Technical Basis for Revised Fission Product Fuel-to-Clad Gap Inventory

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Presentation Outline

1. Fission Product Gap Inventory in Table 3
2. Q&A
3. RIA Transient Gas Release in Table 4
4. Q&A

Main Objectives for Revised Fission Product Gap Inventories

1. Expand applicability of Table 3

2. Provide guidance for calculating plant-specific or design-specific gap inventories

3. Finalize RIA "Interim Guidance"

Technical Basis of Current RG 1.183 Table 3 Gap Inventories

- FRAPCON-3 best-estimate predictions of gap gas release (NUREG/CR-6703, January 2001).
  - Release of stable, long-lived isotopes using Messih model for Westinghouse 17x17 PWR fuel rod.
  - Release of volatile isotopes based upon conservative ANS-5.4 (1982) release model.
  - No manufacturing tolerances.
  - No modeling uncertainties.
  - Typical rod power history.

Table 3[11]

Non-LOCA Fraction of Fission Product Inventory in Gap

Group	Fraction
I-131	0.08
Kr-85	0.10
Other Noble Gases	0.05
Other Halogens	0.05
Alkali Metals	0.12

Limitation on Applicability

- Modern fuel management schemes exceed applicability limit in footnote (11).

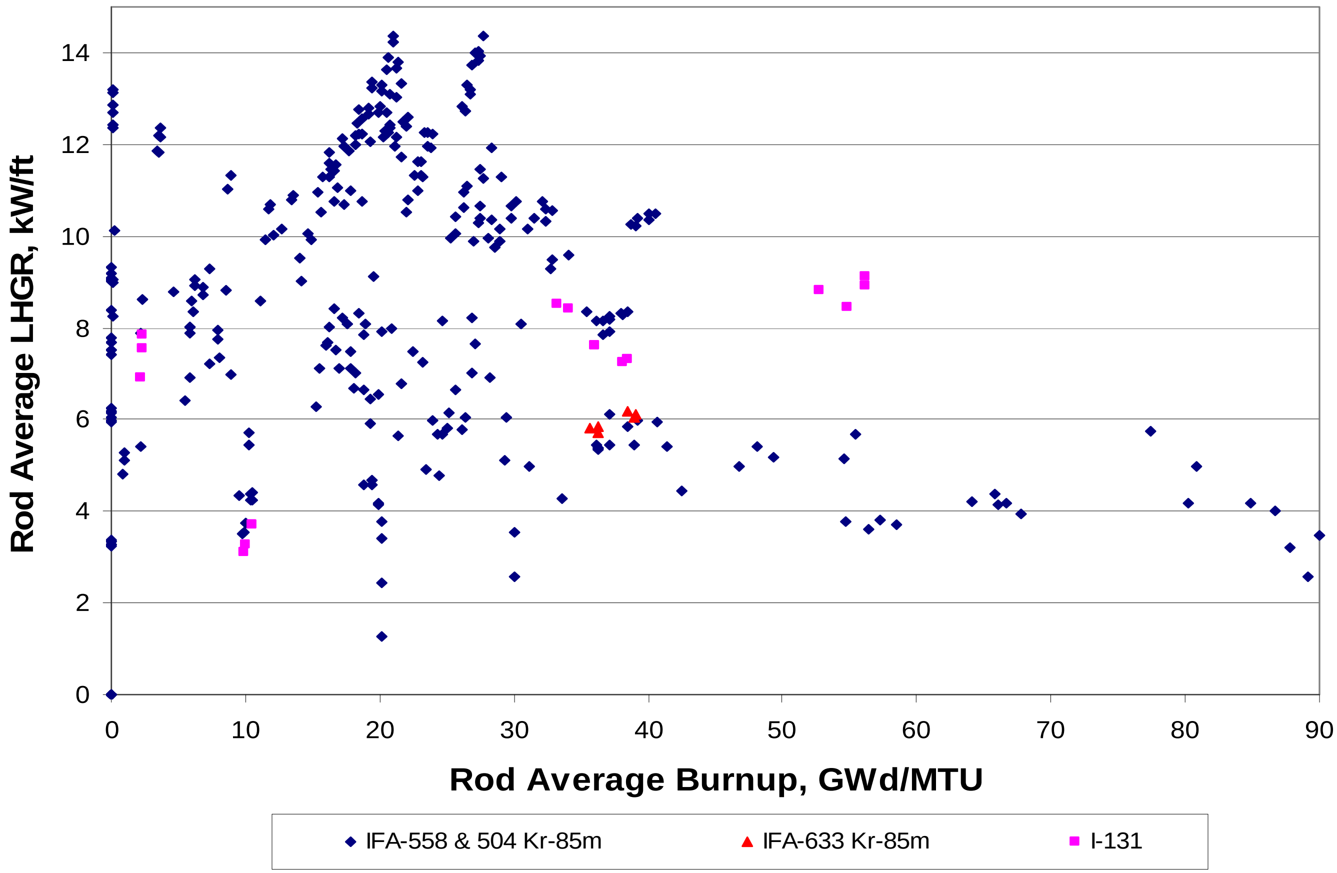
  "…maximum linear heat generation rate does not exceed 6.3 kW/ft peak rod average power for burnups exceeding 54 GWD/MTU."

- Licensees unable to employ RG 1.183 Table 3 fission product gap inventories for AST applications.

- Minimal guidance for calculating plant-specific or design-specific gap inventories.
  - Basis of gap inventories not clearly established in past RGs.

ANS-5.4 Release Model (2009)

- Halden reactor sweep gas experiments measure release of stable and volatile isotopes during power operation.
  - Empirical data used to qualify release model coefficients.



ANS-5.4 Release Model (2009)

- ANS-5.4 (1982) gas release model based on post-shutdown rod puncture measurements of stable, long-lived noble gas along with conservative multiplier on I-131 diffusion coefficient.

  $R/B_{I\text{-}131} \approx (7^*(D_{Stable\ Xe})/\lambda_{I\text{-}131})^{0.5}$ (1982 ANS-5.4)

- ANS-5.4 (2009) gas release model based on in-reactor measurements of volatile, short-lived gas release along with fractal mathematical relationship.

  $R/B_{I\text{-}131} = 2.39 * R/B_{Kr85m}$ (2009 ANS-5.4)

- ANS-5.4 (2009) predicts significantly lower I-131 gas release.

- Technical basis for derivation of revised ANS-5.4 release model in publication (NUREG/CR-XXXX).
  - Describes both best-estimate and conservative models for predicting release of volatile radioactive isotopes of krypton, xenon, and iodine.

Technical Basis for Revised Table 3 Gap Fractions

- By adopting the ANS-5.4 (2009) model, the staff was able to accomplish two objectives:

  (1) Extend rod power history

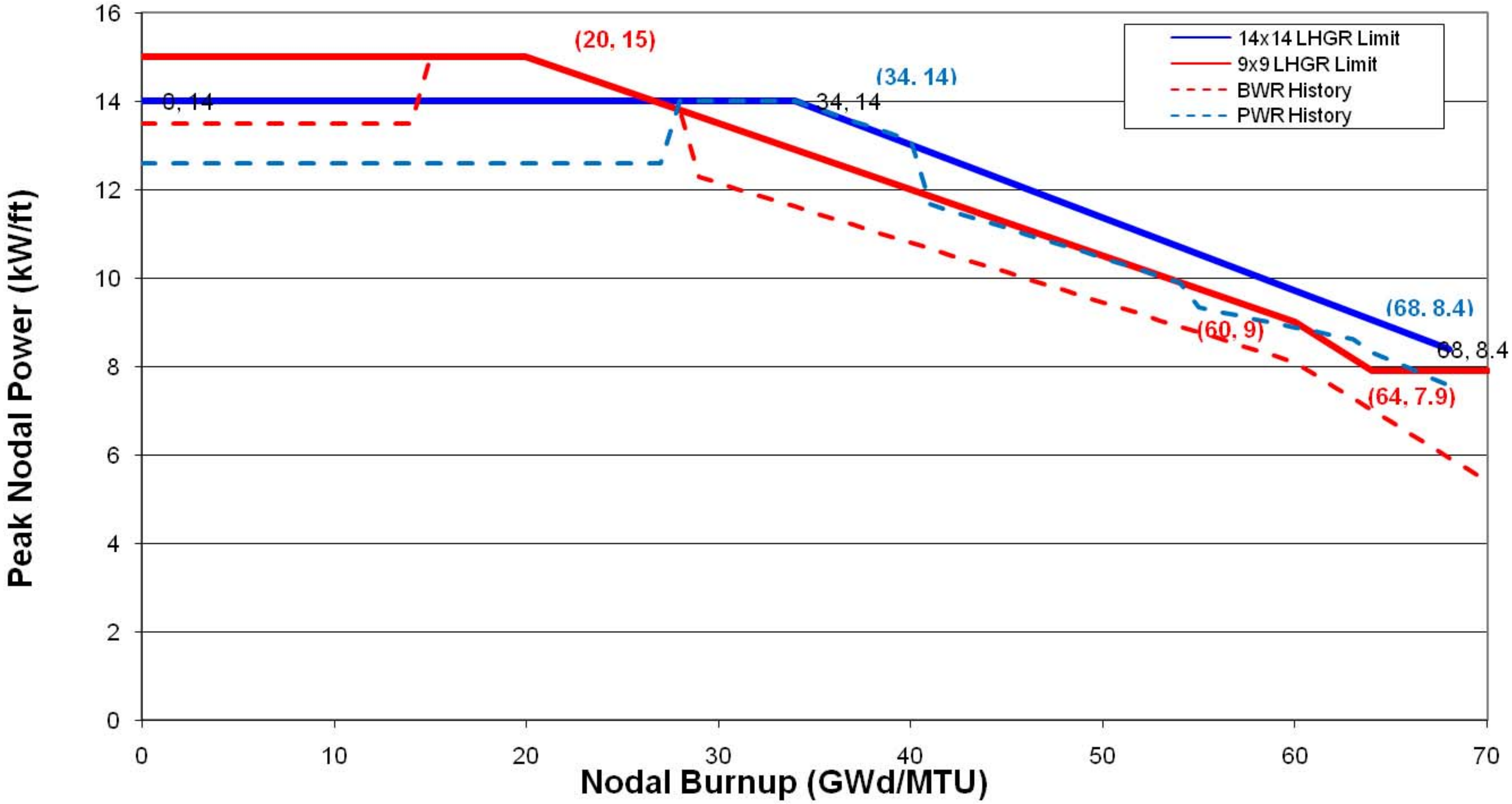
  (2) Account for modeling uncertainties

- Strategy for calculating revised gap fractions:
  - Identify limiting BWR and PWR fuel rod designs
  - Maintain 0.08 I-131 gap fraction
    - Extend power operating envelope until target achieved.
  - Establish standard methodology for calculating 95/95 gap fractions.
    - Reduce regulatory uncertainty for future plant-specific or design-specific license amendments.

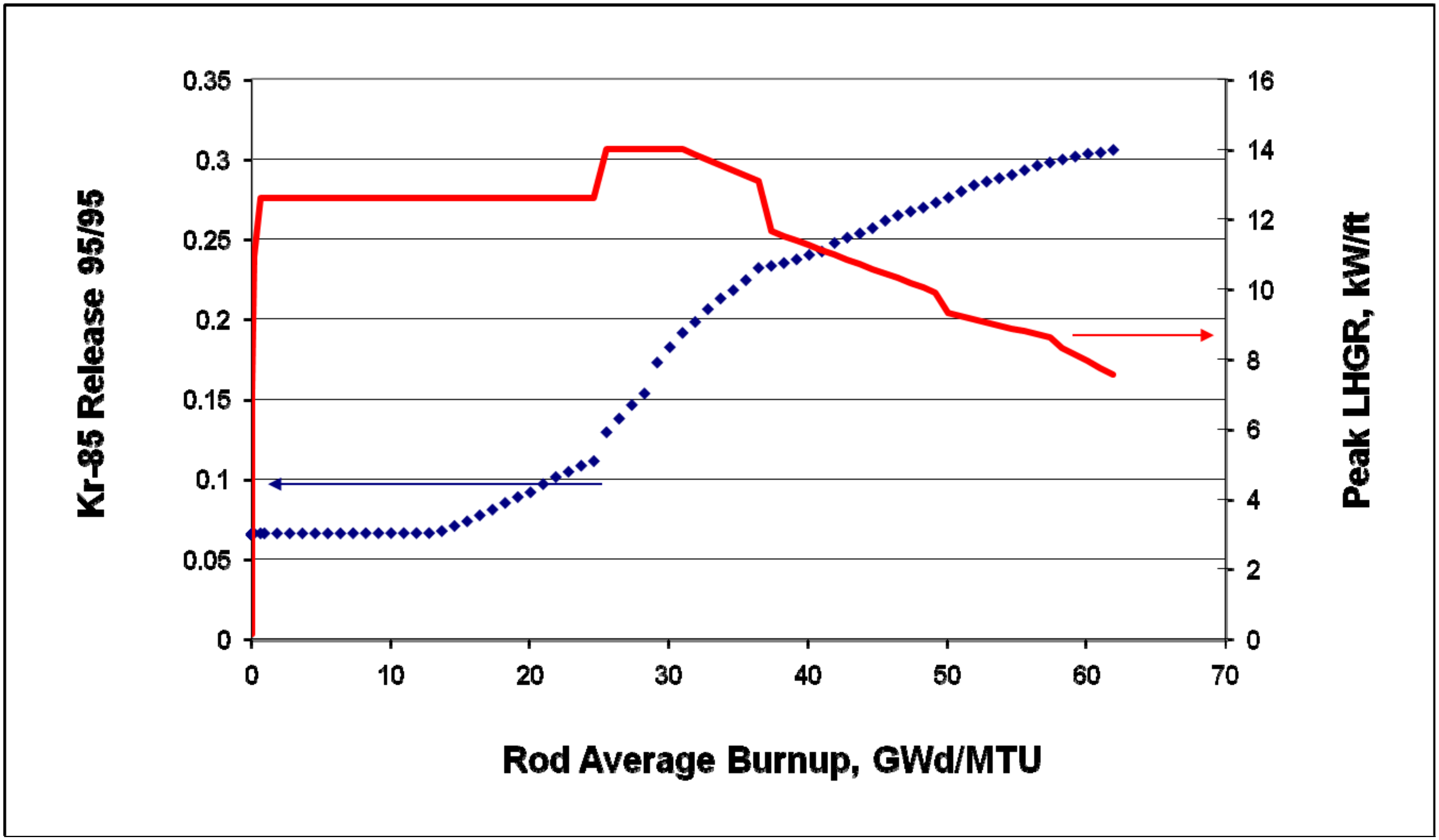
Technical Basis for Revised Table 3 Gap Fractions (cont.)

- FRAPCON-3.3 used to predict fission gas release
  - Release of stable, long-lived isotopes using Messih model at 95/95 upper tolerance level.
    - FGR model uncertainty = 2.77% (1 σ), K_{factor} = 2.355
    - Accounts for higher diffusion coefficient (2x) for cesium isotopes.
  - Release of volatile isotopes based upon ANS-5.4 (2009) model and 5.0 $K_{95/95}$ tolerance factor.
  - Segmented power histories along thermal-mechanical operating limits.

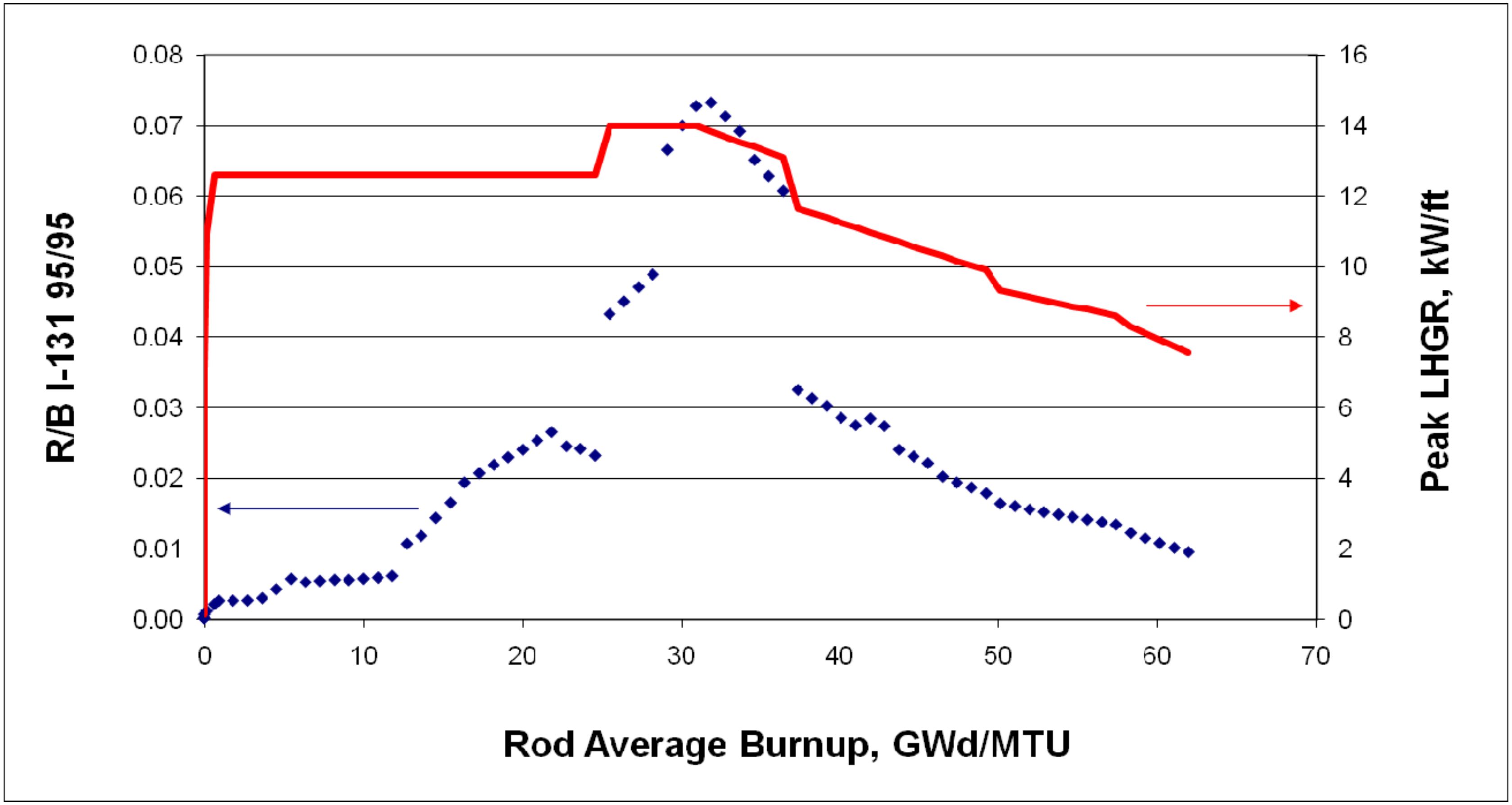
Segmented Power History



Calculated Kr-85 Peak Release



Calculated I-131 Release / Birth



Revised Table 3 Gap Fractions

Calculated gap fractions **strongly** dependent on operating history and fuel rod design.

Group	Gap Inventory Fractions - 95/95 Upper Tolerance			Current RG 1.183 Table 3
	Calculated PWR 14x14 design	Calculated BWR 9x9 design	Maximum	
Kr-85	0.348	0.257	0.35	0.10
I-131	0.073	0.036	0.08	0.08
I-132	0.225	0.111	0.23	0.05
Other Nobles	0.031	0.016	0.04	0.05
Other Halogens	0.042	0.021	0.05	0.05
Alkali Metals	0.457	0.336	0.46	0.12

FRN Question #2

2. Table 3 of DG–1199 provides revised non-loss of coolant accident fission product gap inventories applicable to all current fuel designs. The purpose of revising Table 3 was to expand its applicability by replacing the prior footnote 11 limitation (*i.e.,* 6.3 kw/ft beyond 54 GWd/MTU) with bounding fuel rod power envelopes.

a. Does the bounding fuel rod power envelopes depicted in Figure 1 of DG–1199 provide sufficient fuel management flexibility such that current and anticipated fuel loading patterns will be able to utilize the Table 3 fission product gap fractions?

b. Fission gas release and the resulting fission product gap inventory are sensitive to fuel rod design and rod power history. To maintain consistency with current regulatory guidance, the revised Table 3 remains applicable to all current pressurized water reactor (PWR) and boiling water reactor (BWR) fuel rod designs (limited only by the bounding power envelope). Significant reductions in fission product gap inventories are achievable with specific fuel rod design calculations (*e.g.,* PWR 17×17 versus PWR 14×14) and/or less bounding rod power histories. Should RG 1.183 provide alternate versions of Table 3, each with its own set of applicability criteria?

FRN Question #3

3. Reference 18 of DG–1199 documents the expanded fission gas release empirical database and methods used to calculate the revised Table 3 and Table 4 fission product gap inventories. Are any further fission gas measurements available which would help enhance the gap inventories listed in Table 3 and 4?

Public Comments due January 13, 2009

Transient Fission Gas Release During Reactivity-Initiated Accidents

Current Guidance for RIA Gap Inventory

- Inadequate guidance on RIA fission product inventory.
  - RG 1.77 (1974) Appendix B: "*The amount of activity accumulated in the fuel-clad gap should be assumed to be 10% of the iodines and 10% of the noble gases accumulated at the end of core life, assuming continuous maximum full power operation*."
  - RG 1.183 (2000) Table 3 footnote (11): "*For the BWR rod drop accident and the PWR rod ejection accident, the gap fractions are assumed to be 10% for iodines and noble gases*."
  - NUREG-0800 (2007), SRP Section 4.2, "*The total fission-product gap fraction available for release following any RIA would include the steady-state gap inventory (present prior to the event) plus any fission gas released during the event...*

  Transient FGR = [(0.2286 Δ H) – 7.1419]*

  Where:

  FGR = Fission gas release, % (must be > 0)

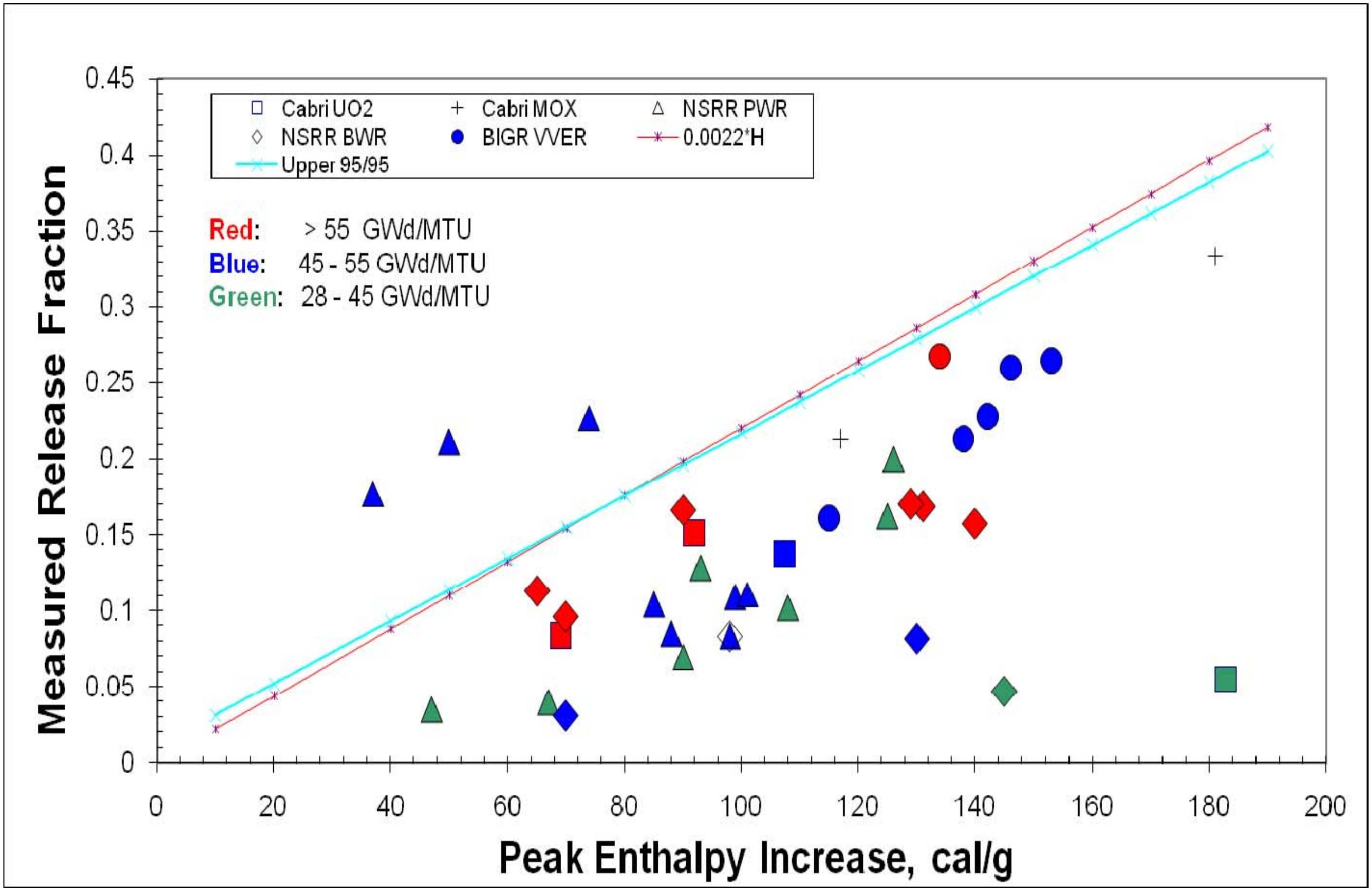
  Δ H = Increase in fuel enthalpy, Δ cal/g"

Transient Fission Gas Release

- RIA test programs (e.g., CABRI, NSRR, BIGR) have measured large quantities of fission gas following in-reactor prompt power excursions.

- Total fission-product inventory available for release (upon cladding rupture):
  1. Steady-state gap inventory present prior to transient.
     - Governed by diffusion and sensitive to operating power history
  2. Transient fission gas released during transient.
     - Fuel pellet fracturing and grain boundary separation are the primary mechanisms for fission gas release during the transient.
     - Transient gas release is dependent on local power increase.

Transient FGR Empirical Database



Revised Guidance for RIA Transient Gas Release

- Transient release of stable, long-lived isotopes based directly on the RIA empirical database.

  Kr-85 Release Fraction, $F_{(Kr\text{-}85)} = 0.0022 * \Delta H$

- Transient release of long-lived Cesium isotopes estimated based on 2x diffusion coefficient.

  Cs-134 Release Fraction, $F_{(Cs\text{-}134)} = 0.0022 * \Delta H * (2)^{0.5}$

- Transient release of volatile short-lived isotopes estimated based upon ANS-5.4 (2009) model and FRAPCON-3 power ramp calculations.

  I-131 Release Fraction, $R/B_{(I\text{-}131)} = 0.0022 * \Delta H * (0.333)$

Revised Guidance for RIA Combined Gap Inventory

Group	Combined RIA Release Fraction
Kr-85	((0.35) + (0.0022 * ΔH))
I-131	((0.08) + (0.00073 * ΔH))
I-132	((0.23) + (0.00073 * ΔH))
Other Nobles	((0.04) + (0.00073 * ΔH))
Other Halogens	((0.05) + (0.00073 * ΔH))
Alkali Metals	((0.46) + (0.0031 * ΔH))

Revised Guidance for RIA Combined Gap Inventory

Example RIA Gap Fraction Calculation

Calculation of I-131 and Kr-85 combined gap fraction for a fuel rod which experienced cladding failure (any failure mechanism) during a PWR control rod ejection event:

Due to the large variation in axial-dependent power peaking factors, the analyst chose to divide the fuel rod into 3 equal length axial regions. The peak radial average enthalpy change in each region is used to calculate the transient fission gas release component of the gap fraction within each axial region.

Axial Region	Peak Enthalpy Increase
Top (region #1)	150 cal/g
Middle (region #2)	25 cal/g
Bottom (region #3)	0 cal/g

Combined $R/B_{(I\text{-}131)}$ = 0.08 + ((0.00073*150/3)+(0.00073*25/3)+(0.00073*0/3))
= 0.123

Combined $F_{(Kr\text{-}85)}$ = 0.35 + ((0.0022*150/3)+(0.0022*25/3)+(0.0022*0/3))
= 0.478

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Questions?