February 10, 2009

MEMORANDUM TO: Robert Taylor, Chief
Dose Assessment Branch
Division of Risk Assessment

FROM: Anthony Mendiola, Chief **/RA/**
Nuclear Performance and Code Review Branch
Division of Safety Systems

SUBJECT: TECHNICAL BASIS FOR REVISED REGULATORY GUIDE 1.183
FISSION PRODUCT FUEL-TO-CLADDING GAP INVENTORY

The purpose of this memorandum is to document the technical basis for revised fission product fuel-to-cladding gap inventories within Section 3.2 of Regulatory Guide (RG) 1.183, “Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors.” Specifically, the non-Loss-of-Coolant Accident (non-LOCA) fission-product gap inventories listed in Section 3.2 of RG 1.183 and used to assess the radiological consequences for the fuel handling accident, pressurized water reactor (PWR) locked rotor event, PWR sheared shaft event, PWR steam line break event, PWR control rod ejection event, and boiling water reactor (BWR) control blade drop event. Enclosure 1 provides proposed revisions to Section 3.2 of RG 1.183. Enclosure 2 contains a Pacific Northwest National Laboratory (PNNL) technical report which supports the recommended RG revisions.

1.0 Background

By letter dated March 30, 2006, the BWR Owner’s Group (BWROG) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review topical report NEDO-33163, “High Burn Up BWR Fuel Rod Gap Release Fractions” (ADAMS ML060940469). The main objective of NEDO-33163 was to extend the applicability of the fission-product inventory gap fractions in Table 3 of RG 1.183 (listed below) to enhance fuel management flexibility.

> Table 3 Footnote 11:
> [11] The release fractions listed here have been determined to be acceptable for use with currently approved LWR fuel with a peak burnup up to 62,000 MWD/MTU provided that the maximum linear heat generation rate does not exceed 6.3 kW/ft peak rod average power for burnups exceeding 54 GWD/MTU. As an alternative, fission gas release calculations performed using NRC approved methodologies may be considered on a case-by-case basis. To be acceptable, these calculations must use a projected power history that will bound the limiting projected plant-specific power history for the specific fuel load. 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.

Employing an older version of FRAPCON-3, the BWROG topical report calculated revised fission-product gap inventories with bounding power histories. The following information was extracted from Table 4A of NEDO-33163:

NEDO-33163 8x8 Bundle Average Gap Release Fractions

	RG 1.183	NEDO-33163
1-131	0.08	0.10
Kr-85	0.10	0.17
Other Noble Gases	0.05	0.10
Other Halogens	0.05	0.05
Alkali Metals	0.12	0.22

After reviewing the information presented in NEDO-33163 and in response to staff request for additional information (RAIs), the staff had concerns with the degree of conservatism within the methods employed in the BWROG calculations. Based upon these concerns, the staff decided to undertake the effort to revise this portion of RG 1.183. Upon completion of this effort, the staff will have satisfied the original objectives of NEDO-33163 (i.e., expanded applicability, fuel management flexibility). Hence, further review or revision of NEDO-33163 is no longer required.

Unrelated to the BWROG topical report, fission gas release measurements taken during reactivity-initiated accident (RIA) test programs in the CABRI, NSRR, and BIGR test reactors challenge the adequacy of the recommended gap fractions in RG 1.183 Table 3 footnote 11 (above). These measurements were used to derive revised gap source terms within the Interim RIA Acceptance Criteria and Guidance (Appendix B, Section 4.2, Standard Review Plan, NUREG-0800). This memorandum documents revised RIA source terms.

2.0 Revised Fission Product Gap Inventories

The inventory of fission gas in the fuel rod plenum prior to an accident (and available for release upon cladding failure) depends on fuel design and power operating history. In addition to diffusion controlled fission gas release during normal operation, a transient fission gas release mechanism (i.e., grain boundary separation and fuel fragmentation) exists during events which experience a large and rapid increase in rod power and fuel temperature. Non-LOCA events may be divided into two categories: (1) events which experience a large and rapid increase in fuel temperature (e.g., PWR control rod ejection and BWR control blade drop) and (2) events which experience little or no increase in fuel temperature (e.g., fuel handling accident, locked rotor, sheared shaft) or events which experience a relatively slow increase in fuel temperature (e.g., PWR main steam line break).

Pacific Northwest National Laboratory (PNNL) was contracted to aid the staff in the development of a technical basis to support revising the non-LOCA fission-product gap inventories in Section 3.2 of RG 1.183. The PNNL technical report documenting this effort is attached. The staff has reviewed the attached PNNL technical report and finds it acceptable.

2.1 Non-LOCA Fission-Product Gap Inventories (Events other than RIAs)

To satisfy the original objective of NEDO-33163 (i.e., expanded applicability, fuel management flexibility), the current applicability limit in footnote 11 (6.3 kW/ft beyond 54 GWd/MTU) needed to be extended. Due to the strong dependency of fission gas release to both fuel rod power and burnup, it is impractical to remove an applicability limit. Instead, the staff chose to extend the fuel rod power/burnup envelope in an attempt to increase the likelihood that future cores would be able to utilize the proposed gap fractions in this memo in a revised RG 1.183.

As the fuel rod power/burnup envelope is extended, the production and release of both stable and volatile radioactive isotopes increase. The trade-off is to extend the applicability without entering a power/burnup region which promotes excessive fission gas release. The BWROG calculations (with an extended power envelope), listed above, produced significantly larger gap inventories relative to the current RG 1.183 Table 3 values.

Fission product gap inventories calculated by the staff using the latest version of FRAPCON-3.3 with the 1982 ANS 5.4 standard (along with an extended rod power history) were excessive - exceeding both the current RG 1.183 and NEDO-33163 calculated gap fractions. Recognizing significant conservatism in the 1982 ANS 5.4 standard iodine release fractions, the staff decided to adopt the proposed revised ANS 5.4 standard. The 1982 standard was based only on measured release of stable noble gas with no in-reactor measurements of volatile, short-lived isotopes. The proposed new standard is based upon in-reactor isotopic gas measurements (including I-131) from the Halden reactor (Norway). Halden's helium sweep gas experiments (Instrument Fuel Assembly (IFA)-504, IFA-558, and IFA-633) were capable of measuring radioactive isotopes released during operation. Section 2.1 of the attached PNNL technical report provides background on the development and validation of the proposed revised standard. The proposed new ANS standard produces lower I-131 release-to-birth (R/B) ratios for the same power envelope which provides margin to expand the power envelope.

One of the staff's primary concerns with the methods utilized in NEDO-33163 was the treatment of fission gas release modeling uncertainties. Examination of the empirical database of fission gas release measurements supporting the proposed revised ANS 5.4 standard reveals a relatively large spread. Section 2.1.1 of the attached PNNL technical report describes the treatment of uncertainties to achieve a 95/95 upper tolerance limit.

Section 2.2 of the attached PNNL technical report summarizes the PWR and BWR fission-product gap inventory calculations. These calculations were performed with a modified version of FRAPCON-3.3 which incorporates the proposed revised ANS 5.4 standard. The expanded rod power envelope used in these calculations satisfies the main objective of NEDO-33163. In addition, these calculations specifically account for modeling uncertainty in order to achieve a 95/95 upper tolerance limit on the gap inventories.

Currently, RG 1.183 Table 3 gap fractions are applicable to all BWR and PWR fuel rod designs (limited only by the footnote 11 limits). For a given power envelope, fission gas release varies significantly between fuel designs. For example, with an identical power history, the calculated gap fractions for a PWR 14x14 fuel rod would be larger than for a PWR 17x17 fuel rod. However, to maintain consistency with the current RG, the staff decided to select the maximum calculated gap fractions (rounded up to nearest 0.01) from the limiting PWR fuel rod design and limiting BWR fuel rod design. These values are listed below along with the current Table 3 gap fractions:

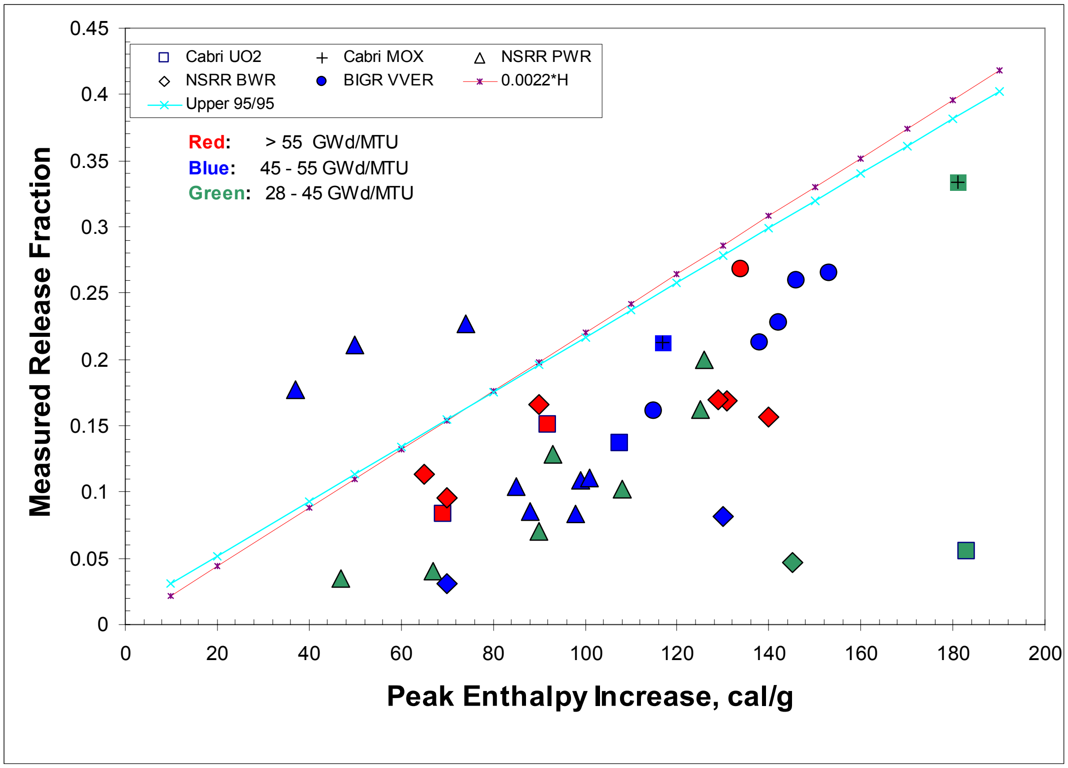
Group	Gap Inventory Fractions - 95/95 Upper Tolerance			Current RG 1.183 Table 3
	Calculated PWR 14x14 design	Calculated BWR 9x9 design	Maximum	
Kr-85	0.348	0.257	0.35	0.10
I-131	0.073	0.036	0.08	0.08
I-132	0.225	0.111	0.23	0.05
Other Nobles	0.031	0.016	0.04	0.05
Other Halogens	0.042	0.021	0.05	0.05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

The revised fission-product gap inventories are applicable to all fuel designs operating within the PWR and BWR rod power envelope depicted in Figures A-1 and A-8 in the attached PNNL technical report. It is important to note that FRAPCON-3 calculations were performed on several rods - each operating on a different segmented power history comprising the overall power envelope. This approach was selected to remove excessive conservatism. The presumption that a single fuel rod operates continuously at the peak power burnup envelope is unrealistic. The segmented power history approach maintains an adequate level of conservatism.

2.2 RIA Combined Fission-Product Gap Inventories

The total fission-product source term during an RIA includes both (1) the steady-state gap inventory present from normal operation prior to the RIA and (2) any transient fission gas released during the event. RG 1.183 Table 3 footnote 11 currently recommends a gap inventory consisting of “10% for iodines and noble gases.” Stable fission gas release measurements taken during RIA test programs in the CABRI, NSRR, and BIGR test reactors challenge the adequacy of the recommended gap fractions.

A compilation of the RIA fission gas release empirical database is provided in Appendix B of the attached PNNL technical report. This data is plotted as a function of increase in radial average fuel enthalpy in the figure below (Figure 6 of PNNL report).



Section 3 of the attached PNNL technical report describes the basis of the revised RIA transient release source terms. It is important to note that the RIA fission gas measurements in the above figure apply to the long-lived Kr-85 isotope. Hence, adjustments are required for the other isotopes to account for potential differences in rates of production and release.

A simplified 95/95 upper tolerance limit of the RIA transient release for the long-lived Kr-85 isotope was developed directly from the empirical database above. Since no measurements were available for cesium, iodine, and short-lived noble gas isotopes, their release fractions were estimated. For the release of long-lived cesium isotopes (Cs-134 and Cs-137), both the current and proposed revised ANS 5.4 standard recommend a factor of 2 higher diffusion coefficient than for noble gases. Recognizing the relationship between release fraction and diffusion coefficient, PNNL was able to develop a release fraction for the long-lived cesium isotopes. For iodines and other short-lived isotopes, radioactive decay plays an important role since activity decreases proportional to the time it takes for the fission gas to be released from the fuel pellet. Recognizing that a relationship exists between the short-lived release-to-birth (R/B) fraction and the stable release fraction, PNNL completed several FRAPCON-3.3 power ramp calculations to estimate the transient release fraction for the short-lived isotopes. The estimated release fractions are listed below.

RIA Transient Fission Gas Release:

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

(b) Cs-134 and Cs-137 Release Fraction, $F_{(Cs\text{-}134,\ Cs\text{-}137)} = 0.0031 * \Delta H$

(c) I-131 and Short-Lived Isotopes Release Fraction, $R/B_{(I\text{-}131)} = 0.00073 * \Delta H$

Where, ΔH is the increase in radial average fuel enthalpy, Δcal/g.

These revised RIA transient fission gas release equations replace the equation provided in Appendix B to NUREG-0800 (Transient FGR = $[(0.2286*\Delta H) - 7.1419]$). The combined, total RIA source term equals the steady-state gap inventory plus the transient gas release.

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

The transient release from each axial node which experiences the power pulse may be calculated separately and combined to yield the total transient FGR for a particular fuel rod. The combined steady-state gap inventory and transient FGR from every fuel rod predicted to experience cladding failure (all failure mechanisms) should be used in the dose assessment. The following example illustrates this calculation.

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

The applicability of the RIA transient fission gas release equations is tied directly to the supporting empirical database. Although a direct correlation of fission gas release with fuel rod burnup was not established, the formation of a high burnup structure and accumulation of fission gas along grain boundaries may impact transient gas release. RG 1.183 release fractions are limited to a rod average burnup of 62 GWd/MTU (Section 3.2, footnote 1). The RIA fission gas measurement database supports this burnup limitation. It is also important to note that none of the fission gas release measurements were taken from specimens which experienced fuel melting. Since fuel melting would promote higher fission-product release, the applicability of the transient release equations are limited to RIA events which do not predict fuel melting.

3.0 Revised Text for RG 1.183

Enclosure 1 provides proposed revisions to Section 3.2 of RG 1.183. These changes capture the proposed revised Table 3 Non-LOCA fission-product gap inventories, a new Table 4 containing RIA combined fission-product inventories, and limitations for their applicability.

Enclosure: As stated

CONTACT: P. M. Clifford NRR/ADES/DSS, 301-415-4043

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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

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

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

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Enclosure:
As Stated
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OFFICIAL RECORD

Proposed Revisions to Section 3.2

of Regulatory Guide 1.183

ENCLOSURE 1

3.2 Release Fractions[11]

Table 1 (for BWRs) and Table 2 (for PWRs) list the core inventory release fractions, by radionuclide groups, for the gap release and early in-vessel damage phases for DBA LOCAs and non-LOCA DBAs where the fuel is melted and the cladding is breached. These fractions are applied to the equilibrium core inventory described in Regulatory Position 3.1.

For non-LOCA DBAs, where only the cladding is postulated to be breached, Table 3 gives the fractions of the core inventory for the various radionuclides assumed to be in the gap for a fuel rod. The release fractions from Table 3 are used in conjunction with the calculated fission product inventory calculated with the maximum core radial peaking factor. The licensing basis of some facilities may include non-LOCA events that assume the release of the gap activity from the entire core (e.g., heavy load drop accident). For events involving the entire core, the core-average gap fractions of Tables 1 and 2 may be used and the radial peaking factor may be omitted.

For reactivity initiated accidents (RIAs) such as BWR control rod drop accident and PWR control rod ejection accident, the total fraction of fission products available for release equals the steady-state fission product gap inventory in Table 3 for a fuel rod plus the transient fission product release resulting from the rapid power excursion. Table 4 list the combined fission product inventory, by radionuclide groups, available for release for a fuel rod during a RIA. The transient fission product release component is presented as a function of increase in radial average fuel enthalpy ($\triangle$H, cal/g). This component of the overall fission product inventory may be calculated separately for each axial node which experiences the RIA power pulse and then combined to yield the total transient fission product release for a particular fuel rod. The sum total of combined fission product inventories from each fuel rod predicted to experience cladding failure (all failure modes) should be used in the dose assessment.

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[11] The NRC has determined the release fractions listed here to be acceptable for use with currently approved LWR fuel with a peak rod average burnup up to 62,000 megawatt days per metric ton of uranium (MWD/MTU) (PWR) and a peak pellet burnup up to 70,000 MWD/MTU (BWR). The data in this section are not applicable to cores containing mixed oxide (MOX) fuel.

Table 1 BWR Core Inventory Fraction Released into Containment Atmosphere

Group	Gap Release Phase	Early In-Vessel Phase	Total
Noble Gases	0.05	0.95	1.0
Halogens	0.05	0.25	0.3
Alkali Metals	0.05	0.20	0.25
Tellurium Metals	0.00	0.05	0.05
Ba, Sr	0.00	0.02	0.02
Noble Metals	0.00	0.0025	0.0025
Cerium Group	0.00	0.0005	0.0005
Lanthanides	0.00	0.0002	0.0002

Table 2 PWR Core Inventory Fraction Released into Containment Atmosphere

Group	Gap Release Phase	Early In-Vessel Phase	Total
Noble Gases	0.05	0.95	1.0
Halogens	0.05	0.35	0.4
Alkali Metals	0.05	0.25	0.3
Tellurium Metals	0.00	0.05	0.05
Ba, Sr	0.00	0.02	0.02
Noble Metals	0.00	0.0025	0.0025
Cerium Group	0.00	0.0005	0.0005
Lanthanides	0.00	0.0002	0.0002

Table 3 Non-LOCA Fraction of Fission Product Inventory in Gap

Group	Fraction
I-131	0.08
I-132	0.23
Kr-85	0.35
Other Noble Gasses	0.04
Other Halogens	0.05
Alkali Metals	0.46

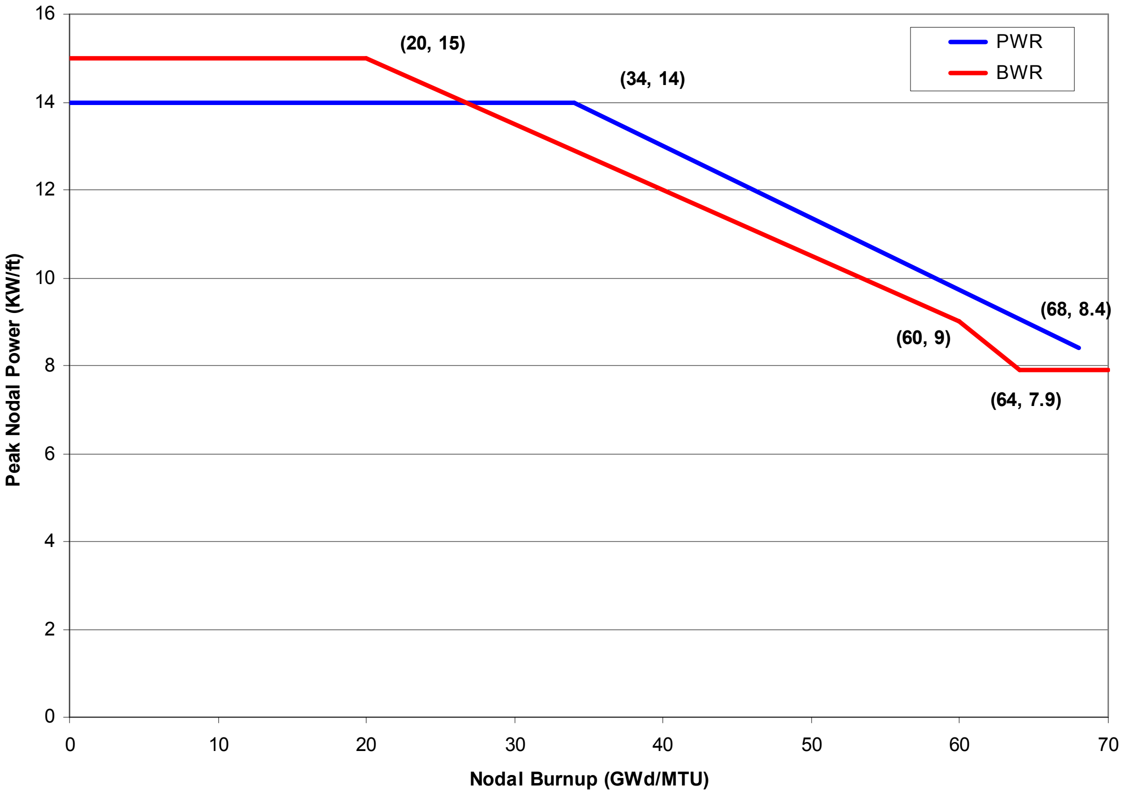
Table 4 Fraction of Fission Product Inventory Available for Release - Reactivity Initiated Accidents

Group	Combined Release Fraction[12, 13]
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))

[12] ΔH = increase in radial average fuel enthalpy, cal/g

[13] Not applicable to fuel rods predicted to experience fuel melting

Figure 1 Maximum Allowable Power Operating Envelope for Non-LOCA Gap Fractions



PNNL Technical Report

Update of Gap Release Fractions for Non-LOCA Events Utilizing the Revised ANS 5.4 Standard

C. E. Beyer

P.M. Clifford

February 2009

ENCLOSURE 2