Core Modeling using Data from the Approval Process for Refueling

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Structure

- Overview of selected core input parameters and their defaults
- Discussion of alternative data sources for core input parameters e.g.:
  - Core dimensions
  - Axial and radial power distribution
  - Decay heat
  - Mass inventory
  - Relation between decay heat and mass inventory
- Summary

Overview of selected core input parameters and their defaults

- Fuel geometry data ($r_{pellets}$, $r_{cladding}$, Δr_{gap}, pitch, cladding)
- Definition of radial core zones
- Axial and radial power distribution (uniform distribution is defaulted)
- Decay heat generated and radionuclide inventory
  - in spent fuel pool (no default)
  - in RPV (defaults based on:
    - Elemental calculation for 3412 MW_t Westinghouse PWR
    - Elemental calculation for 3578 MW_t General Electric BWR
    - Whole core calculation based on 1979 ANS standard for decay heat power)

Fuel geometry data

- Fuel in today's operating PWR is usually provided by different vendors and design data may not be disclosed to L2-PRA-Analyst for MELCOR modeling.
- Fuel geometry data intended for disclosure to different fuel vendors may be found in the RFQ for refueling loads and includes data such as $r_{pellets}$, $r_{cladding}$, Δr_{gap}, pitch and cladding data.
- The default data is found to still be representative of today's 16x16 PWR fuel assemblies but other PWR fuel assemblies e.g. 17x17 and 18x18 require specific modeling.

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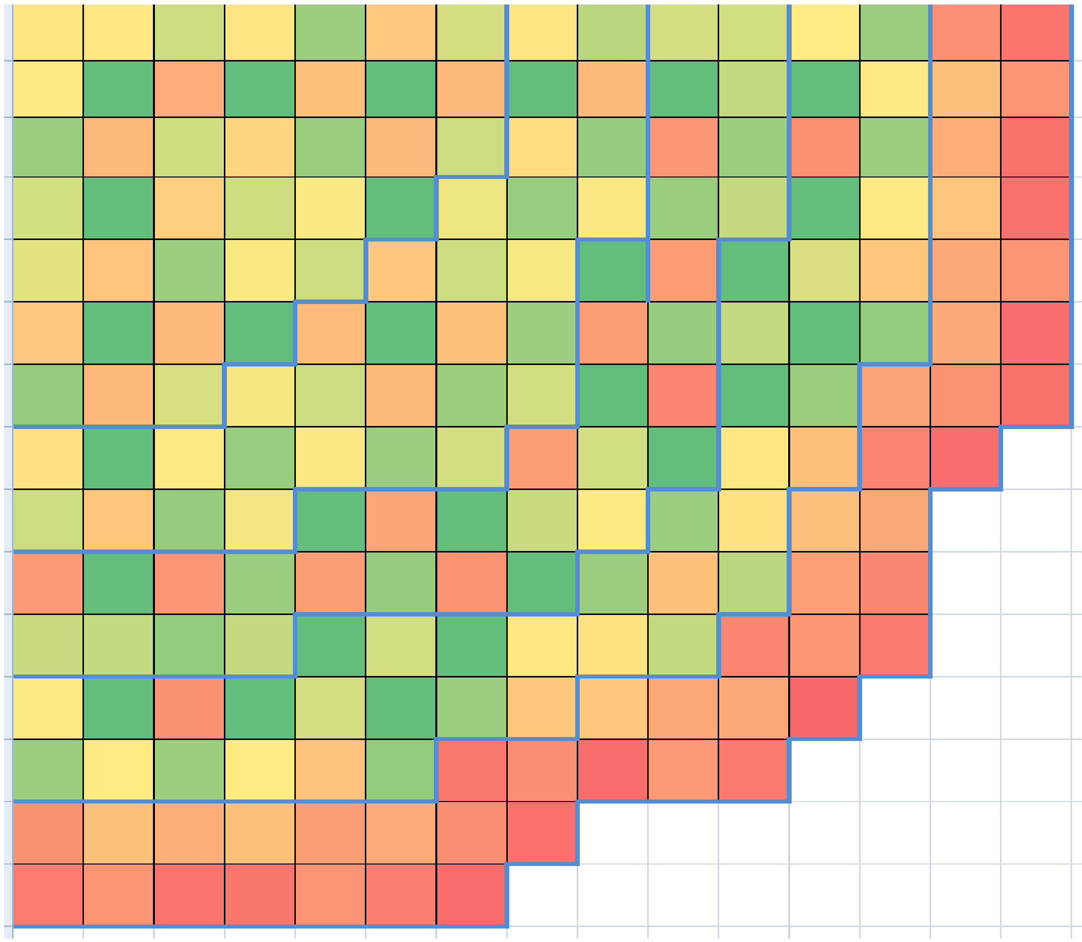
Definition of radial core zones



- Equal area zones are commonly used
- The licensing package usually quotes BOC and EOC burnup for each fuel element (low=green; high=red)
- Comparison of equal burnup zones to equal area zones:
  A=(20%; 16%; 17%; 22%; 25%)
  A=(20%; 20%; 20%; 20%; 20%)
- Except for outer zone the areas are in reasonable agreement considering the fuzziness of the zone boarders (see FRPOW)

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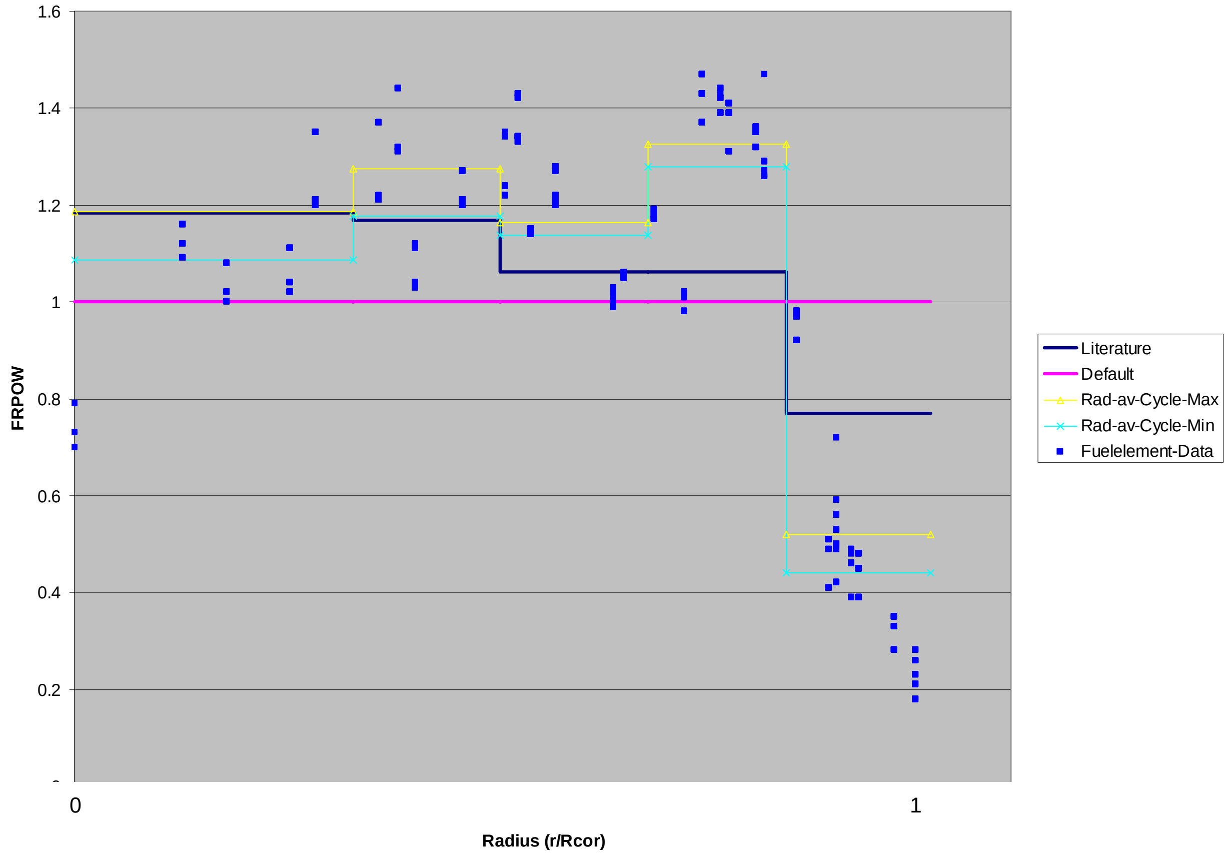
Axial and radial power distribution

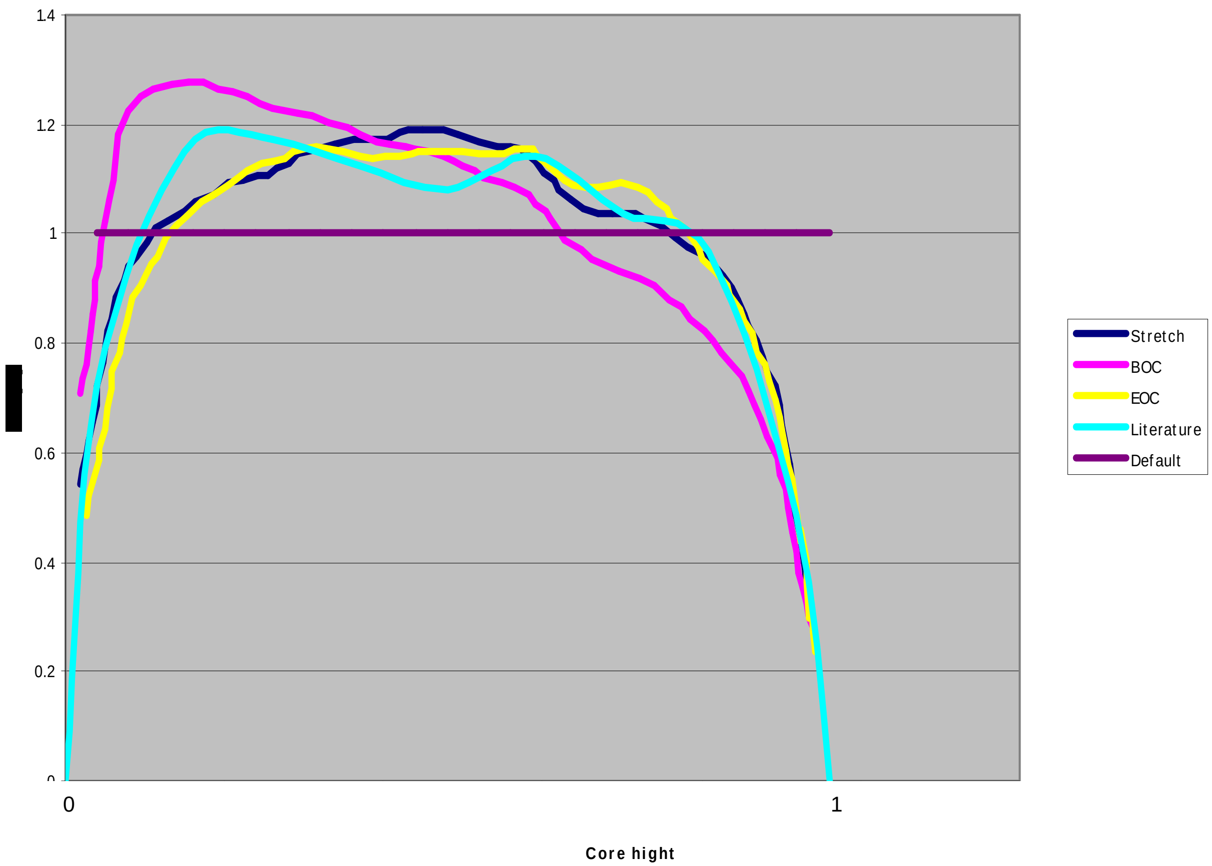
- On CORZjj03 and CORRii03 records MELCOR provides provision for the input of the axial and radial power distribution FZPOW and FRPOW.
- FZPOW as well as FRPOW are defaulted to 1.
- The refueling licensing package usually contains:
  - radial and axial power distributions at 3 or more times during the fuel cycle (e.g. BOC, Gd-Burnout and EOC)
  - Average, maximum and local maximum power factors for each fuel element
    (Using average, maximum or local maximum power factors to derive FRPOW do not produce any significant difference compared to the variation during the cycle.)

Radial power distribution



- Radial power variation as well as variation between different times in the cycle are insignificant compared to the variation between fuel elements for the inner core radii
- A significant drop in power occurs for the outer most ring and should be modeled
- Default as well as literature parameters underestimate the drop for today's cores

Axial power distribution (BWR)



- At BOC the axial power distribution is skew. At MOC and EOC and during stretch out the axial power distribution shows the “classical” cosine shape.
- The standard axial power distribution from literature shows good agreement with real data.
- When using plant specific data from the refueling licensing package the use of EOC should be considered.

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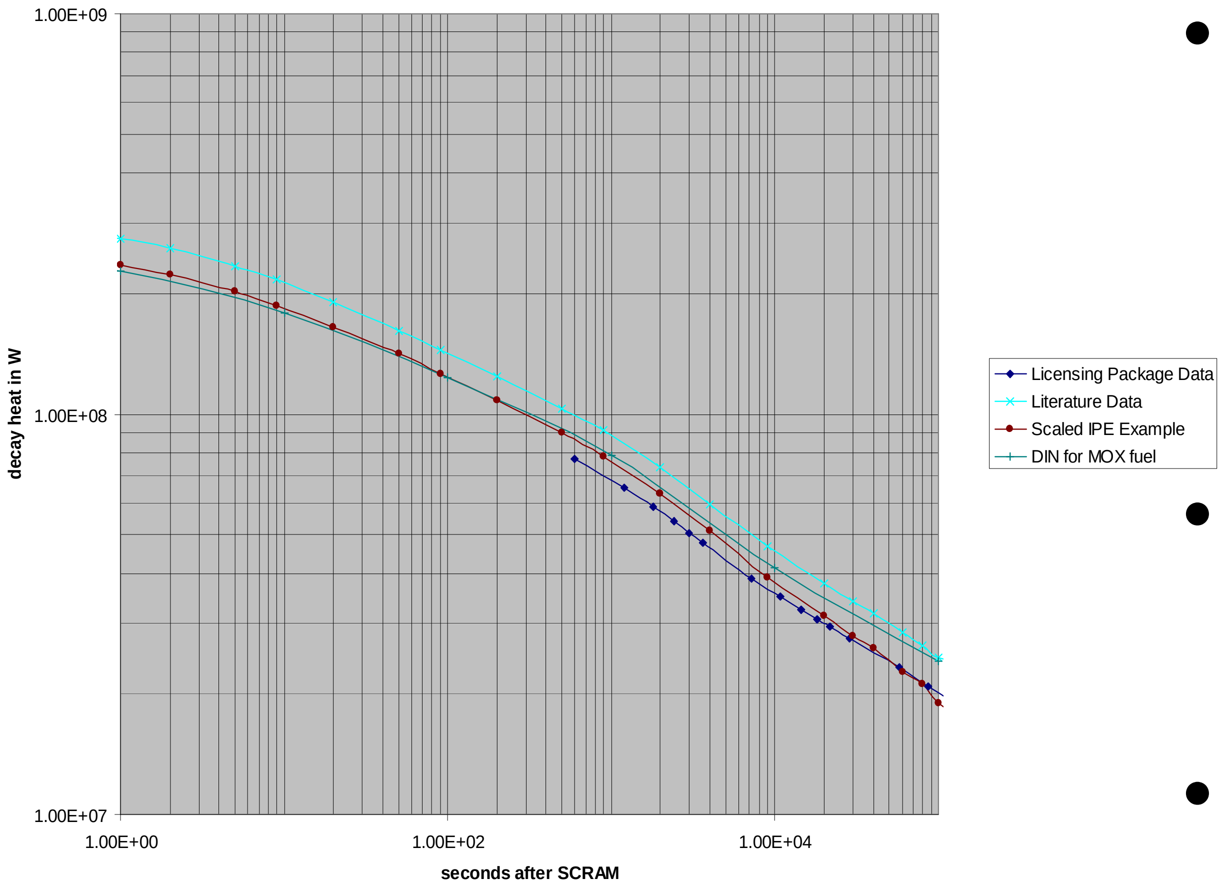
Whole core decay heat



- Scaling the data from the IPE MELCOR-Example for LaSalle (NRC Lit.) reproduces detailed data from the fuel licensing package but underestimates after about 24h
- Using the DIN-Standard for MOX-Fuel to calculate decay heat starts to overestimate after 3h
- The use of detailed data is recommended even though the IPE-example reproduces the data well.

Decay heat in spent fuel pool

- For NPPs with spent fuel pool inside the containment, the decay heat generated in the spent fuel pool contributes to the pressurization of the containment if decay heat removal is lost.
- The licensing package contains:
  - a bounding estimate demonstrating that for the fuel type used decay heat can be removed from the spent fuel pool with the available system.
  - a cycle specific analysis which decay heat needs to be removed from the spent fuel pool during the specific refueling outage.
- During the cycle the decay heat generated in the spent fuel pool drops by a factor of 4 from about 6 MW to 1.5 MW.
- Thus using spent fuel pool data immediately after reload for the decay heat in the pool would be conservative. The use of the decay heat at ≈ 5% of the length of the cycle covers more than 95% of the accident scenarios.

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Element group specific decay heat and masses

- Approaches commonly used:
  - Reference back to default ORIGEN data for PWR (3412 MW_t) and BWR (3578 MW_t)
  - Use mass inventory from official emergency guidelines or generic fuel licensing together with decay heat calculation according to current standard (data for radio nuclides without significant contribution to decay heat are usually estimated from MELCOR default tables)
  - Dedicated ORIGEN runs for UO2 and MOX producing element/isotope specific data. Variants:
    - Burnup according to average of core zones
    - Burnup according to idealized cycles

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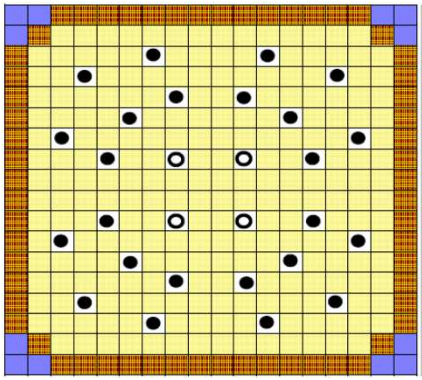
Example of iodine inventories derived using the three methods

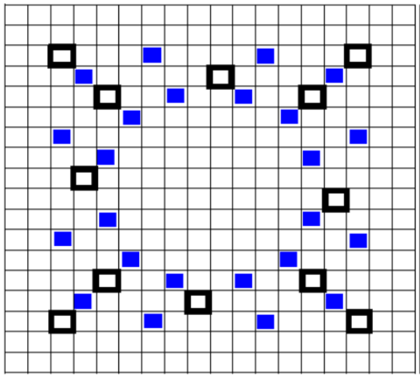
mass inventory in g			
Isotope	ORIGEN using average zone burnup	Scaled MELCOR BWR default	Fuel licensing package
I-131	$1{,}06 \cdot 10^3$	$8{,}54 \cdot 10^2$	$1{,}44 \cdot 10^3$
I-132	$1{,}80 \cdot 10^1$	$1{,}50 \cdot 10^1$	$2{,}97 \cdot 10^1$
I-133	$2{,}23 \cdot 10^2$	$1{,}97 \cdot 10^2$	$3{,}03 \cdot 10^2$
I-134	$1{,}04 \cdot 10^1$	$9{,}12 \cdot 10^0$	$1{,}94 \cdot 10^0$
I-135	$6{,}84 \cdot 10^1$	$5{,}92 \cdot 10^1$	-
Sum	$1{,}38 \cdot 10^3$	$1{,}13 \cdot 10^3$	$1{,}78 \cdot 10^3$

- The three approaches show reasonable agreement except for the low value of I-134 derived from the licensing package data.

Example of ORIGEN run using burnup from idealized cycles (1 of 2)

- Generation of ARP-Libraries for specific fuel type and geometry using SCALE/TRITON





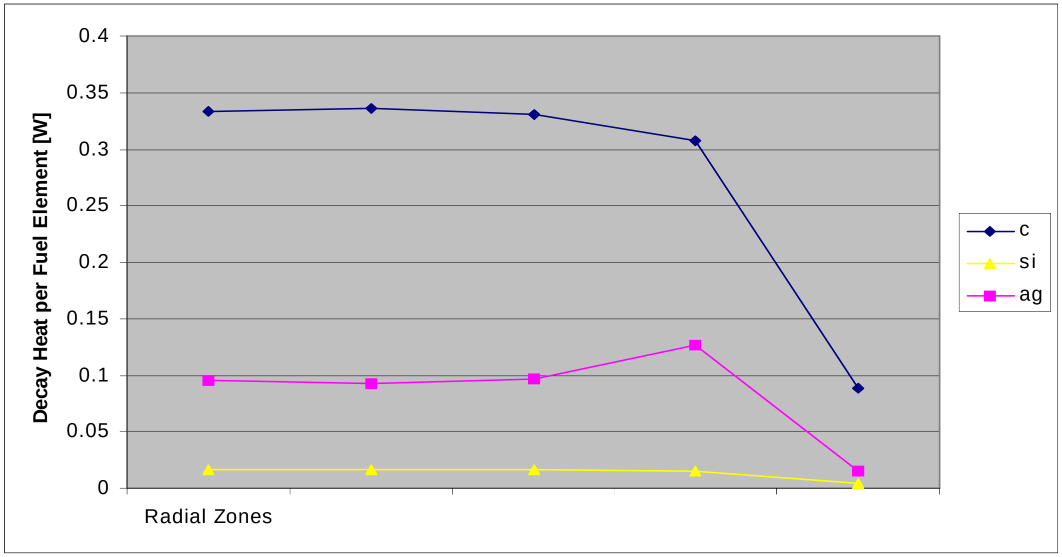
- Simulation of the last cycles relevant to fuel burnup for the specific plant with ORIGEN according to refuel licensing package data.
- Summation of calculated element masses using the burnup states of the different fuel elements according to the latest refueling licensing package.

Example of ORIGEN run using burnup from idealized cycles (2 of 2)

	1st cycle				2nd cycle				3rd cycle				4th cycle				
Element	#UO2	#MOX	m in UO2-FE [kg]	m in MOX-FE [kg]	#UO2	#MOX	m(UO2)[kg]	m(MOX)[kg]	#UO2	#MOX	m(UO2)[kg]	m(MOX)[kg]	#UO2	#MOX	m(UO2)[kg]	m(MOX)[kg]	Sum
ag	32	12	7.65E-03	4.86E-02	36	12	2.36E-02	9.46E-02	40	12	4.29E-02	1.34E-01	37	12	6.39E-02	1.67E-01	1.05E+01
as	32	12	2.58E-05	2.53E-05	36	12	5.11E-05	4.85E-05	40	12	7.40E-05	6.83E-05	37	12	9.51E-05	8.61E-05	1.19E-02
ba	32	12	3.01E-01	2.76E-01	36	12	6.10E-01	5.67E-01	40	12	9.15E-01	8.58E-01	37	12	1.23E+00	1.16E+00	1.48E+02
br	32	12	4.78E-03	3.66E-03	36	12	9.40E-03	7.20E-03	40	12	1.34E-02	1.03E-02	37	12	1.69E-02	1.30E-02	2.06E+00
ce	32	12	6.96E-01	5.72E-01	36	12	1.28E+00	1.08E+00	40	12	1.78E+00	1.55E+00	37	12	2.24E+00	1.99E+00	2.84E+02
cs	32	12	6.21E-01	6.94E-01	36	12	1.26E+00	1.40E+00	40	12	1.84E+00	2.03E+00	37	12	2.38E+00	2.62E+00	3.08E+02
i	32	12	3.86E-02	6.57E-02	36	12	8.12E-02	1.27E-01	40	12	1.25E-01	1.82E-01	37	12	1.69E-01	2.32E-01	2.27E+01
kr	32	12	9.04E-02	4.21E-02	36	12	1.73E-01	8.52E-02	40	12	2.41E-01	1.25E-01	37	12	3.00E-01	1.64E-01	3.48E+01
la	32	12	2.69E-01	2.38E-01	36	12	5.39E-01	4.87E-01	40	12	7.85E-01	7.22E-01	37	12	1.02E+00	9.51E-01	1.26E+02
mo	32	12	6.58E-01	5.92E-01	36	12	1.40E+00	1.26E+00	40	12	2.09E+00	1.88E+00	37	12	2.75E+00	2.49E+00	3.31E+02
nb	32	12	2.49E-02	1.82E-02	36	12	2.43E-02	1.87E-02	40	12	2.29E-02	1.84E-02	37	12	2.16E-02	1.80E-02	4.26E+00
nd	32	12	7.30E-01	6.01E-01	36	12	1.57E+00	1.32E+00	40	12	2.38E+00	2.02E+00	37	12	3.16E+00	2.73E+00	3.72E+02
np	32	12	9.15E-02	4.25E-02	36	12	2.04E-01	6.36E-02	40	12	3.25E-01	8.38E-02	37	12	4.39E-01	1.03E-01	4.30E+01
pd	32	12	1.14E-01	4.28E-01	36	12	3.58E-01	9.70E-01	40	12	6.94E-01	1.55E+00	37	12	1.11E+00	2.16E+00	1.47E+02
pm	32	12	7.20E-02	6.83E-02	36	12	1.08E-01	1.10E-01	40	12	1.22E-01	1.30E-01	37	12	1.23E-01	1.38E-01	2.10E+01
pr	32	12	2.27E-01	1.97E-01	36	12	4.75E-01	4.20E-01	40	12	7.01E-01	6.28E-01	37	12	9.11E-01	8.28E-01	1.11E+02
pu	32	12	2.64E+00	3.72E+01	36	12	4.50E+00	3.26E+01	40	12	5.74E+00	2.86E+01	37	12	6.61E+00	2.51E+01	2.20E+03
rb	32	12	8.56E-02	3.69E-02	36	12	1.63E-01	7.51E-02	40	12	2.27E-01	1.11E-01	37	12	2.83E-01	1.45E-01	3.26E+01
rh	32	12	8.76E-02	1.64E-01	36	12	1.90E-01	3.42E-01	40	12	2.73E-01	4.81E-01	37	12	3.39E-01	5.87E-01	5.20E+01
ru	32	12	4.51E-01	6.99E-01	36	12	9.64E-01	1.36E+00	40	12	1.49E+00	1.97E+00	37	12	2.04E+00	2.56E+00	2.63E+02
sb	32	12	3.06E-03	5.76E-03	36	12	6.49E-03	1.06E-02	40	12	9.78E-03	1.45E-02	37	12	1.29E-02	1.76E-02	1.78E+00
se	32	12	1.23E-02	8.34E-03	36	12	2.43E-02	1.67E-02	40	12	3.47E-02	2.43E-02	37	12	4.43E-02	3.14E-02	5.26E+00
sn	32	12	7.80E-03	1.52E-02	36	12	1.83E-02	3.08E-02	40	12	2.97E-02	4.52E-02	37	12	4.20E-02	5.91E-02	5.46E+00
sr	32	12	2.49E-01	1.00E-01	36	12	4.44E-01	1.91E-01	40	12	6.00E-01	2.75E-01	37	12	7.30E-01	3.54E-01	8.60E+01
tc	32	12	1.80E-01	1.74E-01	36	12	3.56E-01	3.50E-01	40	12	5.10E-01	5.06E-01	37	12	6.48E-01	6.49E-01	8.31E+01
te	32	12	9.53E-02	1.14E-01	36	12	1.97E-01	2.27E-01	40	12	2.96E-01	3.31E-01	37	12	3.95E-01	4.31E-01	4.99E+01
u	32	12	5.30E+02	4.95E+02	36	12	5.21E+02	4.92E+02	40	12	5.12E+02	4.88E+02	37	12	5.04E+02	4.85E+02	9.84E+04
xe	32	12	1.08E+00	1.06E+00	36	12	2.24E+00	2.19E+00	40	12	3.36E+00	3.26E+00	37	12	4.46E+00	4.33E+00	5.45E+02
y	32	12	1.27E-01	5.23E-02	36	12	2.28E-01	9.90E-02	40	12	3.11E-01	1.42E-01	37	12	3.82E-01	1.84E-01	4.46E+01
zr	32	12	8.44E-01	5.24E-01	36	12	1.64E+00	1.05E+00	40	12	2.33E+00	1.54E+00	37	12	2.95E+00	2.01E+00	3.50E+02

Relation between mass inventory and decay heat generation

- Averaging the decay heat per unit element mass inventory over the whole core means that decay heat generated by short lived isotopes is also assigned to the mass inventory of long lived isotopes.
- The outer radial zone has high mass inventory (see slides on zoning and burnup)
- The decay heat generated by the element groups in the outer zone is usually small due to low power density.
- Assigning the mass inventory according to radial and axial power distribution will shift mass inventory to inner zones and thus will result in faster release from the core. Compared to decay heat being unrealistically simulated in outer zones this behavior is to be favored.



Using data from generic emergency guidelines for radiation protection (EGL)

	ORIGEN	EGL	Ratio
Element	m[kg]	m[kg]	EGL/ORIGEN
ag	1.05E+01		
as	1.19E-02		
ba	1.48E+02	2.44E+00	0.0165
br	2.06E+00		
ce	2.84E+02	4.36E+01	0.1532
cs	3.08E+02	1.76E+02	0.5701
i	2.27E+01	9.65E-01	0.0425
kr	3.48E+01	2.77E+00	0.0796
la	1.26E+02	3.36E-01	0.0027
mo	3.31E+02	4.00E-01	0.0012
nb	4.26E+00	4.19E+00	0.9839
nd	3.72E+02		
np	4.30E+01	8.89E+00	0.2067
pd	1.47E+02		
pm	2.10E+01		
pr	1.11E+02	2.25E+00	0.0203
pu	2.20E+03	2.37E+03	1.0771
rb	3.26E+01		
rh	5.20E+01	1.61E-01	0.0031
ru	2.63E+02	2.91E+01	0.1103
sb	1.78E+00	4.93E-02	0.0276
se	5.26E+00		
sn	5.46E+00		
sr	8.60E+01	5.90E+01	0.6865
tc	8.31E+01	3.23E-02	0.0004
te	4.99E+01	8.06E-01	
u	9.84E+04		
xe	5.45E+02	1.15E+00	0.0021
y	4.46E+01	4.42E+00	0.0992
zr	3.50E+02	7.76E+00	0.0222
am	1.04E+05	2.60E+01	
cm		3.92E+01	

- Data for emergency guidelines for radiation protection center on the mass of nuclides relevant to radiation exposure of the public. Thus certain isotopes are neglected resulting in lower masses compared to ORIGEN calculations.
- The method using data from EGL is fit to judge the impact of a severe accident on the public.
- The method uses generally accepted data.

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Example of element decay heat derived from specific ORIGEN run

Element	***ORIGEN using typical cycle burnup (1.4GWe)***	***MELCOR PWR default***
	Decay heat at shutdown (W/kg)	
As	9.50E+07	1.47E+08
Se	3.51E+05	6.18E+05
Br	2.60E+06	4.76E+06
Kr	1.97E+05	3.29E+05
Rb	4.56E+05	6.37E+05
Sr	1.54E+05	1.79E+05
Y	4.92E+05	5.52E+05
Zr	2.99E+04	3.43E+04
Nb	5.16E+06	5.00E+06
Mo	2.94E+04	3.33E+04
Tc	1.74E+05	1.53E+05
Ru	1.13E+04	1.39E+04
Rh	6.25E+04	8.99E+04
Pd	1.26E+03	2.24E+03
Ag	2.95E+04	6.70E+04
Sn	3.66E+05	5.64E+05
Sb	4.08E+06	6.21E+06
Te	1.62E+05	2.73E+05
I	8.32E+05	1.21E+06
Xe	1.68E+04	2.58E+04
Cs	5.01E+04	8.98E+04
Ba	6.12E+04	1.04E+05
La	1.22E+05	2.00E+05
Ce	1.32E+04	1.89E+04
Pr	5.04E+04	7.00E+04
Nd	2.05E+03	2.62E+03
Pm	3.71E+04	4.14E+04
U	5.22E+01	4.80E+01
Np	1.12E+05	8.30E+05

- Element specific decay heat derived for a typical up to date PWR core design shows significant variation compared to MELCOR defaults.

Summary and Conclusion

- The information from the licensing package is a good source for a plant specific model of the core inventory and decay heat to be used in MELCOR calculations.
- Emergency guidelines for radiation protection provide additional inside on the relevance of the core inventory.
- Compatibility data released to fuel vendors for refueling loads provide needed geometry data for core modeling.
- While generic axial power distributions generally provide good agreement, specific core layout should be considered when radial zoning and power distributions are defined.
- Emphasis should be put on decay heat distribution compared to mass inventory.
- For today's PWR core designs significant differences have been observed compared to MELCOR default values.