Lawrence Livermore National Laboratory

Critical and Subcritical Data for the Revision of ANS 8.12 Standard

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ACKNOWLEDGMENT

This work is based on contribution of the following ANS 8.12 Working Group members :

- Dennis Mennerdahl, Consultant, E Mennerdahl Systems, Sweden
- Christopher Tripp, NRC
- Kermit Bunde, DOE, Idaho
- Scott Revolinski, Senior Consultant at Nuclear Safety Associates
- Jason Huffer, and Michael Shea, US MOX Plant
- Dominic Winstanley, Sellafield Ltd, England

Background

- ANS 8.12 -1987, R1993, R2002, R2011, *Nuclear Criticality Control and Safety of Plutonium-Uranium Fuel Mixtures Outside Reactors*

- Revision (in Progress) to expand the Areas of Applicability by providing a wider range of Subcritical Data

- In 2009, WG decided to base the specifications on the ISO standard on MOX powder, and to develop a new set of subcritical limits for homogeneous systems

- ISO MOX Standard 11311 was finally published in 2011

ISO Specifications

The selection and specifications are based on actual fuel fabrication plant experience and studies in France, United Kingdom, Japan and U.S.A

- **ISO Provides Several Sets of Materials**
- **Two Pu/(U+Pu) Ratios:**
  - Pu/(U+Pu) = 35% @ $\rho \leq 3.50$ g $(UO_2+PuO_2)/cm^3$
  - Pu/(U+Pu) = 12.5% @ $\rho \leq 11.03$ g $(UO_2+PuO_2)/cm^3$
- Natural Uranium is specified as:
  - $^{235}U/U_{Total}$ = 0.718 wt.% and $^{238}U/U_{Total}$ = 99.282 wt.%

ISO Specifications (contd./2)

- **Three Pu Isotopic Distributions:**
- P0 => 100 wt. % $^{239}Pu/Pu_{Total}$;
- P5 => 5.00 wt. % $^{240}Pu/Pu_{Total}$; 95.00 wt. % $^{239}Pu/Pu_{Total}$
- P20 was provided w/ imbedded mass Fractions and reduced to:
- P20=> 56/85 $^{239}Pu/Pu_{Total;}$
  17/85 $^{240}Pu/Pu_{Total;}$ (20 wt. %)
  11/85 $^{241}Pu/Pu_{Total;}$
  1/85 $^{242}Pu/Pu_{Total}$

ISO Specifications (contd./3)

- **Two moderation conditions were examined:**
  - 3.0 wt.% water (*This condition is selected because MOX fuel is usually fabricated from mixtures of nearly dry powder and hydrogenated additives*.)
  - Optimally Moderated
- **Three basic geometric shapes were examined :**
  - Sphere - Critical Radius Search
  - Cylinder - Critical Diameter Search
  - Slab - Critical Height Search
- **Two reflection conditions were examined:**
  - 30 cm of water
  - 2.5 cm of water

Differences between ISO and ANS 8.12 Approach

ISO Approach:

- The ISO standard provides a set of calculated critical data that were determined by inter-code comparisons
- Each selected data is the lowest calculated value obtained for that application by the ISO working group members

Differences between ISO and ANS 8.12 Approach

ANS 8.12 Approach, Phase 1:

- Determine the critical data with different methods (codes and cross section sets) to ensure consistency with the ISO data
- ANS standard will only provide subcritical data
- Calculate different parameters corresponding to k_{eff} values at 0.95, 0.98, and 1.0
- These critical and subcritical values are reported in this paper.

Differences between ISO and ANS 8.12 Approach

ANS 8.12 Approach, Phase 2:

- Validation
- Obtain subcritical parameters after correcting for bias and bias uncertainties, and MSM
- Once the upper subcritical limit (USL) is determined, the final subcritical parameters will be determined by interpolation among k_{eff} values of 0.95, 0.98, and 1.0

Six Sets - Calculation

Set 1	J. Huffer/ M. Shea	SCALE 5.0/KENO VI, 238-g ENDF/B-V
Set 2	C. Tripp	MCNP5, ENDF/B-VI
Set 3	D. Mennerdahl	MCNP5, ENDF/B-VII.0
Set 4	S. Revolinski	SCALE 5.1. Keno V.a, 238-g, ENDF/B-VI
Set 5	K. Bunde	MCNP5, ENDF/B-VI
Set 6	D. Winstanley	MONK 9A with JEF 2.2

Annex C, keff = 1, [30 cm water reflection]

		Humidity Rate ≤ 3%			Optimum Moderation		
		Sphere	Cylinder	Slab	Sphere	Cylinder	Slab
		R(cm)	D (cm)	Th.(cm)	R(cm)	D (cm)	Th.(cm)
Pu/(U+Pu) = 35.0% Density ≤ 3.5 g/cm^3	P0	27.4 (27.4 – 27.8)	35.1 (35.1-35.6)	13.4 (13.4-13.9)	12.9 (12.9 – 13.1)	16.7 16.7 – 17.0)	6.1 (6.1-6.4)
	P5	29.6 (29.8 – 30.3)	38.7 (38.7 – 39.5)	15.8 (15.9 – 16.4)	14.3 (14.3 – 14.6)	18.9 (18.9 – 19.3)	7.8 (7.7-8.0)
	P20	31.4 (31.4 – 31.9)	41.3 (41.3 – 42.1)	17.6 (17.6 - 18.2)	16.9 (16.9 – 17.2)	22.8 (22.8-23.1)	10.2 (10.1 – 10.4)
Pu/(U+Pu) = 12.5% Density ≤ 11.03 g/cm^3	P0	21.5 (21.5 – 22.0)	28.9 28.8-29.5)	12.5 12.5-13.0)	14.3 (14.4 – 14.6)	18.8 (18.9-19.2)	7.7 (7.8-8.0)
	P5	24.9 25.0-25.6)	34.2 (34.3-35.1)	16.0 (16.0-16.6)	15.7 (15.8-16.1)	21.1 (21.1 – 21.5)	9.2 (9.2-9.5)
	P20	27.3 27.8-28.2)	38.0 (38.5-39.2)	18.9 (18.9-19.5)	18.8 (18.8-19.1)	25.6 (25.6-26.0)	12.0 (12.0-12.3)

Annex D, keff = 1, [2.5 cm water reflection]

		Humidity Rate ≤ 3%			Optimum Moderation		
		Sphere	Cylinder	Slab	Sphere	Cylinder	Slab
		R(cm)	D (cm)	Th.(cm)	R(cm)	D (cm)	Th.(cm)
Pu/(U+Pu) = 35.0% Density ≤ 3.5 g/cm^3	P0	35.4 (35.5 – 35.9)	49.5 (49.6- 50.2)	25.8 (25.9- 26.3)	14.8 (14.9 – 15.2)	20.6 20.7 – 20.9)	10.4 (10.5- 10.6)
	P5	37.4 (37.5 – 37.8)	52.7 (52.7 – 53.3)	27.9 (28.0 – 28.3)	16.3 (16.3 – 16.5)	22.9 (22.9 – 23.2)	11.9 (11.9- 12.1)
	P20	38.8 (38.8 – 39.2)	54.8 (54.8 – 55.4)	29.3 (29.4 - 29.7)	18.9 (19.0 – 19.2)	26.9 (26.9- 27.2)	14.5 (14.4 – 14.7)
Pu/(U+Pu) = 12.5% Density ≤ 11.03 g/cm^3	P0	25.2 (25.2 – 25.5)	36.3 36.3- 36.8)	20.3 20.3- 20.8)	16.2 (16.3 – 16.5)	22.8 (23.0- 23.2)	11.9 (11.0- 12.1)
	P5	28.8 28.7- 29.3)	41.9 (41.8- 42.6)	24.0 (23.9- 24.4)	17.7 (17.8- 18.0)	25.1 (25.1 – 25.4)	13.3 (13.4- 13.6)
	P20	31.2 31.1- 31.8)	45.6 (45.7- 46.5)	26.5 26.5- 27.0)	20.9 (20.9- 21.1)	29.8 (29.8- 30.2)	16.3 (16.3- 16.6)

Subcritical Data, Annex C,

Table 1, Annex C, Pu Content 35%, Density ≤ 3.50%, Reflection 30 cm of water

			Humidity Rate ≤ 3%			Optimum Moderation		
			k_{eff}=1.0	k_{eff}=0.98	k_{eff}=0.95	k_{eff}=1.0	k_{eff}=0.98	k_{eff}=0.95
Sphere Radius	**P0**	**set 1**	**27.8**	**26.7**	**25.2**	**12.9**	**12.5**	**11.9**
		set 2	**27.8**	**26.7**	**25.3**	**13.0**	**12.6**	**12.1**
		set 3	**27.4**	**26.4**	**25.0**	**13.0**	**12.6**	**12.0**
		set 4	**27.7**	**26.6**	**25.2**	**13.0**	**12.6**	**12.0**
		set 5	**27.8**	**26.8**	**25.3**	**13.1**	**12.7**	**12.1**
		set 6	**27.8**	**26.9**	**25.4**	**13.1**	**12.7**	**12.1**
	P5	set 1	30.0	28.9	27.3	14.3	13.9	13.2
		set 2	30.2	29.1	27.5	14.6	14.0	13.4
		set 3	29.8	28.7	27.0	14.5	14.0	13.3
		set 4	30.0	28.9	27.3	14.5	14.0	13.3
		set 5	30.2	29.0	27.4	14.6	14.1	13.4
		set 6	30.3	29.2	27.5	14.6	14.2	13.4
	P20	**set 1**	**31.5**	**30.5**	**28.9**	**16.9**	**16.2**	**15.3**
		set 2	**31.9**	**30.7**	**29.0**	**17.1**	**16.4**	**15.6**
		set 3	**31.4**	**30.3**	**28.6**	**17.1**	**16.5**	**15.5**
		set 4	**31.6**	**30.5**	**28.8**	**17.1**	**16.4**	**15.5**
		set 5	**31.8**	**30.6**	**28.9**	**17.2**	**16.5**	**15.6**
		set 6	**31.9**	**30.8**	**29.0**	**17.2**	**16.5**	**15.6**

Subcritical Data, Annex C,

Table 2, Annex C, Pu Content 12.5%, Density ≤ 11.03%, Reflection 30 cm of water

			Humidity Rate ≤ 3%			Optimum Moderation		
			keff=1.0	keff=0.98	keff=0.95	keff=1.0	keff=0.98	keff=0.95
Sphere	**P0**	**set 1**	**22.0**	**21.1**	**19.7**	**14.4**	**13.9**	**13.2**
Radius		**set 2**	**22.0**	**21.0**	**19.7**	**14.5**	**14.0**	**13.4**
		set 3	**21.5**	**20.6**	**19.3**	**14.4**	**14.0**	**13.3**
		set 4	**21.8**	**20.7**	**19.5**	**14.4**	**13.9**	**13.3**
		set 5	**21.9**	**21.0**	**19.6**	**14.5**	**14.1**	**13.4**
		set 6	**22.0**	**21.1**	**19.7**	**14.6**	**14.1**	**13.4**
	P5	set 1	25.4	24.2	22.4	15.8	15.2	14.4
		set 2	25.4	24.2	22.5	16.0	15.4	14.6
		set 3	25.0	23.8	22.1	15.9	15.4	14.6
		set 4	25.2	24.0	22.2	15.9	15.4	14.6
		set 5	25.4	24.2	22.5	16.0	15.5	14.7
		set 6	25.6	24.3	22.6	16.1	15.5	14.7
	P20	**set 1**	**28.0**	**26.6**	**24.5**	**18.8**	**17.9**	**16.8**
		set 2	**28.1**	**26.6**	**24.6**	**19.0**	**18.2**	**17.2**
		set 3	**27.8**	**26.3**	**24.2**	**19.0**	**18.2**	**17.1**
		set 4	**27.8**	**26.3**	**24.3**	**19.0**	**18.2**	**17.1**
		set 5	**28.1**	**26.6**	**24.6**	**19.1**	**18.3**	**17.2**
		set 6	**28.2**	**26.7**	**24.6**	**19.1**	**18.3**	**17.2**

Subcritical Data, Annex D,

Table 3, Annex D, Pu Content 35%, Density ≤ 3.50%, Reflection 2.5 cm of water

			Humidity Rate ≤ 3%			Optimum Moderation		
			keff=1.0	keff=0.98	keff=0.95	keff=1.0	keff=0.98	keff=0.95
Sphere	**P0**	**set 1**	**35.9**	**34.9**	**33.5**	**14.9**	**14.4**	**13.8**
Radius		**set 2**	**35.7**	**34.8**	**33.4**	**14.9**	**14.5**	**13.9**
		set 3	**35.5**	**34.5**	**33.1**	**14.9**	**14.5**	**13.9**
		set 4	**35.5**	**34.5**	**33.1**	**14.9**	**14.4**	**13.8**
		set 5	**35.7**	**34.8**	**33.4**	**15.2**	**14.8**	**14.2**
		set 6	**35.7**	**34.8**	**33.3**	**15.0**	**14.6**	**14.0**
	P5	**set 1**	**37.8**	**36.7**	**35.2**	**16.3**	**15.8**	**15.1**
		set 2	37.8	36.7	35.2	16.4	15.9	15.2
		set 3	37.5	36.4	34.9	16.4	15.9	15.3
		set 4	37.5	36.4	34.9	16.3	15.9	15.2
		set 5	37.8	36.7	35.2	16.5	16.0	15.3
		set 6	37.8	36.8	35.2	16.5	16.0	15.3
	P20	**set 1**	**39.2**	**38.1**	**36.4**	**19.0**	**18.2**	**17.3**
		set 2	**39.2**	**38.0**	**36.4**	**19.0**	**18.4**	**17.5**
		set 3	**38.8**	**37.7**	**36.1**	**19.2**	**18.5**	**17.6**
		set 4	**38.8**	**37.7**	**36.1**	**19.0**	**18.4**	**17.4**
		set 5	**39.1**	**38.0**	**36.4**	**19.1**	**18.5**	**17.5**
		set 6	**39.2**	**38.1**	**36.4**	**19.2**	**18.5**	**17.6**

Subcritical Data, Annex D,

Table 4, Annex D, Pu Content 12.5%, Density ≤ 11.03%, Reflection 2.5 cm of water

			Humidity Rate ≤ 3%			Optimum Moderation		
			keff=1.0	keff=0.98	keff=0.95	keff=1.0	keff=0.98	keff=0.95
Sphere	P0	**set 1**	**25.2**	**24.8**	**23.4**	**16.2**	**15.8**	**15.1**
Radius		**set 2**	**25.5**	**24.6**	**23.3**	**16.4**	**15.9**	**15.2**
		set 3	**25.2**	**24.3**	**23.0**	**16.4**	**15.9**	**15.3**
		set 4	**25.2**	**24.3**	**23.0**	**16.3**	**15.8**	**15.2**
		set 5	**25.5**	**24.6**	**23.3**	**16.4**	**16.0**	**15.3**
		set 6	**25.5**	**24.7**	**23.3**	**16.5**	**16.0**	**15.4**
	P5	set 1	28.8	28.0	26.2	17.7	17.2	16.4
		set 2	29.1	27.9	26.1	17.9	17.4	16.6
		set 3	28.9	27.6	25.9	17.9	17.4	16.6
		set 4	28.7	27.5	25.9	17.8	17.3	16.5
		set 5	29.1	27.9	26.2	18.0	17.4	16.6
		set 6	29.3	28.1	26.3	18.0	17.5	16.7
	P20	**set 1**	**31.2**	**30.2**	**28.2**	**20.9**	**20.0**	**18.9**
		set 2	**31.7**	**30.2**	**28.1**	**21.0**	**20.3**	**19.1**
		set 3	**31.4**	**29.9**	**28.0**	**21.1**	**20.3**	**19.3**
		set 4	**31.1**	**29.8**	**27.8**	**20.9**	**20.1**	**19.0**
		set 5	**31.6**	**30.1**	**28.1**	**21.1**	**20.3**	**19.2**
		set 6	**31.8**	**30.4**	**28.2**	**21.1**	**20.3**	**19.2**

Table 1 , Annex C, Sphere, 30 cm Refl

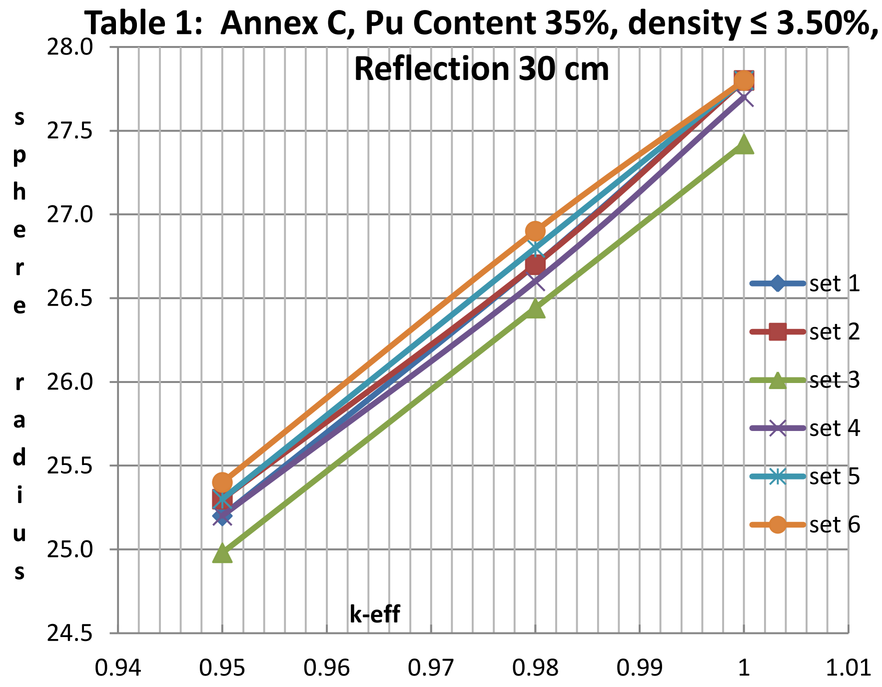


Table 2, Annex C, Sphere, 30 cm Refl, Opt. Mod

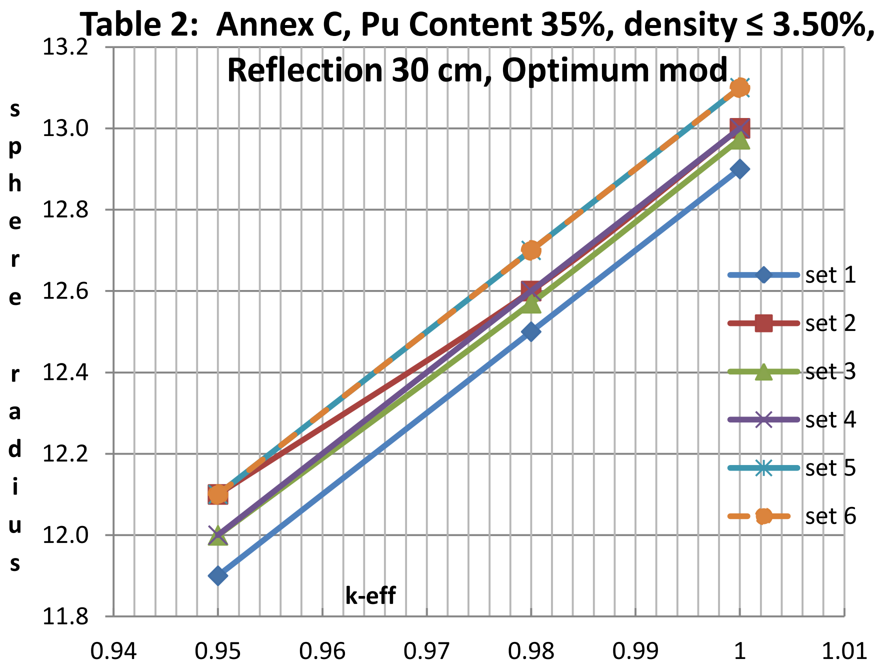


Table 3, Annex D, Sphere, 2.5 cm Refl.

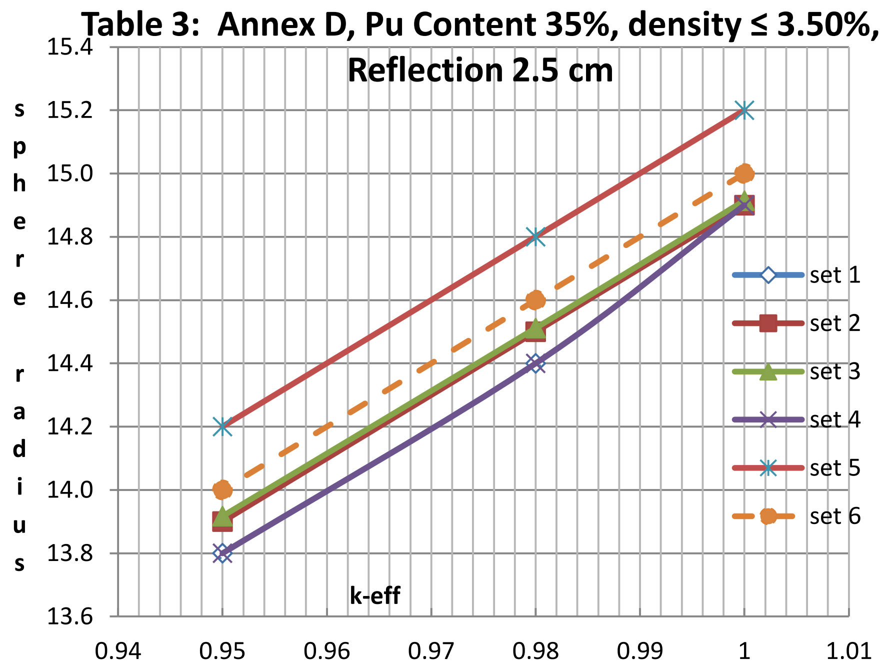
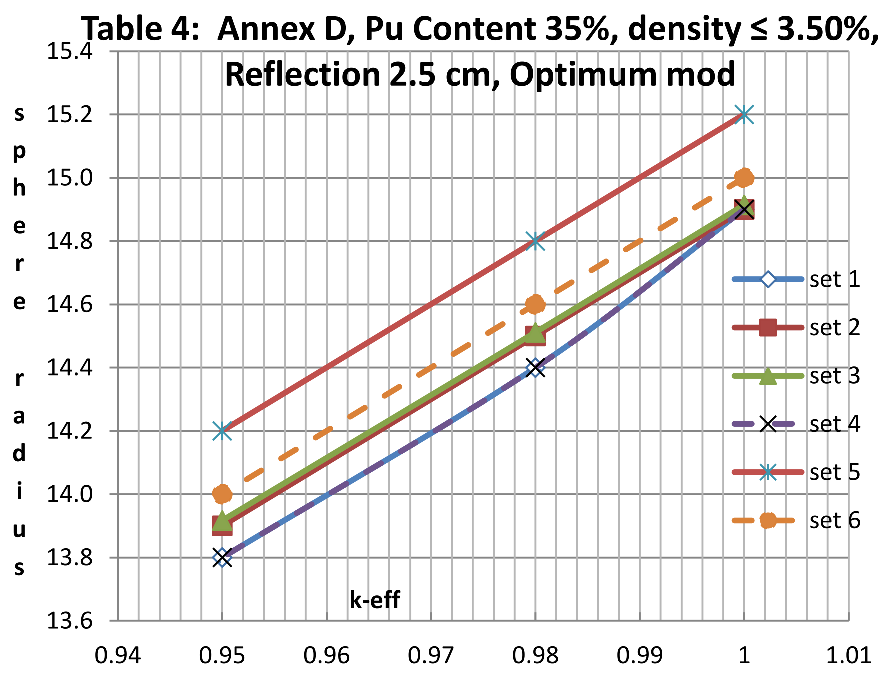


Table 4, Annex D, Sphere, 2.5 cm Refl, Opt. Mod



Six Sets - Results

***Results*:**

- Sets 2, 3 and 6 used multiple codes and cross section sets, but only one set of data was chosen for each set
- The critical dimensions are similar to ISO data in Annexes C and D
- Critical values calculated are on the high sides, which is consistent with the fact that ISO data are based on the lowest calculated value
- The optimum subcritical dimensions vary little among six sets, because the curve corresponding to 'k_{eff} *versus moderation*' flattens out near the optimal point
- The variations in damp oxide parameters among the six sets are reasonable and no particular outliers are noticed

Conclusion

- Significant efforts have been made to generate subcritical dimensions for the revision of ANS 8.12 for wider applicability
- Subcritical parameters (e.g., mass, linear density etc.) have also been generated (Annexes E & F) and will be published
- These data set will be utilized in the validation process to generate the final bias corrected subcritical dimensions and parameters for the ANS 8.12 standard