SAND2012-2334P

March 31, 2012

Severe Accident Analysis with MELCOR

Jesse Phillips
Nuclear Accident Analysis
Dept. 6232

Sandia National Laboratories is a multi program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Fukushima accident has increased (yet again) accident awareness.
- Severe nuclear accidents have been under varying levels of consideration since the 1950s.
- After Three Mile Island, the industry and regulators needed a more complete and rigorous understanding potential accidents.
- Developed several tools (including MELCOR) for modeling accidents based on experiments performed throughout the complex (universities, national labs, etc.)
- These tools allowed for a determination of the impact a nuclear accident would have on society.
- We'll discuss what MELCOR is, what it does, and how it is used.

Fukushima Daiichi (Number 1) Severe Accident

March 11, 2011

- **Earthquake with a magnitude of 9.0 occurs off the coast of Japan producing several tsunami's challenging the nuclear power plant site**
- **Off-site power to the site is disrupted by the earthquake, and reactors (1, 2, and 3) are immediately shutdown**
- **A tsunami, with a height over 14 meters, exceeds in-place tsunami barrier and floods the power plant site 46 minutes after the initial earthquake**
- **Diesel generators and battery power are lost; the site enters what is known as a station blackout accident (no available power to control the reactors)**
- **The three reactors are experiencing "severe accidents" which may result in core meltdown and/or radioactive releases to the environment**

In Brief – Severe Accidents

- **Wash-740 – First notable study on severe nuclear accidents. Applied very gross estimates due to lack of technical knowledge when estimating effect on health, environment, infrastructure, etc. (1953)**
- **Wash-1400 – Similar to modern methods, determines the likelihood of a nuclear accident and then determined the consequence. The overall <u>risk</u> of operating a nuclear power plant was estimated. (1975)**
- **In large respect, severe accidents were not believed likely to occur do to engineered safety systems installed at nuclear power plants, until the accident at the Three Mile Island power plant. (March 28, 1979)**
  - **Significant resources directed towards severe accident analysis. Experiments were performed to better understand all of the phenomena as well as provided the necessary data to begin developing detailed models to improve risk estimates.**

Risk of Severe Accidents

- **Probability Risk Assessments (PRAs) apply a very simple formula**
- **Risk = Probability x Consequence**
  - **Probability is determined by investigating the likelihood of a system failure (parts failure, dependent systems becoming unavailable, etc.)**
  - **Determining consequence requires understanding accident progression to estimate the final adverse effect to people.**
- **MELCOR was developed (early 1980s) to provide insight into accident progression. Radioactive species are tracked from their release from the fuel and throughout the reactor system, until released to the environment.**
  - **Acts as a knowledge repository for past experiments.**
  - **Determines the environment release which can be used by atmospheric dispersion codes.**

MELCOR Code Development

- **MELCOR is developed by:**
  - **US Nuclear Regulatory Commission (NRC)**
  - **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**

Sandia National Laboratories

Countries Using MELCOR for Reactor Analysis

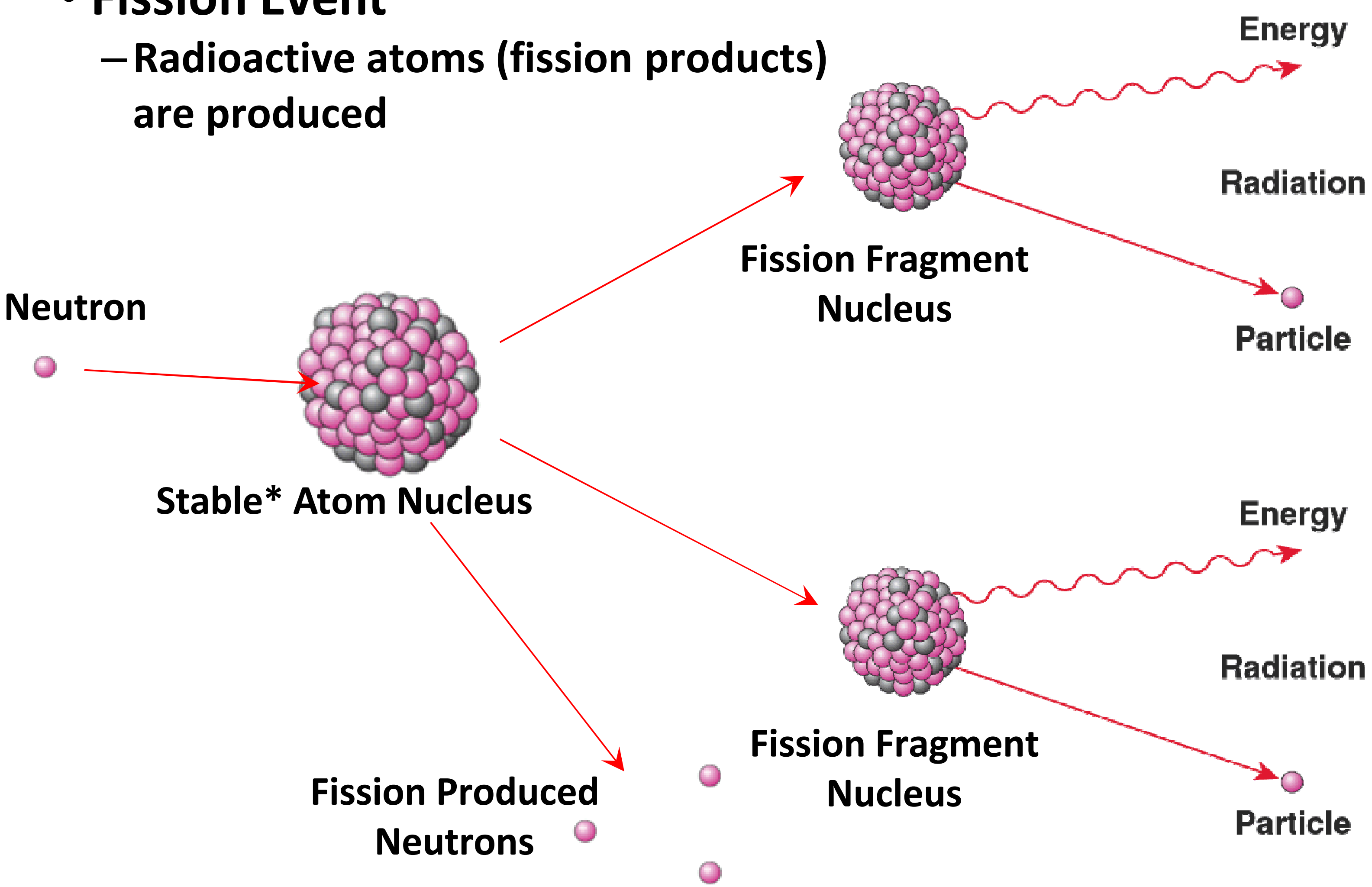
Sandia National Laboratories

Consequence of an Accident

- The severity of an accident is based on the release of fission products to the environment. (We'll discuss what a fission product is soon.)
- Fission products are trapped within the fuel rods during normal operating conditions.
- MELCOR allows us to determine the release of fission products based on a selected accident.
  - Pipes breaking
  - Systems losing power
  - Pumps seizing
  - and so on
- By modeling all the relevant processes, we can estimate the release and transportation of fission products.

Basics – Fission Products

- **Fission Event**
  - Radioactive atoms (fission products) are produced



Fuel to the Reactor System

- Fuel contains uranium isotopes – our quasi-stable nuclei which undergo fission
- Fuel pellets are stacked in 12ft tall fuel rods
- Fuel rods are bundled together into assemblies
- Assemblies are placed in box formations within the reactor core
- The reactor core is located in the reactor vessel
- The reactor vessel is housed with containment and containment with the reactor building

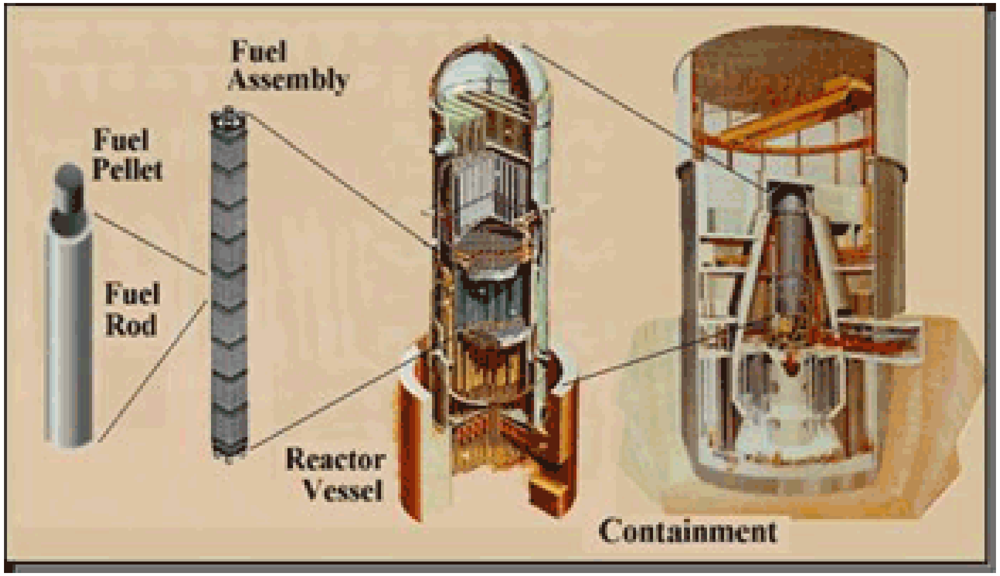


image from www.nrc.gov

Fuel

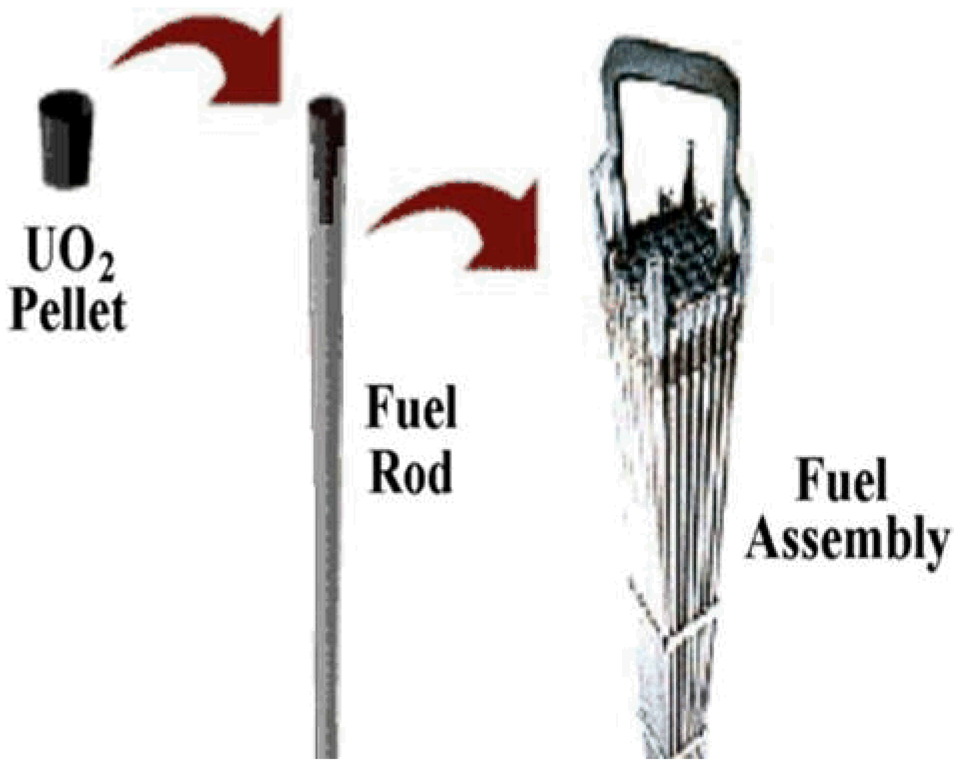
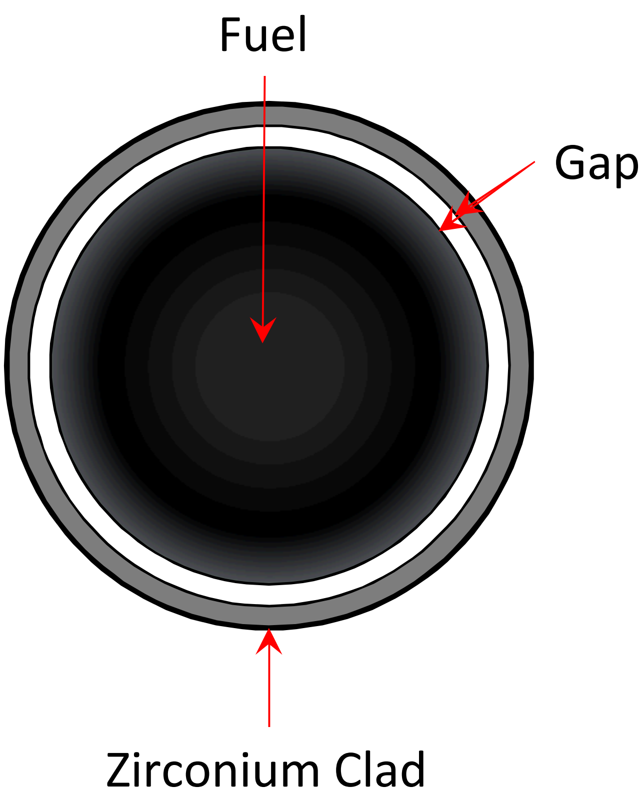


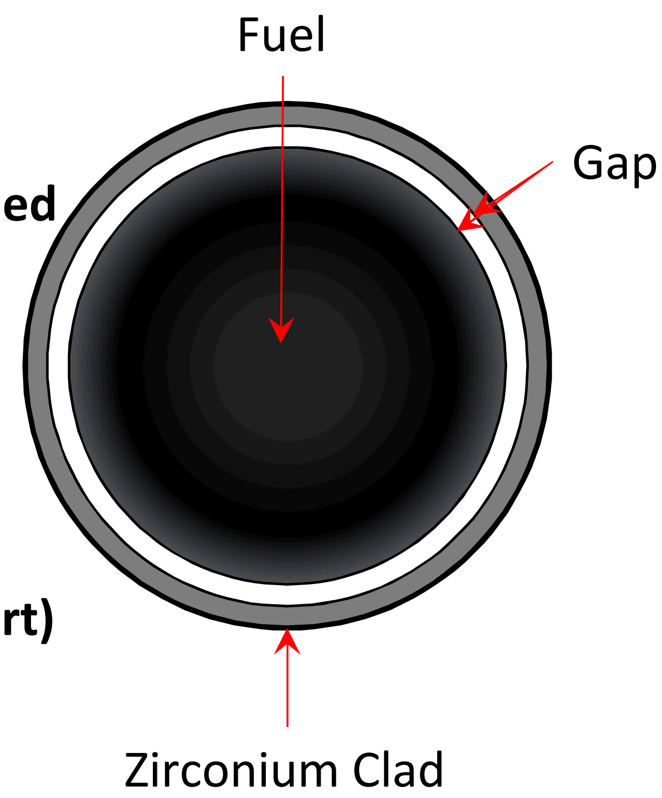
image from www.nrc.gov

Fuel Rod Cross Section



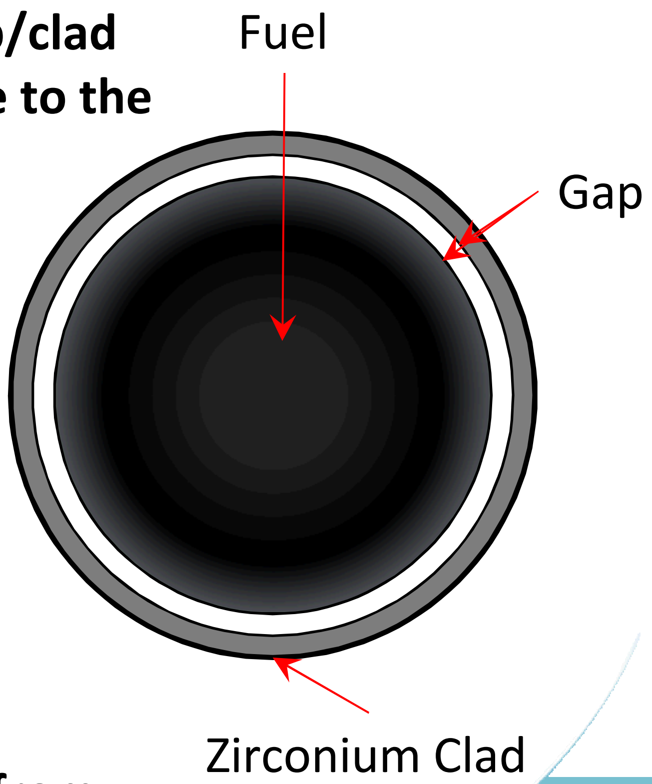
Fuel

- **Fuel**
  - **Fissions occur during normal operations**
  - **Where heat is generated**
  - **Swells early, encroaching on the gap space**
  - **Most non-gaseous fission products maintained**
- **Gap**
  - **Largely disappears**
  - **Fission product gases slowly accumulate (Helium, Xeon, Krypton, etc.)**
  - **Heat transferred from fuel to cladding (in part)**
- **Clad**
  - **Prevents fission products from escaping the core while in tact**



MELCOR Treatment of Fuel

- **Fuel**
  - **Calculates fuel temperature**
    - *Uses fission power or decay power*
  - **Tracks heat produced by fuel and lost to the gap/clad**
  - **Determines the rate fission products are release to the gap**
- **Gap**
  - **Calculates temperature**
  - **Tracks fission product inventory**
  - **Heat transferred from fuel to cladding (in part)**
- **Clad**
  - **Calculates temperature**
  - **Failure mechanisms (melt temperature reach or pressure induced creep)**
  - **Oxidation rate (clad burns by removing oxygen from water, producing hydrogen gas)**



Reactor Core

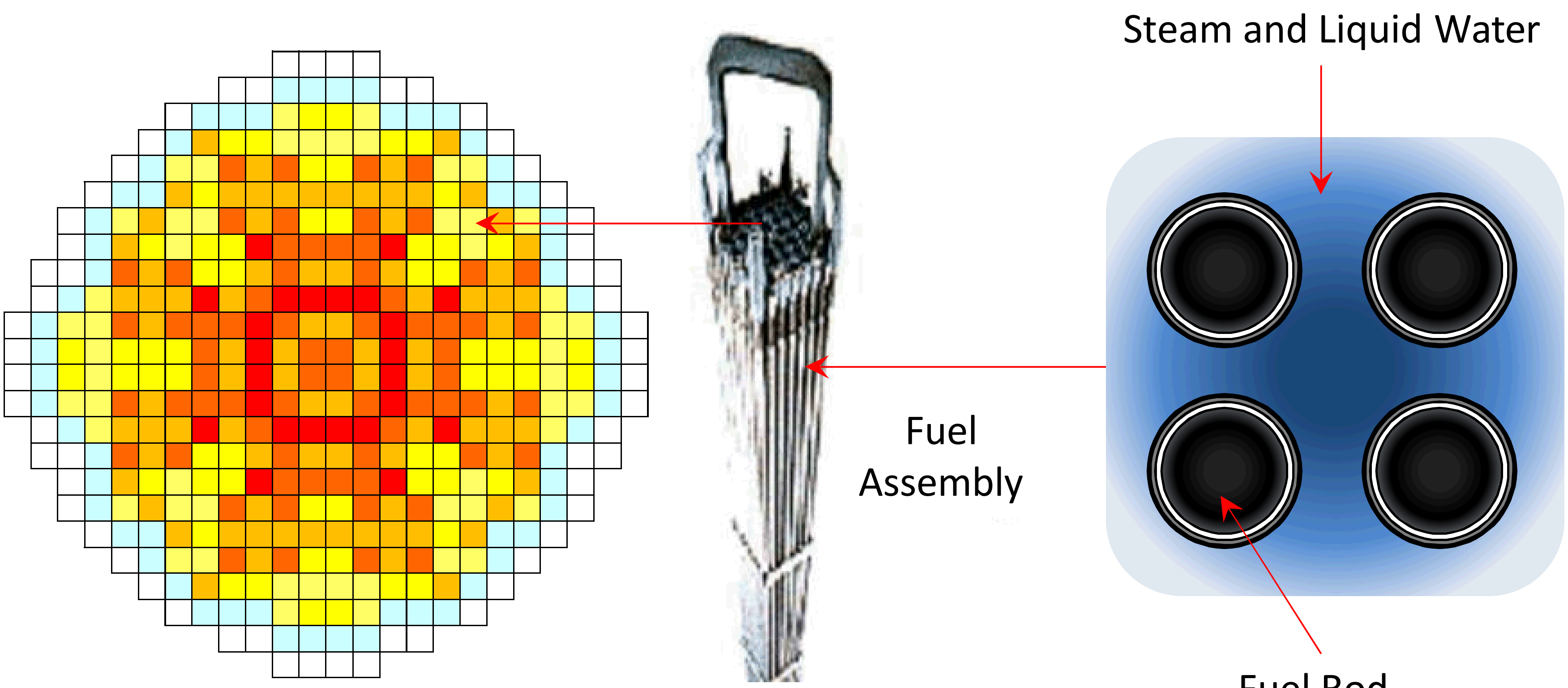
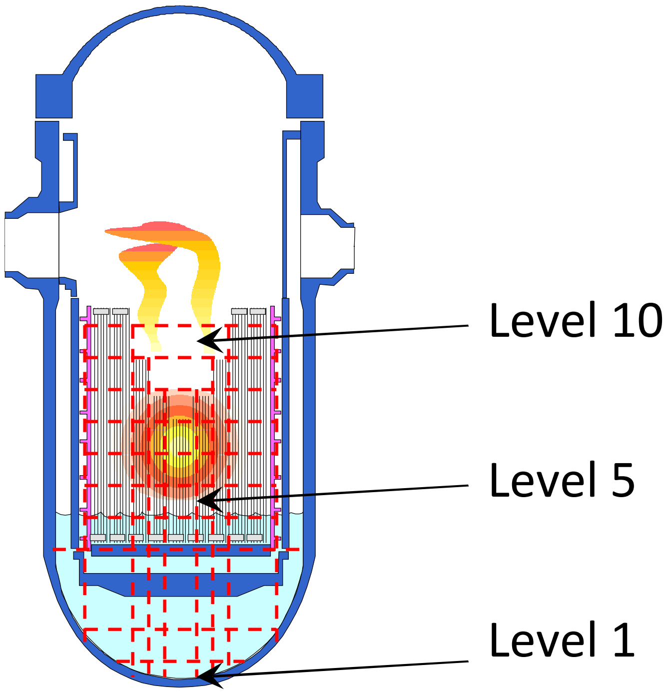
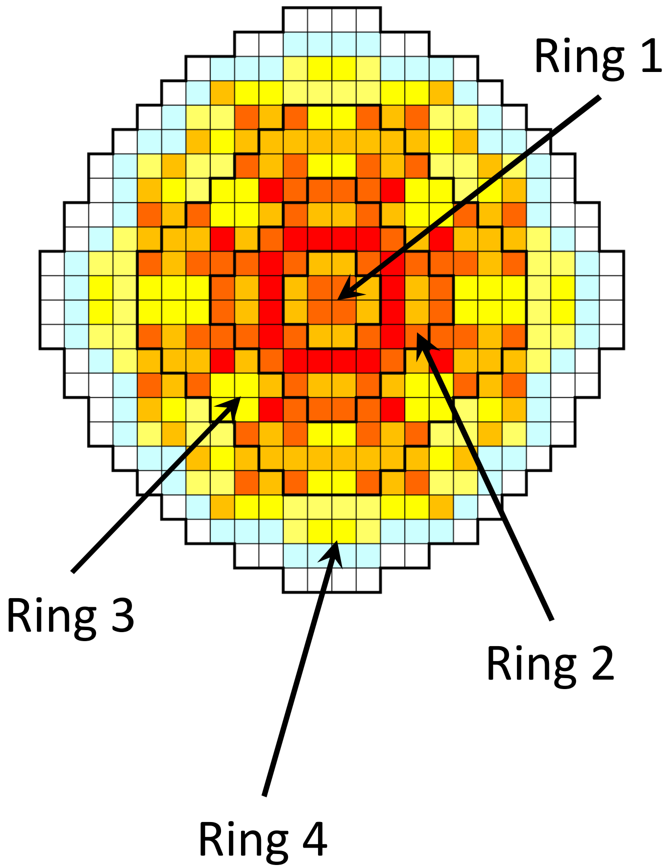


image from www.nrc.gov (cropped)

MELCOR Treatment of the Reactor Core

- **Core is simplified by assuming conditions (temperatures, chemical interaction rates, pressure) can be "lumped" together**
- **Core is divided into "Rings" and "Levels" where all conditions are lumped**
- **Lower head is included**

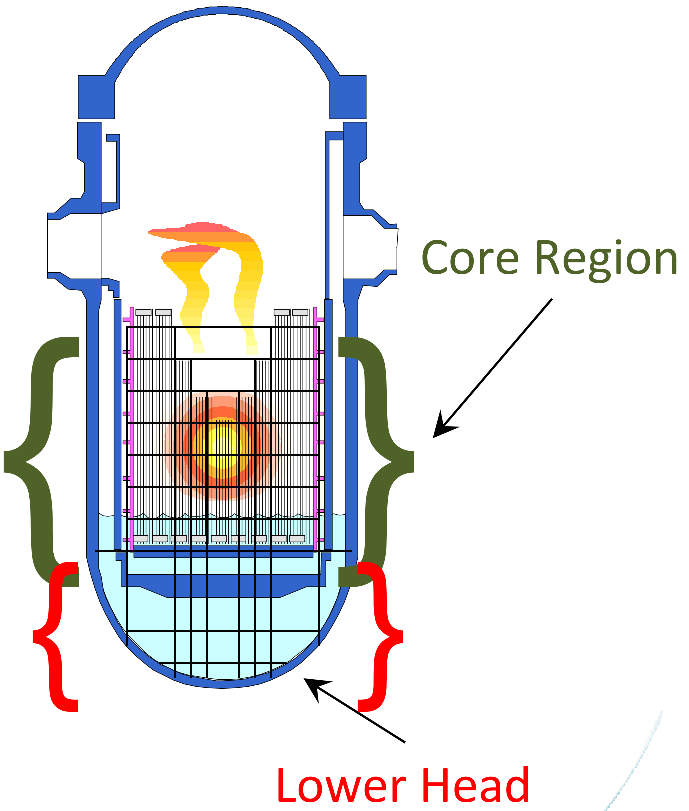




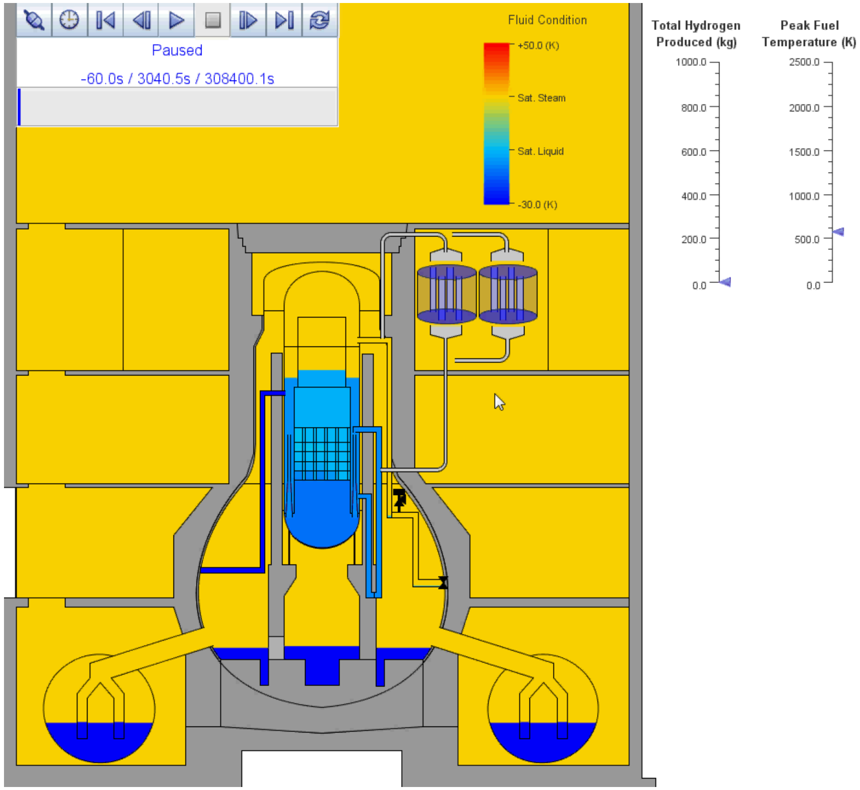
MELCOR Treatment of the Reactor Core

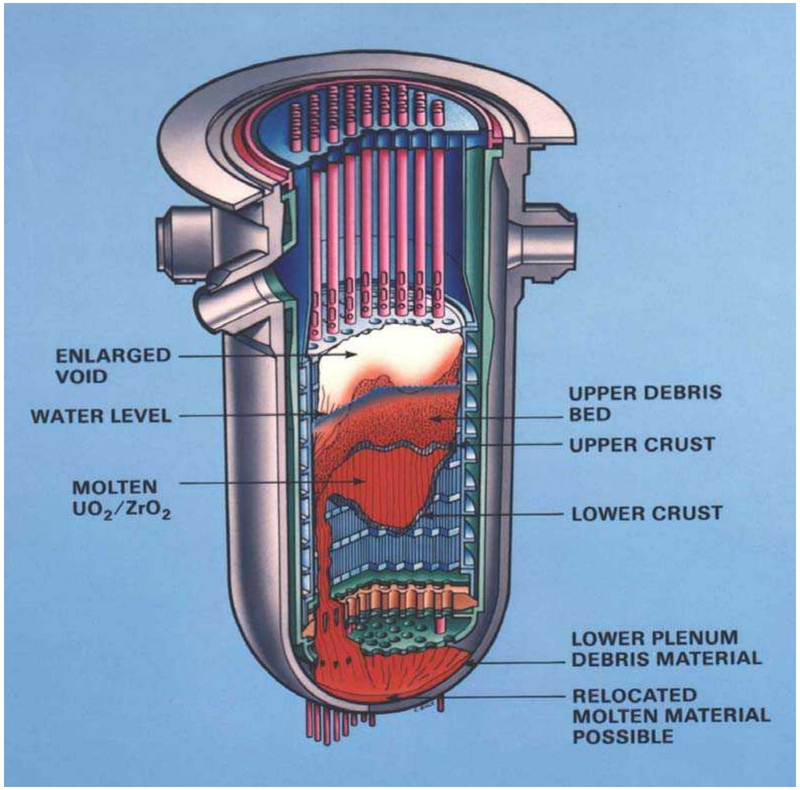
- **Once uncovered, the core may begin to melt**
  - **When submerged, the boiling water removes enough energy to prevent the accident worsening**
  - **When sufficiently uncovered, energy builds in the core and zirconium may begin to burn**
  - **At high temperature, fission products start to relocate out of the fuel**
  - **Zirconium clad may fail allowing fission products out of the core**
  - **Melt and debris begin to move towards the lower head**

- **Zirconium ignition produces more energy than the decay heat of the fission products**
  - **The accident is much more severe and difficult to terminate**
  - **Temperatures rise quickly and the core begins to melt**
  - **Hydrogen is produced**

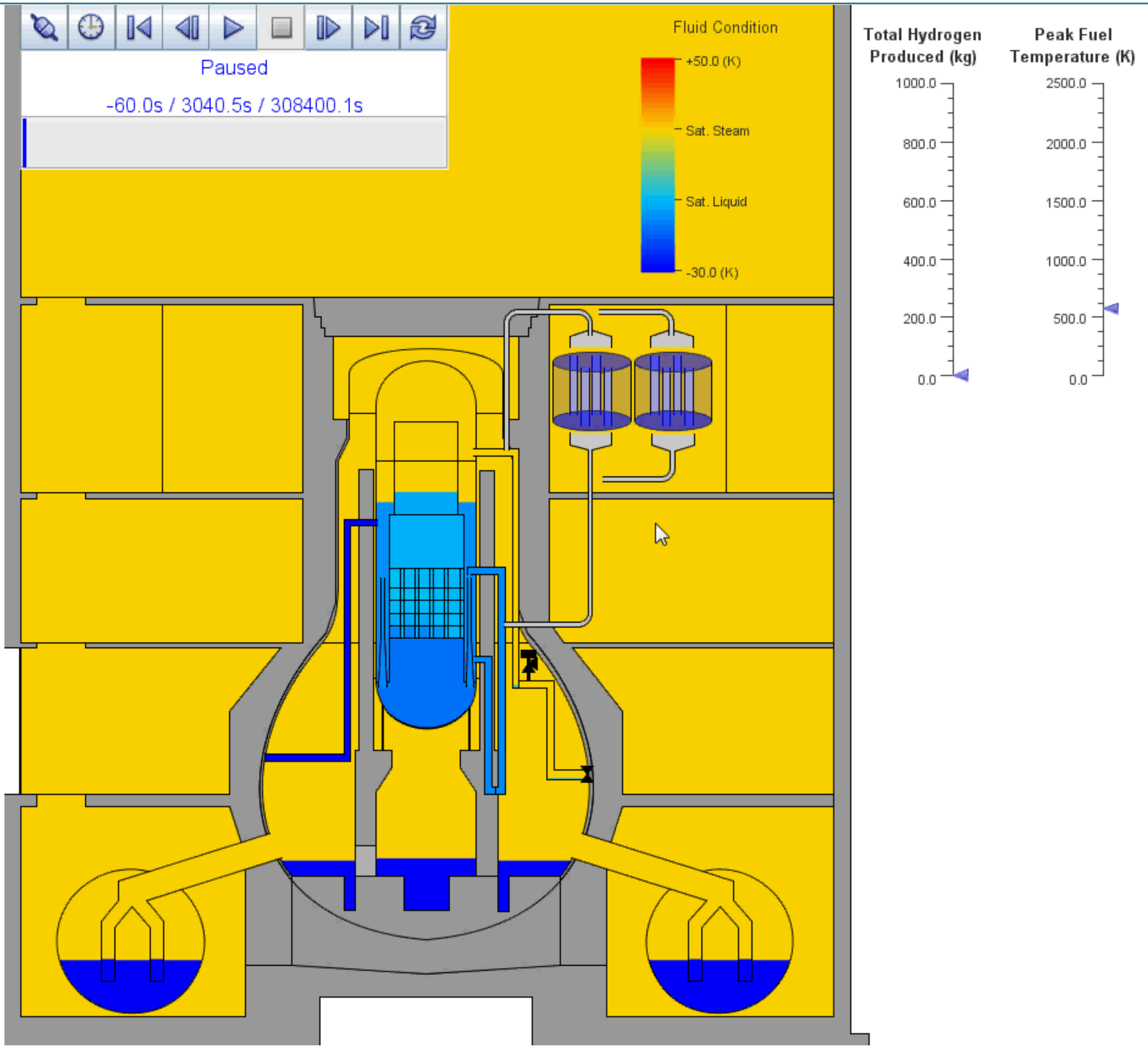


MELCOR Simulation of Boil Off

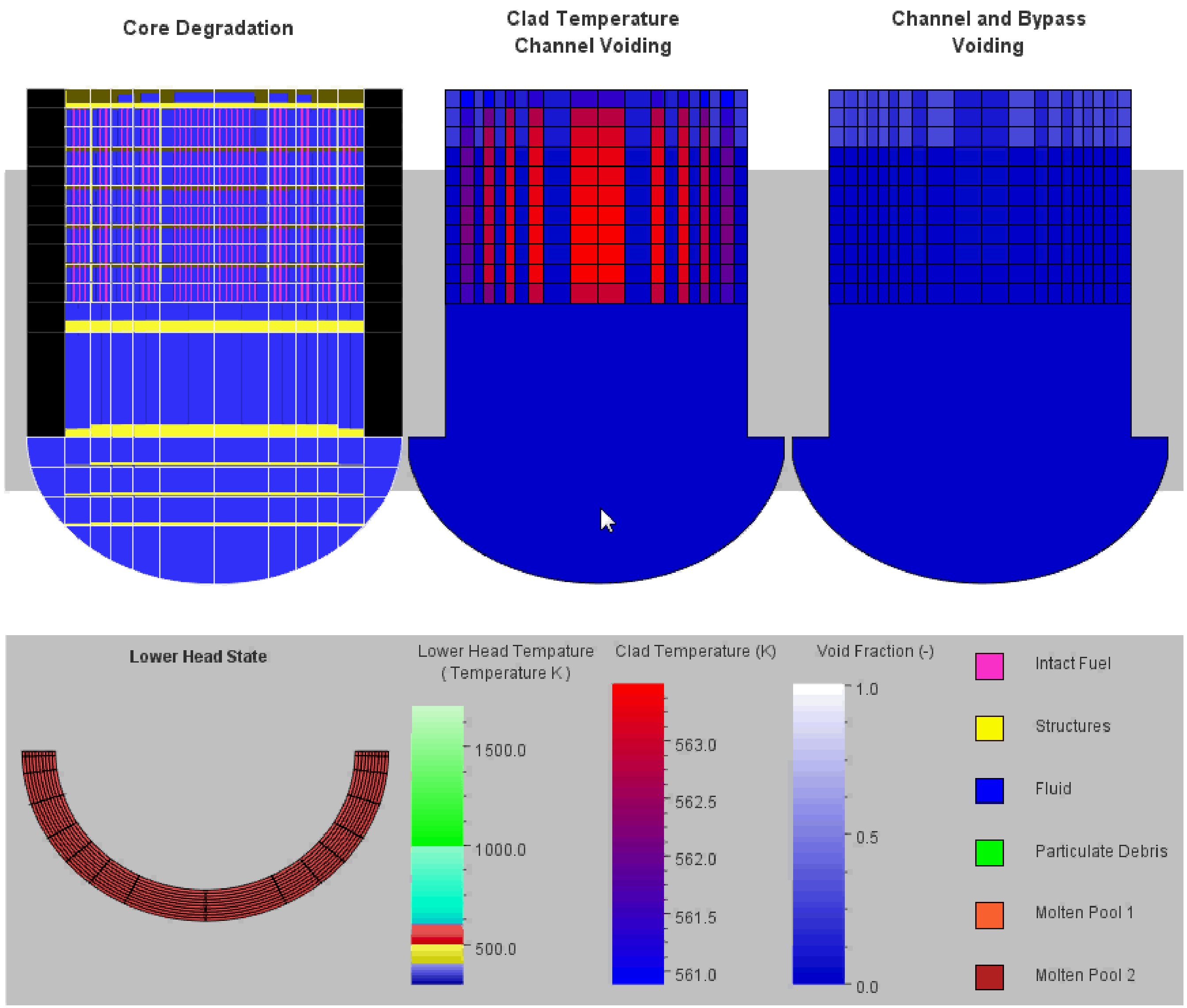




MELCOR Simulation of Boil Off



MELCOR Simulation of Core Relocation



Fission Product Transport

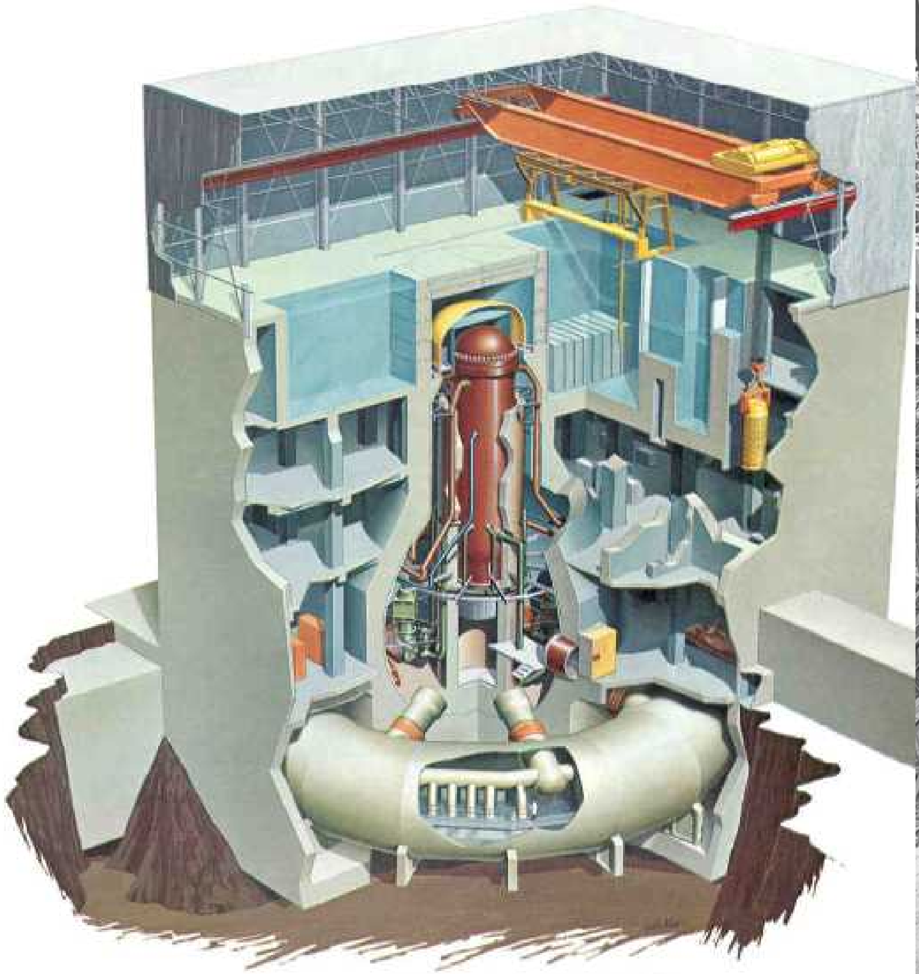
- Significant fission product releases occur once the cladding is compromised
  - A complete reactor model is necessary to track the fission product transportation
  - Once released fission products may condense into aerosols, so vapors and aerosols are present
- Fission products are treated as trace elements
  - Meaning, they share their physical conditions with their immediate surroundings (or host if you will)
  - If being carried by steam or liquid water, they are transported equally with the bulk fluid
  - If condense or deposited on a heat structure, their decay heat partially heats the surrounding bulk fluid as well the heat structure. Should the heat structure temperature rise sufficiently to vaporize the fission product, the fission product will return to the bulk fluid available for environmental release once more
  - Aerosol deposition models used to determine removal rates

Complete Plant Modeling

- **Various safety systems can be modeled to create a robust, complete simulation of the accident**
  - **Pressure relief devices allow steam or liquid to be transferred**
  - **Pump safety injection water can be modeled**
  - **Ice condensers**
  - **Containment sprays**
  - **Hydrogen combustion controllers (burners and passive autocatalytic recombiners)**

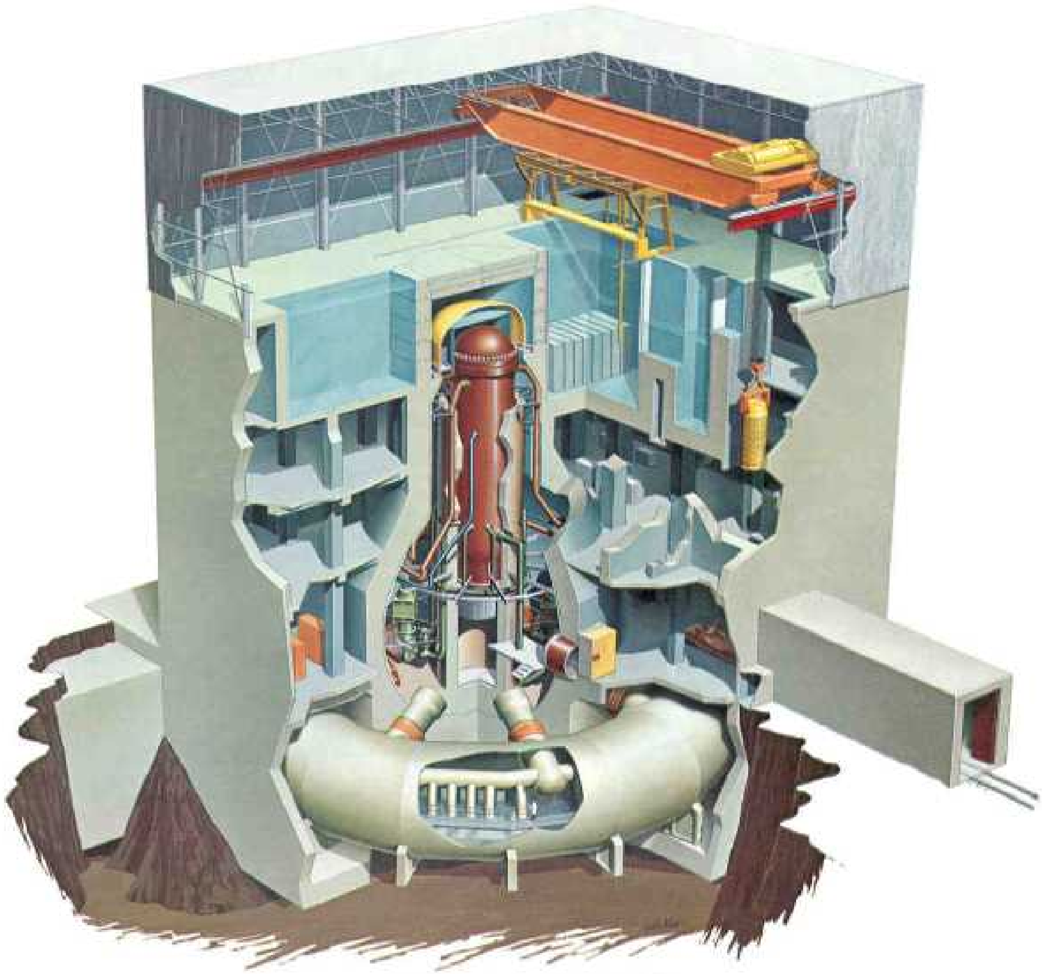
- **Reactors are designed with accidents in mind**
  - **Safety systems are diverse and often redundant, in case of failure**
  - **Three levels of protection prevent fission products from being released**
    - *zirconium cladding*
    - *reactor coolant system boundary*
    - *containment*

BWR Mark I Containment Design

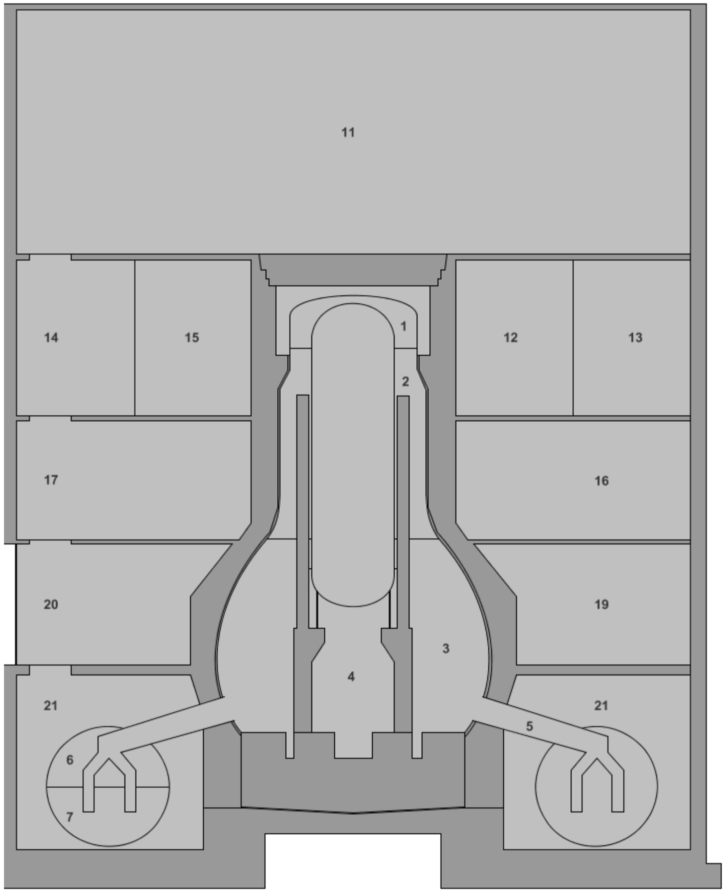


DRYWELL TORUS

Containment and Reactor Building



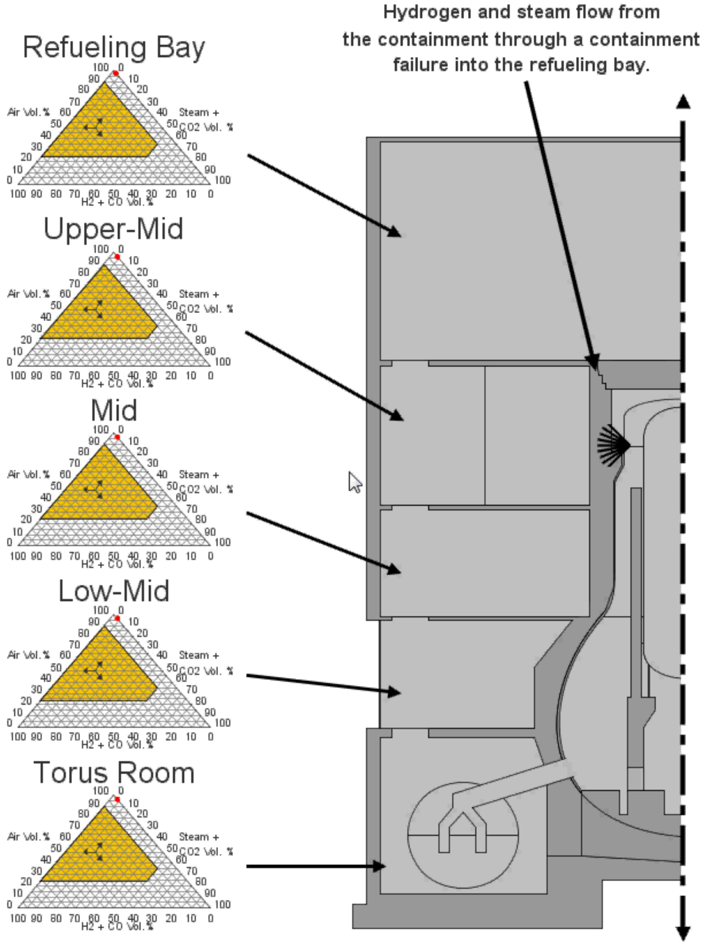
DRYWELL TORUS

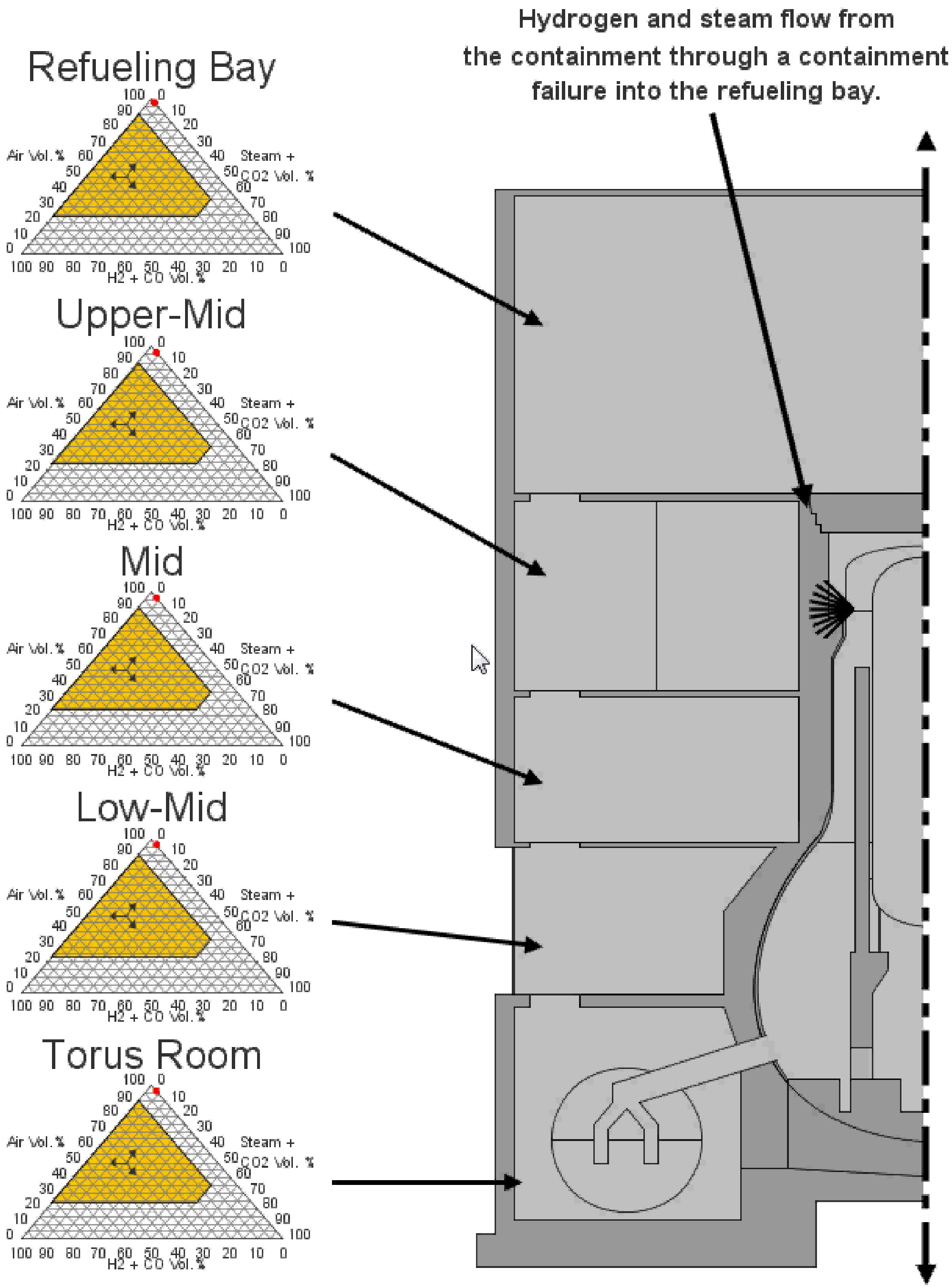


Sandia National Laboratories

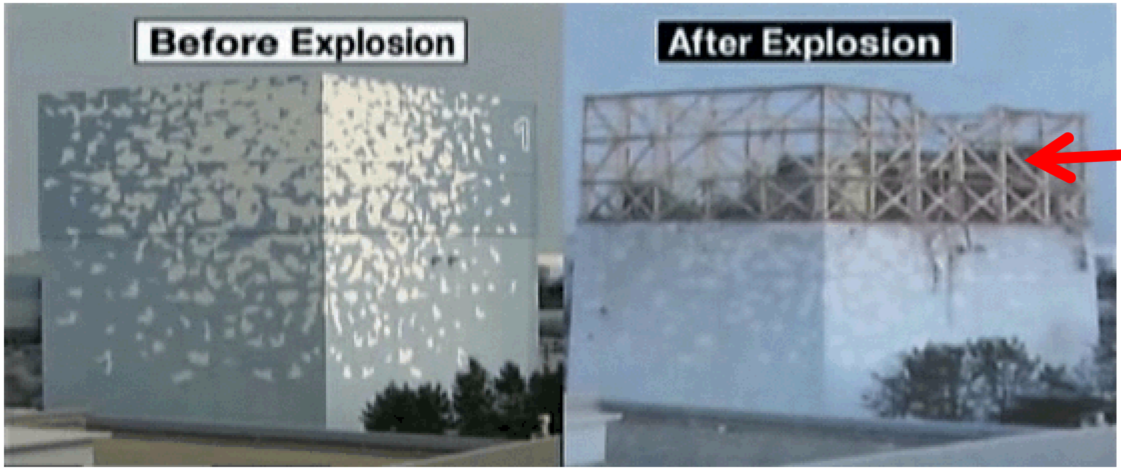
MELCOR Tracking Hydrogen

- Hydrogen, produced from zirconium and steel oxidation (or burning) in steam, is tracked to determine if explosions may occur
- Explosion produce large forces which may fail boundaries, which could be preventing fission product release
- Containment failure also allows fission products to escape




Hydrogen and steam flow from
the containment through a containment
failure into the refueling bay.
Refueling Bay
Upper-Mid
Mid
Low-Mid
Torus Room
Air Vol. %
Steam + CO2 Vol. %
H2 + CO Vol. %

Fukushima Reactor Buildings – Unit 1



Refuel Floor

Reactor Building

Sandia National Laboratories

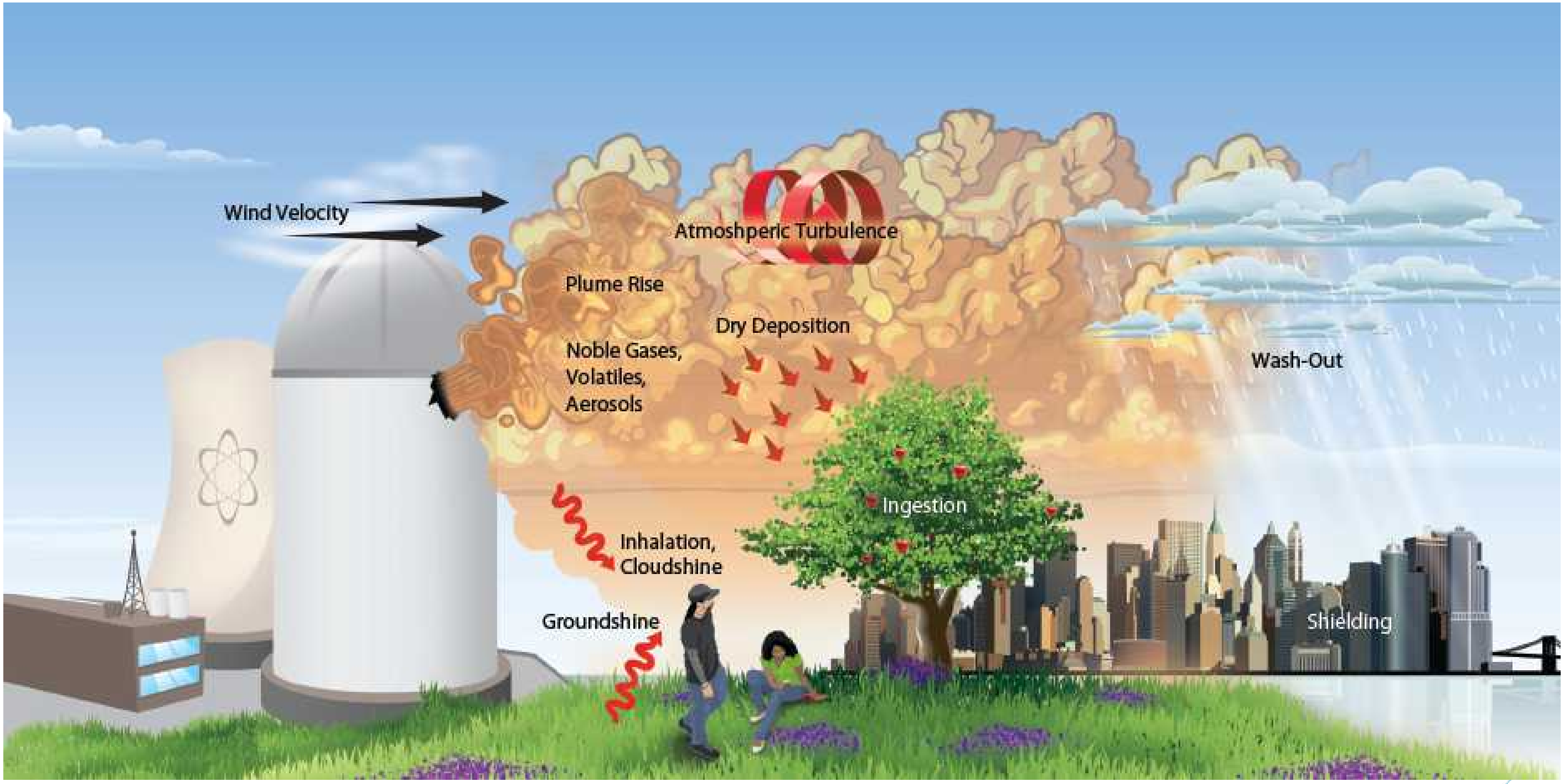
Fukushima Reactor Buildings – Unit 3

Fukushima Reactor Buildings – Unit 3

Reuters

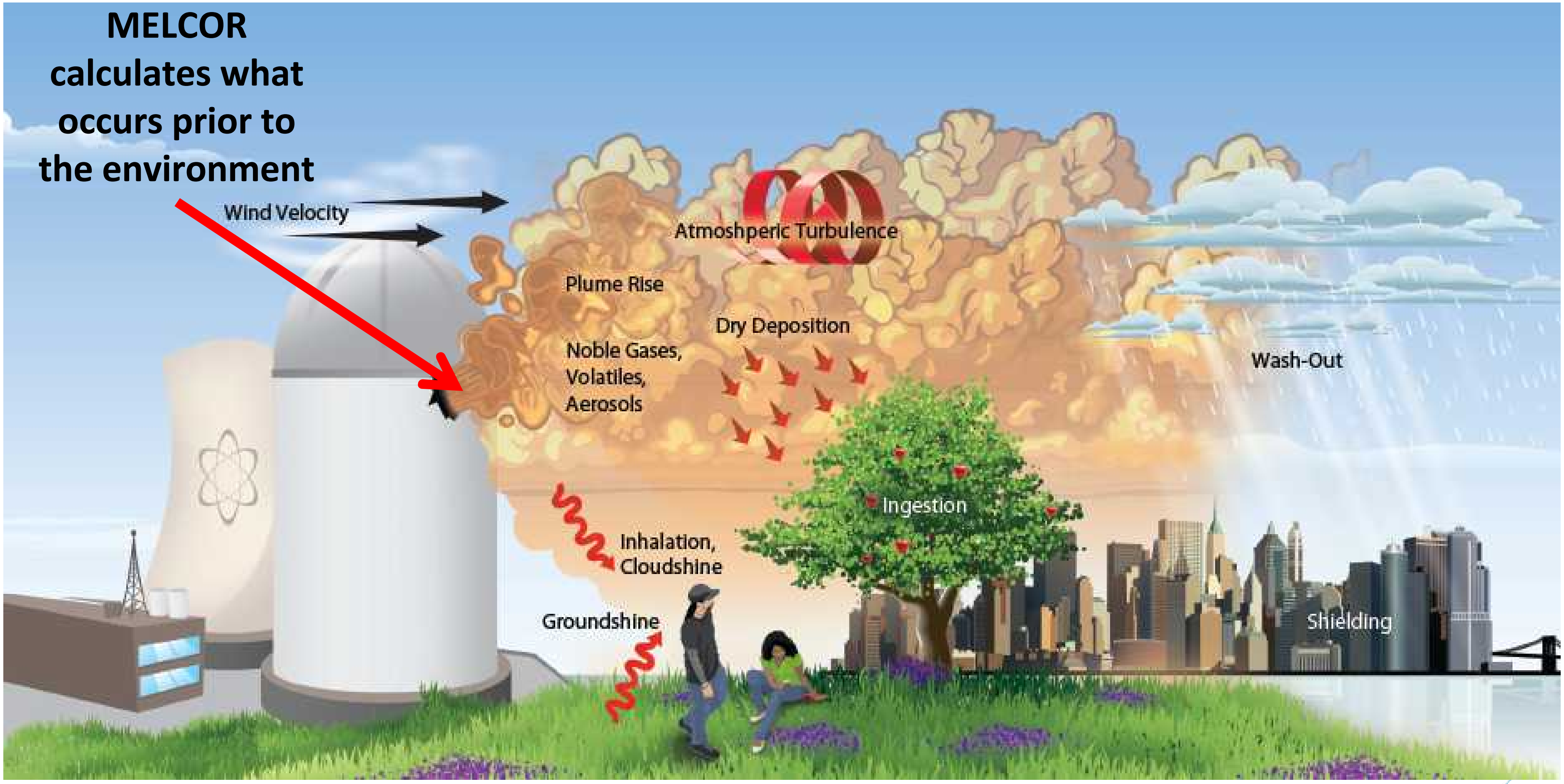
TEPCO

Exposure Pathways



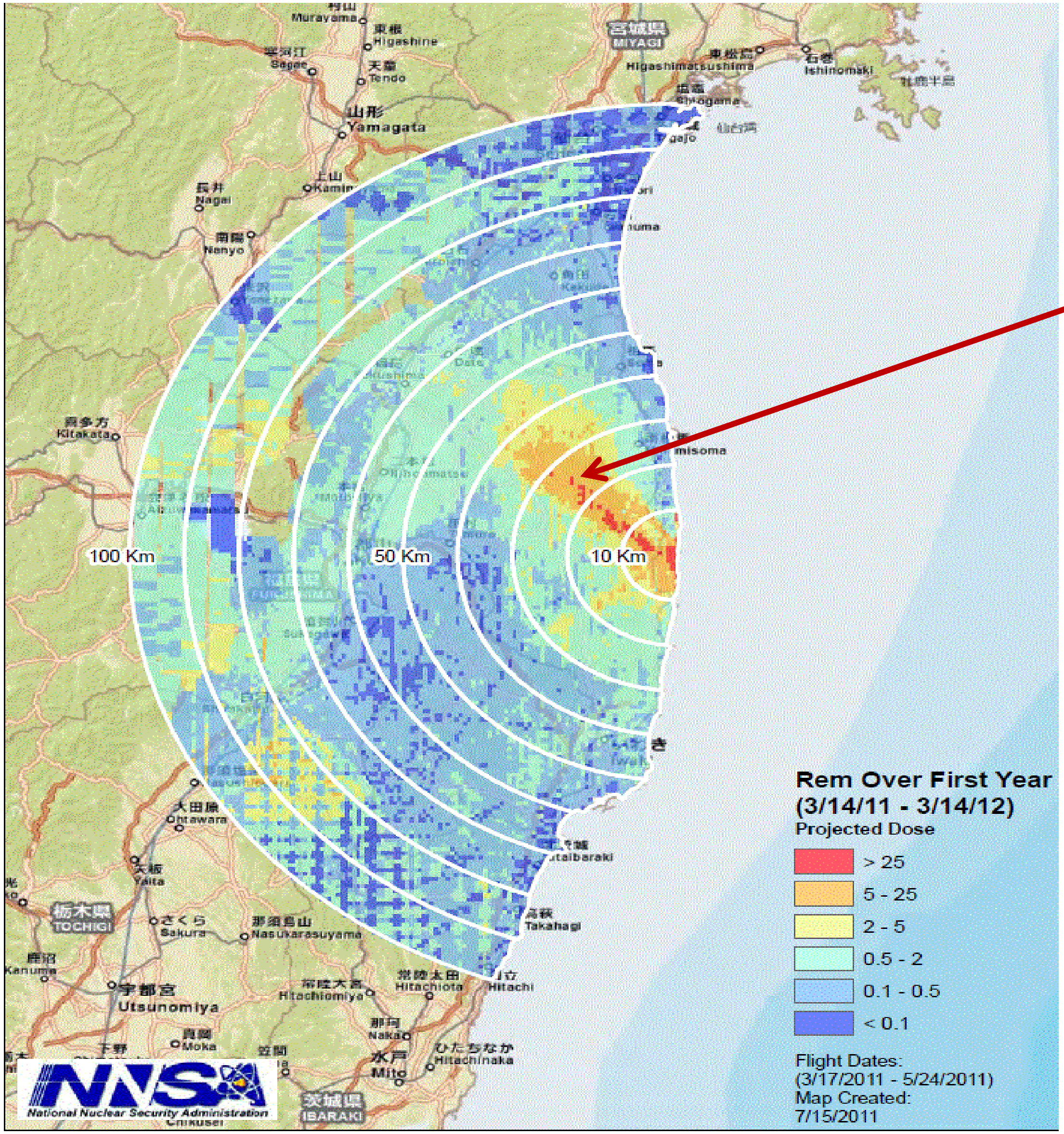
The ingestion pathway could be considered, but uncontaminated food and water supplies are abundant and it is unlikely that the public would eat radioactively contaminated food

Exposure Pathways



Temperature of the gas, height of release, fission products released and their physical/chemical states are provided to dispersion codes to determine the dose to people

Projected First Year Dose from Fukushima



Orange area:
5 to 25 rem

Sandia National Laboratories

NARAC Plume

Background map courtesy of Google

Over 300 plume models such as this were provide to CM-Home Team, NRC, and other government agencies

Conclusion

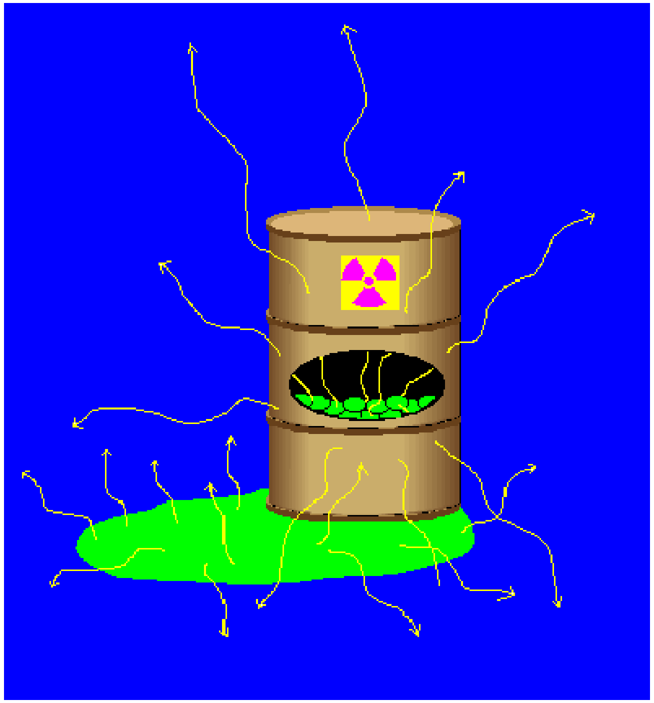
MELCOR acts as a repository of accident phenomena knowledge

- **Allows us predict the harm to people should an accident occur before it ever happens**
  - **This is performed by tracking the fission products as they are released from the core and transported throughout the facility, until released to the environment**
- **By knowing the consequence of an accident, we can determine the risk of operating nuclear power plants**
  - **MELCOR calculates the final release to the environment which is used to determine any dose to people**
  - **Risk = Probability x Consequence - MELCOR contributes to understanding consequence!**
- **Regulators (Governments) and utility providers around the world have access to MELCOR and share in developing methods for applying MELCOR and testing MELCOR**
  - **Nuclear power plant safety is in everyone interested and is shared openly through collaboration**

If time allows (dose discussion)

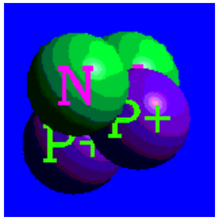
Radiation

- **Radiation is energy**
- **Radioactive material is the physical material emitting the radiation**
- **Radioactive contamination is radioactive material that is in an unwanted place**
  - **Radiation itself is not a contaminant**
- **Exposure to <u>radiation</u> does not result in contaminating the exposed surface, except in the case of neutron activation. Environmental contamination by radioactive materials is highly unlikely to result in activation.**

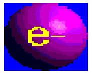


Types of Ionizing Radiation

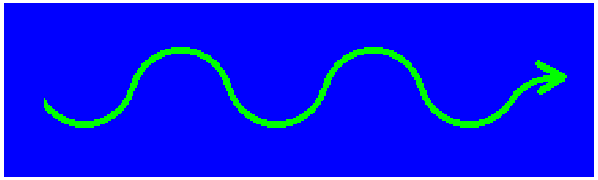
- **Alpha (α) – particle: a helium nucleus:**
  - **2n and 2p, charge = +2**



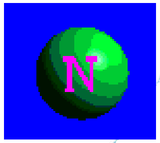
- **Beta (β) – particle: an electron, charge = -1**



- **Gamma (γ) : no mass, charge**



- **Neutron (n) – particle: mass = 1 amu, no charge**



Units of Measure

- **Radioactivity**

  Units of radioactivity are disintegrations/sec

  1 becquerel (Bq) = 1 disintegration/sec = sec^{-1}

  1 curie (Ci) = 3.7×10^{10} Bq

  1 TBq = 10^{12} Bq

  The radioactivity, or "activity", tells you how much of a radionuclide you have. It tells you nothing about the type of emission or delivered dose.

$$A\,(Bq) = \frac{6.02 \times 10^{23} \times \dfrac{mass\,(gm)}{gm.\,atomic\,wt.}}{t_{1/2}\,(sec)}$$

Units of Measure

- **Absorbed energy**

Units of absorbed energy are

1 gray (Gy) = 1 joule/kg of absorber

1 rad = 0.01 joule/kg of absorber = 0.01 Gy

1 Röntgen (R) = amount of gamma or x-ray required to produce ions carrying 1 esu in 1 cm^3 of dry air at STP

1 R ≈ 0.86 rad

These units tell you how much energy is absorbed, but not what the effect of that energy is. Absorption by shielding is a function of both the energy of the radiation and the nature of the absorber.

Units of Measure

Dose

Units of radiation dose are

1 sievert (Sv) = the biological damage done by 1 Gy of gamma or x-ray

1 "Röntgen equivalent man" (rem) = the biological damage done by 1 rad of gamma or x-ray

1 Sv = 100 rem

Sv/Gy = rem/rad = "QF" (formerly RBE) = 1 for most gamma radiation, ≈ 20 for alpha

Dose equivalent (H): absorbed dose x QF x other factors

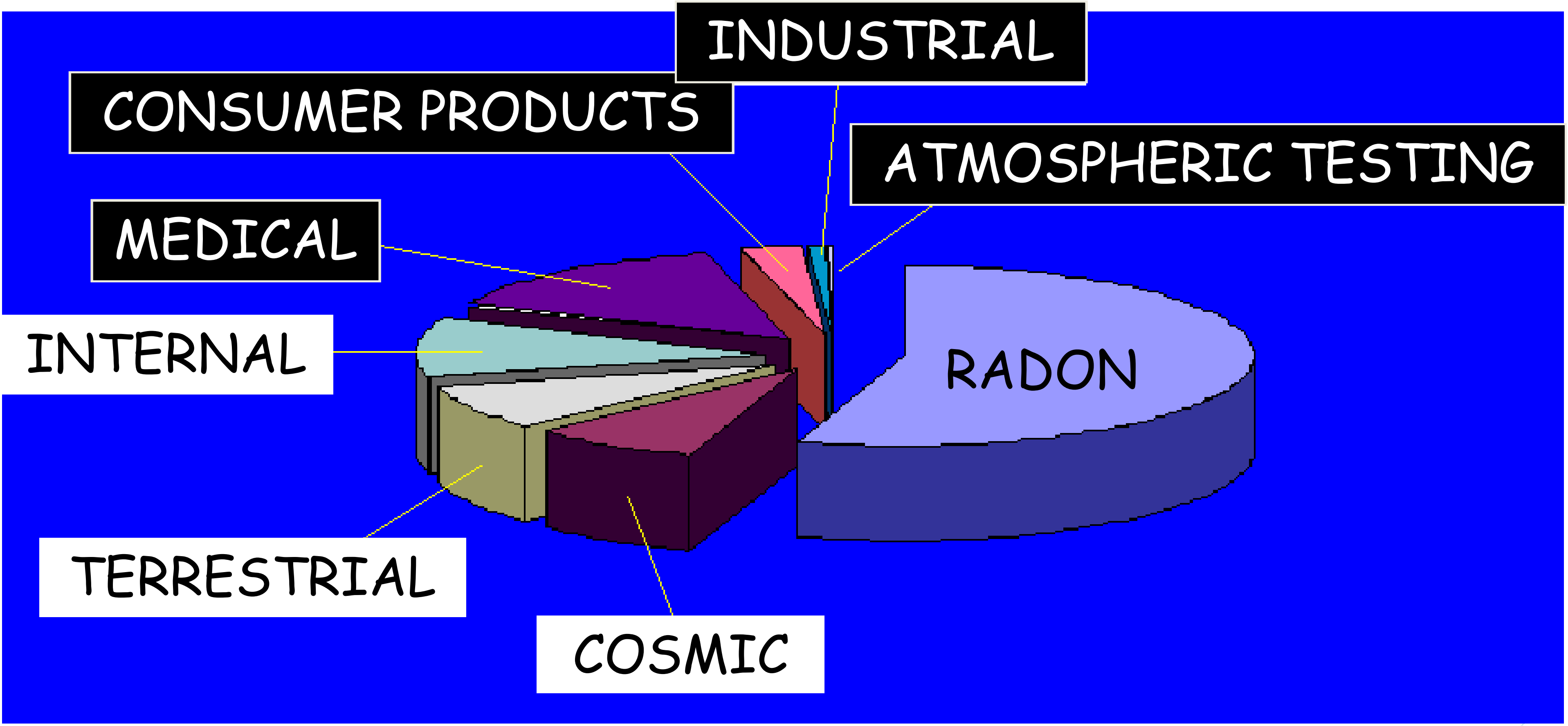
Effective dose equivalent (EDE, Heff) = sum of dose equivalent to each organ x weighting factor for that organ

Units of Measure

- **Dose Conversion Factors (DCF):**
  - **Units are essentially Sv/TBq or rem/Ci**
  - **Found in the Handbook of Health Physics, Federal Guidance Reports (FGR) 11 and 12, and ICRP 68 and 72**
  - **Different for external and internal exposure**

The dose conversion factors are used to estimate the dose to a receptor if the activity or activity per unit area or volume has been measured. "Dosimeters" read directly in dose units.

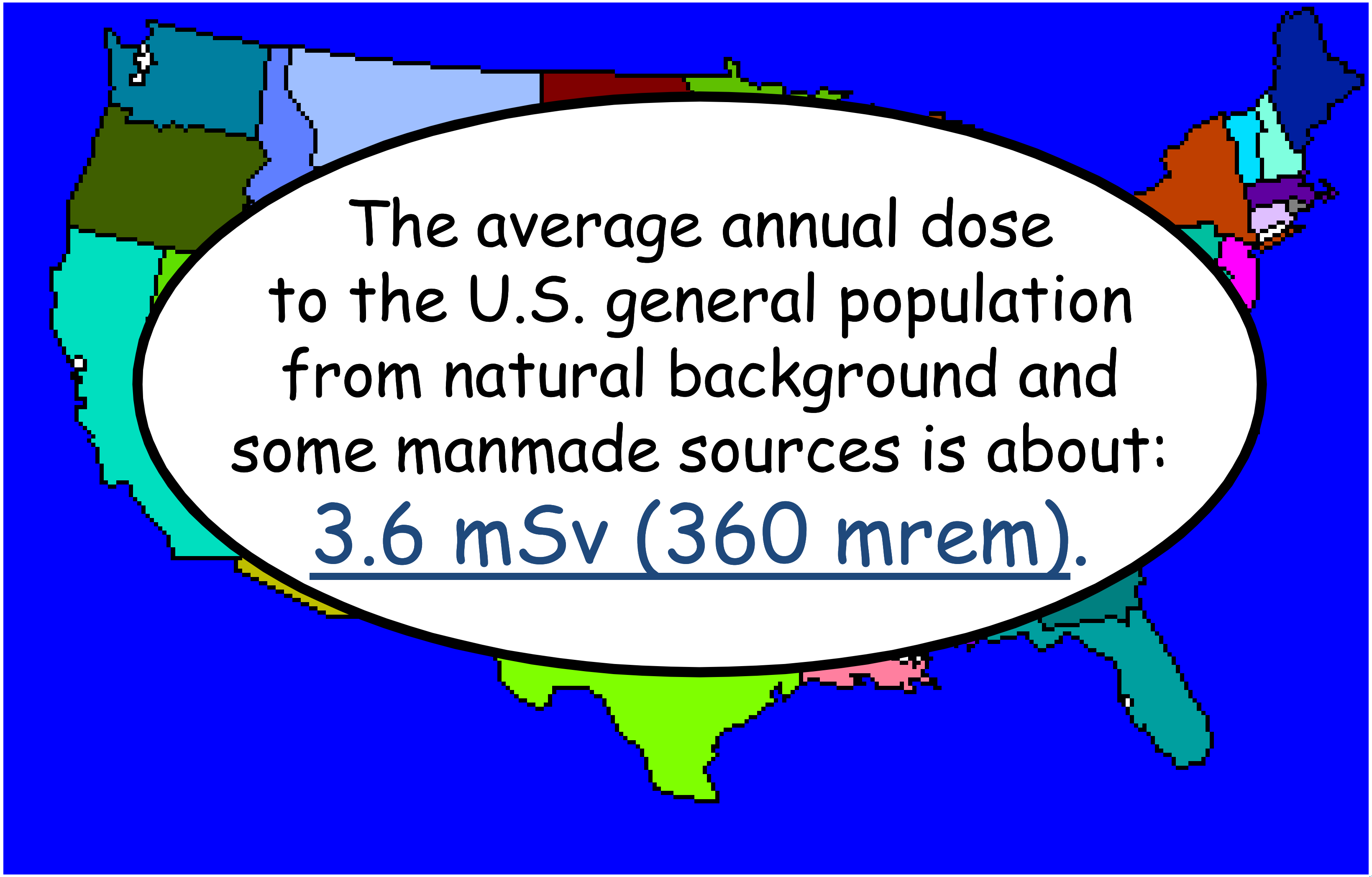
Background Radiation Sources



NATURAL

MANMADE

U.S. Average


The average annual dose
to the U.S. general population
from natural background and
some manmade sources is about:
3.6 mSv (360 mrem).

Acute Exposure Effects

AVG DOSE	DAMAGE
> 5000 rem	Death Within 2 -3 Days
> 500 rem	Gastrointestinal Damage
450 - 600 rem	LD 50-60
200 - 500 rem	Blood System Damaged
100 - 200 rem	Radiation Sickness
25 - 50 rem	Slight Blood Changes
5 rem	NRC Annual Limit