ATTACHMENT A
FRAPCON3.2 Input and Release Calculations for the Duke MOX Lead Test Assemblies

Duke Power Inc. (Duke) has submitted a license request to the Nuclear Regulatory Commission (NRC) to operate 4 mixed oxide (MOX) lead test fuel assemblies (LTAs) in the Catawba PWR, in support of the joint U.S./Russia program for disposition of weapons-grade plutonium. The predicted at-shutdown bounding radioactive gas inventory in the fuel rods available for release in a spent fuel handling accident (often referred to as the "gap inventory" of radioactive isotopes) is one of the items involved in the review of this request.

This analysis has two goals:

1) For design basis accidents that do not involve core-wide fuel damage, affirm that the current regulatory positions on gap fractions in Regulatory Guide 1.183 (Ref. 1), Section 3.2 and Table 2 (reproduced as Table 1 below) are conservative for use with the weapons-grade MOX fuel such as that proposed by Duke Power.

2) In addition to the gap fractions requested above, assess the gap inventory of fission gases in the context of rod pressure of fuel stored in the spent fuel pool. Duke has stated that the pressure would be less than the currently allowable spent fuel pool rod pressure of 1300 psig. The objective of this assessment is to affirm that the current regulatory assumption regarding rod pressure of fuel stored in the spent fuel pool is conservative for use with weapons-grade MOX fuel.

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

Table 1: Non-LOCA Fraction of Fission Product Inventory in Gap From Regulatory Guide 1.183

It should be noted from the above table that the iodine isotopes are the only halogens and the cesium isotopes are the only alkali metals that are calculated using the ANS5.4 analysis methodology. The assignment of elements to the halogen, noble gases, and alkali metal groups, is based on similarity in chemical behavior. The elements considered in this evaluation are appropriate surrogates for the remaining elements in the groups. These later elements are not important contributors to design basis accident radiological consequences.

Code Input

In order to make this assessment, Duke was requested to provide details on MOX rod design and fabrication, and a bounding or peak-rod power history. The geometry of the rod, pellet fabrication, and reactor conditions were provided in Table 1 of the Duke Response to NRC Staff Request for Additional Information dated November 21, 2003 (Ref. 2). The following are the assumptions or changes from this table, which were made in the process of constructing FRAPCON-3.2 code (Ref. 3) input for gas release assessment.

- FRAPCON-3.2 does not consider the isotope, Pu-238, so the small fraction of the fuel that was identified as Pu-238 was modeled as Pu-242.

- The coolant flow rate given was calculated at inlet conditions for the total core cross section area. To reflect the higher power in the LTA, a higher value of $3.0x10^6$ lb/ft^2-hr was used.

- FRAPCON does not have the material properties to model the zirconium-niobium cladding alloy called M5. These analyses were made using the similar material properties of the zirconium-tin cladding alloy called Zircaloy-4.

- FRAPCON does not allow the modeling of chamfered pellets. In order to give the correct volume reduction due to the dish and chamfer, the dish dimensions were increased slightly.

- The run was made using 12 axial nodes, 17 radial fuel nodes, and 45 radial fuel nodes for the gas release routine. These parameters have been found to give reasonably accurate calculations for a 12 foot rod.

The above assumptions are reasonable and should not have a significant impact on the results of the release calculations presented in this report.

Reference 2 provides a table containing effective full power days (EFPD) for each cycle, the MOX fuel lead assembly peak rod exposure at each time step and the radial peaking factor (Fdelta-H). From the values of time and burnup, and the pellet diameter and density, the linear heat generation rate (LHGR) can be calculated for each time step. The power history can also be derived from the Fdelta-H and core average LHGR values for this plant. As might be expected, power histories derived from the peak exposure and time values are very close to the Duke estimated peak exposure of 56.7 GWD/MTM, however, using the power history from the Fdelta-H values and core average power the peak exposure is calculated to be 59.81 GWD/MTM and does not match the peak pin exposure given by Duke of 56.7 GWD/MTM. The two different power histories are shown in Figure 1.

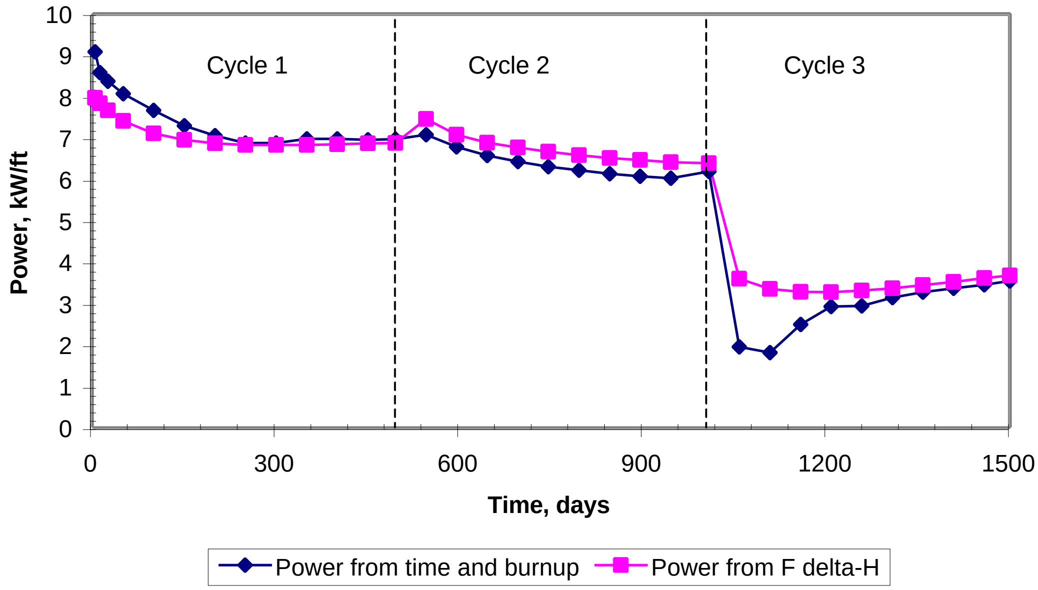

Figure 1: MOX LTA Power histories derived from time and burnup while the other is derived from radial peaking factor and core average power all supplied by Duke

The power history used for this analysis was the one derived from burnup and time; however, some release results are given for the other power history to show that it provides slightly higher release values. The difference between these two power histories can be accommodated by the power uncertainties described later in this report. Time and burnup from Reference 2 provided a power history consisting of 45 pairs of time and power that were used as input for FRAPCON-3.2. The power histories provided in Reference 2 were characterized by Duke as being conservative and bounding for the expected power histories to which the MOX LTAs may be irradiated. Reference 2 also provided 18 axial power profiles and the times that each should be used during the irradiation life of the LTA's. These profiles were input directly into FRAPCON along with the time steps each should be used.

Fission Gas Release Models

The FRAPCON-3.2 code contains two fission gas release models. The first is the ANS5.4 model. The ANS5.4 model can predict both the stable noble gas isotopes, and the radioactive isotopes based on their half-lives. The ANS5.4 model was developed with a thermal conductivity model that did not account for conductivity degradation due to burnup and also did not account for the radial power peaking at the pellet edge due to epithermal neutron buildup of plutonium while the FRAPCON-3.2 code accounts for these effects. The ANS5.4 gas release model has not been calibrated with the FRAPCON-3.2 code and, therefore, the absolute release values calculated with this model in FRAPCON-3.2 will significantly over predict fission product release fractions because the diffusion coefficients contain the effects of fuel thermal conductivity burnup degradation and radial power peaking, which are already modeled in FRAPCON-3.2. This problem can be accommodated by considering the ANS5.4 model in context of the second fission gas release model in FRAPCON-3.2.

The second fission gas release model in FRAPCON-3.2 is the Massih model, which has been calibrated with the new thermal conductivity and radial power models. Its predictions have been verified against a large number of fission gas release data from UO_2 fuel rods and a much smaller database from MOX fuel rods (Refs. 4 and 5, respectively). However, the Massih model is only capable of predicting the stable noble gas isotopes and not the radioactive isotopes. Therefore, the ANS5.4 model is needed to calculate the release values for the radioactive isotopes based on the Massih predictions for the stable isotopes.

Calculational Results

In order to model the release of radioactive products, the MOX LTA calculations were initially run with FRAPCON 3.2 using the Massih gas release model to determine the stable fission gas release. The Massih model has been shown to give good gas release predictions for the stable release for both UO_2 and MOX fuel rods. The FRAPCON-3.2 code was then run with the ANS5.4 model using the power history supplied by Duke but reduced by an amount such that the gas release value predicted by ANS5.4 would match the end of life gas release value predicted by Massih using the Duke power history. A second case was also run where the power history was reduced by a factor such that the peak gas release predicted by ANS5.4 would match the peak gas release predicted by Massih using FRAPCON-3.2 and the power history supplied by Duke. This approach normalizes the effective diffusion coefficients for the ANS 5.4 model such that the ANS5.4 model will now correctly calculate the same stable release fractions for the noble gases as are calculated with the Massih model. Figure 2 shows the gas release predictions for the Massih and ANS5.4 models and the ANS5.4 model with the effective diffusion constants modified to match the EOL and peak Massih stable FGR.

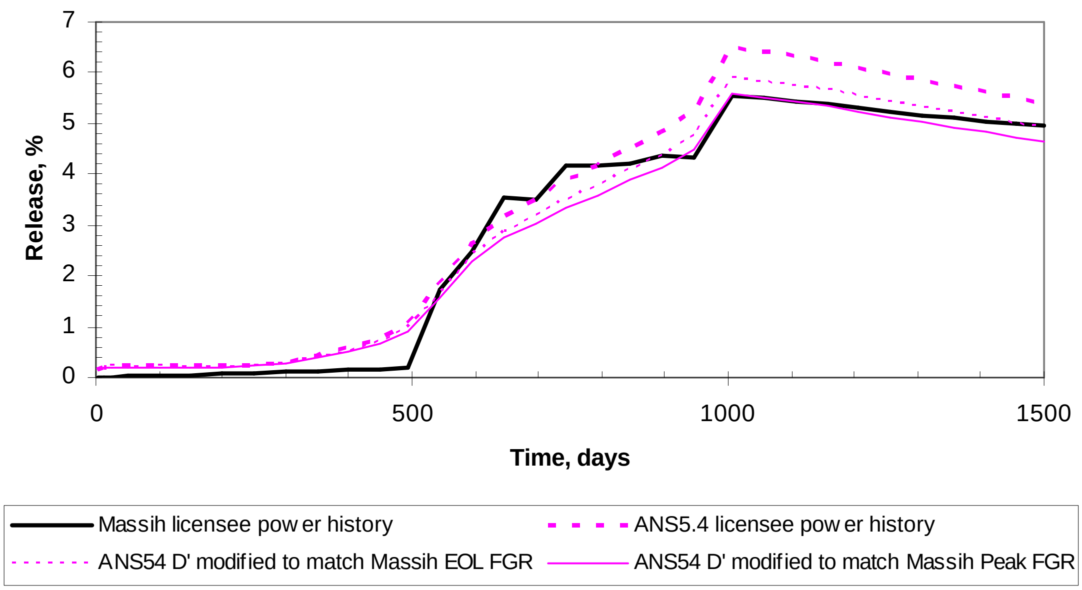

Figure 2: Gas release predictions using the Massih and ANS5.4 models and the ANS5.4 model with the effective diffusion constants modified to match the EOL and peak Massih FGR

Using these modified power histories (resulting in normalized effective diffusion coefficients) the ANS5.4 model was used to predict the release of the radioactive isotopes. For the calculation of I-131, a diffusion constant 7 times that of the noble gases was used and for cesium the diffusion constant was assumed to be 2 times that of the noble gases as recommended by ANS5.4 (Ref. 6). The ANS 5.4 standard also recommends that the release fractions of the long-lived isotopes of Kr-85, Cs-134 and Cs-137 isotopes (half-life of 10.72 years, 2.06 years, and 30.17 years, respectively) be conservatively calculated assuming that they are stable. So the Kr-85 release fraction was calculated using the stable gas routine in ANS5.4 and the Cs-134 and Cs-137 were calculated using the stable gas routine with twice the diffusion constant for noble gases. The shorter lived radioactive isotopes; Kr-87, Kr-88, Xe-133, Xe-135, and I-131 were calculated using the radioactive gas routine in ANS5.4 with 7 times the diffusion constant of noble gases for the I-131. It should be noted that FRAPCON-3.2 using the Massih model will predict best-estimate release fractions for the noble gases when best-estimate input is used, e.g. using best-estimate power histories.

The ANS5.4 standard recommends using time steps of at least two half-lives in the calculation of radioactive release during time-varying power histories. Our review concluded that, for I-131, time steps of 40 days or greater ensure high numerical accuracy for the calculation. In order to accomplish this, the original power history of 45 points was reduced to 33 steps where each time step was greater than 40 days. This power history as determined from burnup and time can be seen in Figure 1. In doing this, several of the axial power profiles that were very similar were combined into a single shape. The FRAPCON predictions using the large time steps were very similar to the predictions using the original 45 time steps.

Table 2 shows the nominal release results at the end of each cycle for the ANS5.4 calculations using the nominal power history modified to match the end of life FGR prediction by Massih. These same results are also shown in Figure 3. Since the release of the isotopes, Kr-87 and Kr-88 are very small; they are not included in the plot in Figure 3.

Table 2: Nominal release results from ANS5.4 with nominal power history modified to match Massih EOL FGR prediction

	Stable Xe & Kr and Kr-85 %	Cs-134 & Cs-137 %	Kr-87 %	Kr-88 %	Xe-133 %	Xe-135 %	I-131 %
End of Cycle 1	1.0	1.4	0.0	0.0	0.3	0.1	0.8
End of Cycle 2	5.9	8.0	0.1	0.2	1.2	0.3	3.8
End of Cycle 3	4.9	6.6	0.0	0.0	0.0	0.0	0.1

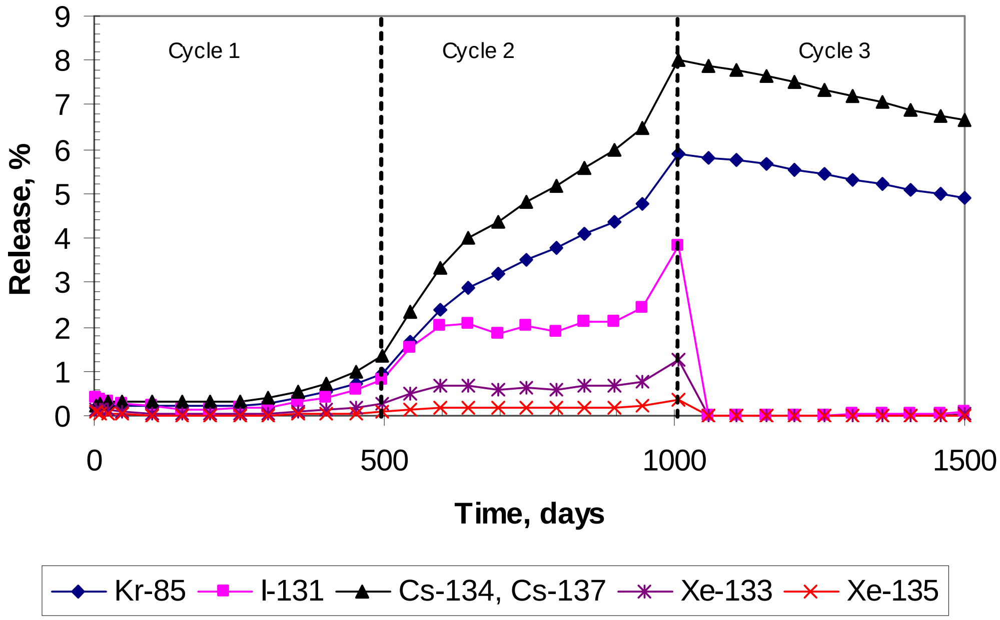

Figure 3: Nominal release results from ANS5.4 with the nominal power history modified to match Massih EOL FGR prediction

Table 3 shows the nominal release results at the end of each cycle for the ANS5.4 calculations using the power history modified to match the peak FGR prediction by Massih which occurred at the end of the second cycle. These same results are also shown in Figure 4. Since the release of the isotopes, Kr-87 and Kr-88 are very small; they are not included in the plot in Figure 4.

Table 3: Nominal release results from ANS5.4 with the nominal power history modified to match Massih peak FGR prediction

	Stable Xe & Kr and Kr-85 %	Cs-134 & Cs-137 %	Kr-87 %	Kr-88 %	Xe-133 %	Xe-135 %	I-131 %
End of Cycle 1	0.9	1.3	0.0	0.0	0.2	0.1	0.8
End of Cycle 2	5.6	7.6	0.1	0.2	1.2	0.3	3.6
End of Cycle 3	4.6	6.3	0.0	0.0	0.0	0.0	0.1

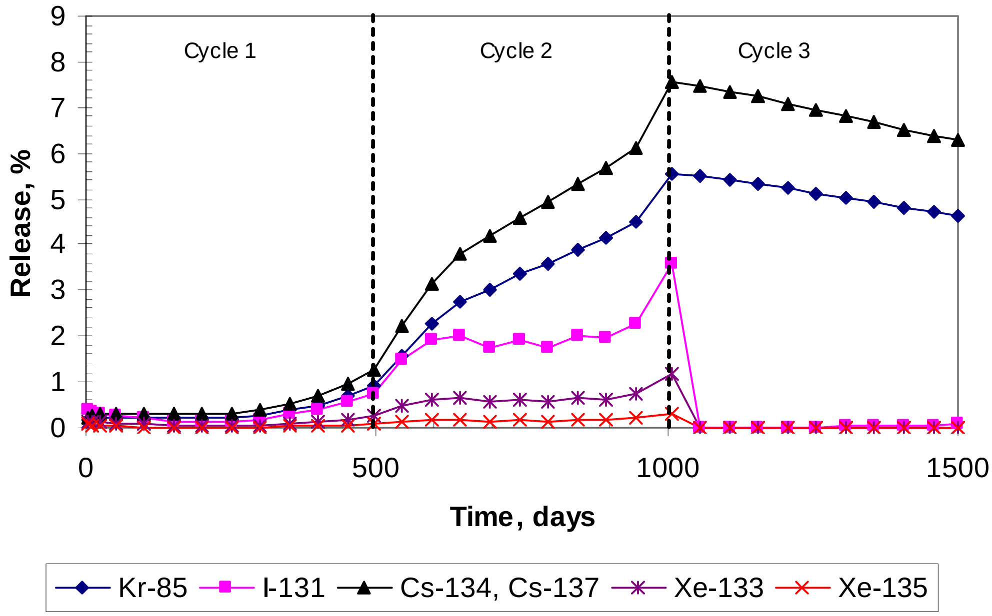

Figure 4: Nominal release results from ANS5.4 with power history modified to match Massih peak FGR prediction

The NRC-NRR request was for releases at rod-average burnups of 25, 45, 50 and 62 GWD/MTM. However, examination of Tables 2 and 3 and also Figures 3 and 4 demonstrate that all the radioactive isotope peak release values occur at EOC2 (provided in Table 3 and Figure 4). These nominal peak release values calculated with the ANS5.4 model at EOC2 are bounded by the Regulatory Guide 1.183 recommended release values for these isotopes.

Limitations of Calculations

The FRAPCON3.2 code has been verified against a wide variety of fuel conditions in terms of rod powers, burnup levels, fission gas release and fuel enrichment. Another important parameter for MOX fuel is stoichiometry, i.e., oxygen-to-metal ratio (O/M). For UO_2 fuel rods the code has been verified for rod powers up to 18 kW/ft, maximum fuel burnups of 65 GWd/MTU, fission gas release up to 33%, and U-235 enrichments up to 13%. For MOX fuel rods the code has been verified for fuel rod-average powers up to 9 kW/ft (steady-state) and ramped rod-average powers up to 10.7 kW/ft, maximum fuel burnups of 60 GWD/MTM, fission gas release up to 25%, percent plutonium up to 6%, and O/M ratios between 1.98 to 2.0. The fuel parameter that has the largest impact on fission product release calculations is the rod power. In relation to this limitation the calculations presented in this report do not include the impact of transients. An example of how fission gas release changes with rod powers will be provided in the next section along with the code calculational uncertainties in fission product release.

Power History and Calculational Uncertainties

The uncertainty in the FRAPCON-3.2 predicted release fractions for the radioactives can be estimated based on the standard deviation of the FRAPCON-3.2 predictions of stable noble gases to measured data from UO_2 and MOX fuel. The standard deviation for UO_2 fuel stable gas predictions of 0.026 absolute release fraction and a standard deviation for MOX of gas predictions of 0.048 absolute release fraction. The actual uncertainty in the MOX predictions is most likely much closer to those for UO_2 fuel but the calculated value is much higher because there are only 6 MOX data points making the uncertainty high because of the small MOX database. In actuality the mechanisms for release from UO_2 and MOX fuel is the same with the primary difference being in the diffusion coefficients for MOX versus UO_2 fuel such that uncertainties should be similar between these two fuel types. Therefore, the UO_2 and MOX predictions compared to data were combined to give an overall standard deviation of 0.031 for absolute release fraction.

The release fractions provided above are nominal release values based upon the power histories derived from Duke provided time and burnup values are reasonably close to nominal for the peak rod in the LTAs. In order to bound possible differences between the expected power history and the actual irradiation of the MOX LTAs, the power was increased by 5%, and the radioactive release values were calculated again with the effective diffusion constant in ANS5.4 modified to match the end of life gas release from Massih. The effective diffusion constant in ANS5.4 was also modified to match the peak gas release from Massih. Table 4 shows the results of these calculations. These results with a 5% conservatism on rod power (calculated from the Duke provided values of time and burnup multiplied by 1.05) show that the peak release values calculated with ANS5.4 model that occur at EOC2 are bounded by the Regulatory Guide 1.183 recommended release values for these isotopes. Table 4 also shows the release results in parenthesis (for the isotopes with release values > 1%) using rod powers (calculated from the Duke provided values of Fdelta-H and core average power multiplied by 1.05). These results with the Fdelta-h powers show that with a 5% increase in power the radioactive releases for Kr-85 and Cs isotopes are slightly higher than those recommended by Regulatory Guide 1.183, i.e., 10.6% versus 10% and 13.6% versus 12%, respectively.

Table 4: Release results from ANS5.4 with power history increased by 5% and the effective diffusion constant modified to match Massih EOL and peak FGR predictions

	Stable Xe & Kr and Kr-85 %	Cs-134 & Cs-137* %	Kr-87 %	Kr-88 %	Xe-133 %	Xe-135 %	I-131** %
Regulatory guide limits 1.183	10.0	12.0	5.0	5.0	5.0	5.0	8.0
ANS5.4 effective diffusion constant modified to match Massih EOL gas release							
End of Cycle 3	7.3 (8.7)	9.6 (11.2)	0.0	0.0	0.0	0.0	0.1 (0.2)
ANS5.4 effective diffusion constant modified to match Massih peak gas release							
End of Cycle 2	8.2 (10.6)	10.9 (13.6)	0.2	0.3	1.8 (2.2)	0.5	5.4 (6.6)
* Cesium is the only alkali metal calculated to be released with the ANS5.4 model ** Iodine is the only halogen calculated to be released with the ANS5.4 model							

Table 5 shows the radioactive fission product release values using the 5% greater power history (calculated from the Duke provided values of time and burnup multiplied by 1.05) plus a 1-sigma to account for code calculational uncertainties. The standard deviation for the stable noble gas release with both UO_2 and MOX data was 3.1%. The standard deviation for the radioactive isotopes was obtained by scaling the standard deviation for the stable release by the ratio of the predicted release of the radioactive isotope divided by the stable noble gas release value. Table 5 also shows the release results in parenthesis (for the isotopes with release values > 1%) using rod powers calculated from the Duke provided values of Fdelta-H and core average power multiplied by 1.05. These results show that with a 5% increase in power plus a 1-sigma due to code calculational uncertainties the radioactive releases for Kr-85 and Cs isotopes are higher than those recommended by Regulatory Guide 1.183.

Table 6 shows the radioactive fission product release values using the 5% greater power history (calculated from the Duke provided values of time and burnup multiplied by 1.05) plus a 2-sigma due to code calculational uncertainties. Table 6 also shows the release results in parenthesis (for the isotopes with release values > 1%) using rod powers calculated from the Duke provided values of Fdelta-H and core average power multiplied by 1.05. These results show that with a 5% increase in power plus a 2-sigma due to calculational uncertainties the radioactive releases for I-131, Kr-85 and Cs isotopes are higher than those recommended by Regulatory Guide 1.183. As noted previously the analyses presented in this report do not evaluate reactivity insertion accidents, this accident scenario will be addressed in a future report to NRC.

Table 5: Comparison of Regulatory Guide limits on Non-Loca release to those calculated release results for MOX LTAs using FRAPCON3.2/ANS5.4 with 5% increased power above Duke powers plus 1-sigma uncertainty on the calculation

	Stable Xe & Kr and Kr-85 %	Cs-134 & Cs-137* %	Kr-87 %	Kr-88 %	Xe-133 %	Xe-135 %	I-131** %
Regulatory guide limits 1.183	10.0	12.0	5.0	5.0	5.0	5.0	8.0
ANS5.4 effective diffusion constant modified to match Massih EOL gas release							
End of Cycle 3	10.4 (11.8)	13.7 (15.1)	0.0	0.0	0.1	0.0	0.2
ANS5.4 effective diffusion constant modified to match Massih peak gas release							
End of Cycle 2	11.3 (13.7)	15.0 (17.6)	0.3	0.4	2.5 (2.9)	0.7	7.5 (8.5)
* Cesium is the only alkali metal calculated to be released with the ANS5.4 model ** Iodine is the only halogen calculated to be released with the ANS5.4 model							

Table 6: Comparison of Regulatory Guide limits on Non-Loca release to those calculated release results for MOX LTAs using FRAPCON3.2/ANS5.4 with 5% increased power above Duke powers plus 2-sigma

	Stable Xe & Kr and Kr-85 %	Cs-134 & Cs-137* %	Kr-87 %	Kr-88 %	Xe-133 %	Xe-135 %	I-131** %
Regulatory guide limits 1.183	10.0	12.0	5.0	5.0	5.0	5.0	8.0
ANS5.4 effective diffusion constant modified to match Massih EOL gas release							
End of Cycle 3	13.5 (14.9)	17.7 (19.1)	0.0	0.0	0.1	0.0	0.2
ANS5.4 effective diffusion constant modified to match Massih peak gas release							
End of Cycle 2	14.4 (16.8)	19.1 (21.6)	0.3	0.5	3.2 (3.5)	0.9	9.5 (10.5)
* Cesium is the only alkali metal calculated to be released with the ANS5.4 model ** Iodine is the only halogen calculated to be released with the ANS5.4 model							

LTA Rod Pressures in a Spent Fuel Pool

Calculations have also been performed with FRAPCON3.2 to determine if the MOX LTAs, when stored in a spent fuel pool, will exceed 1300 psig. These calculations were performed for the four scenarios above, i.e., nominal power history provided by Duke, a 5% increase in rod powers from those provided by Duke, a 5% increase in rod powers plus a 1-sigma code calculational uncertainty, and a 5% increase in rod powers plus a 2-sigma code calculational uncertainty. The MOX LTA rod pressures were conservatively estimated (small conservatism) assuming a spent fuel temperature of 100ºC at a pressure of 1atm. The results are shown in Table 7, demonstrating that even with the most conservative case of 5% power increase plus a 2-sigma uncertainty the rod pressures remain significantly below 1300 psig. Table 7 shows in parentheses the results of these calculations using the rod powers calculated from the values of Fdelta-H provided by Duke. This analysis has not assessed whether the decontamination factor of 200 is conservative at the rod pressures calculated in Table 7.

Table 7: MOX LTA calculated rod pressures in spent fuel pool

	Rod Pressure in Spent Fuel Pool psia	FGR %
Nominal Power History	621 (676)	4.9 (5.9)
Nominal Power History increased by 5%	730 (807)	7.3 (8.7)
Nominal Power History increased by 5% plus 1- sigma on FGR	873 (956)	10.4 (11.8)
Nominal Power History increased by 5% plus 2- sigma on FGR	1015 (1105)	13.5 (14.9)

References

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