thermos-hydraulics and other mechanisms.



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TRISO fuel performance analysis: Uncertainty quantification toward optimization

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Full results are available here:

<https://doi.org/10.1016/j.nucengdes.2023.112401>



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