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Advanced Reactor Operating Experience Data Analysis to Support Risk Estimation: Challenges, Current Practice, and Needs

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Changing the World's Energy Future

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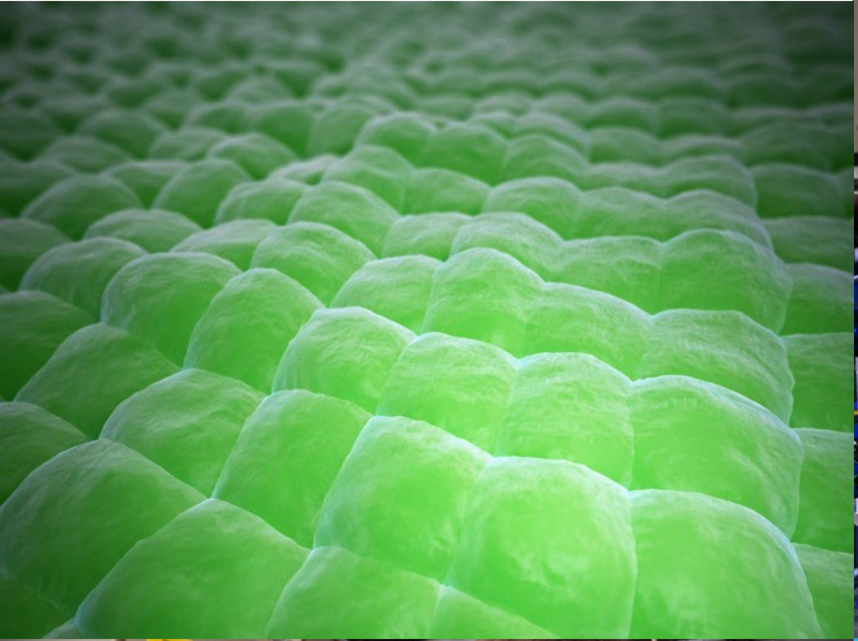

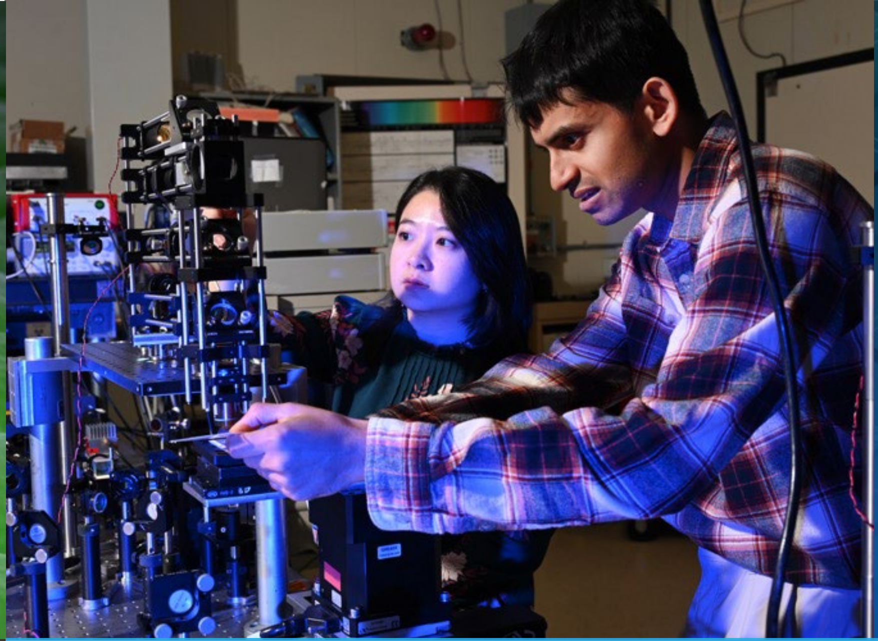

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Advanced Reactor Operating Experience Data Analysis to Support Risk Estimation

Challenges, Current Practice, and Needs

Outline

- Background
- Challenges
- Current and past practices
  - Chinese High Temperature gas-cooled Reactor – Pebble-bed Module (HTR-PM)
  - U.S. Modular High Temperature Gas-cooled Reactor (MHTGR)
- Needs

Background

- Nuclear power plant risk estimation requires input parameters such as component unreliability, initiating event frequencies, and common cause failure probabilities.
- Risk model parameters are typically estimated by using statistical methods based on operating experience (OpE) data. For example:
  - U.S. Nuclear Regulatory Commission Reactor Operational Experience Results and Databases for light-water reactors (LWRs) [1]
    - Collects performance data from U.S. commercial nuclear power plants
    - Characterizes industry-average performance
    - Estimates industry-average risk model parameters
    - Collects various OpE data (component type, failure mode, running hours, failure counts)

Challenges

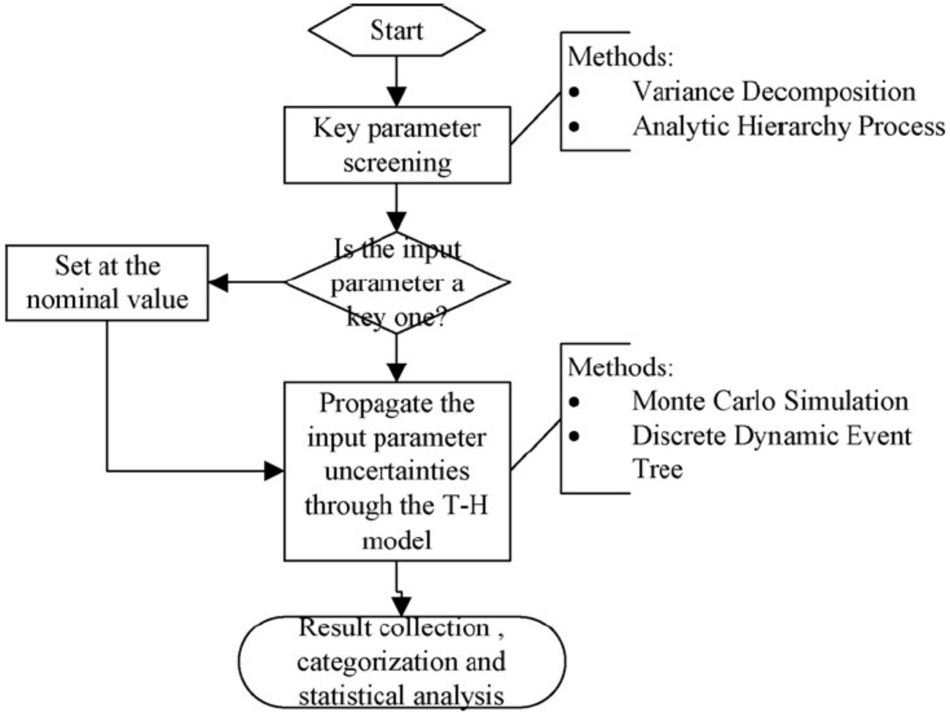
- Challenges exist when applying this same approach to estimate non-LWR (NLWR) risk model parameters.
  - Lack of NLWR OpE data
  - Complications in extrapolating LWR OpE data to NLWRs
    - New systems, structures, and components (SSCs)
      - Passive systems
      - Digital instrumentation and control systems
    - New "demands" (operating environments)
      - Diverse coolant options such as helium and sodium
      - Harsh environments involving high temperatures or corrosivity
    - New "capacities" (material properties)

Current Practice – Chinese HTR-PM

- Chinese HTR-PM overview
  - High-temperature gas-cooled reactor (HTGR) demonstration project
  - Began producing power in 2021, with commercial operation starting in 2023
  - Performed probabilistic risk assessments (PRAs)
    - Piloted the trial use version of the NLWR PRA standard (ASME/ANS RA-S.1.4-2013) [2]
    - Developed and adopted a risk metric for HTR-PM [3]
      - The cumulative frequency of all the beyond-design-basis accident sequences, which may cause off-site (including at site boundaries) individual effective doses in excess of 50 mSv, should under 1E-6 per reactor year
        - PRA output 3.7E-7 < 1E-6 limit

Current Practice – Chinese HTR-PM (cont.)

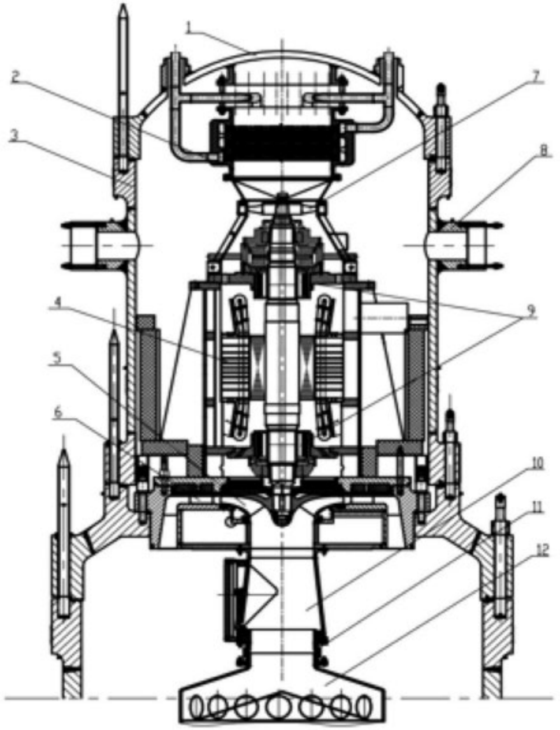
- HTR-PM PRA parameter estimation
  - Statistical approach [3]
    - Relied on a collection of databases, including:
      - Reliability database for German HTR designs [4]
      - Electric Power Research Institute Advanced LWR Utility Requirements document [5]
      - NUREG/CR-6928 [6] and NUREG/CR-2728 [7]
  - Physics-based approach [3]
    - Simulation-based method
      - Passive systems (e.g., loss of residual heat removal system)
  - Expert elicitation approach [3]
    - Loss-of-coolant accident frequency estimated via the expert elicitation process outlined in NUREG-1829



Passive-system reliability evaluation framework (Courtesy: Tong et al. [3])

Current Practice – Chinese HTR-PM (cont.)

- HTR-PM PRA parameter estimation (cont.)
  - Decomposing approach [8]
    - Proposed for first-of-a-kind SSCs
    - Applied to the HTR-PM helium circulator
      - Decomposed the circulator into 12 parts
      - Part failure rates were estimated based on nuclear and non-nuclear databases (e.g., Nonelectronic Parts Reliability Data) [9]
      - The helium circulator failure rate was estimated using a Bayesian network, with inter-part functional dependencies modeled

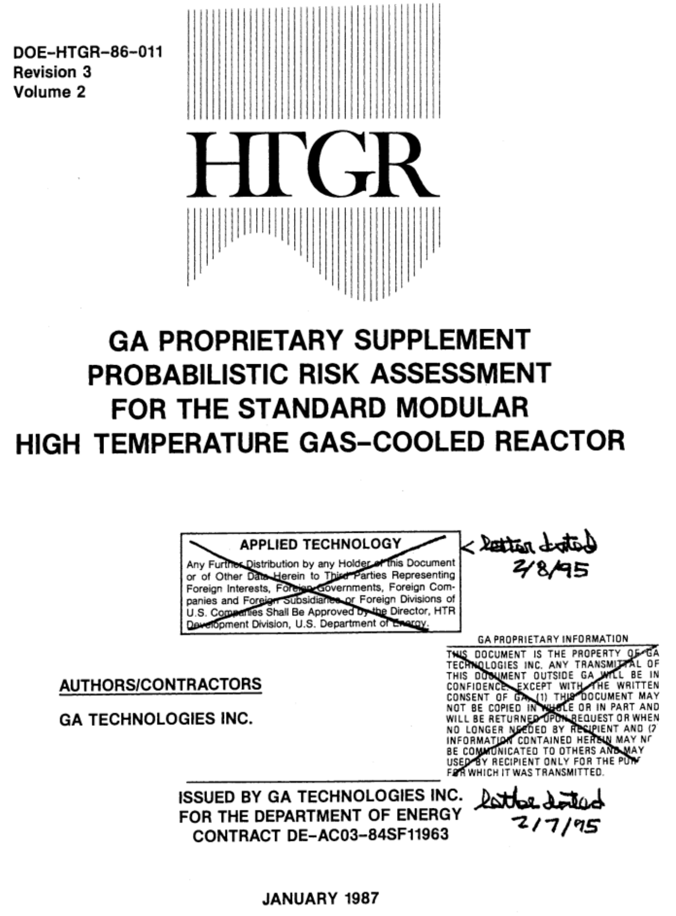


1-Head cover, 2-Motor cooler, 3-Shell, 4-Drive motor, 5-Impeller, 6-Diffuser, 7-Auxiliary impeller, 8-Electrical penetration assembly, 9-Electromagnet bearing, 10-Fan damper, 11-Expansion joint, 12-Inlet box

Structure of a helium circulator
(Courtesy: Chen et al. [8])

Past Practice – U.S. MHTGR

- U.S. MHTGR overview
  - Designed by General Atomics in the 1980s
  - Performed PRA at the pre-application stage [10]
  - Developed a set of risk model parameters
    - Compiled data from various sources, including:
      - HTGR OpE from Peach Bottom Unit I and Fort St. Vrai
      - LWR OpE
      - Non-nuclear applications (e.g., coal plants)
    - Developed a gas-cooled reactor reliability data bank [11]



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HTGR

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PROBABILISTIC RISK ASSESSMENT
FOR THE STANDARD MODULAR
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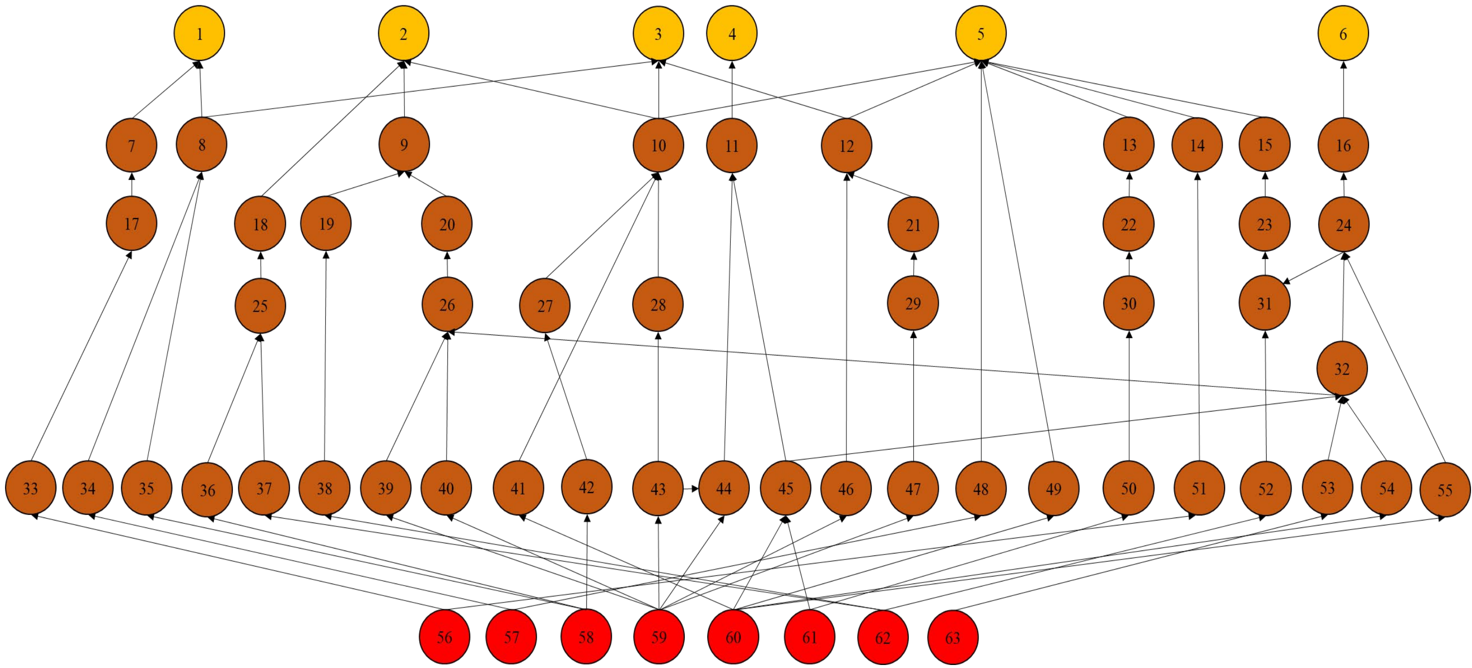
Needs

- **Need #1: Utilize existing data**
  - Curate the broadest, most relevant data possible
  - Adapt existing data to advanced reactors (e.g., k-factor adjustment) [12]
- **Need #2: Enable use of additional data**
  - Push back the level of data collection by, among other things:
    - Decomposing SSCs into parts
    - Determining quantitative relations between degradation and failure
- **Need #3: Prepare to collect new data**
  - Establish guidance on advanced reactor OpE data collection
  - Develop test facilities (e.g., a digital instrumentation and control testbed)
  - Be creative at the data collection level (e.g., part failure data, degradation and near-miss data, and load-capacity data)



INL work on causal failure network construction
(Courtesy: Zhang et al. [13])

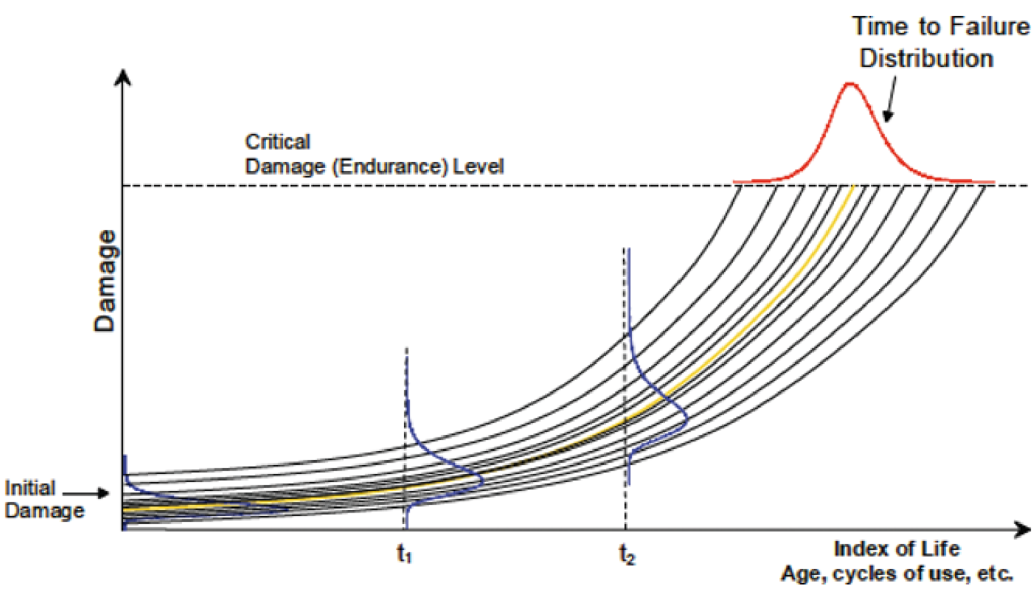
Failure causes

Failure modes

Degradation process

Needs (cont.)

- **Need #4: Embrace hybrid use of parameter estimation methods**
  - Statistical methods
  - Probabilistic physics-of-failure (PPoF) methods [14]
    - Stress-strength model
    - Damage-endurance model
    - Performance requirements model
    - Realized using computational risk assessment [15]
  - Non-PPoF model-based methods
    - Part-to-component model
    - Degradation-to-failure model
- **Need #5: Embrace advanced computational tools and capabilities**
  - RAVEN and other such examples [16]
  - High-performance computing capabilities
  - Artificial intelligence and machine learning capabilities



Damage-endurance model
(Courtesy: Modarres et al. [14])

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