A Dosimetry and Visualization Tool for the Fukushima Daiichi Power Plant

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Rensselaer Polytechnic Institute
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Motivation

Fukushima Daiichi Power Plant before and after the disaster

Photos courtesy of The New York Times
Project Objectives

- Develop a 3-D model of the Fukushima Daiichi Plant and use this model to simulate the events of March/April, 2011 using VR and MCNP
- Incorporate into the model such elements as:
  - Atmospheric dispersion
  - Radiation sources present throughout the incident
  - Human phantom models for dosimetry calculation
Task Groups

1. **Plant CAD Modeling and VR Integration**
   - Justin Vazquez and Aiping Ding

2. **Reactor Analysis and Source Definition**
   - Chao Liang and Tianyu Liu

3. **MCNP Simulation Development**
   - Tianyu Liu and Lin Su

4. **Atmospheric Dispersion Modeling**
   - Benjamin Lawrence and Christopher Gaylord
CAD Models of the Fukushima Daiichi Plant
CAD Models

- Two models developed
  - Reactor site model for VR visualization
  - Simplified model for interpretation into code for MCNP simulation
CAD Model for VR Visualization
CAD Model for VR Visualization

Aerial View of the Fukushima Daiichi Power Plant (provided by from Google Maps)
CAD Model for VR Visualization

3D Model of the Fukushima Daiichi Power Plant (originally developed/provided by turbosquid.com)
CAD Model for VR Visualization

3D Model of the Fukushima Daiichi Power Plant (working version in CAD)
CAD Model for VR Visualization

Artist rendition of a MARK-I BWR reactor (courtesy NRC)

3D model based on artist rendition (developed/provided by turbosquid.com)
CAD Model for VR Visualization

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3D model based on artist rendition (developed/provided by turbosquid.com)
CAD Model for VR Visualization

3-D visual model developed to illustrate steam turbine generator

Photo courtesy of dailykos.com
Placement of the reactor and turbine objects in full reactor CAD model
Placement of the reactor and turbine objects in full reactor CAD model
CAD Model for VR Visualization

Placement of the reactor and turbine objects in full reactor CAD model
Virtual Reality Integration
Creating the EON Application

CAD Models → EON Professional → EON Applications
The steps in EON Studio when building all EON applications but the work procedure may also include other tasks, for example writing scripts.
Integration of CAD Models and Human Phantom into EON

Video available on RPI RMDG website:
http://www.rpi.edu/dept/radsafe/public_html/images/RPIfukushima.mp4
CAD Model for MCNP Simulation
Geometry Simplification for MCNP surface/cell production
(original model developed/provided by turbosquid.com)
CAD Model for MCNP Simulation

Geometry Simplification for MCNP surface/cell production
(original model developed/provided by turbosquid.com)
CAD Model for MCNP Simulation

Placement of reactors on map in CAD
CAD Model for MCNP
Simulation

Addition of other plant buildings and ground features
CAD Model for MCNP Simulation

Completed CAD model for MCNP simulation
Completed CAD model for MCNP simulation
Verifying MCNP Results
Dose distribution measurements will be compared with measurements provided by NISA.
Result Verification

Dose distribution measurements will be compared with measurements provided by NISA.
Reactor and Radiation Source Analysis
### Fukushima Daiichi Reactor Basic Info

<table>
<thead>
<tr>
<th>Unit</th>
<th>Reactor type</th>
<th>Power [MWe/MWth]</th>
<th>Fuel Type</th>
<th>Uranium Load [ton]</th>
<th># Core fuel assemblies</th>
<th># Spent fuel assemblies</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>BWR-3</td>
<td>460/1380</td>
<td>LEU</td>
<td>69</td>
<td>400</td>
<td>292</td>
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<tr>
<td>2</td>
<td>BWR-4</td>
<td>784/2381</td>
<td>LEU</td>
<td>94</td>
<td>548</td>
<td>587</td>
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<tr>
<td>3</td>
<td>BWR-4</td>
<td>784/2381</td>
<td>MOX/LEU</td>
<td>94</td>
<td>548</td>
<td>514</td>
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<tr>
<td>4</td>
<td>BWR-4</td>
<td>784/2381</td>
<td>LEU</td>
<td>94</td>
<td>0</td>
<td>1331</td>
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<tr>
<td>5</td>
<td>BWR-4</td>
<td>784/2381</td>
<td>LEU</td>
<td>94</td>
<td>548</td>
<td>946</td>
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<tr>
<td>6</td>
<td>BWR-5</td>
<td>1100/3293</td>
<td>LEU</td>
<td>132</td>
<td>764</td>
<td>876</td>
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</table>
## Daiichi-3 Core Radioactivity

All values are obtained from SCALE/ORIGEN in unit of [million Curie] at the moment of shutdown.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity</th>
<th>Isotope</th>
<th>Activity</th>
<th>Isotope</th>
<th>Activity</th>
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</thead>
<tbody>
<tr>
<td>$^{140}$Ba</td>
<td>39.9</td>
<td>$^{85m}$Kr</td>
<td>5.7</td>
<td>$^{90}$Sr</td>
<td>1.6</td>
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<tr>
<td>$^{144}$Ce</td>
<td>27.9</td>
<td>$^{87}$Kr</td>
<td>7.9</td>
<td>$^{91}$Sr</td>
<td>30.0</td>
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<tr>
<td>$^{134}$Cs</td>
<td>62.7</td>
<td>$^{88}$Kr</td>
<td>14.8</td>
<td>$^{129m}$Te</td>
<td>1.2</td>
</tr>
<tr>
<td>$^{136}$Cs</td>
<td>0.4</td>
<td>$^{140}$La</td>
<td>40.3</td>
<td>$^{131m}$Te</td>
<td>3.5</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>1.9</td>
<td>$^{99}$Mo</td>
<td>39.7</td>
<td>$^{132}$Te</td>
<td>29.7</td>
</tr>
<tr>
<td>$^{131}$I</td>
<td>20.5</td>
<td>$^{239}$Np</td>
<td>412.0</td>
<td>$^{131m}$Xe</td>
<td>0.2</td>
</tr>
<tr>
<td>$^{132}$I</td>
<td>30.2</td>
<td>$^{103}$Ru</td>
<td>27.6</td>
<td>$^{133}$Xe</td>
<td>44.3</td>
</tr>
<tr>
<td>$^{133}$I</td>
<td>43.5</td>
<td>$^{106}$Ru</td>
<td>6.1</td>
<td>$^{133m}$Xe</td>
<td>1.4</td>
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<tr>
<td>$^{134}$I</td>
<td>36.4</td>
<td>$^{127}$Sb</td>
<td>1.4</td>
<td>$^{135}$Xe</td>
<td>26.2</td>
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<tr>
<td>$^{135}$I</td>
<td>37.6</td>
<td>$^{129}$Sb</td>
<td>5.3</td>
<td>$^{138}$Xe</td>
<td>2.1</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>0.2</td>
<td>$^{89}$Sr</td>
<td>26.1</td>
<td>$^{91}$Y</td>
<td>32.7</td>
</tr>
</tbody>
</table>
Gamma Spectra *hour-by-hour*

Gamma Spectrum of Fission Product After 1 hour

Decay information source:
Berkeley Laboratory Isotopes Project, Korea Atomic Energy Research Institute

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-131</td>
<td>8 days</td>
</tr>
<tr>
<td>Cs-137</td>
<td>30 years</td>
</tr>
</tbody>
</table>
Source Card used in MCNP

Assumptions according to the events and damage happened to the power plants

1) Percentage of radionuclide released;
2) The release pathway.
Radiation Release Events at the Fukushima Daiichi Plant
Overview of Events

- 3/11-14:46 Earthquake
  - Units 1-3: SCRAM
  - Units 4-6: not operating
  - Emergency Core Cooling System
- 15:41 Tsunami
  - Diesel generator damaged
  - Reactor Core Isolation Cooling System
Overview of Events

Diagram courtesy of NRC
Overview of Events

Safety/relief valves

- Residual heat
  → steam → pressure

- Safety relief valves
  manually/automatically opened

Diagram courtesy of scribid.com
Overview of Events

- **Fuel damage**
  - Core uncovery
  - Fuel ballooning & bursting
  - Rapid Oxidation
    - \( \text{Zr} + 2\text{H}_2\text{O} = \text{ZrO}_2 + 2\text{H}_2 \) @1500K
    - \( P(\text{oxid}) > P(\text{decay}) \)
  - Debris bed formation
    - \( \text{Zr} + \text{UO}_2 \) melt@1700K

- Fission product, noble gases (Xe, Kr), \( \text{H}_2 \)

- Plate-out

Diagram courtesy of scribid.com
Overview of Events

- **Primary Containment Depressurization**
- **3/12** - 14:30 Start venting U1.
  - 20:41 Starting venting U3.
- **3/13** - 08:41 Start venting U3.
  - 11:00 Start venting U2.
- **3/15** - 00:02 Start venting U2 again.
Overview of Events

- **Hydrogen Explosion**
  - $2H_2 + O_2 = 2H_2O$
  - 3/12-15:36 U1 @ service building
  - 3/14-11:01 U3 @ service building
  - 3/15-06:10 U2 @ torus wet-well (suspected)
  - 3/15-06:00 U4 @ SFP (reported by JAIF)

Photos courtesy of The New York Times
Overview of Events

- Steam/Smoke

- **3/15**-08:25 White smoke at U2.
- **3/16**-08:34 and -10:00 White smoke from U3.
- **3/21**-18:22 White vapor (steam) erupted at U2
  - 15:55~18:02 Gray smoke erupted at U3.
- **3/27**-White vapor (steam) from U2, U3, and U4.

Stable release

Photo courtesy of en.trend.az
Atmospheric Dispersion Modeling
Atmospheric Dispersion Modeling: Task Objectives

- Model that predicts distribution of radioactive plume as function of time and location off site
  1. Deposition on ground of Cs-137 and I-131 in local area of Japan
  2. Concentration, from ground up to 2 meters, of released radioactivity
Dispersion of Gas from a Continuous Source: Pasquill-Gifford equation (Gaussian Plume Model)

- $\chi = Q \times [-0.5(y^2/\sigma_y^2 + H_e^2/\sigma_z^2)] / (\pi \sigma_y \sigma_z \mu)$

- $H_e = H_s + d(v/\mu)^{1.4}(1+\Delta T/T)$

Source: Chapter 11 from Introduction to Health Physics by Cember and Johnson
HYSPLIT Model

- Model utilized: Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT)
  - Produced by National Oceanic and Atmospheric Administration (NOAA) and Australian Bureau of Meteorology
- Uses National Weather Service’s (NWS) Global Data Assimilation System (GDAS)
  - Accurate (1° lat/long, 3 hr timeframe)
  - Can provide trajectory, concentration, dispersion, and exposure modeling
  - Pre-programmed Cs-137 and I-131

Photo courtesy of NOAA
HYSLIT Simulations
Local Radioactivity Distribution
Simulation

Concentration [µCi/m$^3$] in air from March 14th to March 17th

NOAA HYSPLIT MODEL
Concentration (µCi/m$^3$) averaged between 0 m and 2 m
Integrated from 0200 14 Mar to 0500 14 Mar 11 (UTC)
SUM Release started at 0200 14 Mar 11 (UTC)

Source: 37.423 N 141.033 E

Maximum: 1.1E+01
Minimum: 1.1E-04
Local Radioactivity Distribution Simulation

Deposition $[\mu\text{Ci/m}^2]$ on ground from March 14th to March 17th
Global Radioactivity Distribution Simulation

Concentration $[\mu\text{Ci/m}^3]$ in air from March 14th to March 21st

NOAA HYSPLIT MODEL
Concentration (uCi/m3) averaged between 0 m and 3000 m
Integrated from 0200 14 Mar to 1400 14 Mar 11 (UTC)
SUM Release started at 0200 14 Mar 11 (UTC)

Source: 37.423 N 141.033 E

GDAS METEOROLOGICAL DATA

Maximum: 2.8E-02
Minimum: 1.4E-07
Results from Preliminary MCNP Simulations
Geometry Simplification
Simulation 1 – Assumptions

- Secondary containment for all reactors intact
- Damage to primary containment in Units 1-4
  - Uniformly distributed Cs-137 inside of secondary containment
Simulation 1 – Assumptions

- Secondary containment for all reactors intact
- **Damage to primary containment in Units 1-4**
  - Uniformly distributed Cs-137 inside of secondary containment
Simulation – Tally Definition

- Type 1 mesh tally in MCNPX ver. 2.5.0
  - Modified to calculate equivalent dose in tissue/organ
- Mesh size:
  - $10 \times 10 \times 10$ m cube
- Tallied area:
  - X: -10m - 900m
  - Y: -80m - 1200m
  - Z: 0m - 10m
Simulation 1 – Results

Equivalent Dose Distribution from Cs-137 in Scenario 1
Tally region: X = -10~900m, Y = -80~1200m, Z = 0~10m
Tally Unit: (Sv/h) / (particle/sec)
Simulation 2 – Assumptions

- Secondary containment damaged for Units 1-4
  - Roofs partially removed
- Release of radioactivity
  - Uniformly distributed Cs-137 inside of secondary containment
  - Cylindrical source: R=10m, H=150m
Simulation 2 – Results

Equivalent Dose Distribution from Cs-137 in Scenario 2
Tally region: X = -10~900m, Y = -80~1200m, Z = 0~10m
Tally Unit: (Sv/h) / (particle/sec)
Conclusions & Further Work
What We’ve Learned so Far

- Geometry simplification an effective method for MCNP simulation
- Proper defining of the source term perhaps the most important aspect of simulation
  - Must accurately depict distribution of radionuclides over time
- Methods detailed in the present study could be powerful tool for simulating and planning for emergency situations
Next Stages

- Translation of CAD Model into MCNP
  - Performed either through the use of the MCAM CAD-to-MCNP software, or manual cell definition
- Improvement of source term
  - Improved estimates of radioactive nuclide release
  - Accounting for localized atmospheric dispersion
  - Accounting for radiation from spent fuel pools
- Use of variance-reduction techniques in MCNP
Further Work

- Integration of dose distribution estimates with VR interface
  - Informative, interactive VR simulation
- Determination of dose in human phantoms
  - Simulation of impact on workers affected by the incident
Future Directions

- Simulation of radiation events using Google Earth imagery to model major cities in the U.S.
- Example: New York City
Future Directions

- Simulation of individuals walking and sitting on contaminated ground
  - Cs-137 and Co-60 with concentrations of 30 kBq m\(^{-2}\)
  - Parallel and isotropic planar sources
Special Thanks

- Rensselaer Nuclear Engineering faculty
  - Dr. Peter Caracappa
  - Dr. Sastry Sreepada
  - Dr. Yaron Danon

- Rensselaer Nuclear Engineering students
  - Matthew Mille
  - Rian Bahran
Please contact Justin Vazquez of the RPI Radiation Measurement and Dosimetry Group to attain a copy of any of the simulation videos discussed in this presentation: vazquj4@rpi.edu