Licensing needs for future plants

ACRS workshop on Regulatory Challenges
for Future Nuclear Power Plants

Ron Simard
Senior Director, Business Services
Nuclear Energy Institute

June 5, 2001

NEI

New Nuclear Power Plants - New Momentum

- Growing electricity demand, need for new generating capacity
- Fossil fuel price volatility, clean air constraints
- Improving economics of new nuclear power plants
- Industry consolidation = companies large enough to undertake large capital projects
- Significant public and political support
- Potential for greater certainty in the licensing process

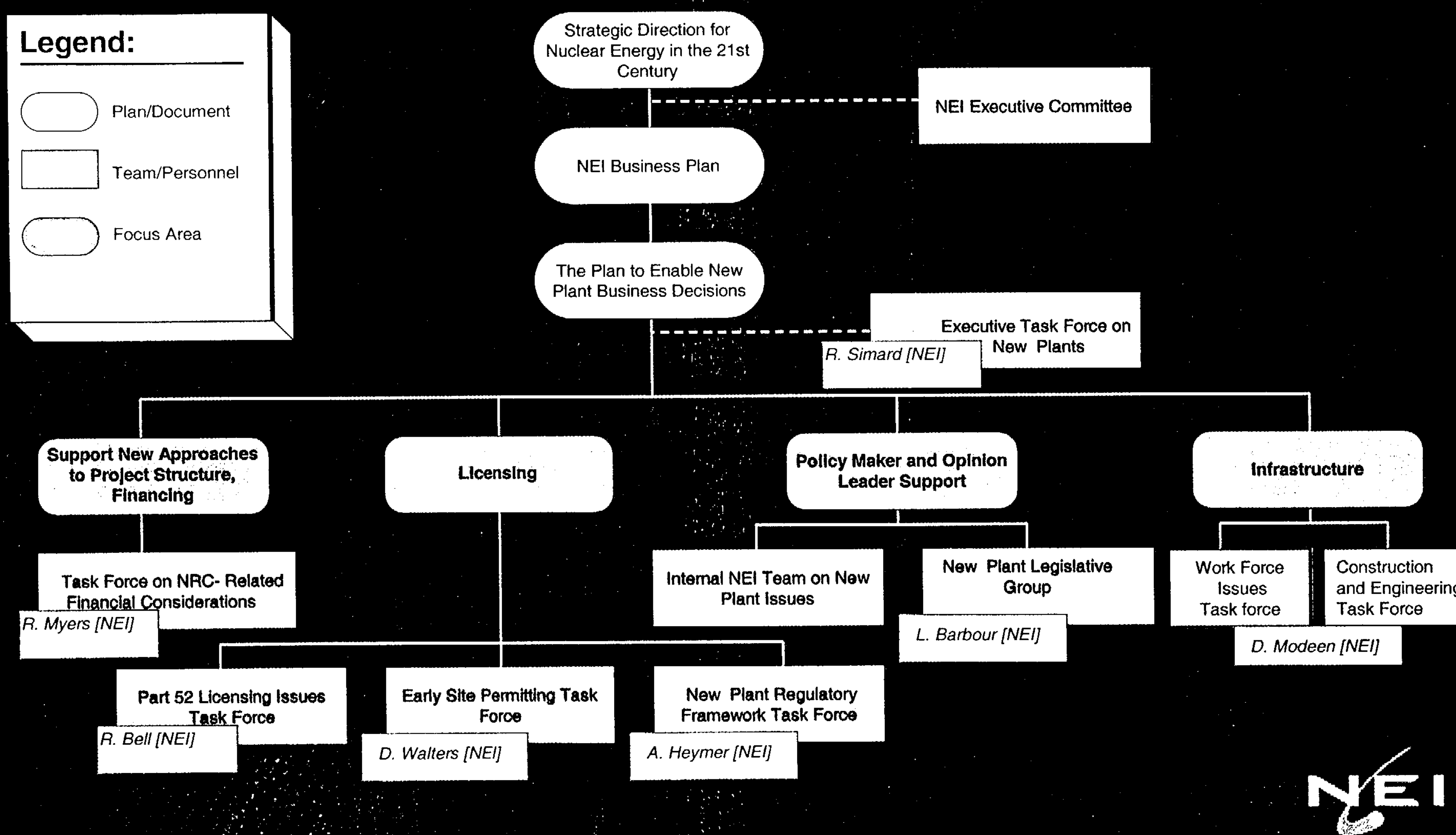
NEI

Focus of efforts to pave the way for new plants

- Policy, legislative, regulatory changes needed to support new approaches to ownership, risk sharing and project financing
- Policymaker support (Administration, Congress and others)
- Infrastructure (people, hardware, services) to support new and current plants
- Licensing, licensing, licensing

NEI

Activities in support of the plan to enable new plant business decisions



Licensing needs with respect to ...

- working out the Part 52 implementation details
- assuring safety and equitable application of regulations to new types of designs
- clarifying how financial related requirements apply in the new business environment

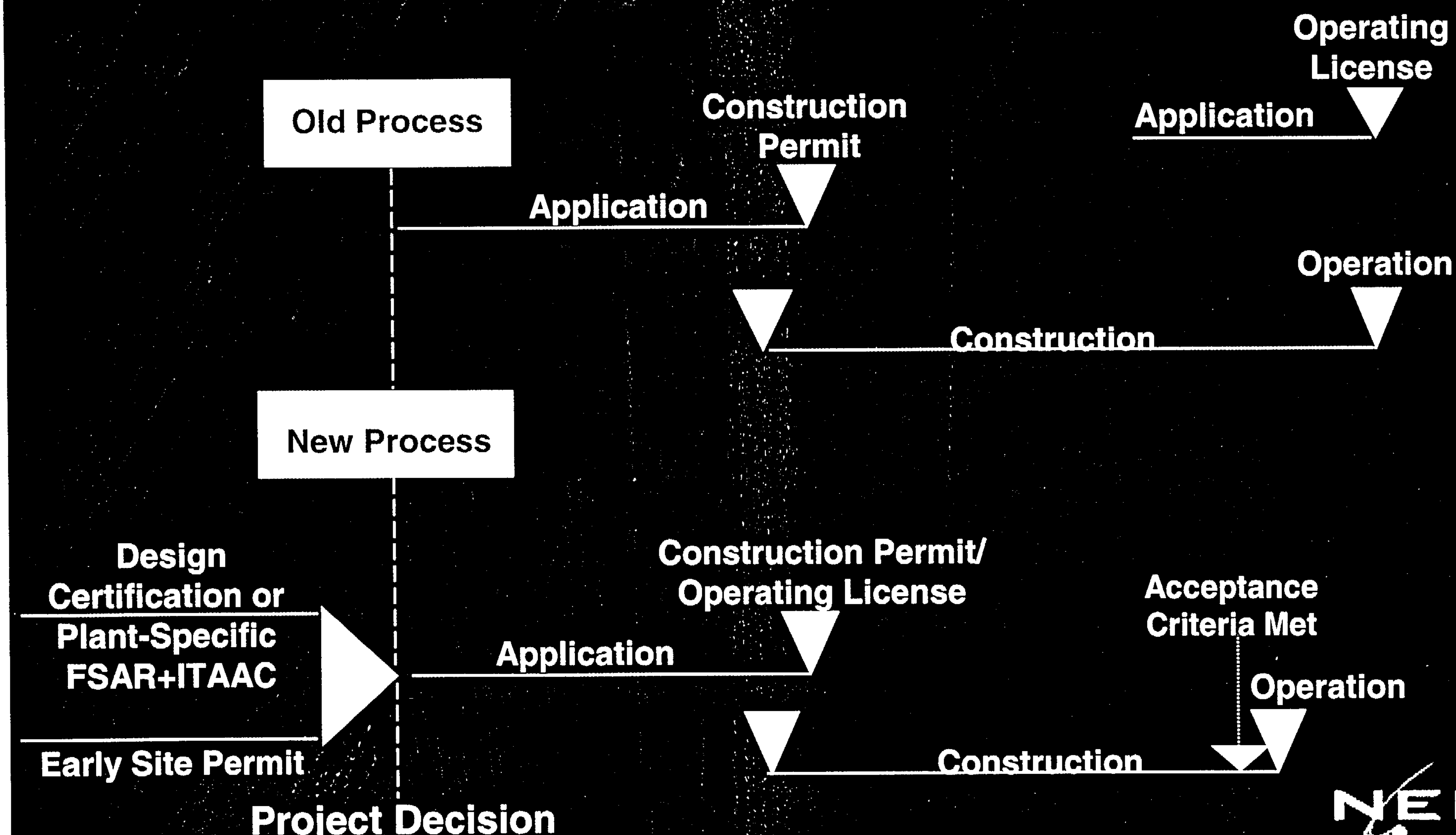
NEI

Examples of Part 52 licensing needs

- a timely and efficient ESP process (e.g., focusing on the incremental impacts of additional reactors at existing sites)
- a timely and efficient process for COL applications and reviews
- an efficient process for construction inspection and ITAAC verification

NEI

New Licensing Process Significantly Reduces Project Risk



NEI

“New design” licensing needs (in addition to safety determinations)

- For modular designs, clarification of
  - number of licenses per facility
  - application of Price Anderson requirements
  - basis for Part 171 annual fees
  - basis for control room staffing
- For gas cooled designs, clarification of
  - decommissioning funding levels
  - generic environmental impacts (Tables S-3, S-4)
  - basis for EP action levels, reporting requirements, implementation of NUREG-0654

NEI

Licensing needs for the new business environment

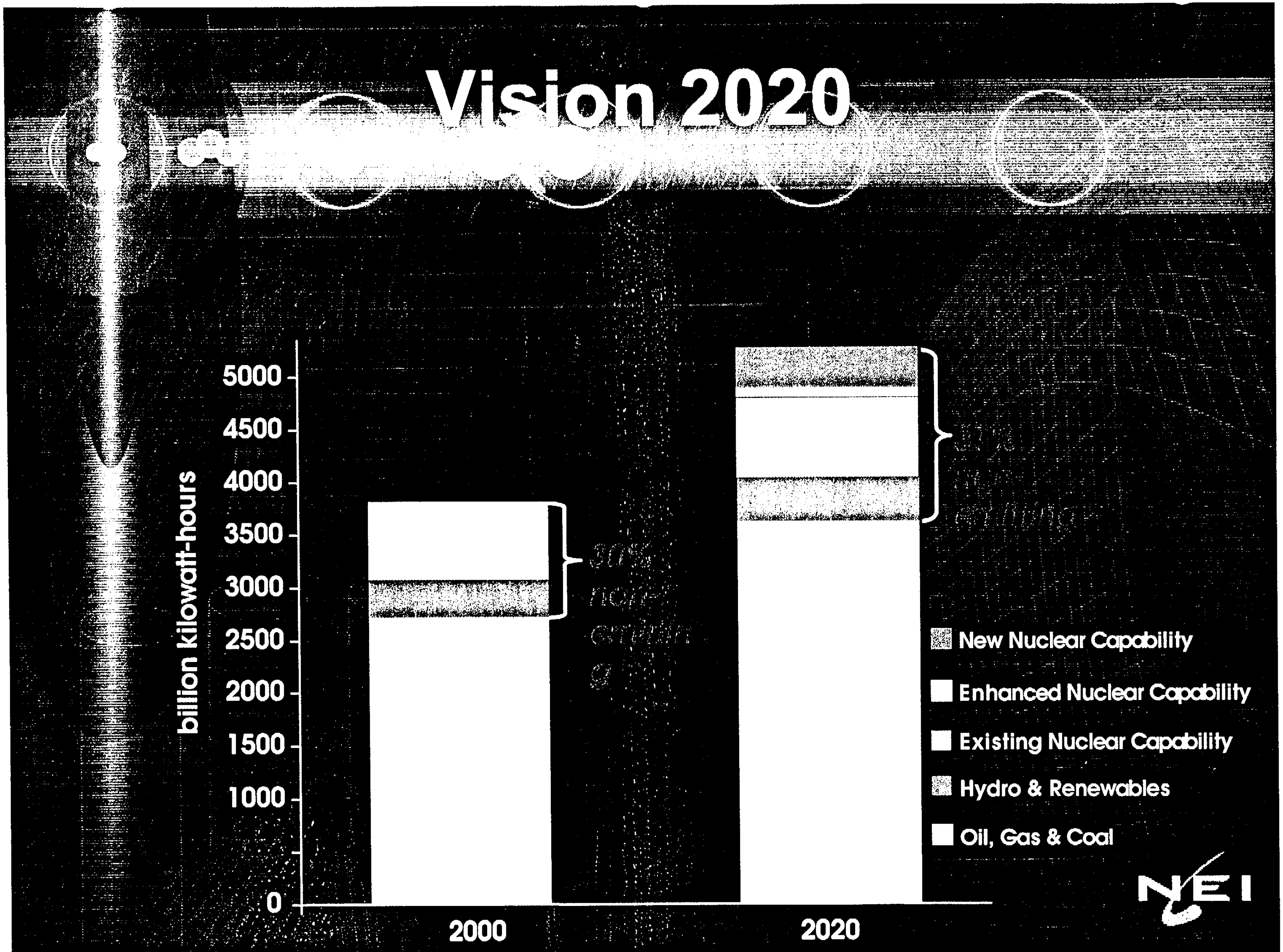
- Clarification of how financial related requirements apply to merchant nuclear plants
  - no need for an NRC antitrust review
  - nature of financial qualifications
  - appropriate mechanisms for decommissioning funding assurance

NEI

The nuclear energy imperative

- DOE projects 400,000 MW of additional capacity needed by 2020 (to replace existing plants that reach end of life and to meet new demand)
- 30% of our current generation is non emitting (nuclear, hydro, renewables)
- maintaining that contribution to clean air will require 50,000 Mwe of new nuclear

NEI


Vision 2020
billion kilowatt-hours
5000
4500
4000
3500
3000
2500
2000
1500
1000
0
2000
2020
New Nuclear Capability
Enhanced Nuclear Capability
Existing Nuclear Capability
Hydro & Renewables
Oil, Gas & Coal
NEI

The Future isn't what it used to be because ...

- Electricity demand will continue to grow
- New nuclear generation is no longer an option
  - it is an imperative
- The business case for new nuclear plants will be clear
- The cost and schedule drivers must be known and manageable to much more certainty than in the past

NEI

The Future isn't what it used to be because ...

NRC will be challenged to

- resolve Part 52 implementation issues in a timely manner
- establish efficient and predictable processes for siting, COL license applications, construction inspection
- respond to an increasing workload with new focus, discipline and efficiency

NEI

ACRS WORKSHOP
Regulatory Challenges for Future Nuclear Power Plants

Safety Goals for Future Nuclear Power Plants

Neil E. Todreas
KEPCO Professor of Nuclear Engineering
Massachusetts Institute of Technology

AM June 5, 2001

HOW TO MISCONSTRUE THIS TALK

I am not talking about:

- NRC Safety Goals - Quantitative Health Objectives - CDF and LERF.
- Suggested Regulatory Requirements for Future Power Plants.
- Soley about Future Power Reactors.
- Goals for Near Term Deployment* Plants (by 2010).

I am talking about:

- DOE and GIF Generation IV Technology Goals.
- Technology Goals formulated to
  - stimulate innovation.
  - suggest metrics for downselection which specifically are not to be construed as regulatory requirements.
- Nuclear Energy Systems Including
  - Fuel Cycles
- Goals for Systems to be Deployed from 2011 to 2030.

* Deployment: Manufacture, construction, and startup of certified plants ready to produce energy in their chosen market.

HOW TO MISCONSTRUE THE GOALS

- Assume that new nuclear energy systems must meet every new goal

  – Tradeoffs among goal parameters must be made for each design. Future markets may value different parameters.

    Desirable outcome is a spectrum of designs each best suiting different market conditions hence different goals.

  – Some goals presently appear unattainable (S+R 3).

  – Most goals are not overly specific because the social regulatory, economic and technological conditions of 2030 and beyond are uncertain.

HOW TO MISCONSTRUE THE GOALS (cont.)

- Assume that all safety considerations are encompassed in the Safety and Reliability Goal grouping (S+R 1, 2, +3)

  – Future designs will likely (but not necessarily) involve new fuel cycles and the capability to produce a broader range of energy products. For these reasons and to enhance the economic performance of electricity-only producing systems,
  I anticipate:
    - New Fuel Materials
    - Higher Burnups
    - Longer Operating Cycles
    - Higher Temperature Operation

  – These trends will be driven by the Sustainability (SU 1, 2, +3) and the Economic (EC 1+2) Goals.

SUSTAINABILITY

Sustainability is the ability to meet the needs of present generations while enhancing and not jeopardizing the ability of future generations to meet society's needs indefinitely into the future.

Sustainability–1.

Generation IV nuclear energy systems including fuel cycles will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective **fuel utilization for worldwide energy production.**

Sustainability–2.

Generation IV nuclear energy systems including fuel cycles will minimize and manage **their nuclear waste and notably** reduce the long term stewardship **burden in the future, thereby improving protection for the public health and the environment**.

Sustainability–3. **Generation IV nuclear energy systems including fuel cycles will increase the assurance that they are a** very unattractive and least desirable **route for diversion or theft of weapons-usable materials.**

SAFETY AND RELIABILITY

Safety and reliability are essential priorities in the development and operation of nuclear energy systems.

Safety and Reliability –1.

Generation IV nuclear energy systems operations will excel in safety and reliability.

Safety and Reliability–2.

Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.

Safety and Reliability–3.

Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

Safety and Reliability –1. Generation IV nuclear energy systems operations will excel in safety and reliability.

This goal aims at increasing operational safety by reducing the number of events, equipment problems, and human performance issues that can initiate accidents or cause them to deteriorate into more severe accidents. It also aims at achieving increased nuclear energy systems reliability that will benefit their economics. Appropriate requirements and robust designs are needed to advance such operational objectives and to support the demonstration of safety that enhances public confidence.

During the last two decades, operating nuclear power plants have improved their safety levels significantly, as tracked by the World Association of Nuclear Power Operators (WANO). At the same time, design requirements have been developed to simplify their design, enhance their defense-in-depth in nuclear safety, and improve their constructability, operability, maintainability, and economics. Increased emphasis is being put on preventing abnormal events and on improving human performance by using advanced instrumentation and digital systems. Also, the demonstration of safety is being strengthened through prototype demonstration that is supported by validated analysis tools and testing, or by showing that the design relies on proven technology supported by ample analysis, testing, and research results. Radiation protection is being maintained over the total system lifetime by operating within the applicable standards and regulations. The concept of keeping radiation exposure as low as reasonably achievable (ALARA) is being successfully employed to lower radiation exposure.

Generation IV nuclear energy systems must continue to promote the highest levels of safety and reliability by adopting established principles and best practices developed by the industry and regulators to enhance public confidence, and by employing future technological advances. The continued and judicious pursuit of excellence in safety and reliability is important to improving economics.

Safety and Reliability–2. **Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.**

This goal is vital to achieve investment protection for the owner/operators and to preserve the plant's ability to return to power. There has been a strong trend over the years to reduce the possibility of reactor core damage. Probabilistic risk assessment (PRA) identifies and helps prevent accident sequences that could result in core damage and off-site radiation releases and reduces the uncertainties associated with them. For example, the U.S. Advanced Light Water Reactor (ALWR) Utility Requirements Document requires the plant designer to demonstrate a core damage frequency of less than 10^{-5} per reactor year by PRA. This is a factor of about 10 lower in frequency by comparison to the previous generation of light water reactor energy systems. Additional means, such as passive features to provide cooling of the fuel and reducing the need for uninterrupted electrical power, have been valuable factors in establishing this trend. The evaluation of passive safety should be continued and passive safety features incorporated into Generation IV nuclear energy systems whenever appropriate.

Safety and Reliability–3. Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

The intent of this goal is, through design and application of advanced technology, to eliminate the need for offsite emergency response. Although its demonstration may eventually prove to be unachievable, this goal is intended to stimulate innovation, leading to the development of designs that could meet it. The strategy is to identify severe accidents that lead to offsite radioactive releases, and then to evaluate the effectiveness and impact on economics of design features that eliminate the need for offsite emergency response.

The need for offsite emergency response has been interpreted as a safety weakness by the public and especially by people living near nuclear facilities. Hence, for Generation IV systems a design effort focused on elimination of the need for offsite emergency response is warranted. This effort is in addition to actions which will be taken to reduce the likelihood and degree of core damage required by the previous goal.

ECONOMICS

Economic competitiveness is a requirement of the marketplace and is essential for Generation IV nuclear energy systems.

Economics–1.

Generation IV nuclear energy systems will have a clear **life-cycle cost advantage over other energy sources.**

Economics–2.

Generation IV nuclear energy systems will have a level of financial risk **comparable to other energy projects.**

CONCLUSIONS

- Future reactors fall in three categories - those which are:
  - Certified or derivatives of certified designs.
  - Designed to a reasonable extent and based on available technology.
  - In Conceptual form only with potential to most fully satisfy the GENIV goals.

  My focus has been on goals for the third category.

- It will be desirable to develop a range of design options in this third category to enable response to a range of marketing demands such as:
  - cheap versus expensive uranium.
  - small versus large power ratings.
  - significant reduction of greenhouse emissions.
  - new fuel cycles to achieve a significant response to the sustainability goals.

  Considerable R+D activity will be required to achieve these goals among which fuels, materials, and coolant corrosion research are the most intensive and long term.

- Consequently it is important that while an early dialogue between designers and regulators occur, the dialogue be framed to encourage & promote fundamental design directions which inherently promote safety. Development of a new regulatory process using risk-based principles is an important element of this dialogue. Interactions which frame the dialogue around the current regulatory framework can have the undesirable intent of discouraging the necessary and desirable exploration of technology and design alternatives.

Licensing Approach for Generation IV Technologies

"License By Test"

Andrew C. Kadak
Massachusetts Institute of Technology

June 5, 2001

Challenges

- Regulations focused on water
- Knowledge of technology lacking
- Regulatory System Rigid
- Infrastructure to Support New Technology Not Developed
- Changes in System take a long time

How to Introduce New Technology in Less than a Lifetime ?

- Go Back to Basic Safety Fundamentals
- Work Within Existing Regulatory High Level Objectives
- Use Risk Informed - Risk Based and Deterministic Analysis
- Assess Gaps in Knowledge
- Prioritize (risk assess)
- License by Test

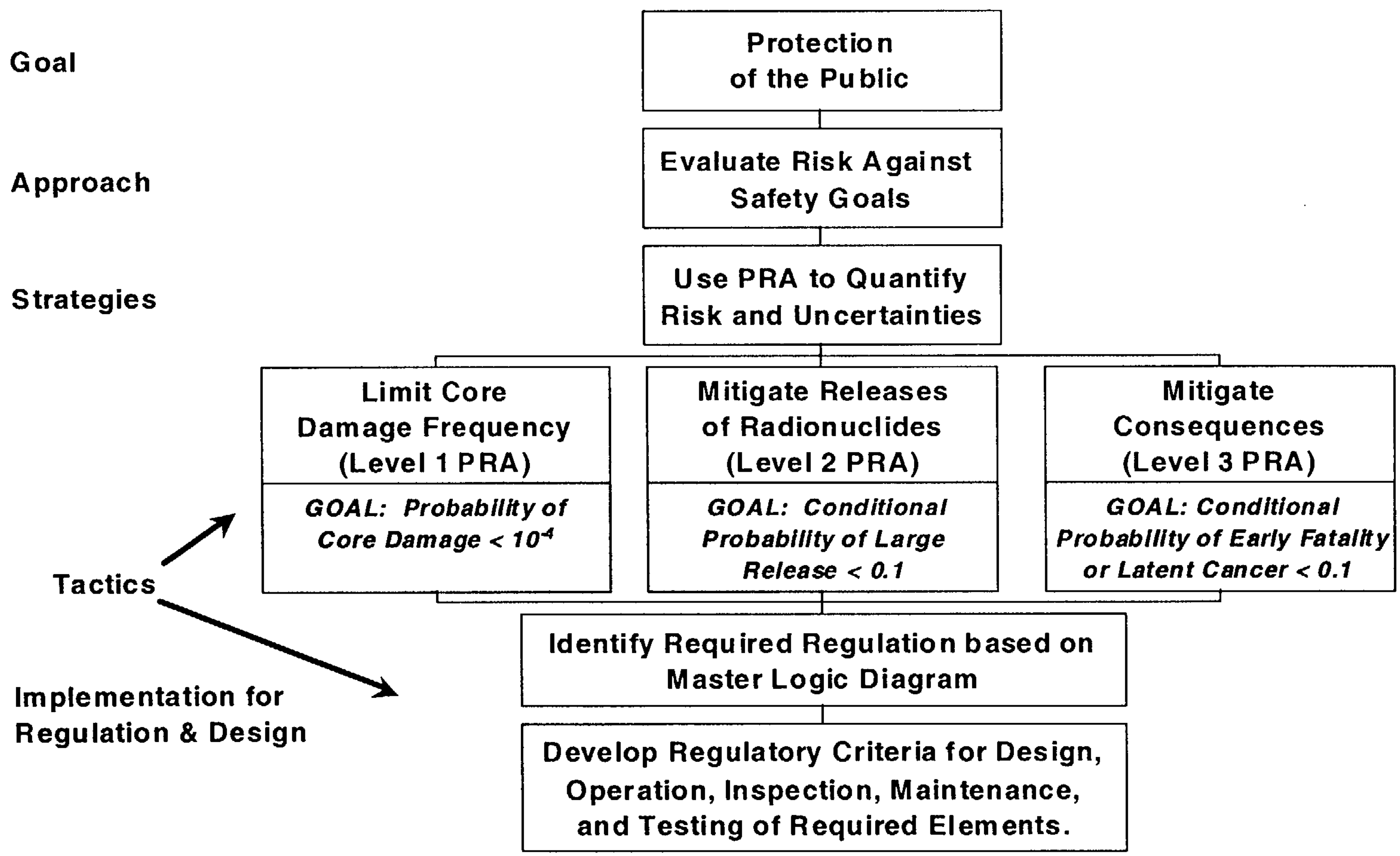
Establish a Safety Basis

- Use Public Health & Safety Goal
- Define Plant Risks:
  - Normal Operating Plant
  - Transients
  - Accident Scenarios
- Identify Safety Margins
- Quantify Risks
- Show Defense in Depth

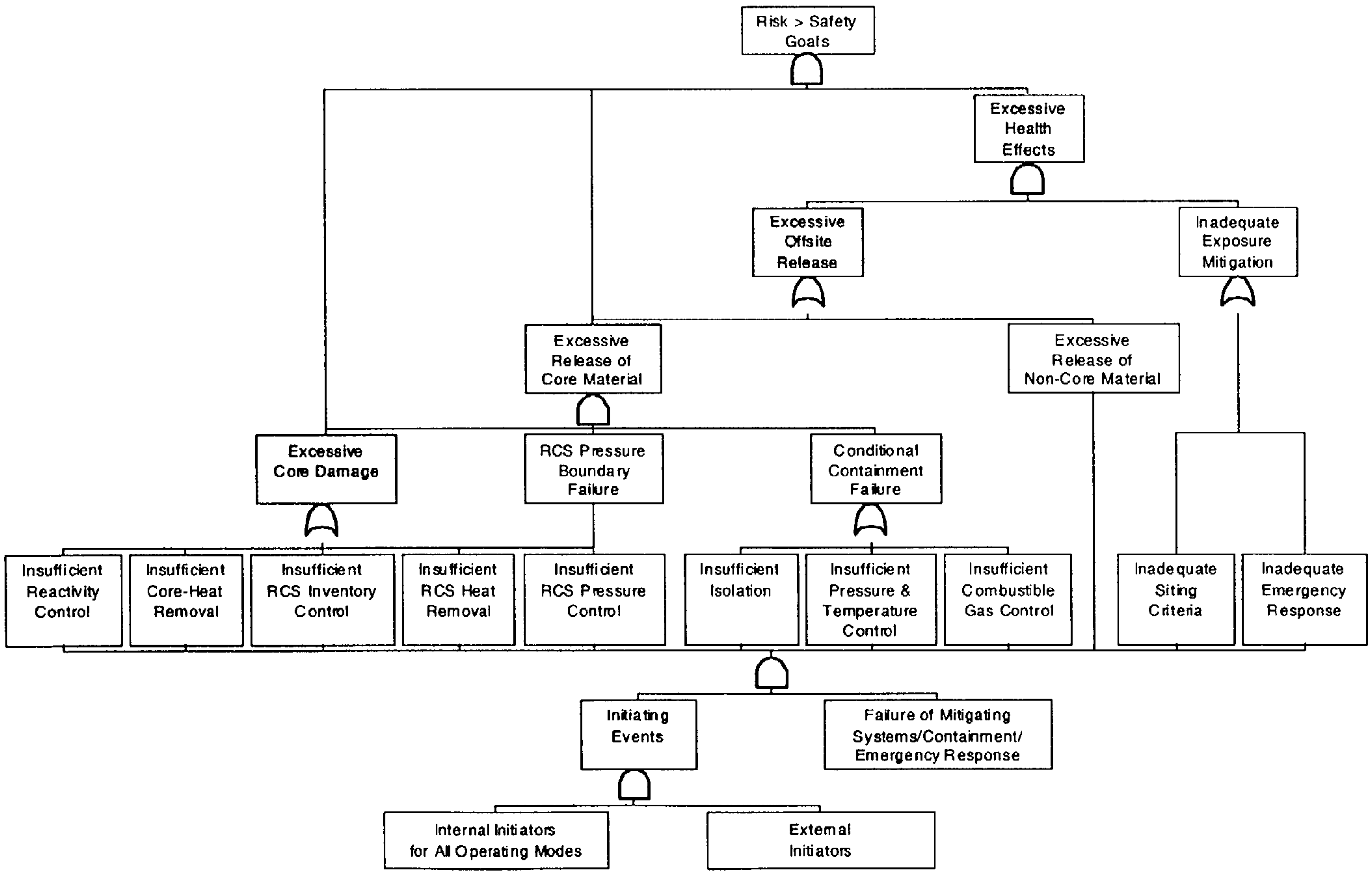
Risk Informed Approach

- Establish a public health and safety goal
- Demonstrate by a combination of deterministic and probabilistic techniques that the safety goal is met.
- Using risk based techniques identify dominant accident scenarios, critical systems and components that need to be tested as a functional system

Risk Informed Approach



Master Logic Diagram for Water Reactors



Council for Nuclear Safety Licensing Approach
For the Pebble Bed Modular Reactor (PBMR)

	SAFETY REQUIREMENTS	EVENT FREQUENCY	SAFETY CRITERIA
a	The design shall be such to Ensure that under anticipated Conditions of normal operation There shall be no radiation hazard To the workforce and members of The public. This must be Demonstrated by conservative deterministic analysis.	Normal operational conditions shall be those which may occur with a frequency up to but not exceeding 10^{-2} per annum.	Individual radiation dose limits per annum of 20 mSv to workers and 250 μSv to members of the public shall not be exceeded. +ALARA+ Defense in depth criteria
b	Design to be such to prevent and mitigate potential equipment failure Or withstand externally or internally originating events which could give Rise to plant damage leading to Radiation hazards to workers or the public. This must be demonstrated By conservative deterministic Analysis.	Events with a frequency in the range 10^{-2} to 10^{-6} per annum shall be considered.	Radiation doses of 500 mSv to workers and 50 mSv to members of the public shall not be exceeded. +ALARA+ Defense in depth criteria
c	The design shall be demonstrated To respect the CNS risk criteria. This must be demonstrated by probabilistic risk assessment using Best estimate + uncertainty analysis.	Consideration shall be given to all possible event sequences.	CNS risk criteria apply. $5X10^{-6}$ Individual risk 10^{-8} Population risk Bias against larger accidents. +ALARA

(CNS is the former name of the National Nuclear Regulator)

Review Existing Regulatory Structure for Gaps

- Based on plant specific safety basis:
  - Identify existing regulations that apply.
  - Use risk based regulatory approach to fill in gaps for areas not covered.
  - Develop implementation approach to General Design Criteria.

Develop Traditional Deterministic Regulatory Approach

- Establish Design Basis Accidents using risk based techniques
- Develop Defense in Depth Basis Using natural physical attributes of designs
- Establish confidence levels for analysis using risk assessment methods

License By Test

- Build Full Size Demonstration Plant
- Perform Critical Tests on components and systems identified using risk informed techniques
- If Successful, Certify Design

Why License By Test ?

- Needs:
  - To validate analyses
  - To shorten time for paper reviews
  - To "prove" what is debatable
  - To reduce uncertainty
  - Show Public and NRC that plant is safe

Tests Required

- Traditional Performance tests of equipment still required for reliability
- Use Risk Based Techniques to identify:
  - Accident Scenarios of Importance
  - Critical Systems
  - Critical Components
- Conduct Integrated System Tests

Examples of Tests

- Loss of Coolant
- Reactor Depressurization
- Natural Circulation
- Rod Withdrawal
- Reactivity Shutdown Mechanisms
- Reactor Cavity Heat Up and Removal
- Selected Component Key Component Failures

Additional Tests

- Balance of Plant Failures - turbine overspeed, loss of heat sink, compressor failures, etc
- Control Rod Ejection (rapid withdrawal)
- Reactor Cavity Heat Up
- Validate Core Physics Models
- Validate Safety Analysis Codes and Methods
- Xenon Transients

Tests Leading Up to Demonstration Facility Tests

- Fuel Performance - Irradiation, post accident heat up, cycling
- Air Ingress - validate chimney model for air ingress potential
- Water Ingress - assess reactivity effect and fuel damage

Reactor Research Facility

- Pebble Bed Reactor as a prototype for this licensing approach.
- Built in Idaho - Full Size w/Containment
- Implement Structured Test Program
- Develop Regulatory Process as Part of Certification of Technology using RRF.
- Research Reactor Continues as facility to innovate and test new technologies for fleet of standard designs.

Will License By Test Be Able to Answer All Questions ?

- No...
- In combination of subtier component tests described and the risk informed analysis, it should provide high confidence of critical safety performance.

Will License by test instill public confidence ?

- Yes,
- By having the public and the media observe these tests, the confidence in the technology and the regulatory will be enhanced.
- $10^{-\text{(pick a number)}}$ is not understandable or effective in safety discussions.
- It will encourage development of naturally safe reactors.

Traditional Regulatory Approach

- Ask General Atomics for MHTGR
- Ask Canadians for Candu
- Ask W about AP-600 - 1000
- Costly - Time Consuming - Risky
- Answers Not always possible to Satisfy NRC staff - Ask Licensees.
- Need An Alternative to the "Bring me a Rock" Process.
- This may be it...

Summary

- For Non-traditional technologies, a new licensing approach is needed for timely deployment.
- Risk Informed Techniques with Safety Goals Appear to meet the Need.
- License By Test is the most direct means of answering difficult questions.
- LBT should increase public confidence.

ACRS Workshop on Regulatory Challenges for Future Nuclear Power Plants

NERI Project on Risk-Informed Regulation

June 5, 2001

Mr. George Davis - Westinghouse

Professor Michael Golay - MIT

Presentation Breakdown

- Mr. George Davis
  - Purpose and Overview
  - Expectations for the Future
- Professor Michael Golay
  - A New Risk-Informed Design and Regulatory Process
  - Example Problem

Westinghouse

INEEL

Idaho National Engineering & Environmental Laboratory

Massachusetts Institute of Technology

Duke Engineering & Services.

A Duke Energy Company

Sandia National Laboratories

NC STATE UNIVERSITY

EGAN & ASSOCIATES, P.C.

Counselors at Law

Purpose of Presentation

- Describe our project and its vision of a new design and regulatory process
  - provide a "work-in-progress" illustrative example
- Explain the need for continuing the development of a new design and regulatory process
  - keep pace with the development and licensing of new reactor design concepts.

Substantial Reductions in Capital Costs and Schedule Will be Needed for New Plants

- Production costs (Fuel plus O&M) for operating plants approaching 1 cent/KW-hr
  - not much room for further improvement
- Future investors likely to require payback of capital costs within 20 years of operation, or less
- Capital costs must be reduced by 35% or more relative to large ALWRs
  - overnight capital cost below $1,000/KWe
  - construction schedule of about 3 years (or less)

Three NERI Proposals Aimed at New Processes to Lower Plant Capital Costs

Program	Basic Objective
Risk-Informed Assessment of Regulatory and Design Requirements	Development of methods for a new design and regulatory process.
"Smart" Equipment and Systems to Improve Reliability and Safety in Future Nuclear Power Plants	Development of methods for demonstrating improved component and system reliability; including on-line health monitoring systems.
Development of Advanced Technologies for Design, Fabrication, and Construction of Future Nuclear Power Plants	Development of methods and procedures for collaborative, internet-based engineering, integrated design analyses, and improved construction schedules.

Comparison of NRC and NERI Risk-Informed Regulatory Processes

The new design and regulatory process must be developed further to support new plant license applications - including Generation IV design concepts.

Risk-Informed Assessment - Interactions With Other Programs

- NERI framework development activities are being coordinated with NEI
  - NEI will emphasize the development of regulations
  - The NERI project will address the overall risk-informed design and regulatory process
  - Westinghouse will be an NEI Task Force member

- It is anticipated that a new risk-informed design and regulatory process will be an input to new plant license applications, including Generation IV reactor concepts.

A New Risk-Informed Design and Regulatory Process

Massachusetts Institute of Technology

George Apostolakis, Michael Golay

Sandia National Laboratories

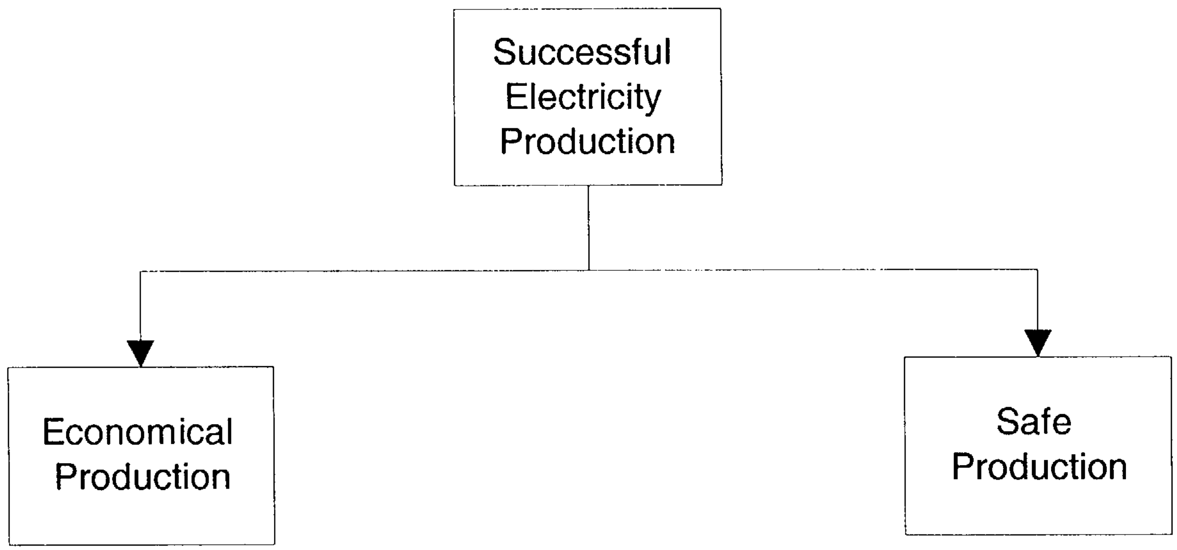
Allen Camp, Felicia Durán

Westinghouse Electric Company

David Finnicum, Stanley Ritterbusch

Overall Goal of Safety-Regulatory Reform

- Create methods to assure consistency of nuclear power plant applicant and regulator in performance/ goals for producing safe, economical power plants

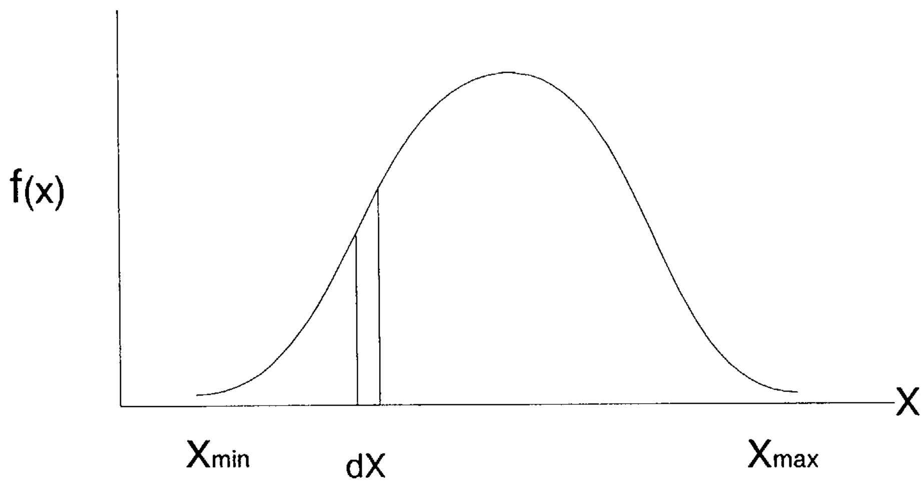


Major Elements:
- Acceptance Criteria
- Comprehensive, consistent assessment methods
- Designers, operators

Major Elements:
- Acceptance Criteria
- Comprehensive, consistent assessment methods
- Regulators, designers, operators

Risk-Informed Regulatory Approach - Fundamental Ideas

- Regulatory decisions are founded upon the informed beliefs of decision-makers.
- Any regulatory belief can and should be stated in a probabilistic format.

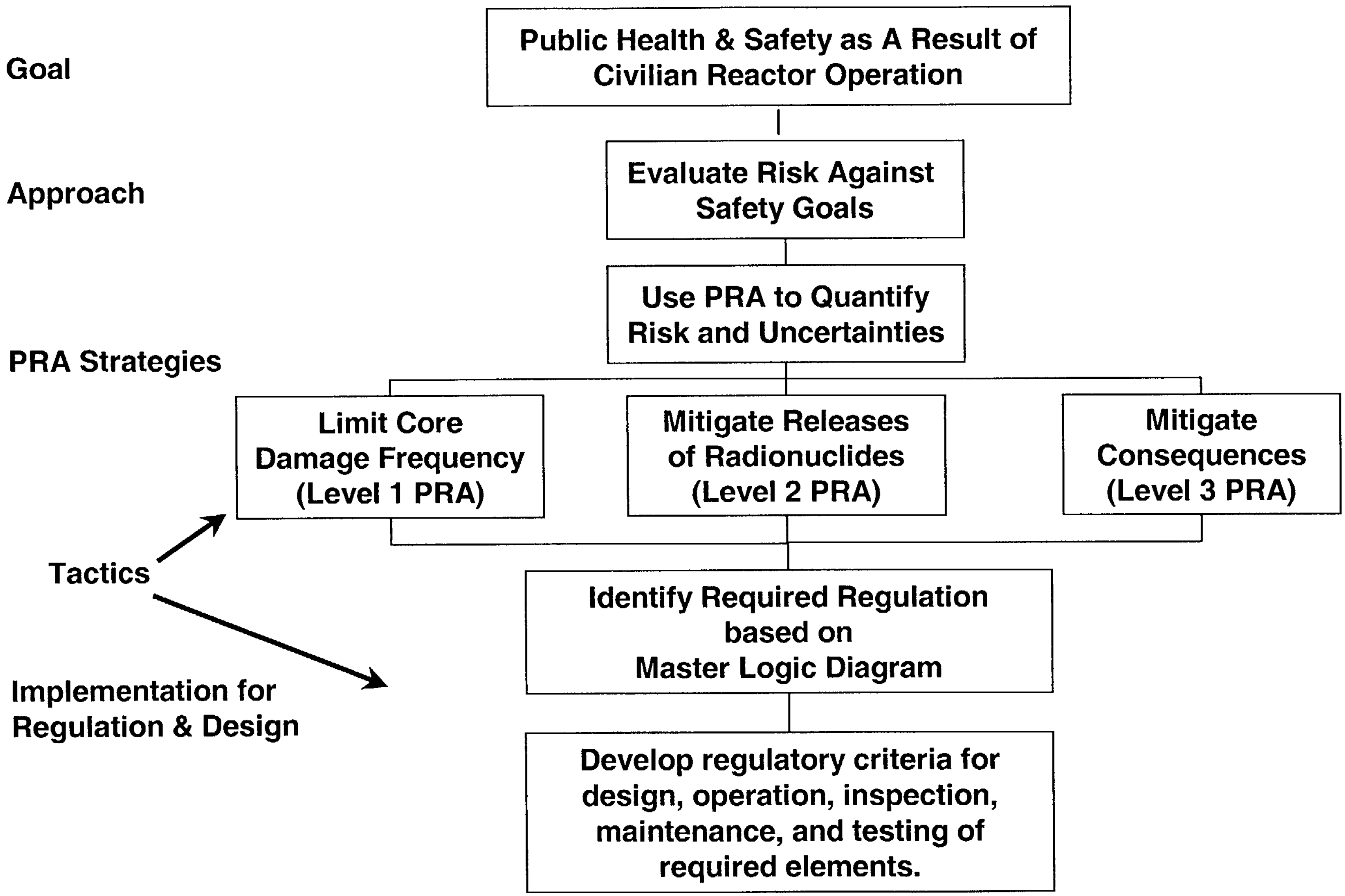


Probability $(x < X < x+dx) = f(x)dx$

- Regulatory acceptance criteria must reflect acceptable best-estimate performance expectations and uncertainties.

Risk-Informed Regulatory Approach - Fundamental Ideas....

- Regulatory questions and acceptance criteria should also be stated within a probabilistic framework.
- The probabilistic framework should be as comprehensive as possible:
  - utilize probabilistic and deterministic models and data where feasible - and use subjective treatments where not feasible,
  - state all subjective judgments probabilistically and incorporate into the PRA,
  - require both license applicant and regulatory staff to justify their decisions explicitly, and
  - initiate resolution process to resolve applicant-regulator disagreements.



Framework for Risk-Based Regulation and Design

Comparison of NRC and NERI Risk-Informed Regulatory Processes

Operating Plants
(NRC/NEI)

Deterministic

Traditional ("Structuralist")
Approach

- Start with current designs and regulatory approvals.
- Justify risk-informed changes.
- Defense-in-depth remains as primary means of assuring safety.

Future Plants
(NERI/New NEI Task Force)

Probabilistic

Risk-Based ("Rationalist")
Approach

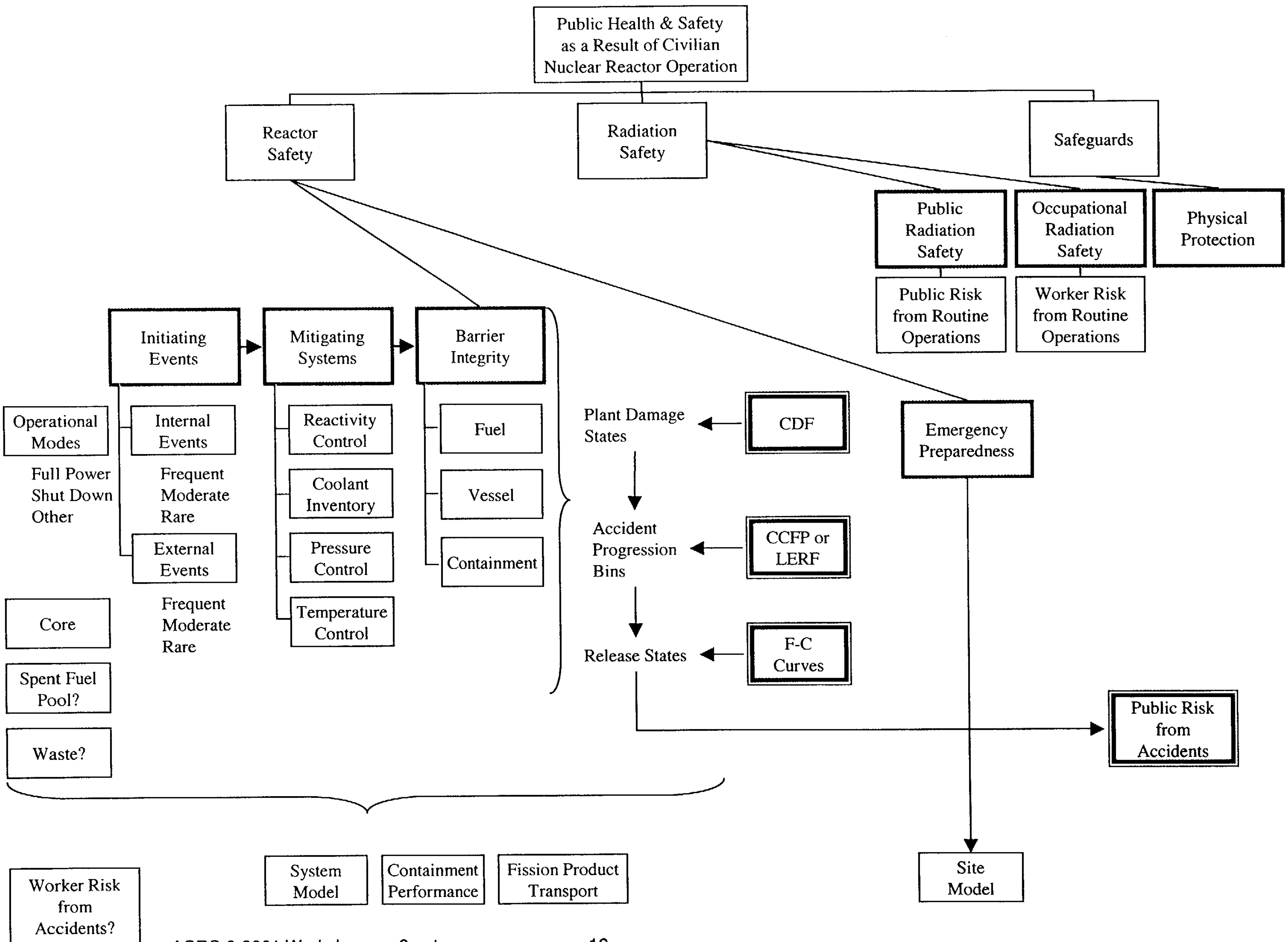
- Develop new design and regulatory process.
- Use firm probabilistic criteria to assure safety.
- Use defense-in-depth and safety margins as needed.

Risk-Informed Regulatory Approach....

- At all conceptual stages of development, nuclear power plant evaluation is performed probabilistically and is supported by deterministic analyses, tests, experience, and judgements.
- Safety results of defense-in-depth, performance margins, best-estimate performance, and subjective judgements are all incorporated into a comprehensive PRA
  - PRA is used as a vehicle for stating evaluator beliefs concerning system performance
- The level of detail of acceptance criteria becomes finer as the level of concept development increases
  - many LWR-based regulatory constructs (e.g., DBAs, GDCs) are not applicable to less mature

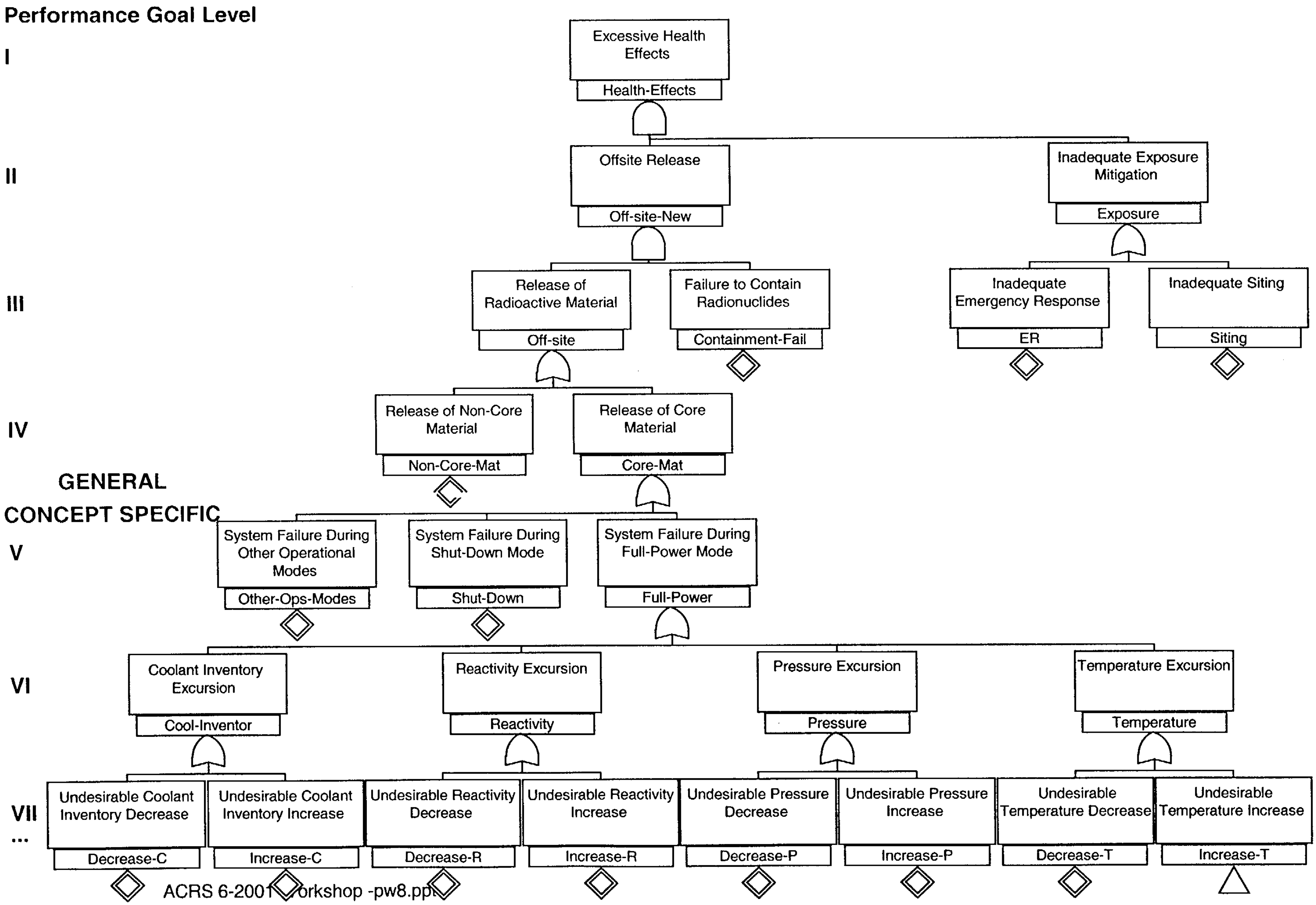
Stages of Nuclear Power Plant Concept Development

Development Stage	Goals and Acceptance Criteria	Evaluation Tools	Relevant Evidence
Initial Concept	High level - qualitative	Qualitative, simple, deterministic	Experiences of other concepts, deterministic analyses
Initial detailed design	High level - quantitative	Quantitative – probabilistic, deterministic	Prior quantitative analyses
Final detailed design	Detailed – quantitative (design-specific subgoals)	Detailed – quantitative – probabilistic, deterministic	Prior quantitative analyses
N-th of a kind for a given plant type	Very detailed – quantitative (design specific criteria – DBAs, GDCs,....)	Very detailed – quantitative, probabilistic, deterministic, tests	Prior quantitative analyses, tests, field experience



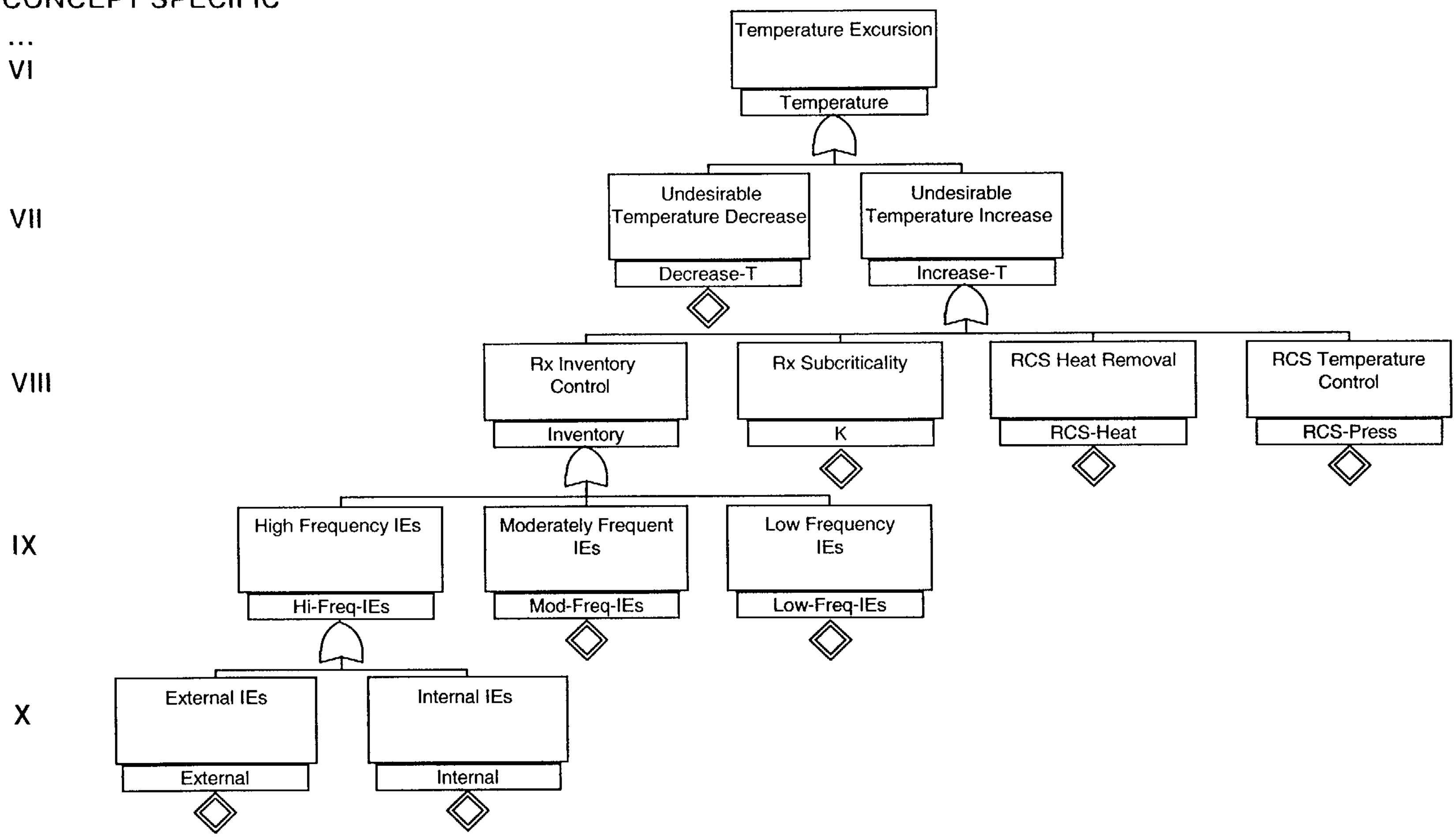
Public Health & Safety as a Result of Civilian Nuclear Reactor Operation
Reactor Safety
Radiation Safety
Safeguards
Public Radiation Safety
Occupational Radiation Safety
Physical Protection
Public Risk from Routine Operations
Worker Risk from Routine Operations
Initiating Events
Mitigating Systems
Barrier Integrity
Operational Modes
Full Power
Shut Down
Other
Internal Events
Frequent
Moderate
Rare
External Events
Frequent
Moderate
Rare
Core
Spent Fuel Pool?
Waste?
Reactivity Control
Coolant Inventory
Pressure Control
Temperature Control
Fuel
Vessel
Containment
Plant Damage States
CDF
Accident Progression Bins
CCFP or LERF
Release States
F-C Curves
Emergency Preparedness
Public Risk from Accidents
Site Model
System Model
Containment Performance
Fission Product Transport
Worker Risk from Accidents?

Master Logic Diagram

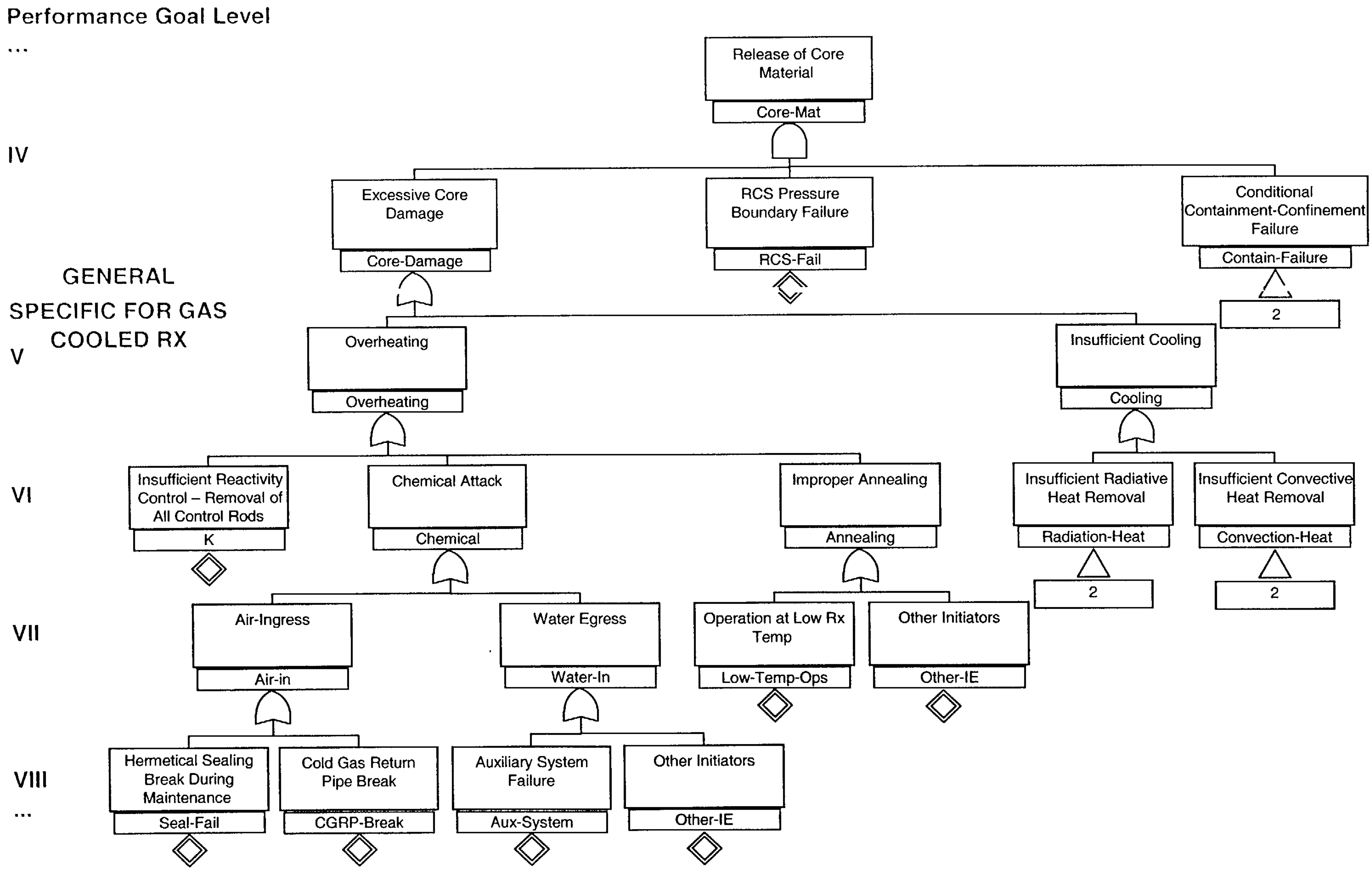


Master Logic Diagram

Performance Goal Level
CONCEPT SPECIFIC

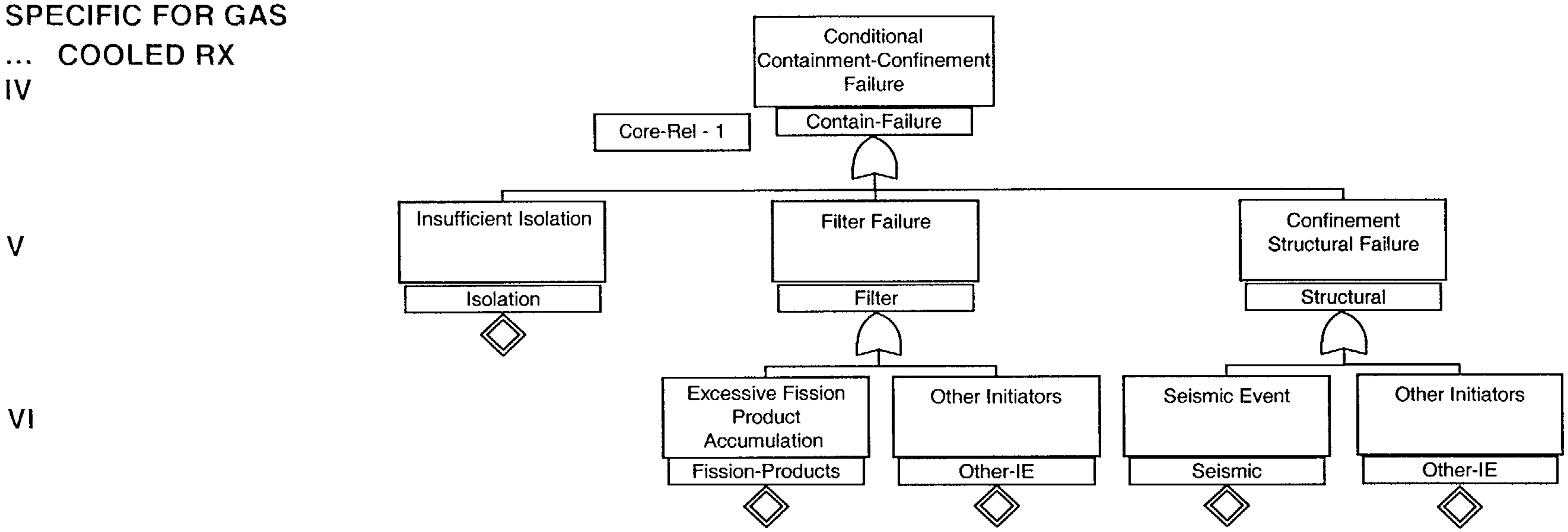


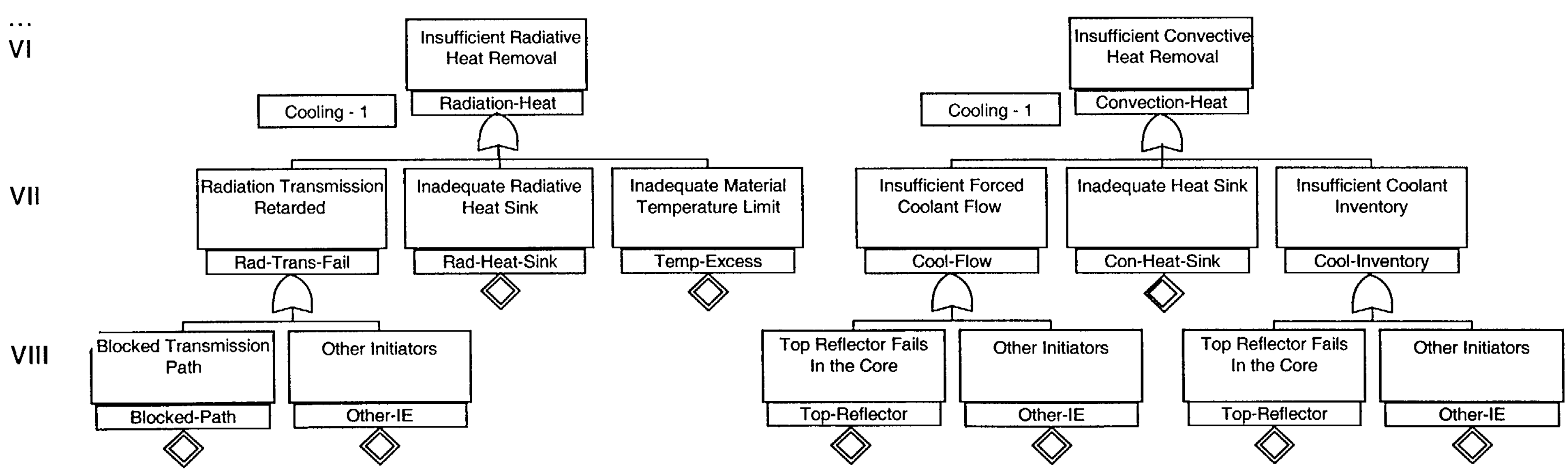
Concept-Specific Master Logic Diagram



Concept-Specific Master Logic Diagram

Performance Goal Level
SPECIFIC FOR GAS
... COOLED RX





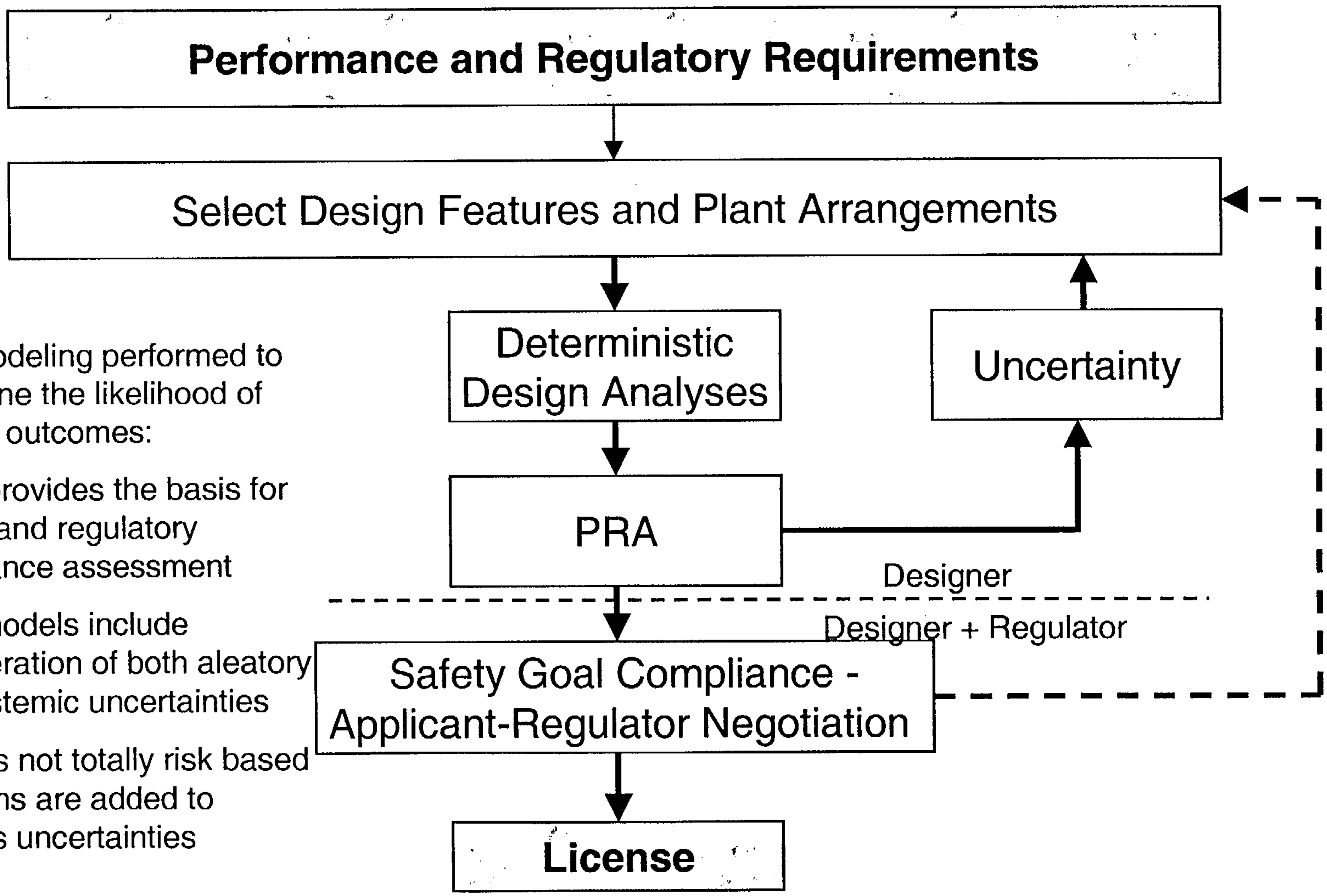
Fundamental Interactions Between License Applicant (or Licensee) and Regulator

- Should be formulated with probabilistic methods
- Acceptability negotiation for new license application or license revision
  - currently is deterministic
  - should be risk-based; completion of procedures, tools, and termination criteria is needed
- Plant construction oversight
  - can be deterministic, subject to risk-based oversight
- Plant operation oversight
  - can be deterministic, subject to risk-based oversight

Basic Design and Regulatory Process - Employed Traditionally, Remains Valid Today

- Designer develops a plant design that both produces power reliably and operates safely
  - responsible for plant safety, using high level regulatory criteria and policies as inputs
- Regulator reviews the design
- Designer and regulator engage in a dialog
  - specific safety features, their performance criteria, and methods of design and analysis
- Documentation is developed throughout the process
  - designer documents the design basis
  - regulator documents the safety evaluation, policies established, and criteria for future reviews (e.g., Reg. Guides and Standard Review Plans, and possibly regulations)

Risk-Informed Design and Regulatory Process - PRA Decision Making



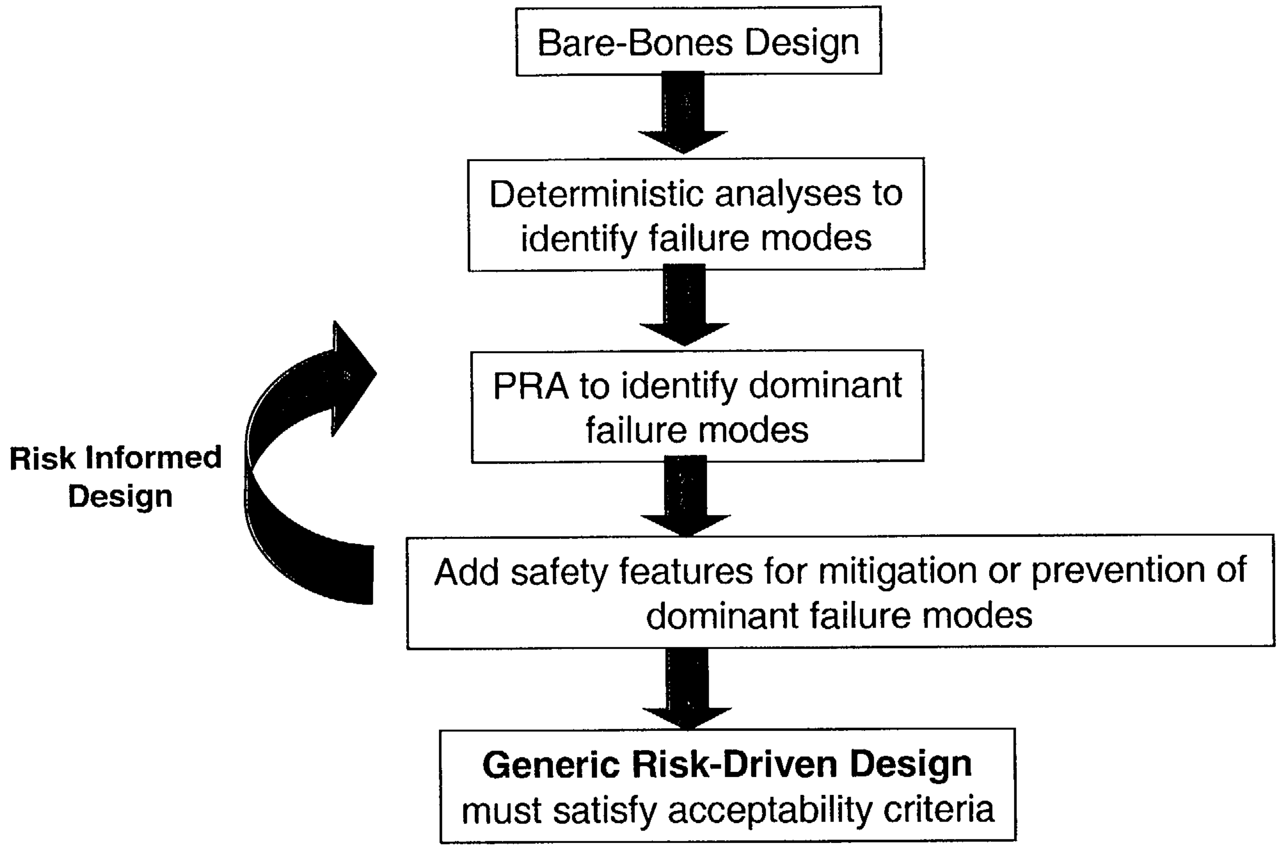
PSA Modeling performed to determine the likelihood of specific outcomes:

- PSA provides the basis for design and regulatory compliance assessment

-PSA models include consideration of both aleatory and systemic uncertainties

- PSA is not totally risk based - margins are added to address uncertainties

Schematic Diagram of the Risk-Driven Generic Design - Builds Upon A Bare-Bones Design, Using an Iterative Process



Classification of Event Sequences Within the Risk-Informed DBA Approach

Classes

Response Required

Initial Sequences
Very Small Leak
Safety Relief Valve Stuck Open
Small Pipe Break LOCA
Pilot Operated Relief Valve Stuck Open
RC Pump Seal Failure
Medium Pipe Break LOCA
Large Pipe Break LOCA

Shared Functional Challenges
Insufficient RCS Inventory Control
Insufficient RCS Pressure Control
Insufficient RCS/Core Heat Removal

Classes	Response Required
Very Small Leak SRV Stuck Open	Normal Coolant Make-Up
Small Pipe Break LOCA PORV Stuck Open RC Pump Seal Failure	Emergency High Pressure Coolant Injection
Medium Pipe Break LOCA Large Pipe Break LOCA	Depressurization and Emergency Low Pressure Coolant Injection

Apportionment of a Performance Goal Into Subgoals

- Designer proposes apportionment - then negotiates with regulator
- Apportionment must reflect what is feasible in the design
- Example shows that the reliability/availability of mitigation systems reflects feasibility of the design

Initiating Event	**Initiating Event Frequency**	**Mitigation Unavailability**	**Core Damage Frequency**
Very Small LOCA	4E-3 /yr	1E-4	4E-7/yr
Small LOCA	2E-4 /yr	1E-3	2E-7/yr
Large LOCA	4E-5 /yr	1E-2	4E-7/yr
Example Acceptability Criterion: Achieved Total CDF due to LOCAs must be less than or equal to **2E-6 /yr**			Achieved Total CDF due to LOCAs: **1E-6 /yr**

Example of Designer's Initial Risk-Informed Submittal to the Regulator

- Two safety system divisions - each contains:
  - two active high-pressure injection trains
  - one active low-pressure injection train
  - cooling water (component cooling, service water, HVAC)
  - two diesel generators
  - DC (battery) power
- Shared support systems
  - chemical volume control system
  - off-site power
- PRA Includes:
  - deterministic analyses, data, models,
  - uncertainties, inter-dependencies, and common-cause failures
  - initiator data are from documented sources (NUREG/CR-5750)
  - component failure frequencies are estimated from existing PRA studies (for this LWR example problem)

Example of Negotiation Between Applicant and Regulator

Design submittal - thought to be acceptable by applicant

↓

Regulator disputes assumptions - requires new data

↓

Result: Risk of failure to have adequate coolant levels too great

↓

Cause: CDF due to high pressure LOCA is dominant contributor

→

Fix: Designer adds depressurization capability and revises PRA

↓

Result: CDF due to LOCA still too high due to the high-pressure LOCA

↓

Fix: Designer adds independent, redundant train of depressurization capability

↓

Result: CDF remains too high due to support system common-cause failures (cooling water pump and diesel)

↓

Example of Negotiation Between Applicant and Regulator....

Design is re-submitted to the regulator

Evaluation-1: Regulator reviews design and PRA with common-cause failure reduction. It is determined that further significant improvements in ensuring adequate core coolant levels cannot be accomplished at a reasonable cost or with an adequate degree of certainty - through use of a cost-benefit criterion.

Evaluation-2: The regulator compares the achieved level of function availability, including uncertainty, to a pre-determined standard to determine if the design is acceptable.

Result: Unavailability criteria have been met and risk metric has decreased by a factor greater than 3. The design is determined to be acceptable.

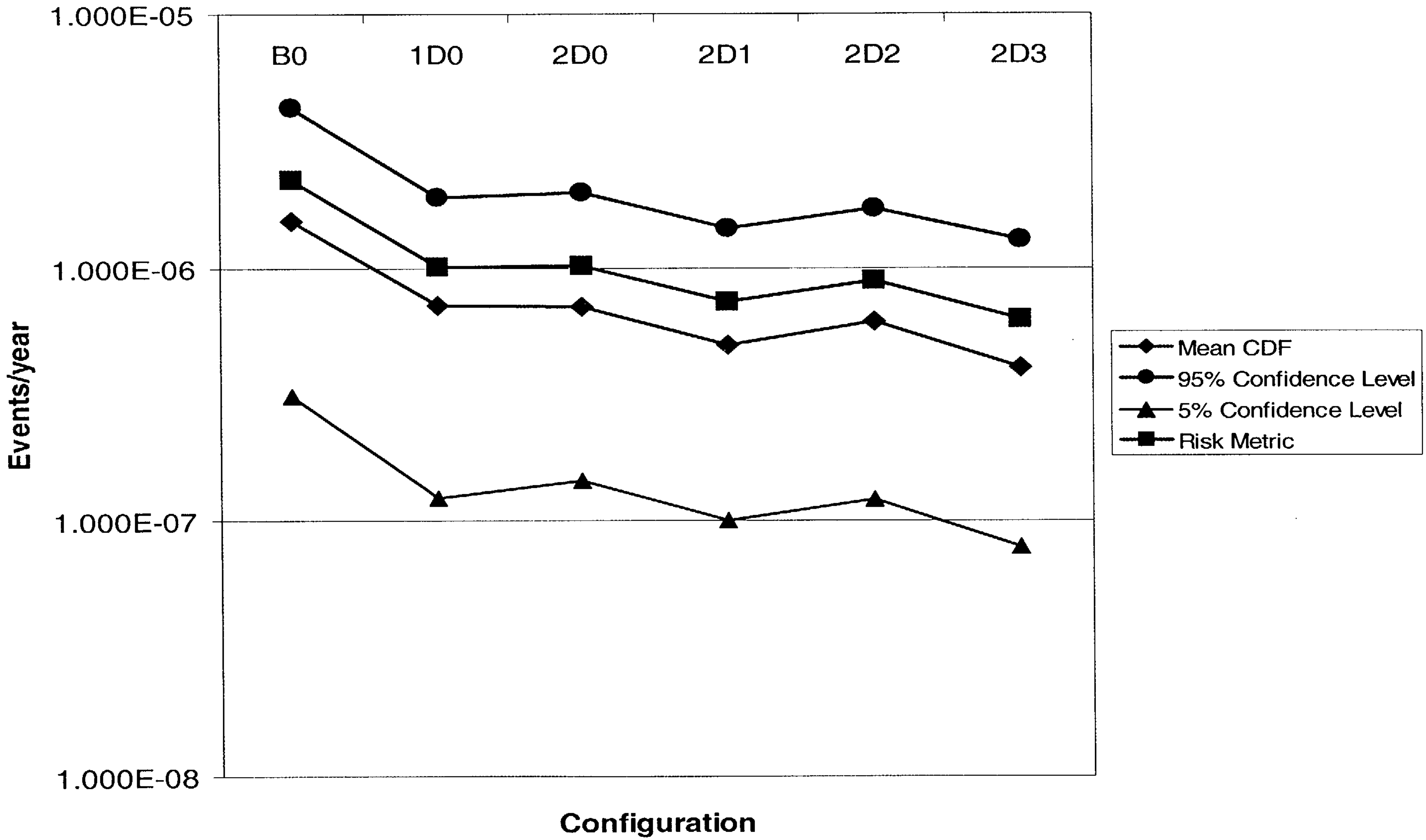
Following the Effects of Design Modifications Upon Important Risk Metric Values

Plant Configuration	Median-CDF	5% Conf.	95% Conf.	Risk Metric*
No Depressurization	*1.528E-06*	*3.093E-07*	*4.278E-06*	*2.216E-06*
One Division of Depressurization	*7.086E-07*	*1.226E-07*	*1.890E-06*	*1.004E-06*
Two Divisions of Depressurization	*7.055E-07*	*1.445E-07*	*1.980E-06*	*1.024E-06*
Depressurization and reduced CW CC Failure**	*4.970E-07*	*1.008E-07*	*1.432E-06*	*7.308E-07*
Depressurization and reduced Diesel CC Failure	*6.120E-07*	*1.211E-07*	*1.718E-06*	*8.885E-07*
Depress with reduced CW and Diesel CC Failure	*4.020E-07*	*7.960E-08*	*1.290E-06*	***6.24E-07***

* Risk metric selected = (0.75 * Median CDF) + (0.25 * 95% confidence CDF)

** CW = Cooling Water; CC = Common Cause

Effects of Design Modifications on CDF



Example Problem - Results & Questions

- Concerns about common cause failures and large uncertainties would lead designers and regulators to conservative design approaches
  - defense-in-depth, safety margins
- Guidelines are needed for consistently reflecting model weaknesses in the probabilistic database
- Consistent acceptance criteria are needed for negotiation guidance and termination
- Practical implementation requires more work
  - more trial examples
  - standardized models, methods, databases
  - methods for treatment of subjective judgements
  - replacements for:
    - GDCs
    - DBAs (risk-dominant event sequences)
    - Standard Review Plan

Summary

- The favored approach for a new design and regulatory process would:
  - use risk-based methods to the extent possible
  - use defense-in-depth when necessary to address model and data uncertainty.
- A new risk-informed design and regulatory process would:
  - provide a rational method for both design activities and applicant-regulator negotiations
  - provide a method for an integrated assessment of uncertainties in design and regulation
  - provide a process that is applicable to non-LWR technologies
- Development of a new design and regulatory process should be continued to support new reactor license applications.

New Plant Regulatory Framework

NRC ACRS Workshop on Advanced Reactors

New Regulatory Framework

Adrian Heymer, NEI

(aph@nei.org, 202-739-8094)

NEI

Benefits of Establishing New Framework

- **Helps establish a new paradigm of thinking**
  - Not burdened by current requirements or interpretations
  - Provides a standard against which to set requirements
- **Provide a platform for agreement on principles and objectives**
  - Ensures issues are focused on safety and are tied to defined safety objectives

NEI

Benefits of Establishing New Framework

- **Provides basis for NRC & industry positions**
- **Improves regulatory consistency**
  - Aligns regulations and oversight process
- **Use Reactor Oversight Framework as basis for starting industry & regulatory interactions**
  - Avoids "re-invention" of framework already accepted by NRC
  - Cultural change burden eased

NEI

New Plant Regulatory Framework

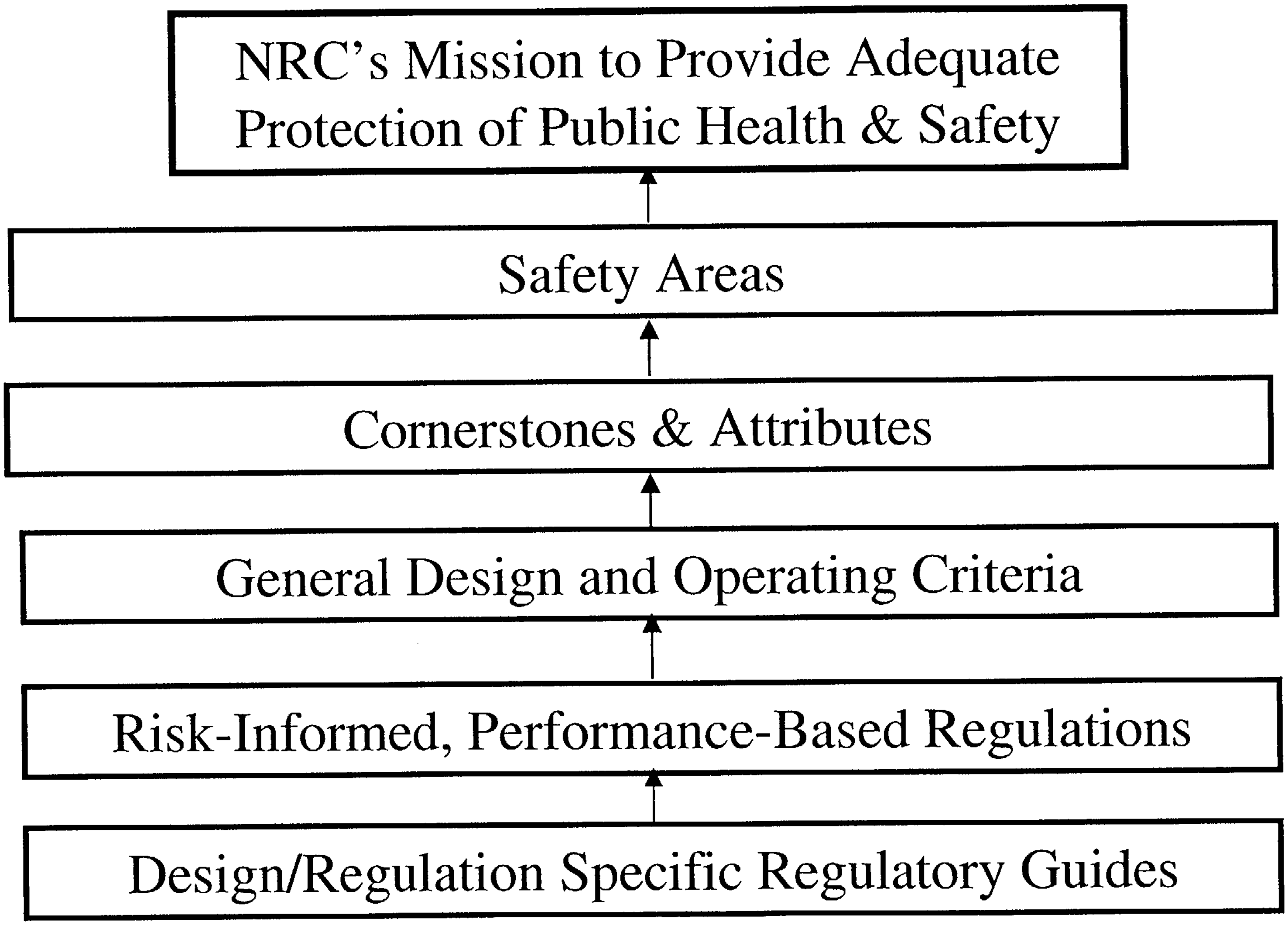
- **Generic to all types of reactor**
- **Top-down approach based on NRC mission**
  - Adequate protection of public health & safety
- **Based on NRC oversight cornerstones**
- **New General Design Criteria**
- **Introduce General Operating Criteria**
- **Develop a new set of generic, risk-informed, performance-based regulations**
- **Develop design-specific and regulation specific regulatory guides**

NEI

Establishing a New Regulatory Framework for New Plants

- **Concept -- Risk-Informed, Performance-Based Licensing and Regulatory Regime**
- **Proof-of-concept application(s)**
  - Use License Renewal and Option 2 models
  - Minimizes hypothetical discussions
  - Definitive schedule to drive resolution process
- **Industry effort consolidates lessons learned from proof-of-concept activities**
  - Vehicle for supporting proof-of-concept positions

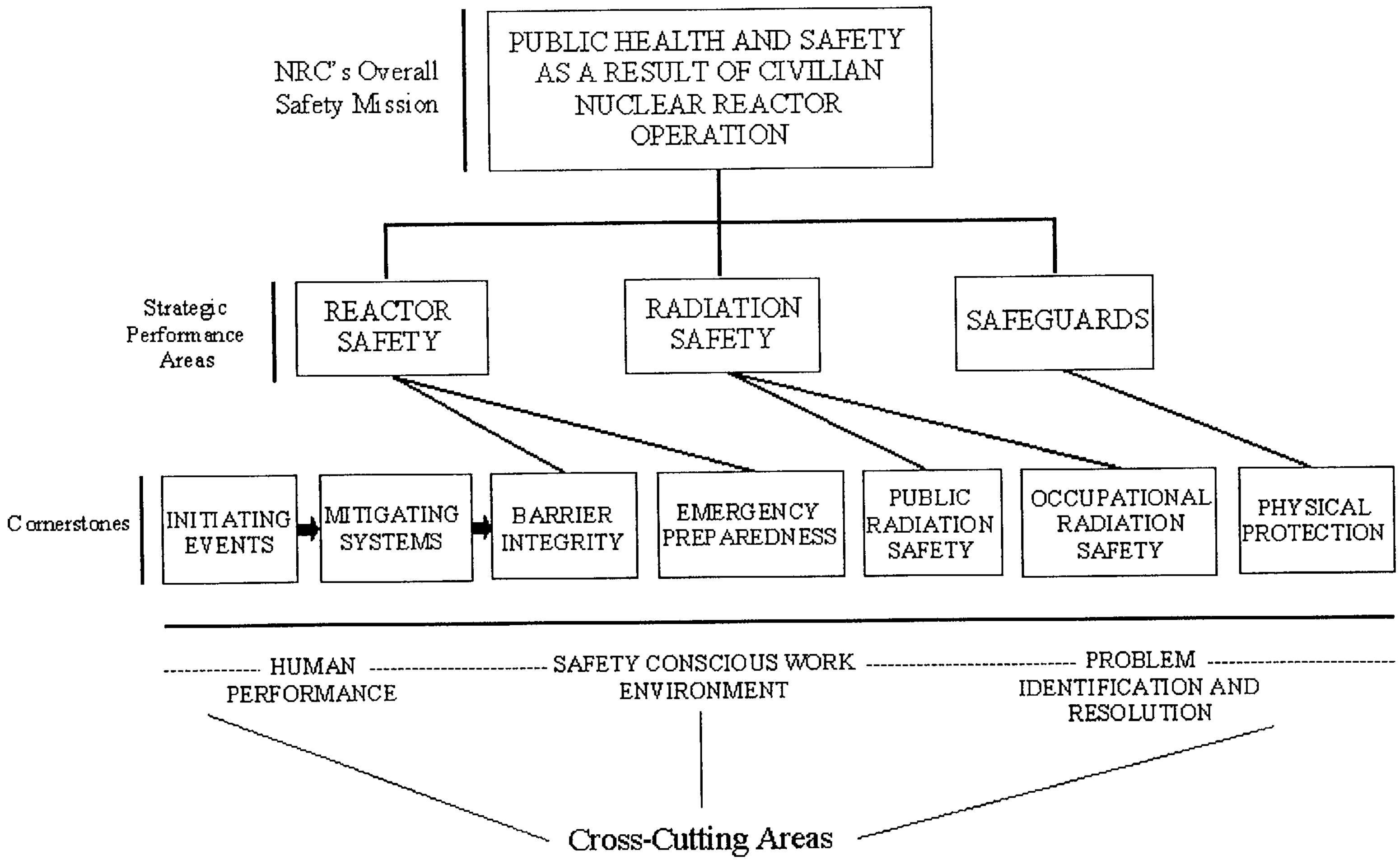
NEI


NRC's Mission to Provide Adequate Protection of Public Health & Safety
Safety Areas
Cornerstones & Attributes
General Design and Operating Criteria
Risk-Informed, Performance-Based Regulations
Design/Regulation Specific Regulatory Guides

DRAFT

NEI

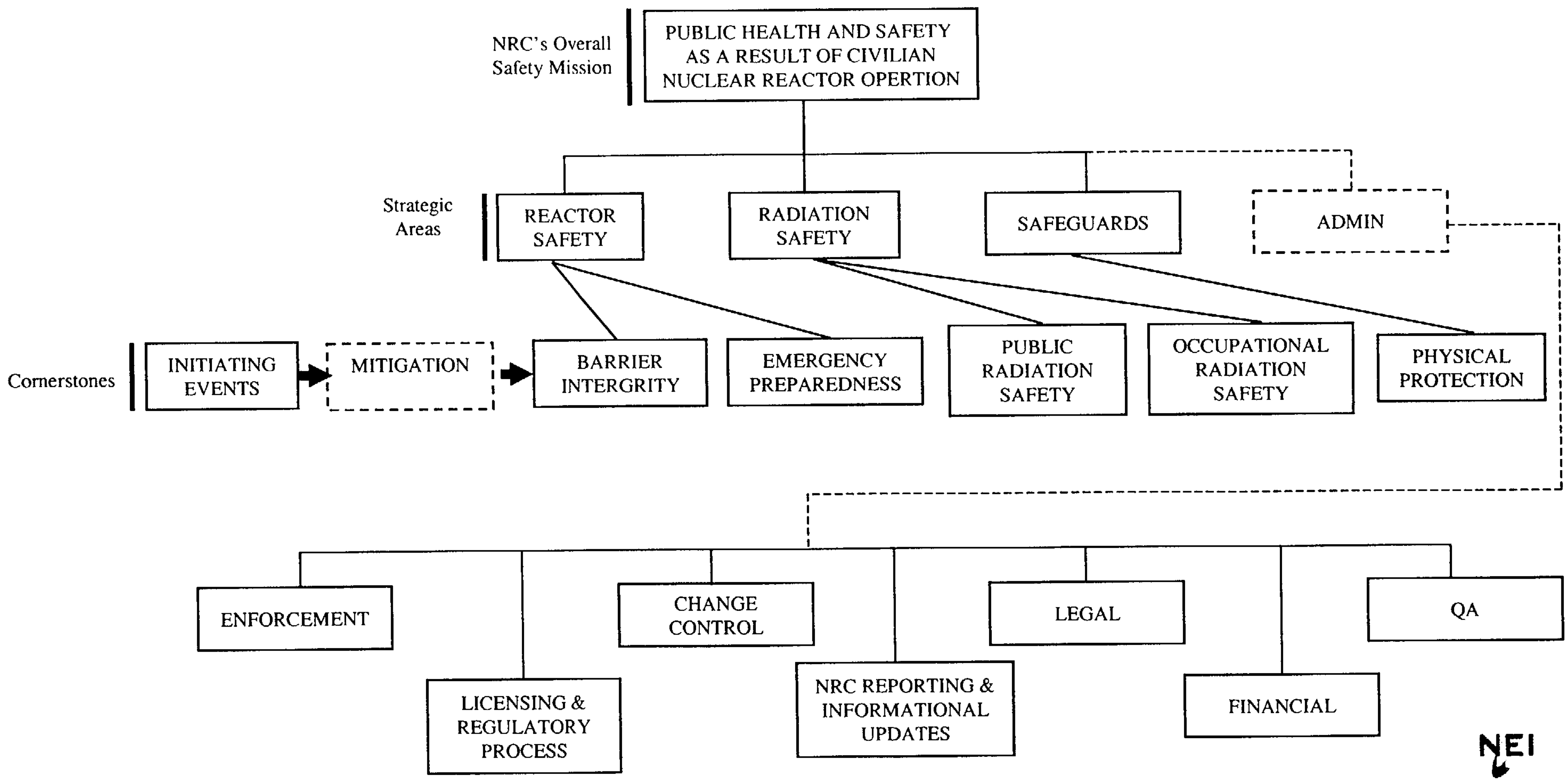
REGULATORY OVERSIGHT FRAMEWORK



NEI

DRAFT

REGULATORY FRAMEWORK FOR NEW PLANTS



NEI

DRAFT

Cornerstones
10 CFR Part 50

- **160 GDCs, Regulations & Appendices**
  - **Initiating Events -- 16**
  - **Mitigation (*Systems*) -- 46**
  - **Barriers -- 27**
  - **EP -- 3**
  - **Pub. Radiation Safety -- 9**
  - **Occupational Safety -- 4**
  - **Safeguards -- 4**
  - **Administrative -- 68**
  - **Financial -- 6**
  - *Operational* -- *23*

NEI

Example of New Regulation

XX.63 Plant configuration management

Licensee shall assess and manage changes in risk that result from maintenance, modifications and operational activities that could degrade safety-significant functions.

DRAFT

Example of New Design Criteria

Protection against natural phenomena

Safety-significant structures, systems, and components shall be designed to withstand, or be protected from the effects of natural phenomena, such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design and protective features shall reflect the most severe natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for uncertainty related to the limited accuracy, quantity, and period of time in which the data have been accumulated.

through the coating layers. The fractional release of ^{110m}Ag was higher than that of ^{137}Cs, which was consistent with the previous work.[10–13] Although the inventory is small, the release of ^{110m}Ag would be troublesome in mainte-

and ^{154}Eu were obtained in the individual coated fuel particles. To compare the irradiation performance of the individual particles, activity ratios, not activities, were used to account for variations in kernel size and to minimize

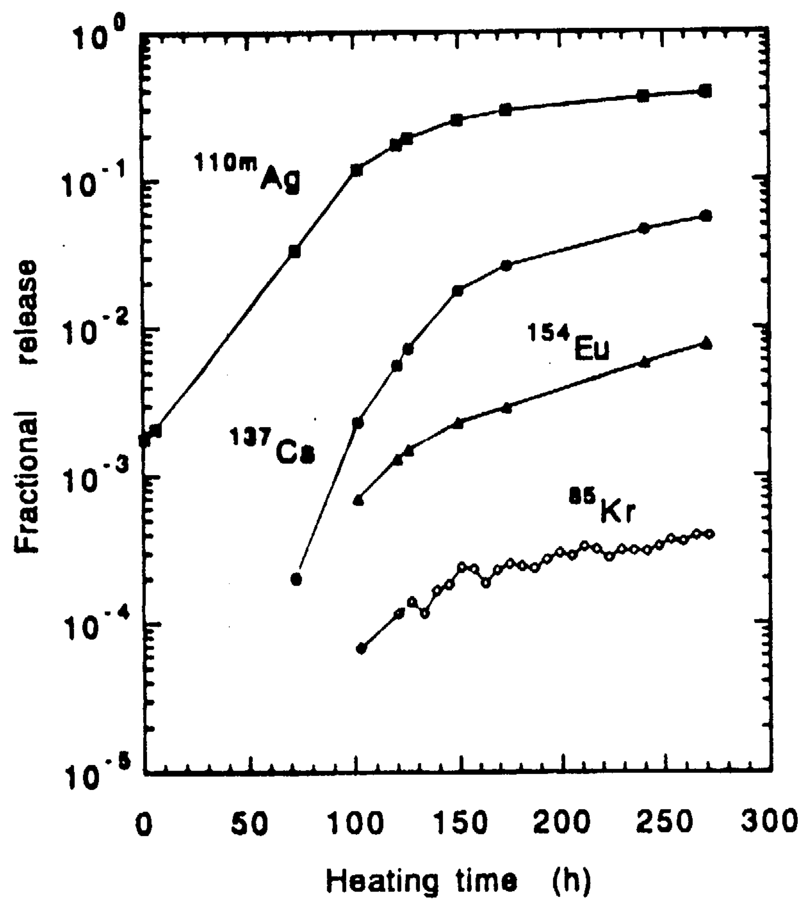


Fig. 2. Time-dependent fractional releases of fission products during the ACT3 heating test at 1700°C for 270 h, obtained by the on-line measurements of fission gas release and intermittent measurements of metallic fission product release.

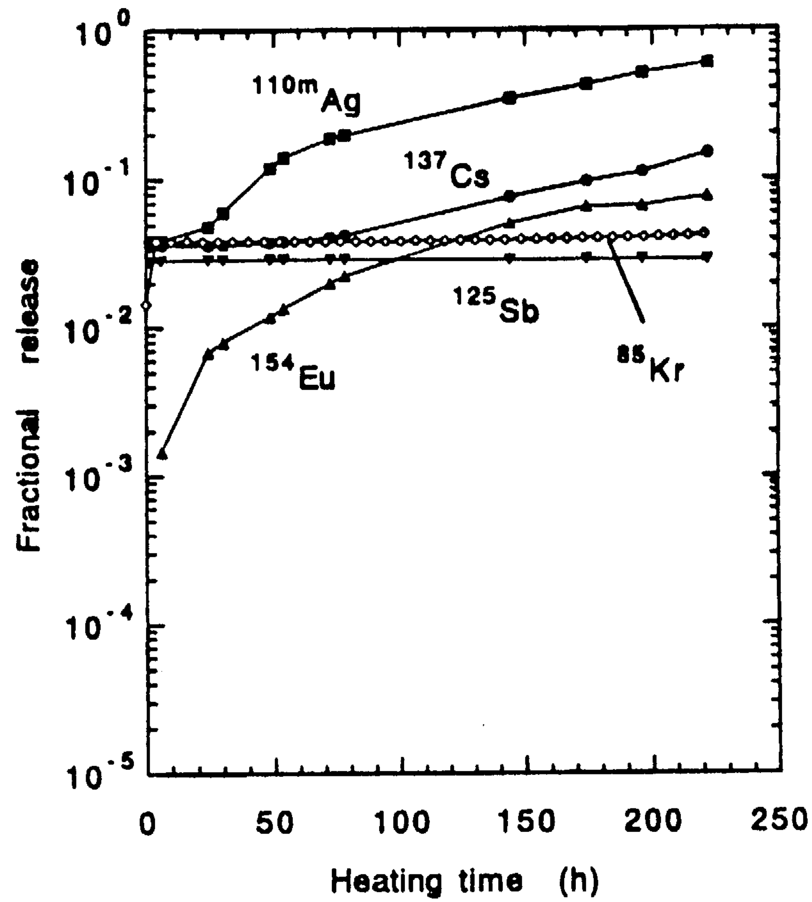
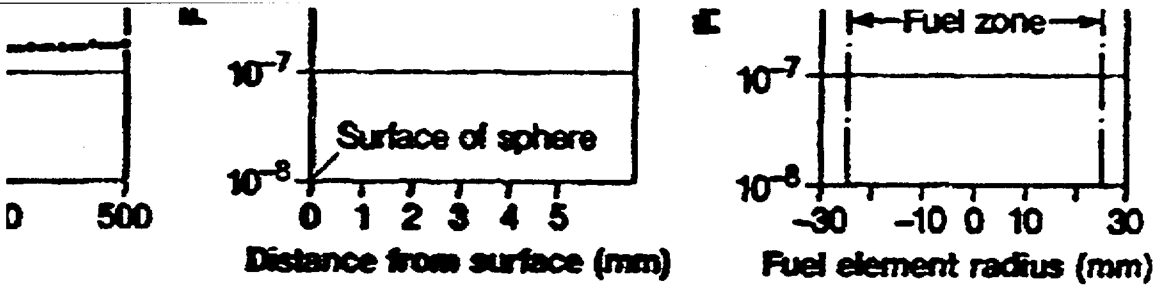
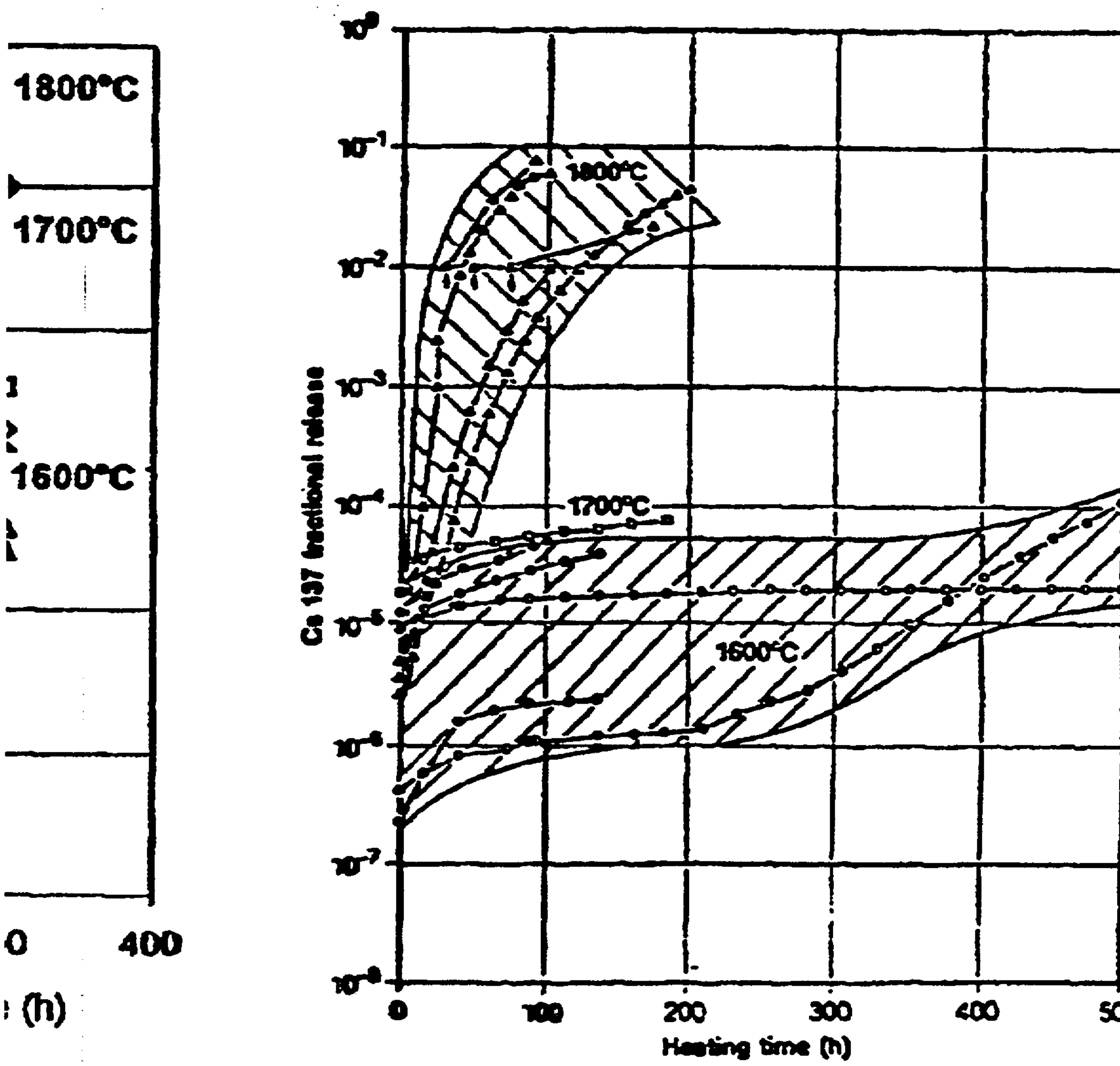


Fig. 3. Time-dependent fractional releases of fission products during the ACT4 heating test at 1800°C for 222 h, obtained by the on-line measurements of fission gas release and intermittent measurements of metallic fission product release.



release and distribution in sphere HFR-K3/1 after irradiation
or 359 days and 1600 °C heating



from fuel compacts (left) and fuel elements (right) with
s

REGULATORY CHALLENGES FOR THE LICENSING OF FUTURE NUCLEAR PLANTS: A PUBLIC INTEREST PERSPECTIVE

Edwin S. Lyman
Scientific Director
Nuclear Control Institute

ACRS Advanced Reactor Workshop
June 5, 2001

THE FUNDAMENTAL DILEMMA OF NUCLEAR POWER EXPANSION

- Without ratepayer or taxpayer subsidy, no new nuclear plants will be built unless they can successfully mimic the desirable economic features of gas turbines:
  - low capital cost
  - short construction time
  - modularity and ease of distribution
- Can this be done safely? Or is nuclear technology incompatible with these objectives?

REGULATORY CHALLENGES

- NRC licensing of advanced plants must ensure that these economic imperatives do not have adverse impacts on
  - Safety
  - Risk of radiological sabotage
  - Waste management and disposal
  - Non-proliferation
  - Full opportunity for public participation

EXAMPLE: PBMR

- PBMR characteristics **fundamental to its economic viability** represent significant deviation from traditional "defense-in-depth"
  - Lack of pressure containment
  - Significant reduction in safety-related SSCs
  - Reduction in EPZ radius by a factor of 40 (exploits regulatory exemption for HTGRs)
  - Greatly increased reliance on fuel integrity under accident conditions for protection of public health
- ACRS (1988): "unusually persuasive argument" required to justify "major safety tradeoff"

PBMR FUEL PERFORMANCE AND SAFETY GOALS

- Source terms must be accurately determined for a full range of potential accidents
  - Pebble performance very sensitive to initial conditions --- relationship poorly understood
  - Robustness of PBMR fuel is being oversold --- significant fission product release (several % of Cs inventory) can occur at 1700-1800°C) --- hundreds of degrees below fuel degradation temperature
  - Quality control is paramount --- BNFL involvement in South African fuel fabrication plant suggests that a fuel quality control programmatic ITAAC is necessary

PBMR SAFETY GOALS

- Safety goals need to be reexamined for advanced reactors
  - Current goals not conservative enough --- could still be met by reactors today with containments removed!
  - "Large release fraction" if EPZs are reduced
- Accident frequencies that could result in LR must be accurately calculated
  - Design-basis LOCA --- safety margin may be too small
  - Air or water ingress
- System upgrades may be necessary to meet goals
  - secondary coolant system (MIT vs. Eskom)
  - advanced fuel coating materials (i.e. ZrC)

RADIOLOGICAL SABOTAGE --- THE "SHOW-STOPPER"?

- Providing adequate physical protection to defend plants against sabotage has proven to be a major challenge:
  - 50% of U.S. nuclear plants failed force-on-force (OSRE) testing of plant security in 2000
  - At Exelon's Quad Cities plant, "deficiencies in the licensee's protective strategy enabled the mock adversaries to challenge the … ability to maintain core cooling and containment" (NRC, October 18, 2000)

RADIOLOGICAL SABOTAGE (cont.)

- No nuclear system can be rendered "inherently safe" from radiological sabotage
  - Deliberate graphite fire in PBMR remains possible even if accidental fire is incredible
  - Reduction in security staffing requirements for PBMRs not technically justifiable
  - Systems with in-situ reprocessing plants (S-PRISM) would be especially attractive targets
- ACRS (1988) recommended that NRC develop guidance for incorporating sabotage resistance into advanced designs --- need early involvement of Reactor Safeguards staff

PBMR WASTE DISPOSAL

- Final waste disposal may be the single largest obstacle to nuclear power expansion
- Spent pebbles create a huge waste problem: per MWD, compared to spent LWR fuel:
  - Volume and weight are about 10 times greater– with proportionate increase in storage and transport requirements
  - Carbon-14 inventory is 10-20 times greater --- problem for unsaturated repository like Yucca Mountain

PUBLIC ACCEPTANCE

- New facility siting is a great challenge:
  - Favors new plants at existing sites in areas of broad public support
  - Trying to greatly increase number of nuclear plant sites is a losing strategy --- but there is little advantage in modularity if available sites remain highly limited
  - Favors minimization of transport of nuclear materials
- Public opposition may only be deterred with a clear commitment to maximize safety:
  - Favors "gold-plating" nuclear plants
  - Inconsistent with attempts to eliminate containment, reduce emergency planning, etc

PUBLIC ACCEPTANCE (cont.)

- Aggressive licensing schedule proposed by Exelon for PBMR (construction to begin in 2004, operation in 2007) will only antagonize antinuclear groups now mobilizing
- "License by test" is just a PR move --- unlikely to be adequate to resolve all safety issues to NRC satisfaction
- Better to proceed more cautiously and make sure that full resolution of all technical concerns is achieved

through the coating layers. The fractional release of ^{110m}Ag was higher than that of ^{137}Cs, which was consistent with the previous work.[10–13] Although the inventory is small, the release of ^{110m}Ag would be troublesome in mainte-

and ^{154}Eu were obtained in the individual coated fuel particles. To compare the irradiation performance of the individual particles, activity ratios, not activities, were used to account for variations in kernel size and to minimize

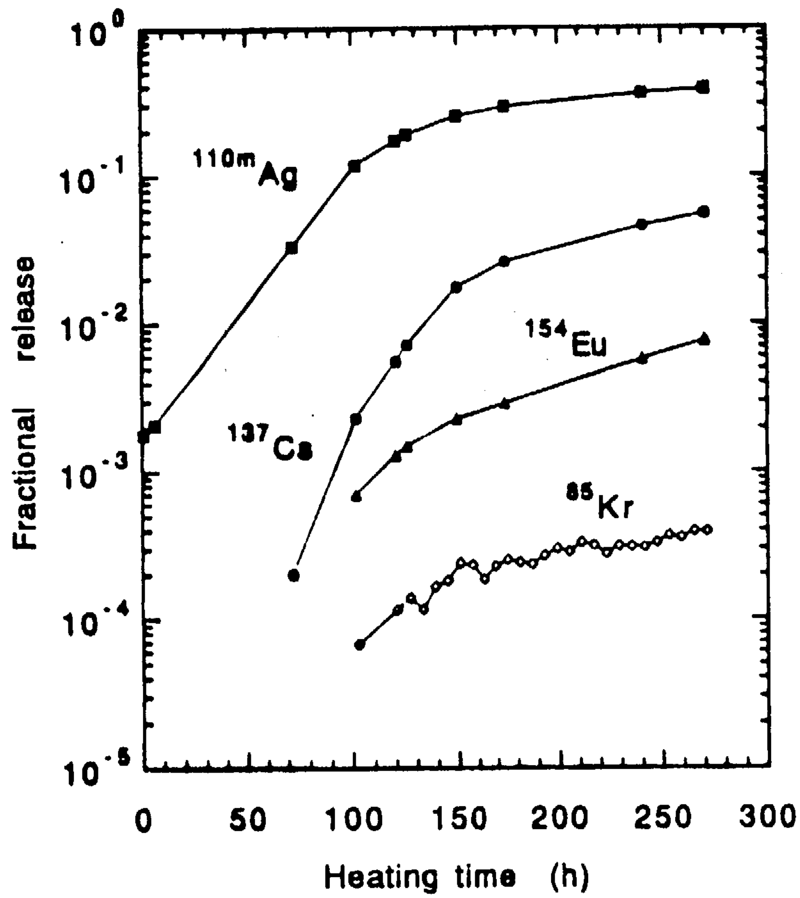


Fig. 2. Time-dependent fractional releases of fission products during the ACT3 heating test at 1700°C for 270 h, obtained by the on-line measurements of fission gas release and intermittent measurements of metallic fission product release.

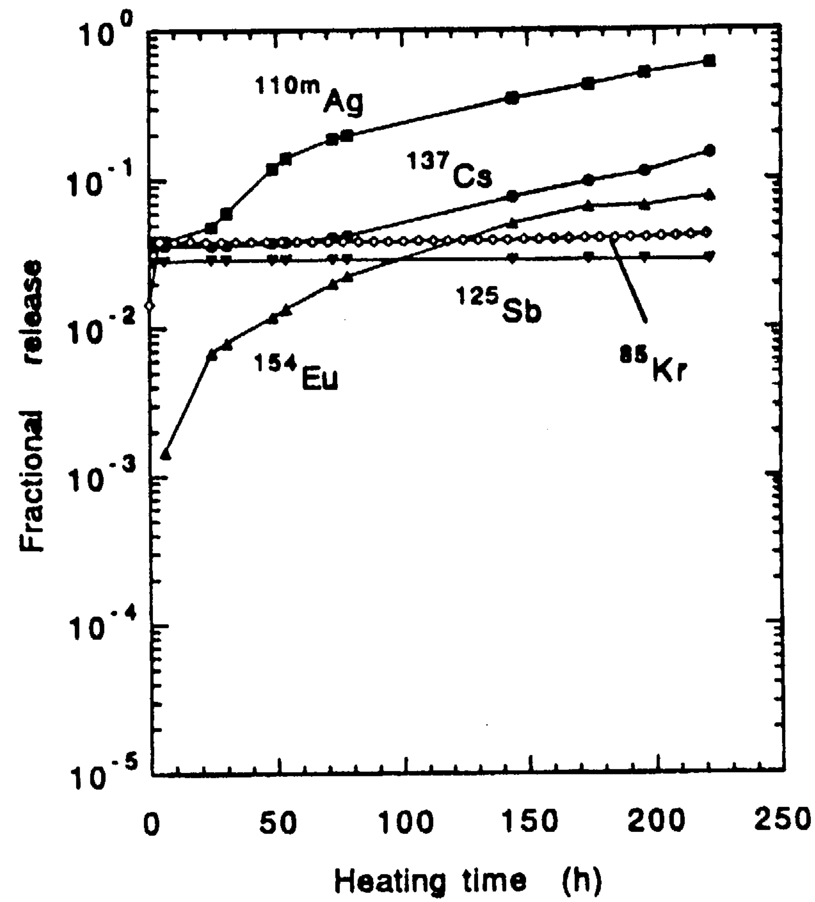
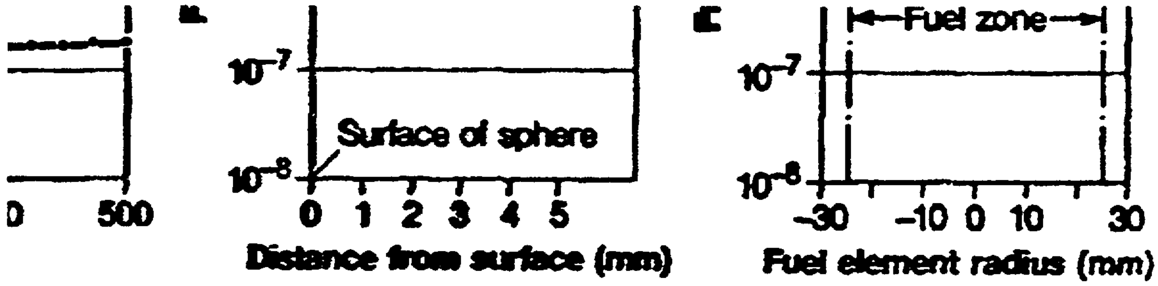
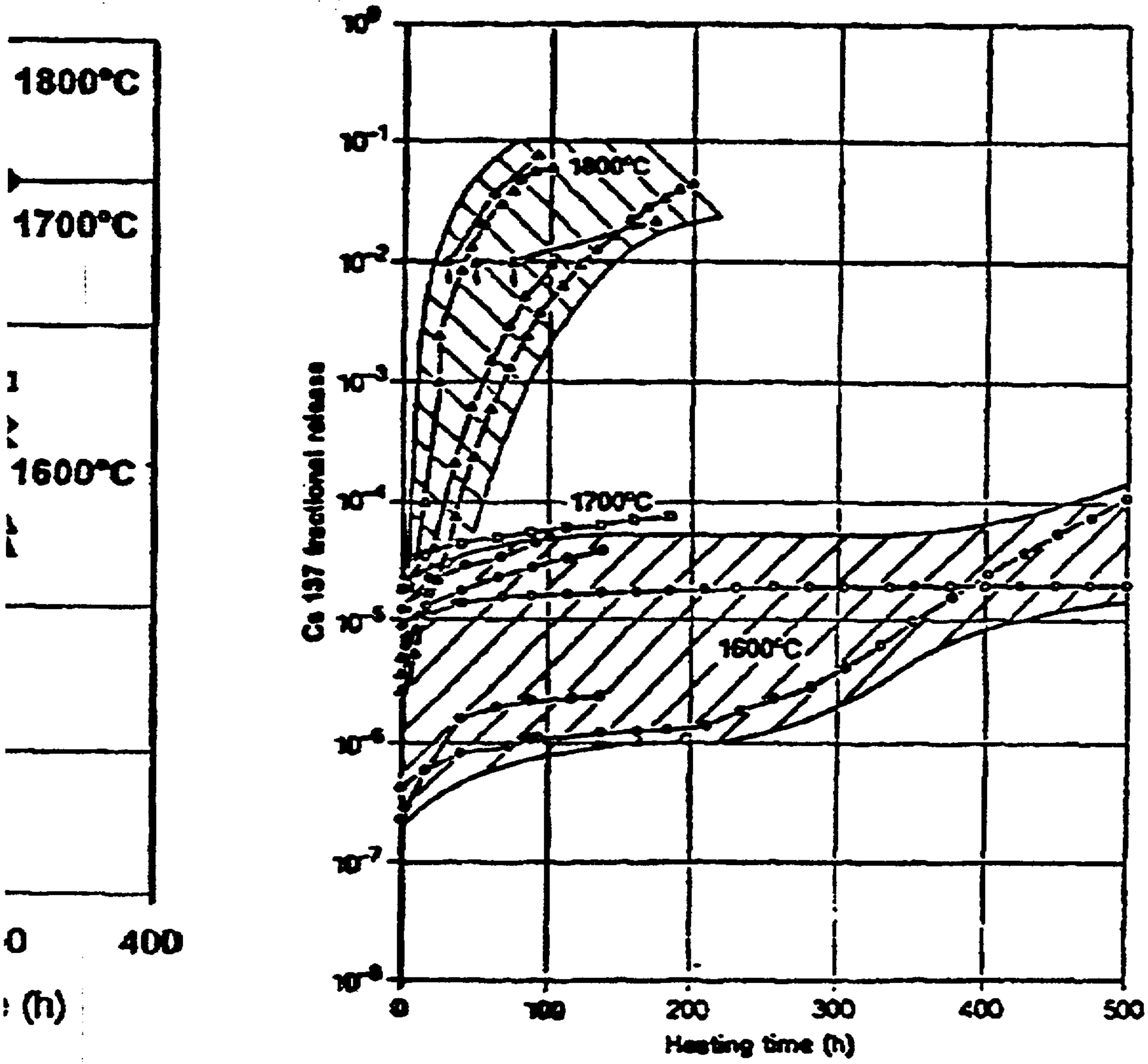


Fig. 3. Time-dependent fractional releases of fission products during the ACT4 heating test at 1800°C for 222 h, obtained by the on-line measurements of fission gas release and intermittent measurements of metallic fission product release.



release and distribution in sphere HFR-K3/1 after irradiation
or 359 days and 1600 °C heating



from fuel compacts (left) and fuel elements (right) with
s

Advanced High-Temperature Reactor for Hydrogen and Electricity Production
(Joint ORNL–Sandia Activity)

Charles Forsberg
Oak Ridge National Laboratory
P.O. Box 2008; Oak Ridge, TN 37831-6180
Tel: (865) 574-6783; E-mail: forsbergcw@ornl.gov

ACRS Workshop: Regulatory Challenges For Future Nuclear Power Plants
Advisory Committee on Reactor Safety
U.S. Nuclear Regulatory Commission
Washington D. C.
June 5, 2001

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

UT-BATTELLE

Outline

- Is a nuclear-based hydrogen economy in our future?
- The Advanced High-Temperature Reactor (AHTR)
  - An option for hydrogen production
  - An option for electric production
- Regulatory implications

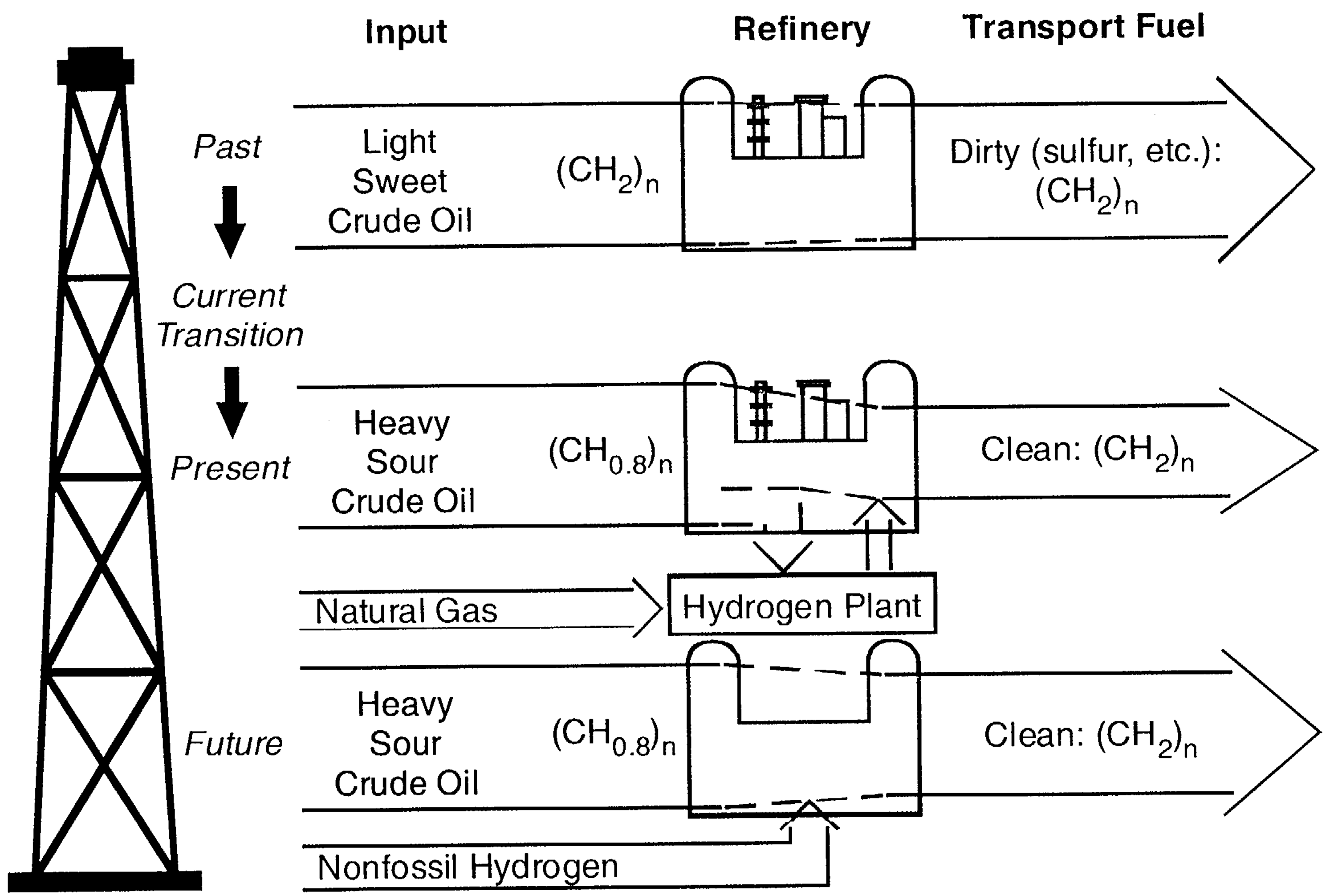
Is a Hydrogen Economy in our Future?

(It may already be here)

Rapid Growth Is Expected in Industrial Hydrogen (H_2) Demand

- Rapidly growing H_2 demand
  - Production uses 5% of U.S. natural gas plus refinery by-products
  - If projected rapid growth in H_2 consumption continues, the energy value of fuel used to produce H_2 will exceed the energy output of all nuclear power plants after 2010
- The chemical industry (NH_3 & CH_3OH) is a large consumer
- Changing refinery conditions are driving up the H_2 demand
  - More heavy crude oils (limited supplies of high-quality crude)
  - Demand for clean fuels (low sulfur, low nitrogen, non-toxic fuels)
  - Changing product demand (less heating oil and more gasoline)
- If nonfossil sources of hydrogen are used, lower-value refinery streams can be used to make gasoline rather than hydrogen—reduced oil imports

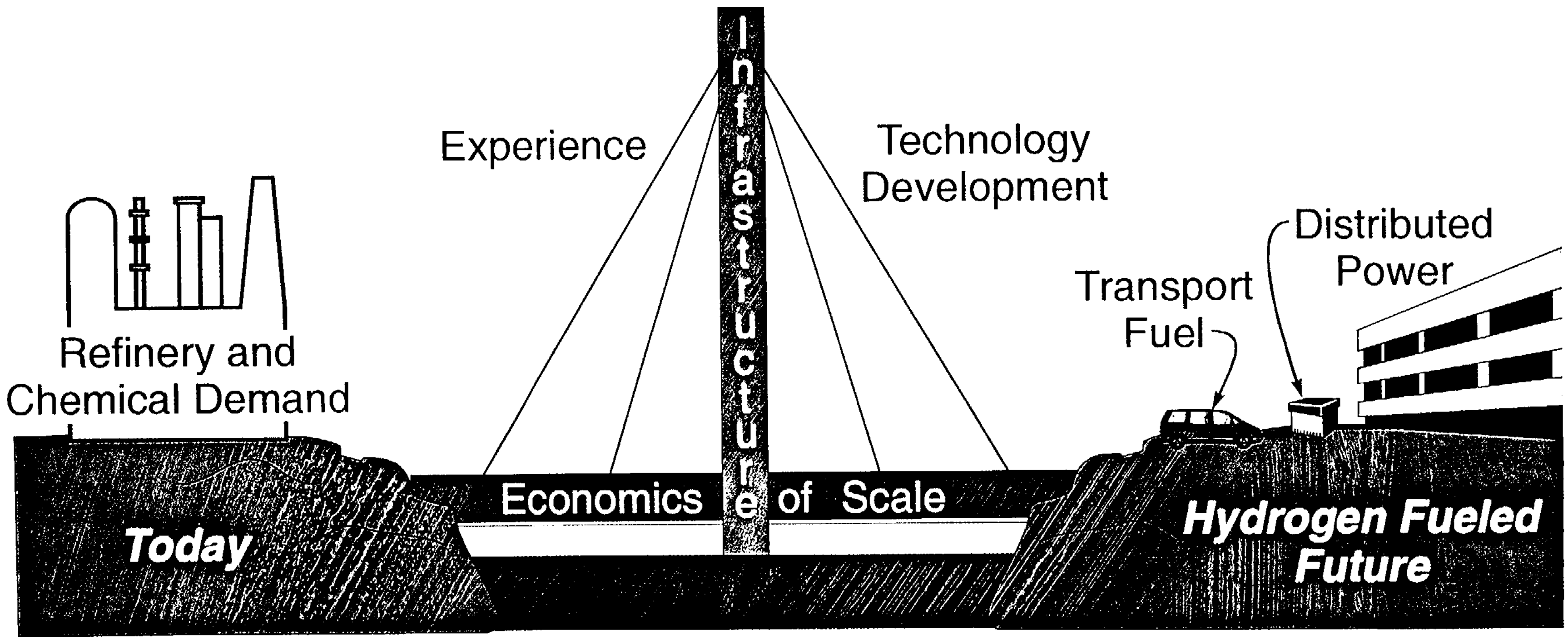
Increased Use of More Abundant Heavy Crude Oils Reduces Refinery Yields, Unless Nonfossil Hydrogen Is Used



Multiple Benefits with Economic Nonfossil Sources of Hydrogen

- Increased transport fuel yields per barrel
  - Lower-value oil components converted to transport fuel rather than to hydrogen (current practice)
  - Reduced imports of crude oil and natural gas
- Greater use of heavy crude oils
  - More abundant with lower costs
  - Western Hemisphere suppliers (Venezuela, Canada, and the United States)
- Competitive chemical and refinery industry
  - Natural gas price increases are increasing H_2 costs
  - Risk of parts of the industry moving offshore
- Lower carbon dioxide emissions

The Growing Industrial Demand for Hydrogen Creates a Bridge to the Hydrogen Economy

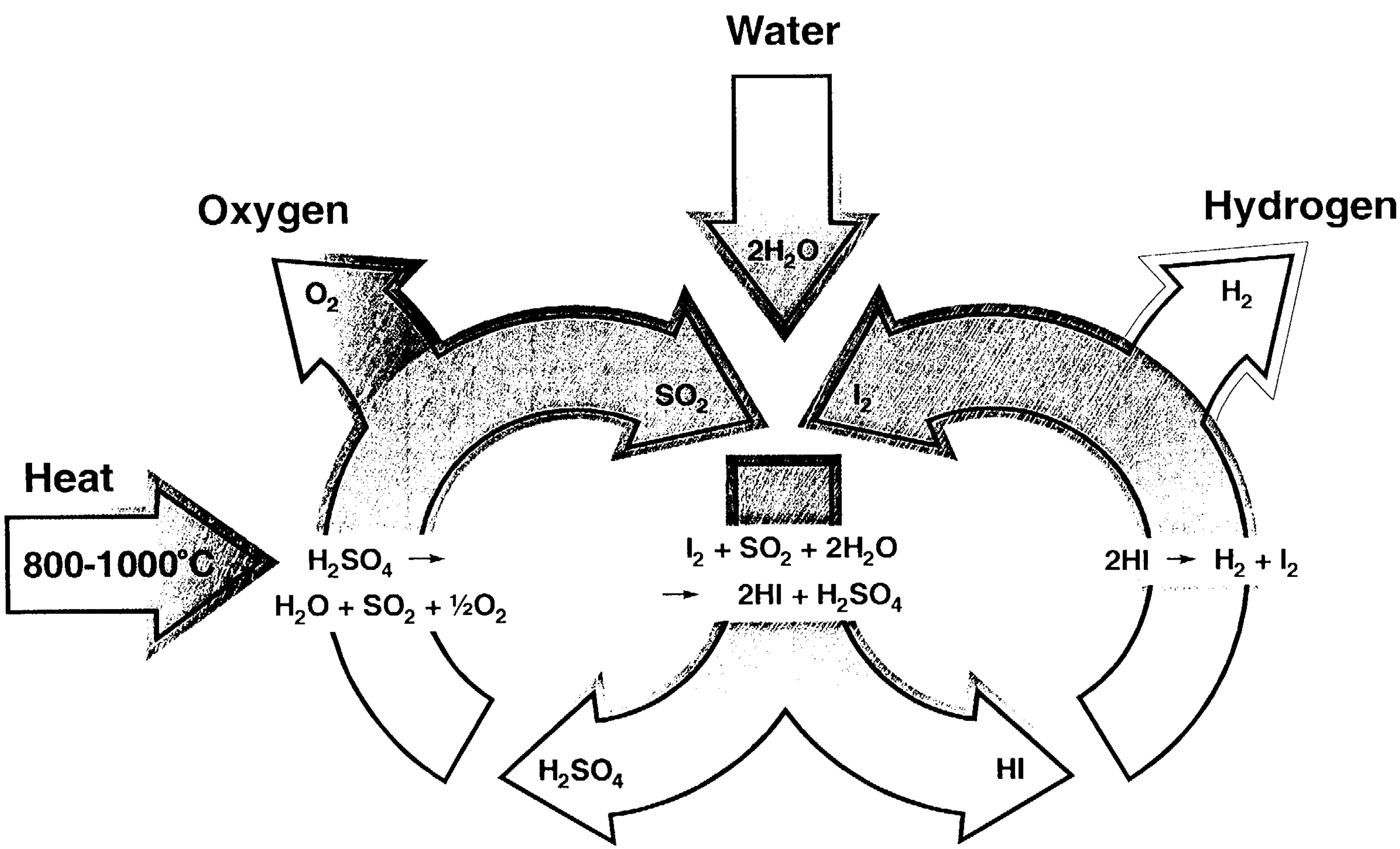


Hydrogen Can Be Produced with Heat from a Nuclear Reactor

- Heat + water ⇛ hydrogen (H_2) + oxygen (O_2)
- Nuclear energy would compete with natural gas for H_2 production
  - Rising natural gas prices
  - Constant (level load) H_2 demand matches nuclear output
- Characteristics of hydrogen from water
  - Projected efficiencies of >50%
  - High-temperature heat is required: 800 to 1000ºC
  - Existing commercial reactors can not produce heat at these high temperatures
  - An alternative reactor concept is required

Chemical Processes Convert High-Temperature Heat and Water to Hydrogen and Oxygen

(Example: Iodine–Sulfur Process)



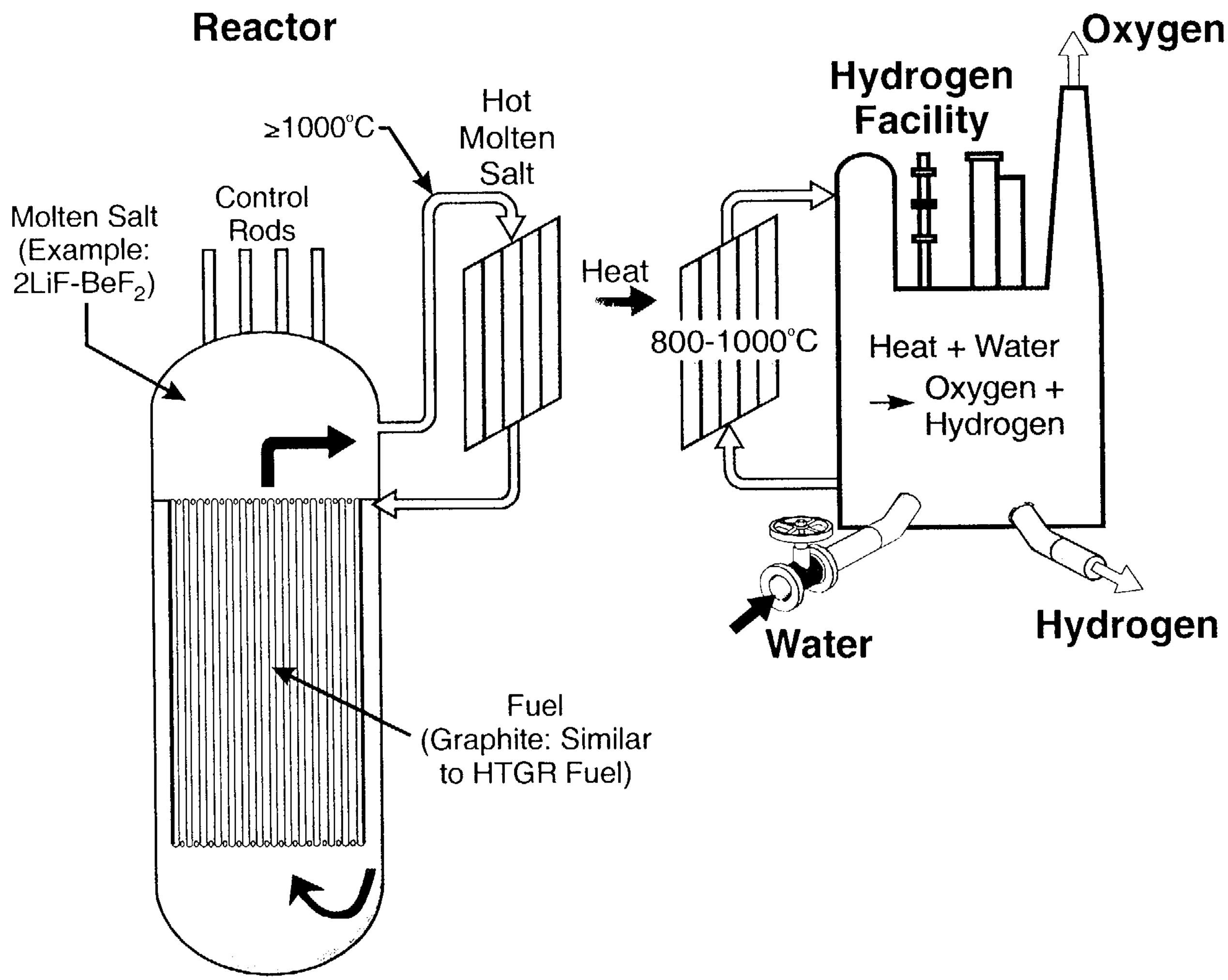
OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

UT-BATTELLE
ORNL DWG 2001-102

An Advanced High-Temperature Reactor (AHTR)—A Reactor Concept for Hydrogen Production

(Different products may require different reactors)

Advanced High Temperature Reactor Coupled to a Hydrogen Production Facility



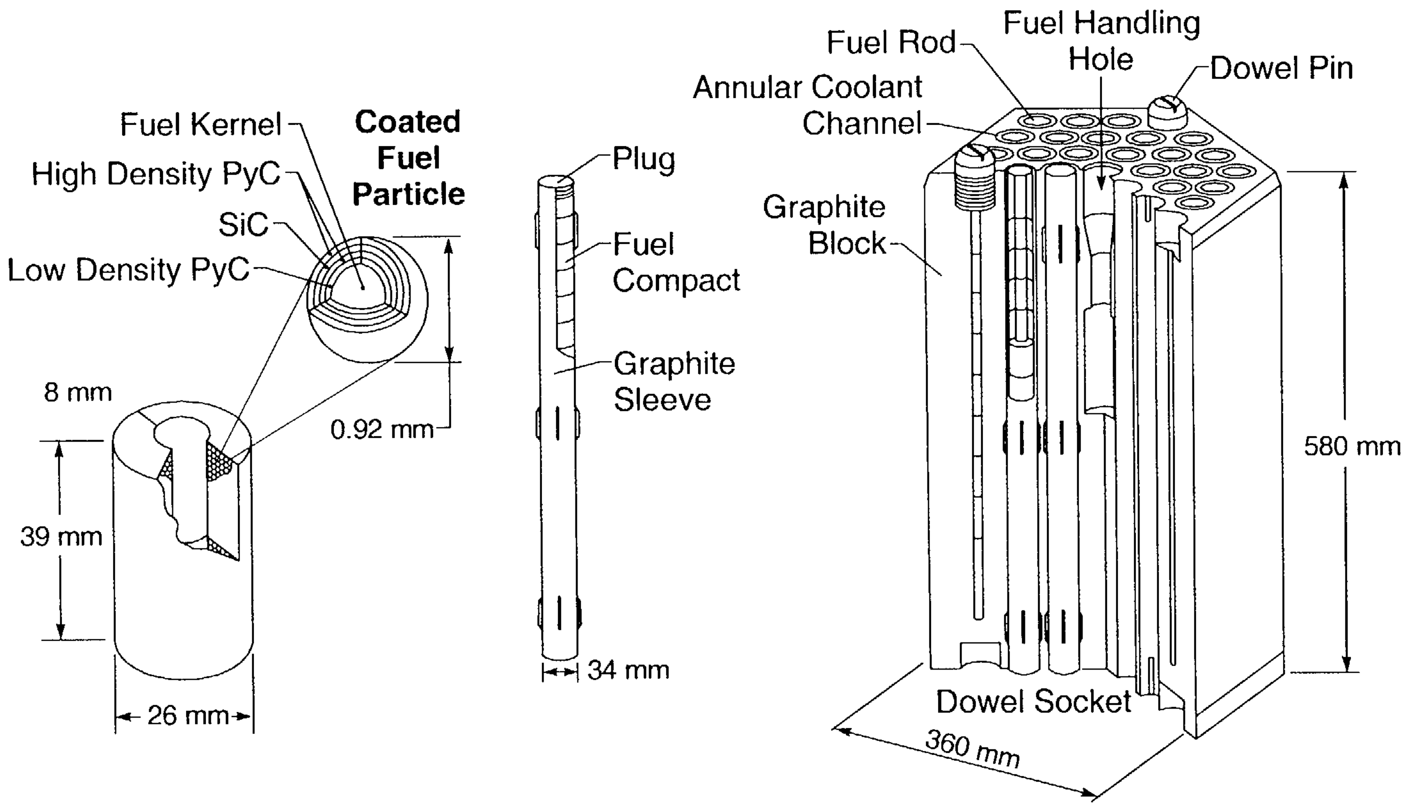
Desired Reactor Characteristics to Produce High-Temperature Heat

- Low-pressure system (atmospheric)
  - Metals become weaker at higher temperatures
  - Low pressures minimize strength requirements
  - Match chemical plant pressures (atmospheric)
- Efficient heat transfer
  - Need to minimize temperature drops between the nuclear fuel and application to deliver the highest-temperature heat
  - Liquid coolant

The AHTR Combines Two Different Technologies To Create an Advanced High-Temperature Reactor Option

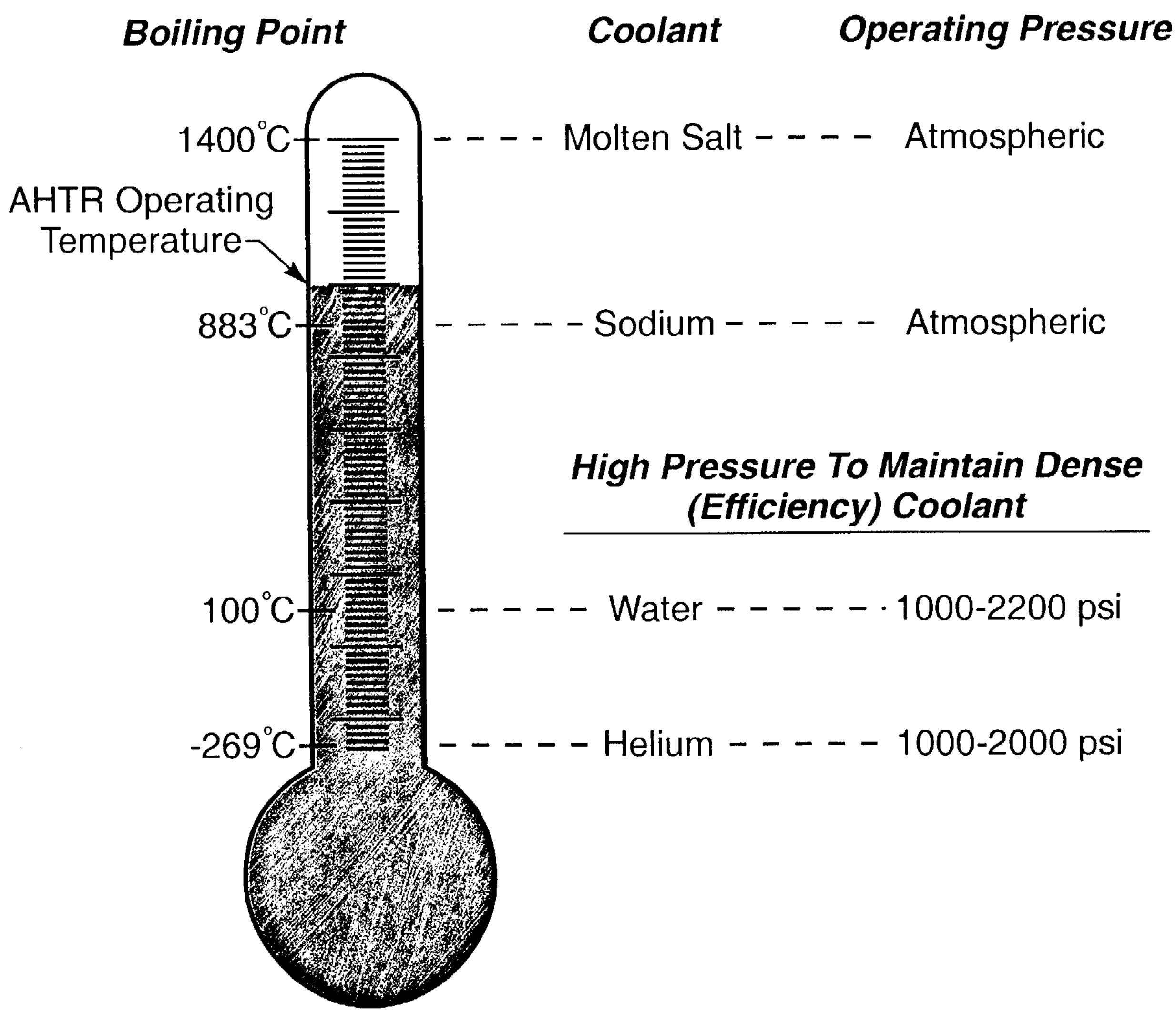
- Graphite-matrix fuel
  - Demonstrated operation at an operating limit of ~1200ºC
  - Same fuel technology planned for modular high-temperature gas-cooled reactors
  - Fuel geometry/dimensions would be different for molten salt
- Molten salt coolant ($2LiF-BeF_2$)
  - Very low pressure (boils at ~1400ºC)
  - Efficient heat transfer (similar to that of water, except it works at high temperatures)
  - Proposed for fusion energy machines

Japanese High-Temperature Engineering Test Reactor Fuel for 950ºC Helium Exit Temperatures



Fuel Compact   Fuel Rod   Fuel Block

Molten Salt Coolants Allow Low-Pressure Operations at High Temperatures Compared With Traditional Reactor Coolants



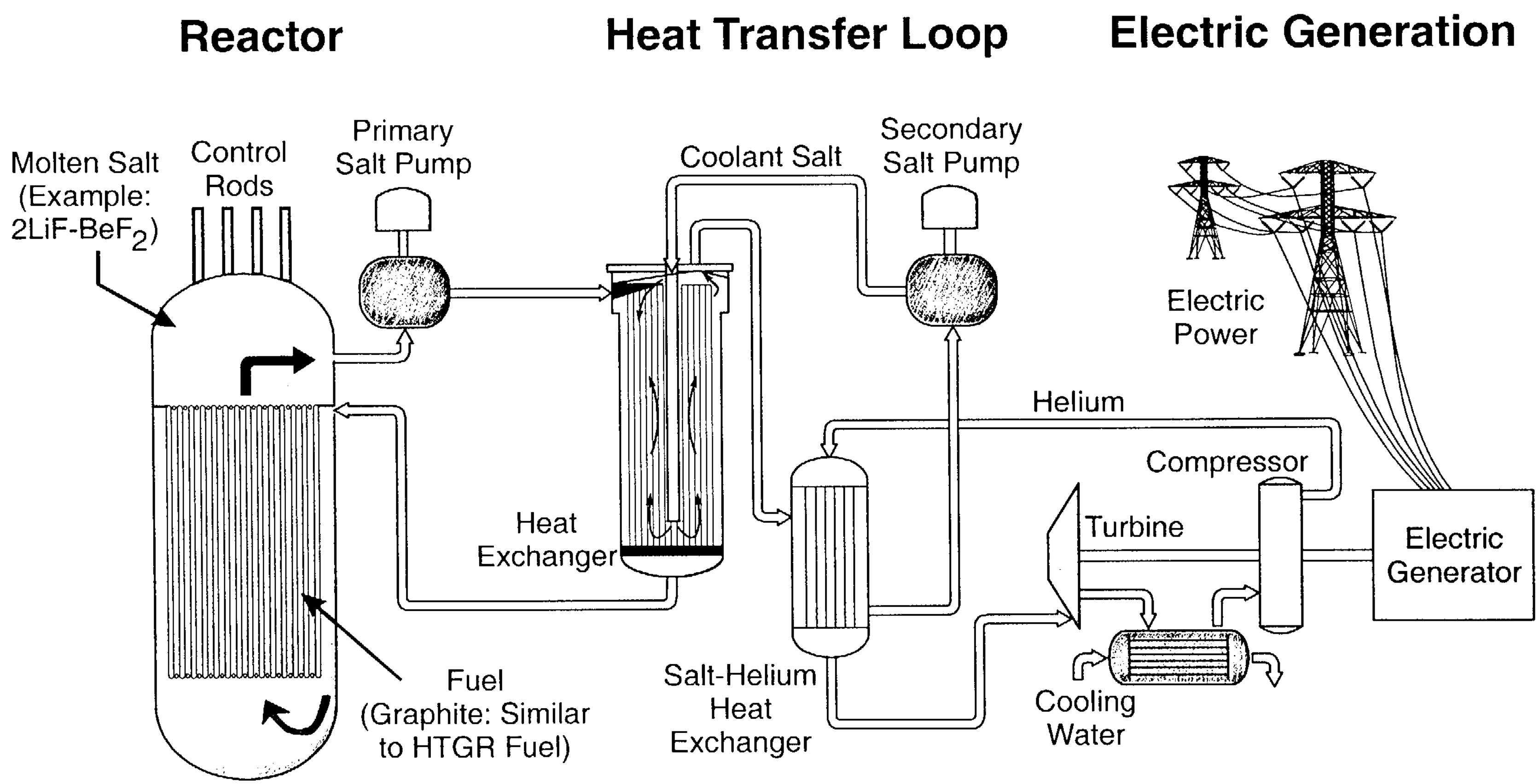
The Safety Case for the AHTR

- Low-pressure (subatmospheric) coolant
  - Escaping pressurized fluids provide a mechanism for radioactivity to escape from a reactor during an accident
  - Low-pressure (<1 atm) salt coolant minimizes accident potential for radioactivity transport to the environment
  - Minimize chemical plant pressurization issues
- Good coolant characteristics provide added safety margins for many upset conditions
- Passive decay-heat-removal system similar to that proposed for other advanced reactors
  - Heat conducts outward from fuel to pressure vessel to passive vessel-cooling system
  - Power limited to ~600 MW(t)

High Temperatures Also Create New Options For Production of Electricity

- High-efficiency helium gas-turbine cycles
  - Conversion efficiency >50% at 1000ºC
  - Provide isolation of power cycle from the reactor using low-temperature-drop heat exchangers
  - Use advanced gas-turbine technology
- Direct thermal to electric production
  - No moving parts (solid-state) methods to produce electricity from high-temperature heat
  - Radically simplified power plant
  - Potential for major cost reductions
  - Longer-term option—solid-state technology is in an earlier stage of development

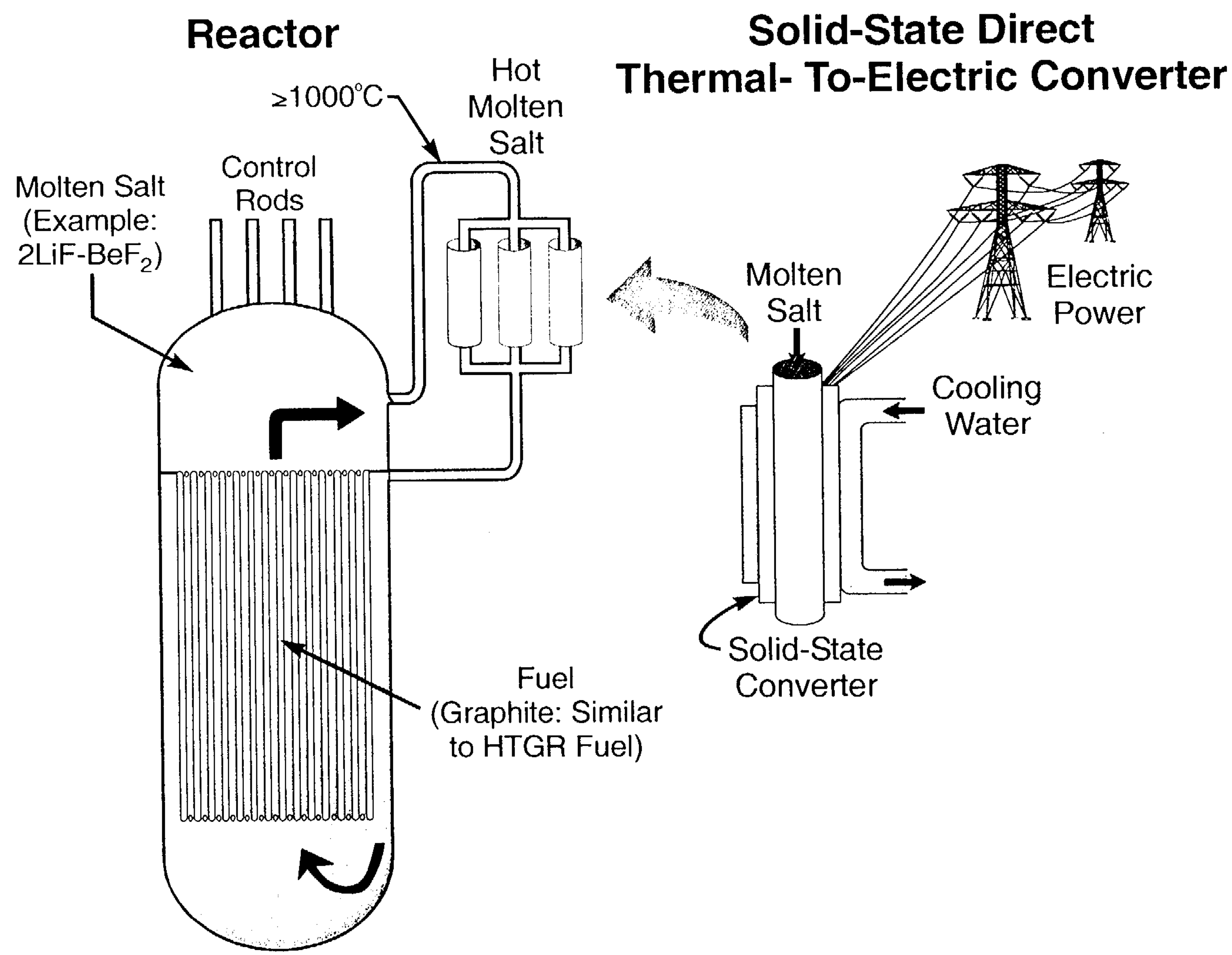
Advanced High Temperature Reactor With Brayton Cycle For Electricity Production



OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

UT-BATTELLE
ORNL DWG 2001-106R

The AHTR May Enable the Longer-Term Option of Direct Conversion of Thermal Energy to Electricity



High Temperatures Create Development Challenges

- AHTR uses some demonstrated technologies
  - Fuels (modified HTGR fuel)
  - Coolant
- AHTR requires advanced technology
  - High-temperature materials of construction
  - Optimized system design
  - Heat exchangers
  - Hydrogen and energy conversion systems

Regulatory Implications of Hydrogen Production

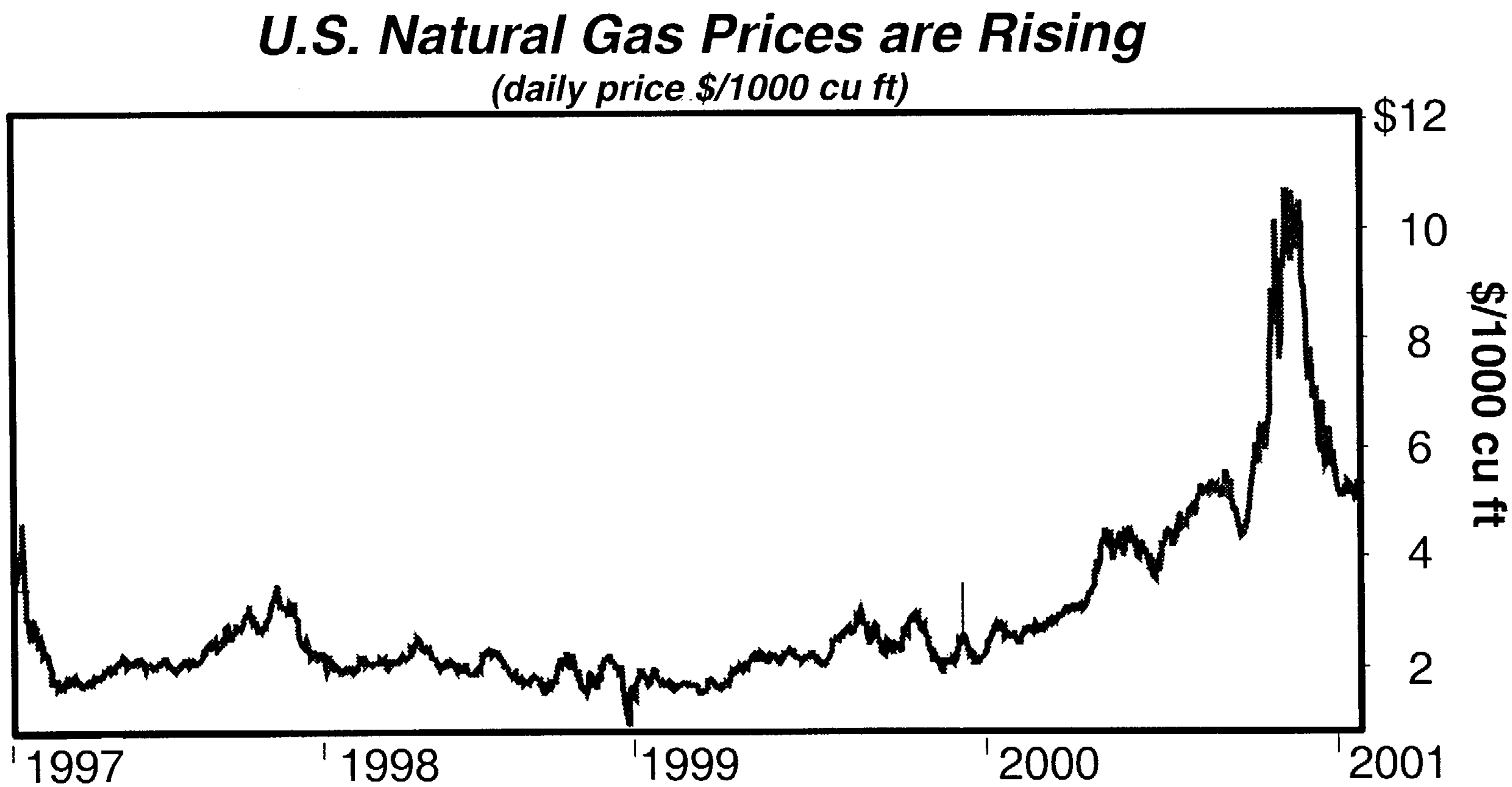
- Different owners: oil & chemical companies
  - Larger than traditional utilities
  - Different perspectives
- Both chemical and nuclear safety must be considered (it is not clear where the primary hazard is)
  - Chemical plant must not impact nuclear plant
  - Nuclear plant must not impact chemical plant
- Non traditional (non-water, non-liquid-metal, non-gas) reactors may be preferred

Conclusions

- Economic methods to produce hydrogen from nuclear power may provide multiple benefits
  - Increased gasoline and diesel fuel yields per barrel of crude oil with reduced dependence on foreign oil
  - Long-term pathway to a hydrogen economy
- High-temperature heat allows for new, more-efficient methods to produce electricity
- Reactors with different characteristics may be preferred for such different uses
  - Very high temperatures
  - Low pressures

Added Information

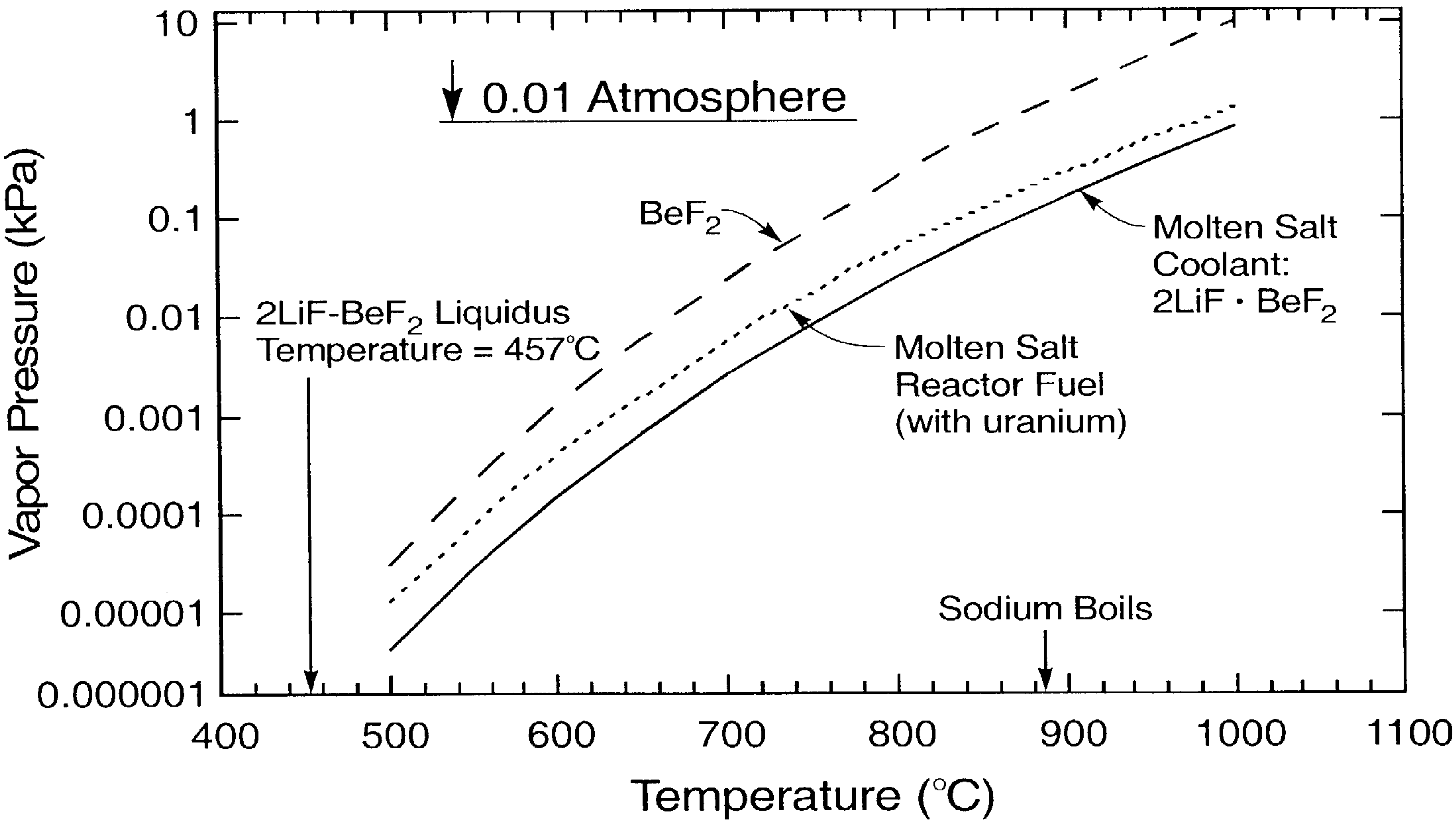
Hydrogen is Made From Natural Gas—If Gas Prices Remain High, a Significant Fraction of the Chemical and Refinery Industry May Move Offshore



There Has Been Extensive Development of Molten Salt Technologies For High-Temperature Nuclear Applications

- Initial development was for the Aircraft Nuclear Propulsion Program
  - Heat transferred from the solid-fueled reactor to the heat exchanger in the aircraft jet engine
  - Molten salts were chosen based on physical (pressure <1 atm.) and nuclear properties
- Molten salts are being considered for cooling fusion reactors (both types)
- Russian studies on molten-salt-cooled reactors

Vapor Pressure of $2LiF\text{-}BeF_2$ Is Low Compared To Other Reactor Coolants



Characteristics of Molten Salts

- For the proposed 2LiF-BeF_2 salt, the temperature rise from the AHTR operating point to the boiling point is ~400ºC
- Several other fluoride salts could be used
- Natural circulation cooling is an option
- Fluoride salts dissolve most fission products and actinides (basis for molten salt fueled reactor)
- Freeze point is ~457ºC
- Large industrial experience with other fluoride salts (aluminum production)

Advanced High-Temperature Reactor