SAND2015-10448PE

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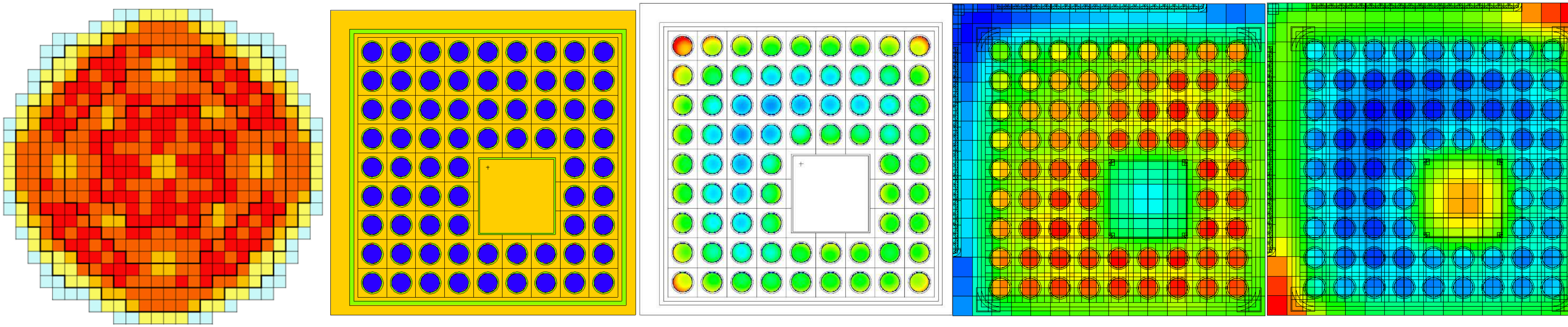


SNL BSAF Phase 2 Activities

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Key accomplishments to date

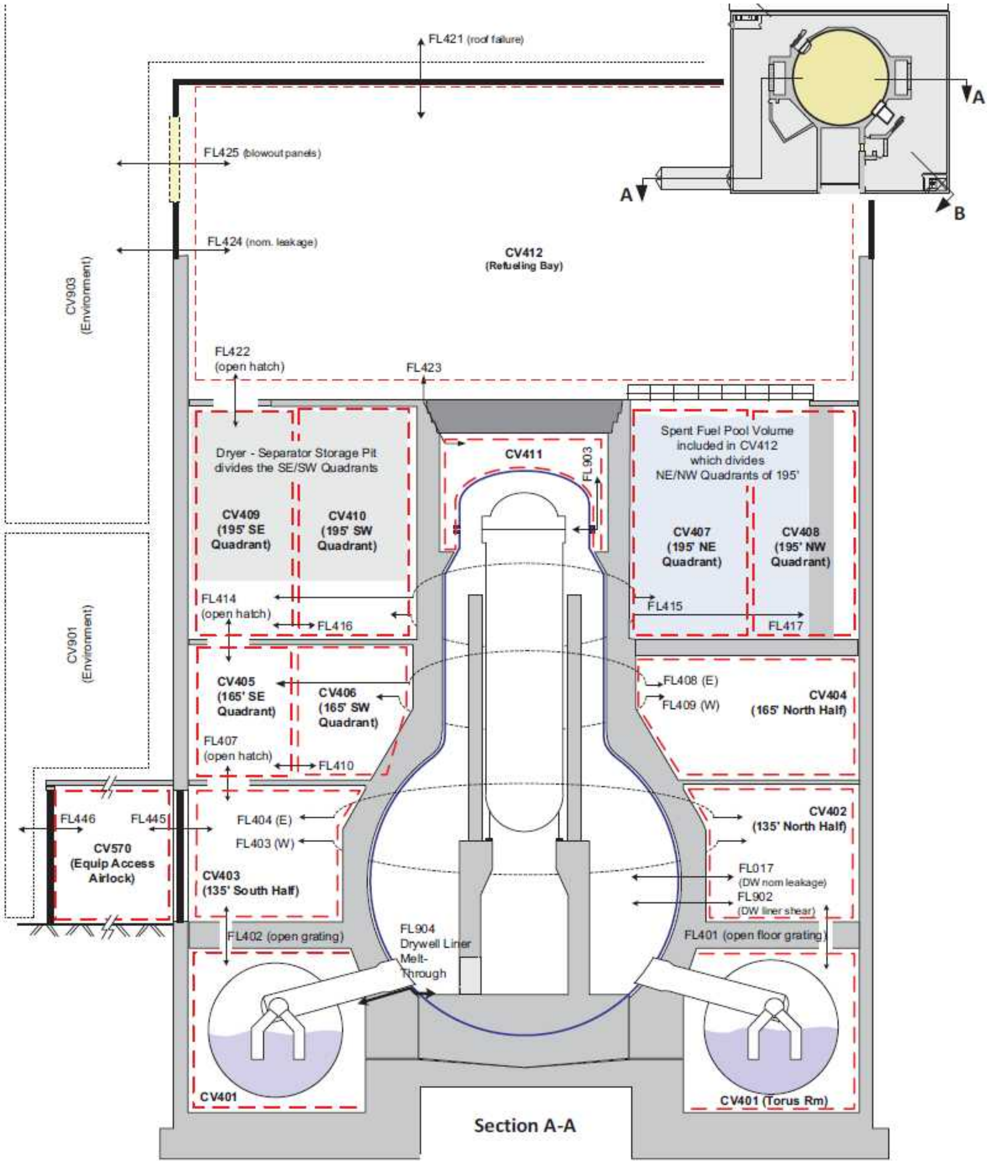
- Unit-specific MELCOR models created for each unit
  - Mechanistic evaluation of severe accident source terms
- Consistent, comprehensive, and reasonably-representative radionuclide inventory information generated (using SCALE6) for Fukushima Daiichi units 1-3
  - Depletion calculations implement (ENDF/B-VII-based) cross section libraries generated by TRITON analyses of Fukushima fuel assemblies
  - Depletion calculations use TEPCO plant data: 3D burnup and power distributions for each unit, enrichments, geometry, etc.
  - Creation of MELCOR class inventories and decay heats, total core decay heats, and isotopic inventories for each unit
- MACCS analyses using source term information via MELCOR/SCALE calculations
- Framework and initial tool development for consistent and scrutable dose calculations for severe accident source terms
  - MCNP dose calculations in the containment and around the plant

Presentation Outline

- Comparison of Peach Bottom reactor building nodalization to TEPCO measured dose rates
  - Floor by floor basis
  - Torus room
  - Refueling bay
- Severe accident source term calculation
  - Neutronic methods
  - Fukushima 134Cs to 137Cs ratio

Peach Bottom Reactor Building Nodalization vs. TEPCO Measured Dose Rates

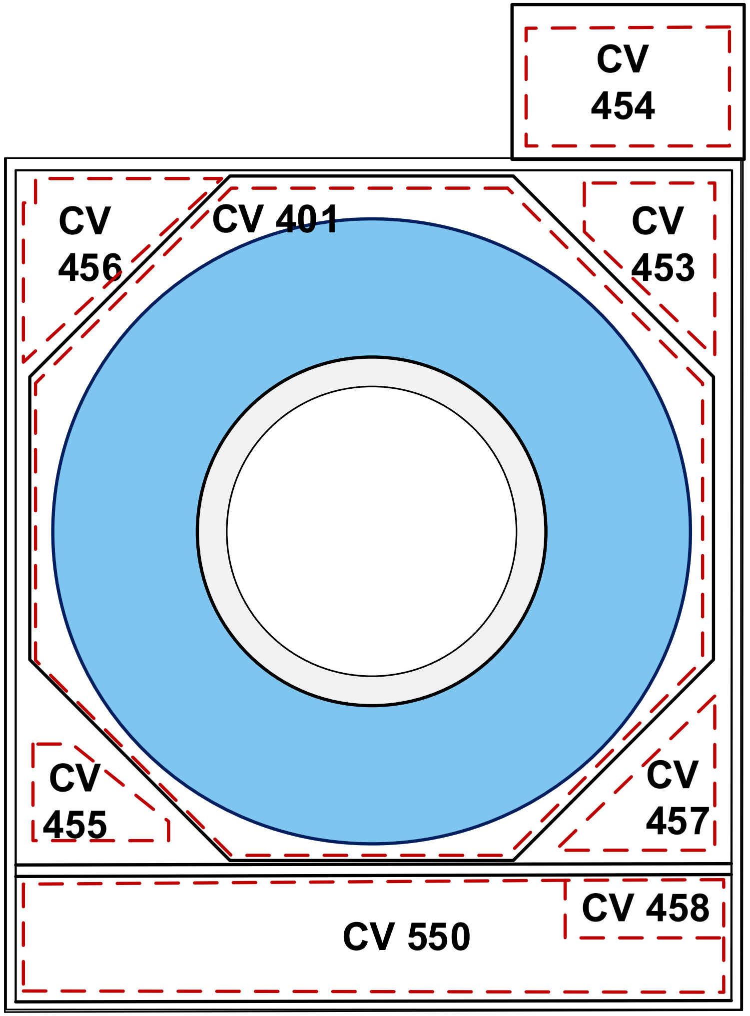
Peach Bottom Reactor Building Nodalization

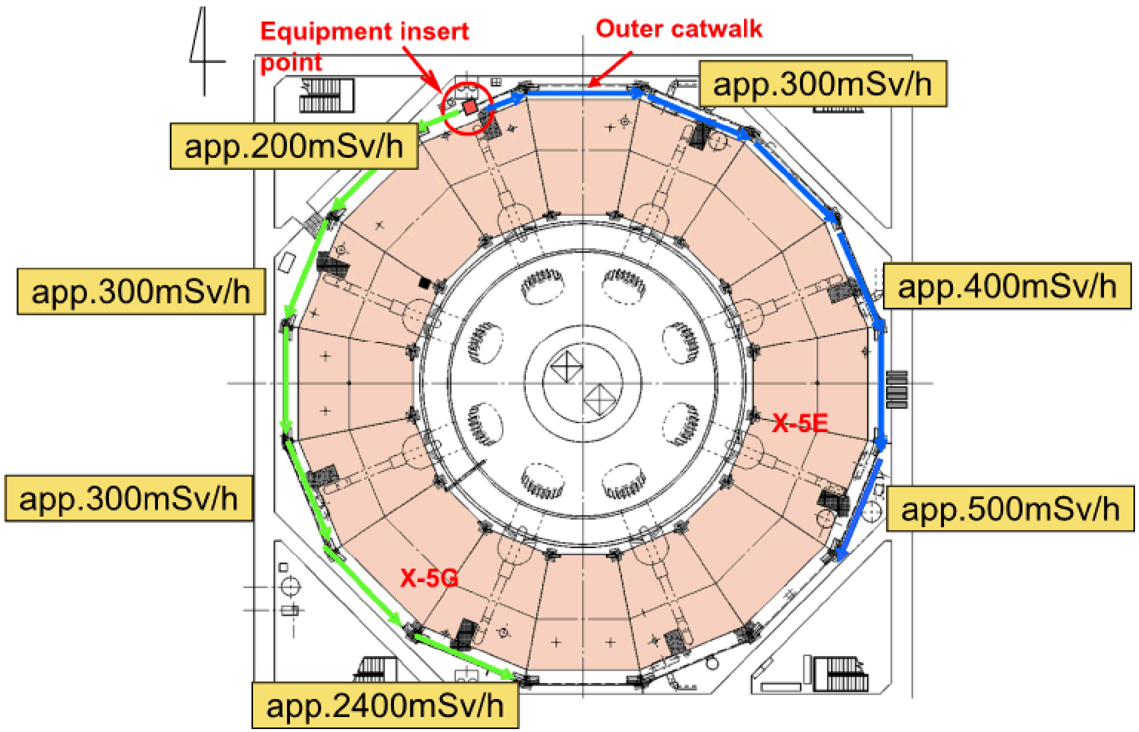


- Five Floors
  - Torus room
  - Refueling bay
- Two to five control volumes (CV) per floor
- Additional CVs
  - Stairwells
  - Equipment access airlock
  - Spent fuel pool
  - Drywell head

Fukushima Daichi Unit 1

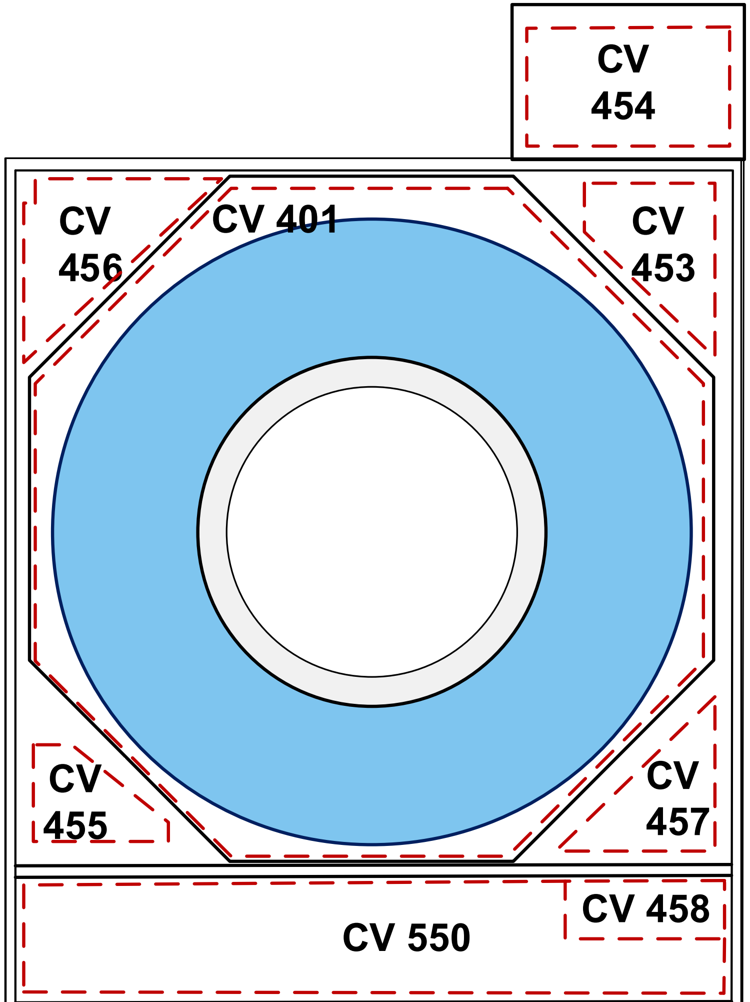
Torus Room – Unit 1

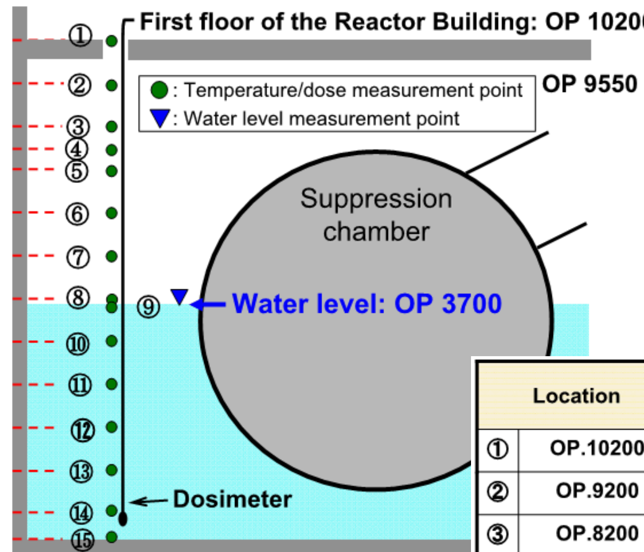




[Graphic courtesy of TEPCO]

Torus Room – Unit 1

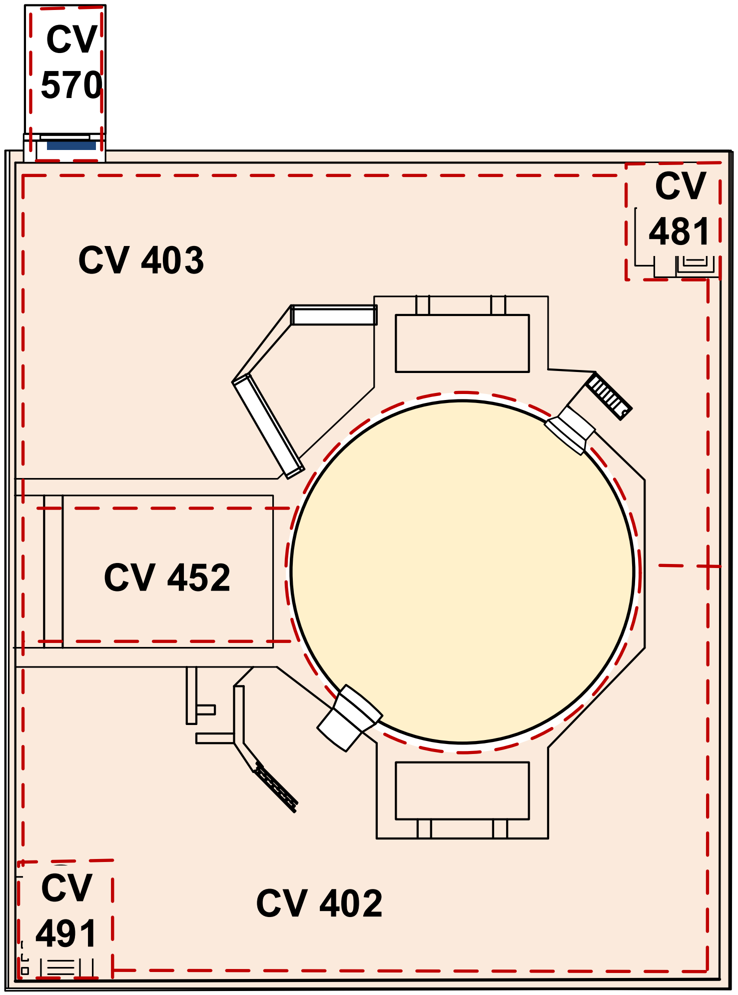




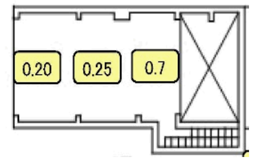
	Location	Temp. [°C]	Dose [mSv/h]
①	OP.10200	4.8	1.5
②	OP.9200	16.3	180
③	OP.8200	17.4	220
④	OP.7700	17.3	230
⑤	OP.7200	16.9	250
⑥	OP.6200	17.1	420
⑦	OP.5200	17.4	780
⑧	OP.4200	17.7	920
⑨	Water level: Approx. OP.3700	19.8	800
⑩	OP.3200	22.7	110
⑪	OP.2200	22.9	93
⑫	OP.1200	22.9	83
⑬	OP. 200	22.9	82
⑭	OP. -800	22.8	90
⑮	OP.-1230	22.8	95

[Graphic courtesy of TEPCO]

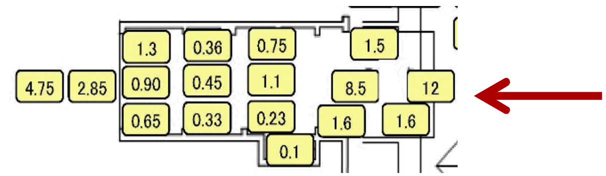
Floor 1 – Unit 1

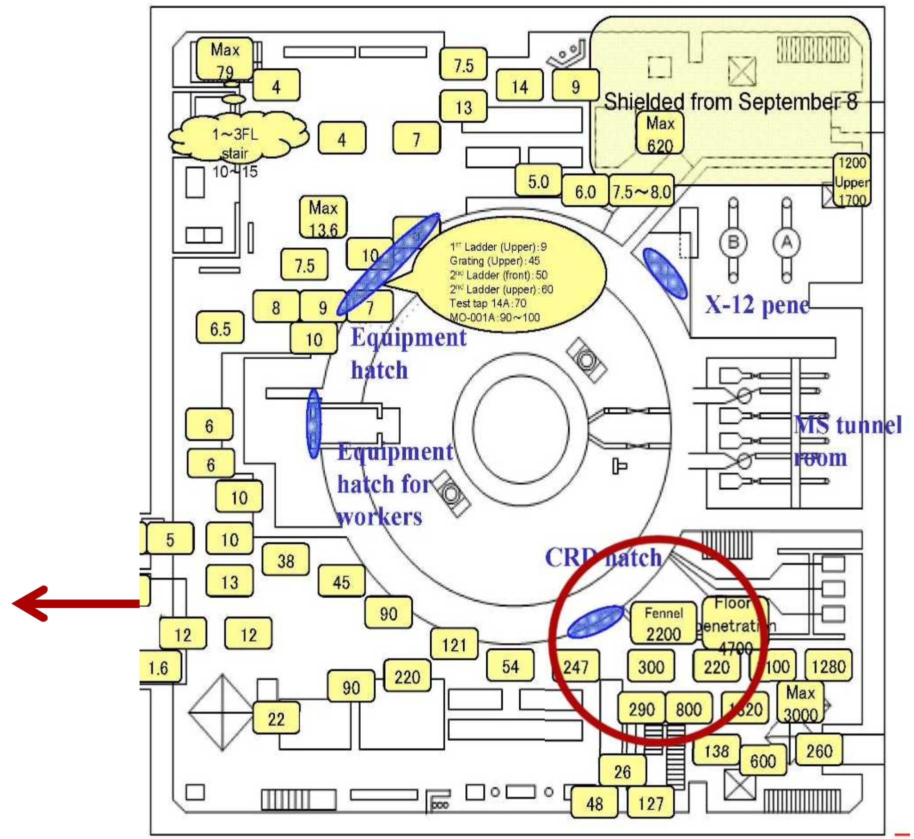


2nd Floor



1st Floor

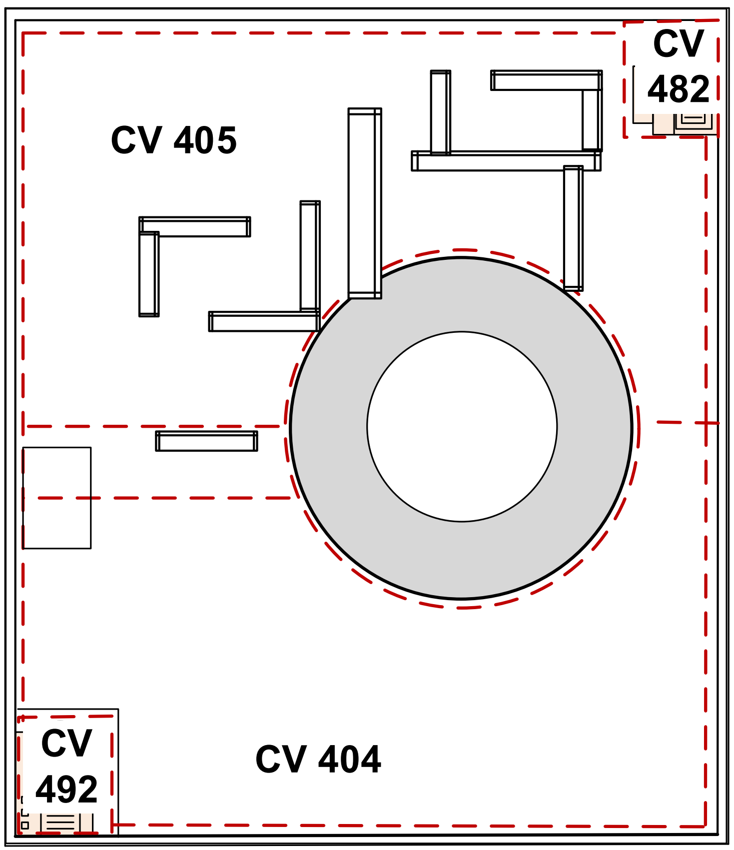


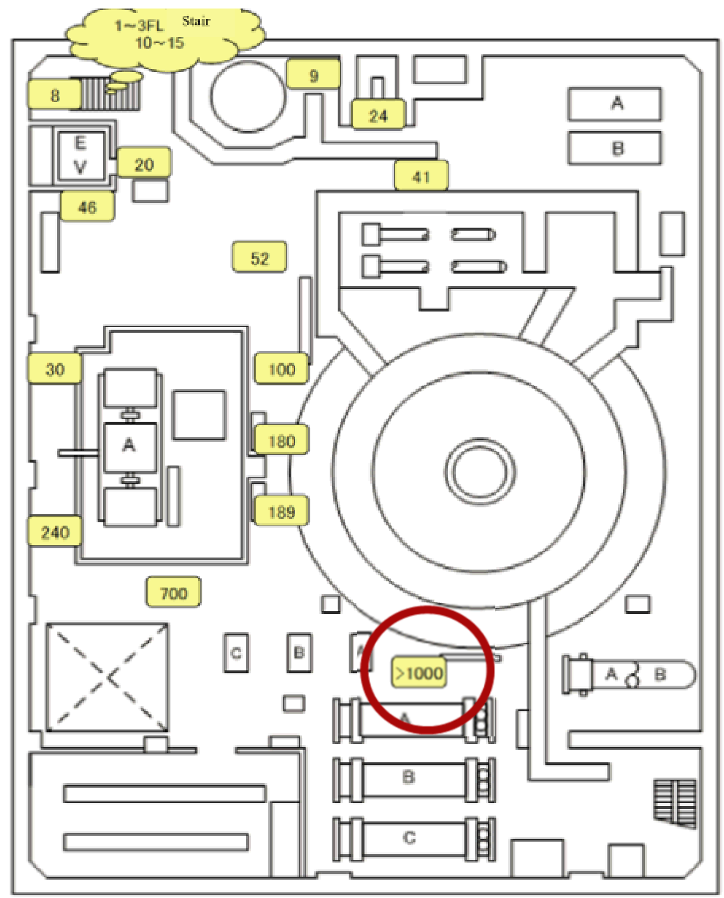


Dose in mSv/hr

[Graphic courtesy of TEPCO]

Floor 2 – Unit 1



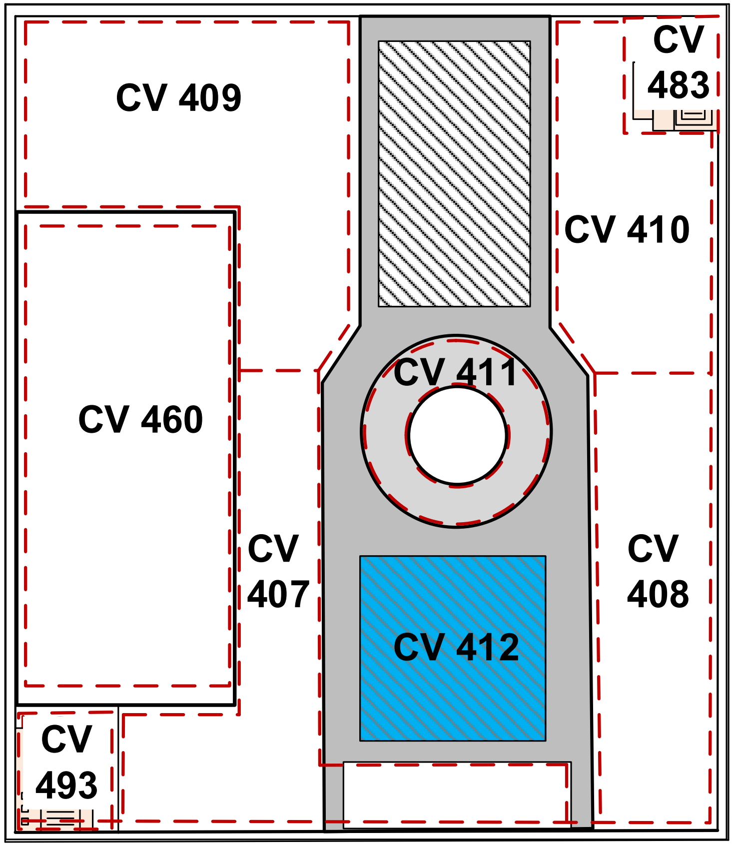


Dose in mSv/hr

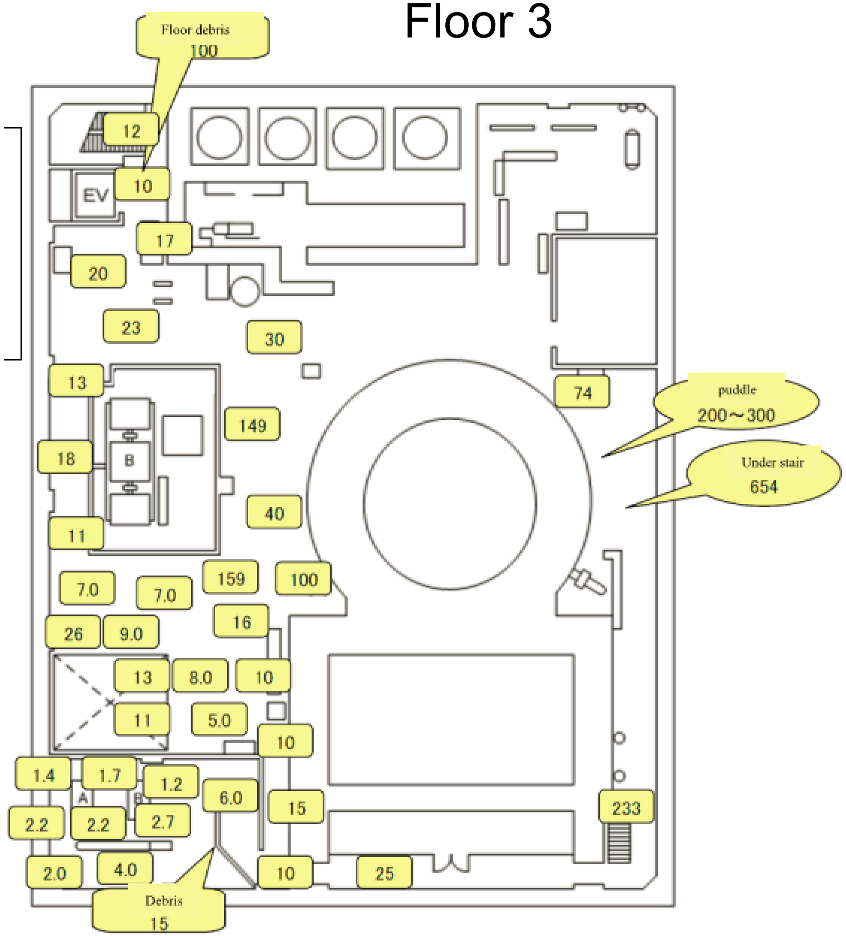
[Graphic courtesy of TEPCO]

Floors 3 and 4 – Unit 1

Floors 3 and 4 Combined



Floor 3

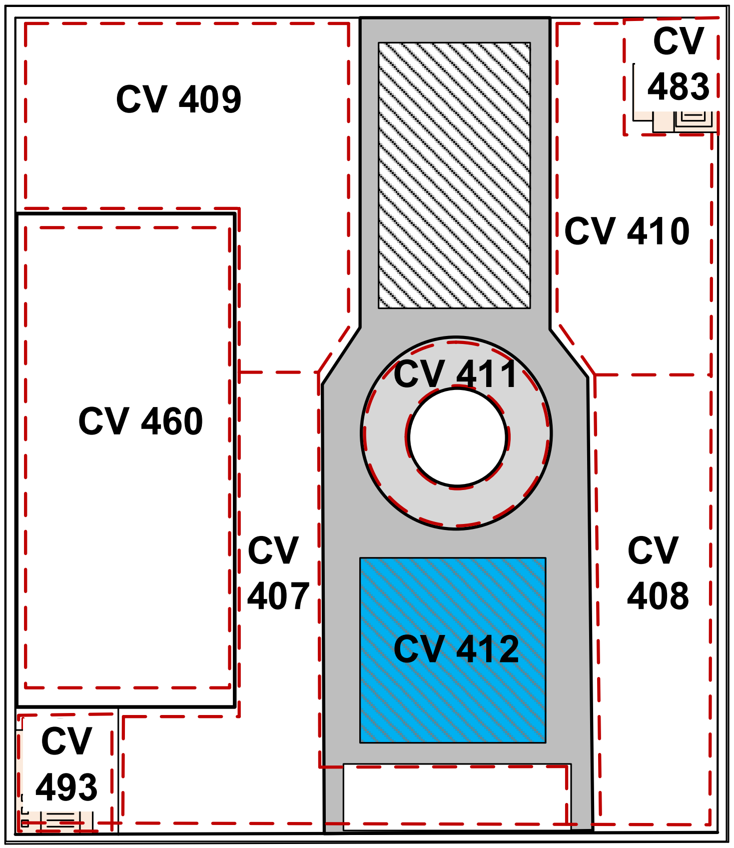


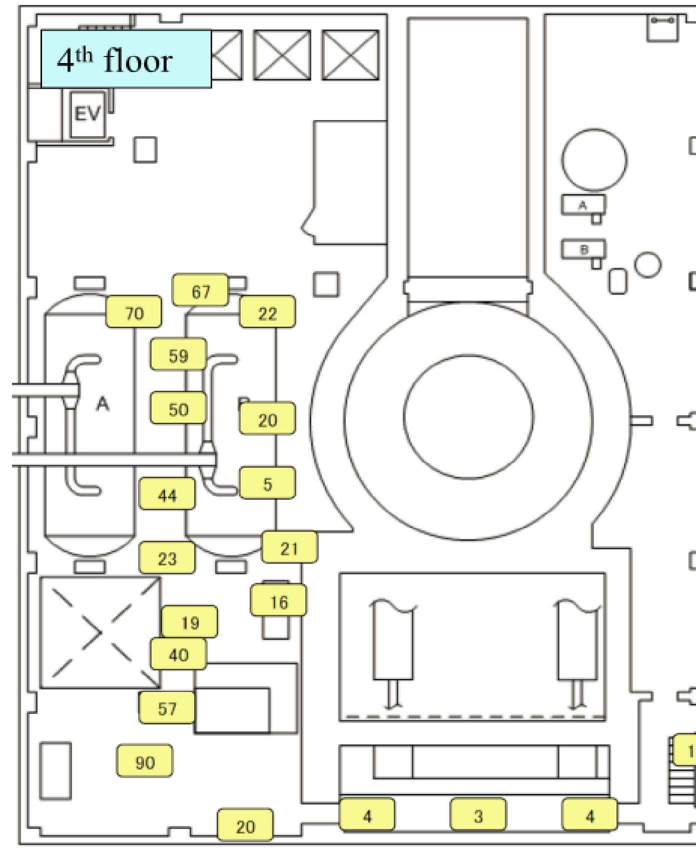
Dose in mSv/hr

[Graphic courtesy of TEPCO]

Floors 3 and 4 – Unit 1

Floors 3 and 4 Combined

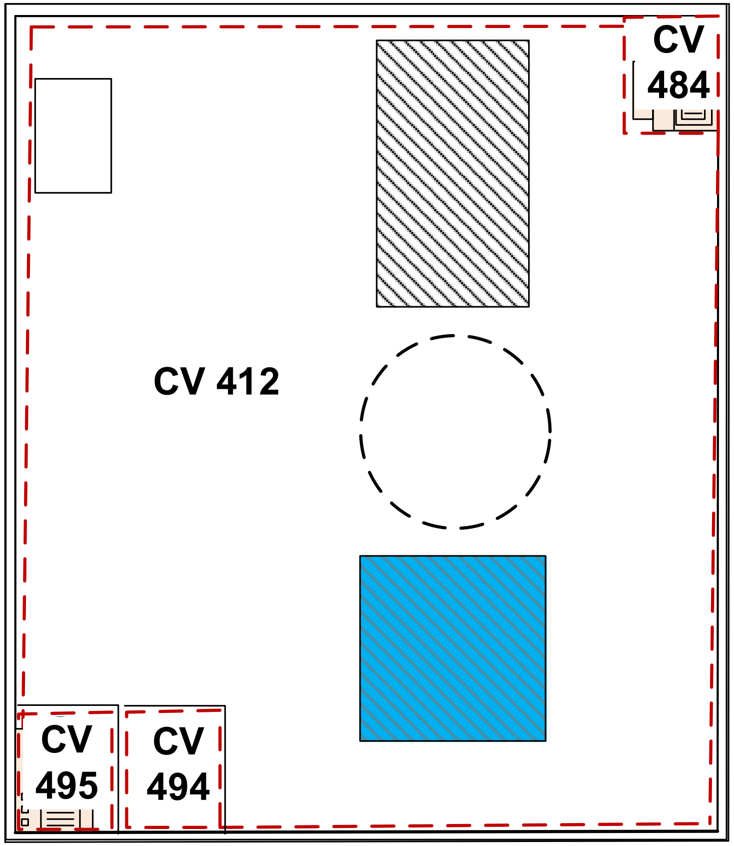


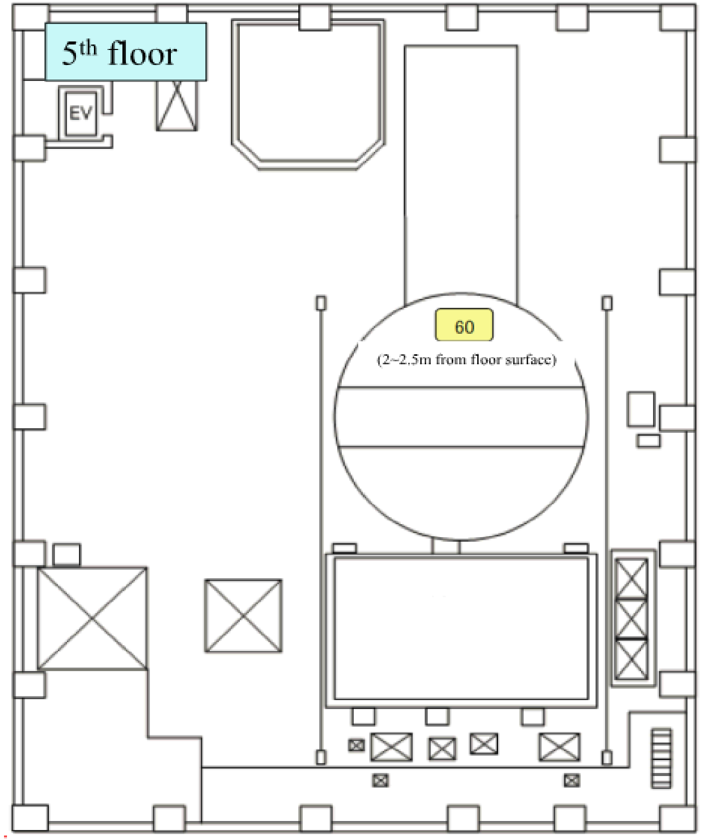


Dose in mSv/hr

[Graphic courtesy of TEPCO]

Refueling Bay – Unit 1



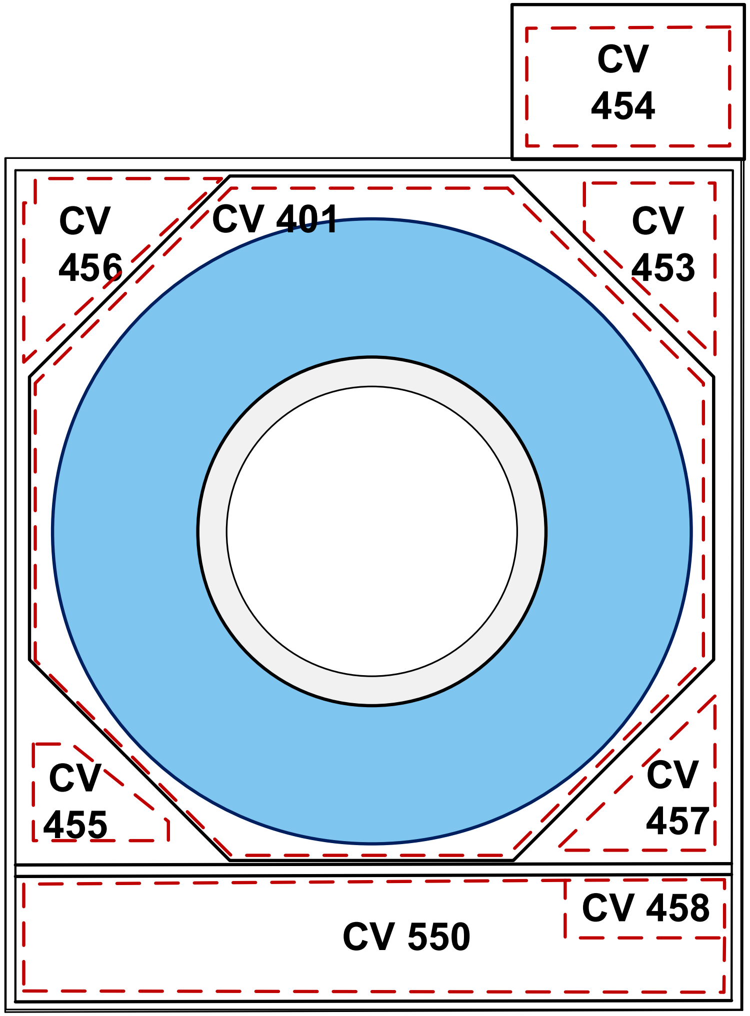


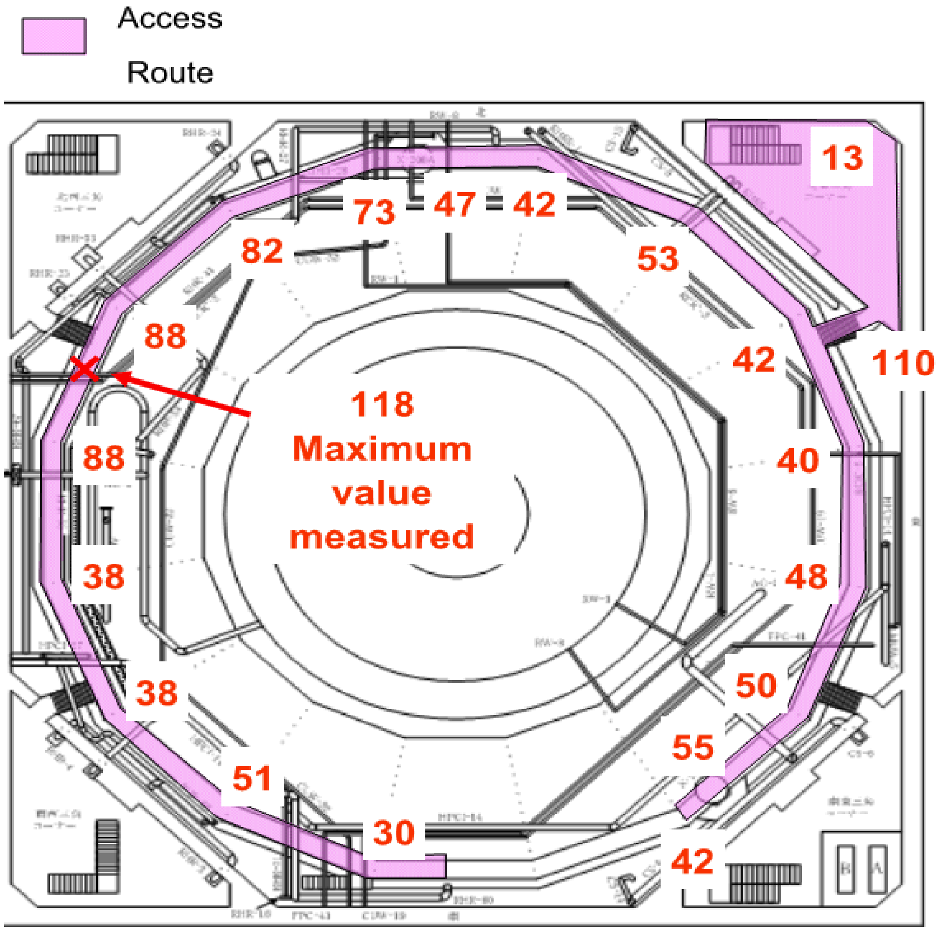
Dose in mSv/hr

[Graphic courtesy of TEPCO]

Fukushima Daichi Unit 2

Torus Room – Unit 2

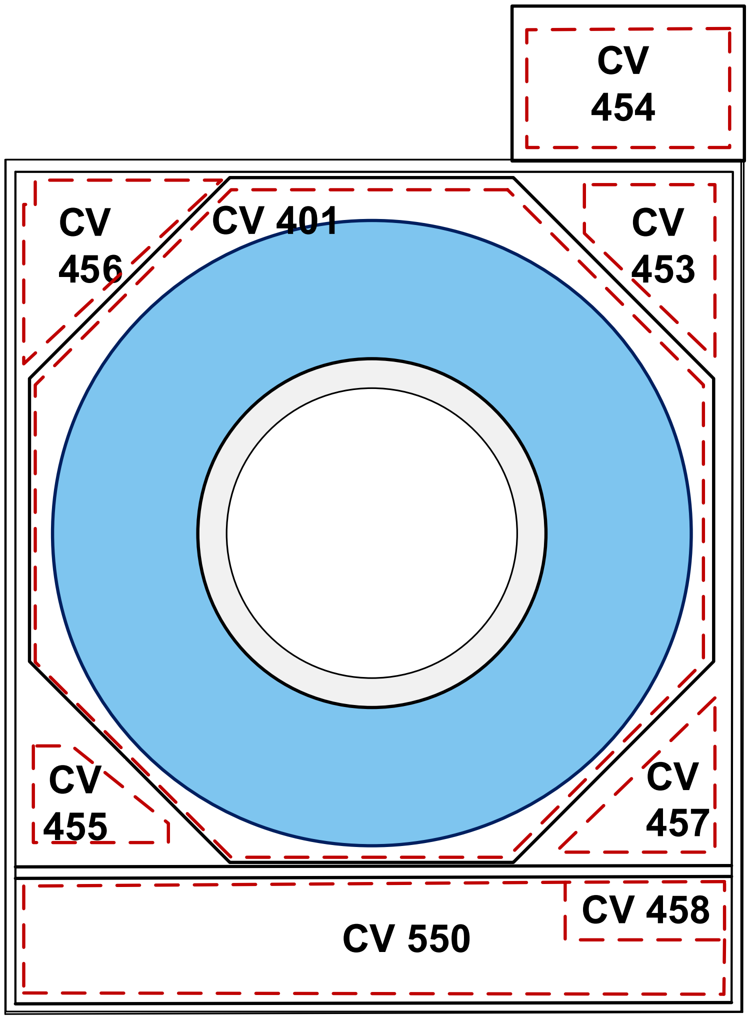


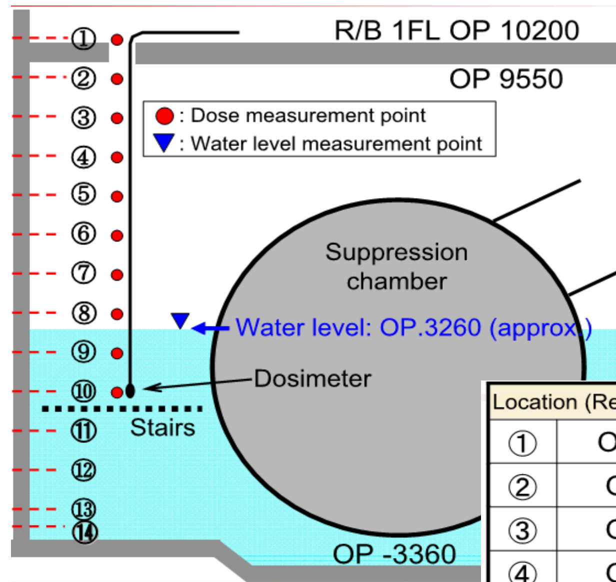


Dose in mSv/hr

[Graphic courtesy of TEPCO]

Torus Room – Unit 2



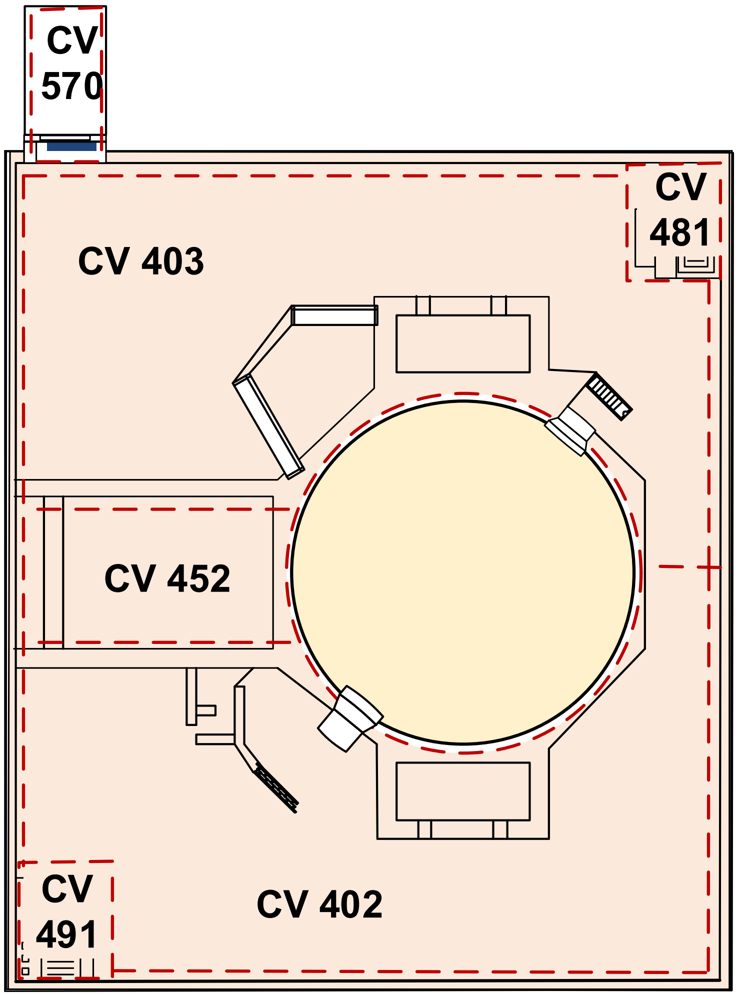


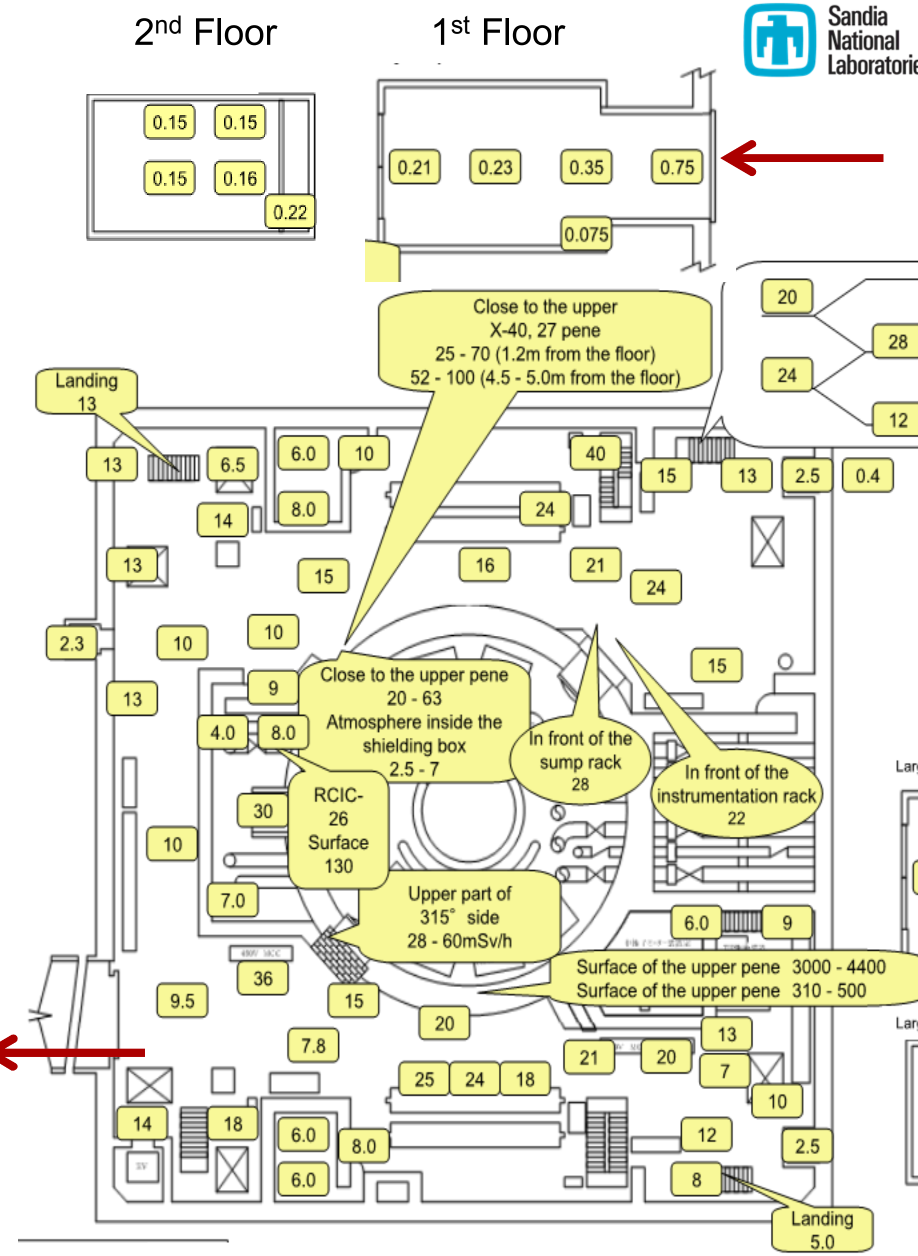
	Location (Reference value)	Dose [mSv/h]
①	OP.10500	4.3
②	OP.9500	6.2
③	OP.8500	10.3
④	OP.7500	15.3
⑤	OP.6500	20.5
⑥	OP.5500	32.8
⑦	OP.4500	74.0
⑧	OP.3500	134.0 (Max.)
—	OP.3260 (Water level)	—
⑨	OP.2500	18.7
⑩	OP.2000	23.7
⑪	OP.500	—
⑫	OP.-500	—
⑬	OP.-1500	—
⑭	OP.-1760	—

[Graphic courtesy of TEPCO]

Sandia National Laboratories

Floor 1 – Unit 2



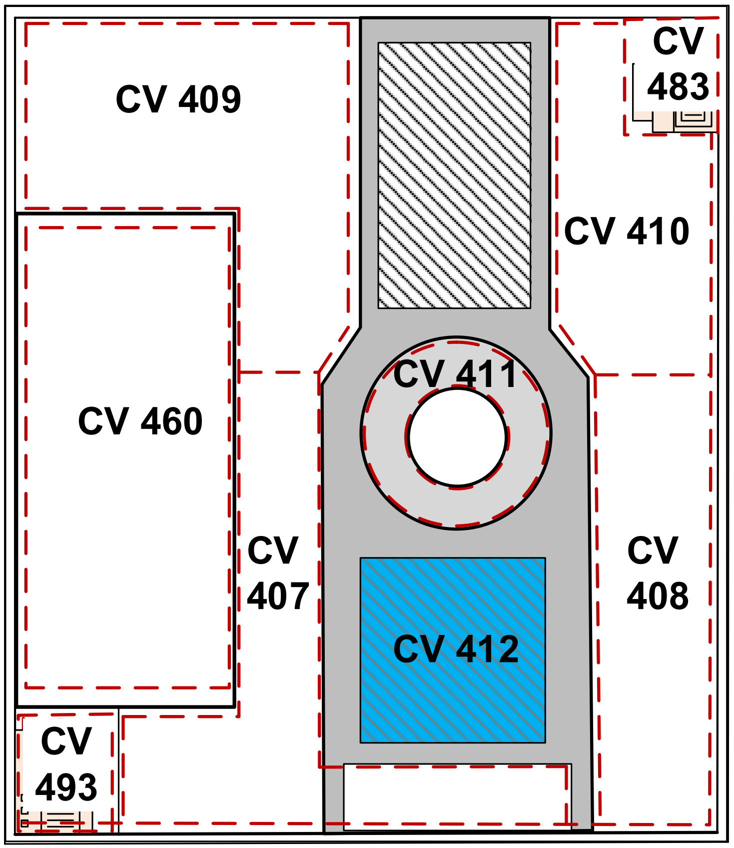


Dose in mSv/hr

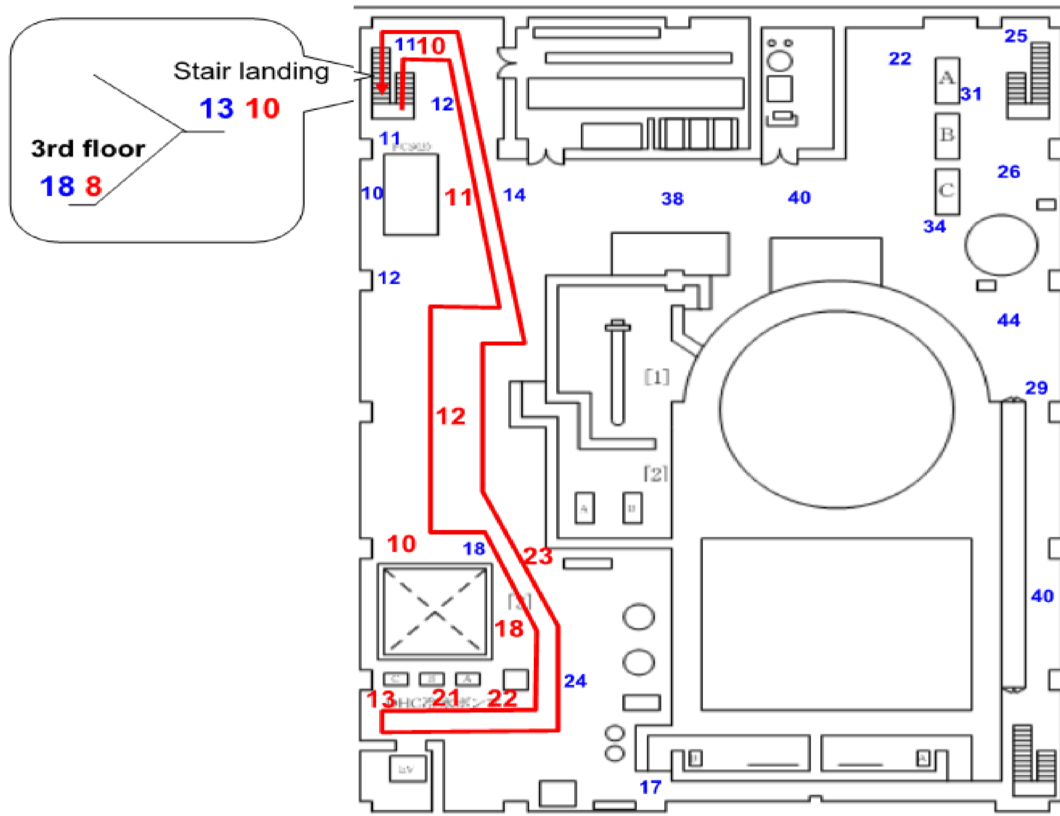
[Graphic courtesy of TEPCO]

Floors 3 and 4 – Unit 2

Floors 3 and 4 Combined



Floor 3



[Legend]

Atmosphere dose rate measured up until February 27

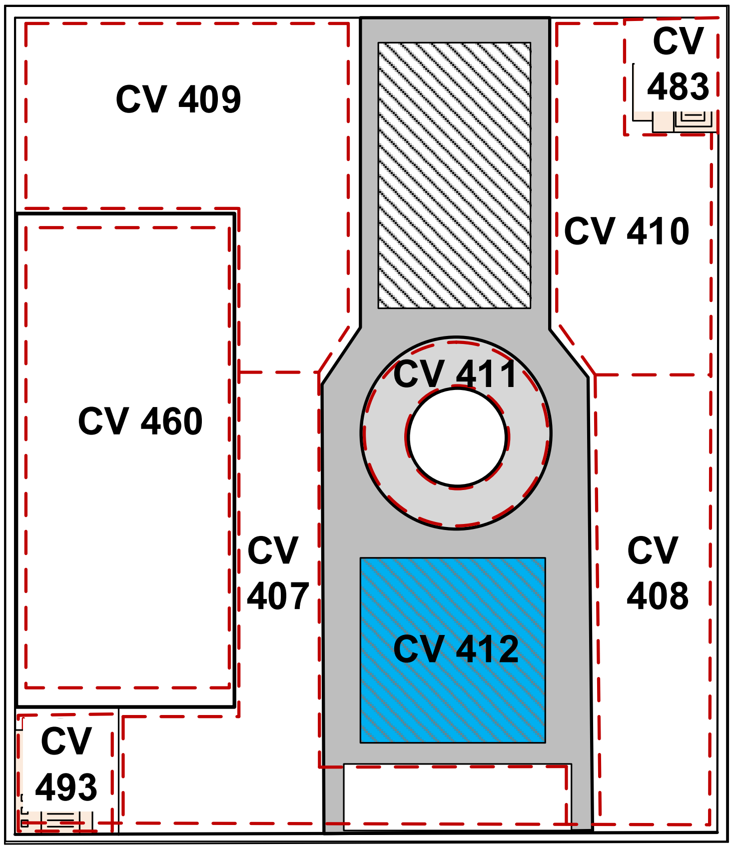
Atmosphere dose rate measured on June 13, 2012

Unit: mSv/h

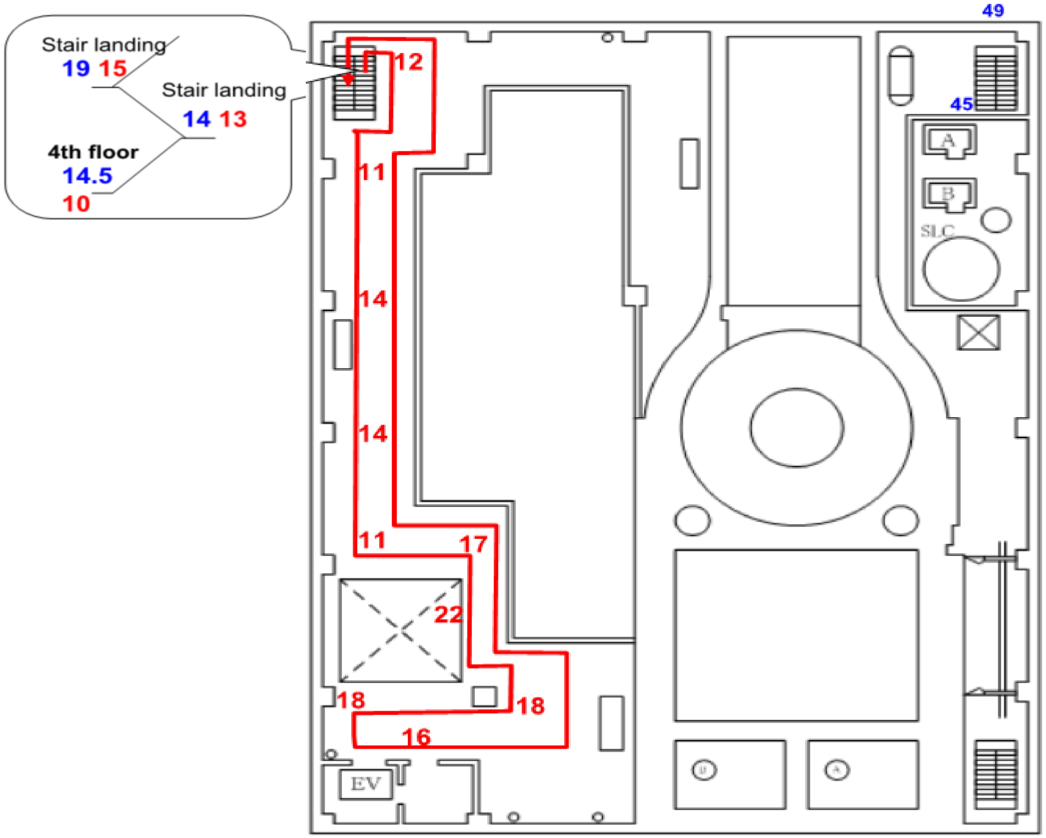
[Graphic courtesy of TEPCO]

Floors 3 and 4 – Unit 2

Floors 3 and 4 Combined



Floor 4



[Legend]

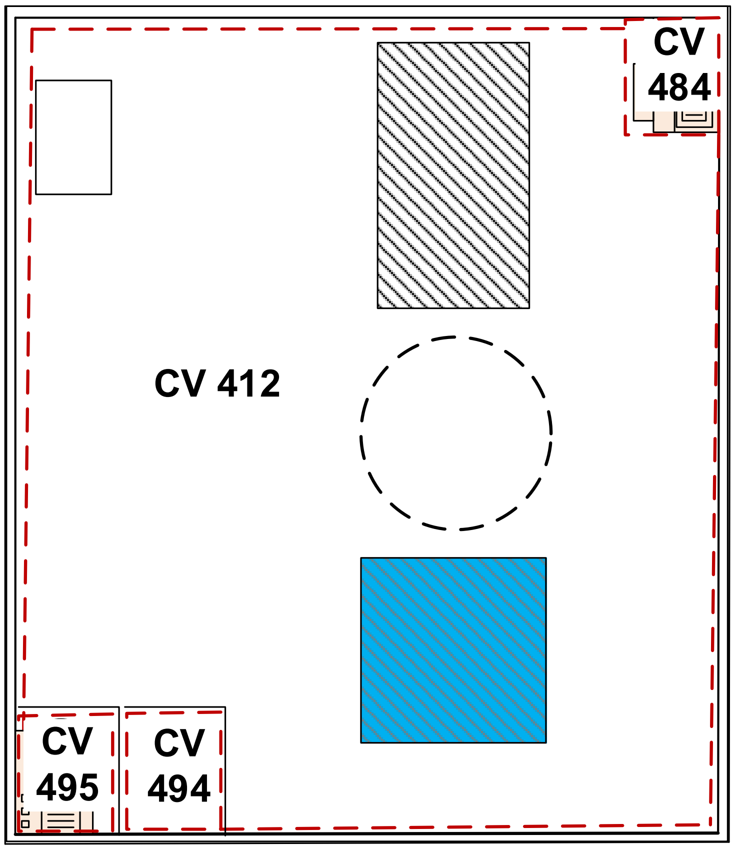
Atmosphere dose rate measured up until February 27

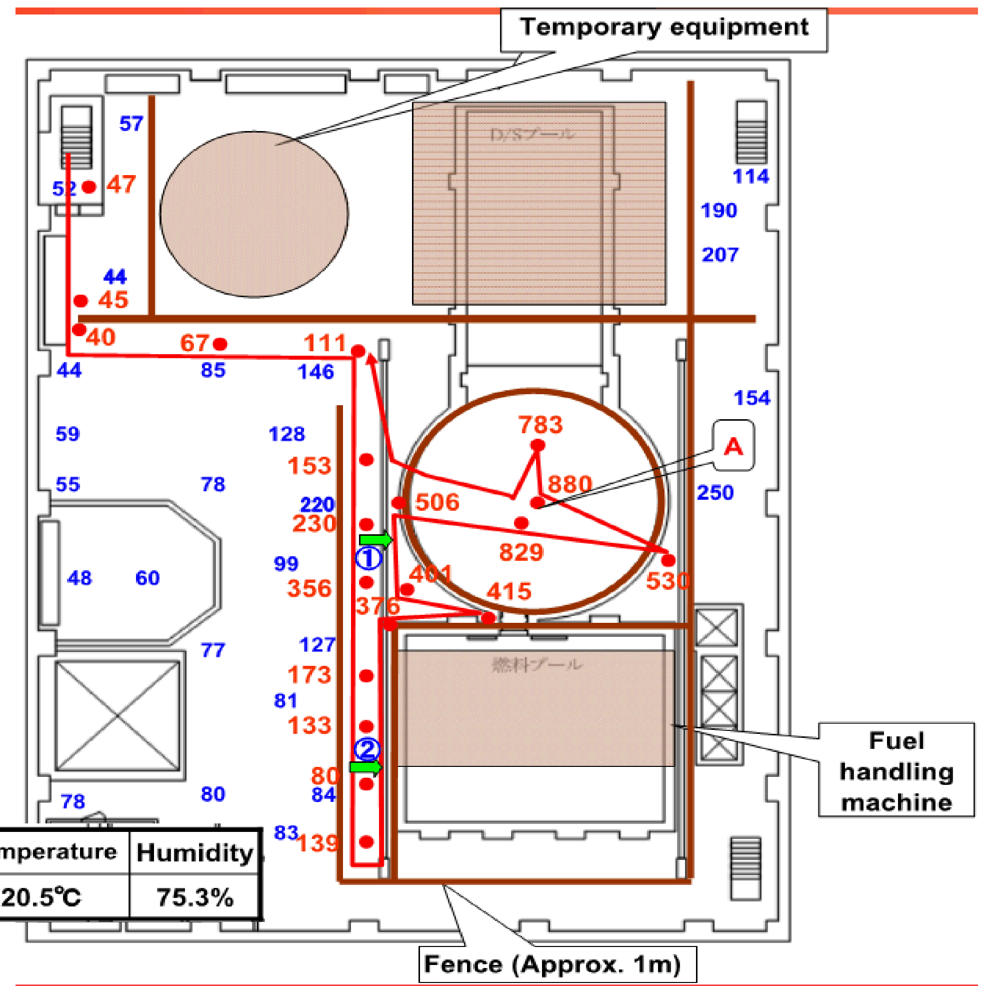
Atmosphere dose rate measured on June 13, 2012

Unit: mSv/h

[Graphic courtesy of TEPCO]

Refueling Bay – Unit 2





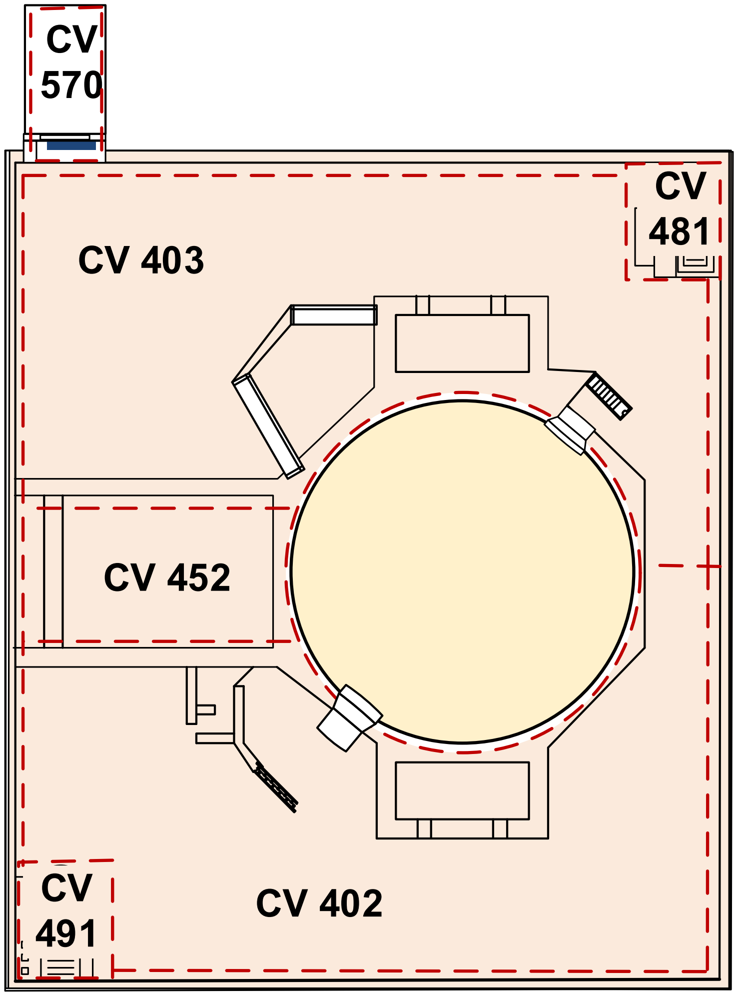
	Temperature	Humidity
A	20.5℃	75.3%

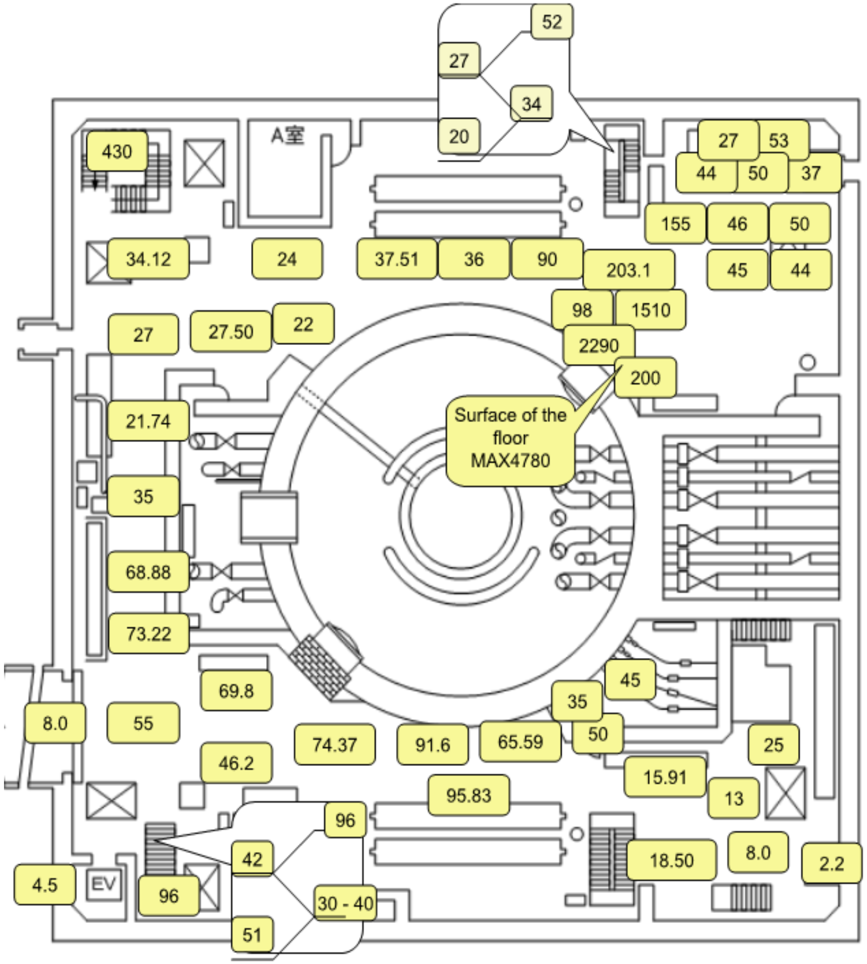
Dose in mSv/hr

[Graphic courtesy of TEPCO]

Fukushima Daichi Unit 3

Floor 1 – Unit 3

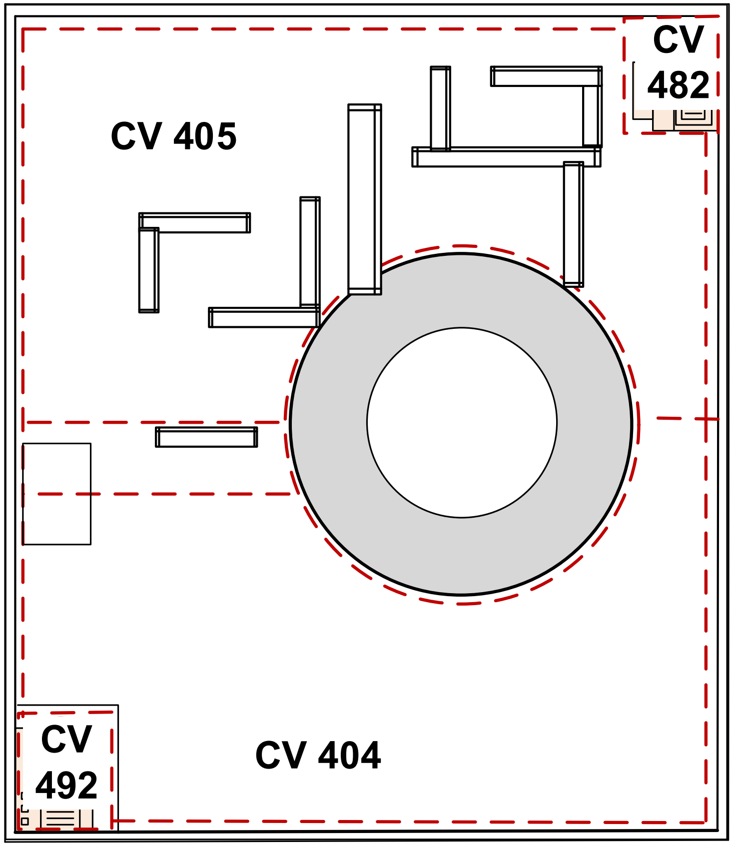


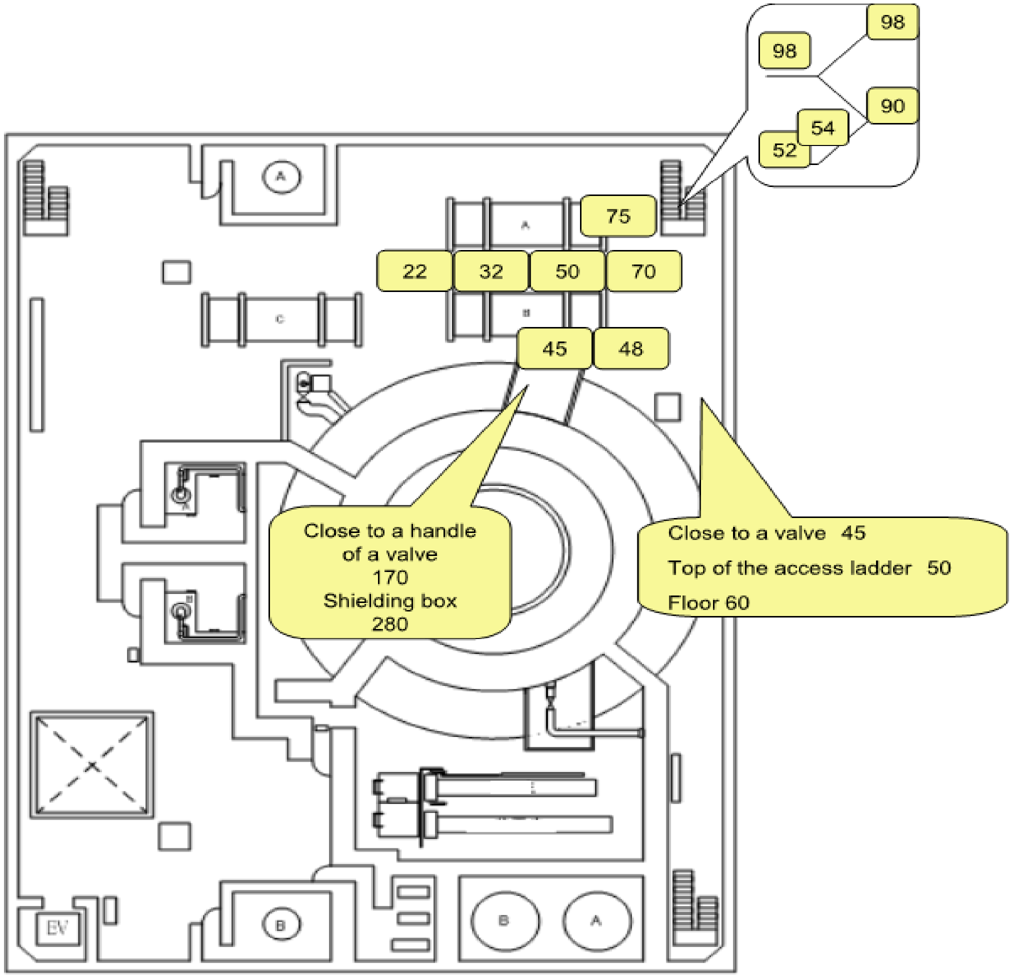


Dose in mSv/hr

[Graphic courtesy of TEPCO]

Floor 2 – Unit 3

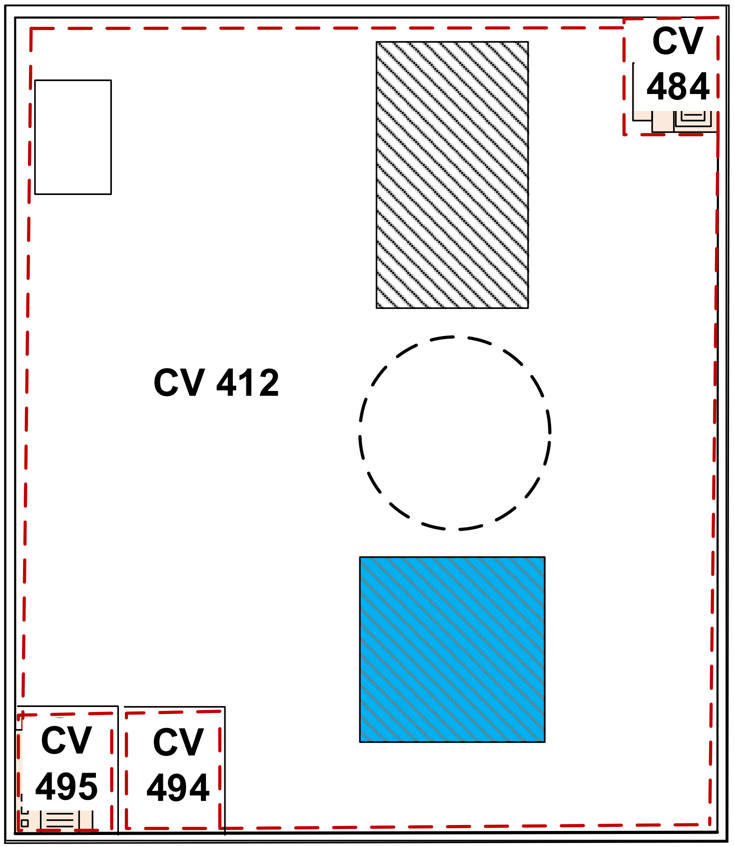


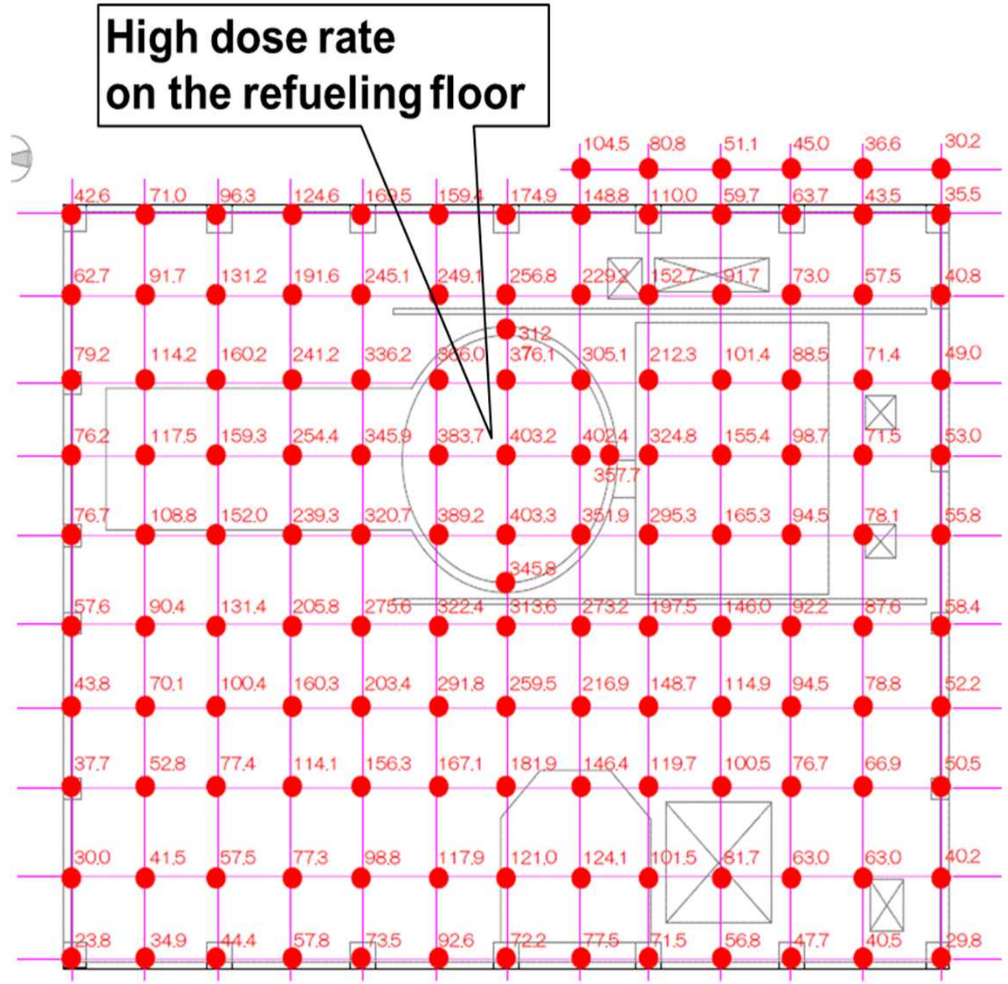


Dose in mSv/hr

[Graphic courtesy of TEPCO]

Refueling Bay – Unit 3





Dose in mSv/hr

[Graphic courtesy of TEPCO]

Severe Accident Source Term Calculation and Analysis

Severe accident source terms

Severe nuclear accident: significant fuel damage, radionuclide release, and transport throughout the plant:

- LWR severe accidents typically involve successful shutdown
- Reactor is assumed to remain shutdown throughout accident
  - LEU fuel lattice with water moderator/coolant: small likelihood of re-criticality or reactivity-driven power increase only if control rods melt and relocate, followed by injection of un-borated water
- With the reactor shutdown, the principal problem of LWR severe accidents is the **radionuclide inventory and associated decay heat**
- Radionuclide transport and corium relocation leads to a moving source of radioactivity
  - First-order impacts on subsequent thermal-hydraulic and dose evaluations

Methods for calculating decay heat and inventory

Potential method	Positive attributes	Negative attributes
Rough approximations • Inventory hand calculations for 'simple' nuclides (e.g. ^{137}Cs) • Formulas for total decay heat • Scaled information from other models	Very quick and simple	Questionable accuracy; information lacks consistency; questionable scaling algorithms (i.e. unique user inventions)
Integral methods/standards e.g. ANS decay heat	Relatively quick and scrutable	Lack consistent nuclide-level inventories; only applicable for integral values (e.g. total decay power); lack of consistent power distributions over RN classes and core
Standalone burnup calculations e.g. ORIGEN-S or CINDER95	Relatively quick; reasonable accuracy	Input development time; still requires neutron transport calculations
Full neutronic simulations Coupled neutron transport (or diffusion) and depletion calculations	High resolution simulations possible; modeling rigor and flexibility	Input development and CPU time; excessive resolution for severe accident needs

SNL approach to decay heat and inventory

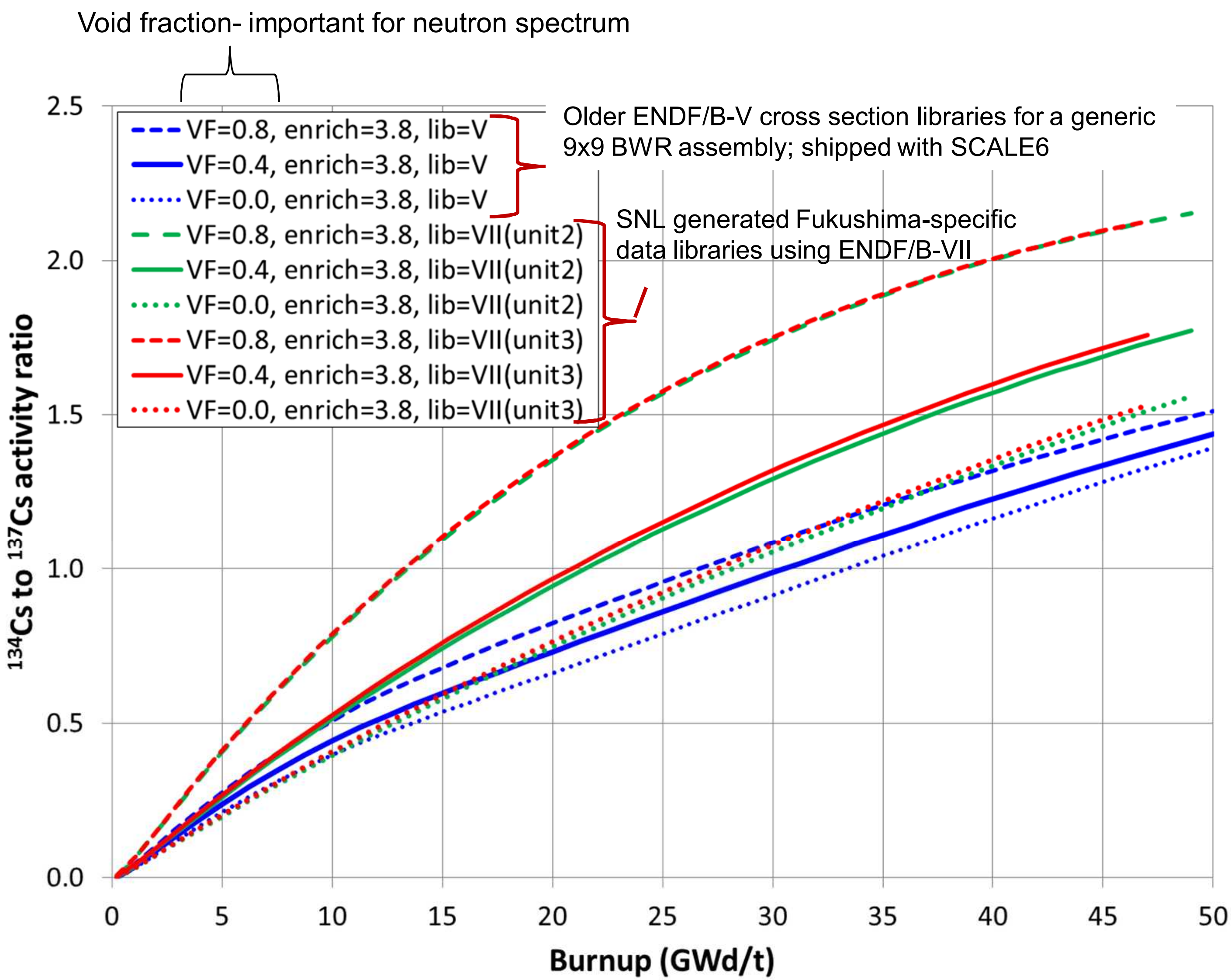
- **(Mostly) use SCALE6, namely TRITON, ORIGEN-S, ARP**
- **Pre-generate cross section libraries using TRITON**
  - Self-shielded 238 group ENDF/B-VII library created using CENTRM
    - CENTRM: fine-energy, 1D discrete ordinate calculation of pin cell
  - TRITON sequence: NEWT+COUPLE+ORIGEN-S
  - Generates collapsed one-group cross sections for ranges of burnups, enrichments, and void fractions (moderator density)
  - Facilitates standalone ORIGEN-S calculations that can still make use of problem dependent cross sections
- **Standalone depletion/decay calculations using ORIGEN-S/ARP**
  - Requires flux-weighted cross sections that reflect the spectral and spatial domain of the core – calculate via TRITON
  - Data generated at discrete levels of levels of burnup, enrichment, and void fraction; ARP interpolates over this data for ORIGEN-S

Other uses of nuclear analyses

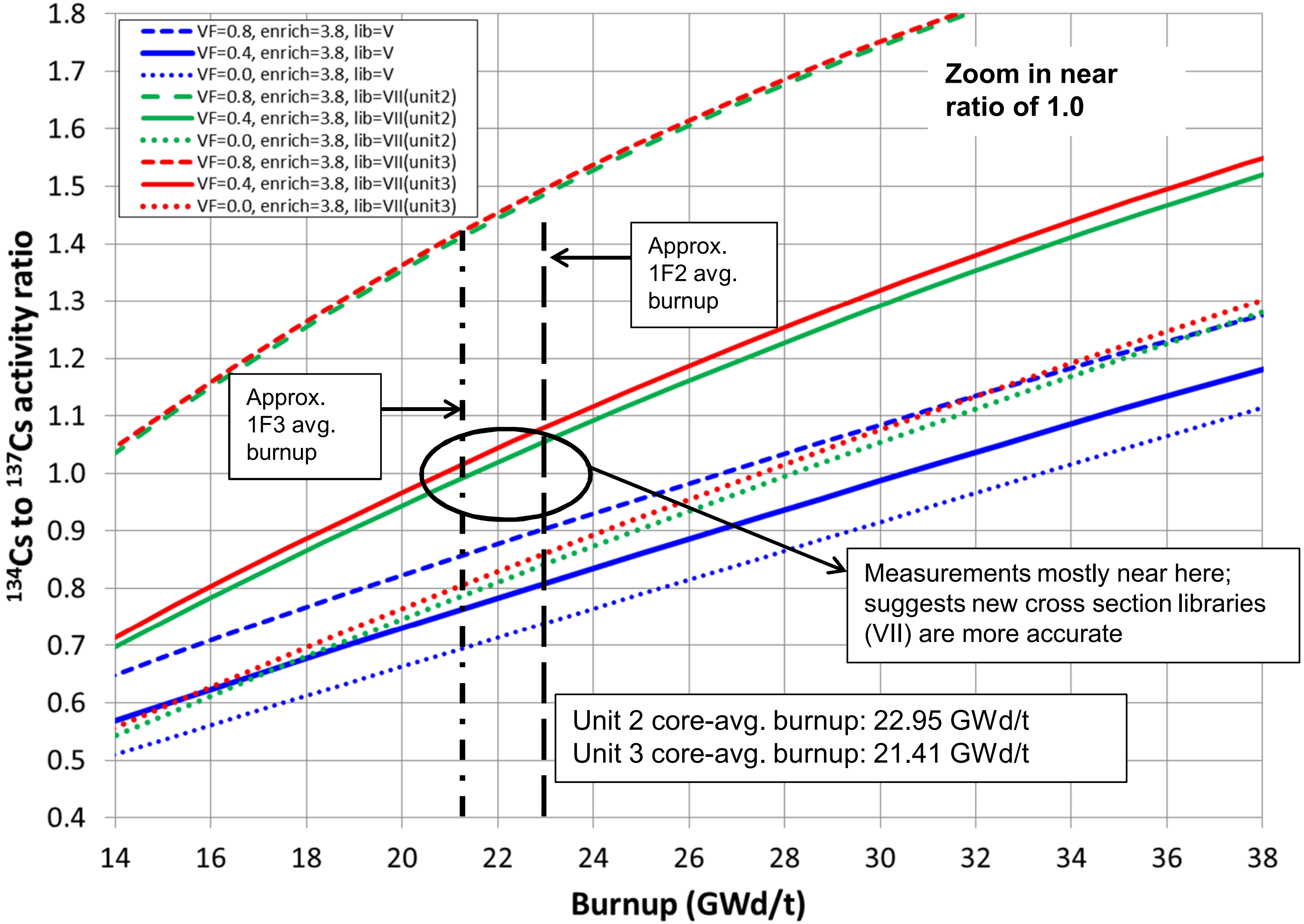
(probably not used directly in *all* SA models)

- **Provide insights on how RN class quantities vary with respect to several variables**
  - Burnup – including spatial distribution over core rings
  - Decay time
  - Reactor type, enrichments, power history, etc.
  - Ex. 1) RN class masses with respect to decay time
  - Ex. 2) Key class/nuclide inventory over 1D core rings
  - Ex. 3) RN class decay powers with respect to decay time
- **Key nuclide characteristics**
  - Ex. 4) $^{134}Cs/^{137}Cs$ ratio
- **Excellent complementary tools for advanced/unique analyses**
  - Uncertainty and sensitivity analyses: vary inventory and decay power
  - BSAF phase 2; containment and plant dose analyses

Cesium Activity Ratios



Cesium Activity Ratios



References:

- State-of-the-Art Reactor Consequence Analyses
  - Project Volume 1: Peach Bottom Integrated Analysis
  - U.S. NRC: NUREG/CR-7110, Vol. 1
- Sandia Report: Radionuclide Inventory and Decay Heat Quantification Methodology for Severe Accident Simulations
  - Jeff Cardoni
  - SAND2014-17667, Unclassified Unlimited Release, September 2014
- Tokyo Electric Power Company Press Releases
  - http://www.tepco.co.jp/en/notice/index-e.html

Backup slides

SNL tools for severe accident inputs

- **<u>Current basic approach</u>: run ORIGEN-S/ARP for each assembly present in the cycle of interest (i.e. cycle with the severe accident)**
  - Use data libraries (via TRITON) to account for problem-dependent details: burnup, enrichment, geometry, MOX, etc.
    - ✓ Why not just do coupled transport/depletion (e.g. TRITON)? -> Need capability to run/re-run many calculations (sensitives/uncertainties)
- **Explicitly model the following characteristics of each assembly**
  - Burnup, power, and decay history (current and previous cycles)
  - Assembly-specific geometry/type (8x8, 9x9, MOX)
  - Assembly-specific enrichment
  - Assembly-specific void fraction – potentially several axial nodes
- **Follow irradiation cycles with a decay calculation with a sufficiently-fine time mesh for decay power curves**
  - Typically 50-100 time steps if linearly interpolating

SNL tools for severe accident inputs [2]

<u>End product from the ORIGEN-S/ARP calculations</u>

Lots of output files containing:

1. **Nuclide masses and activities at moment of shutdown for each assembly (1000+ nuclides)**
2. **Elemental decay power curves (via OPUS) as a function of time after shutdown**
   - Avoids having post-process decay power curves for 1000+ nuclides, for ~100 time steps, and 100+ fuel assemblies – reduces CPU time, RAM and disk space needs

<u>Post-processing is a simple matter of adding everything up:</u>

- Perl script directly generated MELCOR and MACCS input records – lumped RN mass/heat, (MEL)MACCS nuclide inputs
- Summation algorithms are *purposefully* simple

SNL tools for severe accident inputs [3]

Summation algorithms are *purposefully* simple

<u>Lumped RN class masses</u>:

- dominated by stable and long-lived nuclides
  - Why include stable RN masses? → They influence aerosol physics
- Total RN masses vary slowly with time after shutdown
- No shuffling or 'correcting' RN masses to account for decay given a priori knowledge of accident timing
  - This effort has little utility for LWR severe accidents

<u>Lumped RN class decay power curves</u>:

- Elemental-based decay curves directly from ORIGEN-S/OPUS outputs are largely sufficient (*some potential exceptions*)

<u>Model or gain insights on several interesting features</u>

- spatial distributions of RN mass/heat, class powers, etc.

Utility of ORIGEN-S calculations

- **Insignificant CPU time**
- **Reasonable depletion code input and output processing development time**
- **Allows for <u>consistent</u> and reasonably accurate information for severe accident modeling:**
  - Total core decay heat
  - Distribution of decay heat over lumped radionuclide (RN) classes
  - Spatial distribution of decay heat over the core
  - Lumped RN masses *and* nuclide-level inventories
- **Use problem-dependent cross section libraries (e.g. via TRITON) to account for unique burnups, geometries, enrichments, etc.**
  - Since libraries are pre-generated (and interpolated with ARP), ORIGEN-S calculations are very fast even for hundreds of assemblies, hence facilitating sensitivity/uncertainty studies

MELCOR/MACCS nuclear needs

MELCOR

1. Lumped radionuclide (RN) class masses *(chemically/physically similar)*
   - Reflect inventory at shutdown
   - Do not vary with decay time
   - Includes stable nuclides in fuel
2. Lumped RN class decay power curves
   - Each a function of time after shutdown
   - Together with lumped RN masses, determines spatial distribution of decay power
3. Total decay power curves
   - User can optionally scale RN class powers to match a different total power curve; this facilitates sensitivity/uncertainty analysis
4. Construction of unique combination classes (e.g. CsI, Cs_2MoO_4)

(MEL)MACCS

1. Nuclide masses
2. Nuclide activities
   - Masses and activities separated by ORIGEN-S categories – fission products, actinides, light elements
   - Masses and activities reflect moment of shutdown – MACCS performs basic decay calculations for key radionuclides
3. Speciation of RN classes

Note: tends to be a lot of information; lends itself well to **automation** *(work smarter before working harder)*

SNL has developed accurate and automated tools for MELCOR/MACCS inventory and decay heat information to support Fukushima research efforts

SCALE6 in conjunction with automation scripts

- Directly and quickly generate MELCOR/MACCS input records
- Consistent and accurate RN decay heat and inventory information for problem dependent, best-estimate analyses

Ratio dependencies for BWRs – mostly burnup and coolant density (void fraction)

- **Strong function of <u>burnup</u>**
  - The fuel-assembly burnups at shutdown in 1F2/1F3 ranged from ~3 GWd/t to 42 GWd/t
    - Note: each assembly also has axial burnup profiles; peak local burnups are 50-60+ GWd/t
  - Cs-134 is an neutron absorption product of Cs-133 (a fission product); while Cs-137 is a direct fission (and decay) product; note Xe-134 is stable
    - Nuclides produced at different rates
- Strong dependencies on the one-group absorption cross section for Cs-133 given to ORIGEN-S (mostly depends on <u>void fraction</u>)
  - This cross section must be weighted by the problem dependent neutron flux
  - This is a spectrally-spatially integrated value
  - BWR coolant density varies spatially due to bulk boiling, two-phase flow, and axial/radial distributions of void fraction in the core – strong impact on flux
- Second order dependencies:
  - Fuel assembly design
    - 9x9 type in unit 2 vs. slightly different 9x9 type in unit 3
  - Enrichment (assuming it's all LEU), burnable poisons
  - the power history
    - e.g. two assemblies that reach the same total burnup but at different rates will have slightly different $^{134}Cs/^{137}Cs$ ratio

Original Calculations – total core estimates

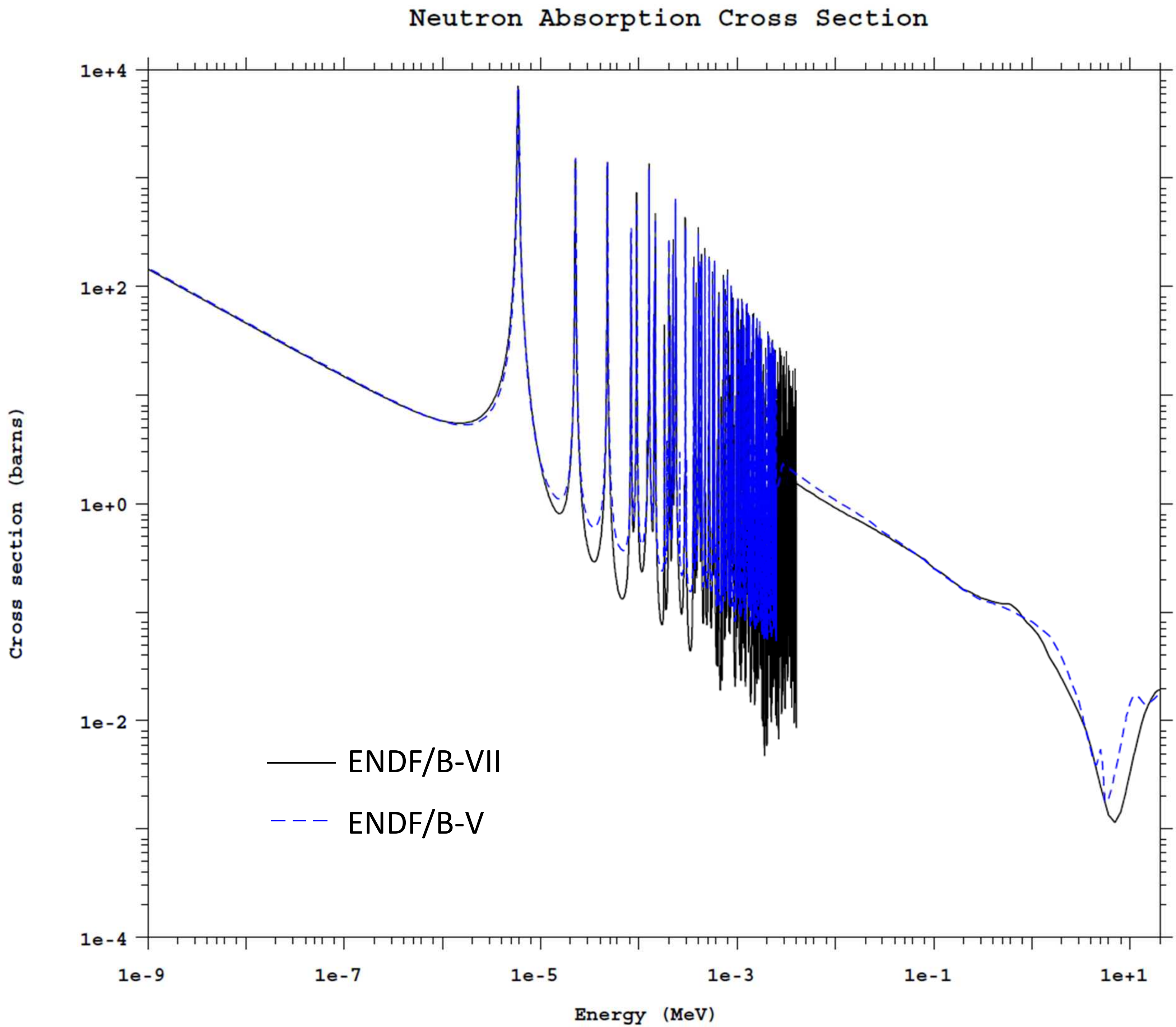
- Calculations are done for each assembly
  - Honors unique characteristics, mainly burnup, of each assembly
- ORIGEN-S/ARP calculations using pre-existing **ENDF-B/V** cross section libraries
  - not fully representative: generic 9x9 BWR assembly
  - decay data from ENDF-B/VII still used
- Only intended for initial severe accident models
- Uses fuel assembly-specific information from TEPCO (burnup, power fraction, etc.)
- Avg. void fraction of 0.4 assumed for each assembly

ORIGEN-S standalone with pre-generated ENDF-B/V cross sections and decay data from ENDF-B/VII.1

	Masses (g)		Activities (Bq)		Mass ratio	Activity ratio
	Cs-134	Cs-137	Cs-134	Cs-137		
Unit 1	3.97E+03	6.36E+04	1.90E+17	2.05E+17	0.063	**0.930**
Unit 2	5.17E+03	7.90E+04	2.48E+17	2.54E+17	0.065	**0.973**
Unit 3	4.54E+03	7.41E+04	2.17E+17	2.39E+17	0.061	**0.911**

Revised calculations

- Use new ARP libraries generated from Fukushima-specific fuel assembly models
  - Made via 2D neutron transport and burnup via NEWT/COUPLE/ORIGEN-S (the TRITON sequence)
  - Use newer ENDF-B/VII cross sections
  - Models the unique Fukushima fuel assembly geometry and materials
    - Including the MOX in 1F3
- Possibly take into account axial void fraction effects
- **Same calculation process otherwise as before**
- **These will be completed shortly**



Neutron Absorption Cross Section
1e+4
1e+2
1e+0
1e-2
1e-4
Cross section (barns)
1e-9
1e-7
1e-5
1e-3
1e-1
1e+1
Energy (MeV)
ENDF/B-VII
ENDF/B-V