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Estimation of Carbon-14 in Nuclear Power Plant Gaseous Effluents

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NRC Public Meeting

June 10, 2010

EPRI Project Objectives

- Review international research and development & data related to Carbon-14 generation and release.
- Review Carbon-14 generation and release mechanisms in nuclear power plants.
- Provide utilities with methodology for accurately estimating carbon-14 generation and release from specific nuclear power plants.
- Benchmark 2-BWRs, 2-W PWRs, 1-CE PWR, 1-B&W PWR

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Calculation of Reactor Coolant C-14 Source Term

- Production reactions
- Target concentrations
- Neutron cross-sections
- Neutron fluxes
- Target quantity in neutron flux

Production of C-14 in Coolant

Nuclear Reactions (in order of importance)

Reaction	Target Abundance (%)	Target Concentration
$^{17}O\ (n,\alpha)\ ^{14}C$	0.038	1.27E22 atoms ^{17}O/kg H_2O
$^{14}N\ (n,p)\ ^{14}C$	99.632	4.28E19 atoms ^{14}N/kg H_2O - ppm N
$^{13}C\ (n,\gamma)\ ^{14}C$	1.07	5.36E17 atoms ^{13}C/kg H_2O - ppm C

Possible Chemical Forms Produced from In-Core ^{14}C Production Reactions

Single Carbon Atom Species		Environment
CO_2	Carbon Dioxide	Oxidizing
CO	Carbon Monoxide	
$HCOOH$	Formic Acid	
$H_2C{=}O$	Formaldehyde	
CH_3OH	Methanol	
CH_4	Methane	Reducing

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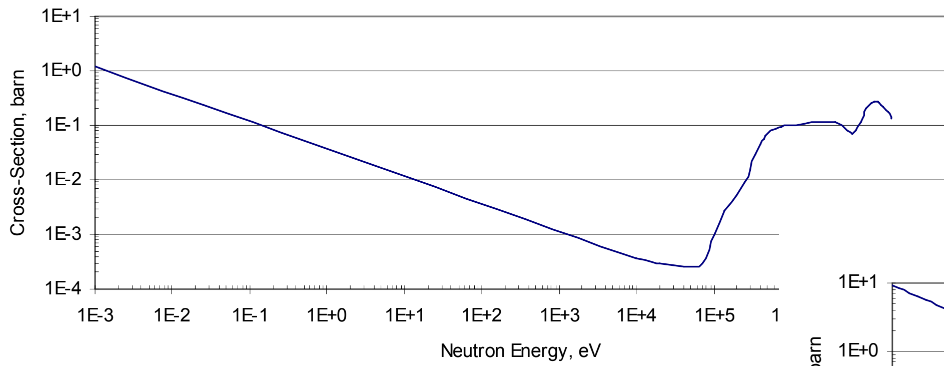
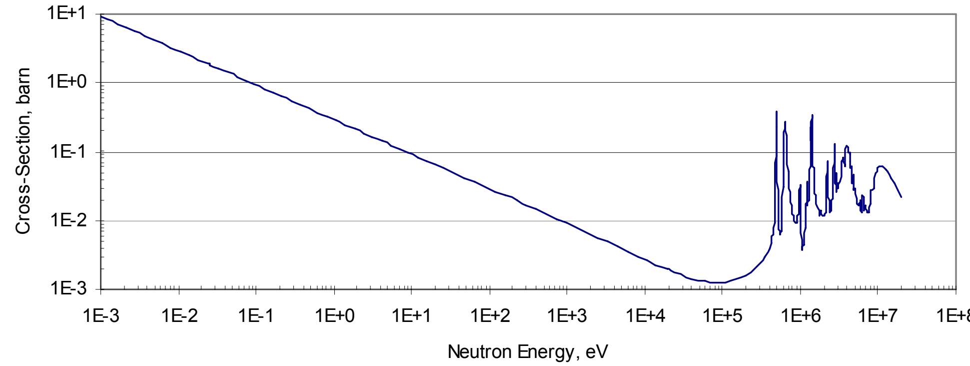
C-14 Production Cross-Sections

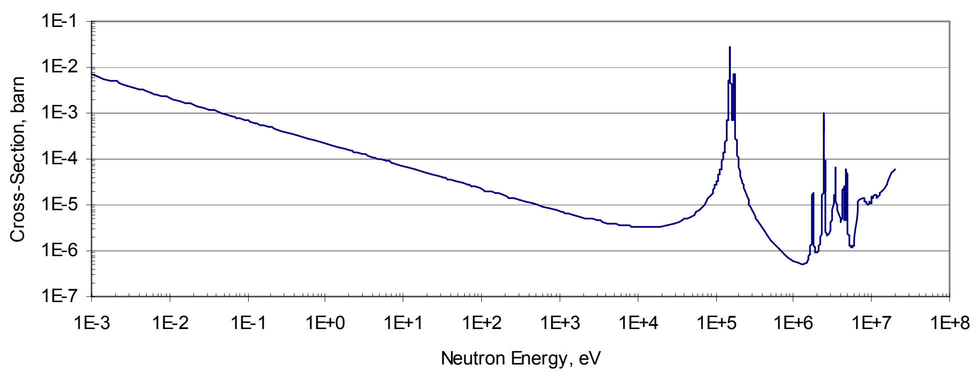
Cross-Section for $^{17}O(n,alpha)^{14}C$ Reaction



Cross-Section for $^{14}N(n,p)^{14}C$ Reaction

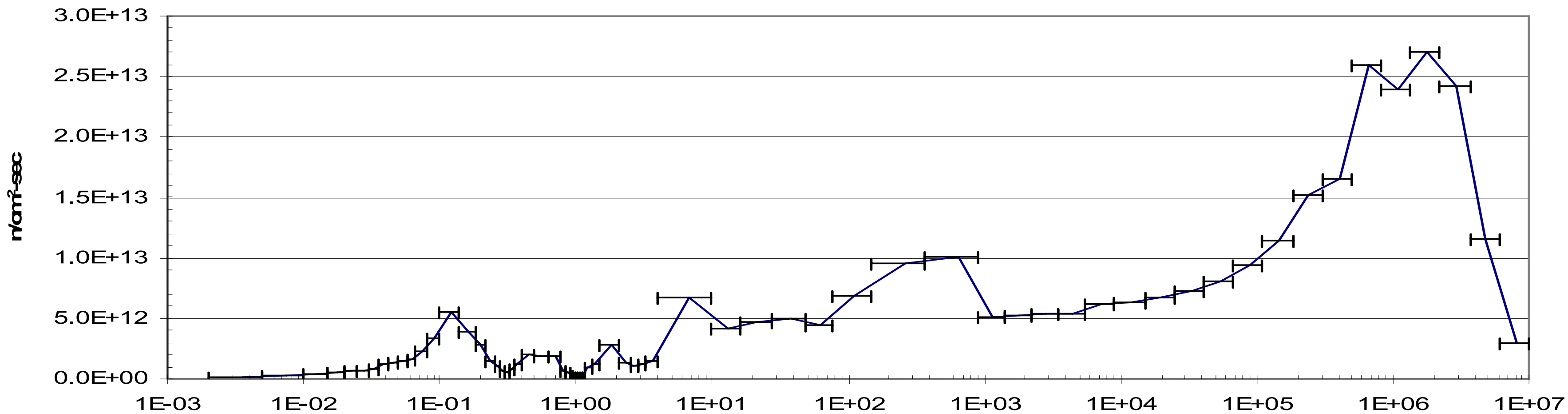


Cross-Section for $^{13}C(n,gamma)^{14}C$ Reaction

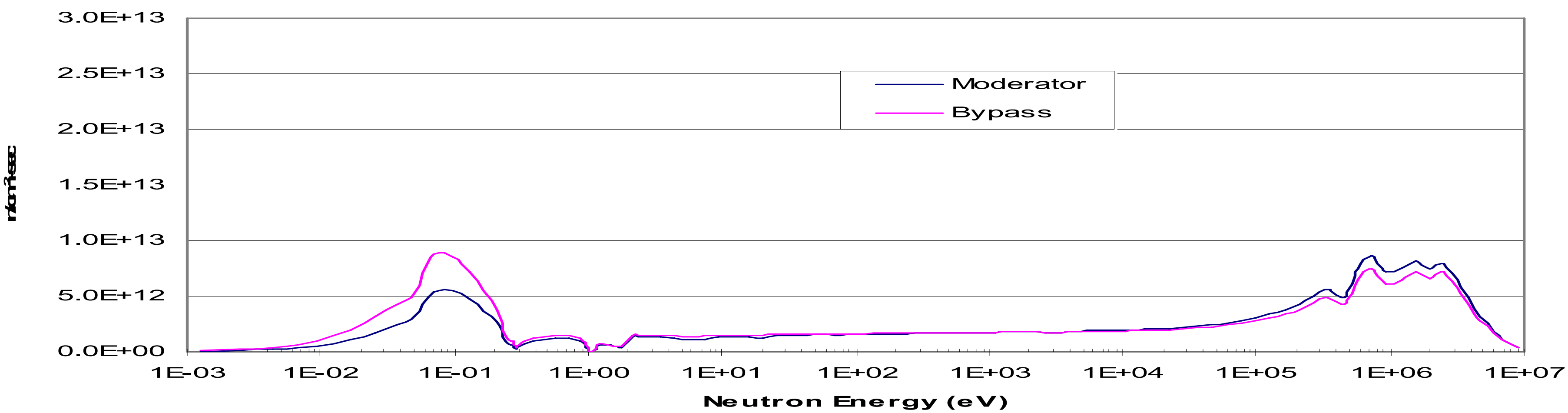


Examples of Neutron Flux Spectra

PWR Neutron Flux - 16 GWd/MTU



BWR Neutron Flux Distribution - 20 GWd/MTU



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"Effective Mass" of Coolant in Active Core

- BWR

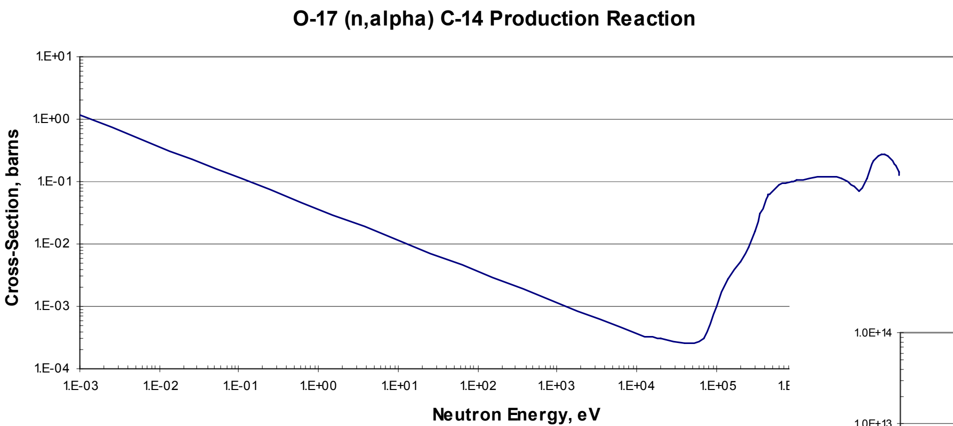
BWR-GALE Code	39,000 kg
Limerick UFSAR	33,975 kg
GE Vessel Drawings	
2894 MW_T, 624 Fuel Assemblies	24,630 kg
3579 MW_T, 748 Fuel Assemblies	29,755 kg
3579 MW_T, 732 Fuel Assemblies	27,805 kg
Oyster Creek, 1860 MWt, 560 Fuel Assemblies	26,254 kg
1593 MW_T, 368 Fuel Assemblies	15,830 kg
Bonka, 1972	33,000 kg
Fowler , 1976, 3579 MW_T BWR/6	39,500 kg

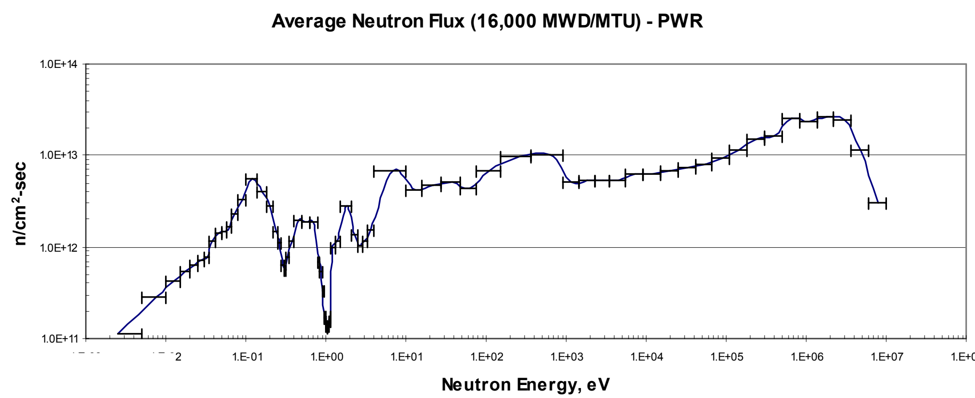
- PWR

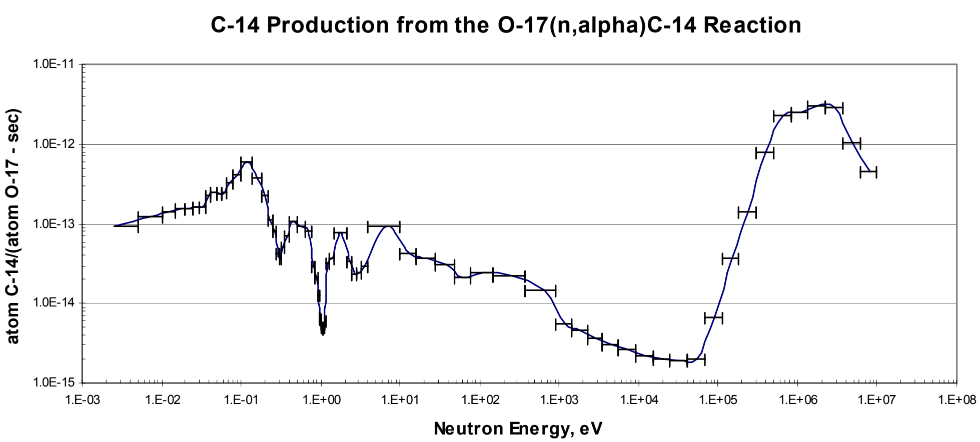
Helmholz (Braidwood 1)	14,100 kg
Bonka (1976)	13,400 kg
Fowler (1976) - 3479 MW_T CE Plant	13,700 kg

- Need site specific value to calculate individual unit source term.

Example Calculation at 16 GWd/MTU
$^{17}O(n,\alpha)^{14}C$ Reaction







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PWR Source Term Example - $^{17}O(n,\alpha)^{14}C$ Reaction

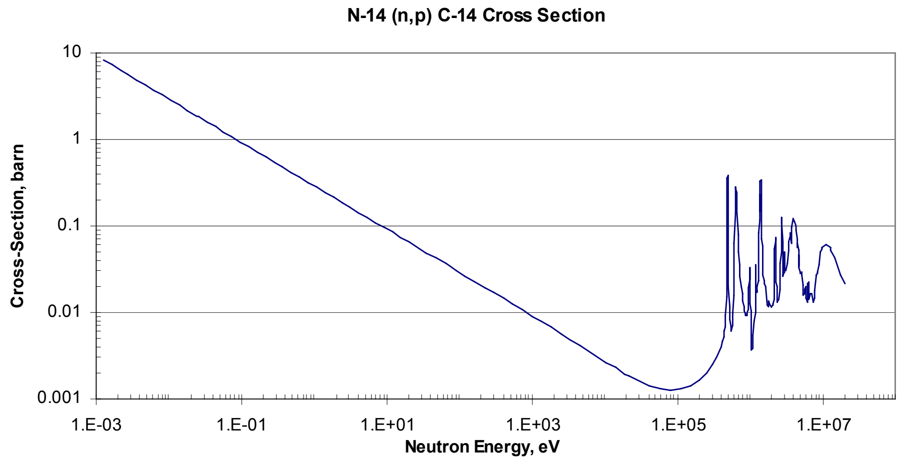
PWR "Effective Cross-Sections" for the $^{17}O(n,\alpha)^{14}C$ Reaction

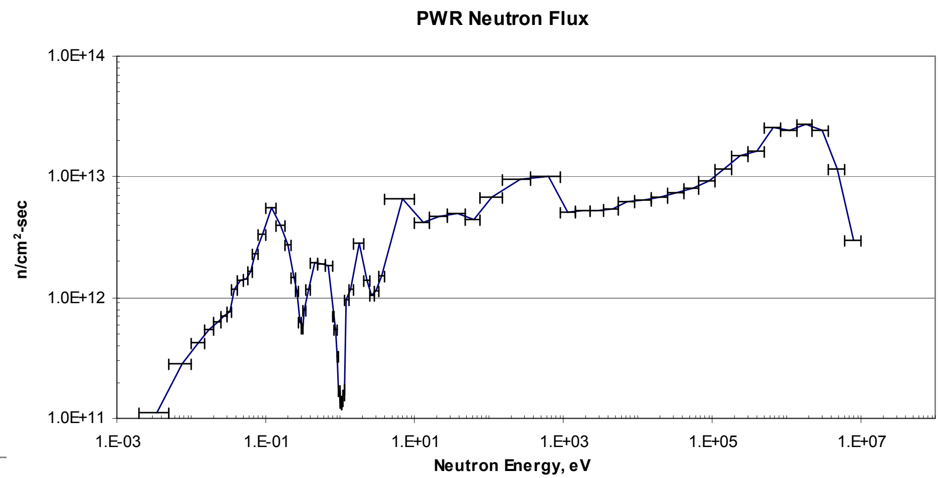
Neutron Group	Group Energy	"Effective Cross-Section", b
Thermal	≤0.625 eV	0.1189
Intermediate	>0.625 eV - <1 MeV	0.0183
Fast	≥1 MeV	0.1504

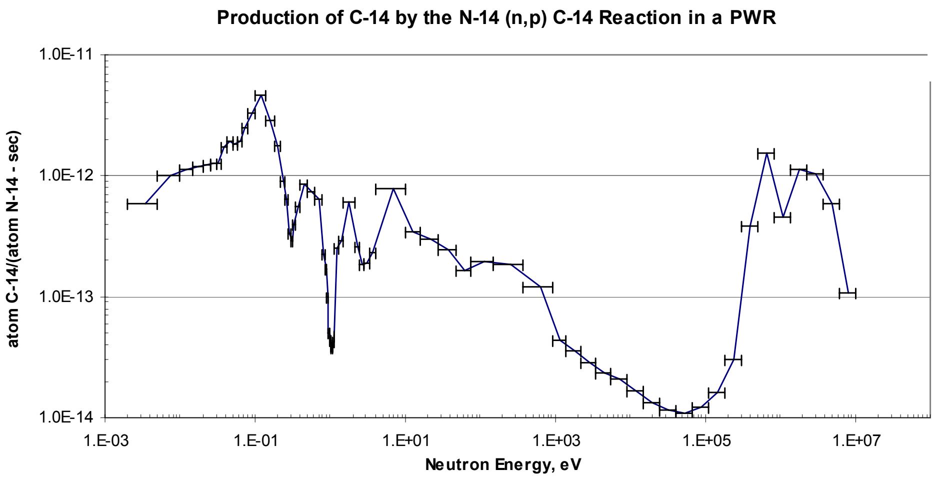
- C-14 production per kilogram of water is 2.475E-5 μCi/sec-kg
- For the 1178 MW_e (~3549 MW_{TH}) PWR with an estimated coolant mass of 14,100 kg, the total production for this reactor would be approximately:

2.475E-5*14,100 = 0.349 μCi/sec
= 11.0 Ci/yr = 9.35 Ci/GW_e-yr
= 13.1 kBq/MWh_{TH} = 0.354 μCi/MWh_{TH}

Example Calculation at 16 GWd/MTU
$^{14}N(n,p)^{14}C$ Reaction







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PWR Source Term Example - $^{14}N(n,p)^{14}C$ Reaction

PWR "Effective Cross-Sections" for the $^{14}N(n,p)^{14}C$ Reaction

Neutron Group	Group Energy	"Effective Cross-Section", b
Thermal	≤0.625 eV	0.9519
Intermediate	>0.625 eV - <1 MeV	0.0358
Fast	≥1 MeV	0.0505

- C-14 production rate per kilogram of water with 1.0 ppm dissolved nitrogen:

  2.10E-7 µCi/sec-kg-ppm N

- At a coolant mass in the core flux of 14,100 kg, the production rate for this reactor would be:

  2.10E-7*14,100 = 2.96E-3 µCi/sec-ppm N or 0.09 Ci/yr-ppm N

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PWR Source Term Example

- For the 1178 MW_e (~3549 MW_{TH}) PWR with an estimated coolant mass of 14,100 kg and 2 ppm N:
  - $^{17}O(n,\alpha)^{14}C$ Reaction = 11.0 Ci/yr
  - $^{14}N(n,p)^{14}C$ Reaction = 0.18 Ci/yr
  - Total = <u>12.8 Ci/yr</u>

BWR Source Term Example - $^{17}O(n,\alpha)^{14}C$ Reaction

"Effective Cross-Sections" for the $^{17}O(n,\alpha)^{14}C$ reaction

		"Effective Cross-Section", b	
Neutron Group	Group Energy	Moderator	Bypass
Thermal	≤0.625 eV	0.1328	0.1387
Intermediate	>0.625 eV - <1 MeV	0.0238	0.0222
Fast	≥1 MeV	0.1106	0.1106

- C-14 Production:

	Moderator Region	Bypass Region
	1.75E-5 µCi/sec-kg	2.05E-5 µCi/sec-kg

- For example, one large 3579 MW_{TH} BWR, is estimated to have 17,100 kg of coolant in the bypass region and 12,650 kg of coolant in the moderator region. The total production for this reactor would be:

1.75E-5*12,655 + 2.05E-5*17,100 = 0.572 µCi/sec
= 18.0 Ci/yr
= 21.3 kBq/MWhth
= 0.575 µCi/MWhth

BWR Source Term Example - $^{14}N(n,p)^{14}C$ Reaction

"Effective Cross-Sections" for the $^{14}N(n,p)^{14}C$ reaction

		"Effective Cross-Section", b	
Neutron Group	Group Energy	Moderator	Bypass
Thermal	≤0.625 eV	1.0560	1.0903
Intermediate	>0.625 eV - <1 MeV	0.0384	0.0423
Fast	≥1 MeV	0.0479	0.0478

- C-14 production per kilogram of water with 1.0 ppm dissolved nitrogen

Moderator Region
2.15E-7 µCi/sec-kg-ppm N

Bypass Region
3.23E-7 µCi/sec-kg-ppm N

- For example, one large 3579 MW_{th} BWR is estimated to have 17,100 kg of water in the bypass region and 12,655 kg of water in the moderator region.

- The total production for this reactor would be:

2.15E-7*12,655 + 3.23E-7*17,100 = 8.24E-3 µCi/sec-ppm N or 0.26 Ci/yr-ppm N

BWR Source Term Example

- 3579 MW_{TH} BWR, is estimated to have 17,100 kg of coolant in the bypass region and 12,650 kg of coolant in the moderator region:
  - $^{17}O(n,\alpha)^{14}C$ Reaction = 18.0 Ci/yr
  - $^{14}N(n,p)^{14}C$ Reaction = Negligible
  - Total = <u>18.0 Ci/yr</u>

What Do We Need To Do To Estimate the C-14 Source Term?

- Core "Average" Neutron Flux
  - BOC, Mid-cycle, EOC
  - Three energy groups
    - Thermal $\leq$0.625 eV
    - Intermediate >0.625 eV - <1.0 MeV
    - Fast $\geq$1.0 MeV
- Use "Effective Cross-Sections" in the three neutron energy groups

- "Effective Mass" of coolant in active core
  - Suggest use mass from "bottom" of active core to "top" of active core
  - BWR → must consider moderator and bypass regions

- Concentration of Nitrogen in the coolant (for PWR; BWR negligible.)

- Calculate BOC, mid-cycle and EOC C-14 source term
  - Average the three values

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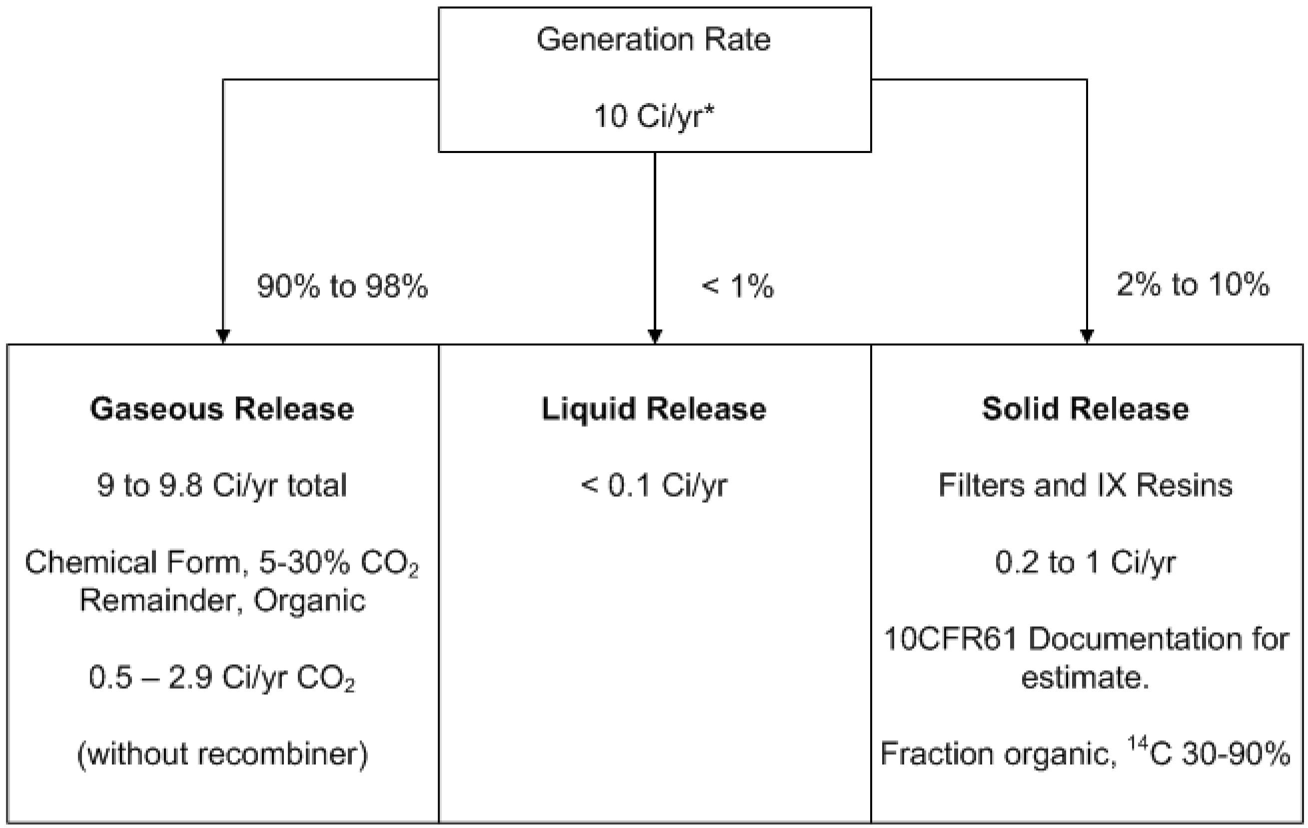
Simplistic PWR Transport Model



*Unit Specific

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Simplistic BWR Transport Model

Generation Rate

15 – 20 Ci/yr*

95% to 99%	< 0.5%	<1% to 5%
Gaseous Release 14 to 19.8 Ci/yr total Building Vent: ~3% Off-gas Vent: ~97% Chemical Form, ~95% CO_2	**Liquid Release** < 0.1 Ci/yr	**Solid Release** IX Resins HWC < NWC 0.2 to 1 Ci/yr 10CFR61 Documentation for estimate.

*Unit Specific

Current Status

- Calculation methodology for generation established.
- Collecting operational data from U.S. utilities to conduct example estimations and compare with available carbon-14 data.
- Draft methodology to be available in Fall 2010.

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