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Safety Targets for Probabilistic Safety Analysis for Swiss Nuclear Power Plants

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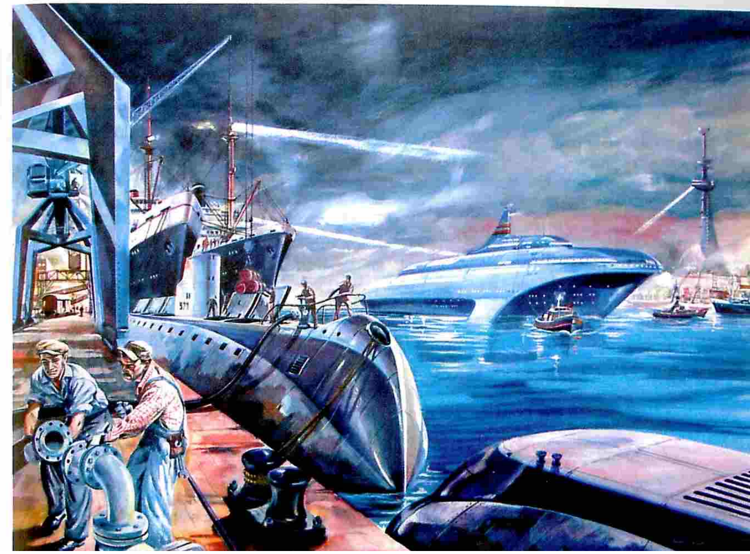
Initial Condition

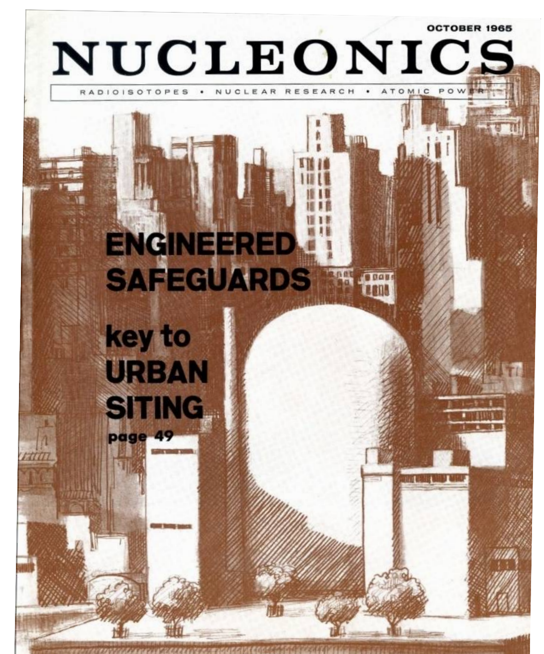
"*The 1950s … atom became a symbol of progress and benefit to humanity. …*" (Char & Csik 1987)



Hydrofoils glide across the oceans with nuclear power.

First safety consideration

- CP-1 (1942): Shutdown Systems (Safety Control Rod Axe Man - SCRAM)
- US Reactor Safeguards Committee required in 1950s: Placing for non-containment plants:
  $R = 0.016\sqrt{P_{th}}$ km
  P_{th} – thermal power in kilowatt



Early Accidents (mostly non-commercial Reactors)

12/12/52 Chalk river, Canada Test reactor NRX, Core Damage, Release
22/07/54 Steam Explosion of BORAX-Reactor NRTS
29/11/55 Idaho Falls, USA, EBR-1, Partial Core Melt
29/09/57 Kyshtym, USSR Waste storage, Chemical Explosion
24/05/58 Chalk river, Canada Test reactor NRU, Fuel rupture, Fire
25/10/58 Vinča, Yugoslavia Test, Reactor Criticality Excursion
26/07/59 Santa Susana Field Lab, Test Rector SRE Excursion, Fuel Melt, Release
03/04/60 Waltz Mill, USA, Test reactor, Core Melt
03/01/61 Idaho Falls, USA, SL-1, Steam Explosion (Rocket Mode)
24/07/64 Rhode Island, USA, Fuel fabrication, Criticality Accident
05/10/66 Newport, USA Power reactor Unit 1 fast breeder, Fuel Assemblies Melted
01/05/67 Chapelcross, UK Power reactor Unit 2 Magnox, Fuel Element Melt, Fire
01/05/67 Chelyabinsk, USSR Fuel fabrication, Radionuclides Dispersal from Lake
21/01/69 Lucens, Switzerland Test reactor coolant loss, Excursion, Explosion
17/10/69 Saint Laurent, France reactor Unit A1 UNGG Partial (50kg U), Core Melt
26/05/71 Moscow, Russia Test facility SF-3 Kurchatov Institute, Fuel Rods fall out
26/09/73 Windscale, UK Reprocessing Shop B 204 Gas leakage, Contamination
06/02/74 Leningrad, USSR Power reactor Unit 1 RBMK-1000, Circuit Rupture
30/11/75 Leningrad, USSR Power reactor Unit 1 RBMK-1000, Core Melt, Release
01/01/77 Beloyarsk, USSR, Power reactor ABM-200 early RBMK Unit 2, Core Melt

Early PSAs

- WASH-740 (1957): Damage 10^{-2}-10^{-4}, Release 10^{-5}-10^{-6} per year
- WASH-1400 (1975) First Large Probabilistic Safety Assessment
- 1983 first full scope PSA Level 1 for Beznau NANO-Optimization

US-Studie zeigt: AKW Beznau 100mal unsicherer als Gösgen!

● Ältere Schweizer Atommeiler sollen jetzt durch Notbunker sicherer gemacht werden

ZÜRICH – Eine neue und noch geheime US-Risiko-Studie für das AKW Beznau zeigt, dass die älteren Werke Beznau und Mühleberg rund 100mal unsicherer sind als die moderneren von Gösgen und Leibstadt. Um die Sicherheitslücke etwas zu schliessen, sollen unter Mühleberg und Beznau Notbunker gebaut werden.

Nur in Mühleberg wurde eine solche Risiko-Studie noch nicht einmal in Auftrag gegeben. Experten rechnen aber mit ähnlich ungünstigen Werten wie für Beznau.

Die Sicherheitslücke zwischen Mühleberg und Beznau einerseits sowie Gösgen und Leibstadt andererseits soll jetzt teilweise geschlossen werden:

● Der unbenannte Notbunker

- Results showed high CDF
- Seismic improvement of cable Trays, electrical cabinets and masonry walls, additional DC train, emergency procedures
- 1987 PSA required by Regulator (Level 1 and 2): Gösgen, Leibstadt, Beznau (Mühleberg)

PSA-Model: Risks considered

Political Risks
Early Decommissioning

Economical Risks
Price drop
Counterfeit spare parts
Insolvent suppliers

Social Risks
Strike
Riots
Sabotage
Wave of resignations

Technical Risks
LOCA
Cooling system failure
pump failure

Human Risks
Incorrect Operation

Natural Risks
Seismic
Flood
Fire, Heat, Drought
Sturm, Hurricane
Cold, Ice, Snow, Hail
Solar Storms

IT-Risks

Health Risks
Pandemics
Epidemic


Pandemiekonzept

Gemeinsames Betriebsführungskonzept

der Anlagen KKB und KKL

während einer Influenza-Pandemie

PSA-Model: Size

Full Power Model

212 Initiating Events

1,200 Random Variables

1,800 Components

7,000 Basic Events

310 Top Events

> 25 Event Trees

> 10^{40} Accident Sequences

> 600 Fault Trees

Computation Time: Hours/Day

10,000 pages

Low Power and Shut Down Model

212 Initiating Events

1,400 Random Variables

1,800 Components

3,500 Basic Events

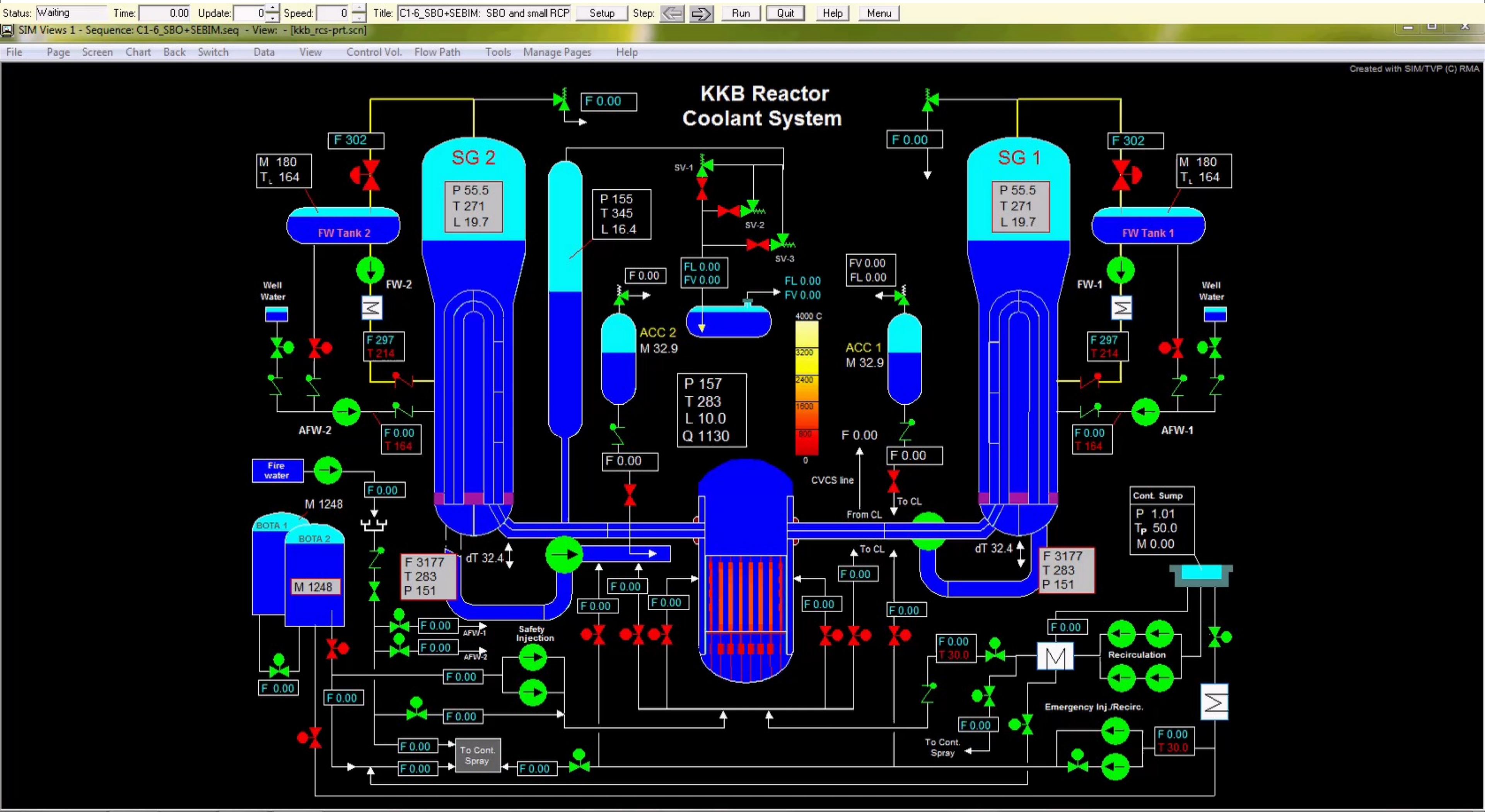
310 Top Events

20 Event Trees

> 500 Fault Trees

Computation Time: Days/Weeks

PSA-Model: Deterministic Computations



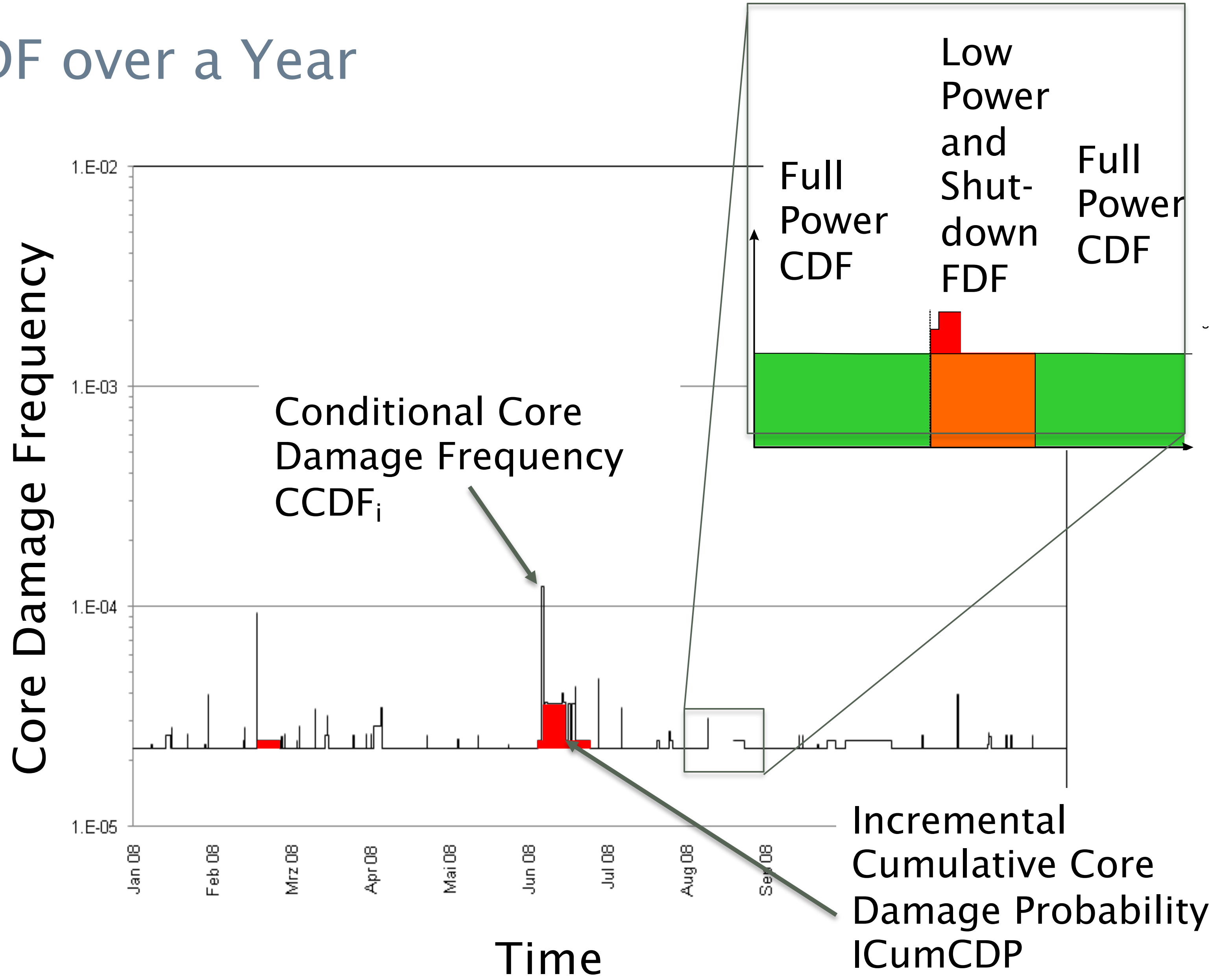
PSA-Model: Levels

Plant Model: 1		Containment Model: 2		Environment Model: 3	
Initiating Event	→	Core Condition	→	Release Category	→	Damages Loss of Human Life
		Core Damage Frequency (per year)		Release Frequency (per year)		Damage Frequency (per year)

Definition of Core Damage (Level 1)

- Maximum fuel rod temperature >1,200° C
- Overall oxidation of fuel rod >17 % of the fuel rod wall thickness
- Hydrogen production >1 % of the theoretically possible hydrogen
- Significant Change of Core
- Loss of Core Cooling

CDF over a Year



Int. Target Values

- USNRC (1982) NUREG-0880:
  CDF: 10^{-4} per year
- IAEA (1988) 75 INSAG-3:
  CDF: 10^{-4} … 10^{-5}
  LRF/LERF: 10^{-5} … 10^{-6}
  (order of magnitude)

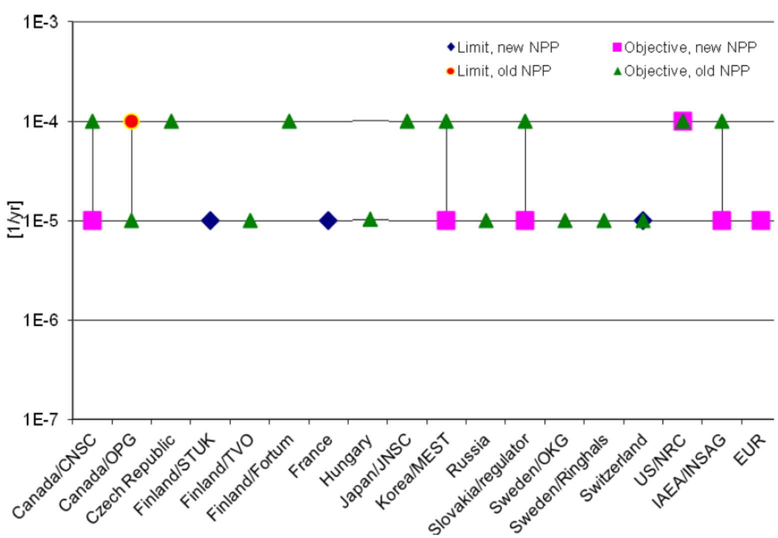


Figure 3 Numerical criteria defined for Core Damage.

Table 1: Core Damage Frequency from Various Country [5,6]

Country	Organization	Frequency	Notes
USA	Regulator	10^{-4} /yr	Objective
UK	Regulator	10^{-4} /yr 10^{-5} /yr	Limit Objective
Taiwan	Licensee	10^{-5} /yr	Limit
Switzerland	Regulator	10^{-4} /yr 10^{-5} /yr	Limit for existing plants Objective for new plants
Sweden	Licensee	10^{-5} /yr	Objective: This is a criteria or safety goal established by the licensees.
Slovak Rep	Regulator	10^{-4} /yr 10^{-5} /yr	Objective for existing plants Objective for new build
Netherlands	Regulator	10^{-4} /yr 10^{-6} /yr	Limit for existing plants Limit for new plants
Japan	Regulator	10^{-4} /yr	Objective
Italy	Regulator	10^{-6} to 10^{-5} /yr	Objective
Hungary	Regulator	10^{-4} /yr 10^{-5} /yr	Limit for existing plants Limit for new plants
France	Regulator	10^{-5} /yr	Objective for new plants
France/ Germany	Designers of EPR	10^{-6} /yr	Objective
Finland	Regulator	10^{-5} /yr	Objective
Czech Rep	Licensee	10^{-4} /yr 10^{-5} /yr	Objective for existing plants Objective for new plants
Canada	Regulator	10^{-5} /yr	Limit for new plants
	Licensee	10^{-4} /yr 10^{-5} /yr	Limit for existing plants Objective for existing
Korea	Regulator		
Slovenia	Regulator	10^{-5} /yr	plants Objective for new build

Isnaeni 2021, Bengtsson et al. 2010, Gu 2018

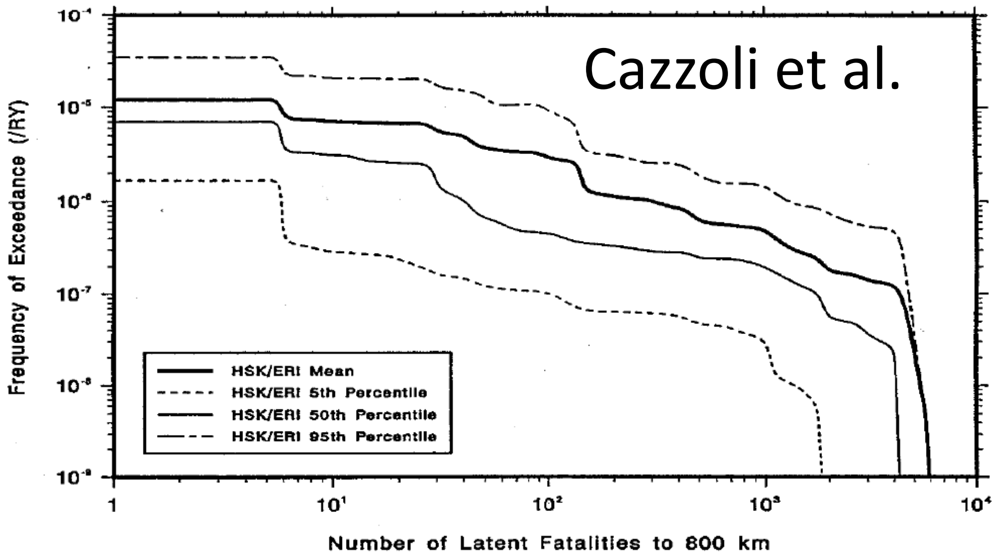
Swiss Target Values (Level 1 and 2)

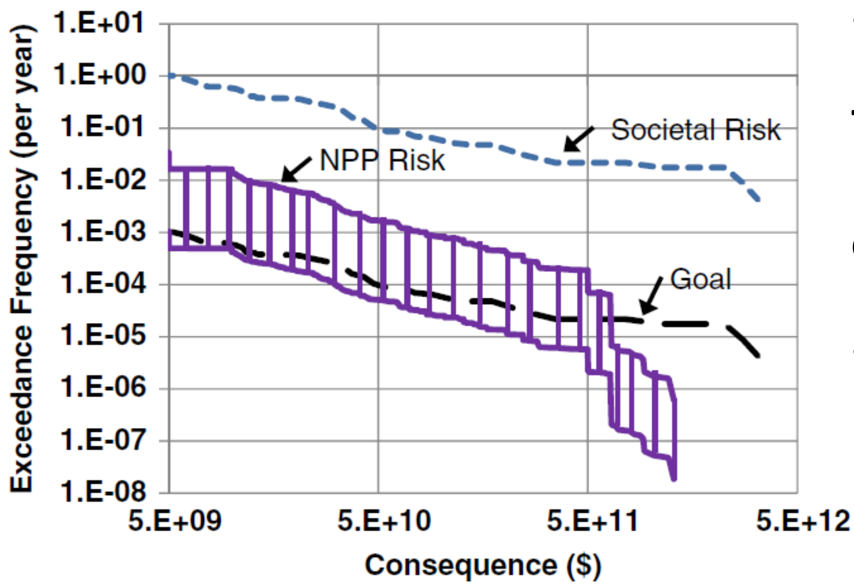
- Regulated by Law and Ordinance (ENSI A06, UVEK-DETEC)
- CDF > 10^{-5} per year, measures must be taken, if appropriate.
- LERF > 10^{-6} per year, measures must be taken, if appropriate.
- CDF > 10^{-4} per year, immediate measures must be taken
- Initiating event … contributes > 60 % to the mean CDF and contribution > 6×10^{-6} per year, measures must be taken, if appropriate.
- Design basis accident shall … assess hazards with a frequency >= 10^{-4} per year for demonstration of adequate protection (HCLFP = 1 % fractile)…

Swiss Target Values (Risk based Maintenance)

- $CDF_{Mean}/CDF_{Baseline} > 1.2$, measures … be taken, if appropriate
- No maintenance-related Conditional Core Damage Frequency per component unavailability configuration > 10^{-4} per year
- Total component maintenance times per calendar year are limited: maintenance-related part of the Incremental Cumulative Core Damage Probability (ICumCDP) < 5×10^{-7}.
- Safety-relevant components: FV ≥ 10^{-3} and RAW ≥ 2
- INES classification of events using ICCDP

Target Values: Level 3





Denning & Mubayi

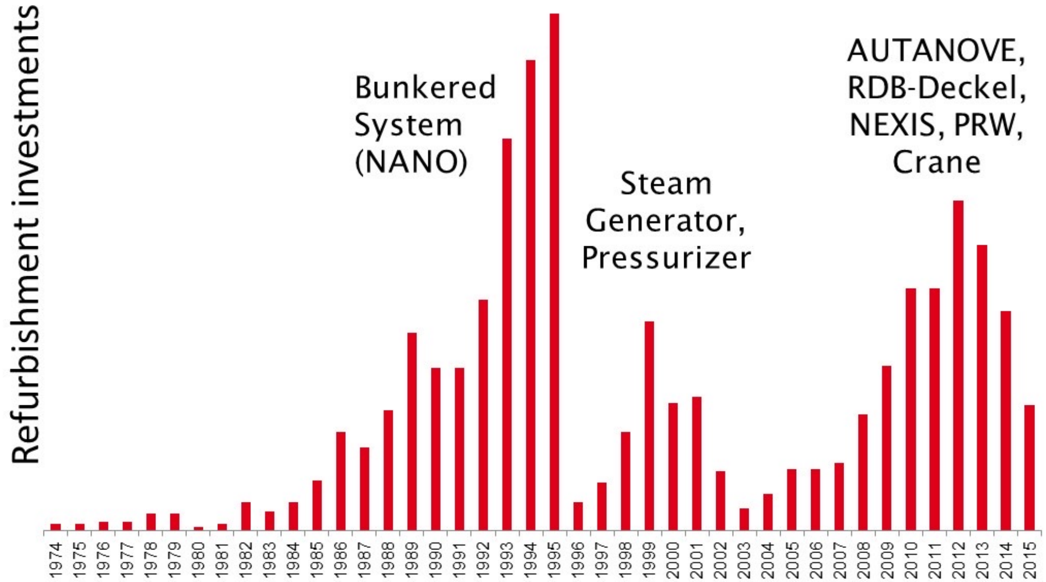
Origin of Target Values (1982)

- risk to individual should < 0.1 % of the sum of fatality risks from other accidents
- should < 0.1 % of the sum of cancer fatality risks resulting from other causes
- UVEK: Deterministic proofs related to safety levels based on Dose (very important)
  Event 10^{-3}: 1 mSv
  Event 10^{-4}: 100 mSv

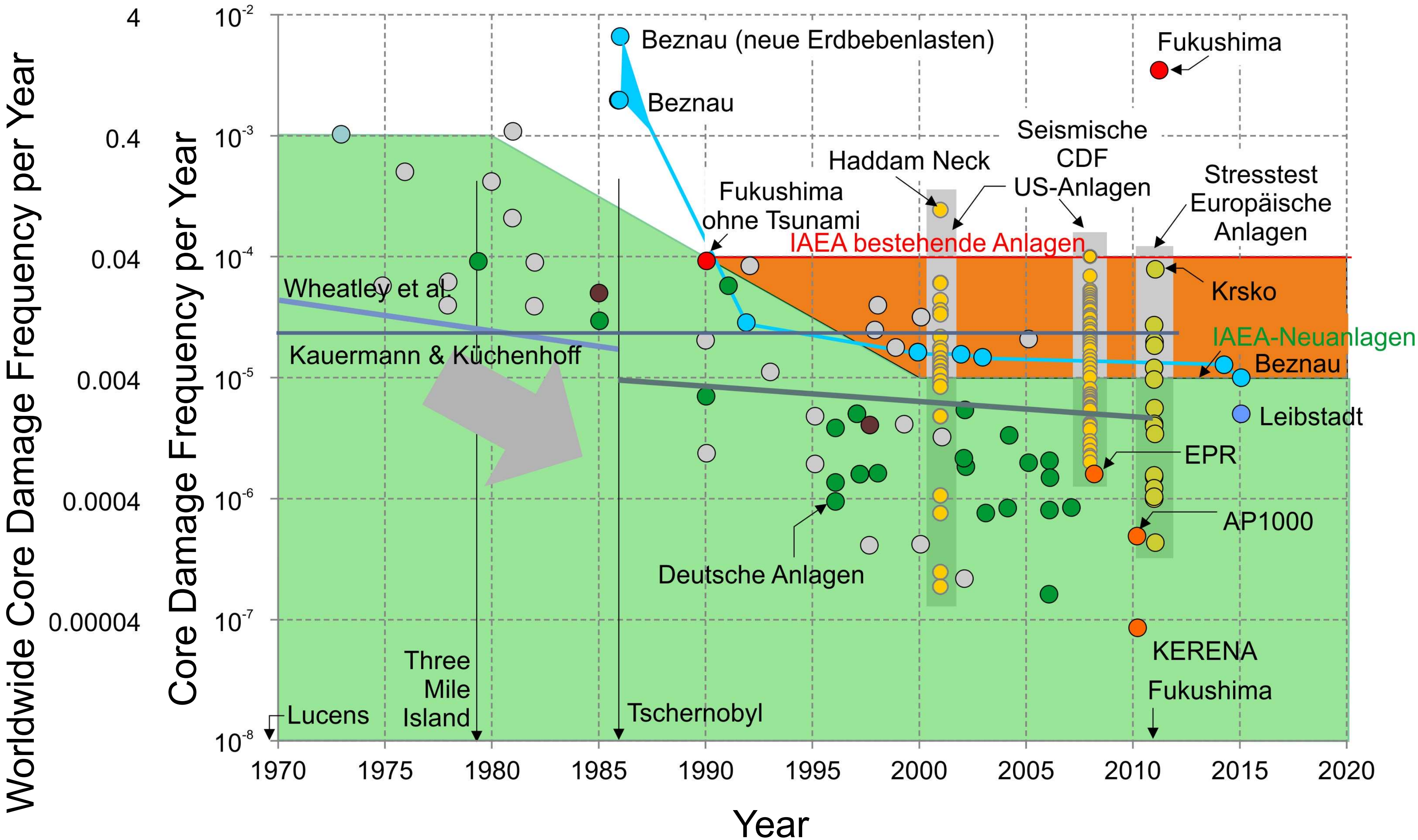
LQI Backwards Calculation and Refurbishment

- *LQI*: Backwards calculation of NANO: about 1 billion CHF
- *LQI*: Backwards calculation of AUTANOVE: < 100 Mill. CHF, but 700 Mill. CHF invested
- One can improve old plants only to a limited extend.
- No good solution keeping old plants running when officiall announced decommission dates

- Overall, 3,000 plant improvements



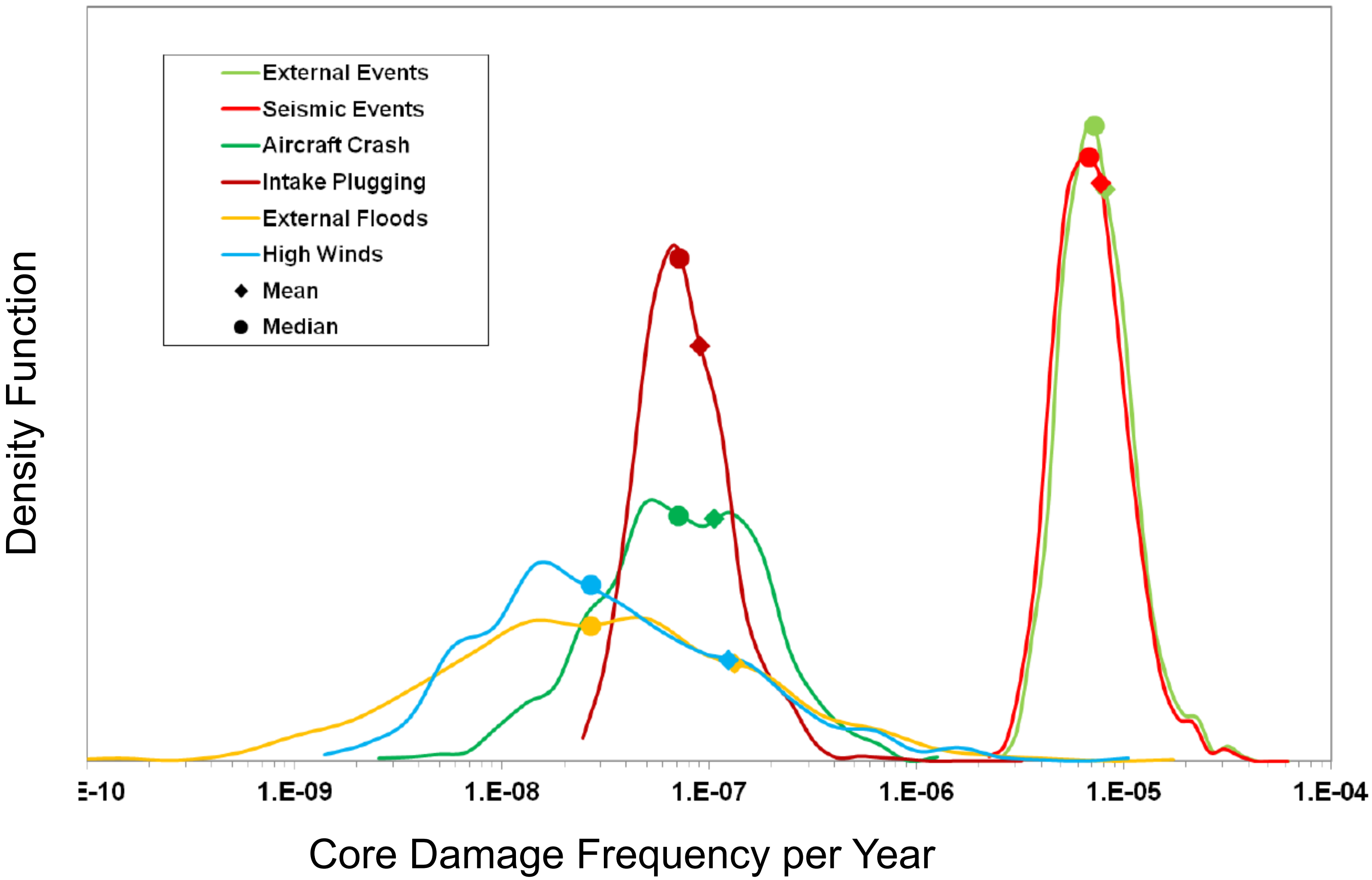
PSA-Models: Results and Backwards Calculation



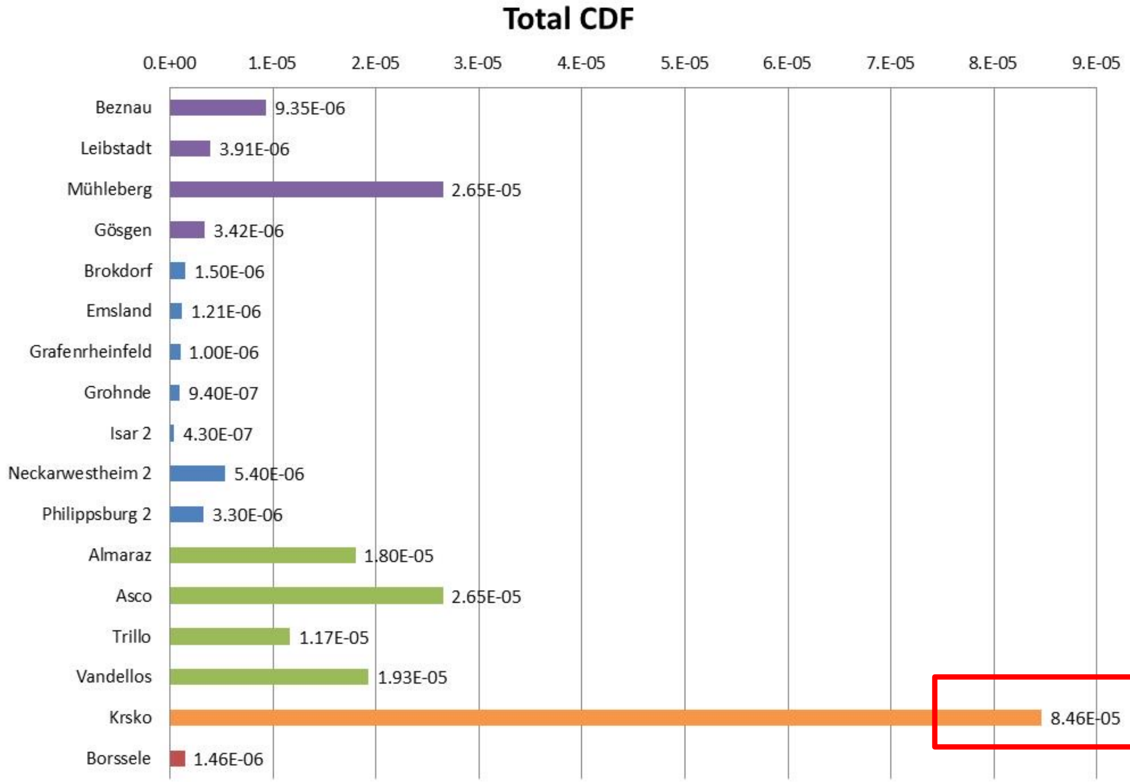
Conclusion

- Early design far too weak (much to optimistic, political will)
- Global annual CDF in 1970s close to 1 (backwards calc.)
- Improvement in PSA results (> two orders of mag. per century)
- Some strong critic against PSA (multi unit sites, correlation, cutoff, importance factors): "*Given the degree of uncertainty and complexity … to … nuclear risk assessment… risk-based probabilistic assessment has proven very limited*." (Dorfman et al. 2013) – I do not agree!
- Large Uncertainty in some Initiating Events (seismic, floods)
- Deterministic Proofs and Safety Margins became more important (shutdown of plant)
- Defense in Depth, Barriers Concept, Continuous Improvement
- Just one Element in Decision Making

Uncertainty



Core Damage Frequency

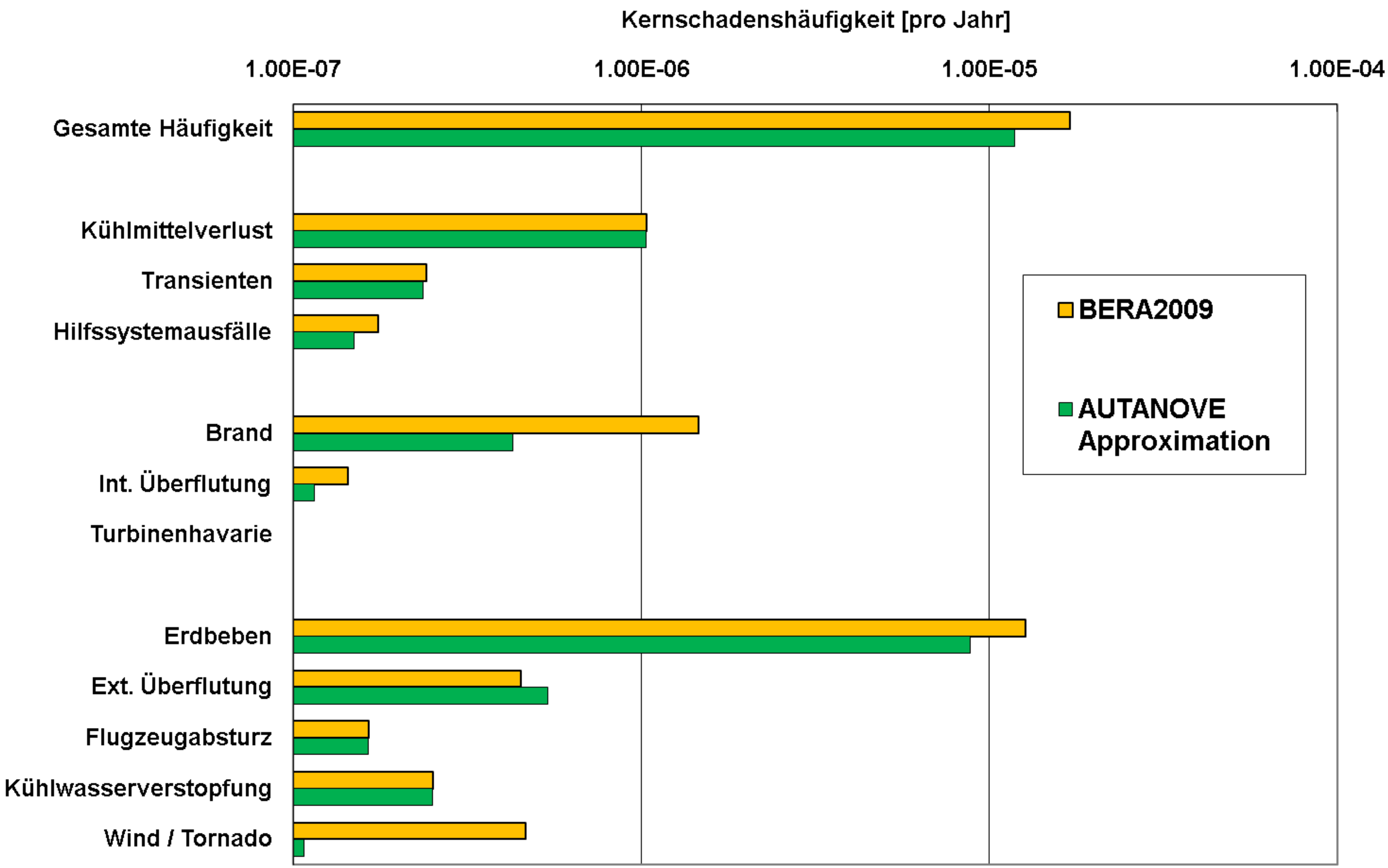


Plants Performing
.2 from NUREG 1742

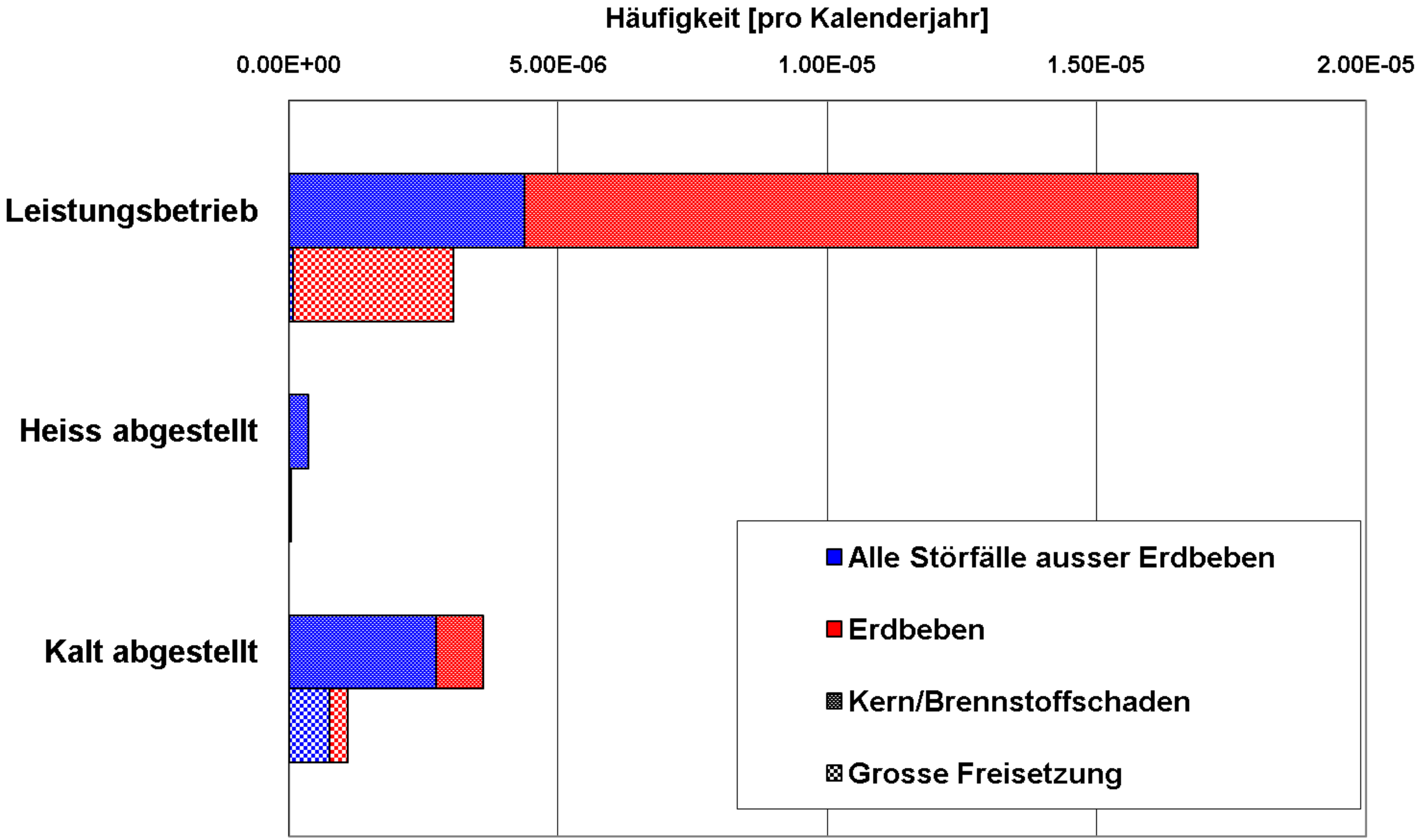
		Plant	Mean Seismic CDF (EPRI)
		1	1.29E-05
			1.30E-05
		& 2	1.40E-05
		2	1.60E-05
		& 3	1.70E-05
		shington Nuclear Project No. 2)	2.10E-05
			3.21E-05
		nd 3	3.47E-05
		n 1 & 2	4.20E-05
Beaver Valley 2	1.03E-05	Pilgrim 1	5.80E-05
Kewaunee	1.10E-05	Indian Point 3	5.90E-05
McGuire 1 & 2	1.10E-05	Haddam Neck	2.30E-04
Seabrook	1.20E-05		

Median of Mean Seismic CDF Value (EPRI Results)	1.20E-05
Mean of Mean Seismic CDF Value (EPRI Results)	2.50E-05

Core Damage Frequency



Core Damage Frequency



Core Damage Frequency

Importance Measure

Measure	Abbreviation	Principle
Risk reduction	RR	$R(\text{base}) - R(x_\text{i} = 0)$
Fussell–Vesely	FV	$\dfrac{R(\text{base}) - R(x_\text{i} = 0)}{R(\text{base})}$
Risk reduction worth	RRW	$\dfrac{R(\text{base})}{R(x_\text{i} = 0)}$
Criticality importance	CR	$\dfrac{R(x_\text{i} = 1) - R(x_\text{i} = 0)}{R(\text{base})} \times x_\text{i}(\text{base})$
Risk achievement	RA	$R(x_\text{i} = 1) - R(\text{base})$
Risk achievement worth	RAW	$\dfrac{R(x_\text{i} = 1)}{R(\text{base})}$
Partial derivative	PD	$\dfrac{R(x_\text{i} + \partial x_\text{i}) - R(x_\text{i})}{\partial x_\text{i}}$
Birnbaum importance	BI	$R(x_\text{i} = 1) - R(x_\text{i} = 0)$

Level 3

Gauss'sches Fahnen-Modell

$$C(x,y,z) = \frac{Q'}{2\pi\sigma_y\sigma_z u} \cdot \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \cdot \left(\exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right)\right)$$

C(x,y,z) = Immissionskonzentration am betrachteten Ort

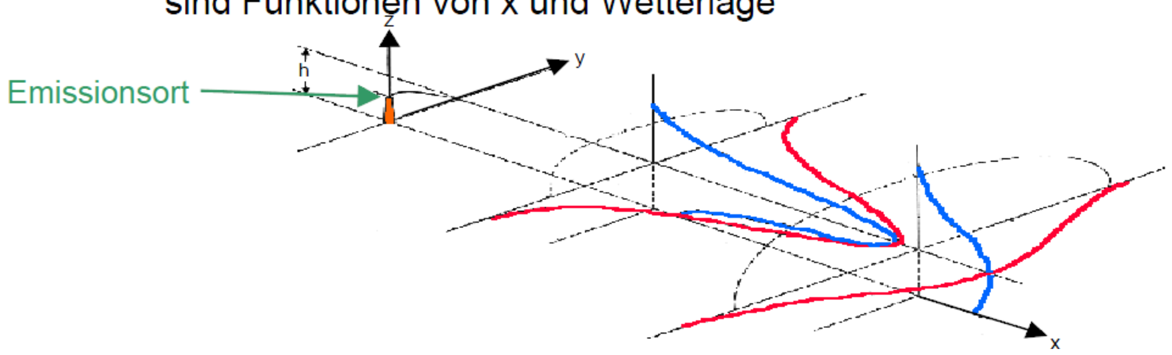
Q' = Emissionsrate, d.h. pro Zeiteinheit freigesetzte Schadstoffmenge

u = gemittelte Geschwindigkeit

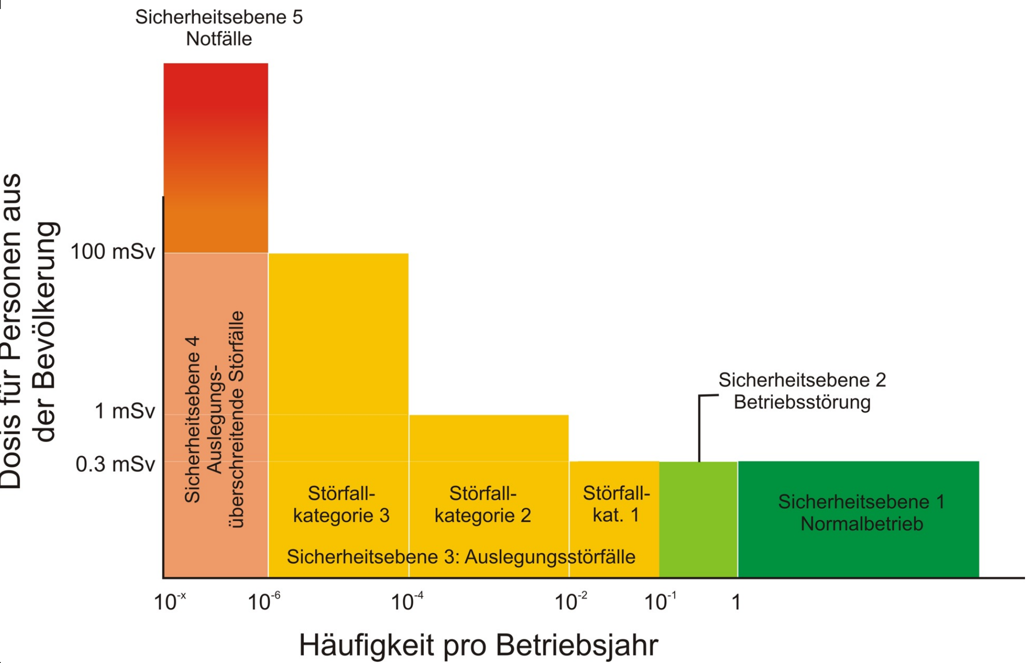
h = effektive Quellenhöhe

x,y,z = Abstände des Bezugspunktes vom Koordinatenursprung, wobei x der Windrichtung entspricht

σ_y, σ_z = Streuparameter der Konzentrationsverteilung in y- bzw. z-Richtung sind Funktionen von x und Wetterlage



Safety Level



Growth of NPPs

Nuclear power growth: 1951–86

Year	Construction starts		Connections to the grid	
	Units	GWe	Units	GWe
1951	1			
1952				
1953	2	0.1		
1954	6	0.5	1	
1955	3	0.1		
1956	9	0.8	1	0.1
1957	12	1.5	1	0.1
1958	7	0.6	3	0.2
1959	6	0.9	5	0.3
1960	10	1.0	6	0.6
1961	6	1.1	2	0.1
1962	8	1.3	10	1.0
1963	5	1.4	7	0.4
1964	10	3.0	8	1.1
1965	10	3.5	9	1.6
1966	16	7.4	8	1.2
1967	23	15.2	10	2.1
1968	38	26.1	6	1.1
1969	17	12.7	11	3.5
1970	37	24.9	6	3.3
1971	22	16.1	16	7.3
1972	22	19.3	16	8.8
1973	23	18.3	20	12.5
1974	35	29.8	26	16.9
1975	40	38.0	15	10.2
1976	29	27.2	19	14.1
1977	15	14.5	18	13.3
1978	21	18.2	20	15.8
1979	21	19.7	8	7.0
1980	23	21.4	21	15.3
1981	12	11.6	23	20.4