Overcoming Challenges in the ZED-2 Reactor Safety Analysis

TRTR Conference

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2010 September 19-24

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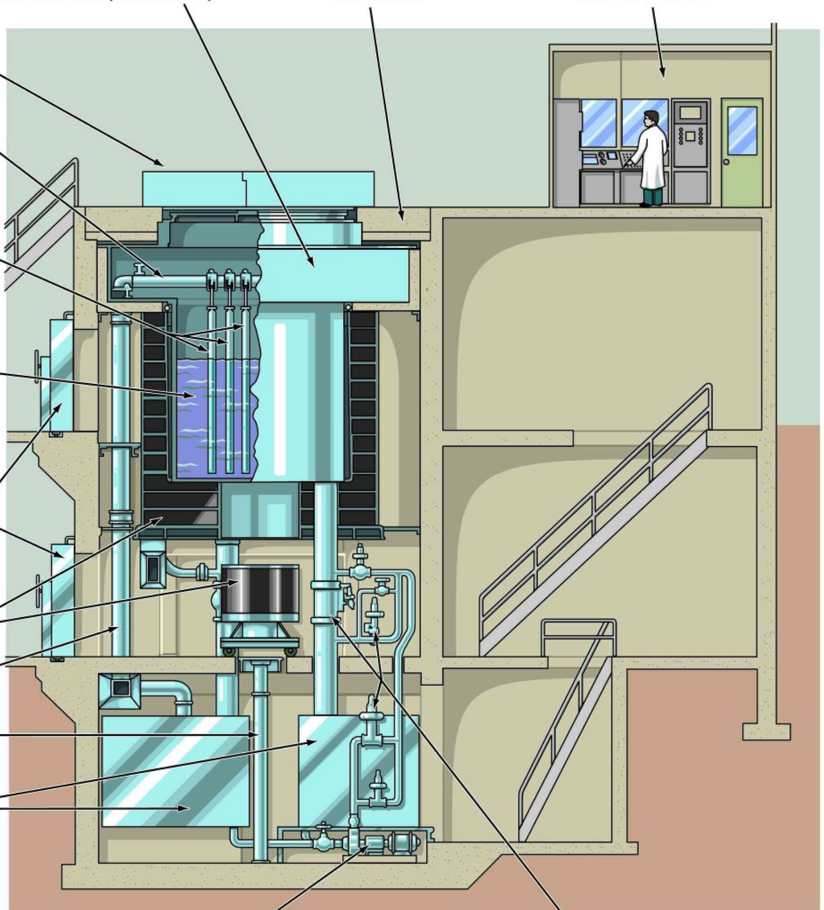
ZED-2 50th Anniversary

- First criticality on 1960 September 7
- 50 years of safe operation achieved two weeks ago
- CNS sponsoring a Technical Workshop on critical facilities and small reactors
  - 2010 November 1-3, Ottawa, Ontario, Canada
  - CNS website: http://www.cns-snc.ca/events
  - Still accepting registrations
  - Tour of ZED-2 on November 3 at CRL

ZED-2 Overview

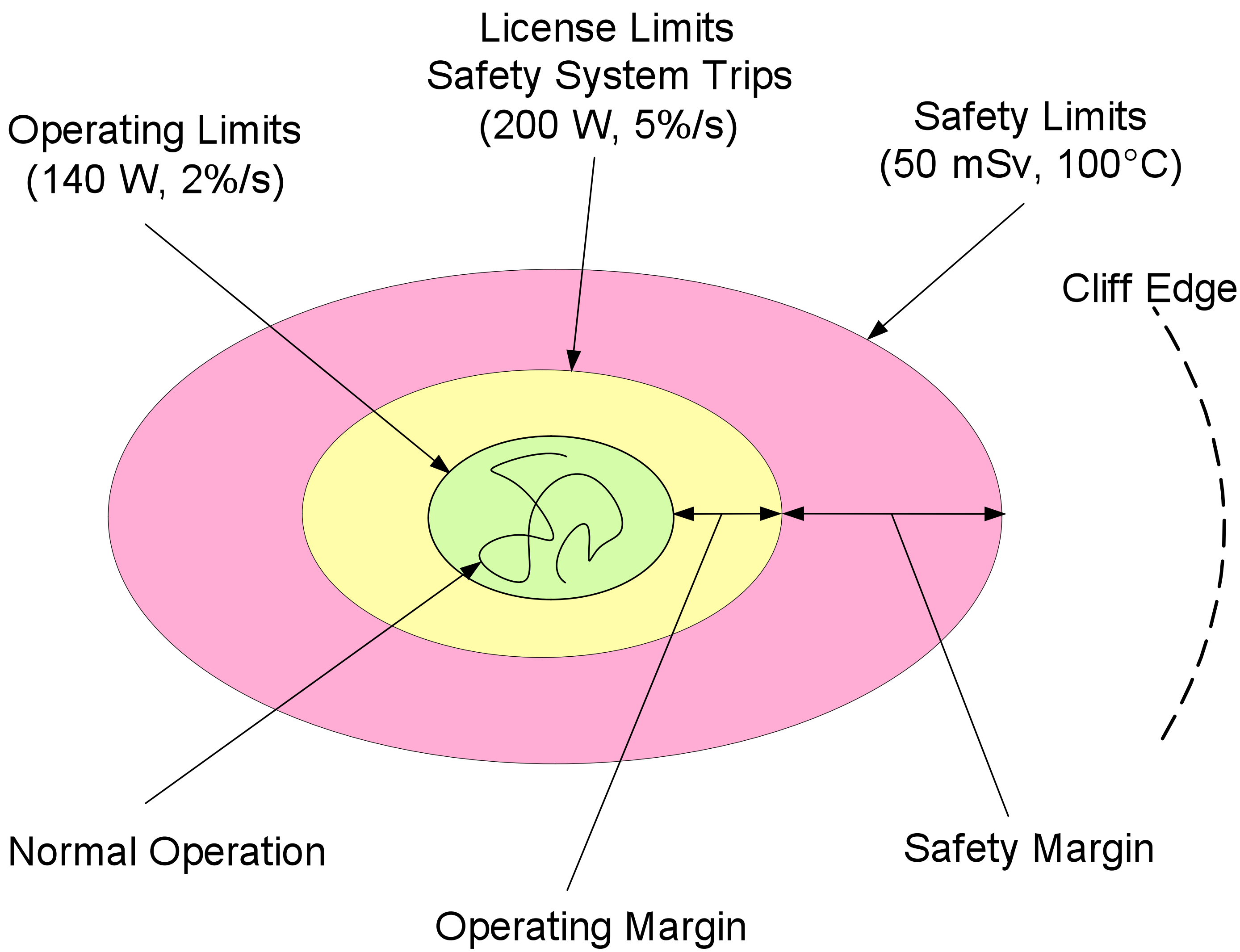


- Cylindrical vessel in which fuel rods are hung vertically
- Pump D_2O moderator into vessel to take reactor critical
- Low power, ~200 W maximum
- Primary shutdown mechanism is moderator dump through 3 lines (1.5 ft dia) back to the dump tanks in the basement
- 8 to 12 standby absorber rods also drop but are not credited in the safety case

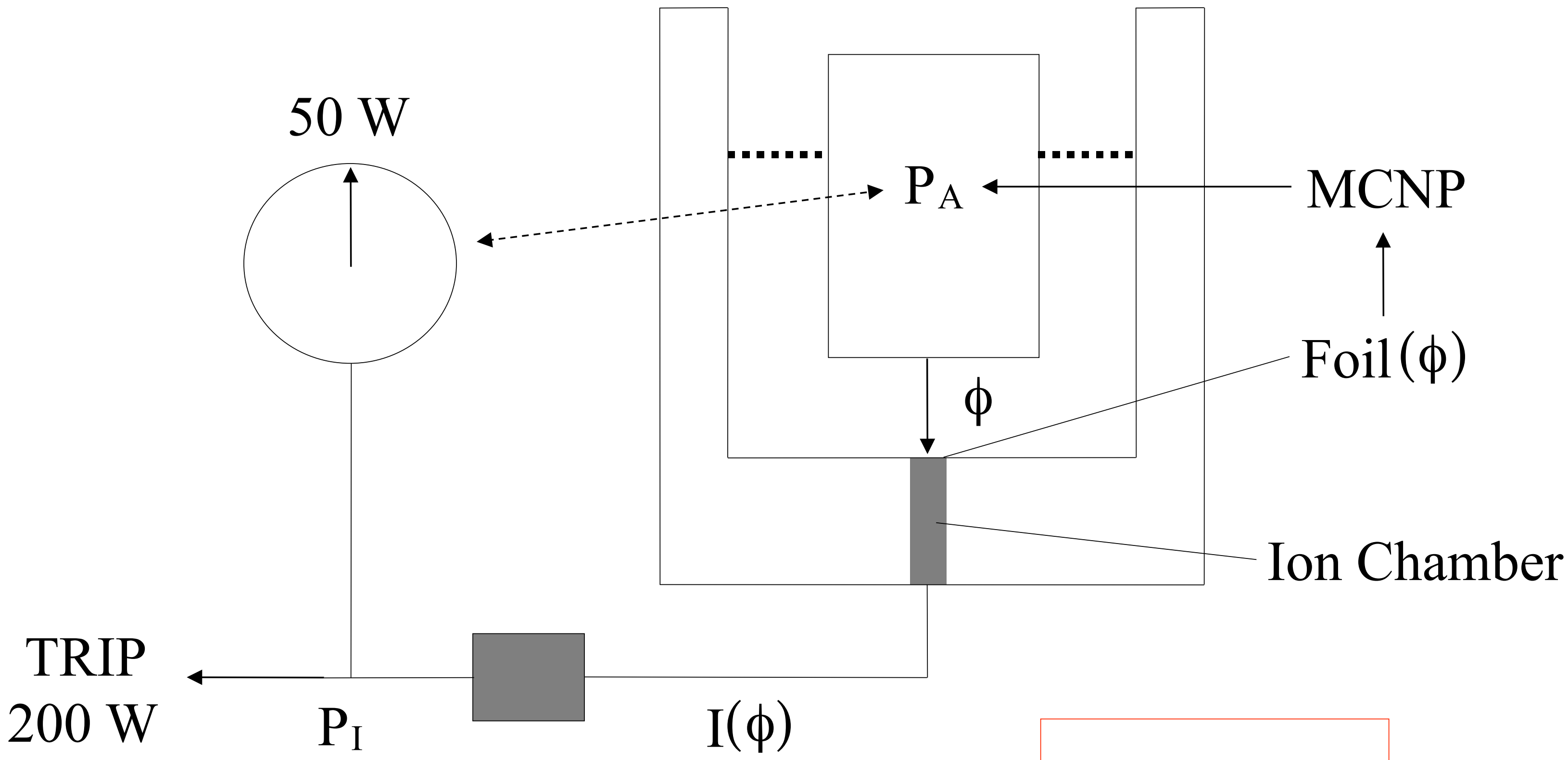
ZED-2's Versatility & Variability

- Can accommodate mixed fuel types in a variable number of fuel rods each with or without CANDU-type or ACR-type channels
- Channel coolants can be light or heavy water, or air, and can vary from channel to channel
  - Some CANDU-type channels can be heated
- Lattices can be square or hexagonal with continuously variable lattice pitch
- Other items can also be placed in the core such as
  - Solid neutron absorbers, self-powered and foil-activation neutron flux detectors, and soluble neutron poisons in the heavy water
- Heavy water purity continuously decreases with time

Defence in Depth



Indicated versus Actual Core Power



$P_I \neq P_A$

ACR LEU Fuel Lesson

- Addendum added to the ZED-2 FSAR to accommodate LEU fuel for ACR experiments
  - Final Safety Analysis Report (supports the license)
- Limits placed on LEU fuel loading, minimum lattice pitch, and maximum reactivity insertion
- Did not include indicated-to-actual power difference
  - When the power difference was assessed, the safety case failed for smallest allowed lattice pitch
  - ZED-2 was shut down by AECL management
  - Errant case “fixed” by reducing safety-case conservatism
  - Operation resumed under a 2nd addendum to FSAR
    - Special CNSC permission was required for each core load
- Clearly a different approach was required to avoid endless revisions to the FSAR for new experiments

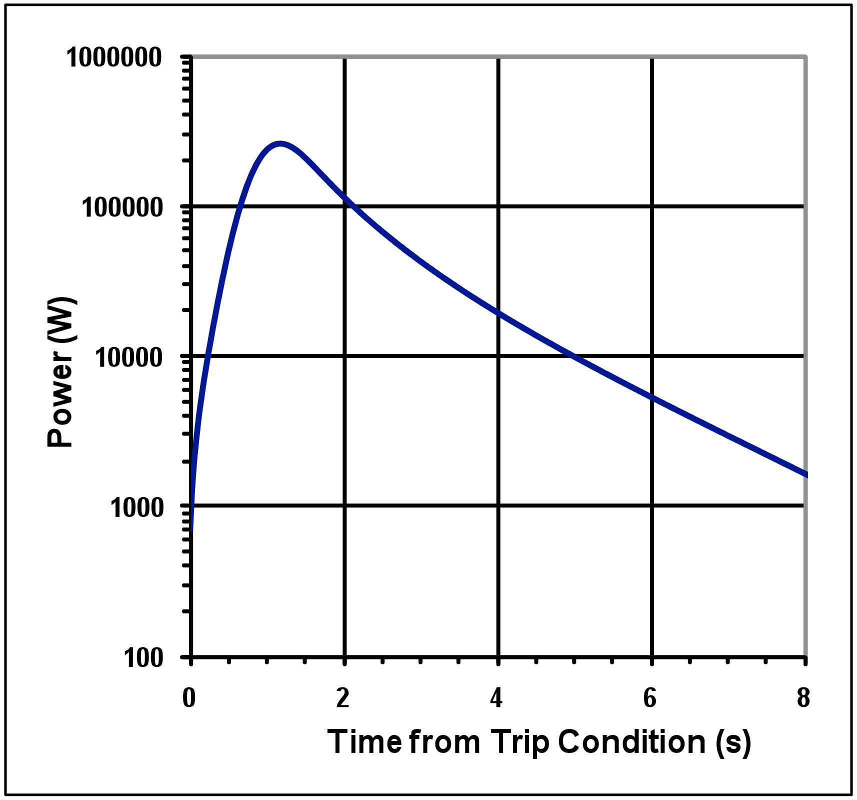
Summary of Reasons for FSAR Upgrade

- Last major rewrite of FSAR in 1985
- Include and quantify safety margins
- Explicitly include impact of the difference between indicated and actual core power
- Include uncertainty analysis
- Challenge: to select an appropriate set of controlled parameters that provides a robust safety case without compromising the facility's versatility while at the same time avoiding endless revisions to the FSAR
- Many other upgrades performed at the same time

– This presentation is confined to the safety analysis

Reference Accident Transient
(Design Basis Accident - DBA)

- Indicated power is at the trip condition (200 W)
- Core parameters at their LCO limits
  - Limiting Conditions for Safe Operation
- Step reactivity insertion:
  $\rho = \beta(U235)+1\ mk = 7.984\ mk$
  $(1\ mk = 10^{-3}\ k = 100\ pcm)$
- U235 is the only fissioning nuclide
- One dump valve fails to open and absorber rods are not credited
- Acceptance Criteria (dose to staff and fuel temperature) depend on total energy generated
- All other credible LOR accidents are bounded by this transient
- Other fissioning nuclides are bounded by this transient



Reference Transient and E_{AC} Equations (LCO Parameters)

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta_{U235}}{\boxed{\Lambda}} n(t) + \sum_i \lambda_i C_i(t) \qquad P(t) = \boxed{P_A} n(t), \quad n(0) = 1$$

$$\rho(t) = \rho_{\text{IN}}(t) + \rho_{\text{OUT}}(t) \qquad \boxed{\rho_{\text{IN}}}(t) = \beta_{U235} + 1\,\text{mk, ramp } 0 \rightarrow 0.1\,\text{ms}$$

$$\rho_{\text{OUT}}(t) = -\boxed{LCR}\frac{H_{\text{ex}}^3}{2}\left[\frac{1}{\left(H_{\text{ex}} - \Delta h(t')\right)^2} - \frac{1}{H_{\text{ex}}^2}\right] \qquad H_{ex} = \boxed{H_c} + D_{ex} \qquad t' = t - t_{DUMP}$$

$$E = \int P(t)dt \qquad E_{AC} = \boxed{M} F_{\Delta H} F_{f\,luxpeak} \Delta T\, C_P \qquad \Delta T = 100°\text{C} - T_0$$

$E < E_{AC}$ ← Deposited Energy Acceptance Criterion

LCO Parameters

- Set of 6 parameters were selected as LCOs
  - Based on reactor physics not physical parameters
    - The parameter values vary significantly with core loading and are calculated for each experiment
  - A limit is specified for each parameter
  - Maximum reactivity insertion:
    - $\rho = \beta_{EXPT}$ +1 mk, limit: $\rho \leq \beta_{U235}$ +1 mk
    - Safety case using U235 bounds other fissionable nuclides
  - Other 5 limits are fixed: LCR, fuel mass, critical height, neutron generation time, actual power at trip
    - e.g., P_A<700 W at P_I = 200 W to address $P_A \neq P_I$
  - Limit values are arbitrary but carefully chosen to satisfy the E_{AC} yet not unduly constrain experiments

Fixed Parameters

- The remaining parameters have fixed values
  - Not calculated for each experiment
  - Some parameter values are selected to bound experiments with additional margin
  - Some parameters don't depend on the experiment
  - Senior ZED-2 Physicist determines if any fixed parameters must be changed for a given experiment
    - Requires new safety case and CNSC acceptance

Uncertainty Analysis

- Uncertainty analysis performed on DBA
  - All 6 LCO parameters at the license limits, including 1σ standard errors (highly unlikely)
  - Fixed parameters included added margins
- Result was that a 98.8% probability that the deposited energy will not exceed E_{AC}
- Very high probability that E_{AC} will not be exceeded at license limits

Quantifying Safety Margins

Case	Margin to E_{AC}	Actual Fuel Temp (°C)
Reference accident transient (at LCO limits)	**6.1**	**56.68**
Worst case assessed (ACR/LEU, 24 cm, Gd in D_2O)	233	50.07
Errant Addendum case (ACR/LEU, 18 cm)	257	50.06
Typical experiments (CANDU/ACR, NU/LEU, D_2O/H_2O)	400-1200	50.01-50.04

- Actual fuel *T* explicitly calculated during transient
  – Fuel *T* safety limit is 100°C (initial fuel *T* is 50°C)
- Quantifies the margins in typical experiments between the actual fuel *T* and the safety limit

Summary of New Safety Case

- Establishes Defense in Depth philosophy
  - Introduces operating and safety margins
- Quantifies the very large actual safety margin
- Robust without compromising ZED-2 versatility
  - Can accommodate virtually any core loading without requiring a revision and CNSC approval of the licensing documents
- Addresses all other shortcomings in previous safety case
  - Includes a rigorous uncertainty analysis
  - Explicitly accounts for indicated-actual power discrepancy
  - Evidence provided that the DBA is in fact bounding

Thank You!

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Reference Transient is Bounding
(Reactivity Inserted and Rate)

Reactivity Inserted β(U235)=6.984	Starting Indicated Power (W)	Deposited Energy (kJ)	Time to Trip (s)
7.984 mk, step **(reference)**	**200**	**412**	**0**
	120	277	0.02
	0.0001	91.9	2.28
2 mk, step (~5%/s period)	200	2.86	0
	120	3.03	1.65
	0.0001	15.3	267
0.495 mk/s (fastest LOR)	120	4.05	4.06
	0.0001	46.3	15.4
0.002 mk/s (slowest LOR)	120	92.1	176
	0.0001	19.9	869

Reference Transient is Bounding
(Fissioning Nuclides)

Kinetics Parameters	Reactivity Limit (mk, step)	Starting Indicated Power (W)	Deposited Energy (kJ)
β(U235)=6.984	7.984 **(reference)**	**200**	**412**
		120	277
		0.0001	91.9
β(Pu239)=2.28	3.28	200	39.1
		120	28.9
		0.0001	15.1
β(Nat-U)=7.36	7.984	200	171
		120	112
		0.0001	25.3

Reference Transient is Bounding
(Actual Power at Trip)

- Actual power at trip (200 W indicated power):

$$P(\mathrm{W}) = F7 \times \frac{202.5}{180.9} \times 4.554 \times 10^{7} \times \frac{200}{50} \times \frac{1}{F2} \times 1.602 \times 10^{-13}$$

Nuclide	Total MeV/fiss (EPRI-NP-1771)	Prompt MeV/fiss (MCNP F7)	Ratio (±0.001)
U235	**202.5**	**180.9**	**1.119**
Pu239	207.0	189.4	1.093
Pu241	210.7	189.0	1.115
U233	198.0	180.8	1.095
U238	206.0	181.3	1.136
Nat-U	202.7	180.9	1.120

Note: 12.5% (1σ) standard error assigned to *P*

Prompt Neutron Generation Time
(called 1/v insertion method or α-static method)

- From static perturbation theory

$$\Lambda = \frac{\left(\Phi^*, \frac{1}{v}\Phi\right)}{\left(\Phi^*, F\Phi\right)} \quad \text{and} \quad \Delta\rho = -\frac{\left(\Phi^*, \Delta M \Phi\right)}{\left(\Phi^*, F\Phi\right)}$$

- Setting $\Delta M = \Delta\alpha / v$ and solving for Λ yields

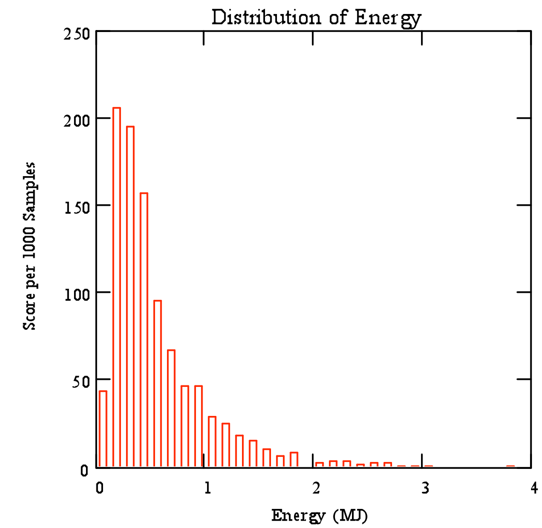
$$\Lambda = \lim_{\Delta\alpha \to 0}\left(-\frac{\Delta\rho}{\Delta\alpha}\right) = -\left(\frac{\partial\rho(\alpha)}{\partial\alpha}\right)_{\alpha=0}$$

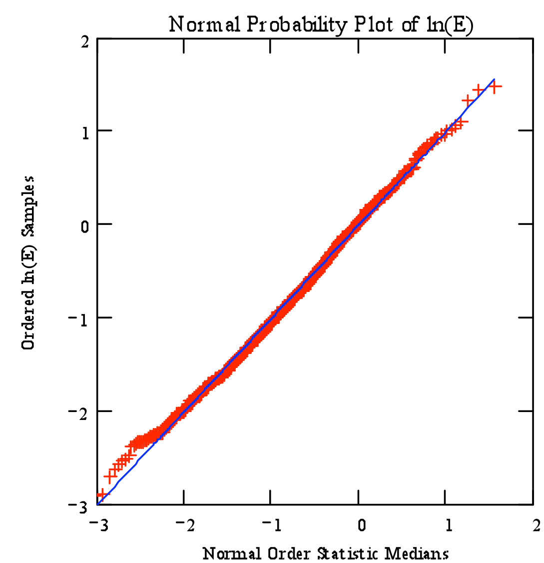
- MCNP4C ACODE option is used to calculate several values of $\rho(\alpha)$ by repeatedly solving *k*-eigenvalue equation with α constant:

$$\frac{1}{k} F\Phi = \left[M + \frac{\alpha}{v}\right]\Phi$$

Uncertainty Analysis

- 17 input parameters set at reference values: Λ, ρ_{IN}, P_A, LCR, H_C, (β_i, λ_i, i=1,6), each with a 1σ uncertainty
  - Uncertainty in M is included in the E_{AC}
  - Remaining parameters at their fixed values
- Repeatedly solve transient randomly sampling all 17 distributions each time
- Produces a log-normal distribution
  - linear normal probability plot of ln(E), R=0.9983
- 98.8% of the ln(E) distribution is less than ln(E_{AC})
- Very high confidence that E_{AC} will not be exceeded in the DBA with all parameters at their LCO limits or fixed values, including uncertainties and margins





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