References and Background

References

See separate handouts

- List of references
- List of acronyms and abbreviations

Continuous Probability Distributions

Background

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Continuous Distributions – General Definitions and Useful Relationships

- Probability density functions (pdfs)

$$f_X(x|\theta) \equiv \lim_{\Delta x \to 0} \frac{P\{x \leq X < x + \Delta x\}}{\Delta x} \qquad f_X(x|\theta) = \frac{dF_X(x|\theta)}{dx} = -\frac{d\bar{F}_X(x|\theta)}{dx}$$

- Cumulative distribution functions

$$F_X(x|\theta) \equiv P\{X \leq x|\theta\} \qquad F_X(x|\theta) = \int_{-\infty}^{x} f_X(x'|\theta)dx'$$

$$P\{x_1 \leq X < x_2|\theta\} = \int_{x_1}^{x_2} f_X(x'|\theta)dx' = F_X(x_2|\theta) - F_X(x_1|\theta)$$

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Continuous Distributions – General Definitions and Useful Relationships

- Complementary cumulative distribution functions

$$\bar{F}_X(x|\theta) \equiv P\{X > x|\theta\} \qquad \bar{F}_X(x|\theta) = \int_x^{\infty} f_X(x'|\theta)dx'$$

- Hazard functions

$$h_X(x|\theta) \equiv \lim_{\Delta x \to 0} \frac{P\{x \le X < x + \Delta x | X > x\}}{\Delta x}$$

$$h_X(x|\theta) = \frac{f_X(x|\theta)}{1 - F_X(x|\theta)} \qquad F_X(x|\theta) = 1 - exp\left(-\int_{-\infty}^{x} h_X(x'|\theta)dx'\right)$$

Continuous Distributions – General Definitions and Useful Relationships

- Moments
  - General

$$E[X^n] \equiv \int_{-\infty}^{x} (x')^n f_X(x')dx'$$

  - Mean Value

$$E[X] \equiv \int_{-\infty}^{x} x' f_X(x')dx'$$

  - Variance

$$Var[X] \equiv E[(X - E[X])^2] = E[X^2] - (E[X])^2$$

- Percentiles
  - General: x_α is the value that satisfies

$$P\{X \leq x_\alpha\} = \alpha \quad \alpha = \int_{-\infty}^{x_\alpha} f_X(x')dx'$$

  - Median $x_{0.50}$

$$0.50 = \int_{-\infty}^{x_{0.50}} f_X(x')dx'$$

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Some Continuous Univariate Distributions

Distribution	Domain	Density Function	Cumulative	Hazard
Exponential	$X \geq 0$	$\lambda e^{-\lambda x}$	$1 - e^{-\lambda t}$	λ
Gamma	$X \geq 0$	$\frac{\beta^{\alpha}}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x}$	Numerical	Numerical
Weibull	$X \geq 0$	$\frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1} e^{-\left(\frac{x}{\beta}\right)^{\alpha}}$	$1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}}$	$\frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1}$
Lognormal	$X \geq 0$	$\frac{1}{\sqrt{2\pi}\sigma x} e^{-\frac{1}{2}\left(\frac{ln x-\mu}{\sigma}\right)^{2}}$	Numerical	Numerical
Gumbel Type I	$-\infty < X < \infty$	$\frac{1}{\beta} exp\left\{-\left[\left(\frac{x-\mu}{\beta}\right) + \exp\left(-\frac{x-\mu}{\beta}\right)\right]\right\}$	$exp\left[-exp\left(-\frac{x-\mu}{\beta}\right)\right]$	$\frac{f_X(x\|\mu,\beta)}{1 - F_X(\mu\|\alpha,\beta)}$
Uniform	$a \leq X \leq b$	$\frac{1}{b-a}$	$\frac{x-a}{b-a}$	$\frac{1}{b-x}$
Beta	$0 \leq X \leq 1$	$\frac{\Gamma(b+a)}{\Gamma(b)\Gamma(a)} x^{a-1}(1-x)^{b-1}$	Numerical	Numerical

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Some Continuous Univariate Distributions

Distribution	Domain	Mean	Variance	Notes
Exponential	$X \geq 0$	$\frac{1}{\lambda}$	$\frac{1}{\lambda^2}$	Reverse J-shaped (mode at x = 0)
Gamma	$X \geq 0$	$\frac{\alpha}{\beta}$	$\frac{\alpha}{\beta^2}$	Reverse J-shaped (mode at x = 0) if $\alpha \leq 1$
Weibull	$X \geq 0$	$\beta\Gamma\left(1+\frac{1}{\alpha}\right)$	$\beta^2\,\Gamma\left(1+\frac{2}{\alpha}\right)-(E[X])^2$	Reverse J-shaped (mode at x = 0) if $\alpha \leq 1$
Lognormal	$X \geq 0$	$e^{\mu+\frac{1}{2}\sigma^2}$	$(E[X])^2 e^{\sigma^2-1}$	Mode: $e^{\mu-\sigma}$ Median: e^{μ} Range Factor ($X_{.95}/X_{.05}$): $e^{1.645\sigma}$
Gumbel Type I	$-\infty < X < \infty$	$\mu + 0.5772\beta$	$\frac{\pi^2}{6}\beta^2$	Mode: μ Median: $\mu - \beta ln(ln(2))$
Uniform	$a \leq X \leq b$	$\frac{b+a}{2}$	$\frac{(b-a)^2}{12}$	
Beta	$0 \leq X \leq 1$	$\frac{a}{b+a}$	$\frac{ba}{(b+a)^2(b+a+1)}$	Uniform if a = b = 1; reverse J-shaped (mode at x = 0) if a < 1 and b ≥ 1; J-shaped (mode at x = 1) if a ≥ 1 and b < 1; unimodal with mode between a and b otherwise.

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Background

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NRC Mission

"The U.S. Nuclear Regulatory Commission licenses and regulates the Nation's civilian use of radioactive materials to protect public health and safety, promote the common defense and security, and protect the environment."

- NUREG-1614 (NRC Strategic Plan)

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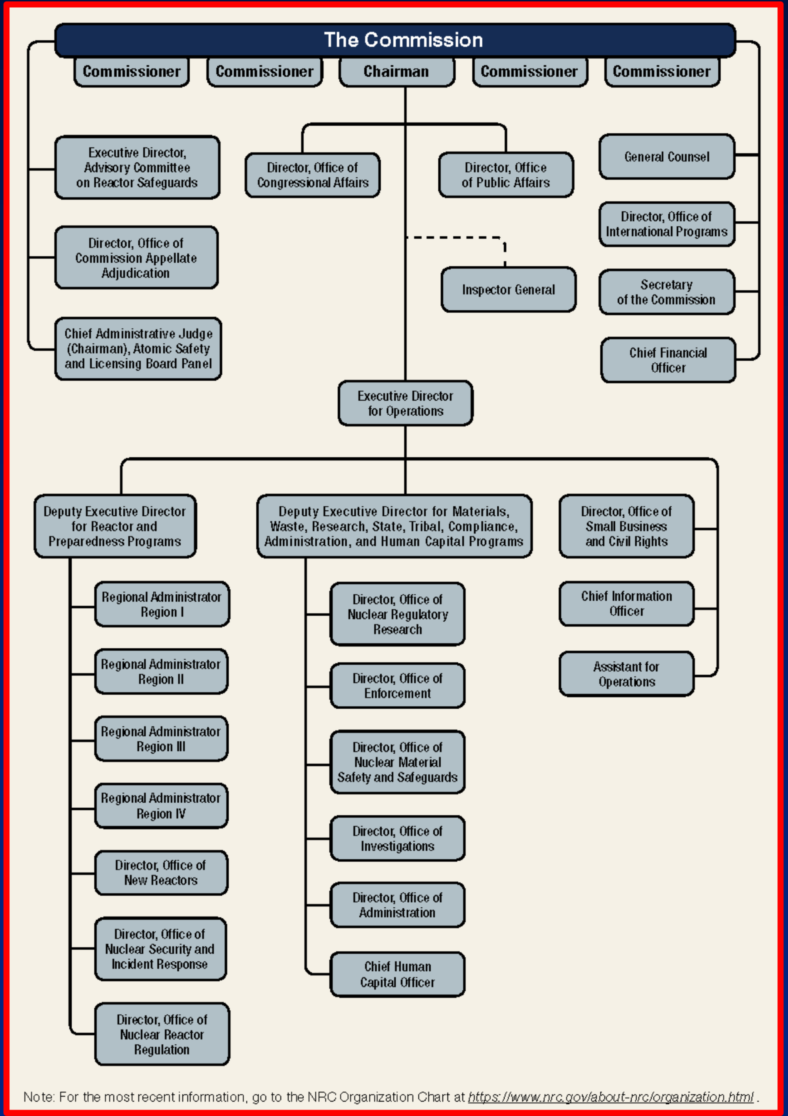
NRC Organization

- Headquarters + 4 Regional Offices
- 5 Commissioners
- Staff and budget (FY 2018)
  - ~3200 staff
  - Total budget ~$940M
  - Research budget ~$43M
- Website: www.nrc.gov
- Information Digest: NUREG-1350, V30



NUREG-1350, v30, 2018

Regulatory Approach

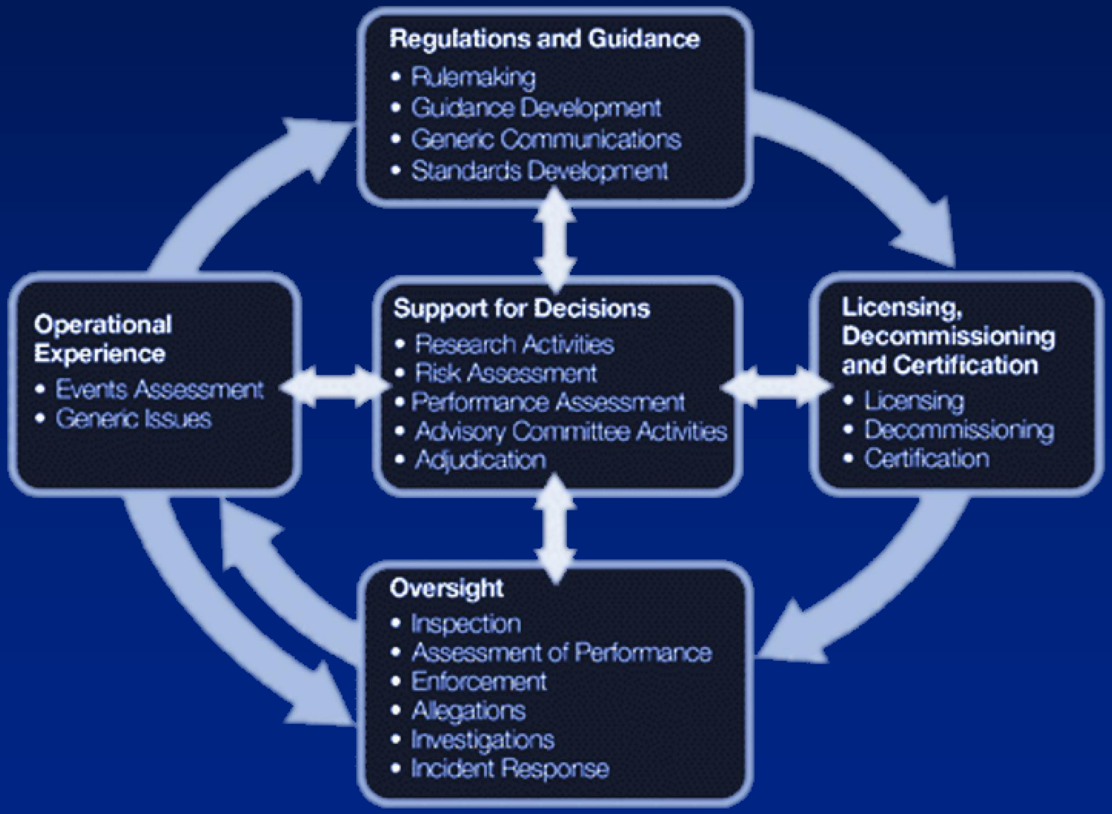
Standard

"Reasonable assurance of adequate protection"

Principles

- Independence
- Openness
- Efficiency
- Clarity
- Reliability

How We Regulate



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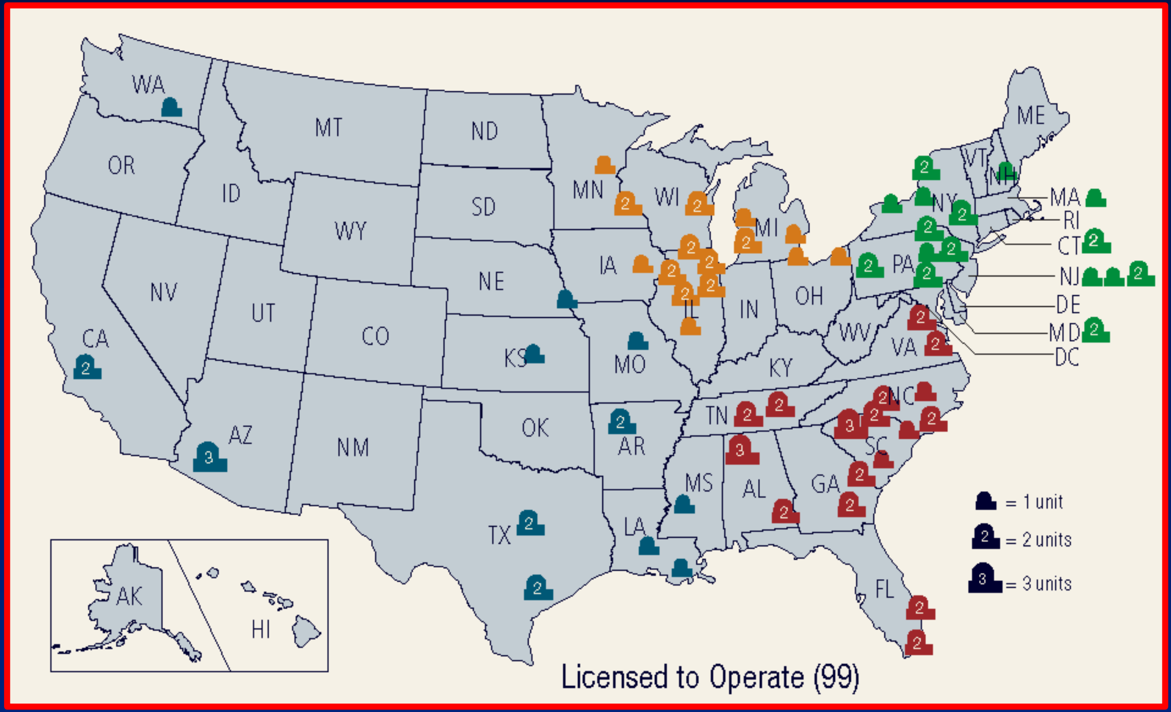
U.S. Nuclear Power Plants



NUREG-1350, v30, 2018

- 99 plants (61 sites)
- ~99 GWe, ~805 GW-hr (2017) = 20% U.S. total
- Worldwide: 450 plants, 394 GWe capacity

Regulatory Documents

- Regulations - http://www.nrc.gov/reading-rm/doc-collections/cfr/
- Regulatory Guide (RG) - http://www.nrc.gov/reading-rm/doc-collections/reg-guides/
- Standard Review Plan (SRP) - http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0800/
- NUREG Series Reports - http://www.nrc.gov/reading-rm/doc-collections/nuregs/
- Policy Statements - http://www.nrc.gov/reading-rm/doc-collections/commission/policy/
- Inspection Manual - http://www.nrc.gov/reading-rm/doc-collections/insp-manual/

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Regulatory Documents - Examples

Regulation

- 10 CFR 50, Appendix A, Criterion 2
- Structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions.

RG

- RG 1.76, “Design-Basis Tornado and Tornado Missiles for Nuclear Power Plants”
  - NUREG/CR-4461, “Tornado Climatology of the Contiguous United States,”
- RG1.221, “Design-Basis Hurricane and Hurricane Missiles for Nuclear Power Plants”
  - NUREG/CR-7004 Technical Basis for Regulatory Guidance on Design-Basis Hurricane-Borne Missile Speeds for Nuclear Power Plants
  - NUREG/CR-7005 Technical Basis for Regulatory Guidance on Design-Basis Hurricane Wind Speeds for Nuclear Power Plants

SRP

- Standard Review Plan Chapter 3.3.1, “Wind Loading”
- Standard Review Plan Chapter 3.5.1.4, “Missiles Generated By Tornadoes And Extreme Winds”

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General Design Criterion 35

Emergency core cooling. A system to provide abundant emergency core cooling shall be provided. The system safety function shall be to transfer heat from the reactor core following any loss of reactor coolant at a rate such that (1) fuel and clad damage that could interfere with continued effective core cooling is prevented and (2) clad metal-water reaction is limited to negligible amounts.

Suitable redundancy in components and features, and suitable interconnections, leak detection, isolation, and containment capabilities shall be provided to assure that for onsite electric power system operation (assuming offsite power is not available) and for offsite electric power system operation (assuming onsite power is not available) the system safety function can be accomplished, assuming a single failure.

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Safety Goal Policy Statement (51 FR 30028; August 21, 1986)

- Commission view on "how safe is safe enough?"
- Two quantitative health objectives (QHO) for the current generation of light water reactors
  - The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed 0.1% of the sum of prompt fatality risks resulting from other accident to which members of the U.S. population are generally exposed
  - The risk to the population in the area of nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed 0.1% of the sum of cancer fatality risks resulting from all other causes.

Safety Goal Policy Statement (cont.)

Based on CDC data,* the QHO's translate to:

- Accidents: 41.3 per 100,000 per year

  41.3/100,000 * 0.001 = ~5E-07/yr

- Cancers: 185 per 100,000 per yr

  185/100,000 * 0.001 = ~2E-06/yr

- Note: these are population-averaged risks to an individual

*See http://www.cdc.gov/nchs/data/nvsr/nvsr64/nvsr64_02.pdf

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Safety Goal Policy Statement (cont.)

Surrogate safety goals*

- LERF <10^{-5} per year => surrogate for early fatality QHO
  - "Worst case" conditional probability of individual prompt early fatality (CPEF) for large early release = 3E-2**
  - 3E-2 fatality risk/large early release * 1E-05 LERF = 3E-7 individual prompt fatality risk/yr.
- CDF <10^{-4} per year => surrogate for latent cancer QHO
  - "Worst case" conditional probability of latent cancer fatality (CPLF) from large release = 4E-03
  - 4E-3 latent fatality/large release * 1E-4 core damage/year * 1 large release/core damage = 4E-07 individual latent cancer fatality risk/yr.

*See NUREG-1860, App. D for a justification
**Based on NUREG-1150 results for Surry (a PWR)

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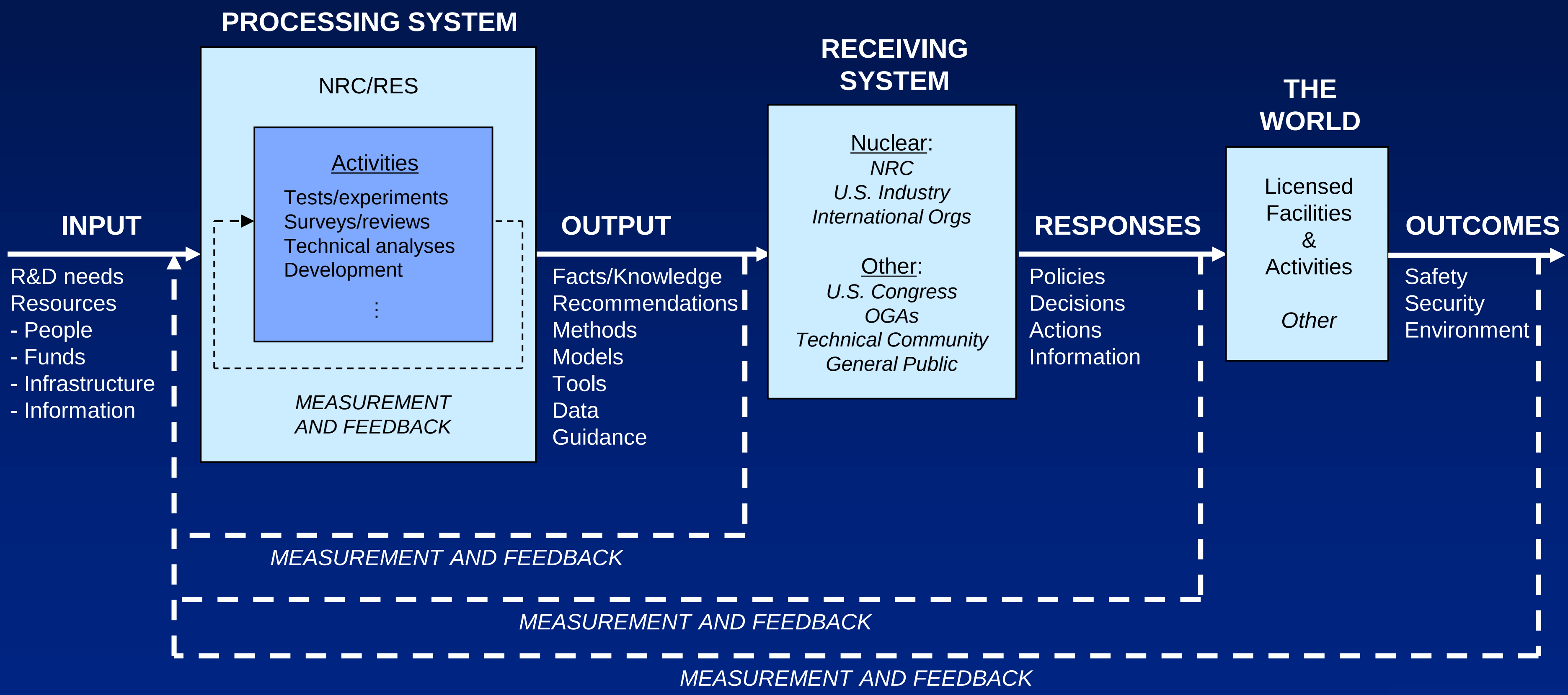
PRA Policy Statement (60 FR 42622; August 16, 1995)

1) The use of PRA technology should be increased in all regulatory matters to the extent supported by the state-of-the-art in PRA methods and data and in a manner that complements the NRC's deterministic approach and supports the NRC's traditional defense-in-depth philosophy.
2) PRA and associated analyses should be used in regulatory matters, where practical within the bounds of the state-of-the-art, to reduce unnecessary conservatism associated with current regulatory requirements, regulatory guides, license commitments, and staff practices. Where appropriate, PRA should be used to support the proposal for additional regulatory requirements in accordance with 10 CFR 50.109 (Backfit Rule).
3) PRA evaluations in support of regulatory decisions should be as realistic as practicable and appropriate supporting data should be publicly available for review.
4) The Commission's safety goals for nuclear power plants and subsidiary numerical objectives are to be used with appropriate consideration of uncertainties in making regulatory judgments on the need for proposing and backfitting new generic requirements on nuclear power plant licensees.

NRC R&D in the System



Adapted from National Research Council, "World-Class Research and Development Characteristics for an Army Research, Development and Engineering Organization," National Academy Press, Washington, DC, 1996, ISBN 0-309-05589-X.

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NRC Information

- Website: www.nrc.gov
- Agencywide Document Access and Management System (ADAMS): http://adams.nrc.gov/wba/
- Jobs (USAJOBS): http://www.nrc.gov/about-nrc/employment/apply.html
- Status of Risk-Informed Activities: https://www.nrc.gov/about-nrc/regulatory/risk-informed/rpp.html