Risk Assessment & Long Term Operation

Mohsen Khatib-Rahbar
Energy Research, Inc.
6167 & 6189 Executive Blvd.
Rockville, Maryland 20852

January 20, 2011
University of Applied Sciences
Brugg, Switzerland

Outline

- Risk assessment studies & long-term operation
- Risk Issues for Operating Plants
- Risk of operating versus new designs
- Status of Containment Challenging Issues for Operating Plants vs. New Designs
- Risk of Operating Plants vs. New plants
- Summary

Risk Assessment Studies

- Probabilistic Safety/Risk Assessment (PSA/PRA) have been performed for most if not every operating plant world-wide. These include:
  - Level-1 (core damage frequency) PSAs for various initiators (internal events, fires, floods, seismic, refueling, low power, shutdown, refueling, etc.)
  - Level-2 (severe accident impact of containment integrity and estimation of radiological releases to environment) – for all U.S., Swiss and most of other European plants.
  - Level-3 (offsite health and other consequences) for few plants.

Long-term Operation

- Systematic process to guide safety improvement for NPPs. NPPs operate for a long-term (over 40 years).
  - Safety is highest priority (i.e., risk of continued operation must remain low).
  - Even though risk studies are not "perfect", nonetheless, the PSA/PRA process has proven very effective in identifying vulnerabilities and in focusing attention:
    - Operators – focus on most risk/beneficial backfits and operational/maintenance improvements.
    - Regulators – focus on issues that drive safety to protect public health/ safety and the environment.
  - Important that PSAs (as for all Swiss plants):
    - Include "non-full power" (outage/refueling) modes of operation.
    - Living (up to date).
    - Follow technically acceptable "standards/guidelines".

Examples of PSA/PRA Limitations

- PSAs model all active (including stand-by) and some passive (pipes, SGs, RPV, etc.) systems, structures, and components (SSCs, operator actions, and impacts of various systems interactions
  - Snap-shots in time, using average failure rates based on actuarial observations and statistics (“short lived” SSCs)
- PSAs do not include:
  - Time change of service-related characteristics and properties of equipment
  - Models for passive or long-lived SSCs. Failure mechanisms such as:
    - Reactor pressure vessel embrittlement;
    - Steam generator tube corrosion and cracking;
    - Environmental qualification for in-containment cables & other electrical equipment; and
    - Fatigue, stress corrosion cracking, and other mechanisms that may affect a variety of metal components,
  - Adequate (generally acceptable) models for computer hardware & “software” reliability.

Risk Issues for Operating Plants

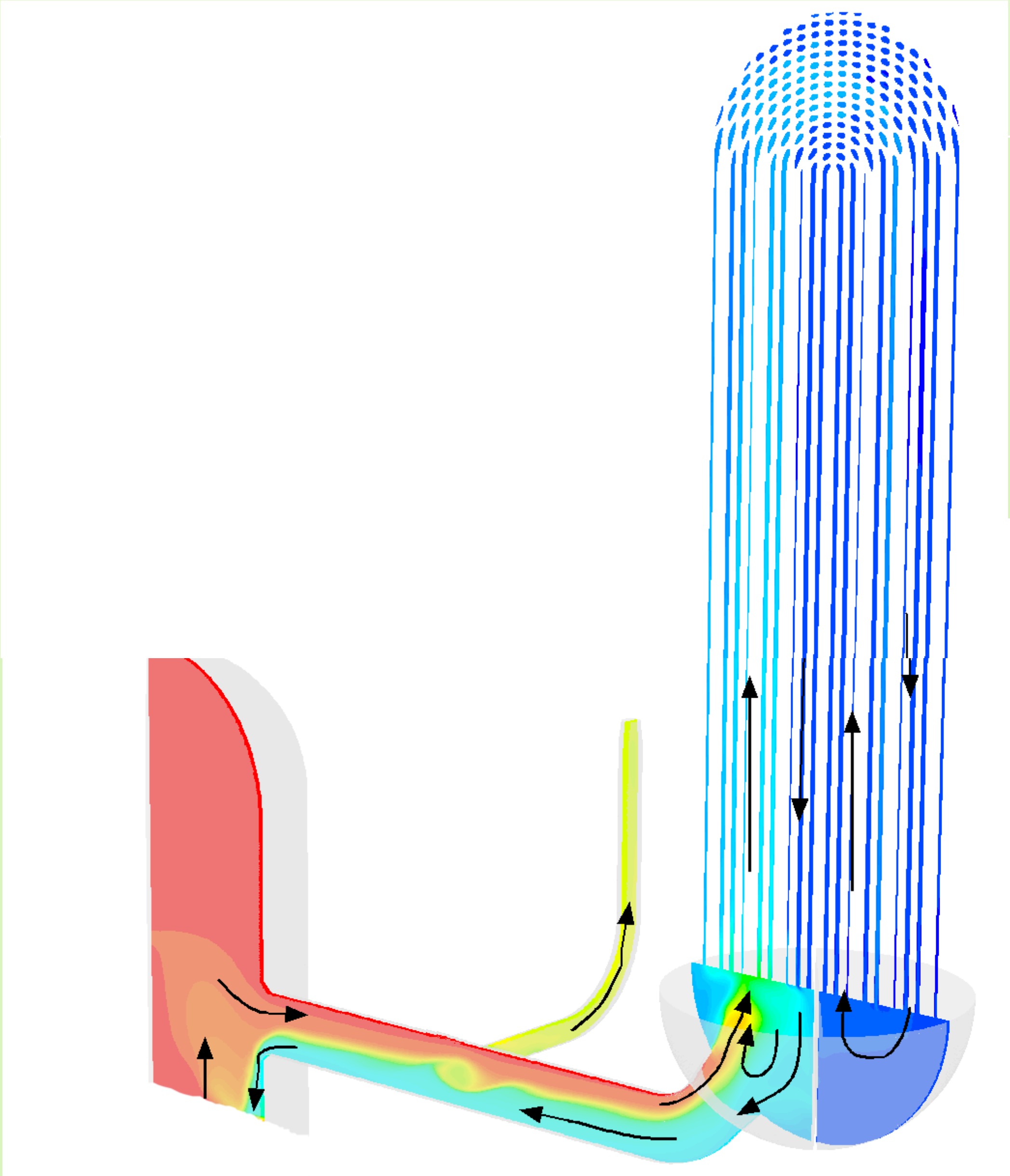
- Results of PSA/PRA studies for operating plants have shown that risk is dominated by:
  - Loss of AC power, support system transients
  - Human errors
  - Induced LOCAs (pump seal leakage) (PWRs)
  - Internal fires and flooding initiators for some units
  - Seismic initiators for units at location with higher seismicity (most important contributor for Swiss plants)
  - Phenomena/processes that result in early failure of the reactor containment
  - Events that result in containment bypass:
    - PWRs:
      - Steam Generator Tube Rupture (SGTR) – as initiator and/or induced
      - Interfacing system breaks outside containment (ISLOCA)
    - BWRs:
      - Unisolated steamline breaks outside containment
      - Other breaks outside containment

Status of Containment Challenging Issues for Operating Plants vs. New Designs

Severe Accident Challenge	Operating Plants	New Designs
In-Vessel Steam Explosions (α-mode)	CCFP $<10^{-4}$. Issue resolved from regulatory perspective	Same as operating plants
Ex-Vessel Steam Explosions	Dynamic loads on structures: • PWRs: not significant to CF • BWRs: some significance to CF	Concerns about structures in cavity/pit ("protective" layers) & core catcher. More significant for BWRs.
High Pressure Reactor Vessel Breach (Vessel Rocketing)	Not significant (CCFP $<10^{-4}$) for most plants (especially those with lower vessel head penetrations)	Most new designs are equipped with depressurization system. CCFP same or lower.
High Pressure Reactor Vessel Breach (Direct Containment Heating)	• Extensively studied (NRC) & shown that CCFP <0.10 (PWRs) (Issue resolved from regulatory perspective) (even without induced failure). • Limited studies for BWRs (lower CCFP due to ADS and/or induced failures/depressurization).	Most new designs are equipped with depressurization system. CCFP same or lower (stronger containments).
Molten Core Concrete Interactions (MCCI)	Significant contributor to containment pressurization & fission product releases (both PWRs & BWRs)	Engineered "methods" (core catcher) to avoid CCI: • Spreading compartment (EPR) • Lower Head Cooling (AP1000) • BiMAC (ESBWR)

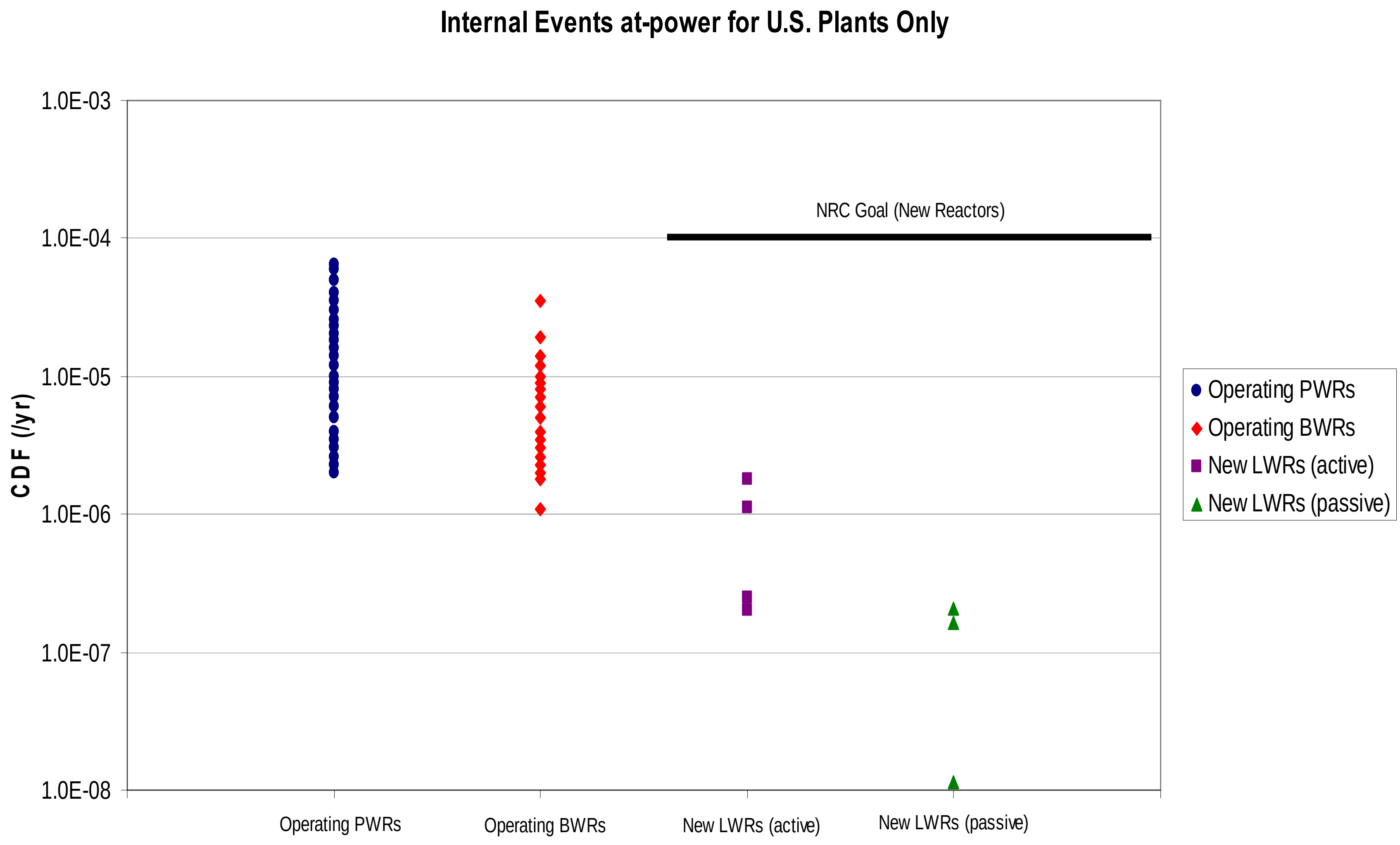
Status of Containment Challenging Issues for Operating Plants vs. New Designs (Cont)

Severe Accident Challenge	Operating Plants	New Designs
Induced Failures of Reactor Coolant System **PWRs:** Hot Leg Nozzles, Hot Leg Pipe, Pressurizer Surge Line, SG Tubes. **BWRs:** Steam Line Nozzles, Failure of SRVs, and Relief Line Vacuum Breakers (that may result in suppression pool bypass).	**PWRs:** At locations other than SG: $0.95 \leq CP \leq 1.0$ Steam Generator Tube Rupture (SGTR): $0 \leq CP \leq 0.05$ (depending on material, extent of flaws [foreign objects], if secondary side depressurized, etc.). Studies on-going – Issue not yet closed **BWRs:** At all locations (SL, SRVs): $0.90 \leq CP \leq 1.0$	Similar, if not depressurized.
Hydrogen Combustion	• Distribution of H_2 difficult to assess (especially for compartmentalized containments). Large, open containments (e.g., Beznau) less susceptible to pocketing (detonable mixtures). • PSA/PRA studies show 0 < CCFP < 0.10 • Hydrogen combustion mitigated by inerting (Mühleberg), deliberate ignition systems (Leibstadt) or Passive Autocatalytic Recombiners (PARs) (Beznau)	Engineered systems to promote mixing and prevent combustion: Inert (ABWR, ESBWR), Igniters (AP1000, APWR), PARs (EPR)



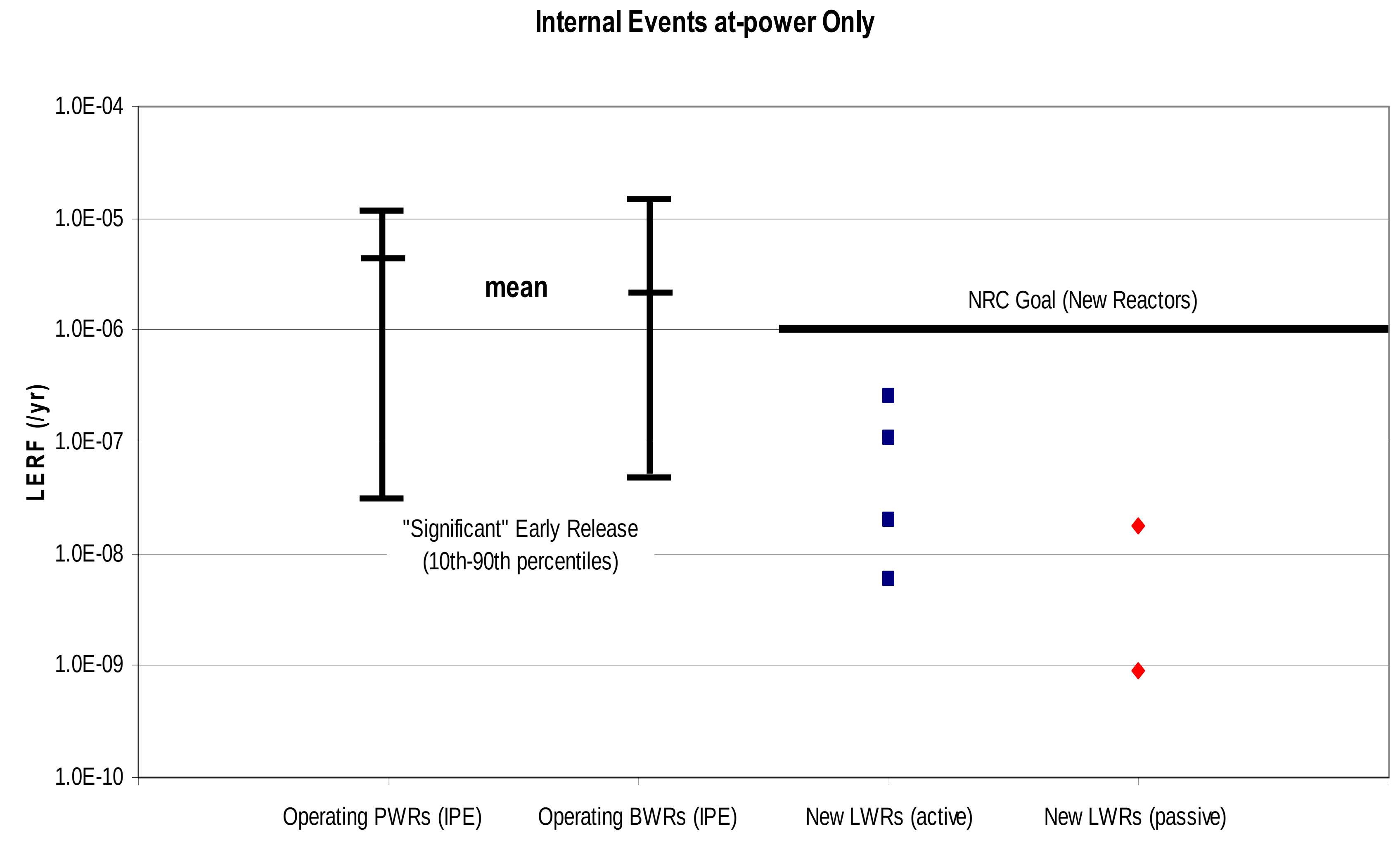
Ref: F. Boyd and K. Armstrong (NRC 2009)

Core Damage Frequency: Operating Plants vs New LWRs



Source: D. A. Dube 2009

Large Early Release Frequency: Operating Plants vs New LWRs



Source: D. A. Dube 2009

Summary

- Risk of operating plants generally understood:
  - Risk and severe accident issues for the most part, understood, and regulatory closure achieved
  - Research that continues is confirmatory and should helps in reducing lingering uncertainties.
- Safety issues for operating plants understood (even though some uncertainties linger):
  - Risk insights being used increasingly to improve operations, guide backfits & new plant designs
  - Safe long-term operation is being assured through various programs (e.g., accident management programs, aging management programs, etc.)

Summary (Cont.)

- Safety improvements for new designs, for the most part, are based or guided by PSA/PRA insights for operating plants
  - Increased separation and diversity
  - Reduction in frequency of interfacing systems LOCAs for PWRs (Refueling Water Storage Pool moved into the containment)
  - Reduction in frequency of high pressure accident scenarios (automatic and improved depressurization systems)
  - Reduction in containment failure probability due to combustion (hydrogen mixing & control systems)
  - Elimination of potential for core concrete interactions and late containment pressurization & failure (lower head cooling or passive cooling of core debris ex-vessel [“core-catchers”] & containment venting for some designs)
  - Generally, strong containments without any potential for direct melt attack (e.g., shell melt-through for some BWR/MARK I)