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Source Term Dispersion Analysis and Construction of the Risk Map around the Peach Bottom Unit-2 Plant Using the ASTEC and JRODOS codes

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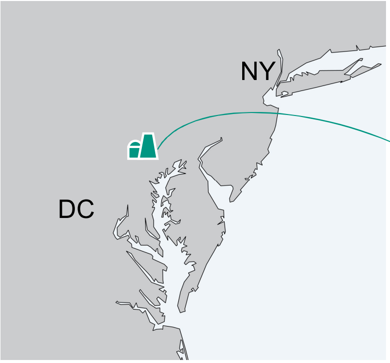
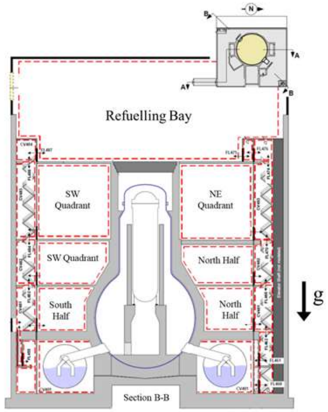
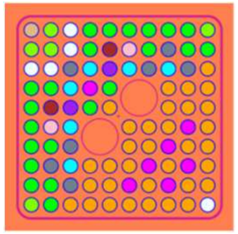
- CASMO Model of the Fuel Assembly
- ASTEC Model of the Plant
- Selected Transient : ST-SBO and Results
- ST-SBO Radiological Impact with JRODOS
- Extension of the Statistical Analysis to Risk Map
- Conclusion and Outlook

Peach Bottom Unit-2 Nuclear Power Plant



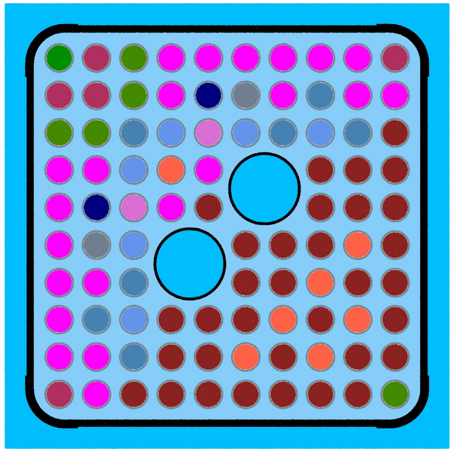




Global Nuclear (A General Electric Sub-Company) Fuel Assembly GE14 10x10

- The Plant is located on East Coast of the U.S.
- General Electric BWR4 Mark-1 Design.
- Operational licence received in 1973.
  - First Authorized Power level 3293 MWth
  - Power upgrade (1994) 3458 MWth
  - Power upgrade (2014) 3951 MWth
  - Power upgrade (2017) 4016 MWth
- Reference study** by U.S.NRC states GE14 10x10 was used for the analysis of the Peach Bottom (in 2013).
- In portfolio of Global Nuclear Company GE14 10x10 is still most recent 10x10 assembly for BWRs.

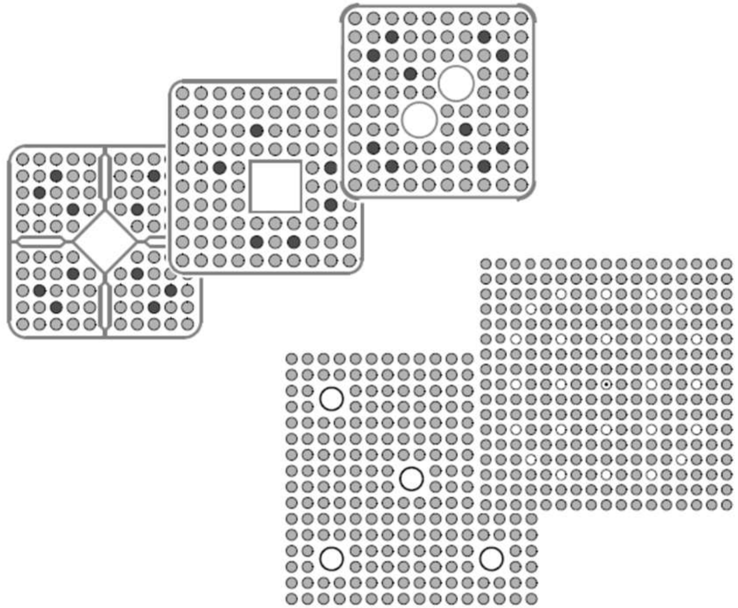
**Bixler, N., Gauntt, R., Jones, J., Leonard, M., State-of-the-Art Reactor Consequence Analysis Project, Volume 1 Peach Bottom Integrated Analysis, NUREG/CR-7110, 2013



CASMO Model of the GE14 10x10 Fuel Assembly

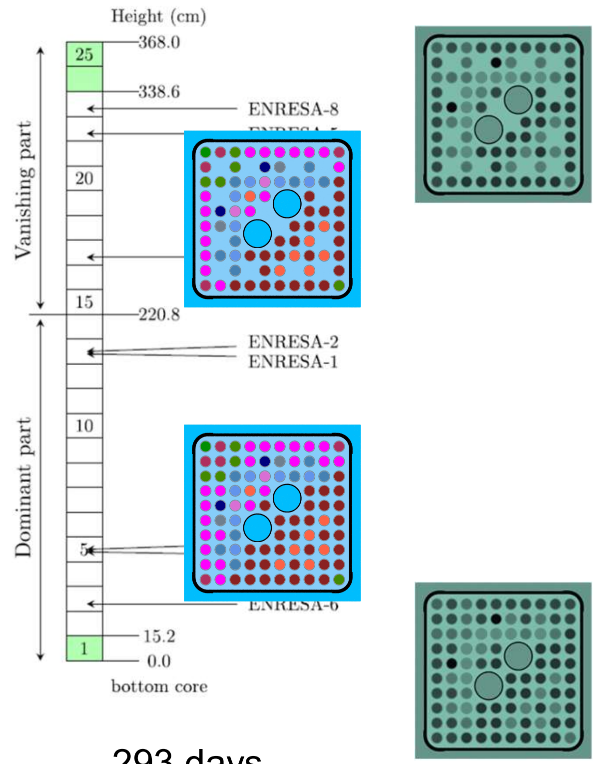
Computational Tool: CASMO

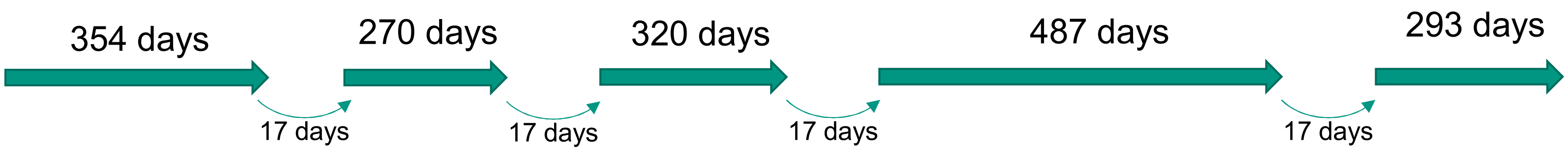
- Advanced lattice physics code for light water reactors.
- Multigroup, two dimensional transport code for the burnup analysis.
- Symmetric and anti-symmetric layout of the light water reactor fuel assemblies can be handled.
- The code has flexibility for storage pool and transportation cask criticality analysis as well.



CASMO Model of the GE14 10x10

- *Between July 2000 – 28 May 2005 one GE14 10x10 fuel assembly was burned in Forsmark 3 NPP.
  - 1792 Days (from 1st of July)
  - 5 Cycles (Beginning of Cycle 16 → end of cycle 20)
  - Rod avg. Burnup 41 MWd/kgU
  - Peak Burnup 56 MWd/kgU
- Extracted one fuel rod from the assembly and samples from the rod investigated (ENRESA samples)
- Based on the known informations of the ENRESA samples, and GE14 10x10 design CASMO input deck was constructed.
  - Assumptions have been made on the void fraction profile, specific power of the assembly and burning period.

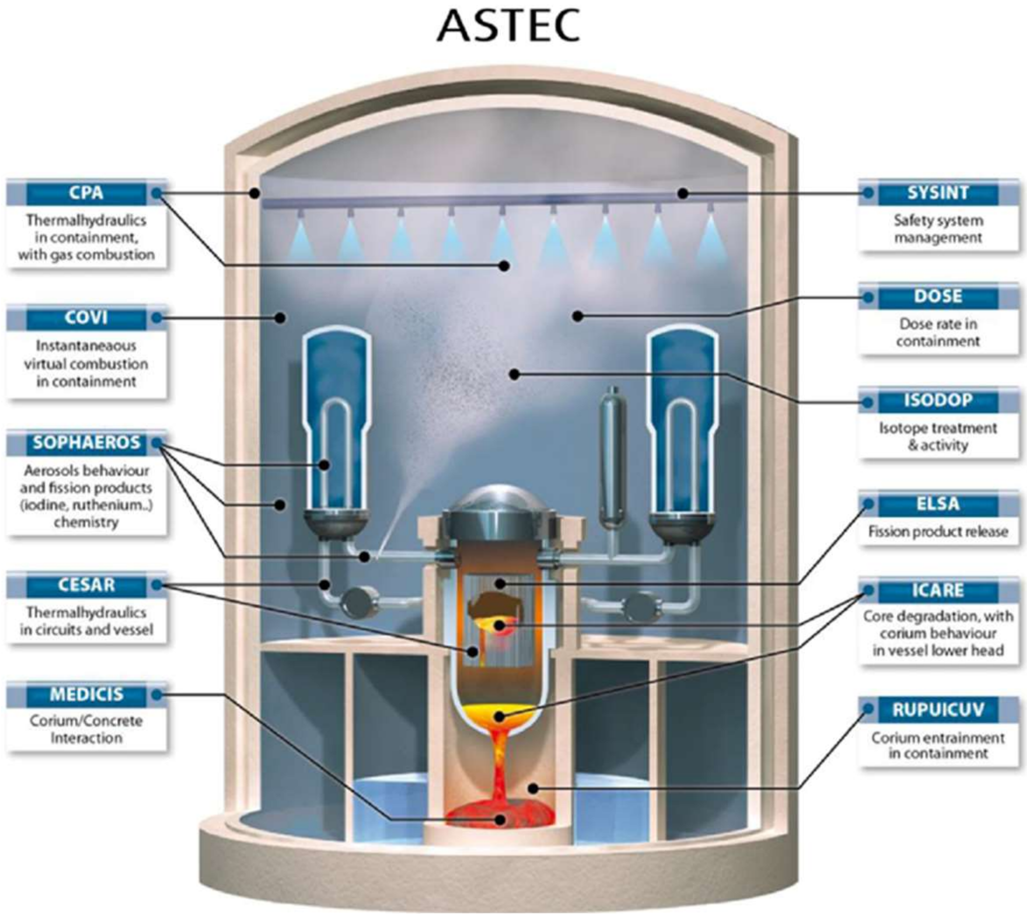




ASTEC Model of Peach Bottom Unit-2 with GE14 10x10 BWR Fuel Assembly and Jet Pump

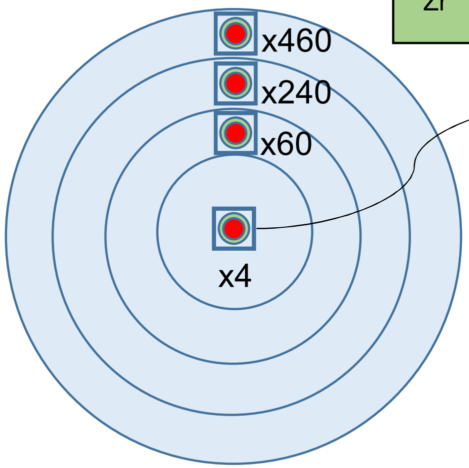
Computational Tool: ASTEC

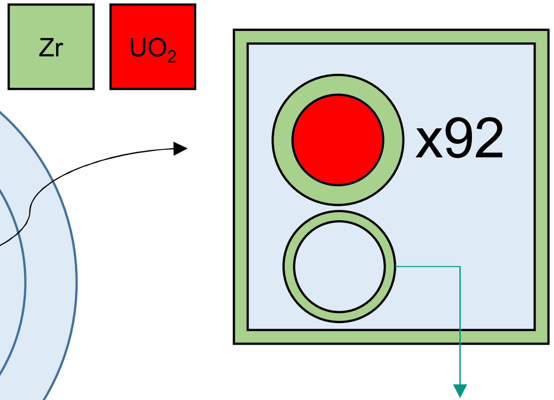
- Accident Source Term Evaluation Code (ASTEC)
- European reference severe accident analysis tool.
- Mechanistic approach of the code allows modular structure of different zones of the plant.
- Starting from the reactor scram up to fission product release to the environment can be handled with the code.



The 11th European Review Meeting on Severe Accident Research (ERMSAR2024), KTH, Stockholm, Sweden, May 13-16, 2024

ASTEC Model of the Peach Bottom Unit-2 Updated Core



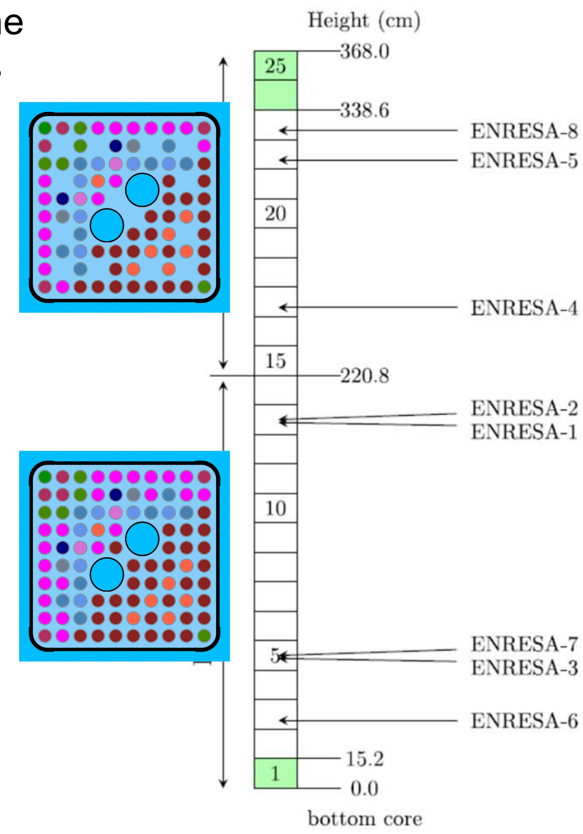


Water rod covers 8 fuel rods area

There are part length rods in the GE14 10x10 model but all rods considered as full length.

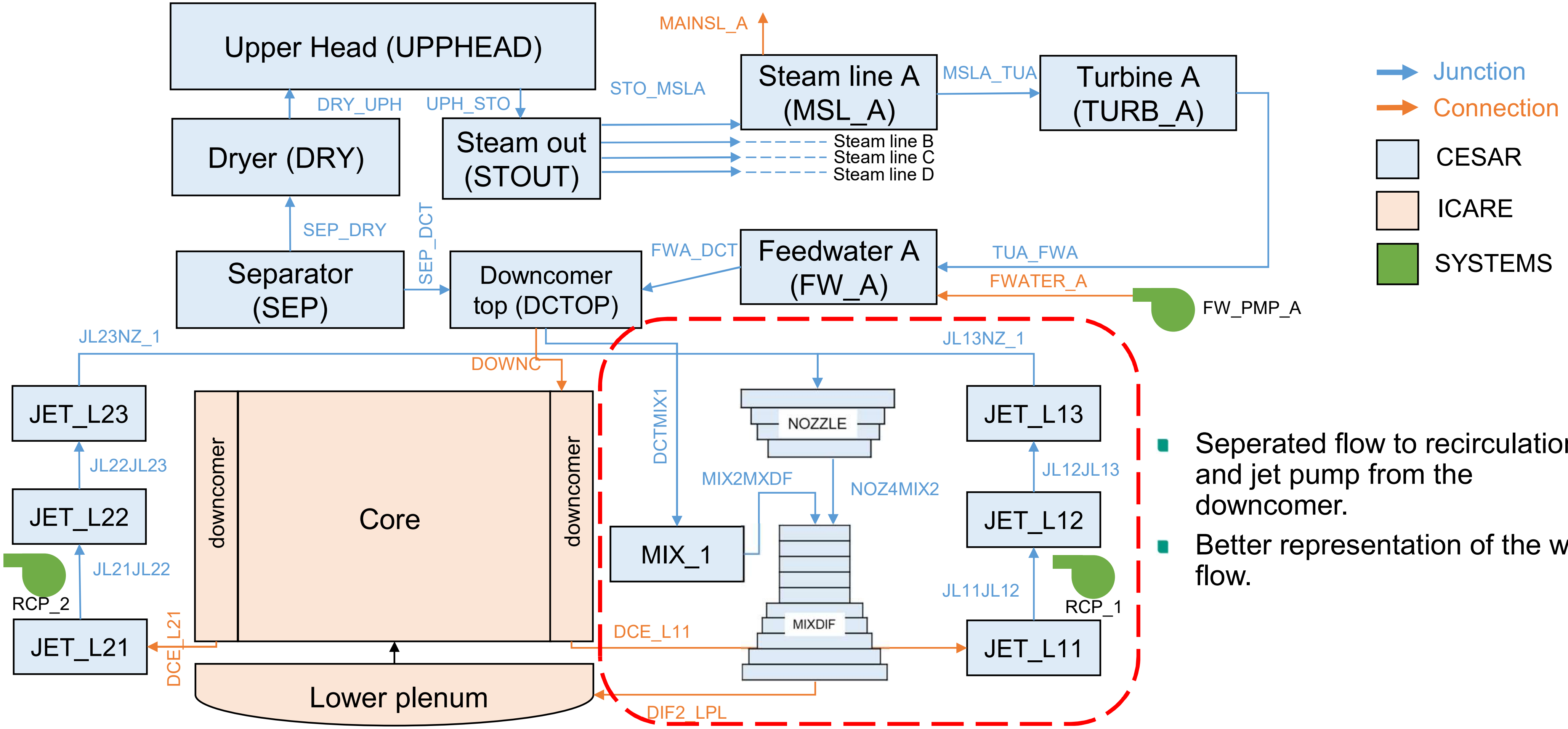
```
STRU NT_HEAT
      UNIT …
      PNOM …

      SR1 POWER
        …
        …
      SR1 PROF
        …
        …
```

Allowed only one NT_HEAT structure



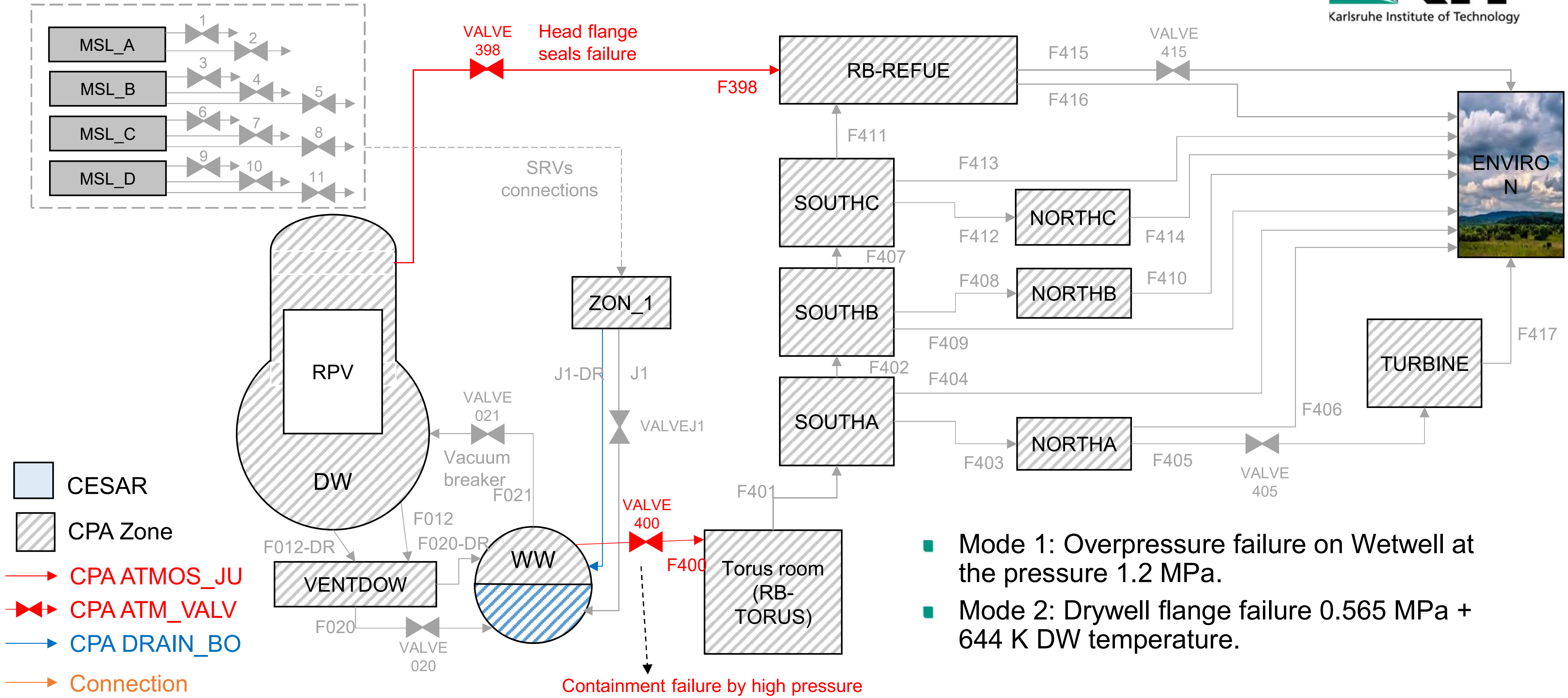
- Number of Fuel Assembly = 764
- Radius of fuel pellet = 4.38 mm
- Clad internal radius = 4.47 mm
- Clad external radius = 5.13 mm
- Water rod internal diameter = 23.21 mm
- Water rod external diameter = 25.21 mm
- Fuel channel inner length side = 134.06 mm
- Canister length = 4119.0 mm

ASTEC Model of the Peach Bottom Unit-2 Updated RPV



- Seperated flow to recirculation and jet pump from the downcomer.
- Better representation of the water flow.

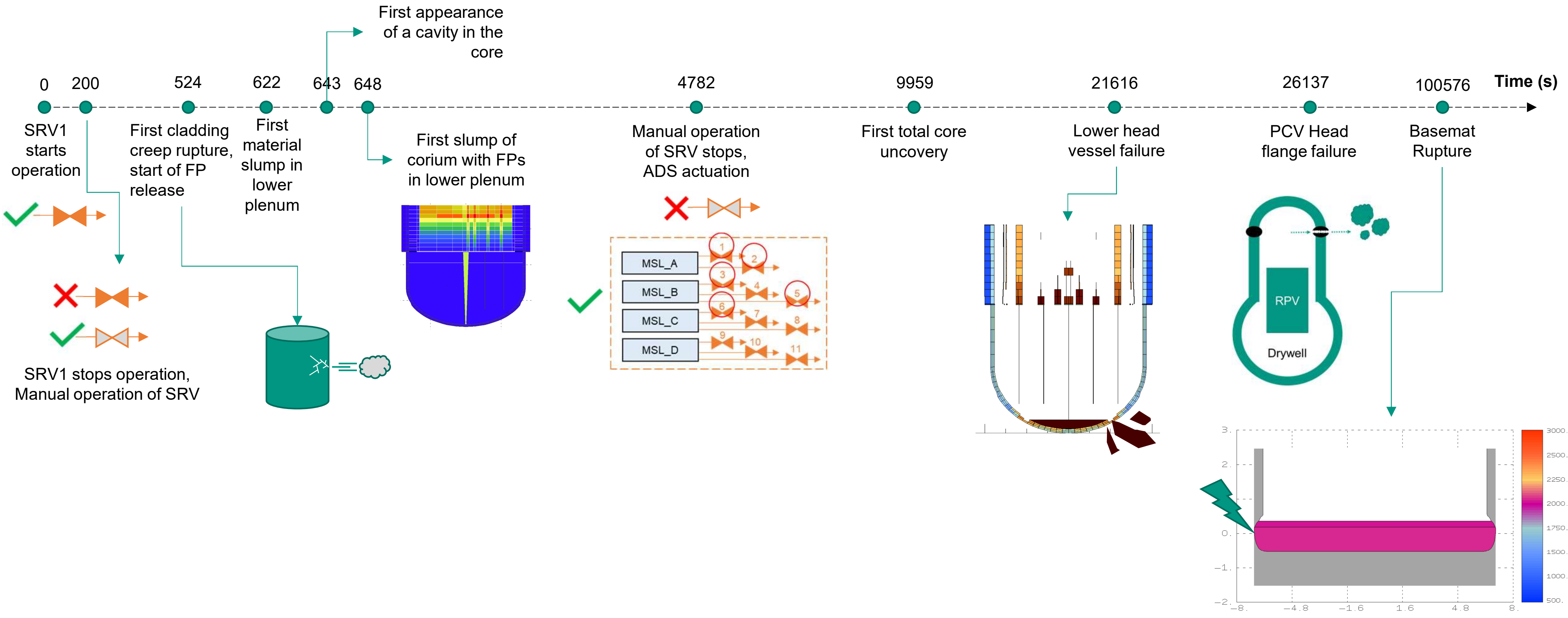
ASTEC Model of the Peach Bottom Unit-2 Containment



- Mode 1: Overpressure failure on Wetwell at the pressure 1.2 MPa.
- Mode 2: Drywell flange failure 0.565 MPa + 644 K DW temperature.

Selected Transient : Short Term Station Blackout and Results

Sequence of Events PB2 ASTEC Model ST-SBO Scenario



The 11th European Review Meeting on Severe Accident Research (ERMSAR2024), KTH, Stockholm, Sweden, May 13-16, 2024

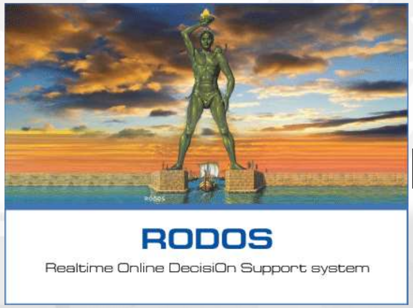
Fission Product Inventory and Retention Fractions

Elements	Inventory (kg)	Primary	Containment	Environment
Kr	68.60	0.105	0.499	0.264
Xe	1025.79	0.105	0.499	0.264
I	36.66	0.172	0.664	0.025
Sb	2.81	0.115	0.572	5.38E-4
Te	93.41	0.141	0.449	3.95E-4
Ag	7.30	0.206	0.657	5.53E-4
Cs	556.56	0.185	0.698	6.77E-4
Rh	79.54	9.85E-5	2.02E-4	1.66E-8
Mo	644.51	0.096	0.402	2.78E-4
Ba	290.09	0.230	0.323	8.08E-5
Sr	166.72	0.152	0.029	6.59E-6
Y	87.65	9.72E-5	1.98E-5	6.21E-8
Nb	3.80	0.0	0.0	0.0
Ru	479.17	0.088	0.160	1.98E-5
Ce	502.68	0.128	0.115	2.71E-5
La	236.88	0.067	0.031	7.09E-6
Eu	27.98	0.049	0.021	4.24E-6

At the end of the simulation released activity to the environment = 2.190E+18 Bq

Fukushima = ~ 6.3E+17 Bq
Chernobyl = ~ 14E+18 Bq

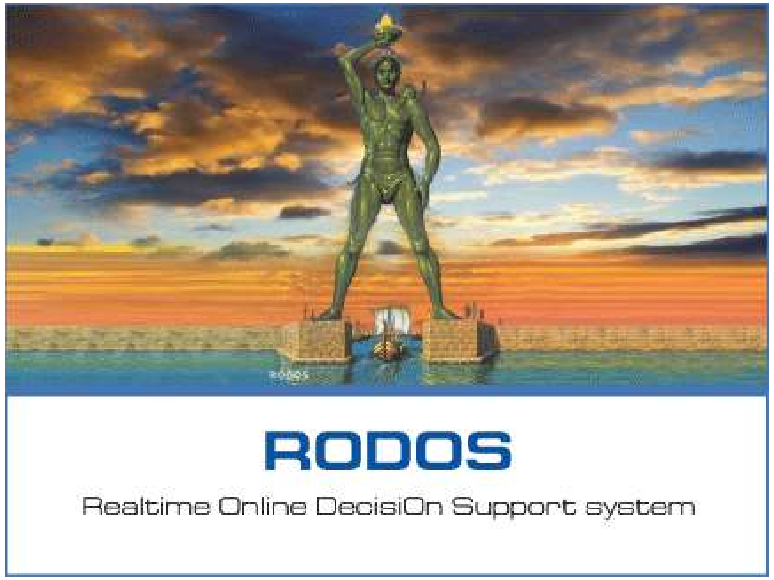
Source term for JRODOS



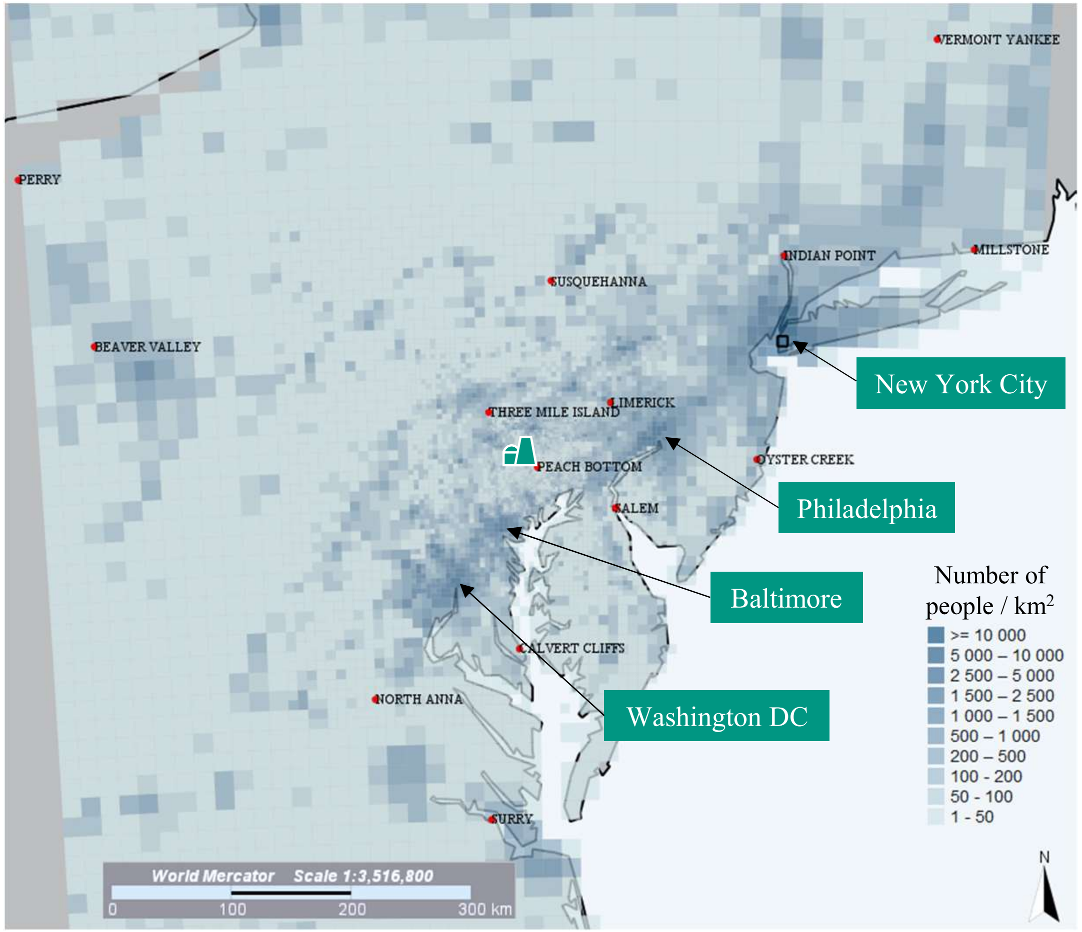
Radiological Dispersion Analysis with JRODOS

Computational Tool: JRODOS

- Java Based Realtime Online Decision Support (JRODOS) System.
- System provides the necessary information to take action to protect society and the environment.
- Starting from the fission product release and exposing the public in possible transport paths for short term and longer term effects can be assessed.
- Regional, national and international emergency management decision can be build by joint efforts.



JRODOS Dispersion Model (ST-SBO) 1/2



- Mesh construction around the plant for radius of 400 km.
- 24 hours calculation.
- No emergency countermeasures taken into account.
- Source term taken from ASTEC simulation environment release results.

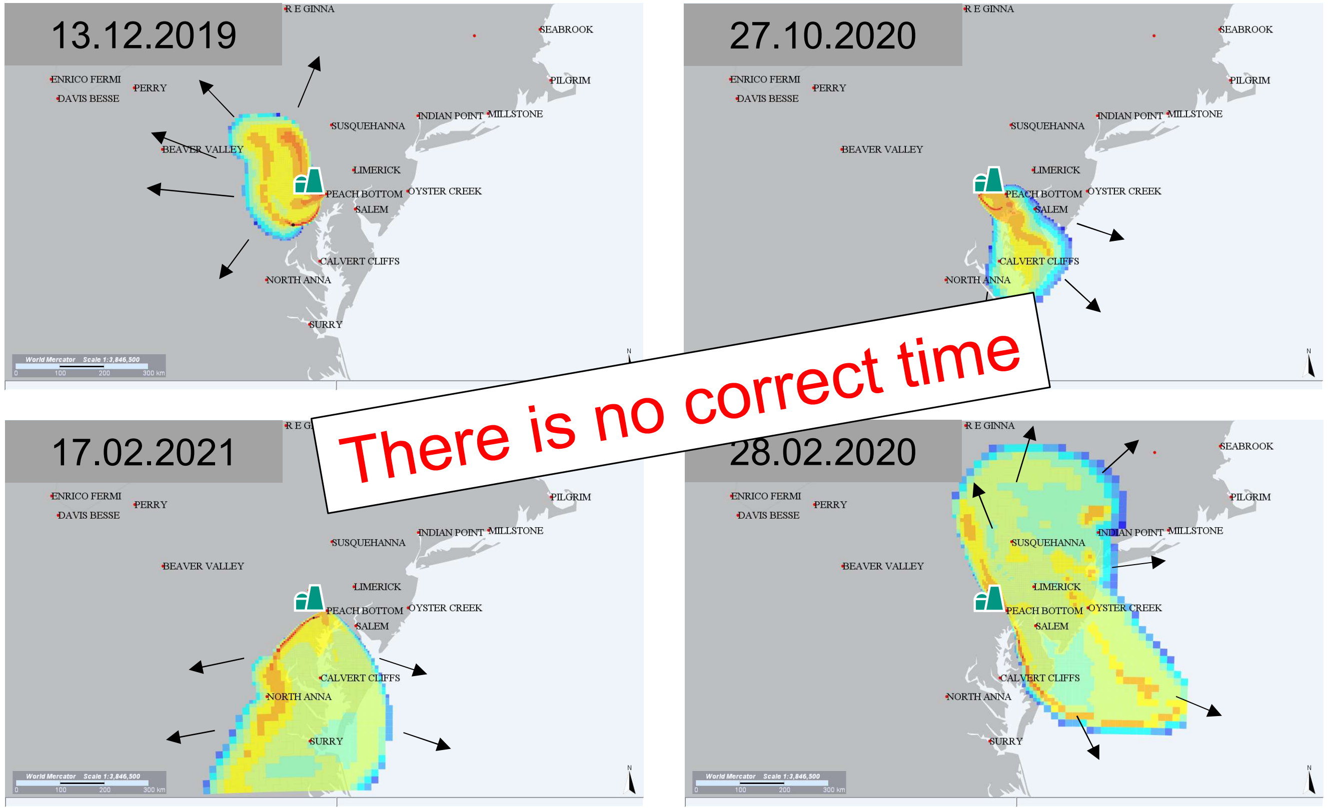
WHERE to look at?

- Most populated cities around:
  - **New York City** : meshes 5554, 5606, 5658, 5607, 5771
  - **Philadelphia** : meshes 3209, 3240, 3241
  - **Baltimore** : mesh 2594
  - **Washington DC** : mesh 2064, 2065

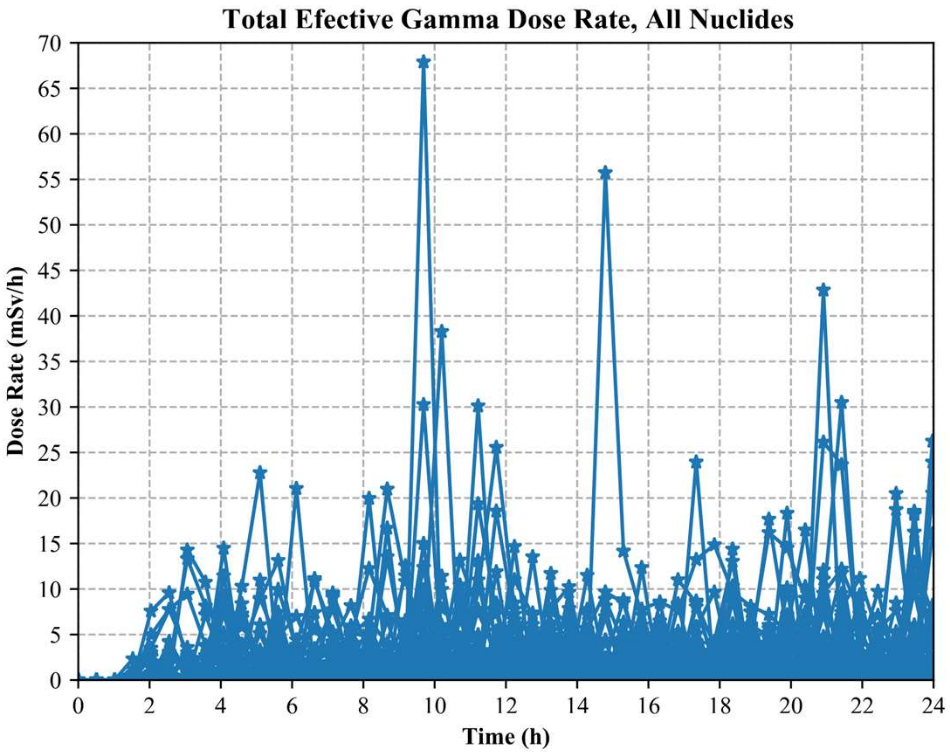
JRODOS Dispersion Model (ST-SBO) 2/2

WHEN is the correct time for
a simulation?

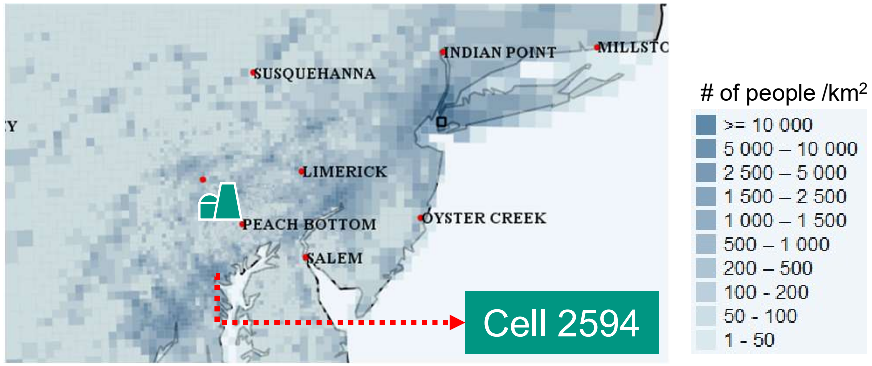
- Same source term for the examples.
- Results are highly disperse.
- There is no correct time to consider among the interested meshes.
- How to proceed?



Statistic Sampling of Source Term with JRODOS 1/3



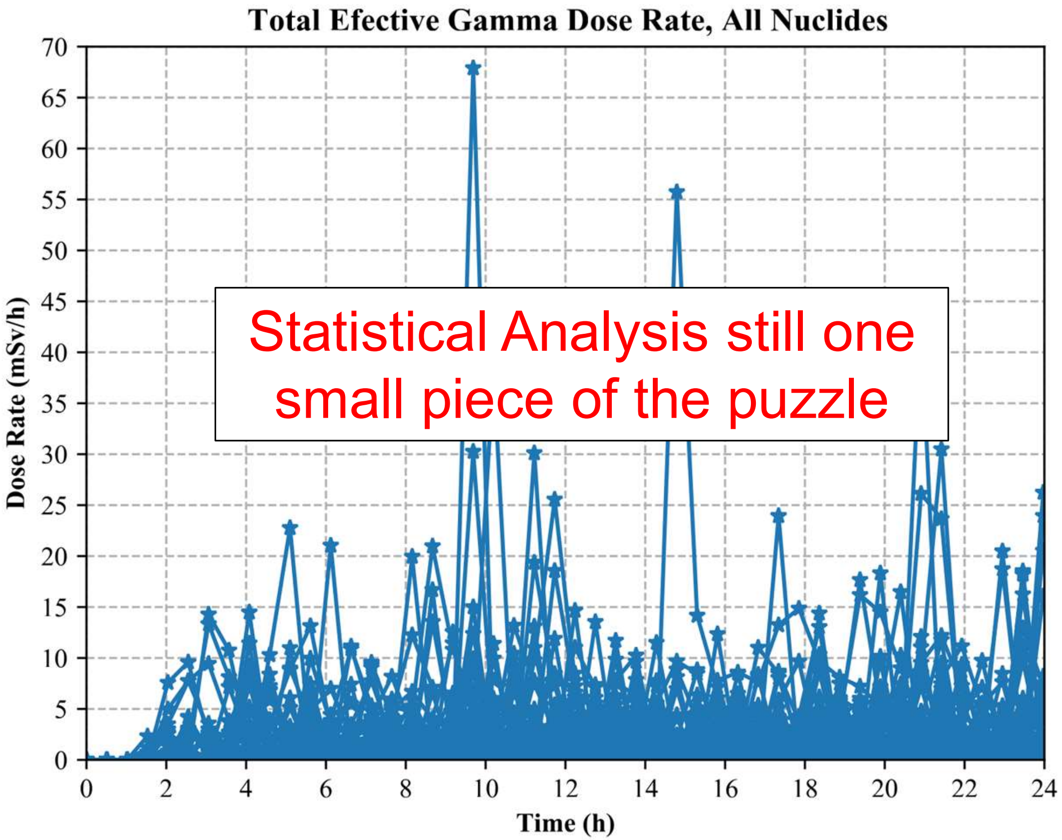
- Making large set of simulation instead of one.
- Multiple runs of 24 hours analysis carried out:
  - 3 years (01.01.2019 – 31.12.2021) = 1095 simulations
- Starting time for the analysis of each day is selected randomly.
- The highest dose rate was recorded:
  - Cell = 2594 (Baltimore)
  - Value = 67.89 mSv/h
  - Release Start Date = 13.12.2019 20:41



U.S. annual limit for whole body total effective dose (*10 CFR 20*)

Radiation worker	*Member of public*
50 mSv/yr	1 mSv/yr

Statistic Sampling of Source Term with JRODOS 3/3



Statistical Analysis still one small piece of the puzzle

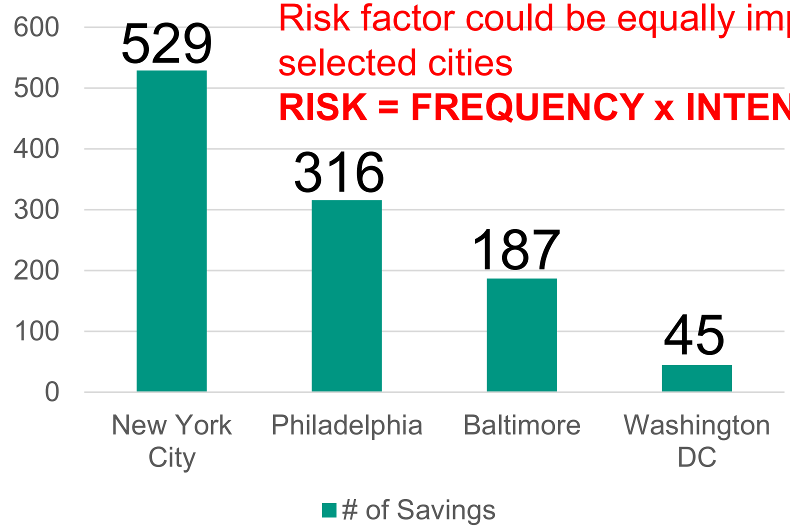
24h calculation each day for 3 Years (01.01.2019-31.12.2021)

Highest dose rate was recorded:

Cell = 2594 (Baltimore)

Value = 67.89 mSv/h

Release Start Date = 13.12.2019 20:41



Risk factor could be equally important for selected cities

RISK = FREQUENCY x INTENSITY

Randomness over Statistical Results of JRODOS 1/2

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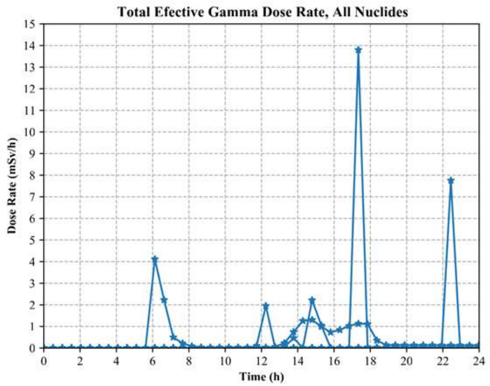
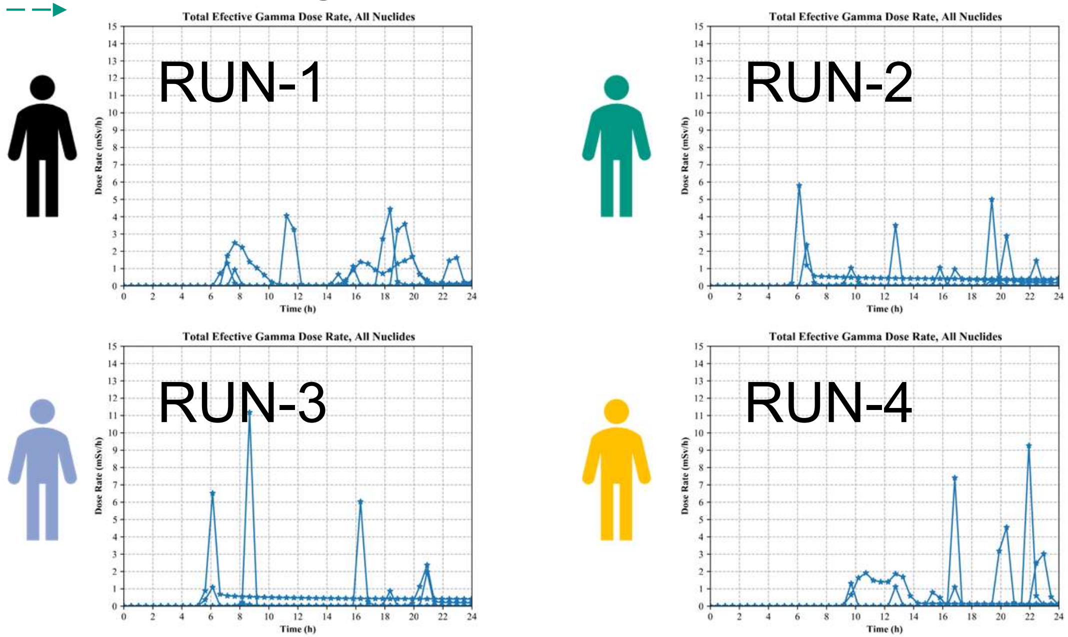
A sample statistical analysis



- Month of February.
- One day simulations for each 28 days of the month.
- Randomly selected the starting point of the release.
- Only one mesh is considered to keep the analysis simple.

Reproducing the statistical result with same input:

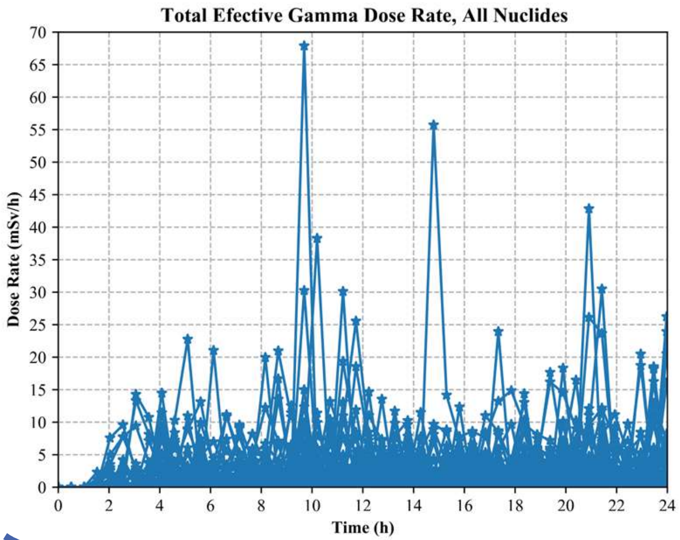


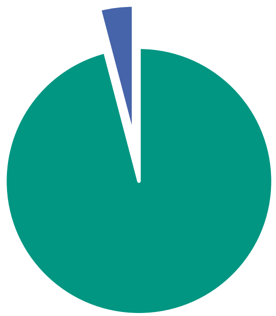
- Depending on the random selection, maximum recorded dose rates can vary more than 100%.
- The one can not conclude a possible consequences without considering all possible scenarios.

Randomness over Statistical Results of JRODOS 2/2

WHAT DO WE HAVE?

- Statistical analysis over the 3 years.
- Random selected starting time for each day.
  - Statistical analysis needs to be enlarged.





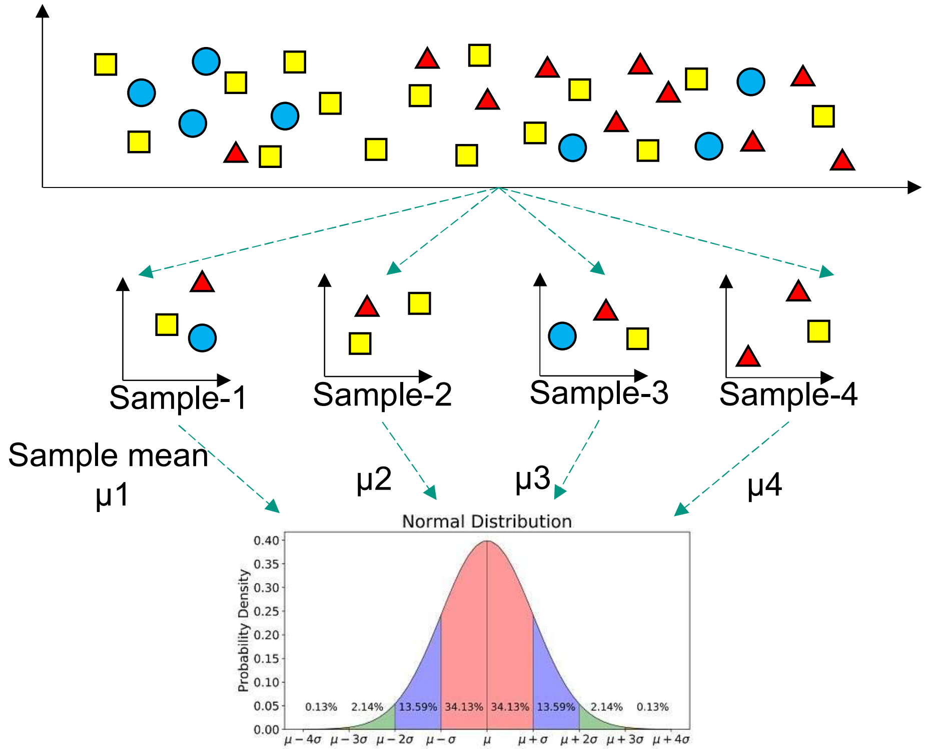
All possible scenarios

HOW TO EXPAND THE DATABASE?

- Resolution of the JRODOS is a minute.
  - One day = 1440 minutes
  - There are 1440 possible starting points in a day.
- Implementing every possible starting point is highly expensive in terms of cpu time.
  - 3 years of statistical analysis run takes about 24 hours.
    - Each day 1 starting point.
  - Considering every possible starting point requires 1440 times of repeating one day simulations.
  - 24 hours x 1440 ≅ 4 years of cpu time
  - Cases which considers longer duration of releases would take longer cpu time.

Central Limit Theorem Application

- 24 hours x 1440 ≅ 4 years of cpu times is expensive in terms of resource and time and deals with very large amount of data.

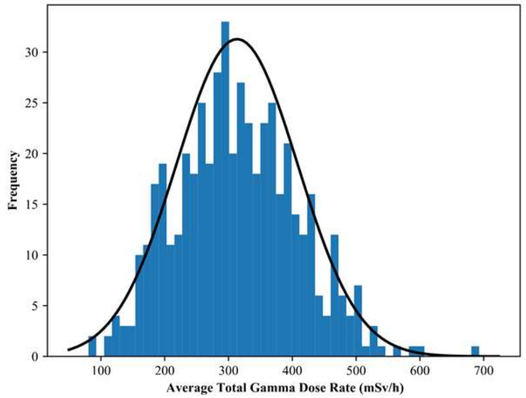


- How to estimate an information about a large dataset by using smaller sizes of samples?

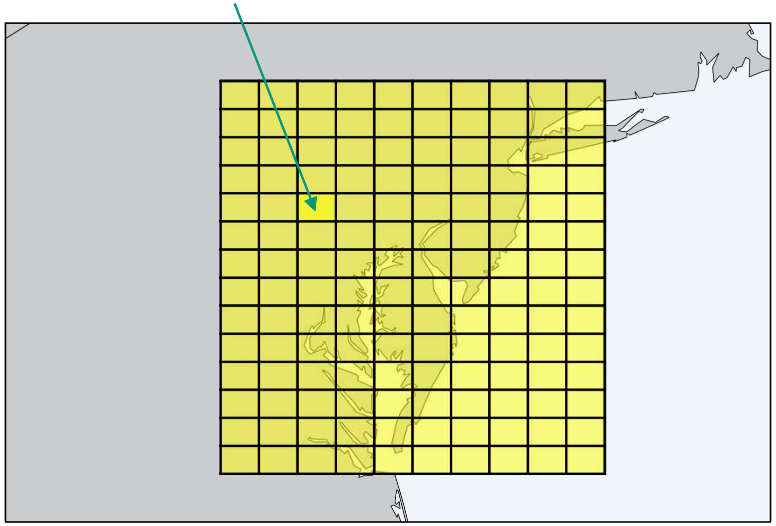
Central Limit Theorem

- Collect samples from the population → combine the informations from samples to draw conclusion about the population.
- Sample mean distributions of any population (regardless of its shape) will approximate to normal distribution.
- Estimation of the average value of large dataset by using smaller samples.
- If the sampling is large enough:
  - Mean of the sampling distribution = population mean

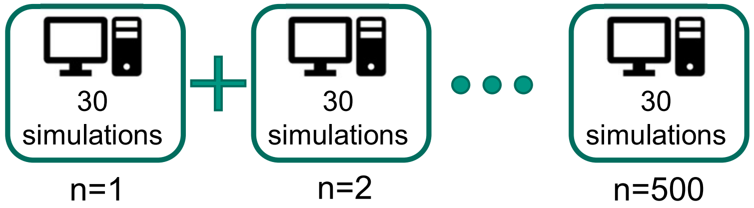
Production of Sampling Mean Distribution



Sampling average distribution on an example mesh



- Year 2021 was selected.
- Each season seperately considered.
  - Winter, Spring, Summer and Autumn have distinctive weather conditions.
  - 500 groups each contains 30 sample simulation for each season.



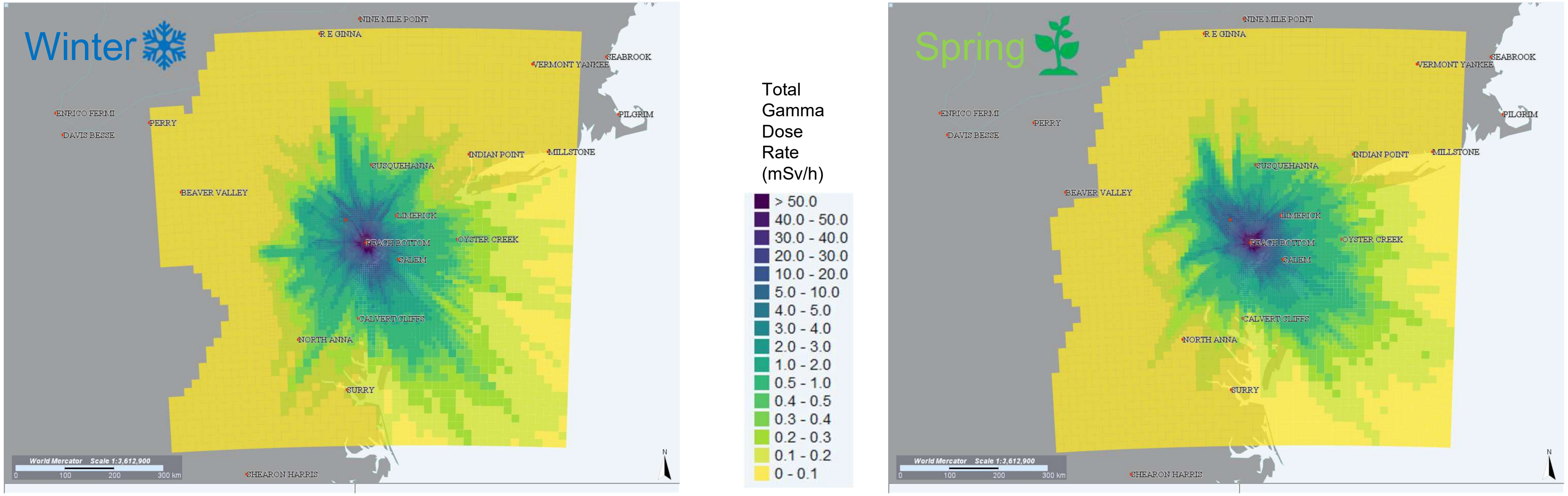
  - 15.000 simulation for each season → 60.000 simulations for a year.

- Assumed to be perfect normal distribution which means:

Mean of the average sampling distribution
=
Mean of the population distribution

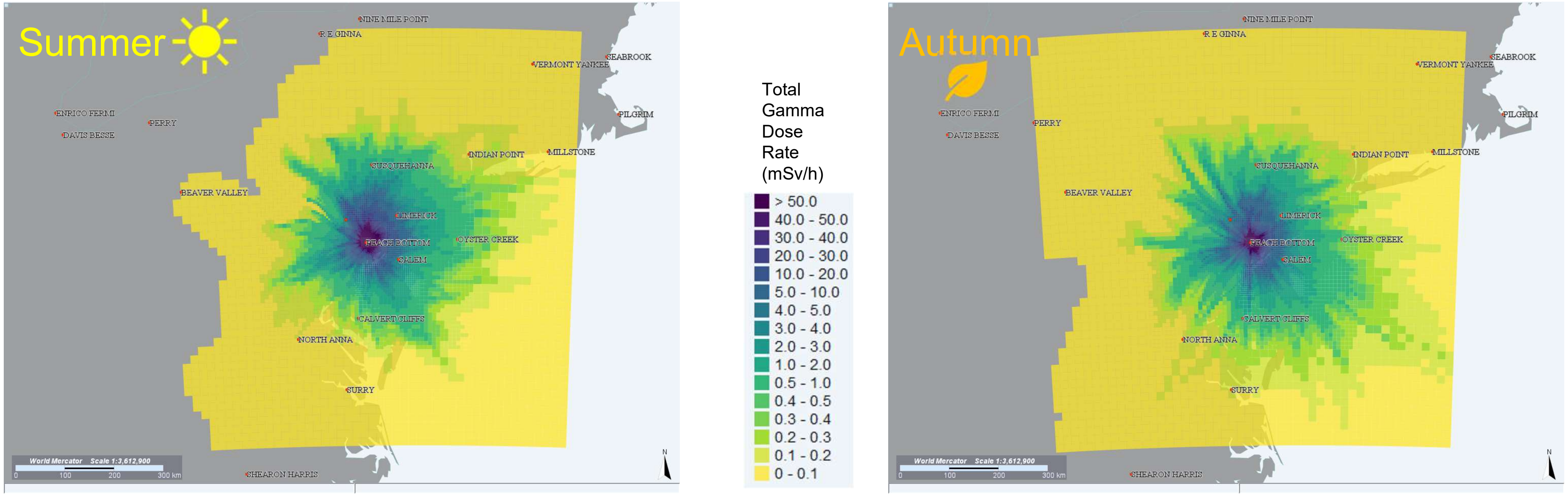
- For each mesh same assumption followed and mean value recorded to create the map.

Peach Bottom NPP Risk Map 1/2



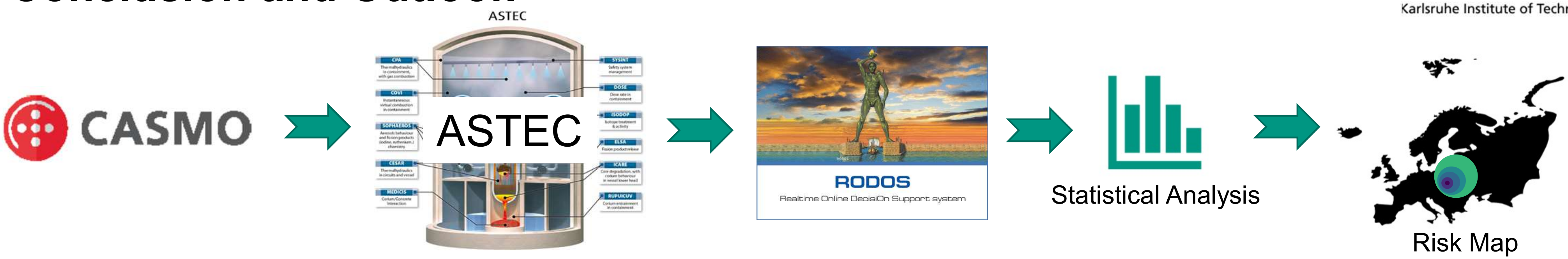
- Winter season has largest span and branches of calculated average total gamma dose rates.
  - Having the largest spread will reduce the average value, but it will require a larger area to be covered in terms of evacuation.
- All major cities: NY, Washington DC, Baltimore and Philadelphia are in the range of the calculated average total gamma dose rates.
- Tendency of the dispersion mostly to West and South-West. Dispersion towards to East is quite limited compare to other directions.

Peach Bottom NPP Risk Map 2/2



- Summer season has largest area of exceeded dose limit due to weather conditions (Up to 38 km from the plant in North direction).
  - Based on the current results highest risk in terms of public safety having a dispersion in Summer season.
- All major cities NY, Washington DC, Baltimore and Philadelphia are in the range of the calculated average total gamma dose rates.
- There is a tendency of the dispersion to the West and South-West considering all seasons.
  - Geographic obstacles and based wind regime directs the overall trend.

Conclusion and Outlook



- More information in one picture than simple dispersion map → Frequency, dose rate, regime, range etc.
- Considering sampling mean distribution and central limit theorem helps to achieve the results *much faster*.
  - 25 days of cpu time << 4 years of cpu time
- Counter measures and evacuation actions will be taken in action to extent the analysis.
  - Can be major pillar to support emergency planning.
- Smaller mesh grid and increased number of the simulation will be performed to achieve better normal distribuation approximation over the all the meshes.
- Approach can be applied new smaller NPP design since the sitings might be closer to the settlements.
- Experince of KIT on performing AI implementation of weather forecasting can improve speed and analysis scope.

Thank You for Your Attention

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