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# NEW CEA HANDBOOKS FOR CRITICALITY SAFETY ASSESSMENT DEMONSTRATIONS

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## ABSTRACT

*Criticality safety assessment demonstrations may be supported by basic 1D calculations performed by neutron transport deterministic codes (standard calculations). In the case of the French CRISTAL V2.0 package, critical and permissible values for simple geometries like spheres, infinite height cylinders or infinite section slabs are determined with the APOLLO2 cell code and its discrete ordinates  $S_N$  module (standard route). The most pertinent values (e.g. values at optimal moderation) are aggregated in documents called handbooks.*

*45 years after the first and up to now unique French handbook, nicknamed "Maubert" from his author, this paper presents new handbooks, prepared by CEA. They compile latest CRISTAL V2.0 standard route results from more than 250 standard calculation reports. Two handbooks have currently been produced: one with critical values, the other with permissible values with a neutron effective multiplication factor,  $k_{eff}$ , criterion equal to 0.95. They both present results for uranium, plutonium, mixed media, and pure actinides fissile material with various physico-chemical, densities and isotopic compositions. The influence of various reflecting and moderating materials has been investigated. Moreover, criticality parameters for several fissile media containing homogeneous neutron absorbers (boron, gadolinium, cadmium) have been determined.*

*These handbooks are available to everyone on request.*

*Additionally, this paper discusses some singular and unexpected results observed while producing those handbooks.*

## KEYWORDS

*Criticality, Handbook, CRISTAL*

## 1. INTRODUCTION

Criticality safety assessment demonstrations in nuclear installations are often supported by 3D neutron transport calculations performed with Monte Carlo codes, which are adapted to each configuration. Sometimes they can also rely on basic 1D calculations performed with neutron transport deterministic codes, called standard calculations. Their purpose is to provide critical and permissible values for simple geometries like spheres, infinite height cylinders or infinite section slabs. The most pertinent values (e.g. values at the optimum of moderation and unmoderated values) are aggregated in documents called handbooks.

In 1978, a handbook compiling critical values was produced by the CEA/IPSN, commonly named "standard Maubert" from the name of its author. In France, for many values of this handbook, there was a consensus between Authorities and licensors. Nearly 40 years later, the CEA Criticality Safety Experts Group (CSEG) has undertaken

a project to overhaul and increase the content of this handbook by:

- Adding new configurations (e.g. fissile media);
- Performing all the calculations with state-of-the-art calculation routes, i.e. the French CRISTAL V2.0 package [1] with the APOLLO2 cell code and its SN module (standard route).

Two handbooks have thus been edited:

- The first compiles critical values (*neutron effective multiplication factor*,  $k_{\text{eff}} = 1$ );
- The second compiles permissible values, for a  $k_{\text{eff}}$  criterion set at 0.95, which is commonly used in French criticality safety demonstrations for normal operating configurations.

This paper first presents the contents of these handbooks and then dwells on singular and unexpected results observed while producing them.

## 2. CONTENTS

Those two new handbooks have been produced as if they were twins: same fissile materials, same paging, same chapters. Only values and colorization can distinguish them. All values are presented in tables (see Fig. 1) and curves are also presented (see Fig. 2) to allow interpolation between values recorded in the tables. Each value provided is justified by a technical report (and its complete reference) produced by the CEA/CSEG where latest code options and capabilities of CRISTAL V2.0 standard route (APOLLO2-S<sub>N</sub>) have been used. Additionally, each value presented in the handbooks has been recalculated with the reference route of CRISTAL V2.0 (TRIPOLI-4<sup>®</sup>) [2] to estimate the deviation between the two routes. Globally, the deviation between the two routes are consistent.

Parameters, for each fissile medium, are mass (in spherical shape), diameter (infinite height cylinder), thickness (infinite section slab), areal density and for homogeneous media, concentration in fissile material (infinite media) and moderation ratio (where water moderating aspect is counterbalanced by intrinsic absorption). For others cases, number of rods, moderation o ratio (for uranium, when water moderating aspect is dominant), enrichment limit, are provided as needed.

For each fissile material, usual reflectors and their thicknesses have been taken into account:

- Water: 2.5 and 20 cm,
- Concrete: 60 cm for 8,93 wt. % water content concrete and 100 cm for 3 wt. % water content concrete,
- Lead/water: 25 cm of lead followed by 20 cm of water.

The Table I below presents, for each chapter of these handbooks, the contents and the field covered.

**Table I. Contents and area covered by the new handbooks**

Chapter	Contents	Field
Homogeneous uranium media	Metallic, oxide (several powder densities), oxyfluoride, salts, nitrate (with or without acidity), hexafluoride (with 0.1HF)	Enrichment from 1.5 wt. % to 93.5 wt. %
Heterogeneous uranium media	Spherules of metallic or oxide uranium UO <sub>2</sub> “PWR” rods	Enrichment from 1 wt. % to 10 wt. % 5 wt. % for PWR rods
Plutonium media	Metallic, oxide (several powder densities), salts, nitrate (with or without acidity, III and IV valence forms)	<sup>240</sup> Pu content from 0 wt. % to 25 wt. %. Other isotopes are determined with a ratio method: <sup>241</sup> Pu/ <sup>240</sup> Pu=11/17 and <sup>242</sup> Pu/ <sup>241</sup> Pu=1/11. The complement to 100 wt. % is <sup>239</sup> Pu
Mixed uranium and plutonium media	Oxide	Pu (pure <sup>239</sup> Pu or 71%/17%/11%/1% composition) mixed with 1.2 wt. % enriched uranium with Pu content varying from 2.5 wt. % to 40 wt. % French FNR “RAPSDODIE” and “PHENIX” isotopic compositions
Actinides	Metallic	Each actinide produced in fission reactors with a half life greater than 6 months

Chapter	Contents	Field
Other moderating materials	Metallic uranium or plutonium, oxide uranium and/or plutonium moderated by polyethylene (CH <sub>2</sub> ) or graphite	CH <sub>2</sub> moderator: uranium with enrichment from 5 wt. % to 93.5 wt. %, plutonium with <sup>240</sup> Pu content equal to 0 wt. % or 17 wt. %, mixed oxide with various isotopic compositions Graphite moderator: pure metallic <sup>239</sup> Pu, 93.5 wt. % <sup>235</sup> U enriched metallic uranium and 5 wt. % <sup>235</sup> U enriched uranium oxide
Others reflectors	Metallic or oxide uranium, metallic plutonium reflected by non usual reflectors	25 reflectors at “saturating” thickness or at variable thickness surrounded by a 20 cm-thick layer of water (complete list available in [3])
Neutron absorbers	Metallic or oxide uranium, metallic plutonium poisoned by a variable concentration of boron, gadolinium or cadmium	Mass or concentration (in a infinite geometry) of pure metallic <sup>239</sup> Pu, 93.5 wt. % <sup>235</sup> U enriched metallic uranium or 5 wt. % <sup>235</sup> U enriched uranium oxide
Dilution laws	Metallic, oxide (maximal density and 3.5 g.cm <sup>-3</sup> powder density), fluoride (uranium only), salts, nitrate	Curves displayed logarithmically (H/X from 0 to 1000)
References		About 250 technical reports (standard calculations) used to elaborate handbooks

E <sub>S</sub> ( <sup>235</sup> U/U <sub>tot</sub> )	M <sub>c</sub> (kg U <sub>tot</sub> )					V <sub>c</sub> (L)				
	Reflector					Reflector				
	2.5 cm water	20 cm water	60 cm conc 8.93%	100 cm conc 3%	25 cm / 20 cm lead / water	2.5 cm water	20 cm water	60 cm conc 8.93%	100 cm conc 3%	25 cm / 20 cm lead / water
93,5 %	1.12	0.85	0.752	0.786	0.653	1.94	1.28	1.11	1.21	1.30
50 %	2.27	1.73	1.52	1.59	1.32	5.66	3.47	2.91	3.18	3.55
30 %	4.09	3.13	2.75	2.86	2.38	12.5	8.16	6.67	7.31	6.70
20 %	6.64	5.09	4.45	4.62	3.85	14.2	9.45	8.18	8.83	7.68
10 %	16.0	12.3	10.7	11.1	9.25	19.2	13.1	11.3	12.1	10.4
7,5 %	23.8	18.5	16.0	16.5	13.8	22.5	15.7	13.5	14.3	12.3
5 %	44.0	34.5	29.7	30.3	25.4	30.2	21.7	18.5	19.4	16.7
4 %	64.0	50.7	43.5	44.2	37.1	37.2	27.2	23.1	24	20.6
3 %	111	89.1	76.2	76.8	64.7	52.0	39.2	33.1	33.9	29.1
2 %	299	247	210	208	176	104	82.6	69.6	69.7	60.0
1,5 %	837	712	608	595	498	237	198	168	165	139

E <sub>S</sub> ( <sup>235</sup> U/U <sub>tot</sub> )	Ø <sub>c</sub> (cm)					T <sub>c</sub> (cm)				
	Reflector					Reflector				
	2.5 cm water	20 cm water	60 cm conc 8.93%	100 cm conc 3%	25 cm / 20 cm lead / water	2.5 cm water	20 cm water	60 cm conc 8.93%	100 cm conc 3%	25 cm / 20 cm lead / water
93,5 %	10.3	8.02	6.90	6.91	7.43	4.33	1.74	0.685	0.492	1.15
50 %	15.1	11.6	9.88	9.88	10.8	7.20	3.14	1.28	0.936	2.11
30 %	20.0	15.9	13.4	13.4	13.4	10.2	5.15	2.17	1.65	2.83
20 %	21.0	17.0	15.1	15.0	14.2	10.8	6.61	3.40	2.65	3.15
10 %	23.4	19.4	17.2	17.1	16.0	12.3	8.12	4.84	3.83	3.94
7,5 %	24.8	20.7	18.4	18.3	17.1	13.2	9.01	5.57	4.47	4.44
5 %	27.5	23.4	20.9	20.6	19.2	15.0	10.7	7.01	5.75	5.43
4 %	29.6	25.5	22.7	22.4	20.9	16.4	12.1	8.13	6.73	6.22
3 %	33.4	29.2	26.1	25.7	23.8	18.8	14.4	10.2	8.55	7.69
2 %	42.6	38.2	34.5	33.7	31.4	24.7	20.3	15.4	13.3	11.7
1,5 %	56.7	52.2	47.7	46.5	42.8	33.8	29.4	23.8	21.2	18.6

E <sub>S</sub> ( <sup>235</sup> U/U <sub>tot</sub> )	m <sub>c.c.</sub> (g U <sub>tot</sub> / cm <sup>3</sup> )					C <sub>i.c.</sub> (g U <sub>total</sub> / L)	(H/U) <sub>c.max.</sub>	(H/U) <sub>c.min.</sub>	CEA reference (CSEG)
	Reflector								
	2.5 cm water	20 cm water	60 cm conc 8.93%	100 cm conc 3%	25 cm / 20 cm lead / water				
93,5 %	0.536	0.460	0.363	0.320	0.260	13.0	2005	-	[U-01] ; [U-73]
50 %	1.03	0.886	0.702	0.62	0.503	24.6	1063	-	[U-02] ; [U-73]
30 %	1.78	1.53	1.22	1.07	0.874	41.7	628	-	[U-03]
20 %	2.76	2.38	1.89	1.67	1.36	63.7	411	-	[U-04] ; [U-73]
10 %	6.00	5.20	4.16	3.68	3.01	134	195	-	[U-05] ; [U-73]
7,5 %	8.41	7.31	5.86	5.2	4.26	183	142	-	[U-06] ; [U-73]
5 %	13.8	12.1	9.76	8.67	7.13	289	89.8	0.22	[U-07] ; [U-73] ; [U-82]
4 %	18.5	16.2	13.2	11.7	9.68	375	68.9	0.43	[U-08] ; [U-73] ; [U-82]
3 %	27.8	24.5	20.0	17.9	14.9	532	48.2	0.66	[U-09] ; [U-73] ; [U-82]
2 %	53.6	48.1	40.1	36.3	30.6	910	27.6	0.98	[U-10] ; [U-73] ; [U-82]
1,5 %	97.8	89.2	76.5	70.1	60.7	1414	17.3	1.33	[U-11] ; [U-73] ; [U-82]

Figure 1. Sample of a table of critical values handbook – Homogeneous uranium media

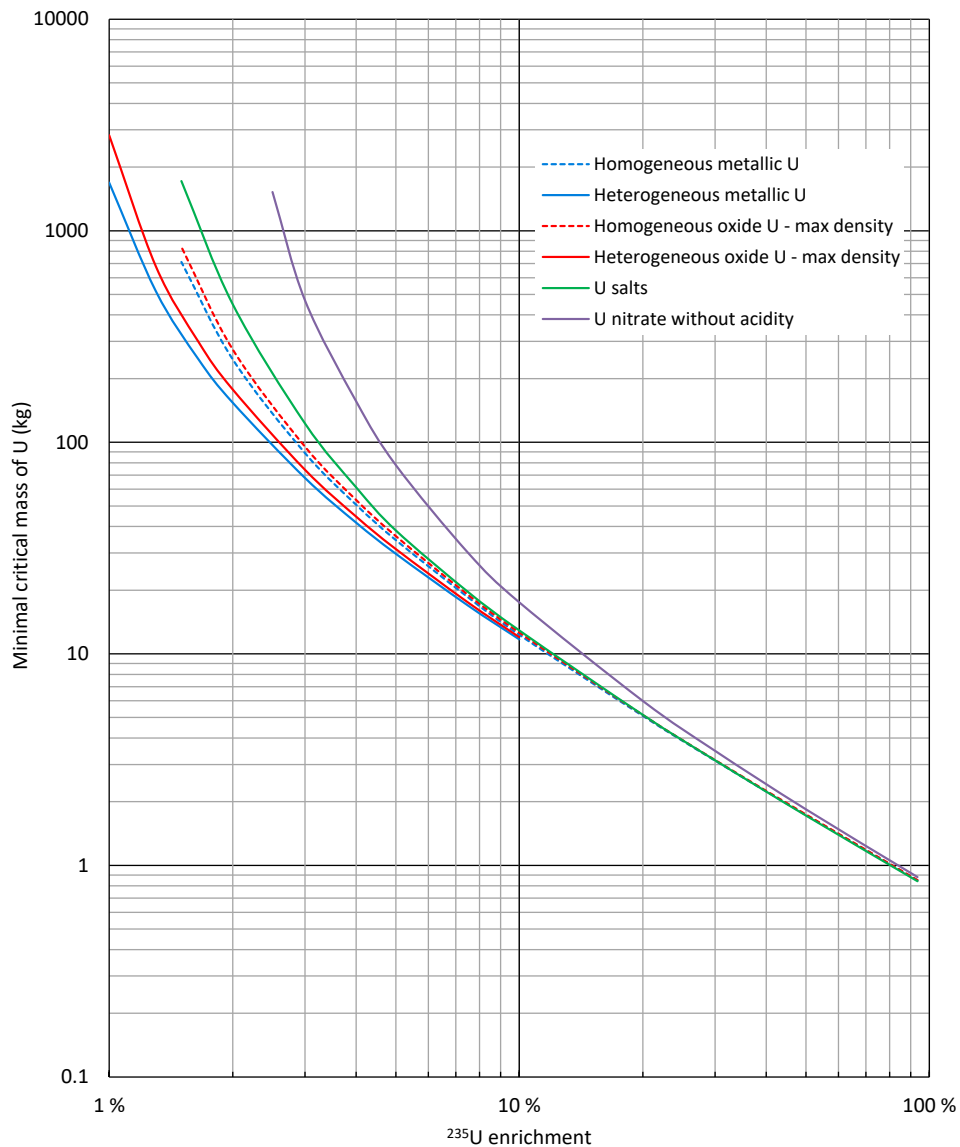


Figure 2. Sample of curves from the “critical handbook” – Mass limits for uranium media

These handbooks are available to everyone upon request from the authors by e-mail (in French until now with an English translation in progress).

### 3. UNEXPECTED RESULTS – CRITICALITY IS ALWAYS A CHALLENGE

#### 3.1. Lead as a reflector is always more conservative than full water reflection

Commonly, considering lead as reflector conducts to more restrictive critical and permissible limits than full water reflection. However, the moderating properties of water, even used as a reflector, returns to the fissile material moderated neutrons. Therefore, if fissile material is unmoderated, critical and permissible limits obtained with full water reflection can be lower than those obtained with lead as reflector, as shown in Fig. 3.

$r_0$ ( <sup>240</sup> Pu/ $Pu_{tot}$ )	$M_c$ dry (kg $Pu_{tot}$ )					CEA reference (CSEG)
	Reflector					
	2.5 cm water	20 cm water	60 cm conc 8.93%	100 cm conc 3%	25 cm / 20 cm lead / water	
0 %	7.38	5.44	5.03	5.44	5.58	[P-01]
5 %	7.73	5.76	5.29	5.70	5.82	[P-02]
10 %	8.09	6.04	5.54	5.96	6.09	[P-03]
15 %	8.49	6.34	5.80	6.24	6.37	[P-04]
17 %	8.65	6.46	5.90	6.35	6.50	[P-05]
20 %	8.92	6.66	6.08	6.54	6.68	[P-06]
25 %	9.38	7.01	6.38	6.87	7.02	[P-07]

Figure 3. Table extracted from critical handbook – Unmoderated metallic Pu

### 3.2. Derivability break for geometry controlled fissile material containing uranium

Figure 2 shows a perfectly smooth shape for mass limits versus enrichment in <sup>235</sup>U for various chemical forms. Conversely, especially for geometrically controlled parameters, curves have displayed some kind of break, as shown in Fig. 4 below. This “singularity” has an explanation: optimal geometry is obtained when  $B_m^2$  is maximal. As maximal  $B_m^2$  at H/U=0 grows faster than the one observed at higher moderation ratio, the minimal value is the minima value between fully moderated optimum ratio and dry optimum ratio. Technical notes have been produced to determine, precisely, where this optimum-change occurs. These crushes can be observed for metallic U and oxide U whose dry compounds have a high density value (see blue and red dotted lines).

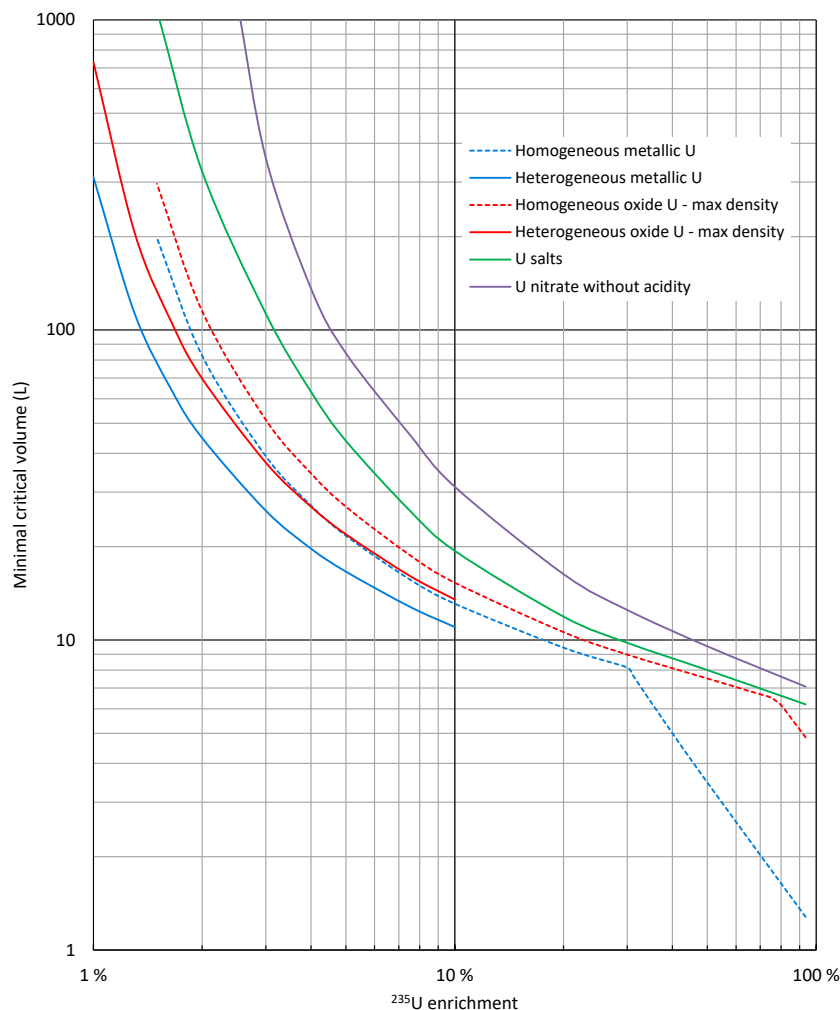


Figure 4. Sample of curves from the “critical handbook” – Volume limits for uranium media

This singularity also occurs for MOX media with the Pu content varying inside the fissile material (curve break beyond a Pu content value).

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