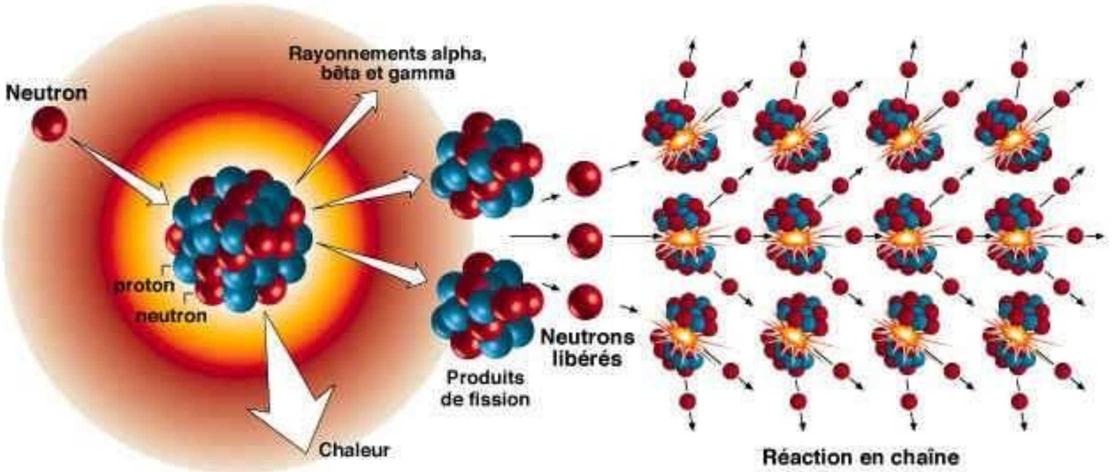
Analysis of past criticality accident - use of ISO 16117



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Boulogne-Billancourt

Plan

- TC85/SC5/WG8 ISO standards
- ISO 16117
- Past criticality accidents
- Simplified formulae to estimate the total number of fissions – Comparison with past criticality accidents
- Conclusions

International Organization for Standardization

- TC 85 : Nuclear energy, nuclear technologies, and radiological protection
  - SC 5: Nuclear installations, processes and technologies
    - WG 8: Nuclear criticality safety (convenor : Dr Doug BOWEN (ORNL, USA))
    - Meeting every year (Helsinki, Finland, May 15-18, 2018)
- 8 ISO standards published (4 related to criticality accidents)
- 3 ISO projects

Reference	Title
ISO 1709:2018	Principles of criticality safety in storing, handling and processing
ISO 7753:1987	Performance and testing requirements for criticality detection and alarm system
ISO 11311:2011	Critical values for homogeneous Plutonium-Uranium oxide fuel mixtures outside of reactors
ISO 11320:2011	Emergency preparedness and response
ISO 14943:2004	Administrative criteria related to nuclear criticality safety
ISO 16117:2013	Estimation of the number of fissions of a postulated criticality accident
ISO 27467:2009	Analysis of a postulated criticality accident
ISO 27468:2011	Evaluation of systems containing PWR UOX fuels — Bounding burnup credit approach
ISO 21391	*Geometrical Nuclear Criticality Safety dimensions*
ISO 22946	*Solid Waste (excluding Irradiated and non-Irradiated Nuclear Fuel)*
ISO 23133	*Nuclear Criticality Safety Training for Operations*

ISO 16117:2013 - Estimation of the number of fissions of a postulated criticality accident

- Goal: to provide a methodology to estimate a reasonably maximal value of the number of fissions of a postulated criticality accident.

- Contents
  - General principles
  - Input data
  - Use of simplified models (accidents, experiments, formulae)
  - Use of calculation tools
  - Annexes
    - Lessons Learned from Accidents
    - Experimental Results
    - Simplified formulae
  - Bibliography (146 references)

ISO 16117:2013 - Key messages

- The estimation of the number of fissions is linked to the consequences of a criticality accident
  - The highest number of fissions may not necessarily lead to the maximum doses for workers and the public because of its location

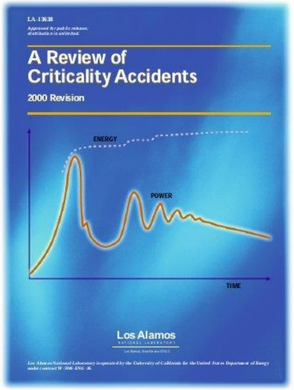
- The use of the simplified models route should be firstly considered

- Final estimation of the number of fissions need to take into account sensitivity studies

- Comparison between the calculation tool results and experiments/accidents close to the chosen assumptions of the postulated criticality accident should be documented

  → *this OECD effort can be used to help answer this recommendation*

Past criticality accidents



- *A review of criticality accidents, 2000 Revision*. LA-13638

- Annex B of the ISO 16117:2013

- Two categories:
  - criticality accidents in nuclear fuel processing plants (22)
  - criticality accidents in reactor and critical experiments (38)

- Warning – criticality accidents are not benchmark !
  - No precise information for all input data and results

Simplified formulae to estimate the total number of fissions – Comparison with past criticality accidents

- Nakajima's article at ICNC 2003 (Japan)
  - "*Applicability of Simplified Methods to Evaluate Consequences of Criticality Accident Using Past Accident Data*"

- Various formulae to estimate number of fissions (Nf)
  - Nf = *f*(duration, volume): **empirical relations**
    - Barbry (1982): CRAC and SILENE experiments
    - Olsen (1974): CRAC experiments
  - Nf = *f*(volume): **relations based on heat energy**
    - Nomura (1995)
    - Tuck (1974)
    - Knemp-Duluc (2008) → NCSD 2009 article ("*New improvement in simplified methods of estimating the number of fissions during a criticality accident in solution*")

Formulae based on heat energy

- Number of fissions=

  Energy to bring the solution to the boiling state $\boxed{(N_f)_1 = \varepsilon \cdot m_{sol} \cdot C_p \cdot [T_{boil.} - T_0]}$

  + Energy to evaporate a given mass $\boxed{(N_f)_2 = \varepsilon \cdot \Delta H_{vap} \cdot \Delta m_{water}}$

- For practical purposes, m_{sol} and Δm_{water} replaced by solution volume
  - $m_{sol} = d_{sol}.V$
  - $\Delta m_{water} = d_{water}.(V - V_{final})$ (or $d_{sol}.(V - V_{final})$)

- Advantage of this method:
  - estimate Nf for every kind of geometry and solution

- Limitations:
  - no recondensation of the solution during boiling
  - no forced cooling

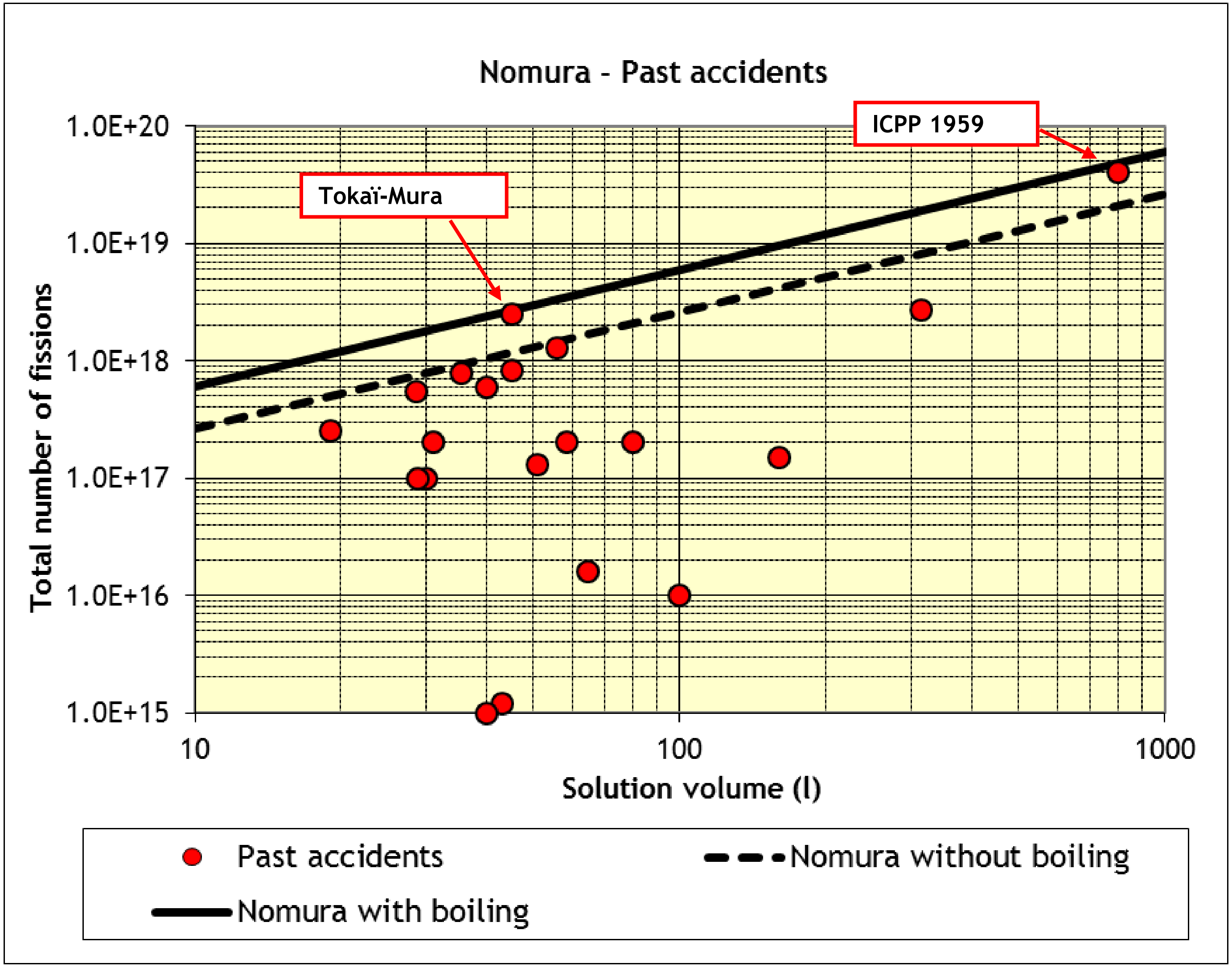
Formulae based on heat energy

- No boiling → $Nf = Nf_1$
- Boiling → $Nf = Nf_1 + Nf_2$

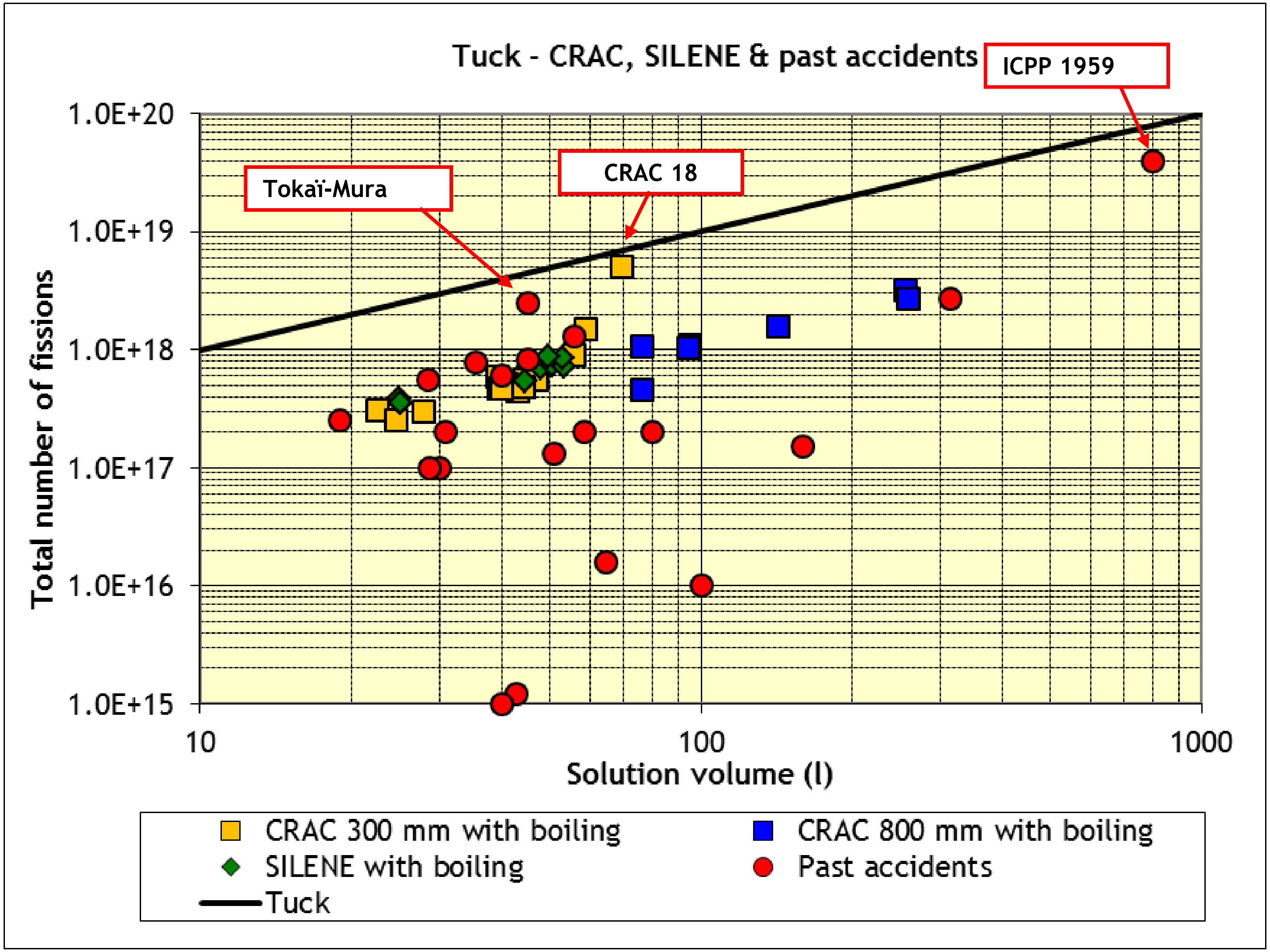
Formulae	Nomura	Tuck	Knemp-Duluc
$(Nf)_1$	$2.6x10^{16}.V$	-	$1.3x10^{16}.m_{sol}$
$(Nf)_2$	$3.4x10^{16}.V$	$10^{17}.V$	$8x10^{16}.[m_{sol}-m_{sol\_c}(\phi)]$

Less easy to use it because minimum critical mass <u>of solution</u> is not fluently used

Nomura formula



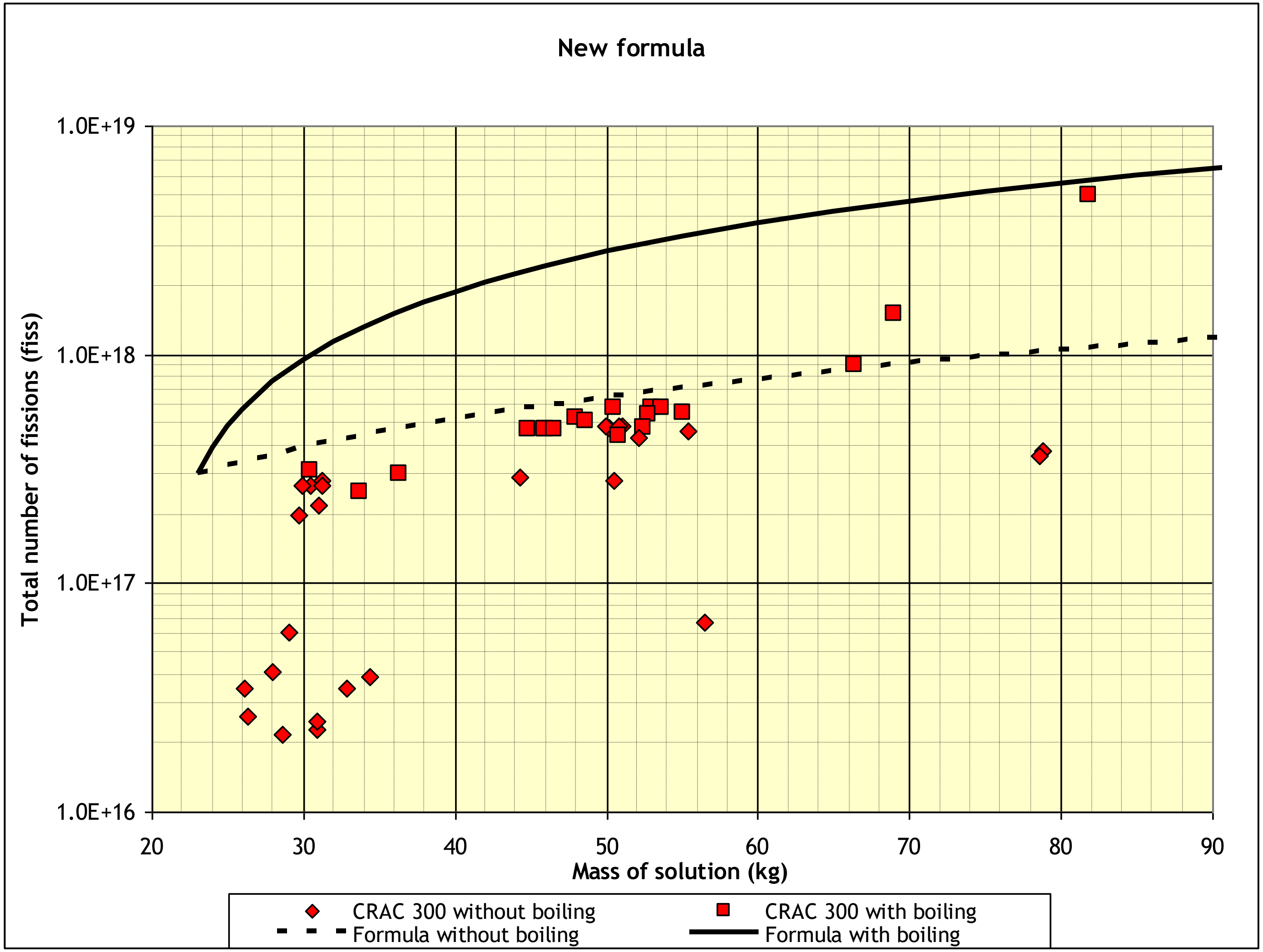
Tuck formula



Knemp-Duluc formula

$$\boxed{\check{m}_c(\phi) = 23\ kg}$$

for CRAC 300 mm



Conclusions

Simplified formulae

- can be useful to estimate number of fissions but don't take into account time dependence and complex phenomena → need tools
- same kind of comparison for first spike (but « first spike » needs to be defined)

ISO 16117

- gives a methodology and advices to estimate number of fissions

OECD SG-4 working group

- this effort will help answer the ISO 16117 recommendation regarding the "validation" of tools and methods

INSTITUT
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Faire avancer la sûreté nucléaire

Thank you for your attention !

Formula	Unit	Nomura	Tuck	Knemp-Duluc	
Nf_1	fission	$2.6x10^{16}.V$	-	$1.3x10^{16}.V.d_{sol}$	$1.3x10^{16}.m_{sol}$
Nf_2	fission	$3.4x10^{16}.V$	$10^{17}.V$	$8x10^{16}.[V-V_c(\phi)]$	$8x10^{16}.[m_{sol}-m_{sol\_c}(\phi)]$
Conversion factor (ε)	fission/J	$3.3x10^{10}$	$3.11x10^{10}$	$3.51x10^{10}$	
Maximal solution density (d_{sol})	kg/l	1.85	~1.2	-	
Specific heat (C_p)	J/(kg.°C)	4184	-	4184	
Temperature rise ($T_{ébul}$-T_0)	°C	90 °C	-	90 °C	
Vaporization enthalpy (ΔH_{vap})	J/kg	$2.26x10^6$	$2.26x10^6$	$2.26x10^6$	
Heat loss	-	10 % of Nf_1	20 % of Nf_2	Null	
Fraction of vaporization	-	25 % of V	100 % of V	$[V-V_c(\phi)]$	$[m_{sol}-m_{sol\_c}(\phi)]$

Knemp-Duluc formula

No.	Site	Duration	Total fissions (fissions)
4	Y-12	20min	1.3×10^{18}
6	ICPP	20min	4.0×10^{19}
10	Hanford	37h30min	8.0×10^{17}

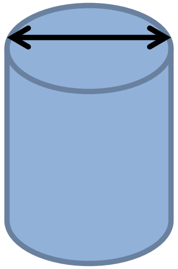
Boiling mentioned

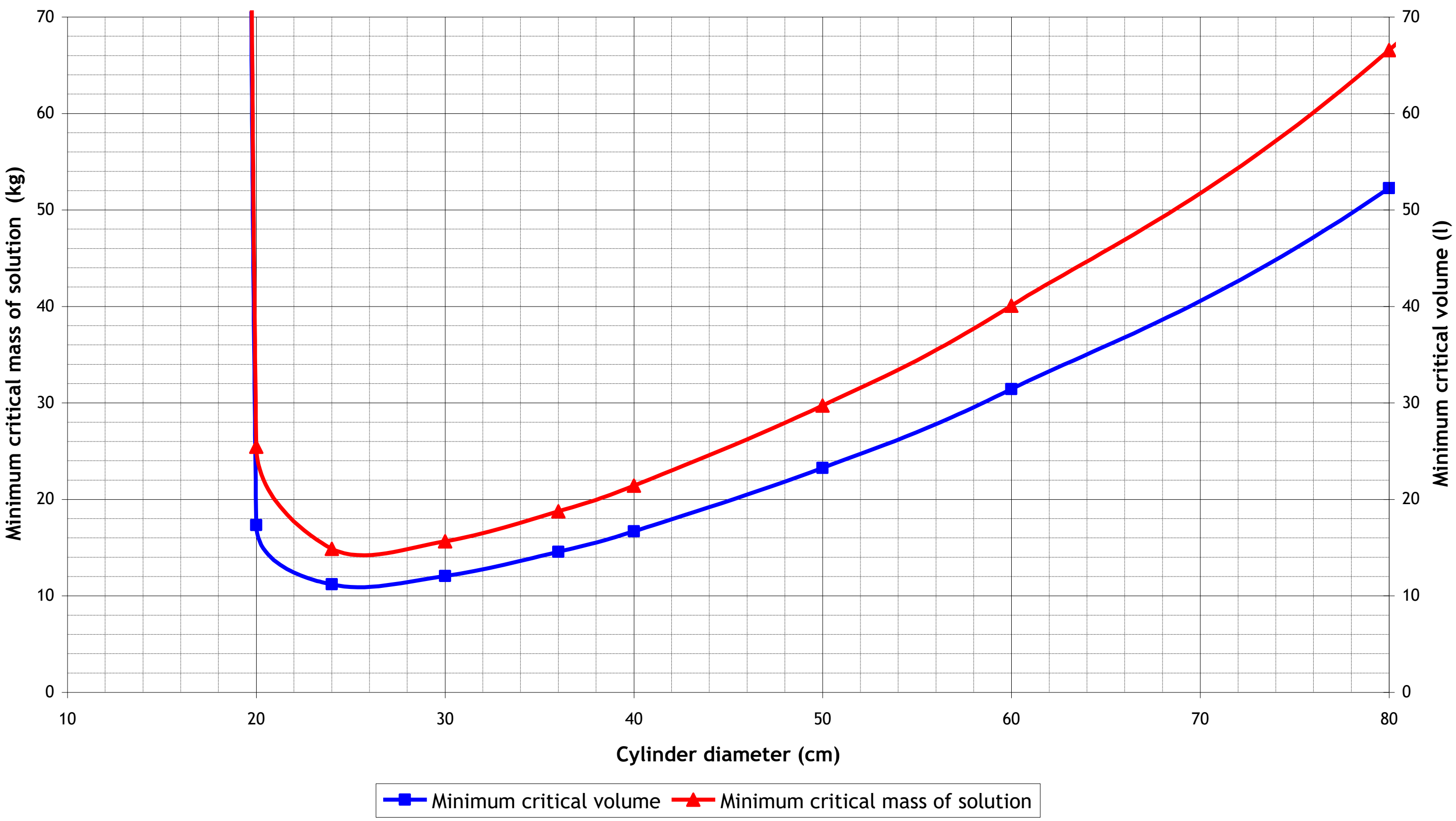
$$\boxed{N_f = 1{,}3.10^{16}\cdot m_{sol} + 8.10^{16}\cdot\left[m_{sol} - \check{m}_c(\phi)\right]}$$

Need to be determined

Knemp-Duluc formula

Cylinder diameter





Knemp-Duluc formula

No.	Site	Duration	Total fissions (fissions)	Estimated total fissions (fissions) without boiling (Nf_1)
4	Y-12	20min	1.3×10^{18}	7.7×10^{17}
6	ICPP	20min	4.0×10^{19}	1.1×10^{19}
10	Hanford	37h30min	8.0×10^{17}	6.1×10^{17}

Boiling mentioned

$$\boxed{N_f = 1{,}3.10^{16} \cdot m_{sol} + 8.10^{16} \cdot \left[m_{sol} - \check{m}_c(\phi) \right]}$$

Knemp-Duluc formula

No.	Site	Duration	Total fissions (fissions)	Estimated total fissions (fissions) without boiling (Nf_1)
12	Tomsk	10h20min	7.9×10^{17}	5.1×10^{17}
16	Mayak	7h	5.5×10^{17}	4.1×10^{17}
22	Tokai-mura	19h40min	2.5×10^{18}	8.8×10^{17}

Boiling not mentioned

Influence of heat loss ?

Knemp-Duluc formula modification

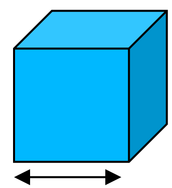
- Non-boiling cases

- Heat loss by convection

$$(Nf_1)_{non-adiabatic} = \underbrace{\varepsilon.m_{sol}.C_p.\left[T_{boiling} - T_{initial}\right]}_{(Nf_1)} + \underbrace{\int_0^t \varepsilon.h(t').S(t').\left(T(t') - T_{ext}(t')\right).dt'}_{\textbf{Heat loss}}$$

- For practical reasons, each parameter is assumed to be independent of the time

$$S = \kappa.V^{2/3} = \kappa.\left(\frac{m_{sol}}{d_{sol}}\right)^{2/3}$$



$$\left.\begin{aligned} S &= 6.a^2 \\ V &= a^3 \end{aligned}\right\} \kappa = 6$$

$$\boxed{(Nf_1)_{non-adiabatic} = (Nf_1).\left(1 + \frac{\kappa.h.t}{\left(4.184x10^5\right).\left(m_{sol}\right)^{1/3}.\left(d_{sol}\right)^{2/3}}\right)}$$

Knemp-Duluc formula

No.	Site	Duration	Total fissions (fissions)	Estimated total fissions (fissions) without boiling (Nf_1)	Estimated total fissions (fissions) without boiling (with heat loss) $(Nf1)_{non\text{-}adiabatic}$
12	Tomsk	10h20min	7.9×10^{17}	5.1×10^{17}	1.3×10^{18}
16	Mayak	7h	5.5×10^{17}	4.1×10^{17}	8.5×10^{17}
22	Tokai-mura	19h40min	2.5×10^{18}	8.8×10^{17}	1.8×10^{19}

Boiling not mentioned

TABLE III. Comparison of the new formula with past criticality accidents data

No.	Site	Fissile media	Fuel Volume (litre)	Total U or Pu conc. (g/l)	Estimated mass of solution (kg)	Vessel diameter (cm)	Minimum critical mass of solution (kg)	Total fissions (fiss)	Estimated total fissions (fiss) without boiling	Estimated total fissions (fiss) with boiling	Duration
1	Mayak	Pu	31	27.5	32.2	40	24	2.0×10^{17}	4.2×10^{17}	-	< 1min
3	Mayak	U(90)	58.4	418	91	75	59	2.0×10^{17}	1.2×10^{18}	-	< 1min
4	Y-12	U(93)	56	40	59	55.2	34	1.3×10^{18}	7.7×10^{17}	2.8×10^{18}	20min
5	LASL	Pu	160	19.4 (*)	164	100	108	1.5×10^{17}	2.1×10^{18}	-	< 1min
6	ICPP	U(91)	800	42.5	846	-	*390*	4.0×10^{19}	1.1×10^{19}	4.7×10^{19}	20min
7	Mayak	Pu	19	47	20.3	34.8	21	2.5×10^{17}	2.6×10^{17}	-	1h50min
8	ICPP	U(90)	40	200	51	61	41	6.0×10^{17}	6.6×10^{17}	-	< 3min
10	Hanford	Pu	45	30.2	47	45.7	29	8.0×10^{17}	6.1×10^{17}	2.0×10^{18}	37.5h
11	Mayak	Pu	80	16.6	82	45	28	2.0×10^{17}	1.1×10^{18}	-	1h40min
12	Tomsk	U(90)	35.5	71	39	39	21	7.9×10^{17}	5.1×10^{17}	-	10h20min
13	Tomsk	U(90)	64.8	31.4	67.8	50	30	1.6×10^{16}	8.8×10^{17}	-	16h
14	Wood River	U(93)	51	55	55	45.8	26	1.3×10^{17}	7.1×10^{17}	-	1.5h
16	Mayak	U(90)	28.6	77	31.6	45	26	5.5×10^{17}	4.1×10^{17}	-	7h
17	Mayak	Pu	28.8	54.8 (*)	31.1	37.4	22.5	1.3×10^{17}	4.0×10^{17}	-	> 15min
18	Windscale	Pu	40	54.5 (*)	43.2	61	45	1.0×10^{15}	5.6×10^{17}	-	10s
19	ICPP	U(82)	315.5	23.5	325	61	41	2.7×10^{18}	4.2×10^{18}	-	1.5h
22	Tokai-mura	U(19)	45	370	67.5	45	*36*	2.5×10^{18}	8.8×10^{17}	-	19h40min