Using SCALE for Radiation Transport Simulations to Determine Radiation Environment in I^{2}S-LWR

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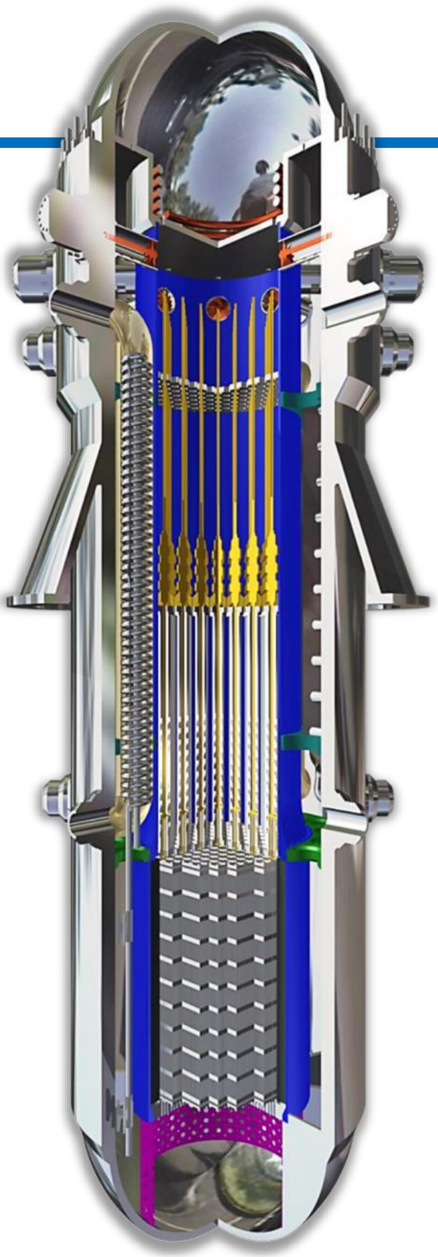
I^2S-LWR Background

REQUIREMENTS:

- Large power LWR (1 GWe class) for 'mainstream' US deployment
- Enhanced safety
- Fuel - enhanced accident tolerance
- Economically competitive

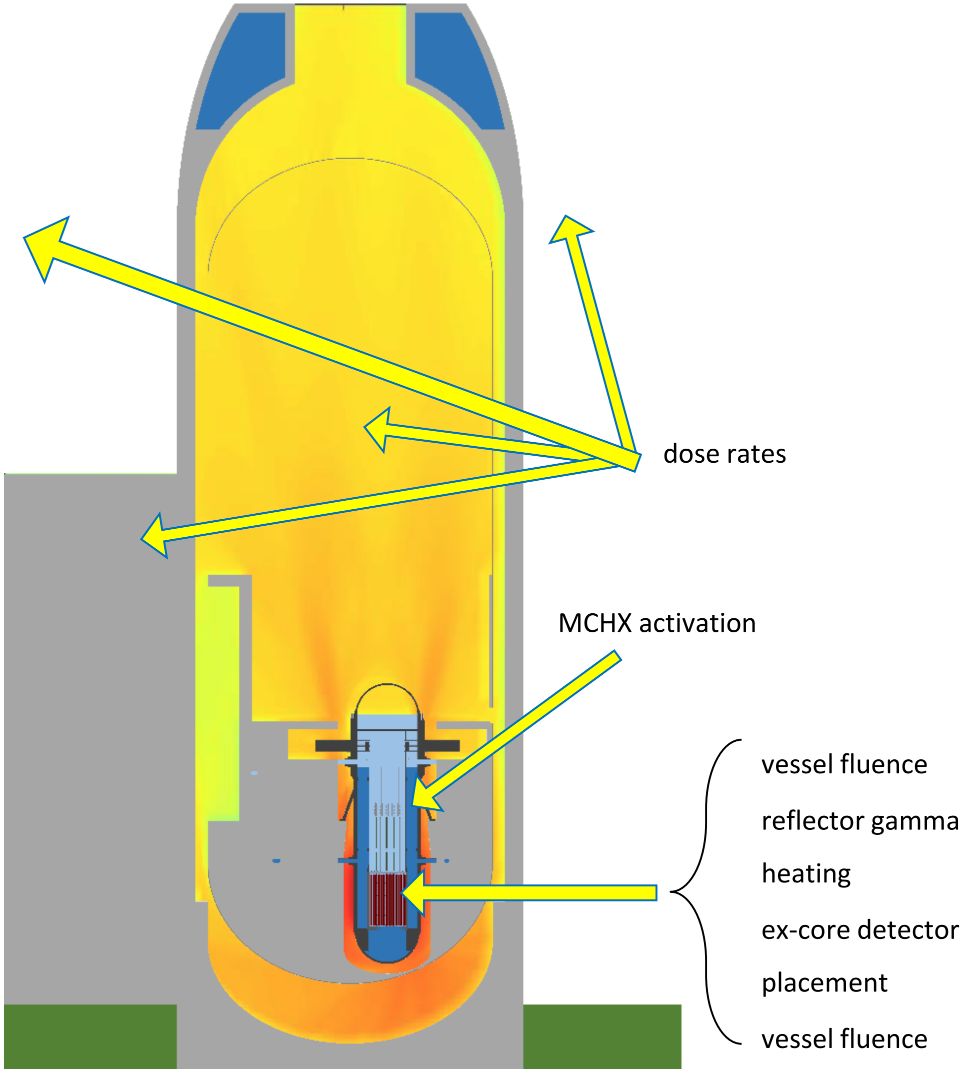
KEY TECHNOLOGIES:

- Integral layout
- Integral primary components
- High power density fuel/clad system (silicide fuel / SS cladding)
- High power density (micro-channel type) primary HX (mC-PHX)
- Steam Generation System (mC-PXH + Flashing Drum)



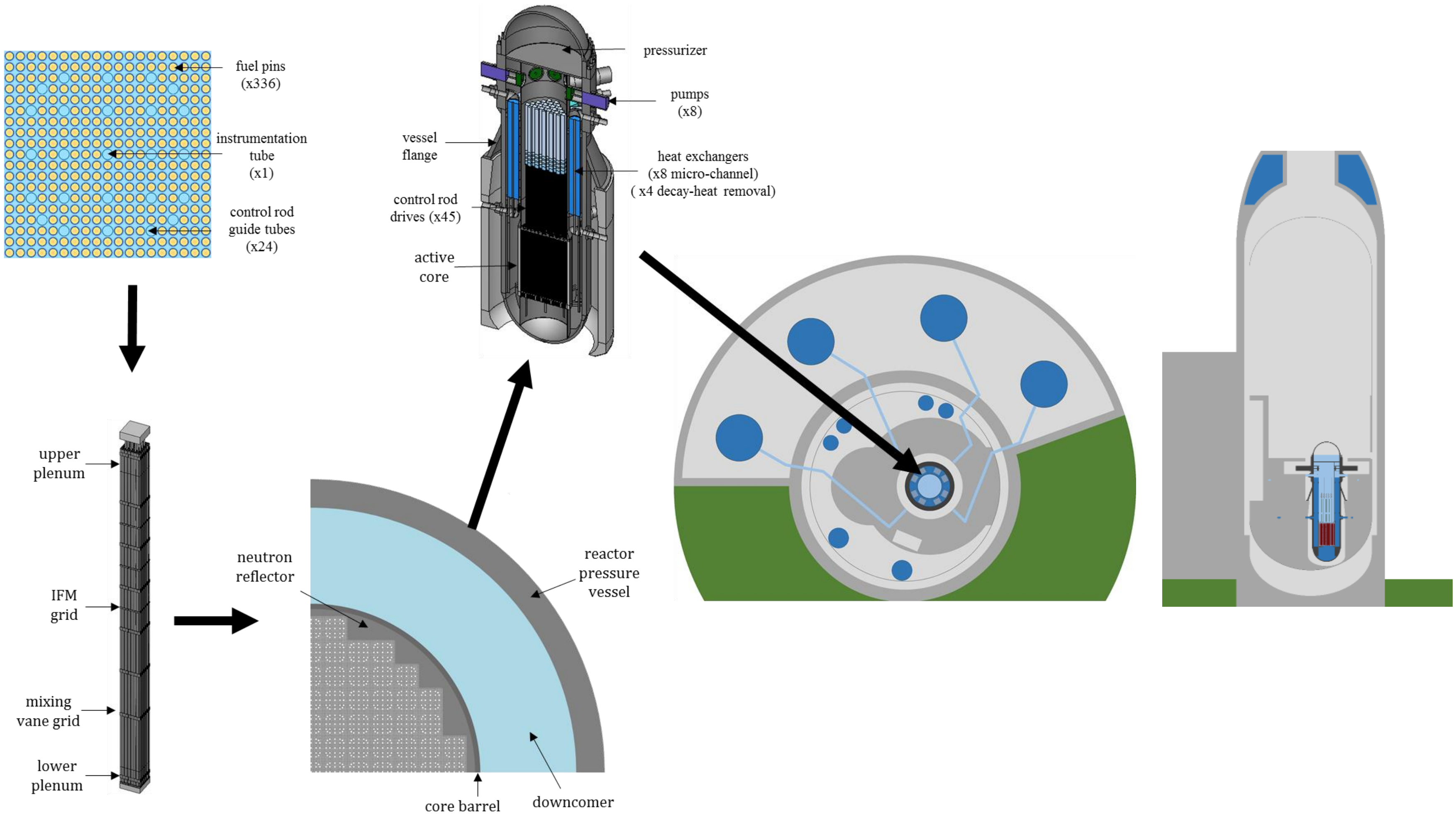
IRP Tasks

- RPV lifetime assessment
- SiC detector Placement
- Gamma heating in radial neutron steel reflector
- MCHX activation
- Dose in nuclear island



I²S-LWR Shielding Model

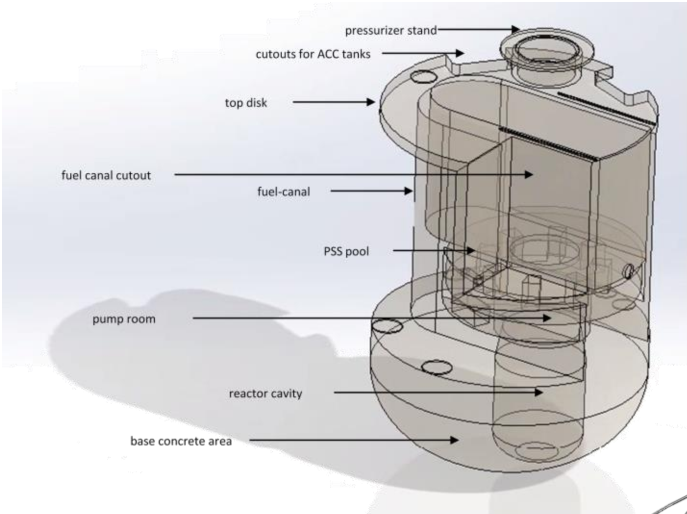
- ~ 3000 lines to describe detailed geometry and materials

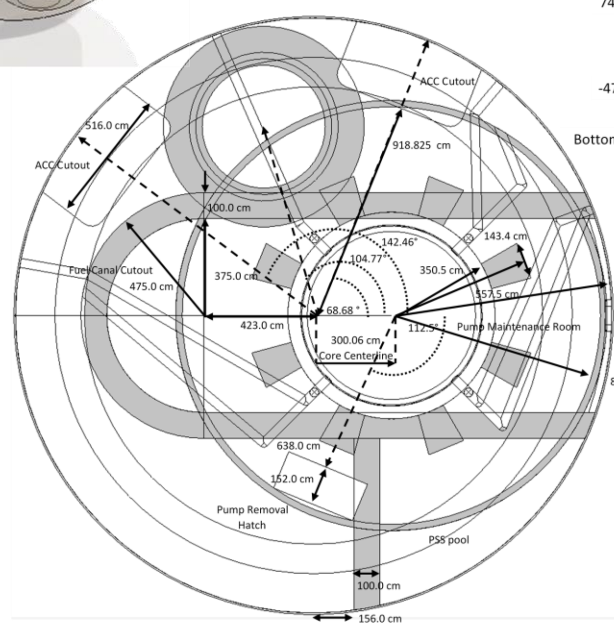


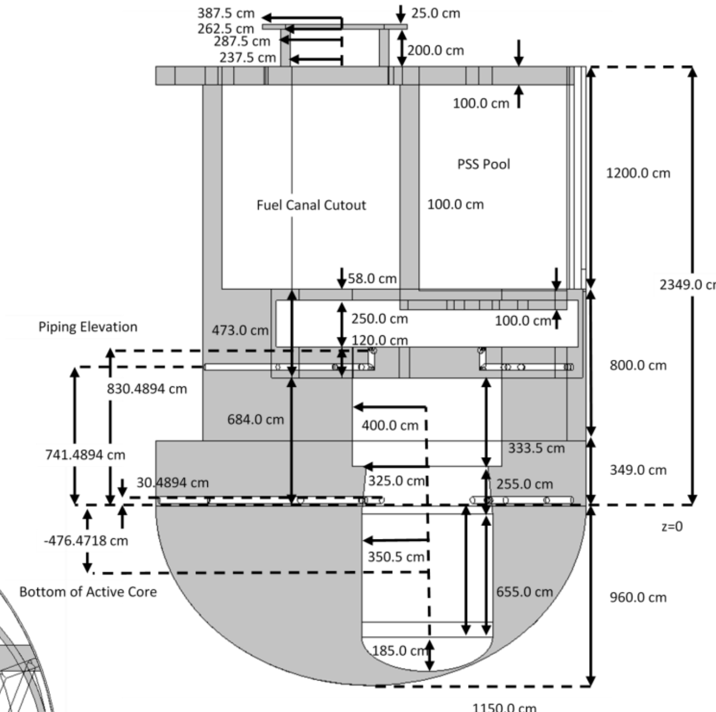
I²S–LWR

Containment Vessel Layout

- CV layout extracted from CAD files provided by Westinghouse



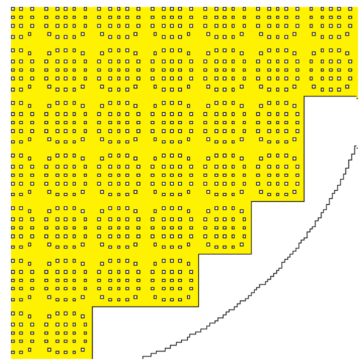




FIXED-SOURCE DESCRIPTIONS

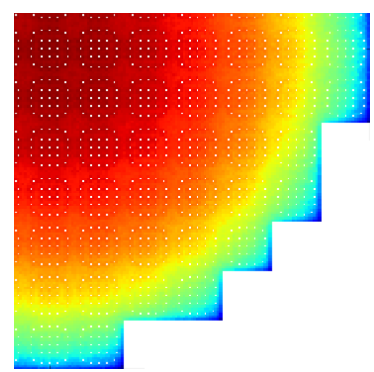
Initial Fixed-Sources

- Preliminary studies using two fixed-source descriptions:
  1. Flat-source: HIGH leakage - conservative for shielding results



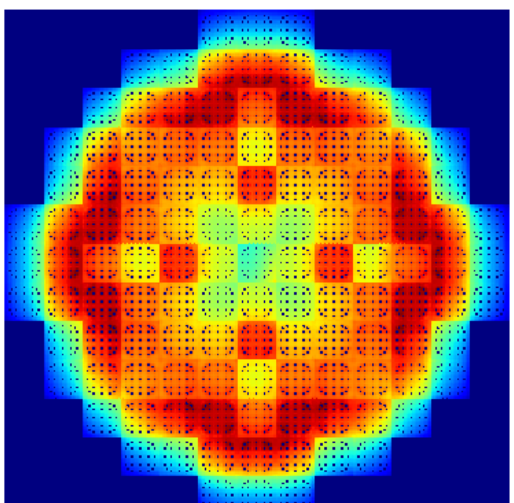
  2. Center-peaked Source (fresh fuel / roughly cosine) – LOW leakage – minimum leakage (not conservative)

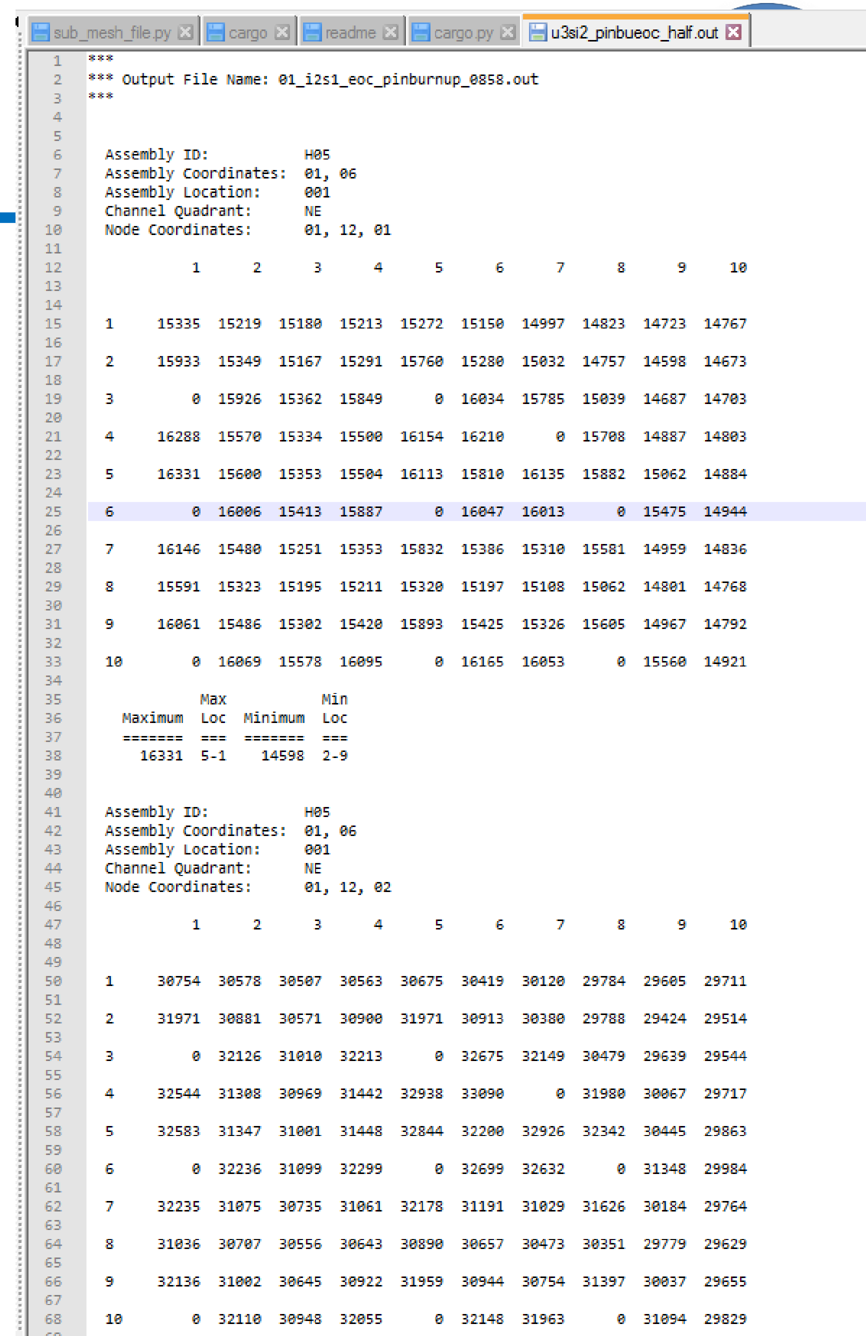
	7	8	9	10	11	12	13
7	1.955	1.890	1.718	1.445	1.103	0.724	0.355
8	1.900	1.840	1.666	1.398	1.057	0.678	0.308
9	1.727	1.667	1.502	1.242	0.913	0.541	
10	1.447	1.399	1.242	1.000	0.696	0.364	
11	1.102	1.059	0.913	0.695	0.419		
12	0.727	0.680	0.543	0.365			
13	0.359	0.309					



Accurate Fixed-Source description

- based on equilibrium cycle from Westinghouse
  - received output file with quarter-core axial pin-wise burnups
  - 225,129 lines





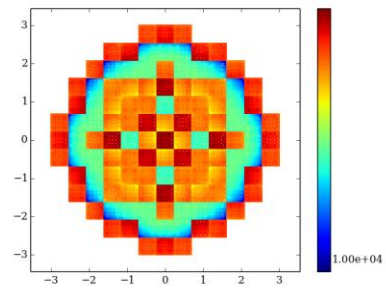

```
***
*** Output File Name: 01_i2s1_eoc_pinburnup_0858.out
***


 Assembly ID:              H05
 Assembly Coordinates:     01, 06
 Assembly Location:        001
 Channel Quadrant:         NE
 Node Coordinates:         01, 12, 01

            1      2      3      4      5      6      7      8      9     10


 1      15335  15219  15180  15213  15272  15150  14997  14823  14723  14767

 2      15933  15349  15167  15291  15760  15280  15032  14757  14598  14673

 3          0  15926  15362  15849      0  16034  15785  15039  14687  14703

 4      16288  15570  15334  15500  16154  16210      0  15708  14887  14803

 5      16331  15600  15353  15504  16113  15810  16135  15882  15062  14884

 6          0  16006  15413  15887      0  16047  16013      0  15475  14944

 7      16146  15480  15251  15353  15832  15386  15310  15581  14959  14836

 8      15591  15323  15195  15211  15320  15197  15108  15062  14801  14768

 9      16061  15486  15302  15420  15893  15425  15326  15605  14967  14792

 10         0  16069  15578  16095      0  16165  16053      0  15560  14921

              Max            Min
   Maximum    Loc  Minimum   Loc
   =======    ===  =======   ===
     16331    5-1    14598   2-9


 Assembly ID:              H05
 Assembly Coordinates:     01, 06
 Assembly Location:        001
 Channel Quadrant:         NE
 Node Coordinates:         01, 12, 02

            1      2      3      4      5      6      7      8      9     10


 1      30754  30578  30507  30563  30675  30419  30120  29784  29605  29711

 2      31971  30881  30571  30900  31971  30913  30380  29788  29424  29514

 3          0  32126  31010  32213      0  32675  32149  30479  29639  29544

 4      32544  31308  30969  31442  32938  33090      0  31980  30067  29717

 5      32583  31347  31001  31448  32844  32200  32926  32342  30445  29863

 6          0  32236  31099  32299      0  32699  32632      0  31348  29984

 7      32235  31075  30735  31061  32178  31191  31029  31626  30184  29764

 8      31036  30707  30556  30643  30890  30657  30473  30351  29779  29629

 9      32136  31002  30645  30922  31959  30944  30754  31397  30037  29655

 10         0  32110  30948  32055      0  32148  31963      0  31094  29829

```

Fixed-Source description

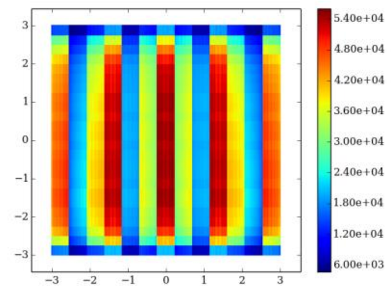
- developed python script with detailed classes to define full-core
- read in data from text file and look at burnups

(MWd/MTHM)

- Need to convert to average fission power distribution
- Known: final BU, shuffling pattern
- Assume: ΔBU is average power
- Create map of full-core shuffling pattern
- Extend python classes to read in assembly shuffling pattern and positioning
- $\Delta BU_{cycle} = \Delta BU_{final} - \Sigma \Delta BU_{previous}$



radial BU with linear scale



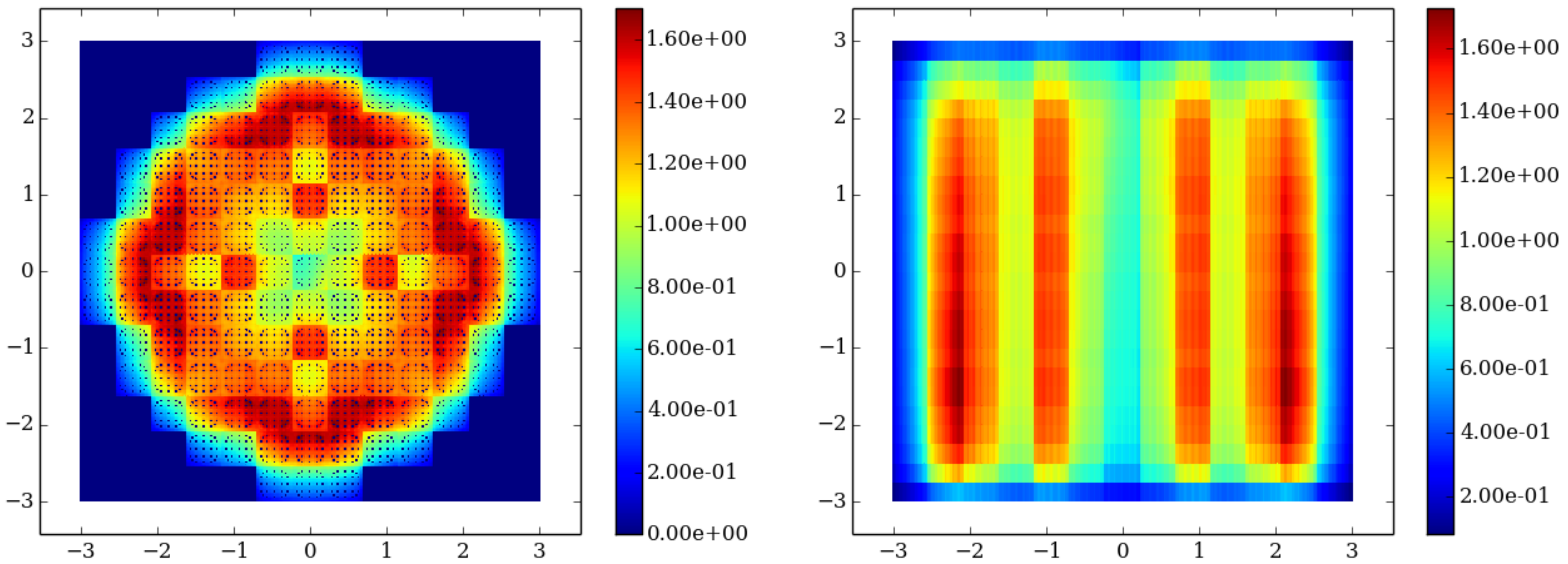
axial burnup with log scale

	N	M	L	K	J	H	G	F	E	D	C	B	A	
1	N1	M1	L1	K1	J1	H1	G1	F1	E1	D1	C1	B1	A1	1
2	N2	M2	L2	K2	J2	H2	G2	F2	E2	D2	C2	B2	A2	2
3	N3	M3	L3	K3	J3	H3	G3	F3	E3	D3	C3	B3	A3	3
4	N4	M4	L4	K4	J4	H4	G4	F4	E4	D4	C4	B4	A4	4
5	N5	M5	L5	K5	J5	H5	G5	F5	E5	D5	C5	B5	A5	5
6	N6	M6	L6	K6	J6	H6	G6	F6	E6	D6	C6	B6	A6	6
7	N7	M7	L7	K7	J7	H7	G7	F7	E7	D7	C7	B7	A7	7
8	N8	M8	L8	K8	J8	H8	G8	F8	E8	D8	C8	B8	A8	8
9	N9	M9	L9	K9	J9	H9	G9	F9	E9	D9	C9	B9	A9	9
10	N10	M10	L10	K10	J10	H10	G10	F10	E10	D10	C10	B10	A10	10
11	N11	M11	L11	K11	J11	H11	G11	F11	E11	D11	C11	B11	A11	11
12	N12	M12	L12	K12	J12	H12	G12	F12	E12	D12	C12	B12	A12	12
13	N13	M13	L13	K13	J13	H13	G13	F13	E13	D13	C13	B13	A13	13
	N	M	L	K	J	H	G	F	E	D	C	B	A	

	N	M	L	K	J	H	G	F	E	D	C	B	A	
1	00	00	00	00	00	J4	G11	E4	00	00	00	00	00	1
2	00	00	00	H4	J8	FR	FR	FR	E8	F4	00	00	00	2
3	00	00	G6	FR	FR	FR	G2	FR	FR	FR	F7	00	00	3
4	00	K6	FR	G9	D11	B8	E5	M8	K11	J7	FR	D6	00	4
5	00	F5	FR	C10	J3	L8	FR	L6	C5	L10	FR	H5	00	5
6	K5	FR	FR	F12	H11	K4	J11	D4	H3	H12	FR	FR	D5	6
7	C7	FR	M7	J5	FR	C9	K2	L5	FR	E9	B7	FR	L7	7
8	K9	FR	FR	F2	F11	K10	E3	D10	F3	H2	FR	FR	D9	8
9	00	F9	FR	C4	L9	C8	FR	C6	E11	L4	FR	H9	00	9
10	00	K8	FR	E7	D3	B6	J9	M6	K3	G5	FR	D8	00	10
11	00	00	H7	FR	FR	FR	G12	FR	FR	FR	G8	00	00	11
12	00	00	00	H10	J6	FR	FR	FR	E6	F10	00	00	00	12
13	00	00	00	00	00	J10	G3	E10	00	00	00	00	00	13
	N	M	L	K	J	H	G	F	E	D	C	B	A	

Fixed-Source description

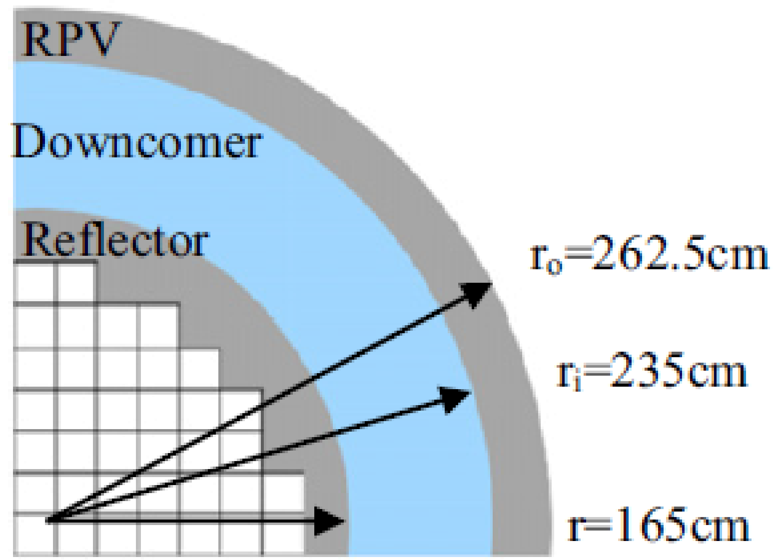
- total peaking factor of 1.69 (very close to expected value of 1.7)
- (assumed watt fission spectrum for uranium everywhere … plutonium has a harder spectrum and therefore more leakage)



REACTOR PRESSURE VESSEL LIFETIME ASSESSMENT

RPV lifetime assessment

- Will the reactor vessel rupture in a 100 year lifetime?
- Fast neutron fluence (>1MeV) in steels
  - slowly degrades mechanical properties through neutron embrittlement based on Cu and Ni in steel and welds
  - lifetime fluence cutoff 2e19 n/cm^2
- based on preliminary design
- 2 fixed-source neutron sources
  - high-leakage, flat source
  - low-leakage, center-peaked source
- 3 ratios of volume percent of steel/water in reflector
  - 100/0
  - 90/10
  - 70/30

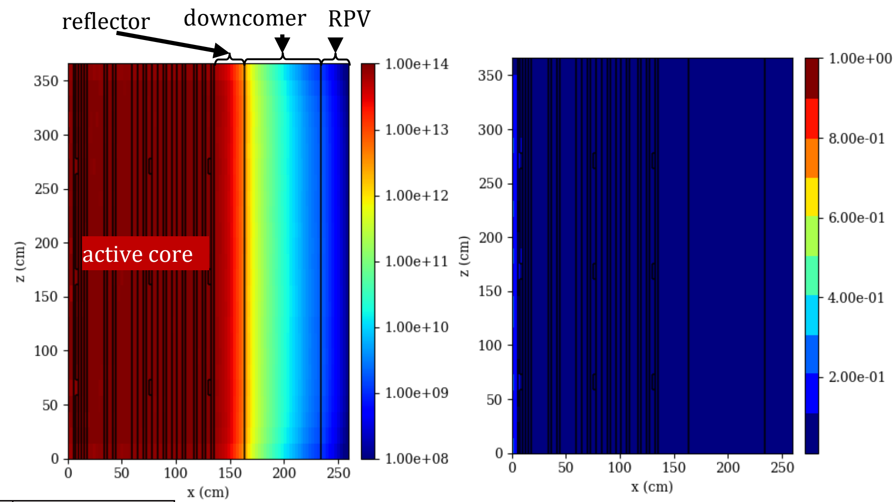


radial view of RPV layout

RPV lifetime assessment

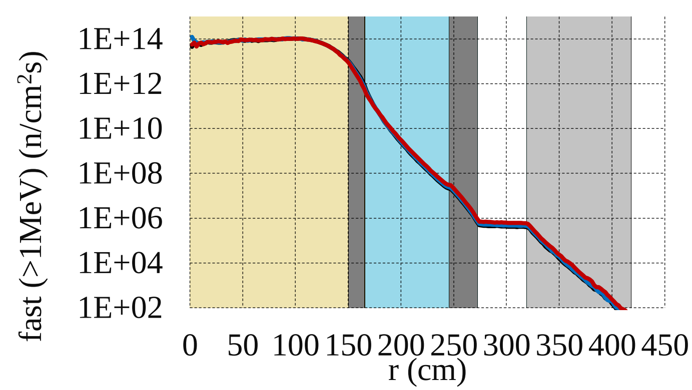
- "Radiation Damage Assessment in the Reactor Pressure Vessel of the Integral Inherently Safe Light Water Reactor (I2S-LWR)", ISRD-15, published 2016 EPJ Web of Conferences

high leakage core w/ steel/water ratio 70/30 in reflector is safe for 100 year lifetime



Case	100-year Fast Fluence (> 1 MeV) [(10^{19}) n/cm^2]					DPA/s	100-year DPA
	Max**	Avg. 1/8T	Avg. 1/4T	Avg. 1/2T	Avg. 3/4T		
Flat (70/30*)	1.531±1%	0.805±1%	0.584±1%	0.266±1%	0.112±1%	3.14E-12±2%	8.93E-03±4%
Flat (90/10*)	1.148±1%	0.627±1%	0.451±1%	0.204±1%	0.086±1%	2.47E-12±2%	7.01E-03±4%
Flat (100/0*)	1.060±2%	0.552±1%	0.395±2%	0.178±2%	0.075±2%	2.24E-12±4%	6.38E-03±4%
Center-peaked (70/30*)	0.143±2%	0.076±2%	0.052±2%	0.021±2%	0.008±2%	4.08E-13±2%	1.16E-03±2%
Center-peaked (90/10*)	0.118±1%	0.058±2%	0.040±2%	0.017±2%	0.006±2%	3.22E-13±2%	9.14E-04±2%
Center-peaked (100/0*)	0.113±3%	0.054±2%	0.037±2%	0.015±3%	0.006±4%	2.87E-13±2%	8.15E-04±2%

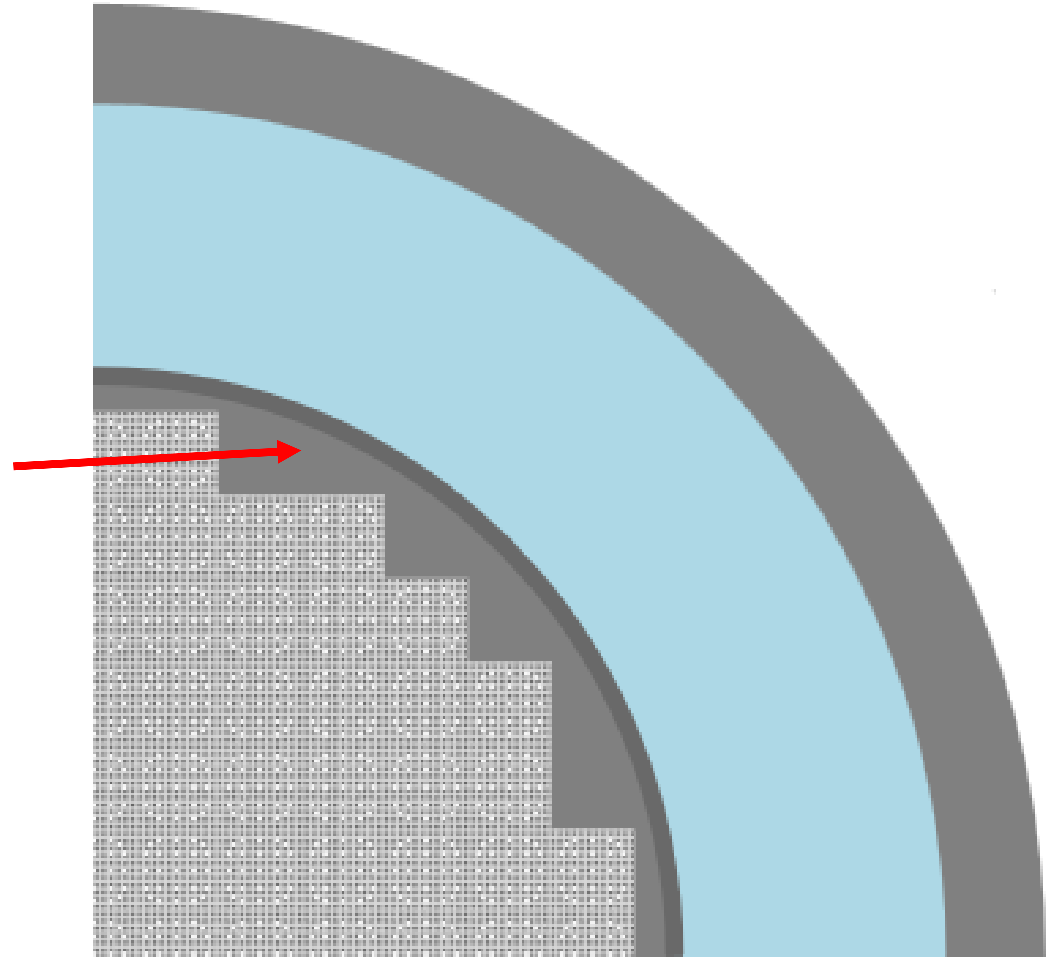
*The numbers represent ratios of homogenized steel-water volume percentages.
**Max and Avg. refer to azimuthal maximum and average values found at an elevation of the core midplane and radially in the inner portion of the RPV.



GAMMA HEATING IN RADIAL NEUTRON REFLECTOR

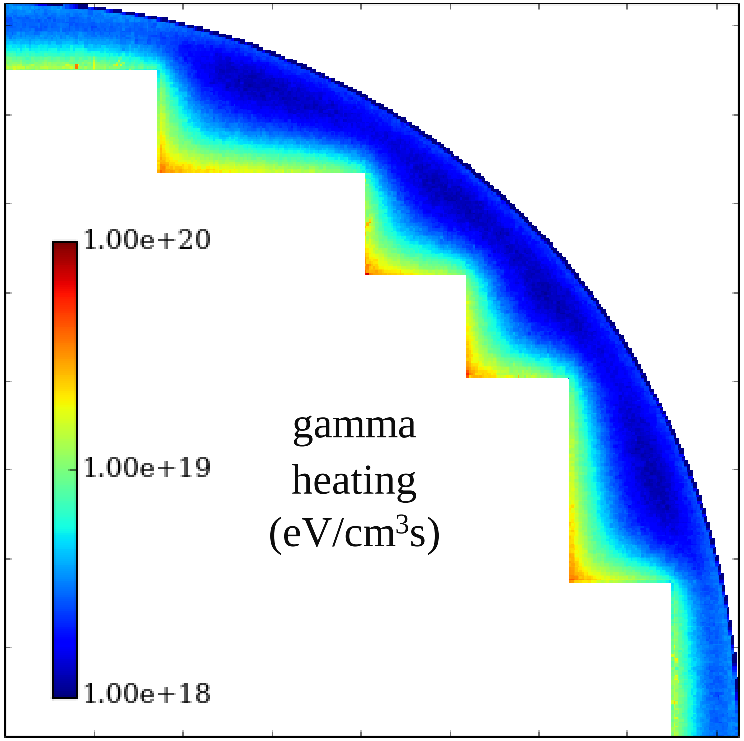
Gamma Heating in Reflector

- KERMA (kinetic energy released per unit mass) factors for n+γ heating
  - not a default in MAVRIC
  - extracted from updated BUGLE-96 shielding library (developed @ ORNL)
- Adjoint solution
  - Adjoint source: n+γ KERMA factors in reflector
  - 27n+19g multigroup library
  - 128x128x106 mesh
  - S_4P_1
- Parallel MC
  - 32 simulations
  - 6 hours of wall time



Gamma Heating in Reflector

- 5.95 MW generated in reflector
  - large amount of heat
  - about what expected
  - not a problem for cooling channel designs with low water volume



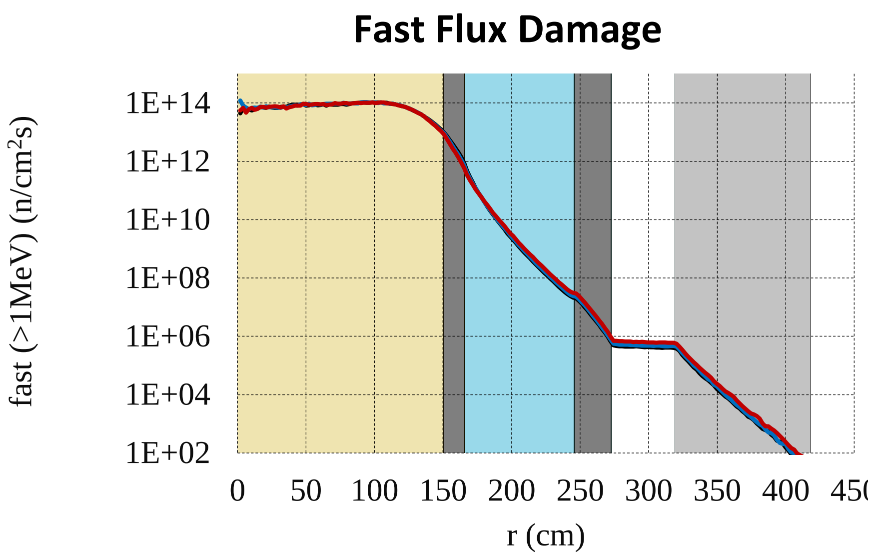
"Calculating Gamma Heating in the I²S-LWR Radial Steel Reflector", Timothy Flaspoehler and Bojan Petrovic, ANS Winter Conference.

EX-CORE SILICON CARBIDE DETECTOR PLACEMENT

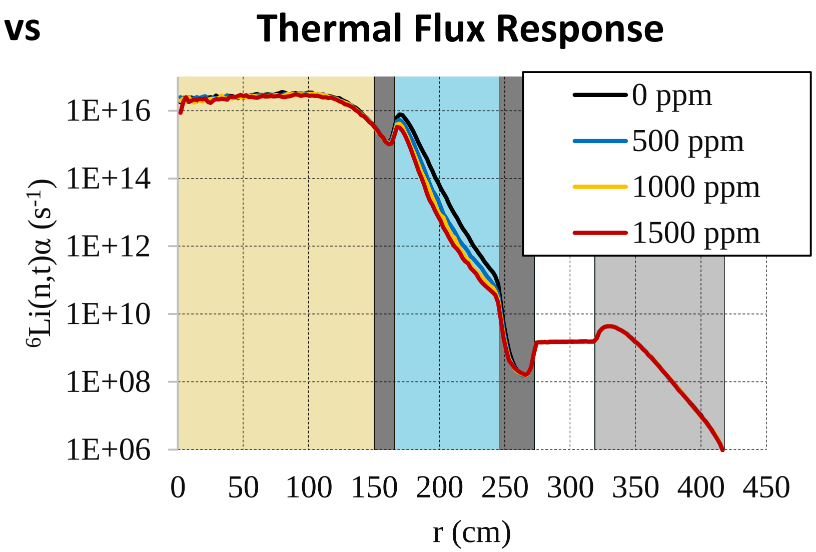
ex-Core SiC Detector Placement

- GOAL: balance radiation damage vs. sensitivity
  - large downcomer region (good as shield, bad for ex-core detectors)
  - SiC can detect fast and thermal neutrons
- 12 separate cases
  - 4 boron concentrations (0,500,1000,1500 ppm)
  - 3 reflector homogenizations (100/0, 90/10, 70/30)
- Adjoint solution
  - adjoint source: entire flux radially through concrete cavity
  - 27 group library
  - P_3/S_8
  - 128x128x64 mesh
  - 30 minutes on 8 CPUs per solution
- MC tallies
  - 12 hour simulations
  - ~ 65 million source particles

ex-Core SiC Detector Placement



vs



ex-Core SiC Detector Placement

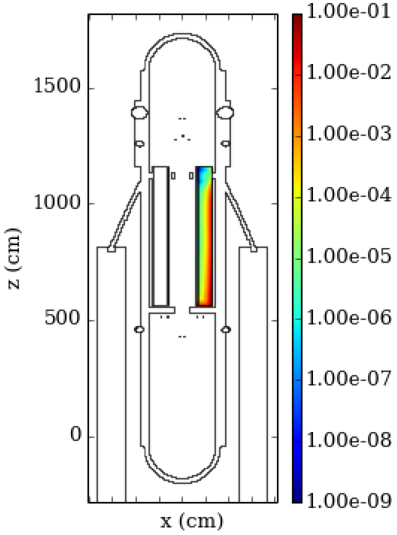
- Results: feasible to have detector with enough resolution that can last the lifetime of the plant without being replaced

radial position (cm)	fast flux E>1MeV ($cm^{-2}s^{-1}$)	30 year fast fluence (cm^{-2})	60 year fast fluence (cm^{-2})	100 year fast fluence (cm^{-2})	thermal flux E<0.625eV ($cm^{-2}s^{-1}$)				6Li depletion (% per year)	thermal monitor lifetime
					0 ppm	500 ppm	1000 ppm	1500 ppm		
165	8.92E+11	8.45E+20	1.69E+21	2.53E+21	6.19E+12	4.62E+12	3.96E+12	3.51E+12	11.2	move or shield
170	2.89E+11	2.74E+20	5.48E+20	8.22E+20	2.10E+13	1.44E+13	1.11E+13	9.20E+12	40.6	move or shield
175	8.16E+10	7.72E+19	1.54E+20	2.32E+20	1.35E+13	6.99E+12	4.70E+12	3.59E+12	26.3	move or shield
185	2.03E+10	1.92E+19	3.85E+19	5.77E+19	3.15E+12	1.22E+12	6.87E+11	4.19E+11	6.14	replace each cycle
195	4.67E+09	4.42E+18	8.84E+18	1.33E+19	4.66E+11	1.08E+11	5.83E+10	3.39E+10	0.908	may be replaced
205	1.24E+09	1.17E+18	2.34E+18	3.51E+18	5.76E+10	1.53E+10	6.57E+09	4.58E+09	0.112	may be replaced
215	4.18E+08	3.96E+17	7.91E+17	1.19E+18	**1.05E+10**	**2.79E+09**	**1.83E+09**	**1.21E+09**	0.0203	plant lifetime
225	1.34E+08	1.27E+17	2.54E+17	3.80E+17	2.00E+09	6.70E+08	4.61E+08	3.26E+08	3.85E-03	plant lifetime
235	5.03E+07	4.76E+16	9.53E+16	1.43E+17	6.07E+08	2.33E+08	1.43E+08	1.15E+08	1.18E-03	plant lifetime
245	2.38E+07	2.25E+16	4.50E+16	6.75E+16	1.99E+08	9.54E+07	6.49E+07	4.92E+07	3.82E-04	plant lifetime
cavity	4.34E+05	4.11E+14	8.22E+14	1.23E+15	1.82E+06	1.82E+06	1.83E+06	1.82E+06	4.17E-06	plant lifetime

	Detector Placement		**Good Value**		**Acceptable but not ideal**		**High damage or low response**

"Feasibility of Ex-Core In-Vessel Nuclear Instrumentation for Integral Inherently Safe Light Water Reactor (I2S-LWR)", Bojan Petrovic, Timothy Flaspoehler, The 2015 International Conference on Applications of Nuclear Techniques, Crete, Greece, June 14-20, 2015

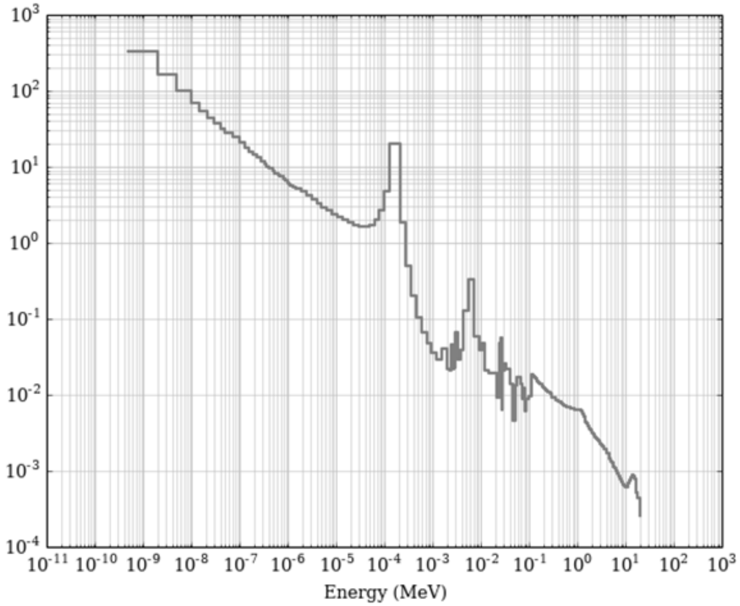
MICRO-CHANNEL HEAT EXCHANGER ACTIVATION



Reaction Rate ($b/cm^2 s$)

MCHX Activation

- reference
  - *AP1000 DCD (Design Control Document)* defines impurity levels in primary steel components (close to the core):
    - » maximum 0.05 w/o of Cobalt
- ^{59}Co (100% of natural cobalt) impurities generate ^{60}Co
- ^{60}Co ($t_{1/2}$=5.27 yr) beta decays emitting 1.17 and a 1.33 MeV gamma rays



Cross Section for $^{59}Co(n,\gamma)^{60}Co$.

MCHX Activation

- Different Pathways
  - impurities

$$^{59}_{27}Co + n \rightarrow ^{60}_{27}Co + \gamma$$
$$^{60}_{27}Co \xrightarrow{5.27y} ^{60}_{28}Co + ^{0}_{-1}e + \bar{\nu}_e + \gamma$$

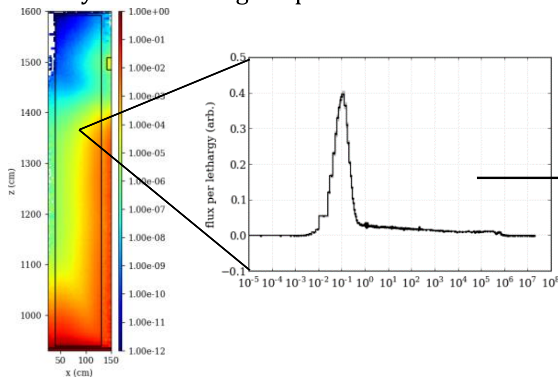
  - iron isotopes

$$^{58}_{26}Fe + n \rightarrow ^{59}_{26}Fe + \gamma$$
$$^{59}_{26}Fe \xrightarrow{44.5d} ^{59}_{27}Co + ^{0}_{-1}e + \bar{\nu}_e + \gamma$$
$$^{59}_{27}Co + n \rightarrow ^{60}_{27}Co + \gamma$$
$$^{60}_{27}Co \xrightarrow{5.27y} ^{60}_{28}Co + ^{0}_{-1}e + \bar{\nu}_e + \gamma$$

  - (?) possible unknown pathways

MCHX Activation

1. MAVRIC: use biased MC to obtain mesh tally with converged spectra in each voxel

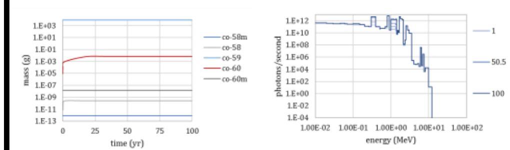


2. CSAS-MG: generate 238-group AMPX master library

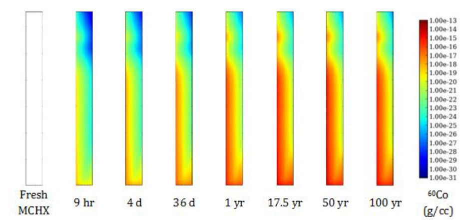
3. AJAX: convert AMPX master library to AMPX working library

4. COUPLE: collapse 238-group working library to 1-group activation library

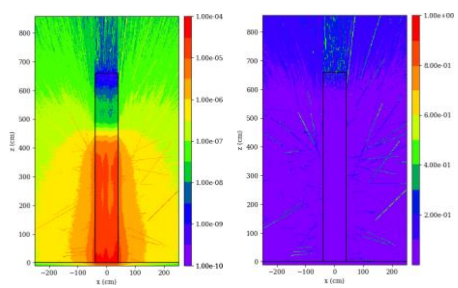
5. ORIGEN-S: calculate isotopics and gamma source for each voxel



6. a combination of scripts and executables process ORIGEN-S output back into 3Dmap files for isotopics and mesh source files for the fixed gamma source

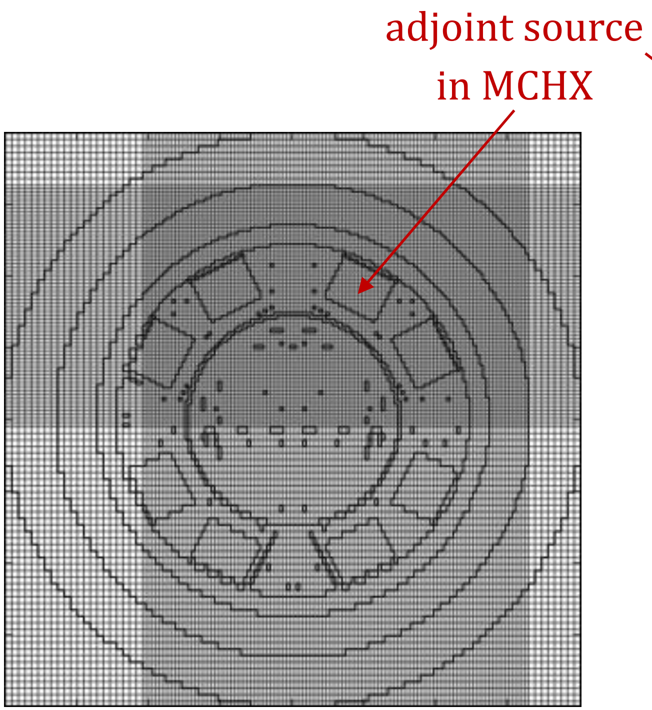


7. MAVRIC: dose rate distributions from activated MCHXs

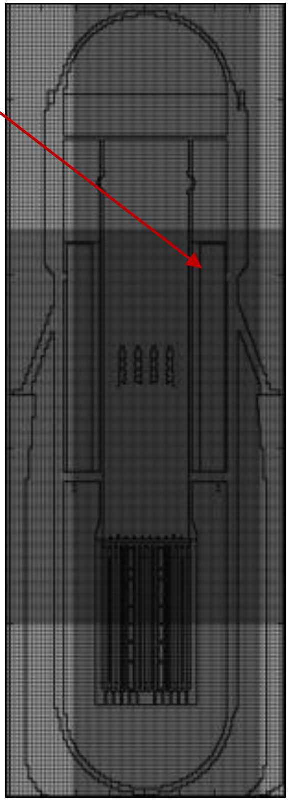


MCHX Activation

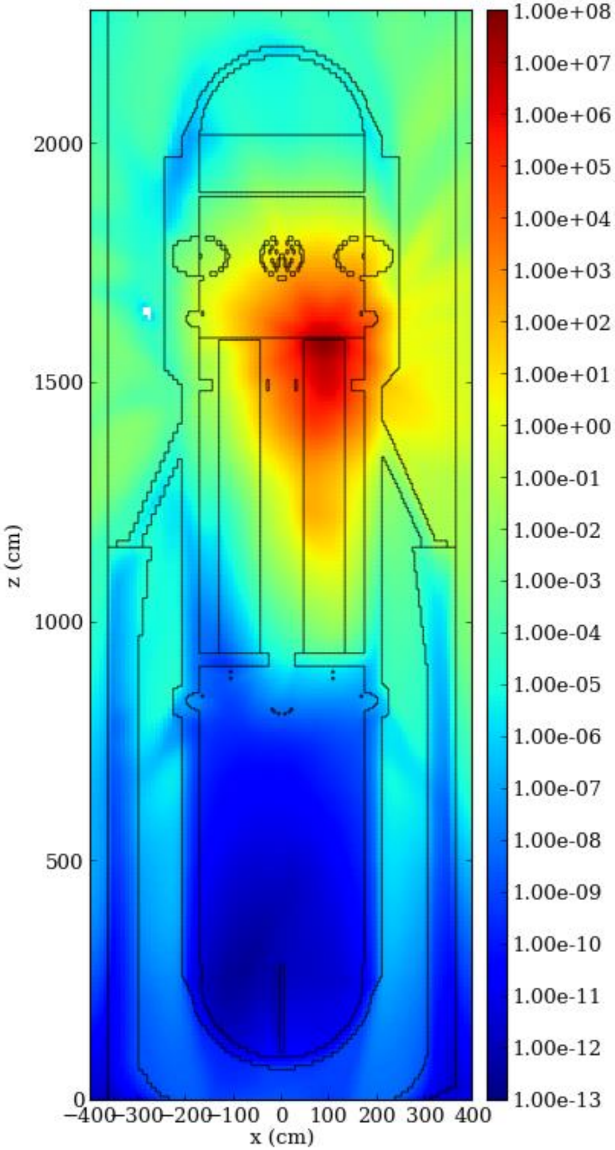
- Adjoint source
  - FW-CADIS
  - total neutron flux in MCHX
- Adjoint solution
  - Coarse-group library provided poor MC results
  - 238-group library refined mesh (147x125x370)
  - P_1S_4 Legendre scattering / quadrature set
  - 12.2 Gb importance map



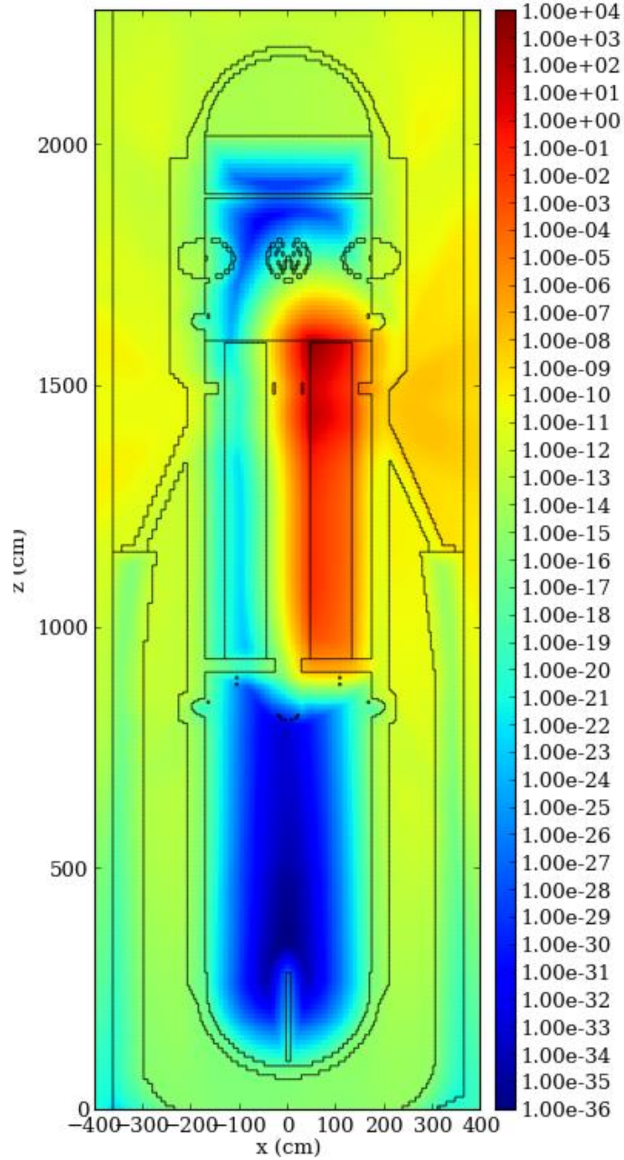
(a) top



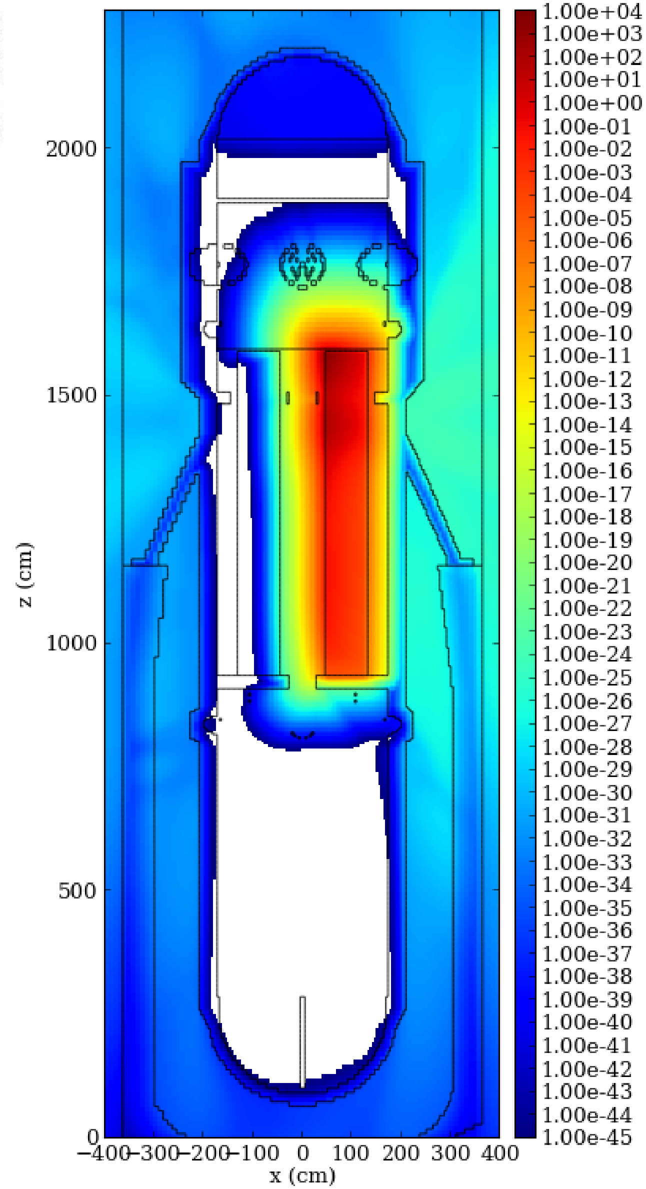
(b) front



group 1



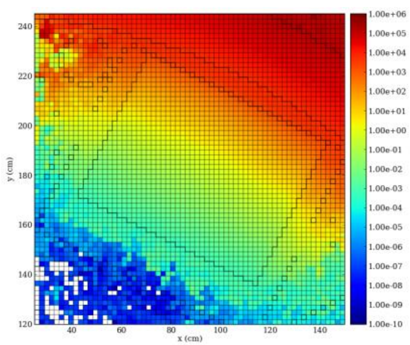
group 100



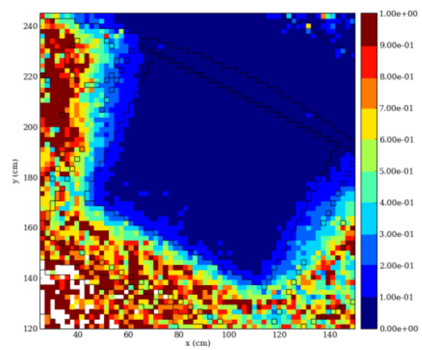
group 238

MCHX Activation

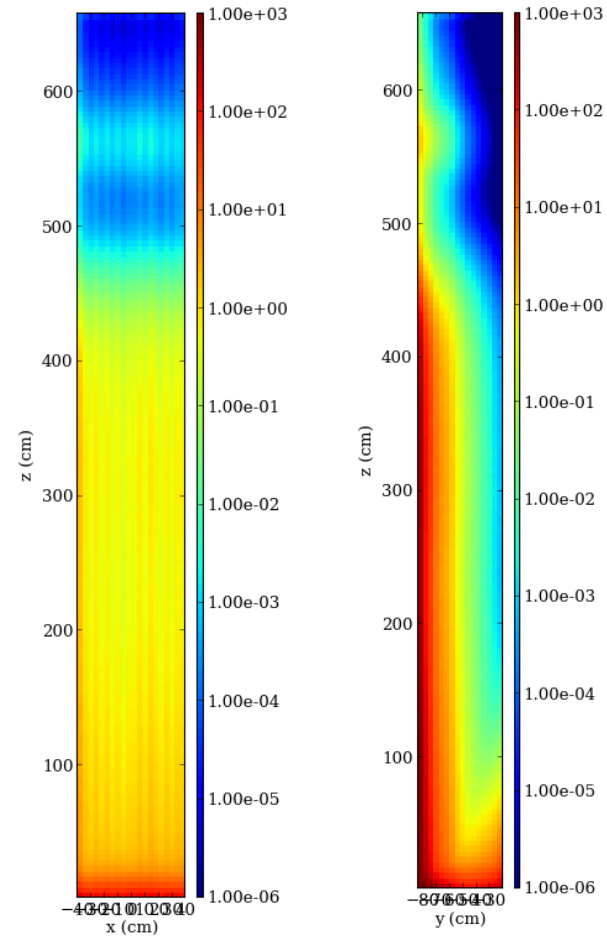
- Biased MC Results
  - 14 parallel runs
  - 4 day wall-clock time
    (55 day CPU time)
  - 1.3 billion source particles



total neutron flux

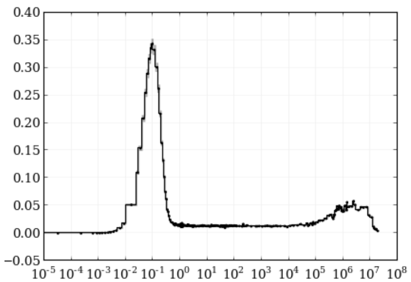


relative uncertainty



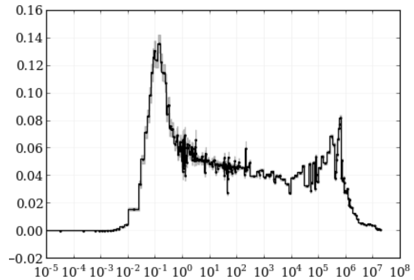
$$^{59}_{27}Co + n \rightarrow {}^{60}_{27}Co + \gamma$$

MCHX Activation



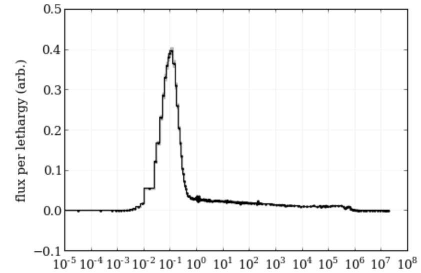
(a) inner side closest to core

$\sigma_{\square} = 15.5 \pm 0.70\%\ b$



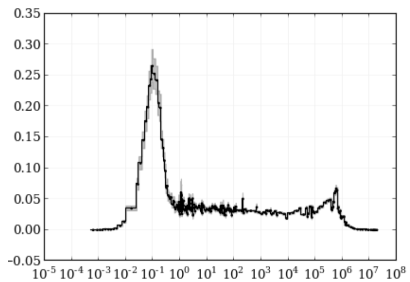
(b) center

$\sigma_{\square} = 7.35 \pm 1.2\%\ b$



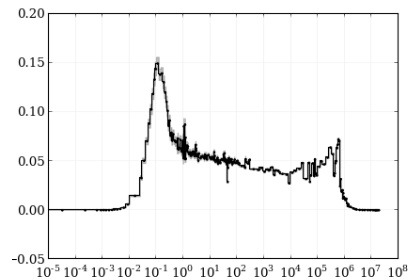
(c) outer edge closest to RPV

$\sigma_{\square} = 17.8 \pm 0.66\%\ b$



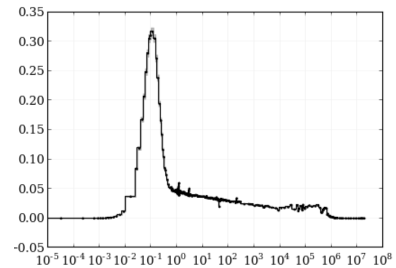
(a) inner side closest to core

$\sigma_{\square} = 12.2 \pm 2.4\%\ b$



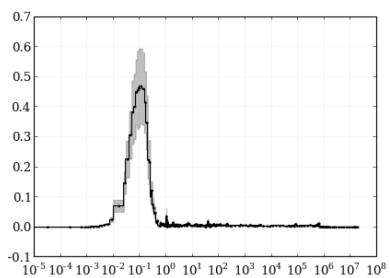
(b) center

$\sigma_{\square} = 7.64 \pm 1.0\%\ b$



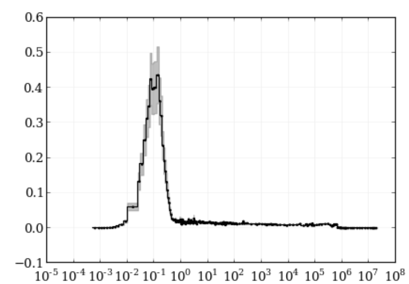
(c) outer edge closest to RPV

$\sigma_{\square} = 14.2 \pm 0.56\%\ b$



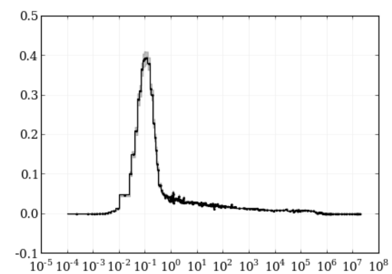
(a) inner side closest to core

$\sigma_{\square} = 21.6 \pm 7.3\%\ b$



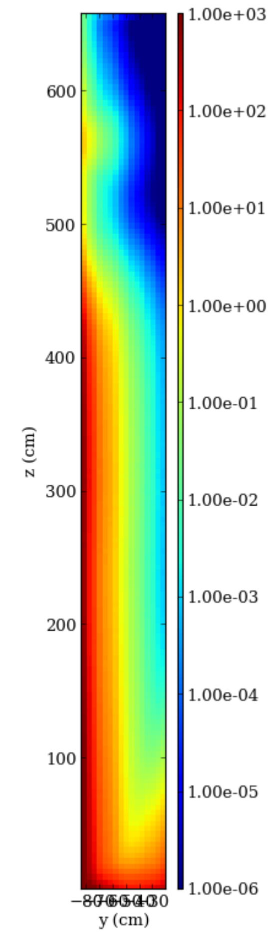
(b) center

$\sigma_{\square} = 19.1 \pm 4.7\%\ b$



(c) outer edge closest to RPV

$\sigma_{\square} = 17.2 \pm 1.3\%\ b$



Georgia Tech

I²S–LWR

MCHX Activation

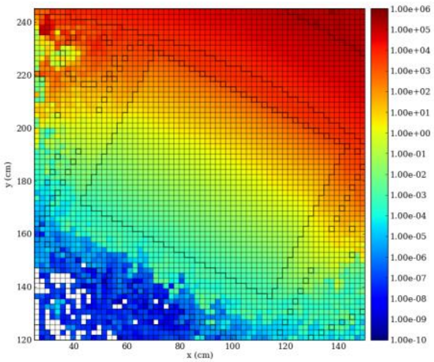
- ORIGEN-S template file

1. csas-mg (same)
2. ajax (same)
3. nitawl (same)
4. couple (neutron spectra)
5. origen (total fluence rate)

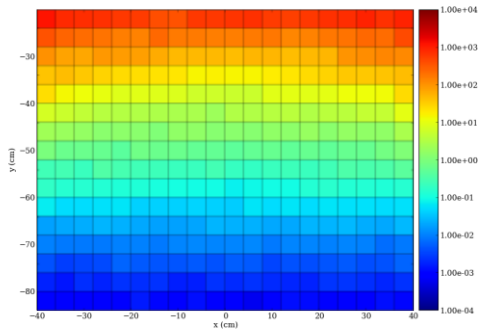
- Run these in parallel (x32)
- 3.75 hours

```
=csas-mg    parm=(nitawl,chk)
cross sections for couple sample problem
238group
read comp
 wtptapmt 1  7.25  7
                                 24000 21
                                 13027 5
                                 42000 3
                                 6000 0.08
                                 14000 0.7
                                 25055 0.4
                                 26000 69.82
                       0.7 555   end
 h2o      1 den=0.765 0.3 555   end
end comp
end
=ajax
0$$ 88 e  1$$ 1  1t
2$$ 11 0  2t
end
=nitawl
0$$ 88 e  1$$ 0 9 e
t
2$$ 24000 13027 42000 6000  14000 25055 26000 8016 1001
t
end
=couple

0$$ a3 80 a5 4 a6 33 e
1$$ a4 1 a15 0 a16 8 0 238 e t
'mchx spectrum
9**
@flux
done
end
=origen
-1$$ 1000000
0$$ a4 33 e
1$$ 1 1t
mchx activation
3$$ 33  a3 1 0 a10 0 a11 0 a12 0 a16 2 a33 47 e t
35$$  0 4t
56$$ 10 a3 1 0 a13 25 5 3 32 2 1 e
57** a3 1-15 e 5t
mchx activation
 mavric fluence rate
@power
60** 0.001 0.01 0.1 5i1 100
65$$ 0 0 0 a4 9r1 a7 9r1 f0 e
66$$ 2 a5 1 a9 1 e
@isotopes
@densities
75$$  25r4
81$$ 2 0 26 1 a7 200 e
82$$ f2 e
83**
```

MCHX Activation

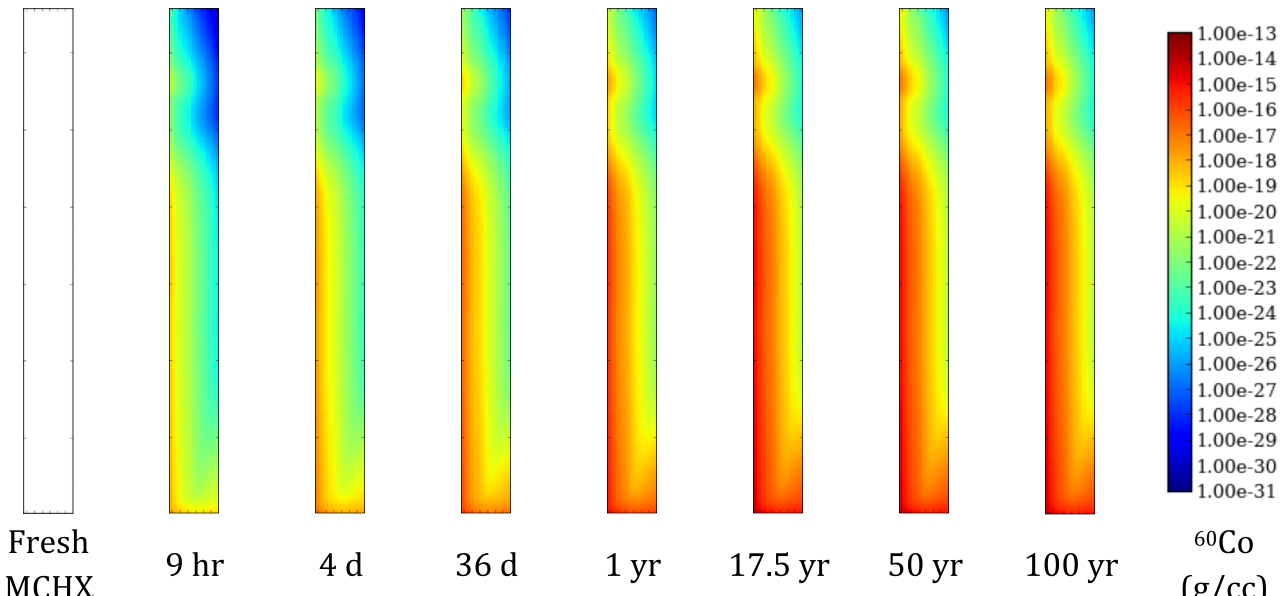


MC results



rotate to normal of MCHX

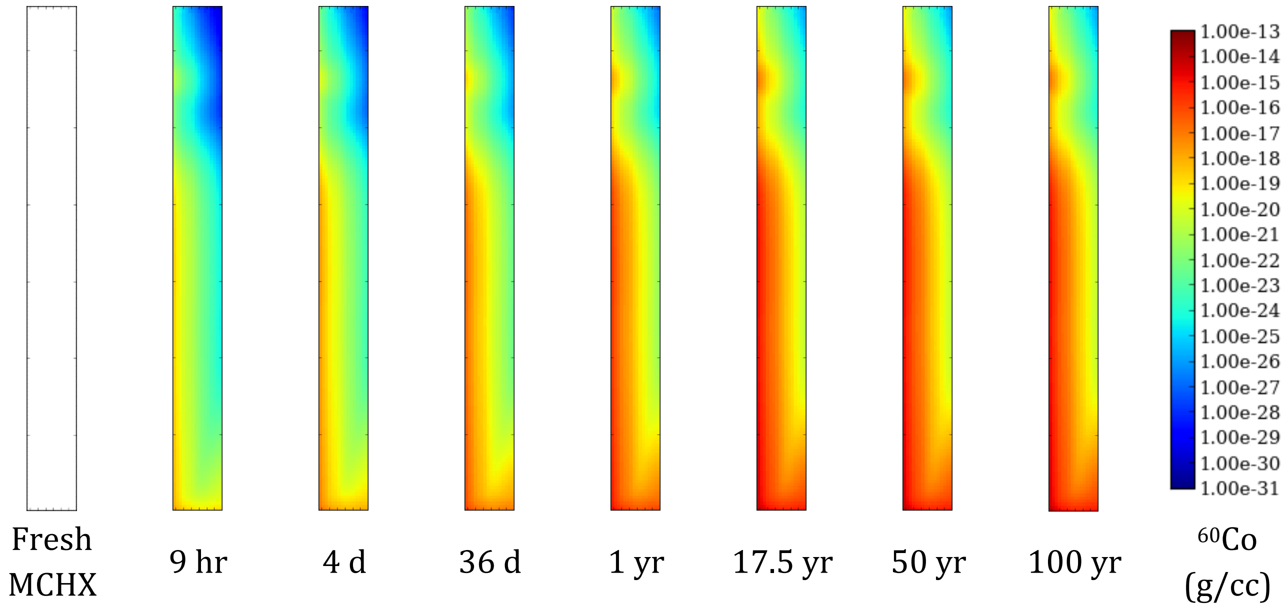
deplete each voxel w/ ORIGEN-S



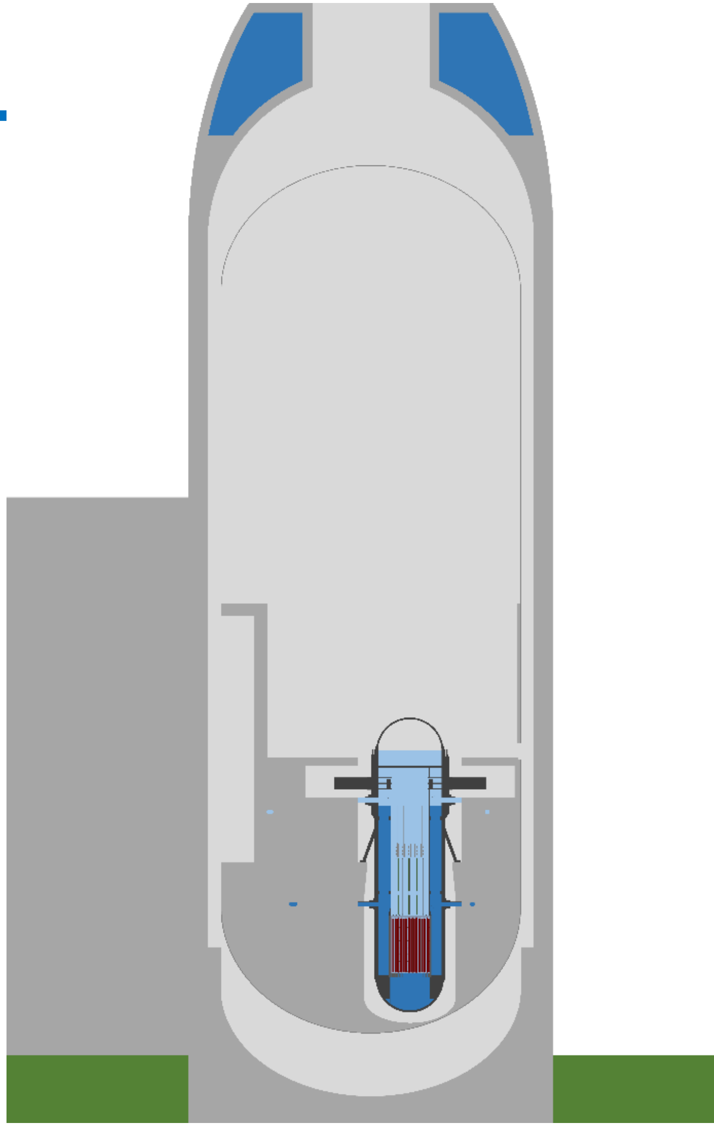
project time-dependent isotopics, gamma source, etc. to 3Dmap

MCHX Activation

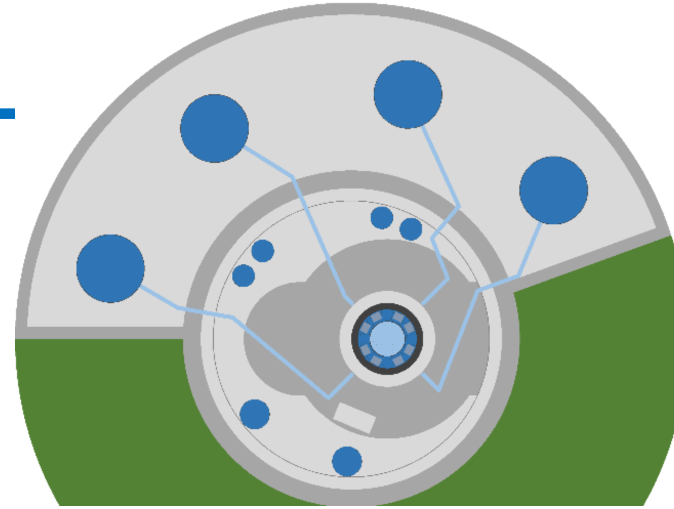
- CONCLUSION:
  - Max Co-60 at equilibrium (30 years) below IAEA free-release limit
    - » (0.4Bq/g > 0.3 Bq/g)
  - Therefore, safe for maintenance with no extra shielding
  - May need to cool down for one half-life after decommissioning



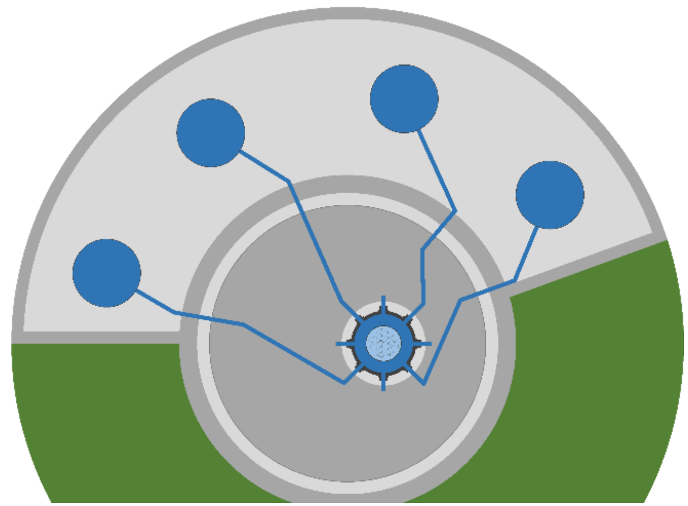
DOSE DISTRIBUTION THROUGHOUT NUCLEAR ISLAND



(a) front view of the shield building enclosing the CV



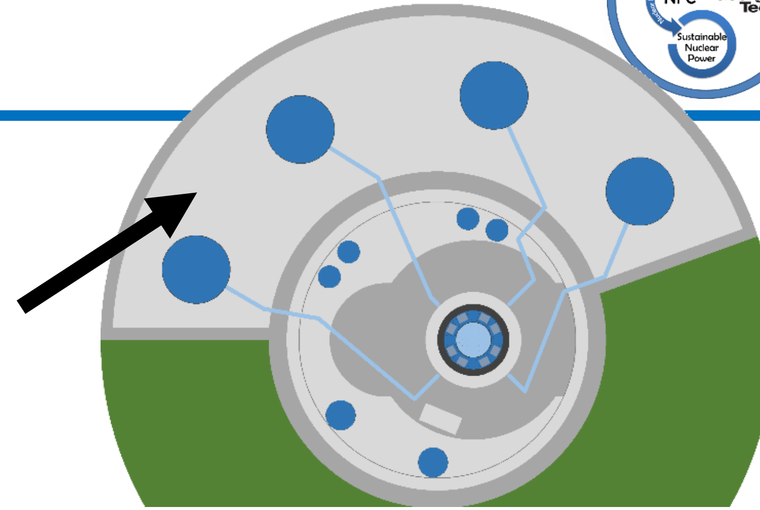
(b) top view showing the hot leg piping from MCHXs to the SGS

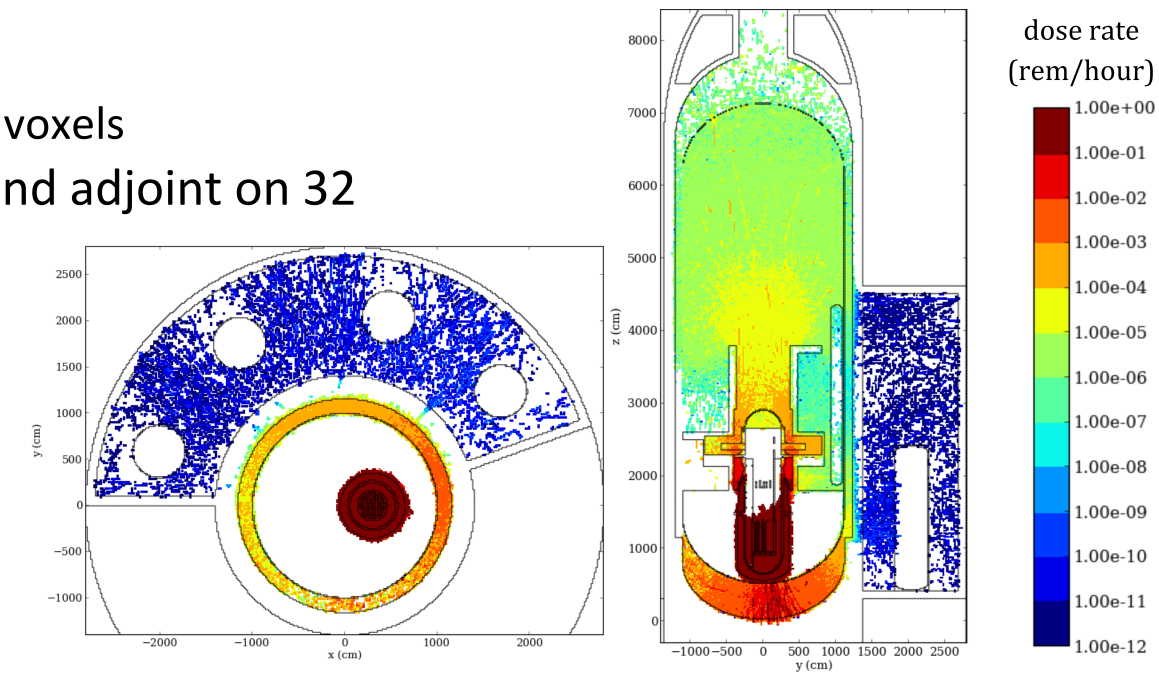


(c) top view showing the cold leg piping from the SGS back to the MCHXs

Dose rate distributions

- Preliminary results
- Adjoint solution
  - adjoint source: n+γ dose rate in room with flashing drum
  - 46 group library
  - P_1/S_4
  - 320x240x498 mesh
    - » 17 cm side length of voxels
  - 26 hours for forward and adjoint on 32 CPUs
  - ~256Gb of memory
- MC results
  - 1 billion particles
  - 10 runs in parallel

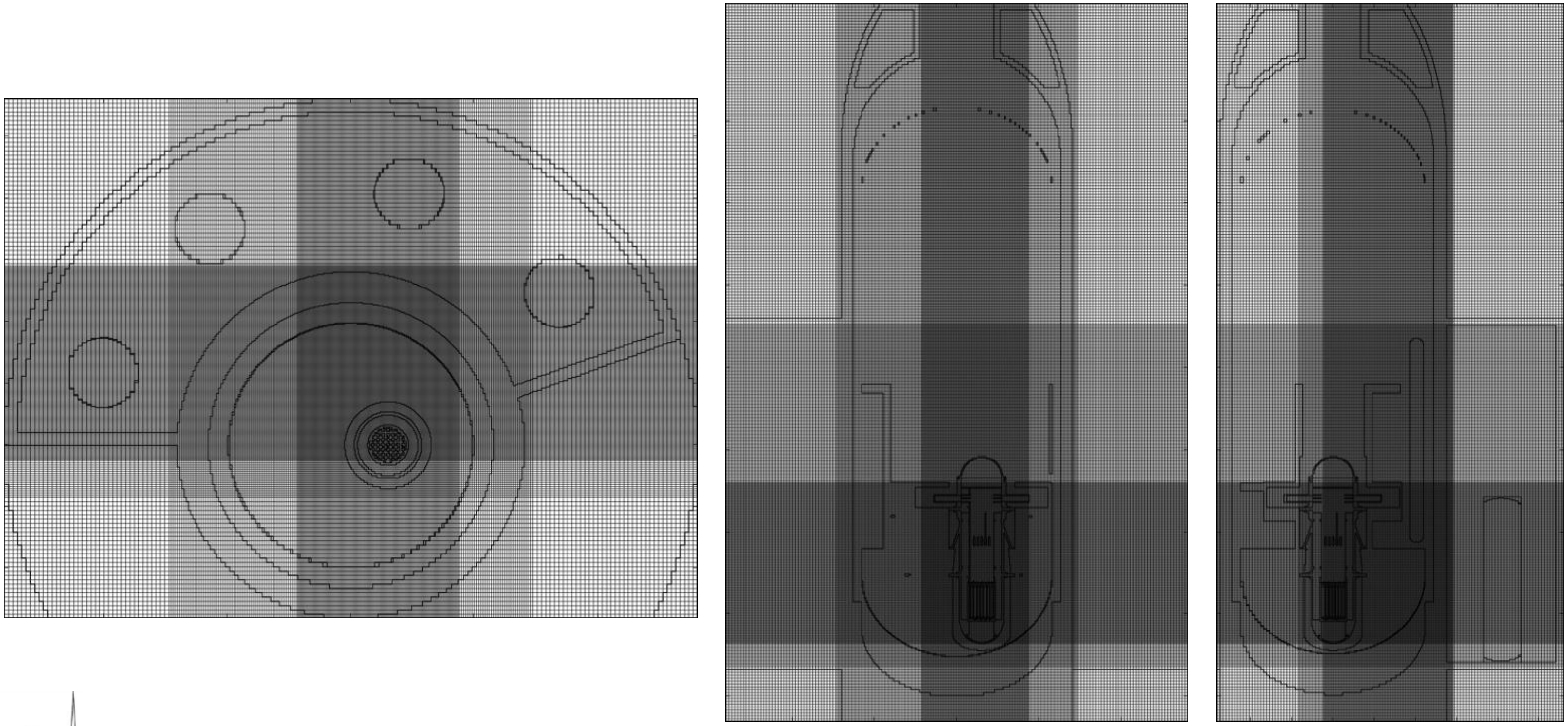




(a) top view (b) side view

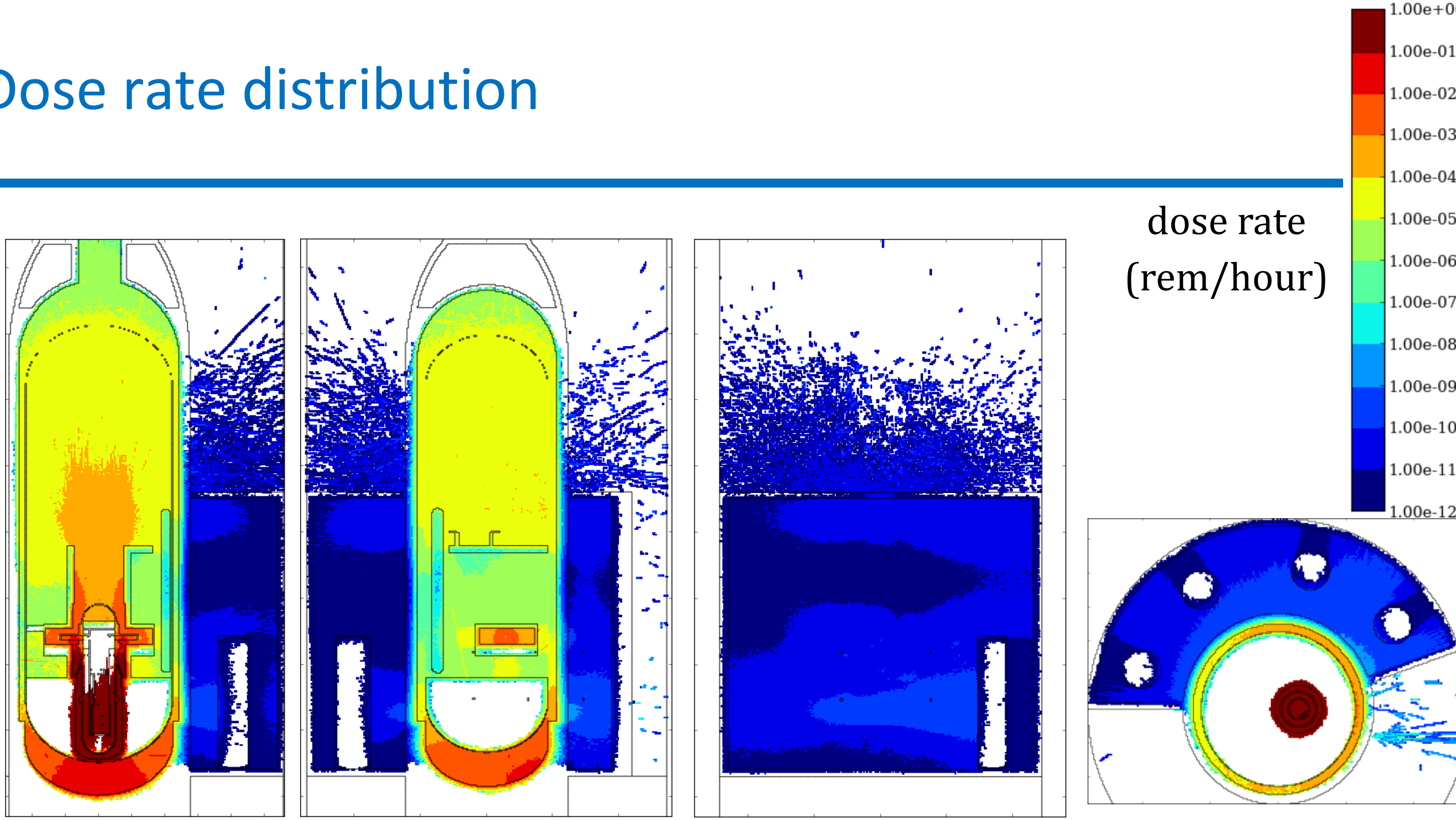
Dose rate distribution

- Good results using mesh refinement
- Adjoint solution
  - 46 group library P_1/S_4 322x267x483mesh (14GB)
    - » 9 cm side length of voxels
  - 32 hours for forward and adjoint on 32 CPUs



(a) top (b) front (b) side

Dose rate distribution



(a) side view at core centerline (x=~300cm)

(b) front view showing max flux leaving concrete shield (y=~800cm)

(c) front view showing large cross section of SGS room (y=~1450cm)

(d) top view at core centerline and showing the max flux leaving concrete shield (z=~1175cm)

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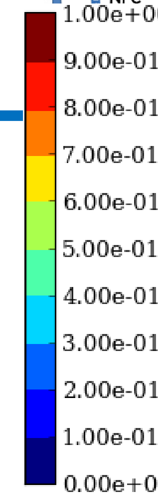
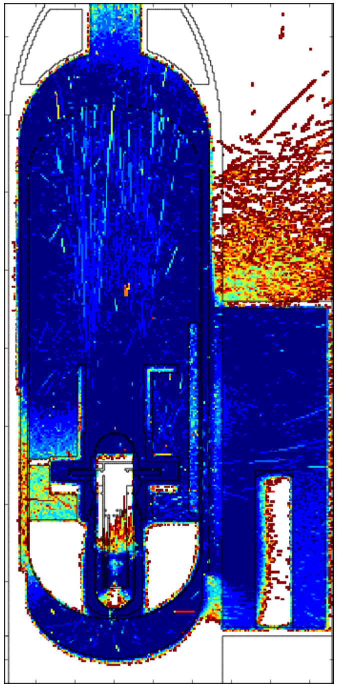
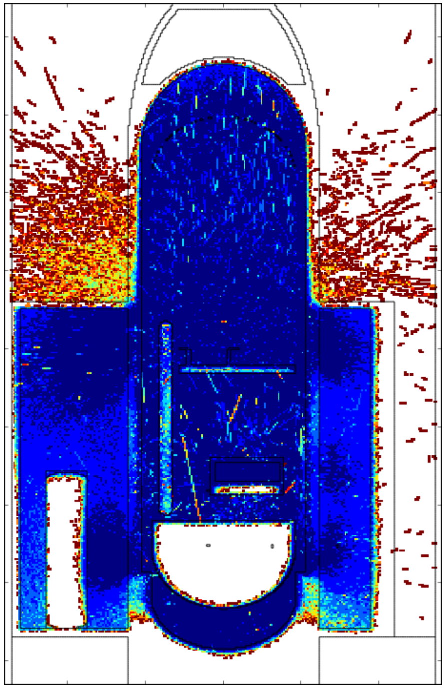
Dose rate distribution

relative uncertainty

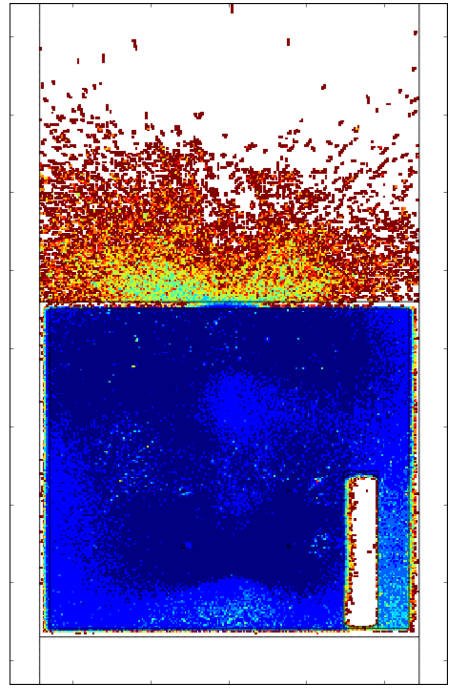




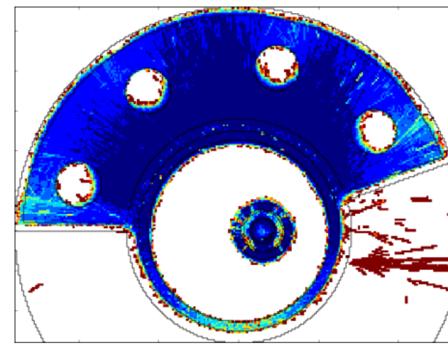
(a) side view at core centerline (x=~300cm)



(b) front view showing max flux leaving concrete shield (y=~800cm)



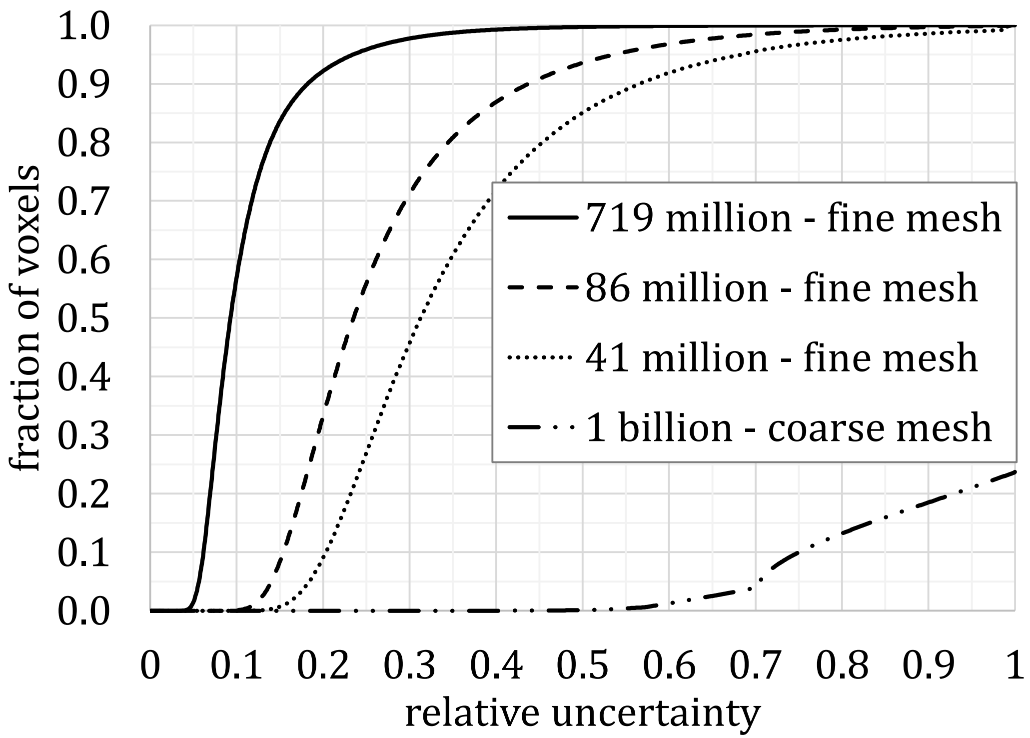
(c) front view showing large cross section of SGS room (y=~1450cm)



(d) top view at core centerline and showing the max flux leaving concrete shield (z=~1175cm)

Dose rate distribution

- MC results
  - 10 “parallel” CPUs
  - 719 million source particles
  - 56% of voxels <10% rel. unc.
  - 92% of voxels < 20% rel. unc.
  - 99% of voxels < 35%



- Conclusions
  - Large dose rate problem on detailed model
  - Achieved good results using manually refined mesh

Conclusions

- Demonstrated the use of Scale sequences (MAVRIC, ORIGEN-S COUPLE, KENO) for shielding studies within a large detailed model

- RPV lifetime assessment
- SiC detector Placement
- Gamma heating in radial neutron steel reflector
- MCHX activation
- Dose in nuclear island