ALPHA-STATIC CRITICALITY SAFETY ANALYSIS

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SAFETY REQUIREMENT

The Nuclear Regulatory Commission (NRC) requires nuclear systems to maintain strict control over the neutron multiplication factor (k). Putting an upper limit of k=0.95 gives the system a safety margin so that a reactor does not exceed a critical configuration. A key aspect of this regulation is the Shutdown Margin (SDM), which mandates that reactors remain subcritical with a k typically below 0.99 when all control rods are fully inserted. Reactors must also manage reactivity through control rods, burnable poisons, and soluble boron, with safety analyses confirming that reactivity levels are within safe limits. These requirements ensure reactors can achieve a safe emergency shutdown and maintain operational stability.

K- VS ALPHA-STATIC

The k-eigenvalue might not be the best metric as it completely ignores the time characteristics of the neutron behavior. It becomes less accurate as the system deviates from being critical. In contrast, the alpha-eigenvalue, or alpha-static, considers the time characteristics, making it as accurate as using dynamic calculation. Therefore, it is another metric worth considering to show how subcritical a system is and how it changes with time.

NEUTRON TRANSPORT

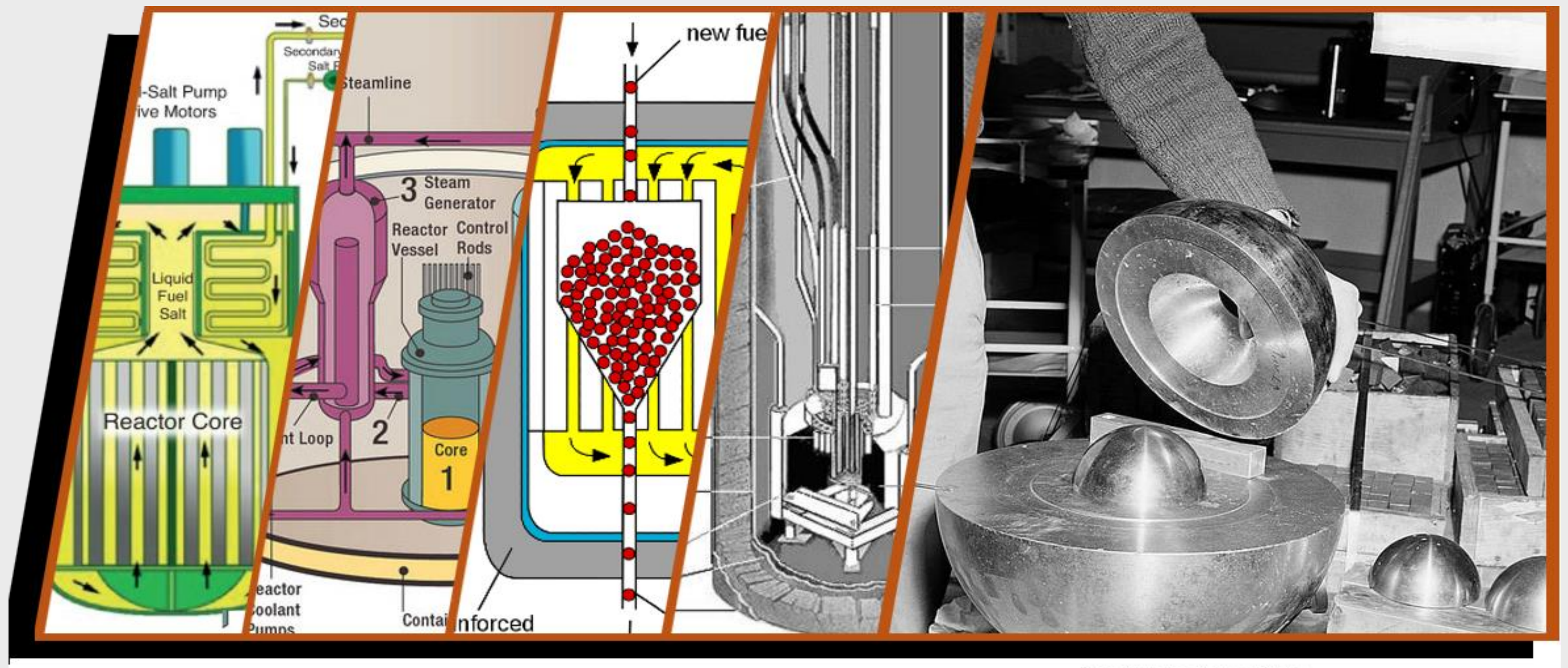
$$\frac{1}{v}\frac{d}{dt}\Phi + L\Phi = F\Phi$$

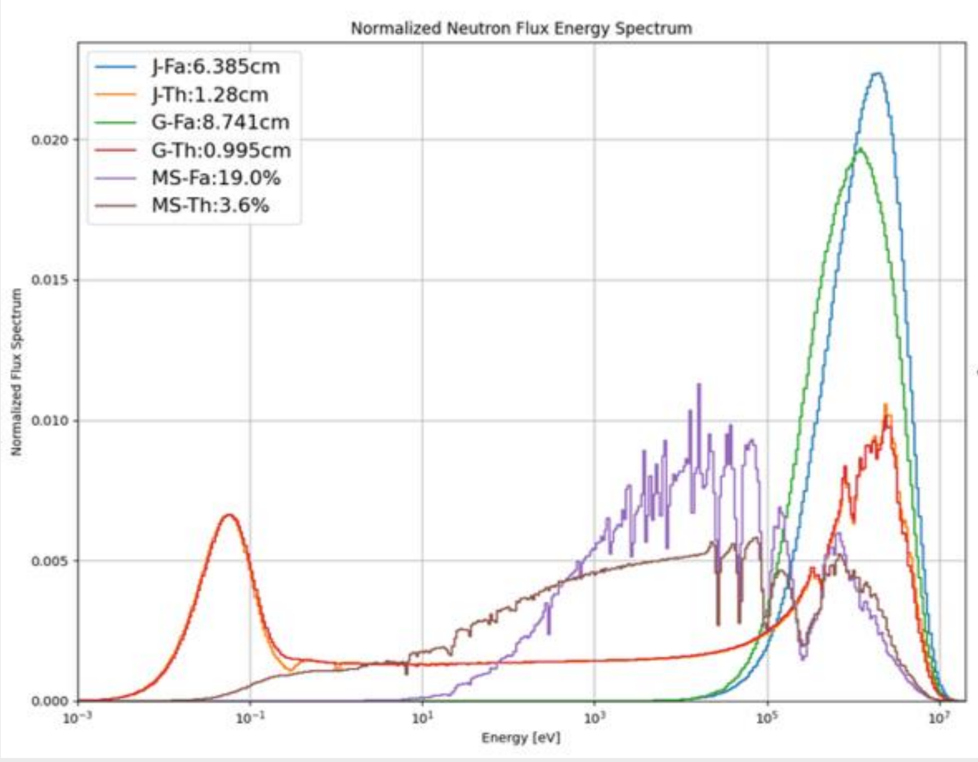
$$\frac{d}{dt}\Phi(\mathrm{t}) = 0 \rightarrow L\Phi = \frac{1}{k}F\Phi \rightarrow k \equiv \frac{F}{L}$$

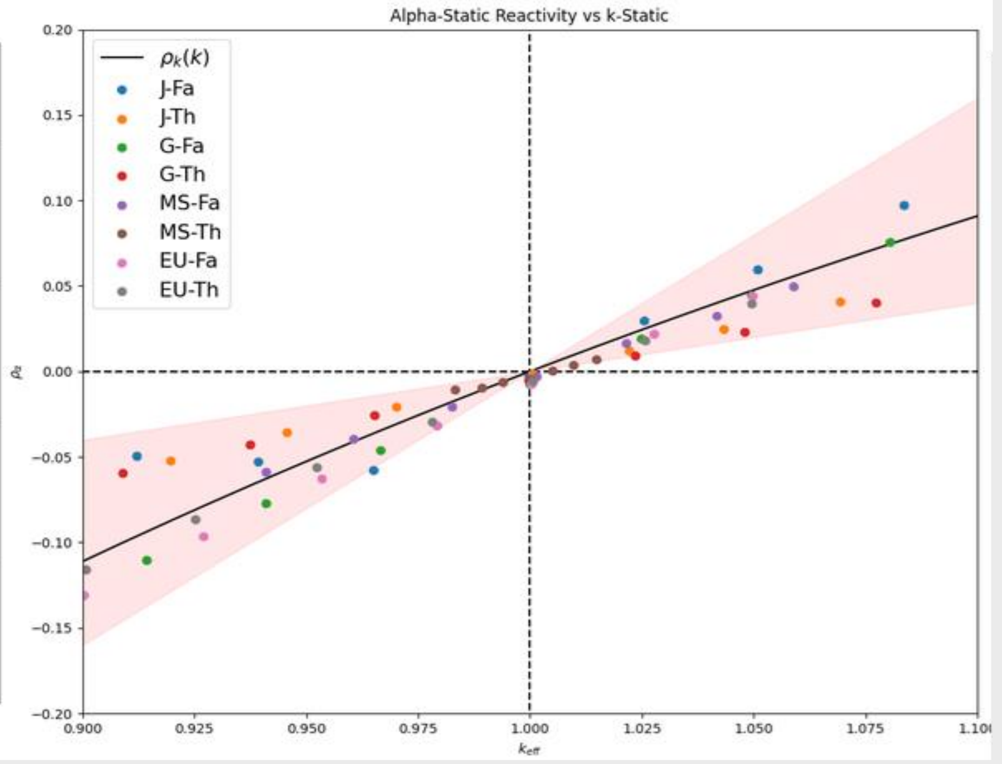
$$\Phi(\mathrm{t}) = \Phi_0 e^{\alpha t} \rightarrow \frac{\alpha}{v}\Phi + L\Phi = F\Phi \rightarrow \alpha \equiv v(F-L)$$

Φ = Neutron Flux, v = Neutron Speed

L = Loss Operator, F = Fission Operator







EXAMINED SYSTEMS

System	Regime	Geometry	Variable	Fuel	Moderation
Jezebel	Fast	Sphere	Radius	Pu	None
	Thermal	Sphere	Radius	Pu	Water, 1000:1
Godiva	Fast	Sphere	Radius	U	None
	Thermal	Sphere	Radius	U	Water, 1000:1
Enriched Uranium	Fast	Sphere	Enrich%	U	None
	Thermal	Sphere	Enrich%	U	Water, 1000:1
Moderated Uranium	Varies	Sphere	Mod Ratio	U	Water
	Varies	Sphere	Mod Ratio	U	Graphite
MSBR	Fast	Hex Lattice	Bred%	Th, U	FLiBe, Zircalloy
	Thermal	Hex Lattice	Bred%	Th, U	FLiBe, Graphite

- Jezebel: Benchmark critical mass Pu & Ga sphere
- Godiva: Benchmark critical mass HEU sphere
- MSBR: Molten Salt Breeder Reactor, Th232 → U233
- All systems (except MSBR) are homogenous
- Enrichment refers to weight% of U-235
- Bred% refers to amount of Th converted into U233

ALPHA-STATIC REACTIVITY

- Reactivity has always been used as a metric for criticality in nuclear systems, traditionally defined by k_{eff}, defining divergence from critical.
- With Alpha-Static analysis, reactivity is instead defined by the time characteristic constant α and the mean generation time Λ, which is defined by the mean life-time l and the multiplication factor k.
- These values are derived from OpenMC simulation.
- Allows for a unitless, nearly linear, and compatible metric in safety analysis.

$$\rho_\alpha = \alpha_p\Lambda = \frac{\alpha_p l}{k_{\alpha p}}, \qquad \rho_k = \frac{k-1}{k}$$

$$\alpha = v(F-L), \qquad \Lambda = \frac{l}{k}, \qquad l = \frac{1}{vL}, \qquad k = \frac{F}{L}$$

UNIVERSAL SAFETY METRIC

From the right plot we can see that k-static is the same for different systems. But the alpha-static reactivity does change which gives physical meaning that represents the real behavior of the system. With alpha-static reactivity a new universal safety metric could be set by regulating bodies like the NRC, if it gains traction. From our results the alpha reactivity value looks very promising. Based on this initial study, it appears a better universal criticality safety metric can be derived base on alpha-static reactivity.

VERIFICATION

- OpenMC is an open-source community-developed Monte Carlo simulation code for neutron and photon transports.
- Prior to running simulations using the developmental version of OpenMC's alpha-static code package, a verification process was conducted by comparing other computational benchmarks to values calculated by the OpenMC alpha-static code package.
- Computational benchmarks from Venner et al. (2003), Cullen et al. (2003), and Zoia et al. (2014) were used in the verification process.

System	Calculated k-effective for 75% of critical mass	
	Venner (MCNP5)	OpenMC
Full Density Pu-239	0.920	0.924
Full Density U-235	0.935	0.933
Pu-239 & H2O	0.940	0.939
100% enriched U & H2O	0.926	0.936
50% enriched U & H2O	0.928	0.939
30% enriched U & H2O	0.949	0.942

Note: Venner et al. (2003) used JEF2.2 nulcear data library

Fuel (Godiva)	Regime	Criticality	Prompt Alpha (1/μs)		
			Cullen (TART)	Zoia (TRIPOLI-4)	OpenMC
Homogenous	Fast	Critical	-0.739	-1.09	-1.095*
Homogenous	Fast	Supercritical	144.7	144.9	145.8
Heterogenous	Fast	Supercritical	146.6	146.9	147.8
Homogenous	Thermal	Supercritical	0.653	0.671	0.675
Homogenous	Fast	Subcritical	-1.048	-0.979	-0.962*

* Represented by median value

Note: Cullen et al. (2003) and Zoia et al. (2014) used ENDF/B-VI and ENDF/B-VII nuclear data libraries, respectively.

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