Analysis of Effective Gadolinium Depletion Model

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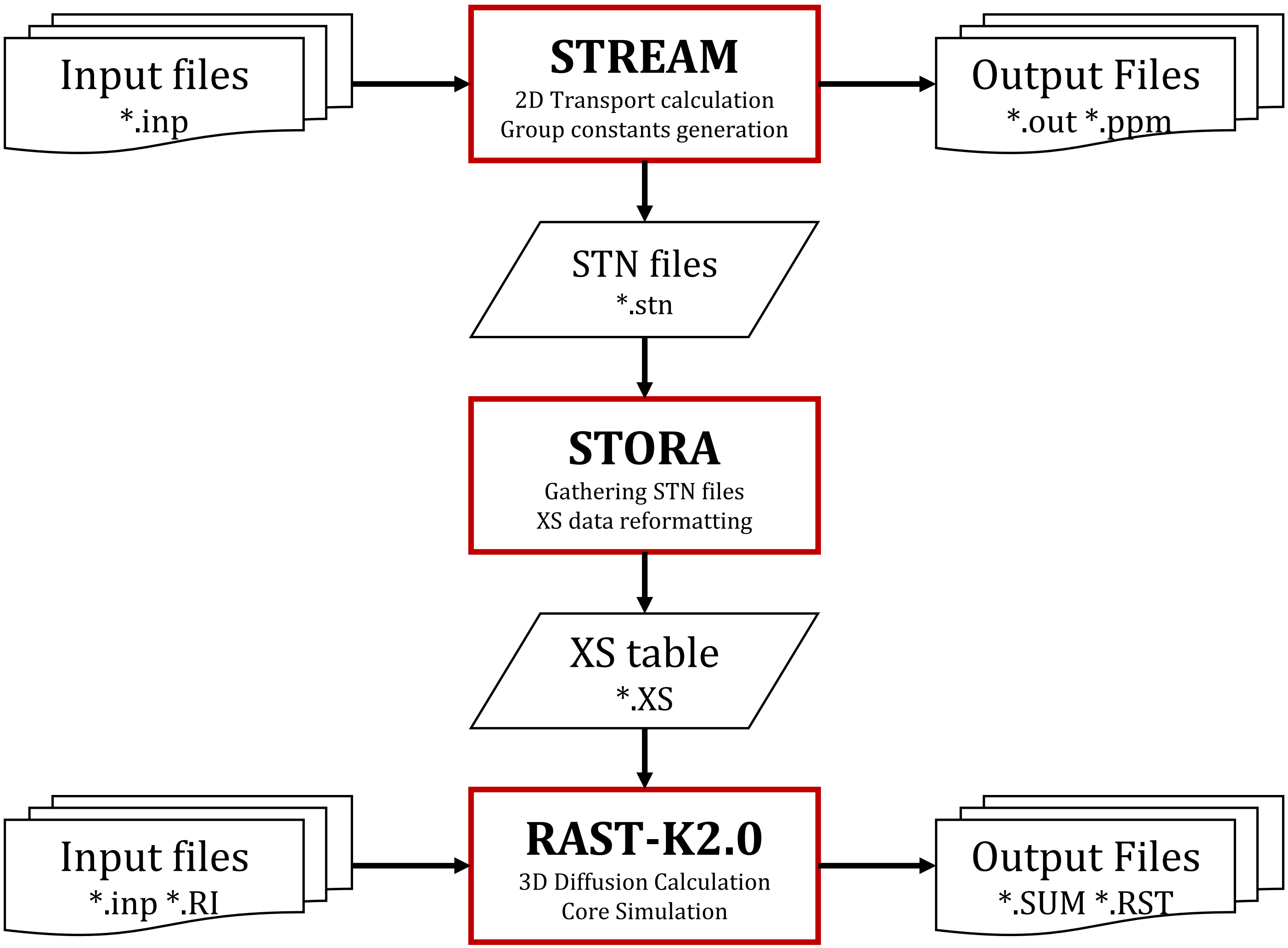
Introduction

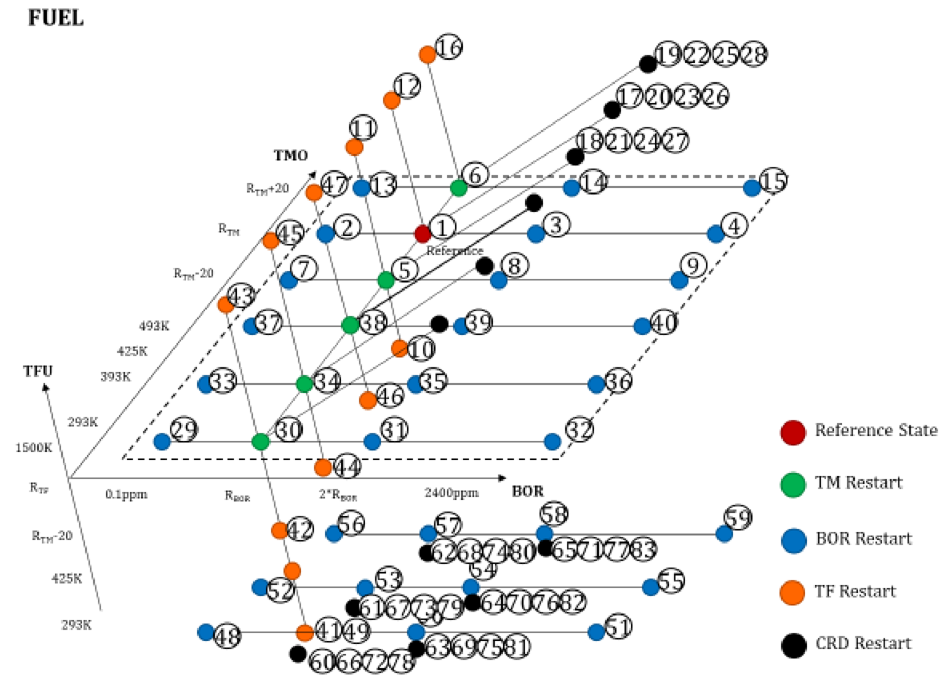
STREAM/RAST-K Code System

▪ Flowchart of 2-step Approach

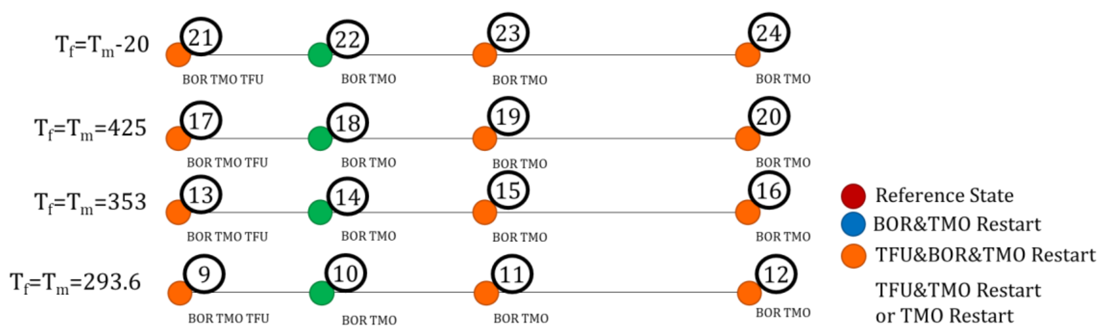


Case Matrix

- **Full Case Matrix for Fuel**
  - **Burnup Steps (~80 MWd/kg)**
  - **42 burnup steps for FA without BA**
  - **More burnup steps for FA with Gd**
  - **14 restart points**
    - $\Sigma = \Sigma_{base}(BU) + \Delta\Sigma_{TMO}(BU,TMO)$
      $+\Delta\Sigma_{BOR}(BU,BOR)$
      $+\Delta\Sigma_{TFU}(BU,TFU) + \Delta\Sigma_{\boldsymbol{CRD}}(BU,TMO,BOR)$



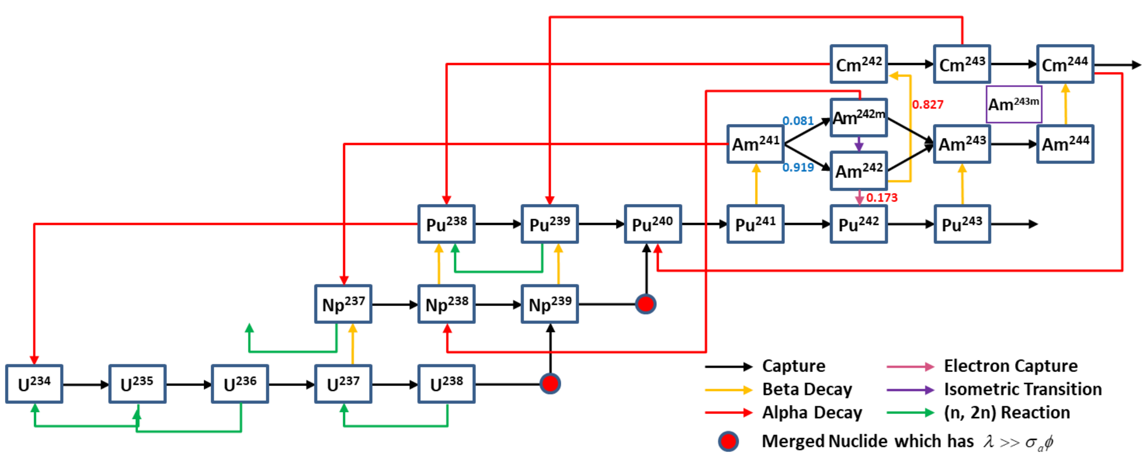
- **Full Case Matrix for Reflector**

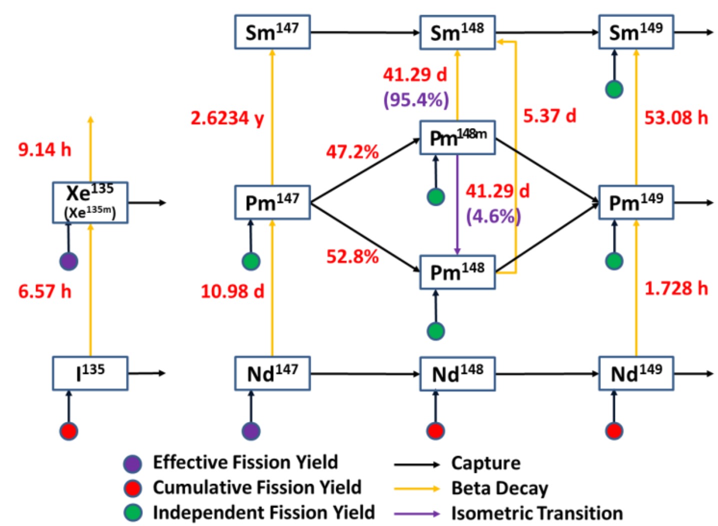


Depletion Modules in RAST-K 2.0

- **Microscopic Depletion**
  - **Capability to track the number density and XS of major isotopes**
  - **Available to consider history effect for major isotopes**
- **CRAM (Chebyshev Rational Approximation Method)**
  - **Converged well even with shorter half life of isotope**
  - **Adopted for heavy nuclides chain and fission products chain**

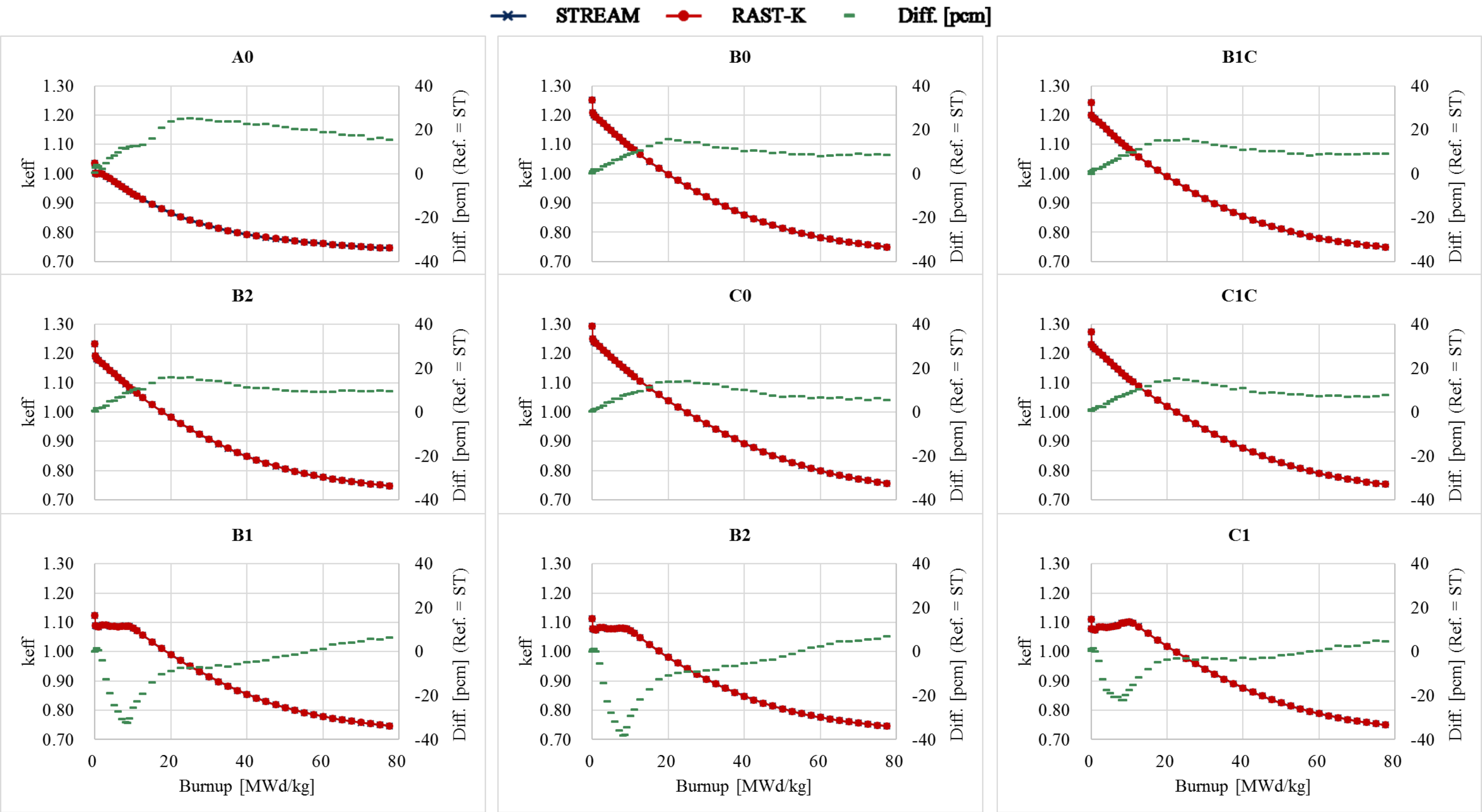
$$\dot{\mathbf{N}} = \mathbf{A}\mathbf{N} + \mathbf{b},\ \mathbf{N} = e^{\mathbf{A}t}\mathbf{N}_0 + \left(e^{\mathbf{A}t} - \mathbf{I}\right)\mathbf{A}^{-1}\mathbf{b} \qquad e^{\mathbf{A}t} = \alpha_0\mathbf{I} + 2\,\mathrm{Re}\left[\sum_{i=1}^{k/2}\alpha_i\left(\mathbf{A}t - \theta_i\mathbf{I}\right)^{-1}\right]$$





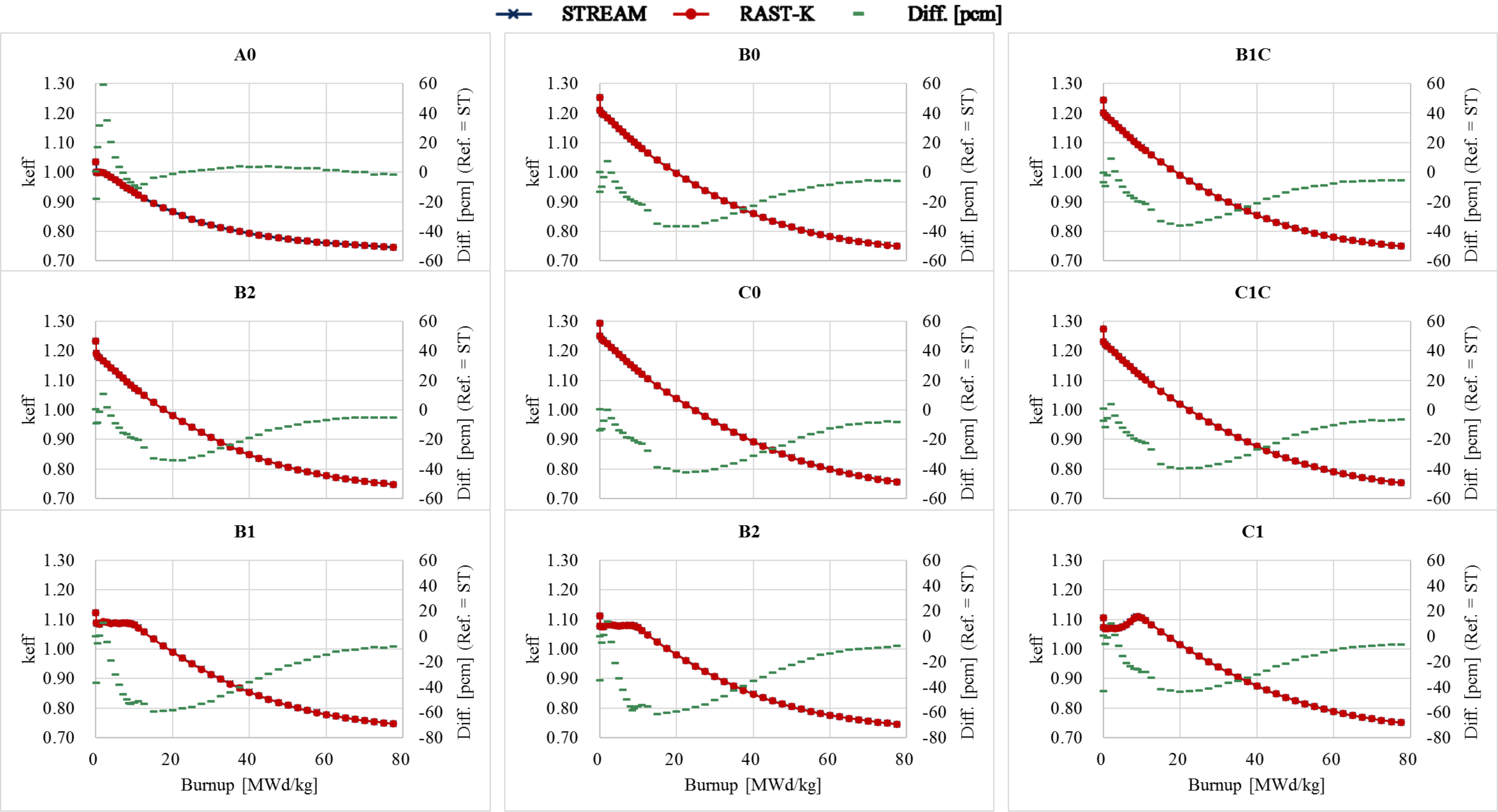
Microscopic Depletion Verification I

- **Heavy Nuclides Chain Result for SKN1 FA sets**
  - A0~C1C: FA w/o BA difference ~ ±20 pcm
  - B1~C1: FA w/ gadolinia difference~± 30pcm



Microscopic Depletion Verification II

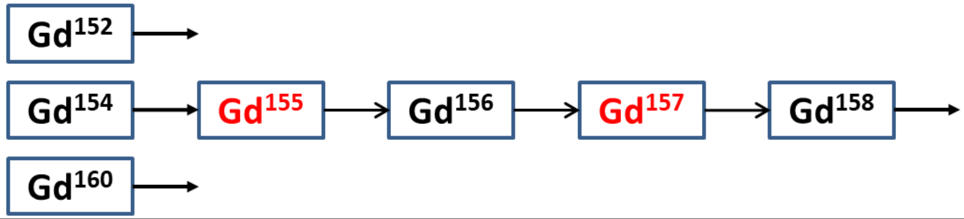
- **Heavy Nuclides + FPs Chain Result for SKN1 FA sets**
  - A0~C1C: FA w/o BA difference ~ ±40 pcm
  - B1~C1: FA w/ gadolinia difference~± 80pcm



Gd Depletion Solver

Gd Isotopes Burnup Chain

I. Direct Numerical Solution of Linear Chain



$$\frac{dN_m(t)}{dt} = N_{m-1}(t)\sigma_{m-1}(t)\varphi(t) - N_m(t)\sigma_m(t)\varphi(t), \left(\mathrm{m} = {}^{154}\mathrm{Gd} \text{ to } {}^{158}\mathrm{Gd}\right),$$

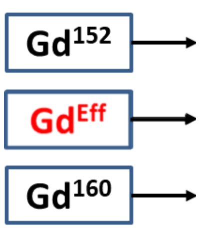
where N_m = the number density of isotope m, as a function of time (t)

$\sigma_{\mathrm{m}}(t)$ = the microscopic absorption cross section of isotope m

$\varphi(t)$ = the neutron flux

II. Effective Gd Isotope Depletion

These definitions depend only on the structure of burnup chain, not on cross sections



$$N_{\mathrm{Gd^{eff}}} = 5N_{\mathrm{Gd^{154}}} + 4N_{\mathrm{Gd^{155}}} + 3N_{\mathrm{Gd^{156}}} + 2N_{\mathrm{Gd^{157}}} + N_{\mathrm{Gd^{158}}}$$

$$\sigma_{\mathrm{Gd^{eff}}} = \frac{\Sigma_{\mathrm{Gd^{154}}} + \Sigma_{\mathrm{Gd^{155}}} + \Sigma_{\mathrm{Gd^{156}}} + \Sigma_{\mathrm{Gd^{157}}} + \Sigma_{\mathrm{Gd^{158}}}}{N_{\mathrm{Gd^{eff}}}}$$

where $N_{\mathrm{Gd^{eff}}}$ = the effective number density

$\sigma_{\mathrm{Gd^{eff}}}$ = the effective microscopic cross section

Simulation Code

- **Tested Code**
  - **STREAM/RAST-K 2.0**
  - **Reference code: STREAM**

- **STREAM Calculation Conditions**
  - **3-ring for Fuel pins, 10-ring for Gadolinia pins**
  - **Quadratic depletion for Gd isotopes**
  - **Critical spectrum OFF**
  - **Reflective B.C. for all directions**

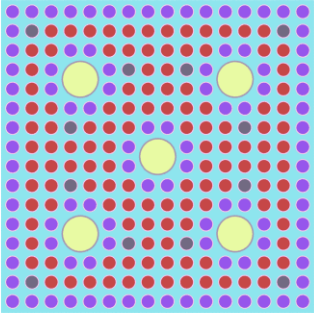
- **RAST-K 2.0 Calculation Conditions**
  - **Microscopic Depletion**
  - **Eigenvalue search mode**
  - **Reflective B.C. for all directions**
  - **Transient Xe, Transient Sm**

Test Model I

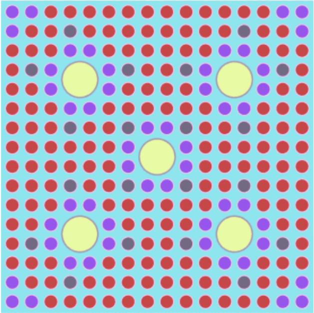
▪ Test Model

- **16 × 16 Combustion Engineering (CE) type fuel assembly**
  - 850 K for fuel, 584 K for other materials
  - Boron concentration of 700 ppm

Case	Fuel Pin (^{235}U wt.%)	Fuel Pins	Gadolinia Pin (^{235}U/Gd_2O_3 wt.%)	Gd Pins
1	3.4/2.9	124/100	0.7/6.0	12
2	4.7/4.1	164/52	2.2/8.0	20



Case 1



Case 2

▪ 35 Depletion Steps for Gadolinia Assembly

0 0.1 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5
8 8.5 9 9.5 10 11 12.5 15 17.5 20 22.5 25 27.5 30 32.5 35 37.5
40

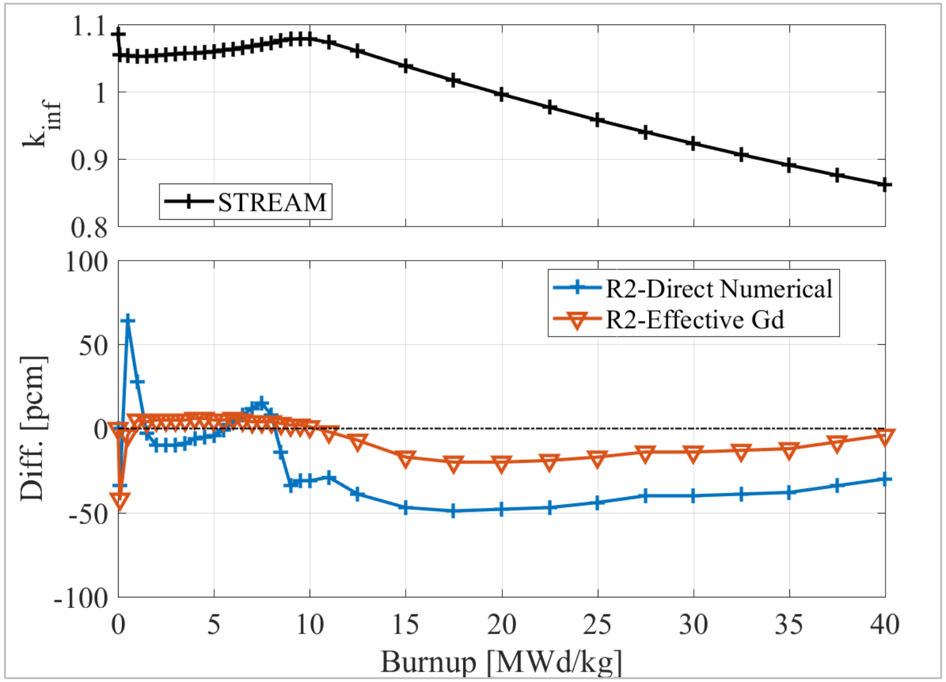
Test Cases I Depletion Results – k_{inf}

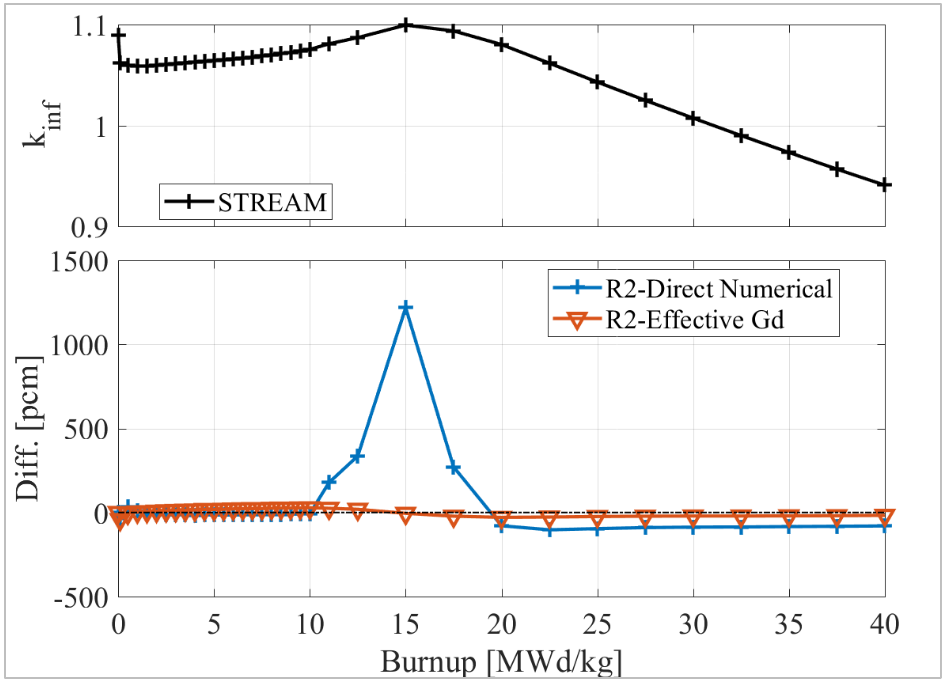
Case 1

- **Effective Gd ±20 pcm diff**
- **Direct Numerical Sol. ±60 pcm diff**

Case 2

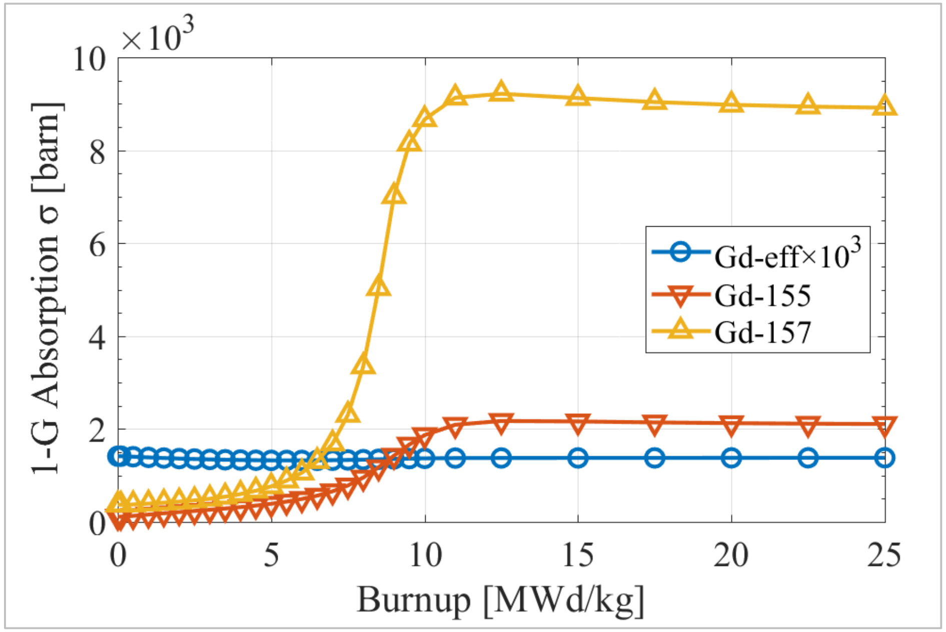
- **Effective Gd ±30 pcm diff**
- **Direct Numerical Sol. >1000 pcm diff**



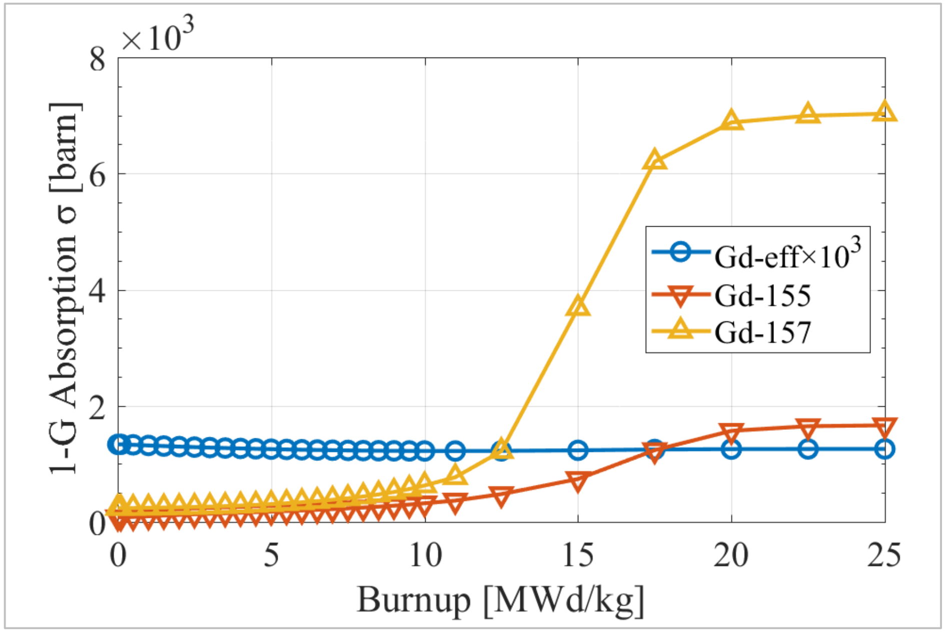


Test Cases I Depletion Results – 1G Absorption XS

Case 1



Case 2



Test Cases II

- **35 Depletion Steps for Gadolinia Assembly (Coarse)**

0	0.1	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5
8	8.5	9	9.5	10	11	12.5	15	17.5	20	22.5	25	27.5	30	32.5	35	37.5
40																

- **70 Depletion Steps for Gadolinia Assembly (Fine)**

0	0.1	0.5	1	1.5	2	2.5	3	3.5	4	5	5	5.5	6	6.5	7
7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	13	13	13.5	14	14.5	15
15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	21	21	21.5	22	22.5	23
23.5	24	24.5	25	25.5	26	26.5	27	27.5	28	29	29	29.5	30	30.5	31
31.5	32	32.5	35	37.5	40										

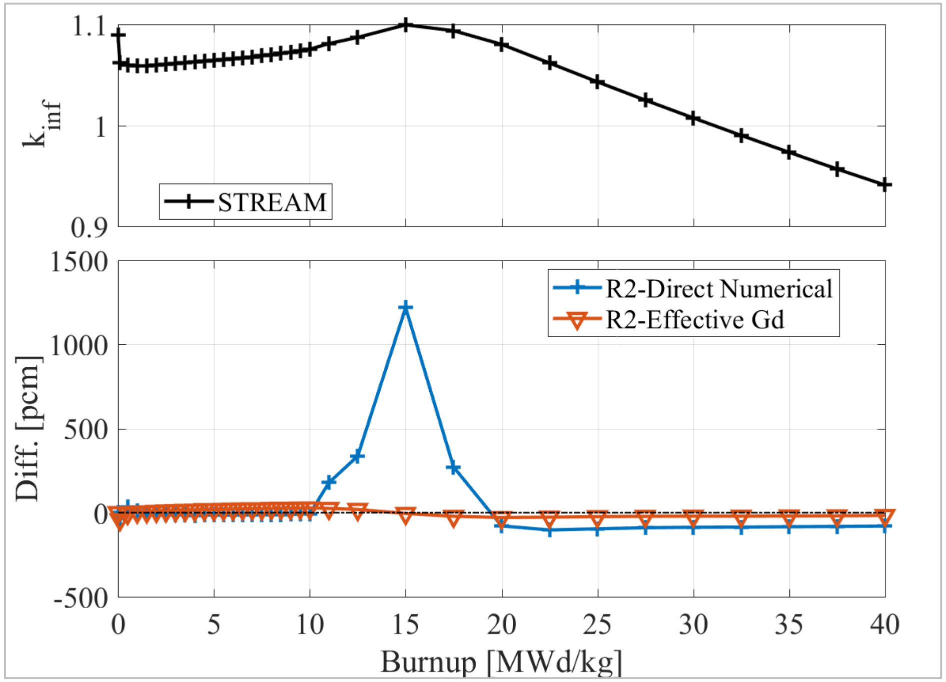
Test Cases II Depletion Results – k_{inf}

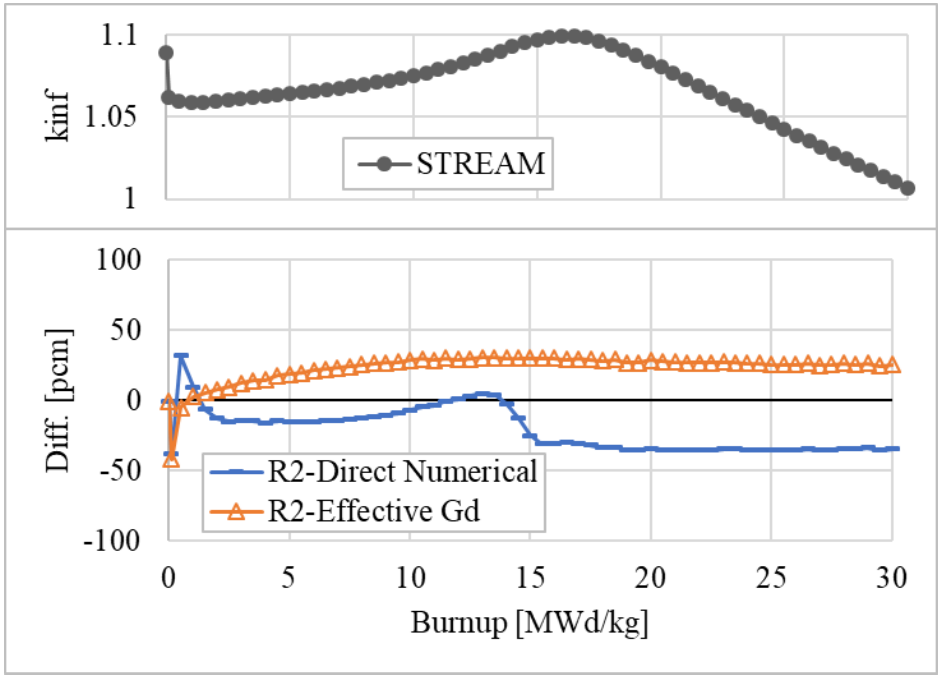
Case 2-Coarse

- Effective Gd ±30 pcm diff
- Direct Numerical Sol. >1000 pcm diff

Case 2-Fine

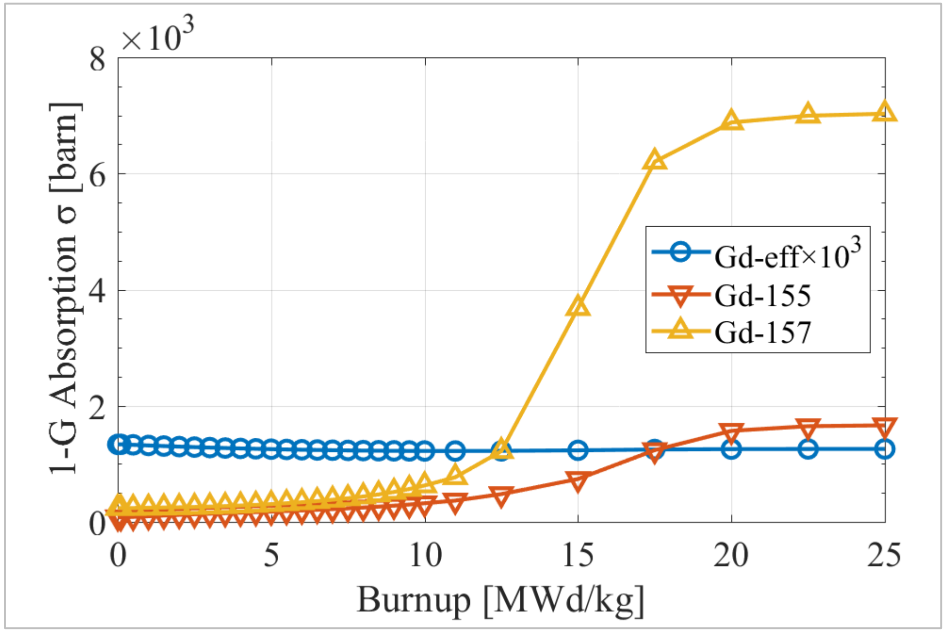
- Effective Gd ±30 pcm diff
- Direct Numerical Sol. ±40 pcm diff



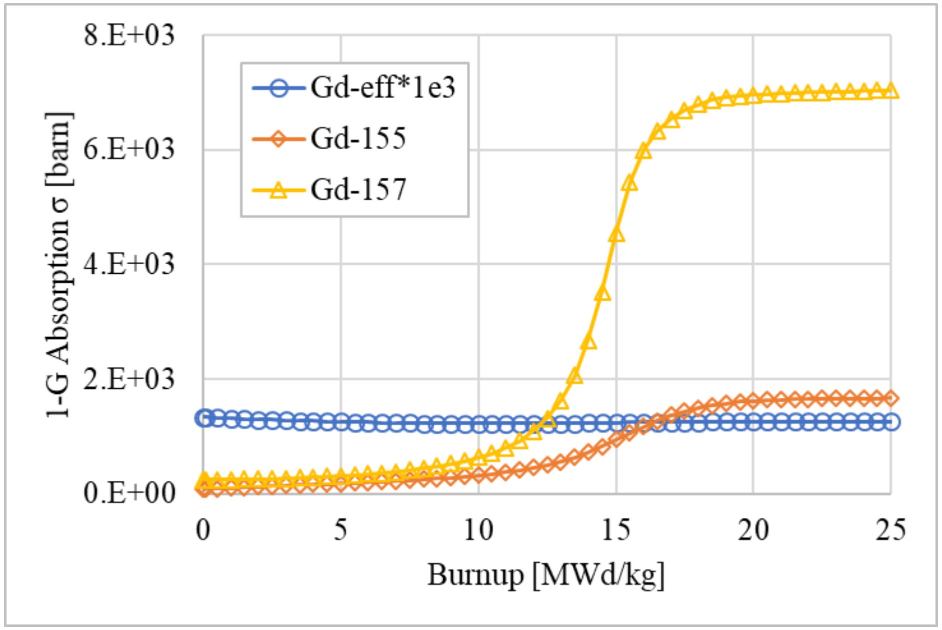


Test Cases II Depletion Results – 1G Absorption XS

Case 2-Coarse



Case 2-Fine



Test Cases III

- **70 Depletion Steps for Gadolinia Assembly (Fine, Same)**

0	0.1	0.5	1	1.5	2	2.5	3	3.5	4	5	5	5.5	6	6.5	7
7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	13	13	13.5	14	14.5	15
15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	21	21	21.5	22	22.5	23
23.5	24	24.5	25	25.5	26	26.5	27	27.5	28	29	29	29.5	30	30.5	31
31.5	32	32.5	35	37.5	40										

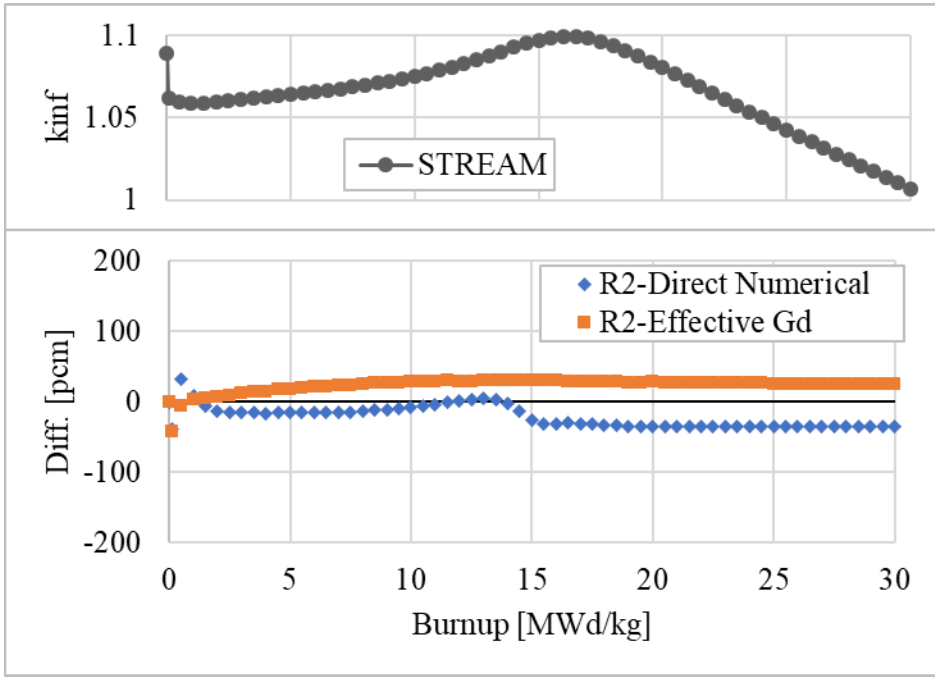
- **Random step depletion calculation (Random)**

0	2	4	6	8	10	12	14	16	18	20
22	24	26	28	30	32	34	36	38	40	

Test Cases III Depletion Results – k_{inf}

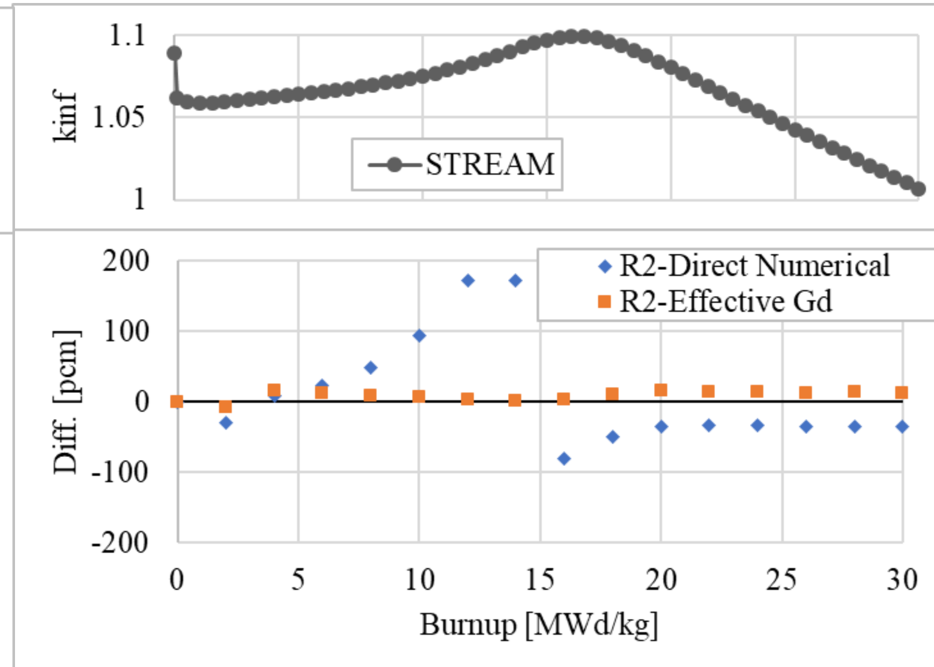
Case 2-Fine, same

- Effective Gd ±30 pcm diff
- Direct Numerical ±40 pcm diff



Case 2-Random

- Effective Gd ±30 pcm diff
- Direct Numerical Sol. ±180 pcm diff



	R2-DNS		R2-effGd	
	Total	XSFB	Total	XSFB
Time [sec]	1.942	0.275	1.946	0.270
Change [%]	-	-	0.211	-2.035

Conclusions

- **Conclusions**
  - **Analysis about two kinds of Gd depletion models**
  - **Direct Gd linear chain depletion**
    - The direct Gd linear chain depletion model needs finer burnup steps to get acceptable accuracy
    - Individual isotope amount can be tracked
  - **Effective Gd depletion**
    - The effective Gd depletion model provides accurate solution within 20 pcm due to the linear change of absorption cross section as a function of burnup
    - Simulation time is faster
  - **The effective Gd depletion model is suitable for RAST-K 2.0.**

- **Future Works**
  - **Quadratic Depletion as burnup**

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