SAND2007-2962C

4th US-China Peaceful Uses of Nuclear Technology

Working Group 1: Nuclear Energy and Safety Technologies

MELCOR/MACCS for Severe Accident Analysis

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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MELCOR Code Development Project

- **MELCOR is developed by:**
  - **US Nuclear Regulatory Commission**
  - **Division of Systems Analysis and Regulatory Effectiveness**
  - **Office of Nuclear Regulatory Research**
- **MELCOR Development is also strongly influenced by the participation of many International Partners through the US NRC Cooperative Severe Accident Research Program (CSARP)**
  - **Development Contributions – New models**
  - **Development Recommendations**
  - **Validation**

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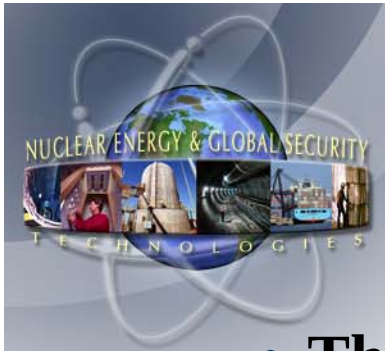
MELCOR Users Worldwide



What is MELCOR ?

- **Thermal-hydraulics code**
  - **Non condensible gases, steam and liquid water**
- **Heat transfer code**
  - **Heat structures**
  - **Convection, conduction, radiation**
- **Aerosol transport and deposition code**
  - **Size dependent aerosol mechanics**
- **Flow network analysis code**
- **Control Volume Code – lumped parameter**
- **Building and containment analysis code**
- **Severe reactor accident submodels**
- **Built to analyze severe reactor accidents but capable of general hazards analysis of facilities**

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Role of MELCOR

- **MELCOR originally conceived as a PRA code**
  - **Modeling was to be as simple and fast-running as possible**
  - **Uncertainties to be dealt with through sensitivity studies**
  - **Substantial user flexibility to be allowed**
- **MELCOR is now viewed as a state-of-the-art tool for source term calculations**
  - **Most modeling is mechanistic, sometimes simplified**
  - **Evolving as a repository of our knowledge of severe accident phenomenology**
- **Application of MELCOR is not limited to reactor accidents**

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Timeline of Nuclear Safety Technology Evolution

Tier 1: MELCOR Integrated Code

Consolidated Codes

Tier 2: Mechanistic Codes
SCDAP, CONTAIN, VICTORIA

Phenomenological Experiments
(PBF, ACRR, FLHT, HI/VI, HEVA)

Phebus FP, VERCORS

European Codes

Deterministic Bounding Analysis

Probabilistic Risk Informed Analysis

Risk Informed Regulation

Chicago Critical Pile

Atomic Energy Act of 1946 (AEC)

Atomic Energy Act of 1954

USS Nautilus

Shippingport

AEC

TMI-2

Chernobyl

9-11-2001

NUREG-1150

MOX LTA
revised 1465

1940 1950 1960 1970 1980 1990 2000 2010

Windscale

TID 14844
source term

NRC

WASH 1400

NPP Siting Study

NUREG 0772

NUREG 1465
alternate source term

NP-2010 and Gen-IV

Emerging Issues

MOX, High Burnup, Life Exension
Environmental Concerns
Global Warming and
Vulnerability to Terrorism

Nuclear Technology Outlook

Optimistic

Guarded

Pessimistic

Overview of MELCOR

- **MELCOR has been developed at Sandia National Laboratories for the USNRC**
  - **Project began in 1982**
  - **Development of new capabilities still underway**
- **Major concern was integration**
  - **Replace collection of simple, special purpose codes**
  - **Eliminate tedious hand-coupling between modules**
  - **Capture feedback effects**
    - **Coupling of temperatures, release rates, and decay heating**
    - **Relocation of heat sources, including deposition**

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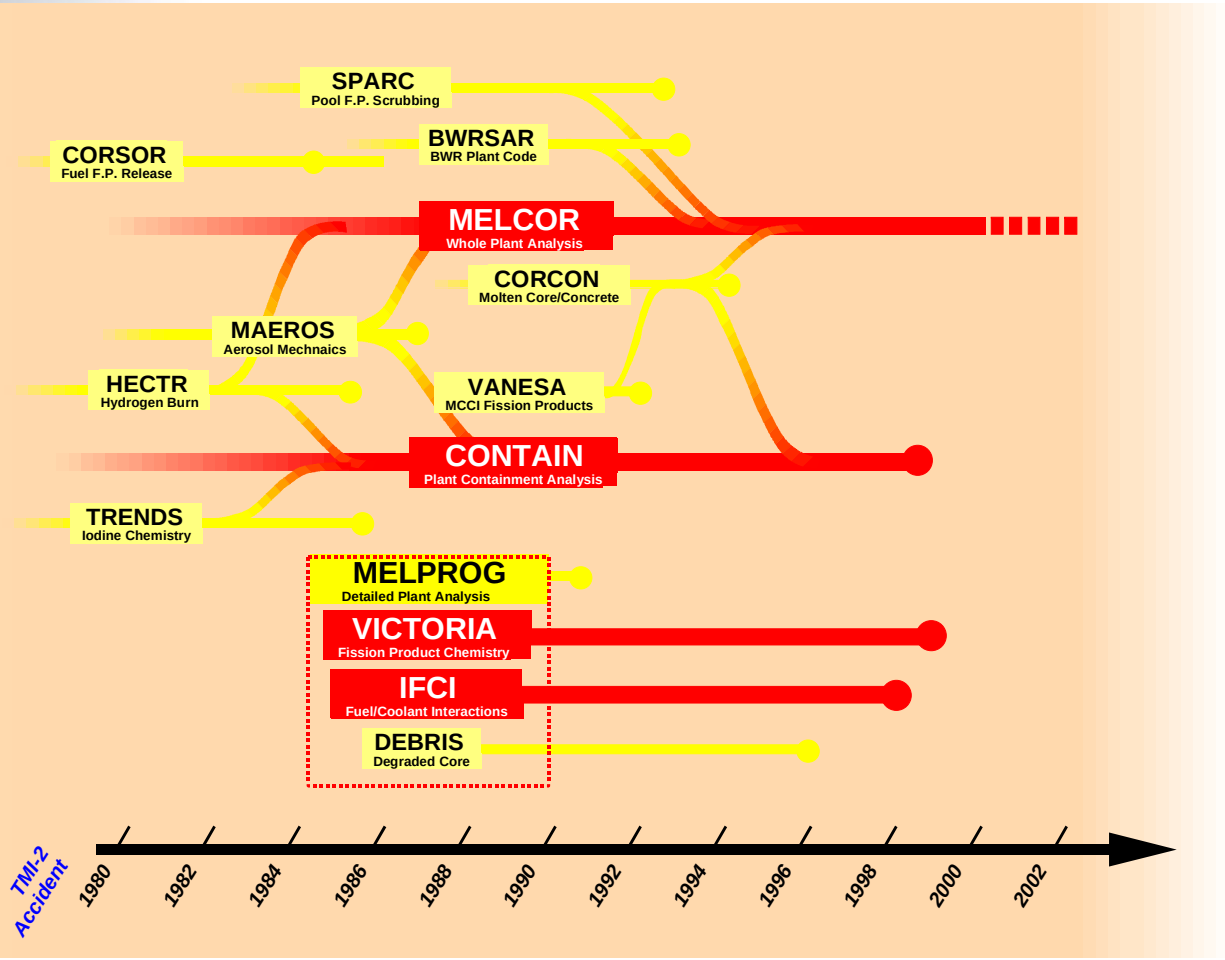
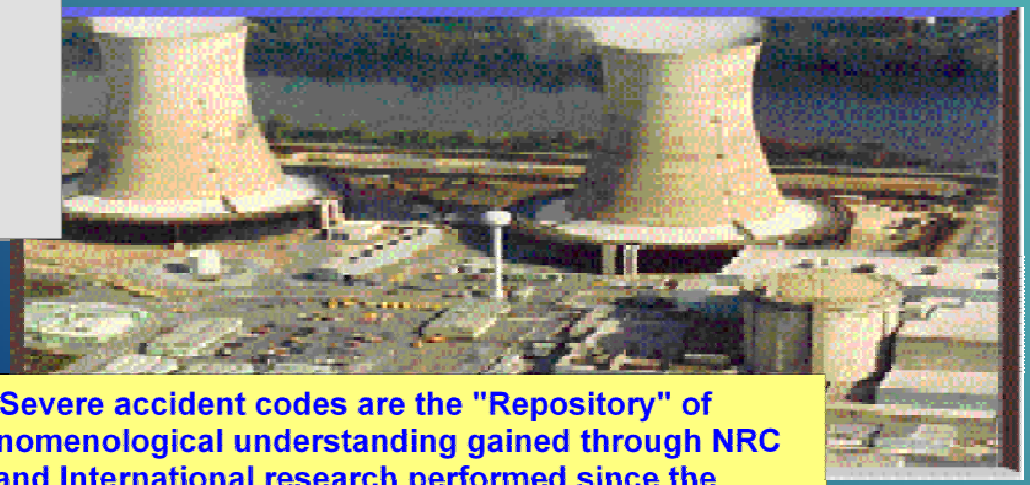
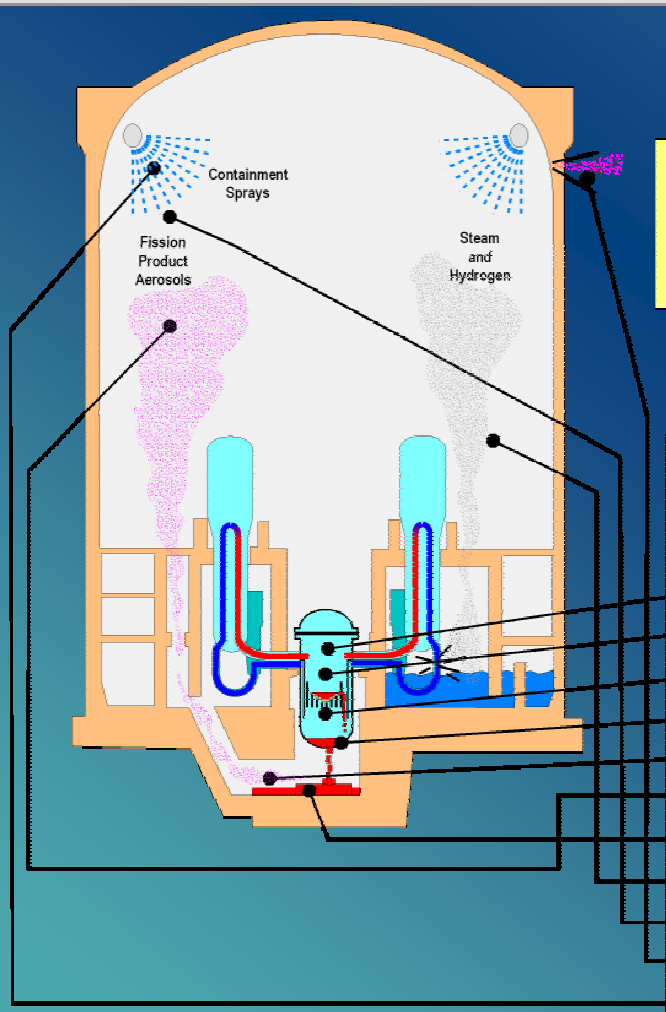
MELCOR: Integrated Physics and Coupled Phenomena



Modeling and Analysis of Severe Accidents in Nuclear Power Plants



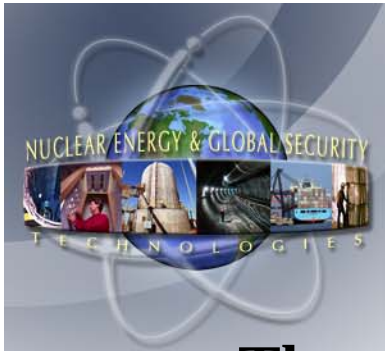


Severe accident codes are the "Repository" of phenomenological understanding gained through NRC and International research performed since the TMI-2 accident in 1979

***Integrated* models required for self consistent analysis**

Important Severe Accident Phenomena

	MELCOR	CONTAIN	VICTORIA	SCDAP RELAP 5
Accident initiation	■	□	□	■
Reactor coolant thermal hydraulics	■	□	□	■
Loss of core coolant	■	□	□	■
Core meltdown and fission product release	■	□	◢	■
Reactor vessel failure	■	□	□	■
Transport of fission products in RCS and Containment	■	■	■	□
Fission product aerosol dynamics	■	■	■	□
Molten core/basemat interactions	■	■	□	□
Containment thermal hydraulics	■	■	□	□
Fission product removal processes	■	■	■	□
Release of fission products to environment	■	■	■	□
Engineered safety systems - sprays, fan coolers, etc	■	■	□	□
Iodine chemistry, and more	■	□	□	□



MELCOR Phenomenological Modeling General Topics

- **Thermal/hydraulic response**
  - **Reactor cooling system**
  - **Reactor cavity, containment, and confinement buildings**
  - **Thermal response of plant structures**
- **Combustible gas generation, transport, and deflagration**
  - **Hydrogen from Zircaloy and steel**
  - **Carbon Monoxide from B_4C and carbonaceous concrete**
- **Aerosol/vapor release, behavior, transport, deposition**
  - **Fission products in fuel and gap**
  - **Aerosols from concrete attack**
  - **Water aerosols, including hygroscopic effects**

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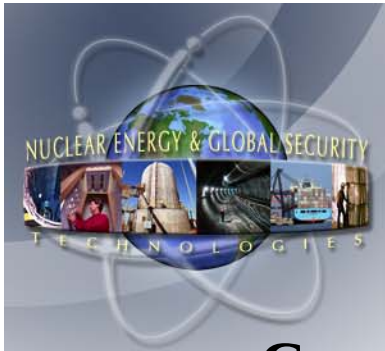

MELCOR Phenomenological Modeling Reactor Oriented

- **Core heatup and degradation**
  - **PWRs, BWRs, and other designs (e.g., VVER)**
  - **Fission product release models**
- **Ex-vessel molten core/concrete interactions**
  - **Concrete attack and erosion**
  - **Fission product release and aerosol generation**
- **Relocation of decay heat sources**
- **High pressure melt ejection, direct containment heating**
- **Performance and impact of Sprays and Engineered Safety Systems**
  - **Sprays, filters, fans, coolers, ice condensers, hydrogen recombiners**

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MELCOR Development Approach

- **Generic models**
  - **No "built-in" nodalization**
- **Building block approach**
  - **More flexibility means greater user responsibility**
- **In general, no duplication of function**
  - **No in-line materials properties, use MP package**
  - **CVH models primary, secondary, and containment**
- **Maintainable code structure**
  - **Modular architecture, portable to new systems**
- **Excellent documentation**
  - **User Guide and Reference Manuals**
  - **Volume 3: Reference Problems**

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MELCOR Packages

- **Major pieces of MELCOR referred to as "Packages"**
  - **Larger than usually implied by "module"**
  - **Do *not* correspond to ancestral codes**
- **Three general types of packages in MELCOR**
  - **Basic physical phenomena**
    - **Hydrodynamics, heat and mass transfer to structures, gas combustion, aerosol and vapor physics**
  - **Reactor-specific phenomena**
    - **Decay heat generation, core degradation, ex-vessel phenomena, sprays and ESFs**
  - **Support functions used by both**
    - **Thermodynamics, equations of state, other material properties, data-handling utilities, equation solvers**

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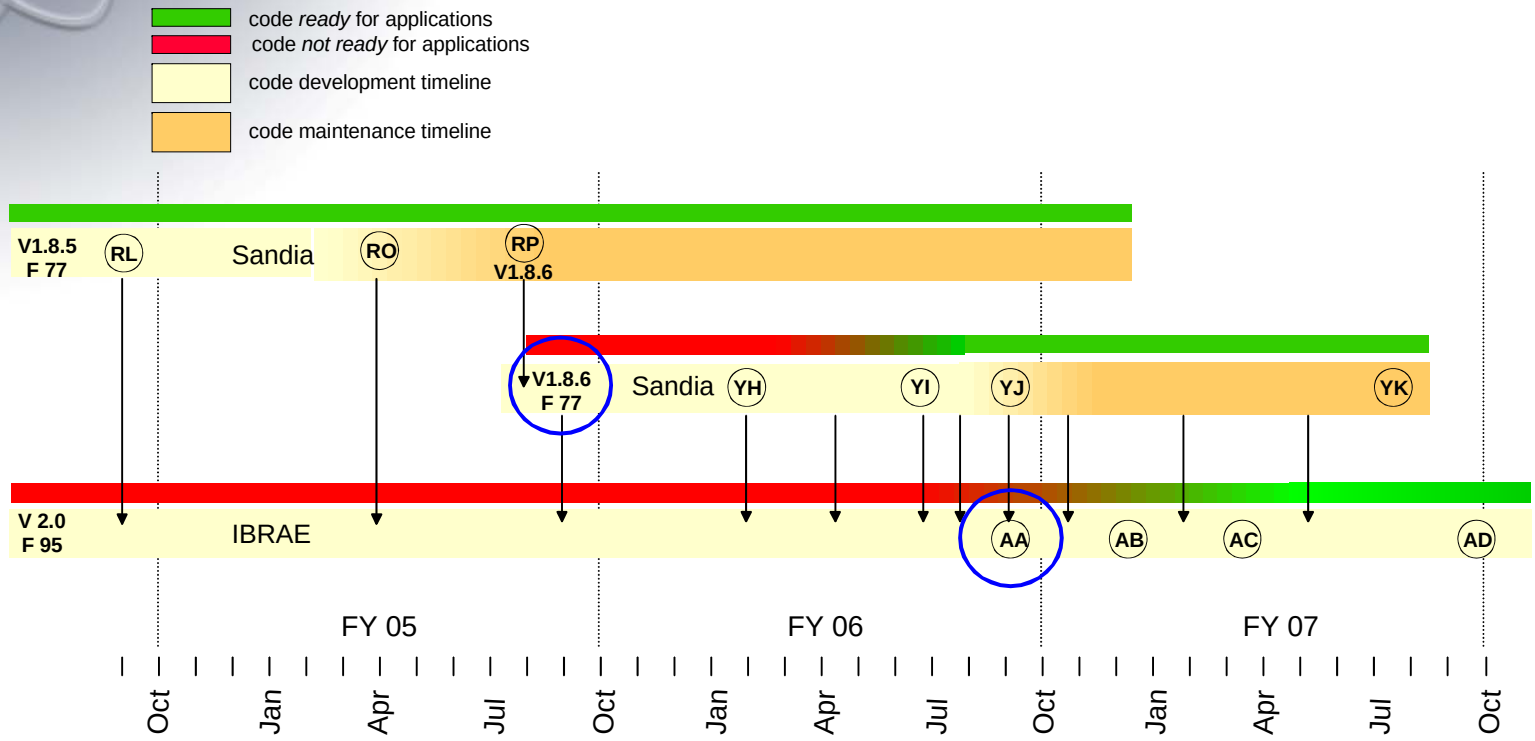
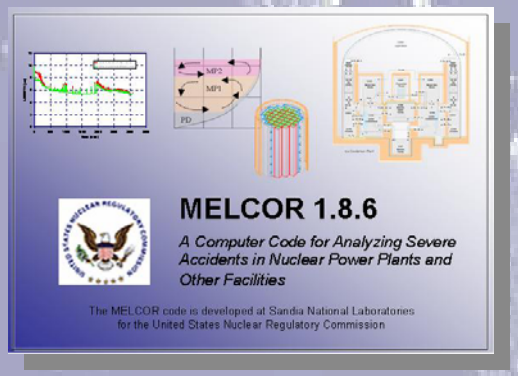
Current MELCOR Development



- **Maintain several versions of the code during development**
  - **Comparison of results between versions**
- **MELCOR 2**
  - **Beta version released September 2006**
  - **Completing assessment matrix before official release**

Current Code Releases and International Workshops



MELCOR 1.8.6 code release in September 2005 and International MELCOR Users' Training Workshop

MELCOR 2.0 release of modernized F95 version last week, also with

8th international workshop attended by 70 persons from the US and around the world.

MELCOR 1.8.6 Development Activities
Core Heatup and Fission Product Release

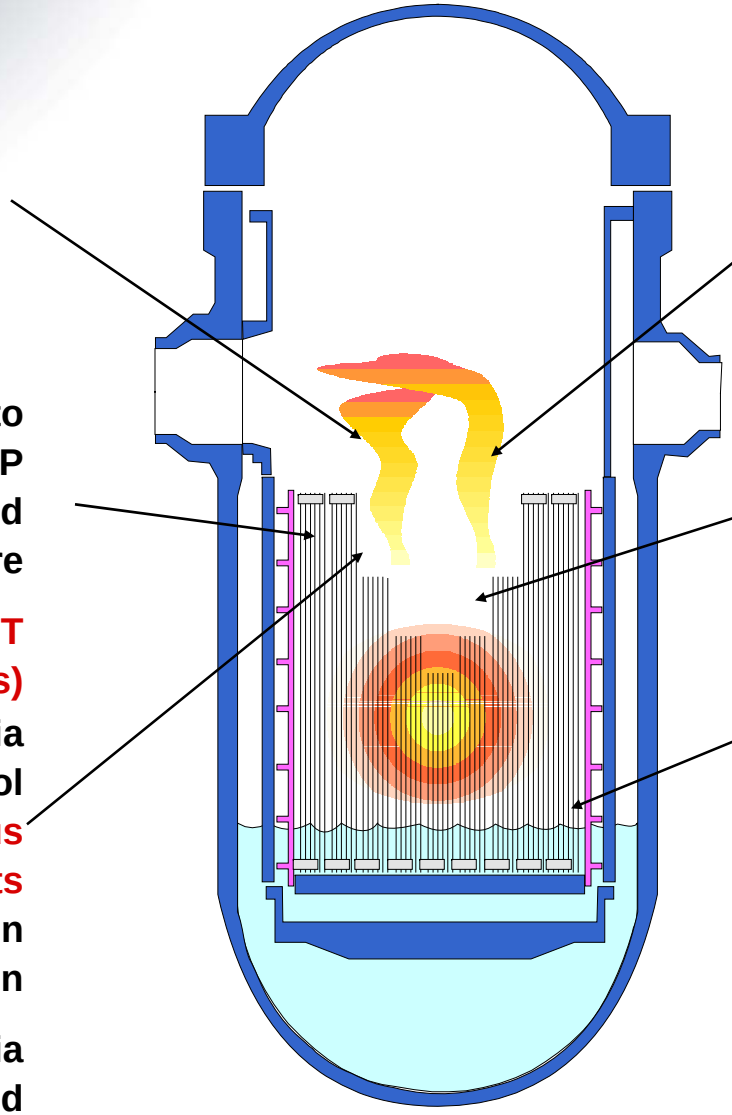
Fission product specie/volatility modified (Cs_2MoO_4) – Phebus Tests – affects RCS deposition

RN Package expanded to allow analysis of FP release from mixed MOX/LEU core

(French VERCORS and RT tests)

Fuel failure criteria expanded via control function – Phebus tests – affects hydrogen generation and melt progression

BWR failure criteria expanded



Ag release model added – Phebus Tests – important for iodine chemistry

- Important to agglomeration

B_4C oxidation model added (PWR) – QUENCH Tests, Phebus FPT-3

Quench-reflood modeling – QUENCH tests – quench front not necessarily water level

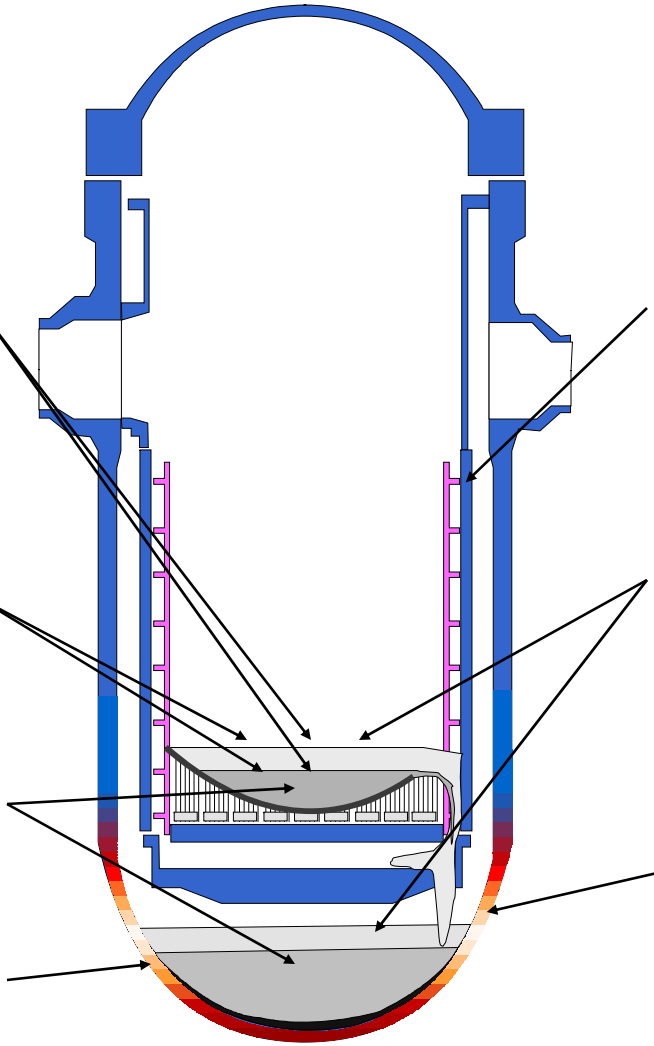
MELCOR 1.8.6 Development Activities
Late Phase Melt Progression

Molten pool stratification into light and heavy layers in core and lower head (RASPLAV,MASCA)

Fission product partitioning between melt phases (RASPLAV,MASCA)

Natural convection heat transfer in circulating melt pools

Insights from OECD LH program in creep-rupture models for lower head



Core periphery baffle and formers added to COR package – allows TMI-like side wall melt release

Molten pool / crust model added to core and lower head regions (TMI-2)

Curved lower head description added to COR (BH integration) including 2-D heat transfer

MELCOR 2.0

- **Source code completely re-written in Fortran-95 by IBRAE**
- **Essentially equivalent to MELCOR 1.8.6 modeling**
  - **Many MELCOR1.8.6 execution issues resolved**
  - **Bit-for-bit parity between v1.8.6 & v2.0**
- **New data management scheme was realized with object oriented approach and different levels of responsibility**
  - **Program level**
  - **Package level**
  - **Object level**
- **Dynamically allocated memory**
  - **Arbitrary number of objects (CVs, FPs, Cells, etc.) limited by the available system memory**

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MELCOR Assessed Against Numerous Separate Effects and Integral Experiments

- **Separate effects tests**
  - **More tightly controlled conditions**
  - **Limited or specific range of phenomena**
- **Integral tests**
  - **Combine many simultaneous physics aspects**
  - **Often less precisely characterized test conditions**
  - **Broader range of phenomena investigated**
- **Actual Accident Studies: TMI-2**
  - **Combines all relevant physics at full scale**
  - **Least well instrumented and characterized "experiment"**
  - **An ultimate basis for code validation**
    - **Bearing in mind, not every accident should be expected to be the same as TMI-2**

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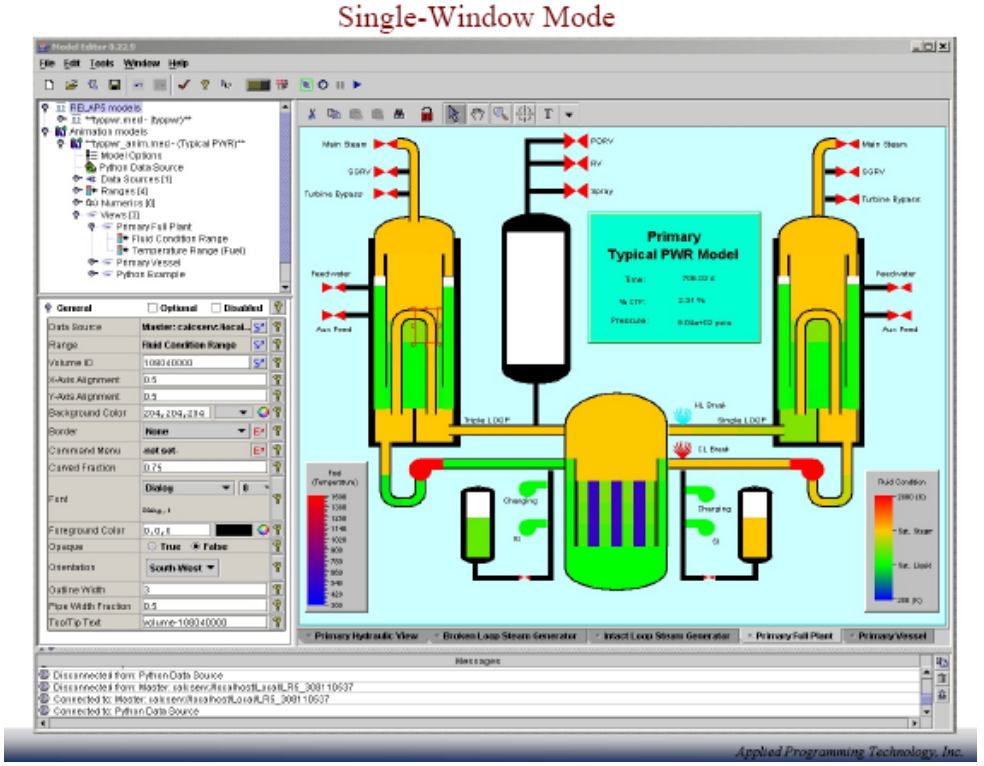
MELCOR Assessments

- MELCOR 2.0 Assessment Matrix
- Example Experiments
  - Phebus
  - Quench
  - OLHF/LHF
  - RASPLAV
  - LOFT
  - PANDA
  - FLECHT/SEASET
  - CORA13
  - LACE
  - NUPEC
- Three-Mile Island

- **MELCOR 2.0 Assessment Matrix**
  - **Over 70 calculations currently in the assessment matrix**
  - **Performed by Sandia National Labs and Russian Academy of Science**
  - **Results to be published with MELCOR 2.0 release**
- **Test calculations cover a broad range of phenomenon**
  - **Core uncovering (i.e., TMI-2 and LOFT-FP2),**
  - **Core damage/melt relocation (TMI-2, PHEBUS, LOFT-FP2)**
  - **Core to upper plenum natural circulatin (TMI-2)**
  - **Natural circulation within SG tubes (i.e. IIST)**
  - **Core to lower plenum natural circulation (i.e., BACCHUS tests)**
  - **Lower head failure (i.e., LHF & OLHF)**
  - **FP release (i.e., ORNL HI & VI, VERCORS, PHEBUS)**
  - **Containment Thermal Hydraulics (i.e., CVTR, HDR, NUPEC, Marviken blowdown, CSTF ice condenser, PANDA etc.)**
  - **Aerosol Deposition (i.e., ABCOVE, SUPRA pool scrubbing, DEMONA, etc.)**

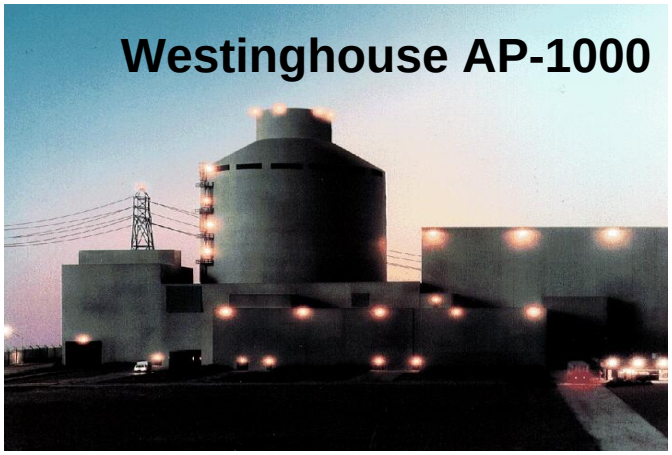
Supporting Applications

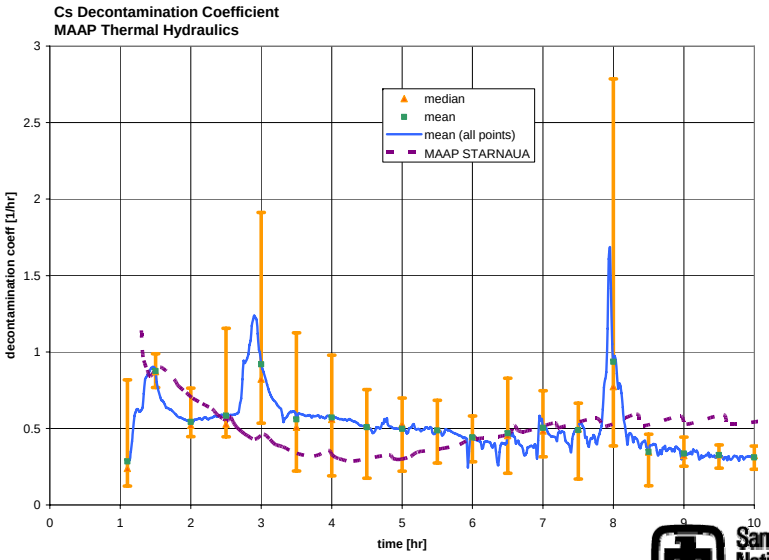
- **SNAP**
  - Symbolic Nuclear Analysis Package develped by API – MELCOR Plug-in
- **PTFREAD**
  - EXCEL add-in for generating plots, analyzing data, and creating AVI's.
- **MELCOR 2.0 GUI & Converter**
  - Utility for generating MELCOR 2.0 input decks and converting existing MELCOR 1.8.6 decks to new format
- **Uncertainty Software**
  - Suite of tools for running MELCOR in batch, Monte Carlo sampling of variables and analyzing statistics



New Reactor Design Certification AP-1000

- **Severe accident source term considered in DBA analysis**
  - **Control room habitability**
  - **Site boundary dose**
- **Design basis accident conditions (eg. AP1000 3BE DVI line break)**
- **MELCOR used in Containment analysis**
  - **NUREG-1465 Alternative Source Term**
  - **MAAP T-H used**
- **Uncertainty analysis determined distribution for fission product depletion constant**





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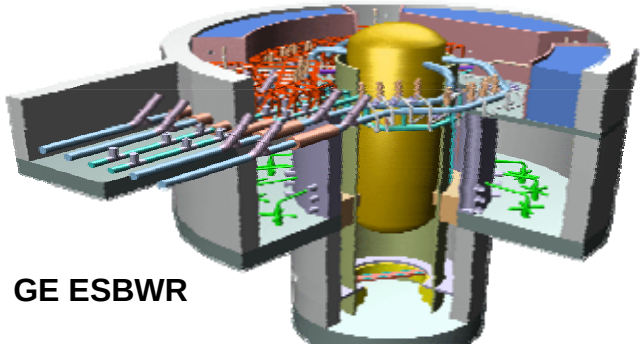
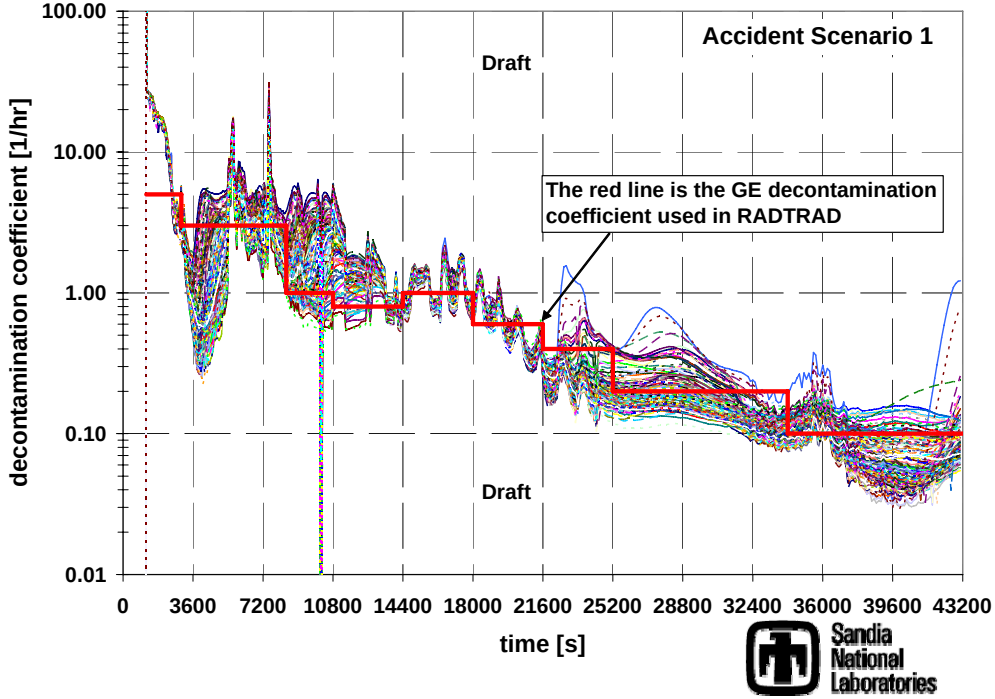
New Reactor Design Certification
ESBWR

- **Assessment of control room and site boundary dose underway using MELCOR to evaluate industry analysis**
- **Containment systems more complex and coupled to primary system**
  - **PCCS system scrubs fission products to RWST**
  - **Suppression pool scrubs fission products also**
  - **Vessel can provide ongoing source of steaming**
- **MELCOR models aerosol transport, settling and performance of safety features**
  - **Iodine behavior an emerging focus**



GE ESBWR



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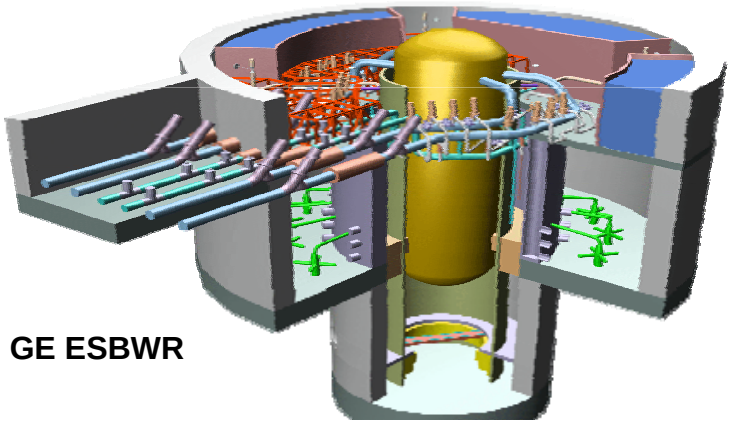
License Amendment Issues
BWR MSIV Leakage

- **License amendments requesting relaxation of valve leakage requirements**
- **Regulatory source terms considered in assessing dose from valve leakage**
- **Severe accident codes can assist in the assessment of fission product transport to leakage location**
  - **Account for transport processes**
  - **Account for natural deposition processes**
- **Assist in refinement of regulatory guides**


GE ESBWR

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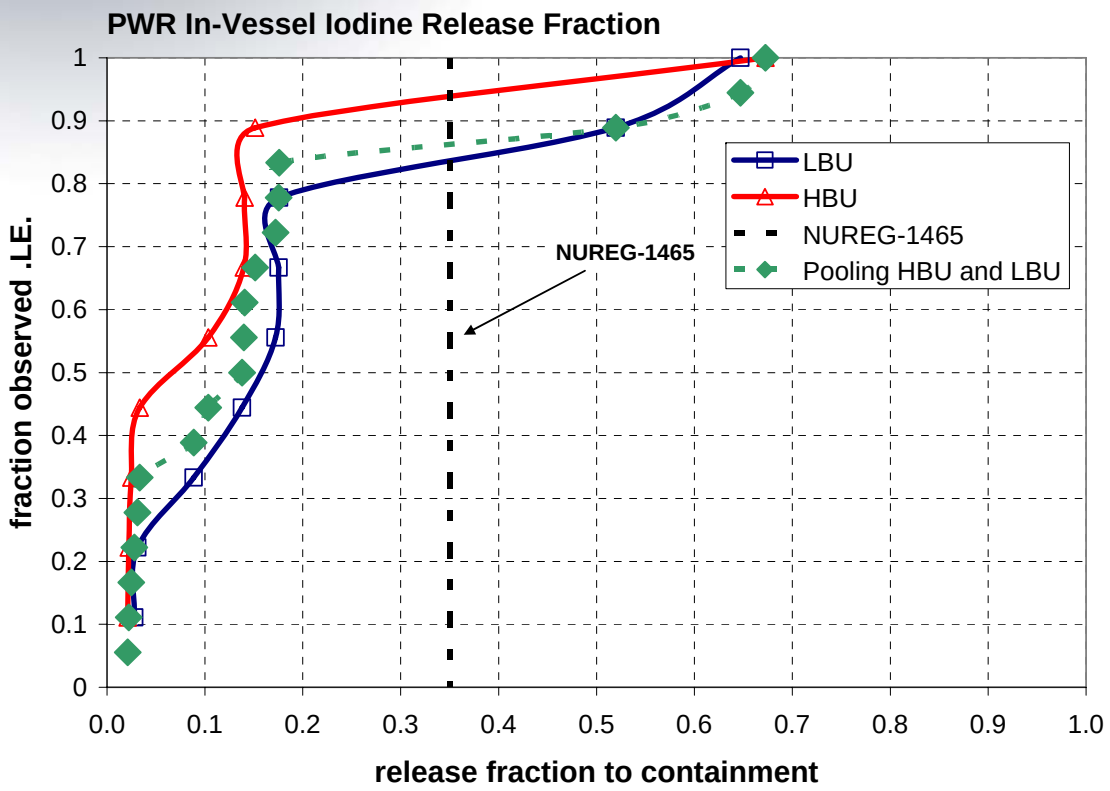
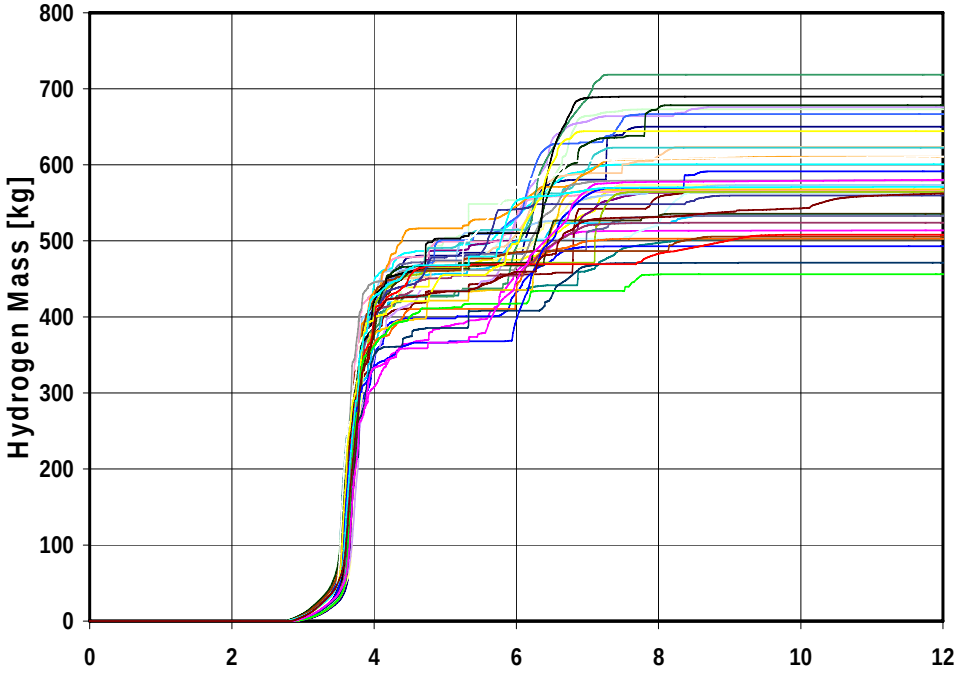
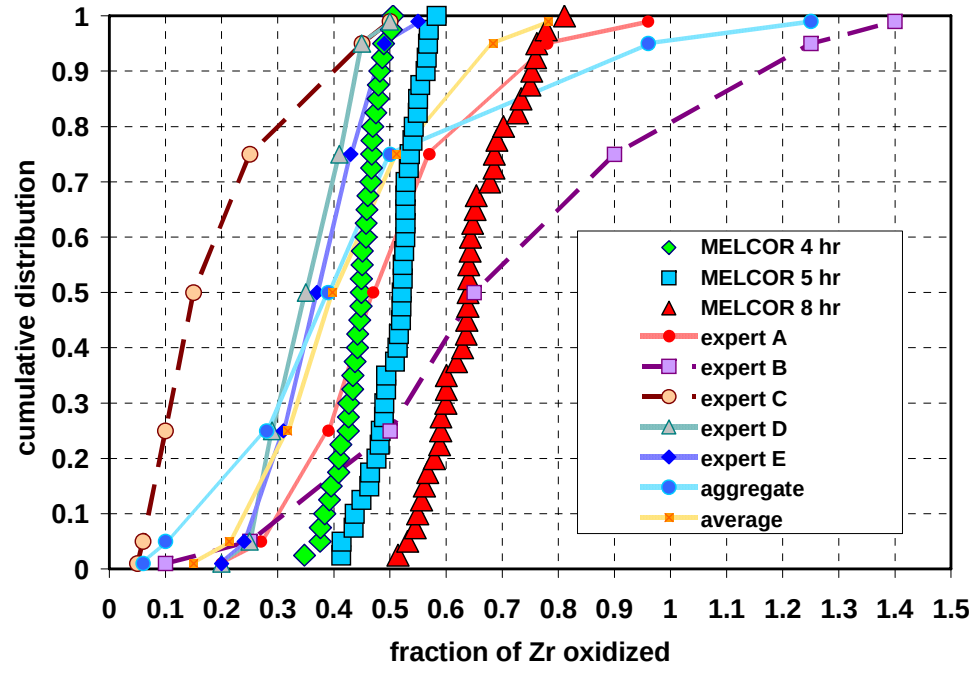
License Amendment
High Burnup and MOX



- **Ensemble of PWR accidents with core damage**
  - **SBO, SB and LB-LOCA**
- **Source term to containment generally lower than NUREG-1465 by factor 2**

Risk-Informing Regulation
H_2 Rulemaking





- H_2 Uncertainty range in Sequoyah supporting hydrogen rulemaking
- MELCOR produces narrower distribution compared to subjective expert elicitation
- Code approach provides objective estimates with greater certainty

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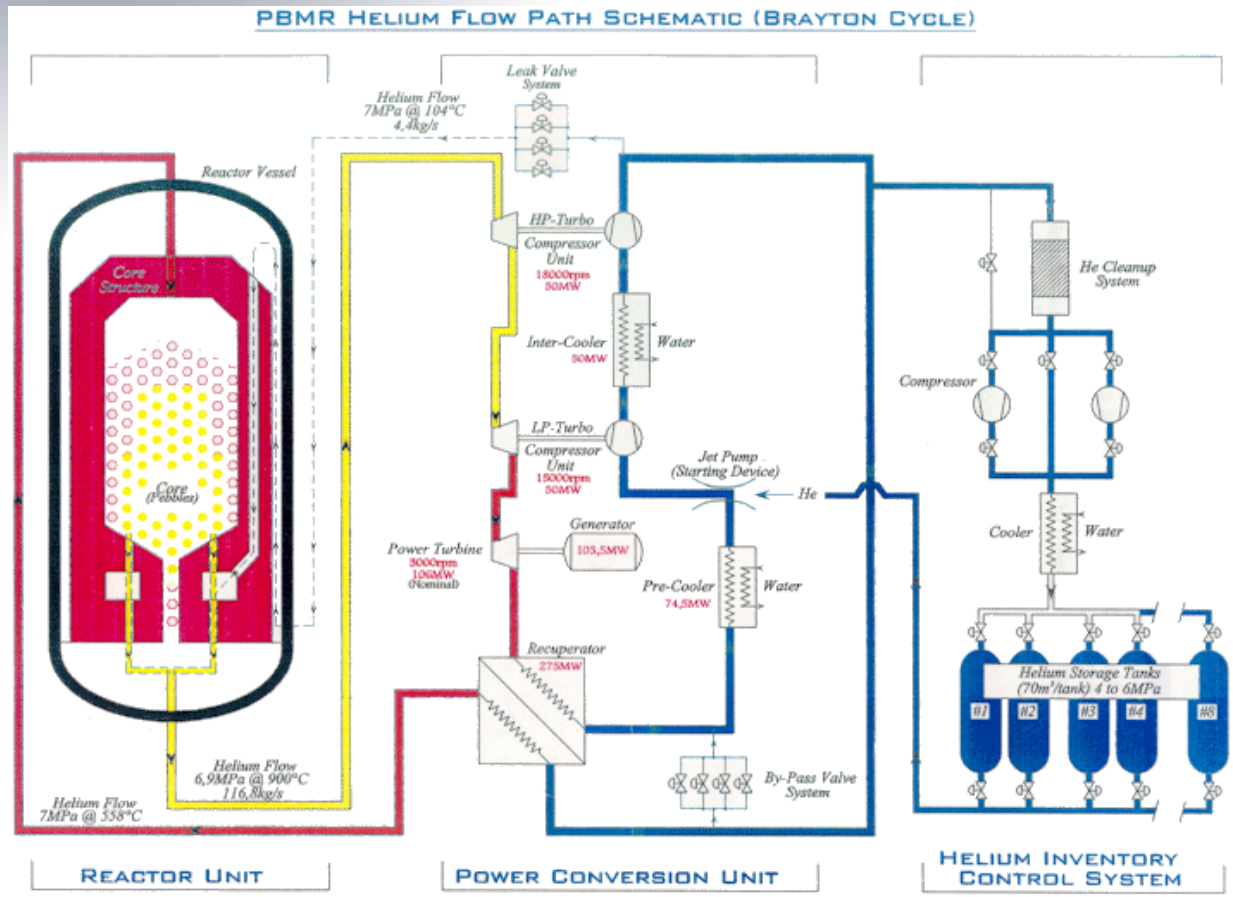
Gen IV HTGR Applications



- SNL-funded development of HTGR capabilities
- Helium coolant
- Graphite fuel and structure
  - Oxidation
- Heat exchanger model developed
- Brayton cycle modeled
- No FP release model yet

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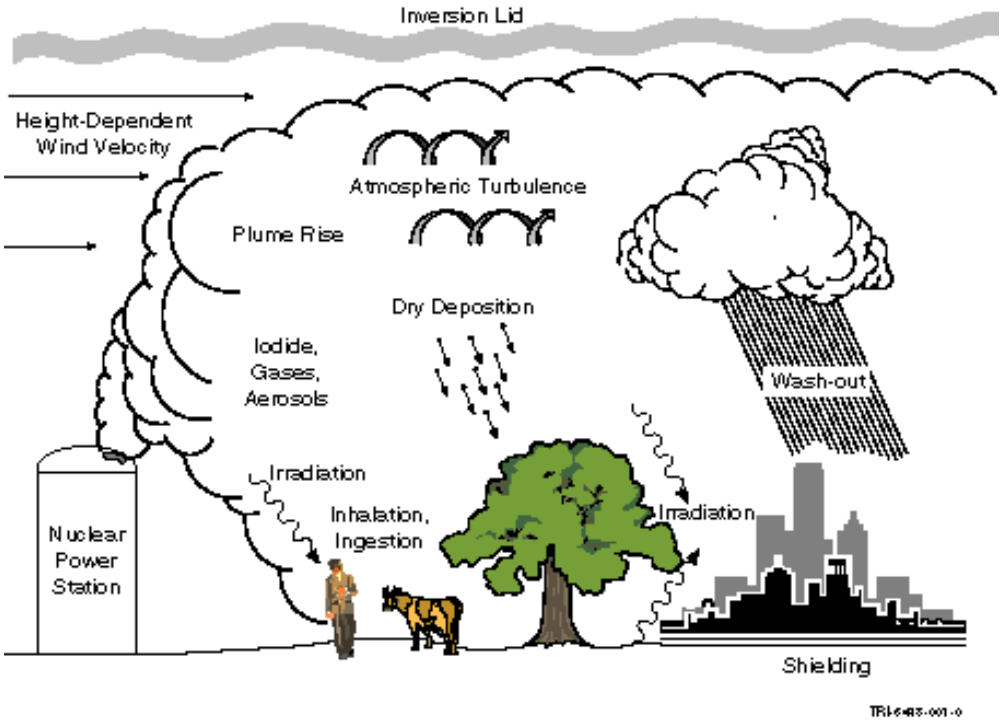
MACCS2

- **MACCS2 is used to analyze offsite consequences from an accidental atmospheric release of radioactive material.**
  - **Early and latent health effects**
  - **Land contamination**
  - **Economic impact**
- **Types of uses:**
  - **Support level-3 PRA analyses**
    - **MELCOR source-term predictions**
  - **Planning**
  - **Cost-benefit analyses**



Past MACCS2 Development I

- **Extend limits and enhance flexibility**
  - **Increase limit on plume segments (to 10)**
  - **Increase limit on number of chemical groups (to 20)**
  - **Increase limit on number of aerosol bins (to 20)**
  - **Output land contamination values and areas (by concentration and dose)**
  - **Limit extended to 10^{25} Bq for radionuclide inventory**
- **Enhance compatibility with user interface (WinMACCS)**
  - **Tabs in input file**
  - **Binary output file**
- **Automate importing data from MELCOR (MELMACCS)**

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Recent MACCS2 Development

- **Model improvements and additions**
  - **Alternatives to LNT assumptions**
  - **Plume-rise model (Briggs, 1971 and 1972)**
  - **Long-range atmospheric dispersion**
  - **KI ingestion model**
  - **Diurnal variations in mixing height**
  - **Evacuation speed multiplier to account for effect of precipitation on traffic**
  - **Alternative input of plume heat content (mass rate and density)**

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Recent and Ongoing Applications

- **Plume model adequacy evaluation (RES/DSARE)**
- **Evaluation of competing evacuation/sheltering strategies (NSIR/EPPO)**
- **Rebaselining NUREG-1150 consequences for CRIC-ET (RES/DSARE)**
  - **Used to evaluate risk-significance of candidate generic issues**

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