Theoretical Work on Consequence / Risk

from severe accidents at nuclear power stations

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Vg# 1

Consequence Assessment

- Source term assessment from accidents or security incidents
  - Plant damage -> core damage
  - Timing and magnitude of radioactive release to environment
- Transport assessment
  - Atmospheric transport
  - Deposition and fallout
- Consequence Assessment
  - Acute dose and prompt health effects
  - Chronic dose and latent health effects
  - Land contamination and economic consequences

Vg# 2

Outline

- Timeline of reactor safety technology
- Developments over past 25 years
- Overview of current safety code development status
  - MELCOR – accident progression and source term quantification
  - MACCS – atmospheric transport and consequence quantification
- Examples of code use, validation and benchmarking

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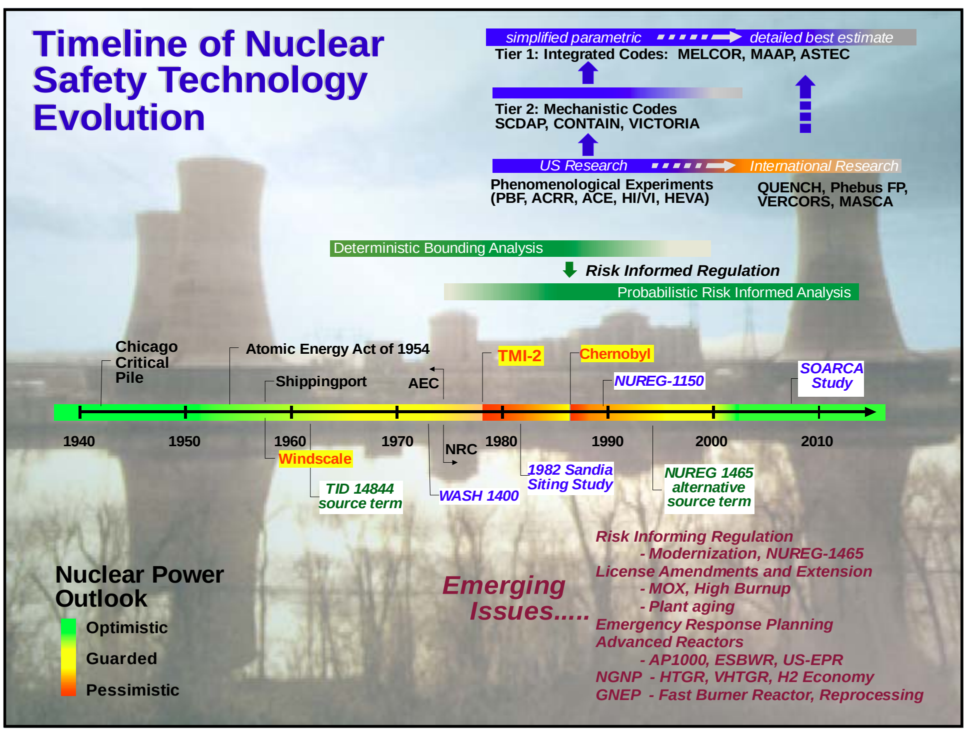

NRC Safety Codes are Used Worldwide

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MELCOR 2.0 International Workshop CSARP Member Attendees

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Taiwan Status with USNRC Cooperative

- **Taiwan INER organization member of CSARP group until last year**
- **INER has MELCOR version 1.8.6 and the MACCS codes (current version is MELCOR 2.0)**
- **Future INER-CSARP status and access to USNRC safety codes unclear at this point**

Accident and Plant Damage Progression Source Term Quantification

Overview of MELCOR

- MELCOR has been developed at Sandia National Laboratories for the USNRC
  - Project began in 1982
    - Motivated by Wash1400 and TMI-2
  - Code under continuous development for 21 years
    - Emerging issues
    - New experimental information
    - Repository of knowledge on severe accident phenomena
- Major emphasis is on performing integrated and self consistent analyses
  - Diverse physics, widely varying timescales
  - Coupled phenomena and non-linear feedback
  - Self consistent treatment
    - Eg. Decay heat follows released fission products diminishing core decay heating

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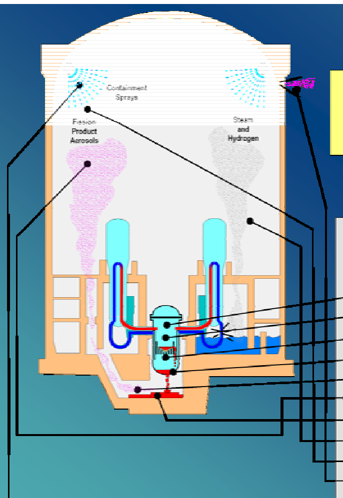
Modeling and Analysis of Severe Accidents in Nuclear Power Plants



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 Development Activities
Core Heatup and Fission Product Release

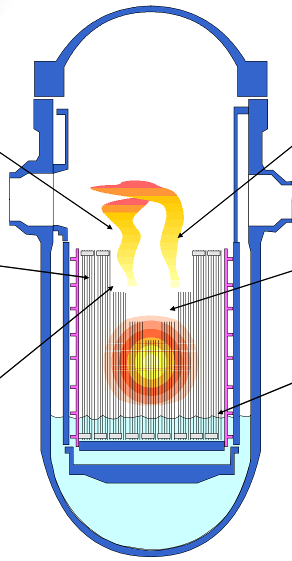
Fission product specie/volatility modified (Cs_2MoO_4) – Phebus Tests – affects RCS deposition

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

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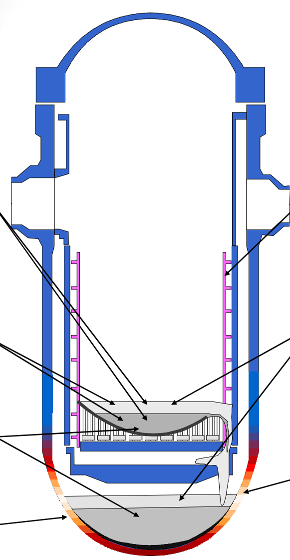
MELCOR Development Activities
Late Phase Melt Progression

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

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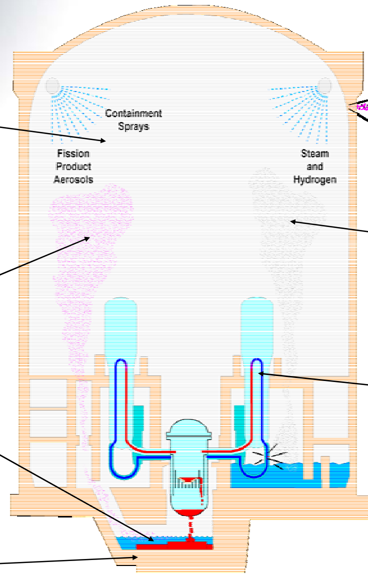
MELCOR Development Activities
Containment Modeling

Control function specification of volume velocities for heat transfer added

Total airborne mass by control volume type added as control function argument

Modifications to MCCI model to explore enhanced cooling by overlying water (ANL ACE and MACE)

Numerical improvements to CAV package



Fission product flows through flow paths added to plot file (MACCS)

Separate plot variables for hydrogen produced from Zr, SS and B4C added to plot file

Developing improved models for FP retention in steam generators (ARTIST program) (post 1.8.6)

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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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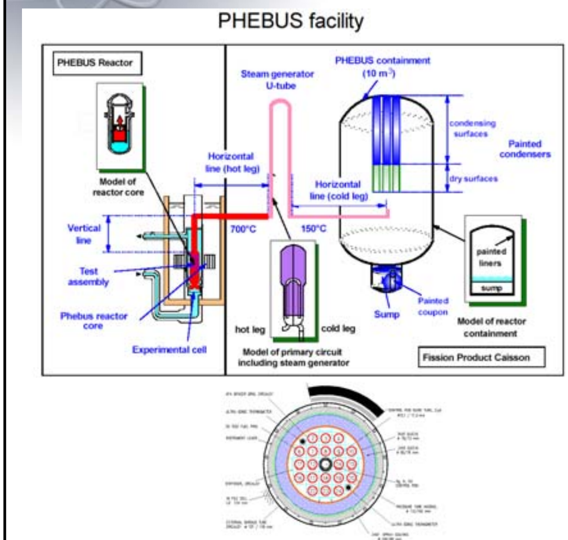
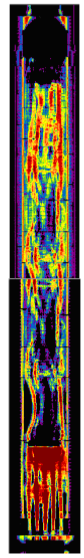
Phebus Program Benchmarking with MELCOR





- Integral tests
- Prototypic fuel
  - Fission heating
  - Pre-irradiated fuel
- Verification of
  - Fuel damage
  - Melt progression
  - Hydrogen generation
  - Fission product release and transport
  - Deposition in RCS
  - Containment behavior
- All Phebus experiments completed
  - Documentation lagging

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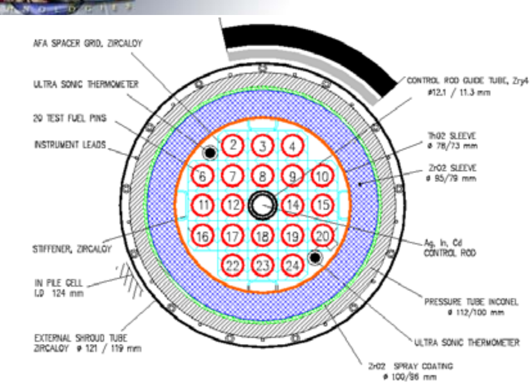
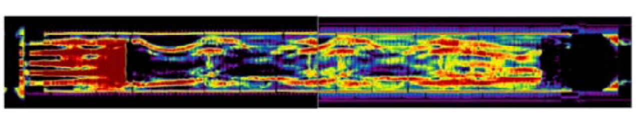
Fuel Rod Test Assembly





- Irradiated BR-3 fuel
- Ag/In/Cd or B_4C control rod
- Grid spacers
- Fuel damage
  - Zr oxidation
  - U-Zr-O interactions
  - Molten pool

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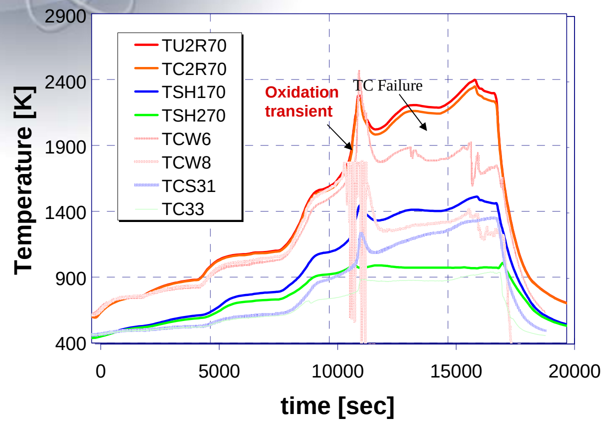
FPT-1 Bundle Temperatures at 700 mm



- Fission heat in FPT-1 initially drives thermal response
- Steam oxidation transient drives FP release and fuel melting

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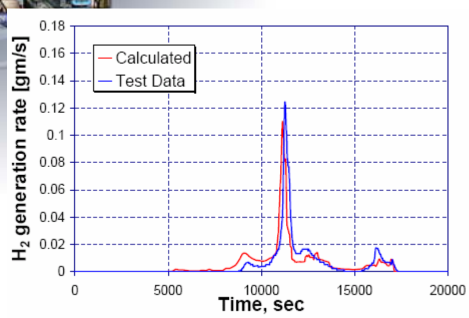
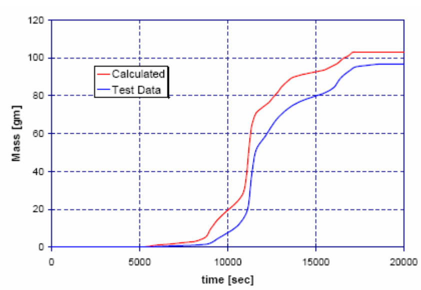
Steam Oxidation and Hydrogen Generation in FPT-1





- Steam oxidation models verified by calculated thermal response and by calculated hydrogen generation

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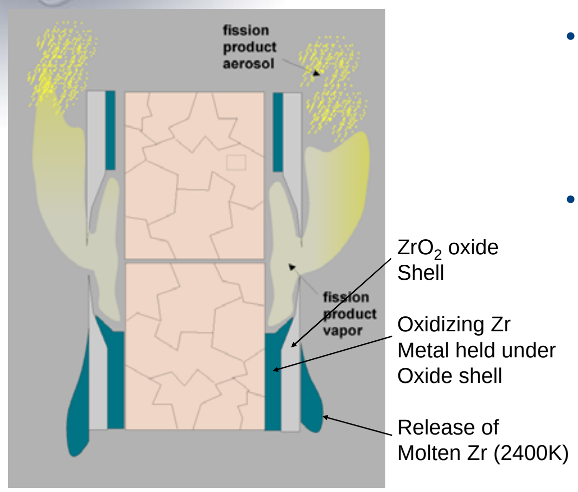
Fuel Degradation Modeling



- **Molten metallic Zr breakout temperature (2400K)**
- **Fuel rod collapse**
  - **2500K, or**
  - **Time at temperature function**

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Oxidation Transient Drives Fuel Damage

- **Tomography on FPT-1 bundle after fuel damage transient**
- **Zr oxidation drives severe damage**
- **Also drives thermal release of fission products**

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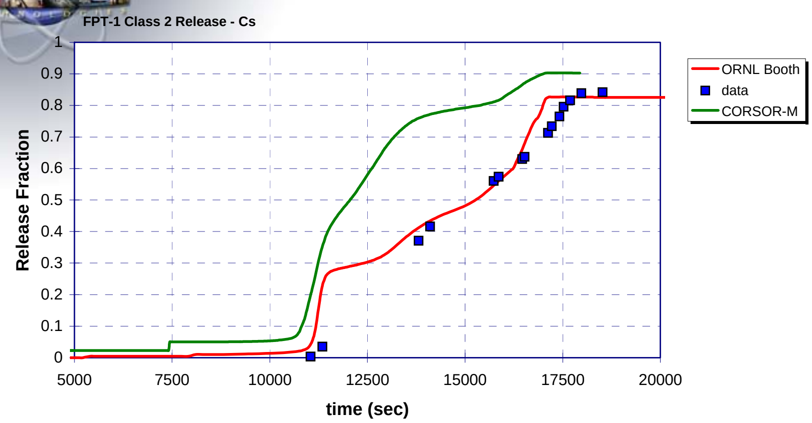
Cs Release from FPT-1 Fuel



- ORNL Booth model captures kinetics well
- CORSOR-M over-predicts early release

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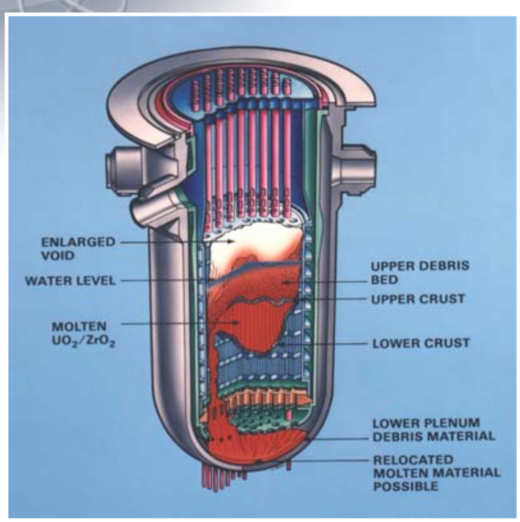
TMI-2 Assessments



- Accident code assessments against TMI-2 ongoing in international comparison exercises
- MELCOR models for melt progression significantly refined based on TMI-2 and experiments

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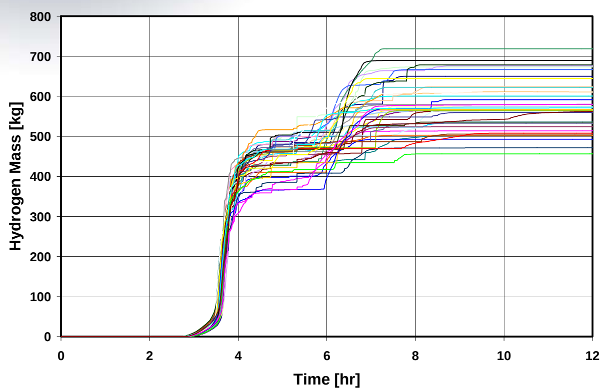
Uncertainty Quantification in Source Term Quantification



- Uncertainty in assumed input and modeling leads to range of results
- Limited uncertainty characterization to be performed

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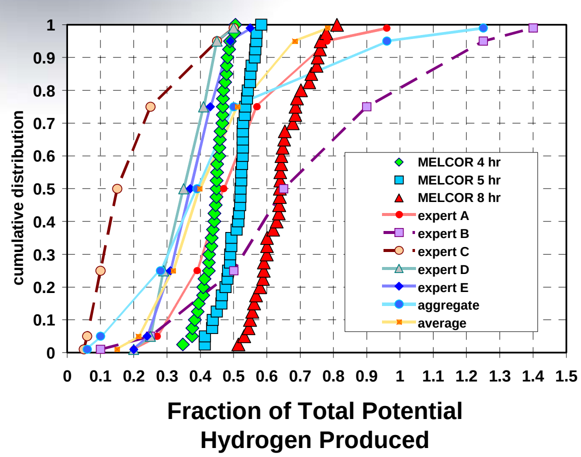
MELCOR H_2 Uncertainty Compared to NUREG-1150 Expert Elicitation



- Hydrogen uncertainty band increases with time into accident
- MELCOR produces narrower uncertainty range estimate compared to subjective expert elicitation
- Code approach provides objective basis with greater certainty
- Regression analysis reveals main contributors to uncertainty

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Consequence Assessment

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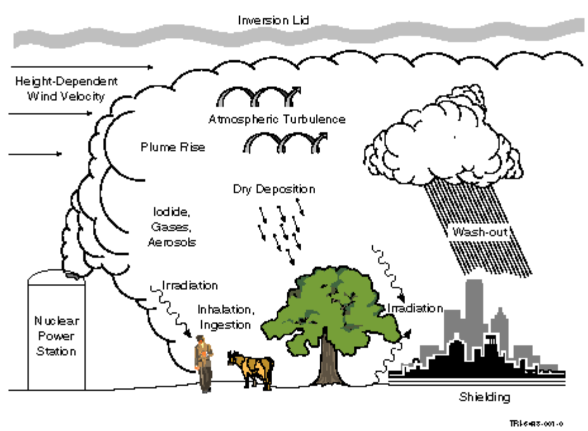
Outline

- **Uses**
- **Recent and Ongoing Development**
- **Future directions**



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NRC Uses for 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

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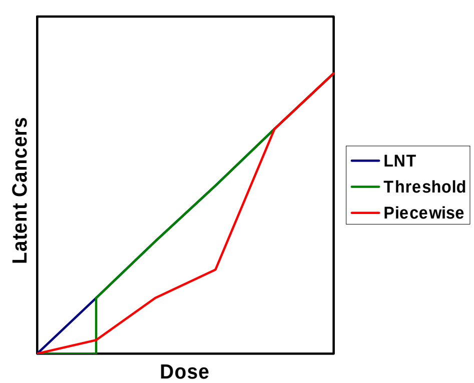
MACCS2 Development

- Recent and ongoing development (RES/DSARE)
  - New capabilities (Y6786)
    - KI ingestion model
    - Land-contamination estimation
    - Dose-threshold model
  - Pursuit of best-estimate modeling
    - Improved dose threshold model for latent health effects
      - Annual/lifetime threshold
      - Piecewise-linear dose model
    - Enhanced plume modeling
      - Buoyancy
      - Dispersion
    - Improved model for mixing height
  - MACCS2 inputs (Y6628)
    - Distributions to capture degree of belief



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Supporting Development

- WinMACCS development (Y6628)
  - Input file builder
    - Single run
    - Multiple runs
    - Multiple realizations using LHS for parameter sampling
  - Graphical display of output
- MELMACCS development (Y6802)
  - Tool for calculating source terms from MELCOR output
  - Creates MACCS2 input

MACCS2 Training

- Accident consequences analysis training (P-301) for the NRC (Russ Anderson through INEEL)
- Training and support for Kalinin PRA (John Lane through BNL)
- Training workshop for DOE's Severe Accident Working Group (SAWG)

Recent and Ongoing Applications - Vulnerability

- NPP vulnerability to aircraft
  - Surry & Peach Bottom (RES/DET)
  - Indian Point & Limerick (RES/DSARE)
  - Sequoyah & Grand Gulf (RES/DSARE)
- Vulnerability of spent fuel pool (done by RES)
- Vulnerability of fuel in dry-cask storage (NMSS/SFPO)
- Research and test reactor (RTR) vulnerability (35 sites) (NRR/DRIP)
- Vulnerability of Greek Demokritos reactor for 2004 Summer Olympics

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Recent and Ongoing Applications – Other NRC

- Plume model adequacy evaluation
- Evaluation of competing evacuation/sheltering strategies
- Rebaselining NUREG-1150 consequences for CRIC-ET
  - Used to evaluate risk-significance of candidate generic issues

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Future Directions

- Driven by trends in advanced reactors and fuels
  - High-burnup fuel
  - MOX fuel
  - PBMR
  - ACR 700
- Consequence analyses will require
  - Reactor- and fuel-specific fission-product inventories
  - Routine quantification of input and weather uncertainties
  - Quantification of effect of a dose threshold
  - More cohorts
- Focus should be to improve models strategically to minimize unnecessary regulatory burden

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Future Code Needs

- Integrated weather and input parameter sampling
- Threshold model for multiple cohorts
- Faster run times
  - Improved code architecture
  - Dynamic memory allocation
  - Distributed computing
- Support for multiple fission product inventories
- Improved models for rate-dependent health effects
- More flexible and detailed economic model

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Future Data Needs

- Access to more and better data
  - Surface roughness
  - Land use
  - Diurnal variations in population
  - Economic Data
  - Weather data

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Emergency Response and Accident Mitigation

Vg# 36

Application in Emergency Response
New Thrust Area with NRC

- Use of codes in fast-running mode for Emergency Response
  - Plant data in emergency sent to NRC headquarters
- Fast-running predictive tools forecast possible accident progression
  - Projected timing of core uncovering
  - Estimated time to fuel damage
  - Estimated timing and magnitude of radioactive release
  - Efficacy of mitigative and recovery actions
- Assist in decision making for emergency actions
- Training under realistic conditions

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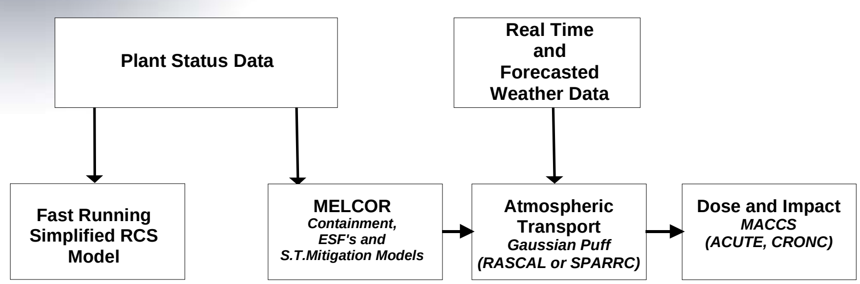
MELCOR and MACCS
Supporting Emergency Response



Information Flow in Emergency Response Tool

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Mitigation of Radioactive Releases
Mitigation Measures

- Use water-fog sprays to knock down fission product aerosol
  - Spray droplet size and flow rate very important
- Use of dense smoke or fog to agglomerate fission product aerosol to larger particl sizes
  - Enhance gravitational fallout
  - More favorable size for spray scrubbing
- Use special foams
  - Trap fission products
  - Stabilize deposited fission products
- Chemical stabilization of aqueous iodine sequestered by water sprays
- Spray mitigation of drained spent fuel pool
  - Cooling
  - Scrubbing

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Summary

- MELCOR code is a tool for evaluating radiological source term to environment from accidents or events at nuclear power stations
  - Plant damage state
  - Progression of core damage
  - Timing and magnitude of radiological releases
  - Effects of mitigative measures
- MACCS code is tool for calculating atmospheric dispersion and consequences of source term release
  - Prompt and latent health effects
  - Economic consequences

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