KW Consulting Fission Gas Release Model

The KW Consulting fission gas release model was initially developed as an updated model for the ANS-5.4 radioactive isotope release standard. Since the mechanisms of fission gas release are the same for both stable and unstable fission gas isotopes, the KW Consulting gas release model has been developed to be a state-of-the-art gas release model for the predict the release of both the stable fission gas isotopes and the gap fractions of the radioactive isotopes, during both fuel rod steady state operation and during operational transients. The model has been developed to (1) give acceptable predictions for stable fission gas release for both steady state operation and operational transients, (2) give acceptable predictions for the unstable isotope release, in particular the release of the ^{131}I isotope that is the major contributor to fuel handling accident doses, and (3) not require excessive computational resources, either in run time or code memory, so that the KW Consulting gas release model can be readily integrated into existing fuel rod performance codes.

The model is based on four mechanisms for fission gas release:

- gas diffusion to grain boundary bubbles, with resolution at the grain boundary surface. Gas is released from the grain boundary bubbles when the bubbles interlink, with interlinkage occurring when the gas concentration in the grain boundary bubbles exceeds a saturation concentration. This release mechanism is needed to predict stable fission gas releases of more than a few percent.

- grain boundary sweeping into the grain boundary bubbles. When grain growth occurs, gas at the periphery of the grains can be swept directly into the grain boundary bubbles. This is a non-diffusional mechanism for transport of gas within the grains directly into the grain boundary bubbles.

- direct diffusion release to the rod void volume. This release mechanism is needed to obtain any significant radioactive isotope release prior to grain boundary bubble interlinkage.

- recoil/knockout release directly to the rod void volume. This mechanism is needed to match stable fission gas release data for rods that operated at low temperatures throughout life, such that grain boundary bubble interlinkage does not occur. The recoil/knockout release model in the 1982 ANS-5.4 model, with a release fraction proportional to burnup, is used, with a modified burnup dependence to match steady state stable fission gas release data for high burnup rods that operated at moderate powers throughout life. This model does not make any significant contribution to the release of the unstable isotopes.

The diffusion models are based on solutions to the diffusion equation in an effective spherical grain. The Forsberg and Massih technique of approximating the diffusion equation response function by a series with a small number of terms is used. The model for resolution at the grain boundary bubble surfaces is based on the Speight-Turnbull boundary condition for the gas concentration at the grain surface, $C(a) \propto N_{gb}$, where C is the gas concentration in the grain, a is the effective grain radius and N_{gb} is the gas concentration in the grain boundary bubble. The model has been modified to allow for an effectively instantaneous release of some of the resolved gas when the temperature increases, to model the rapid release of some of the fission gas retained in the fuel due to microcracking due to rapid power transients. This microcracking modification enables the model to give acceptable predictions for both the steady state and the transient fission gas release data.

The KW Consulting fission gas release model has been implemented in a self-contained Fortran module. The model has been calibrated to stable and unstable gas release data using the FRAPCON 3.4 fuel rod performance code, using a driver subroutine to interface between the KW fission gas release model subroutines and FRAPCON3.4. The FRAPCON stable fission gas release database, which consists of 23 rods irradiated under steady-state conditions and 18 rods with end-of-life overpower transients, has been used to calibrate the model to stable fission gas release data. Unstable isotope release data from the Halden IFA-504 and IFA-558 gas flow rig tests has been used to calibrate the model to unstable isotope release data.

Results for the stable fission gas release calibration are shown in Figures 1 through 4. These stable fission gas release calibration results are comparable to those obtained with other fission gas release models, e.g., the FRAPCON3 Massih fission gas release model.

Predictions for the IFA-504 and IFA-558 unstable isotope release data are shown in Figures 5 through 10. These IFA tests have obtained a large amount of data and there is a large amount of scatter in the predicted vs. measured results for these tests. This large scatter is typical of the evaluations of these unstable isotope release data, e.g., a similar degree of scatter is obtained with the model proposed for the updated ANS-5.4 standard. The technologically most significant unstable isotope release data are the ^{131}I data, since this isotope has a comparatively long half-life, 8.04 days, and gives the largest contribution to radiological doses due to accidents during in-reactor operation or during fuel handling. The KW Consulting fission gas release model calibration to the IFA-504 and IFA-558 unstable isotope release data has been selected to give a best estimate prediction for the high power ^{131}I release data, while giving a calibration to the shorter-lived isotope release data consistent with a best estimate model, within the scatter of the IFA-504 and IFA-558 release data.

Figures 5 through 7 show the ^{131}I release data predicted vs. measured and predicted/measured ratios vs. burnup and power, respectively. These Figures show that the KW Consulting model gives a best estimate prediction of the higher power, greater than 15 kW/m, ^{131}I data, and that there is no bias as a function of burnup within this power range. However, the model underpredicts the lower power, less than 15 kW/m, ^{131}I release data.

Due to the significant scatter in the comparisons with the shorter-lived isotope release data, and the large amount of IFA-504 and IFA-558 data for these shorter-lived isotopes, the KW Consulting gas release model predicted vs. measured comparison for these shorter-lived isotopes is best summarized by plotting the average of the logarithm of the measured-to-predicted ratios, with 1σ error bars to indicate the range of the scatter. Figure 8 shows these results for all the IFA-504 and IFA-558 data, Figure 9 shows the results for the data before there is any grain boundary bubble interlinkage, and Figure 10 shows the results for the data after grain boundary bubble interlinkage first occurs. Since the mean ln(M/P) is approximately 0, except for the ^{135m}Xe and ^{133}Xe isotopes, Figure 8 shows that the calibration is a best estimate calibration to all the IFA-504 and IFA-558 data. However, Figures 9 and 10 show that the model on average overpredicts the isotope release data prior to grain boundary bubble interlinkage, and on average underpredicts the data after grain boundary bubble interlinkage. However, again except for the ^{135m}Xe and ^{133}Xe data, the 1σ error bars all overlap the best estimate average ln(M/P) = 0 line, and these Figures show that statistically the model is a best estimate model both before and after grain boundary bubble interlinkage occurs.

The KW Consulting detailed diffusion model solution for the unstable isotope release does not account for enhancement of the release rates due to precursors. The ^{135m}Xe isotope has a much larger precursor enhancement of the release than any of the other isotopes measured in the IFA-504 and IFA-558 tests, which is the reason why the KW Consulting model systematically underpredicts the ^{135m}Xe release data in Figures 8, 9 and 10. Since there are no precursor enhancement effects for the ^{131}I release, not accounting for the precursor effects does not effect on the KW Consulting model comparison with the ^{131}I release data. The model also significantly and uniformly underpredicts the long-lived ^{133}Xe release data. It is believed that this underprediction of the ^{133}Xe data is due to the difficulty of the ^{133}Xe release data measurement.

It is expected that similar fission gas release calibration results would be obtained with the implementation of the KW Consulting fission gas release model in other fuel rod performance codes, though it is anticipated that there would be slight changes in the model calibration constants, depending on the details of the other models in the fuel rod performance code and the stable fission gas release database used for the model calibration.

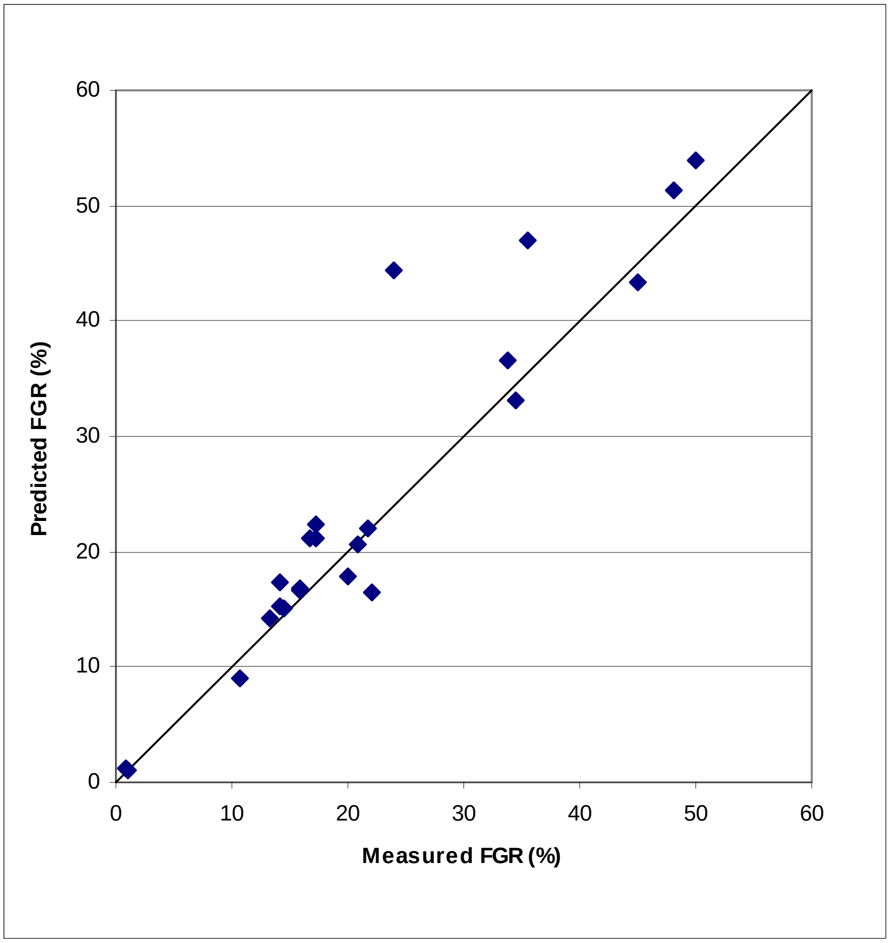

Figure 1 – Steady-state stable fission gas release measured vs. predicted comparison

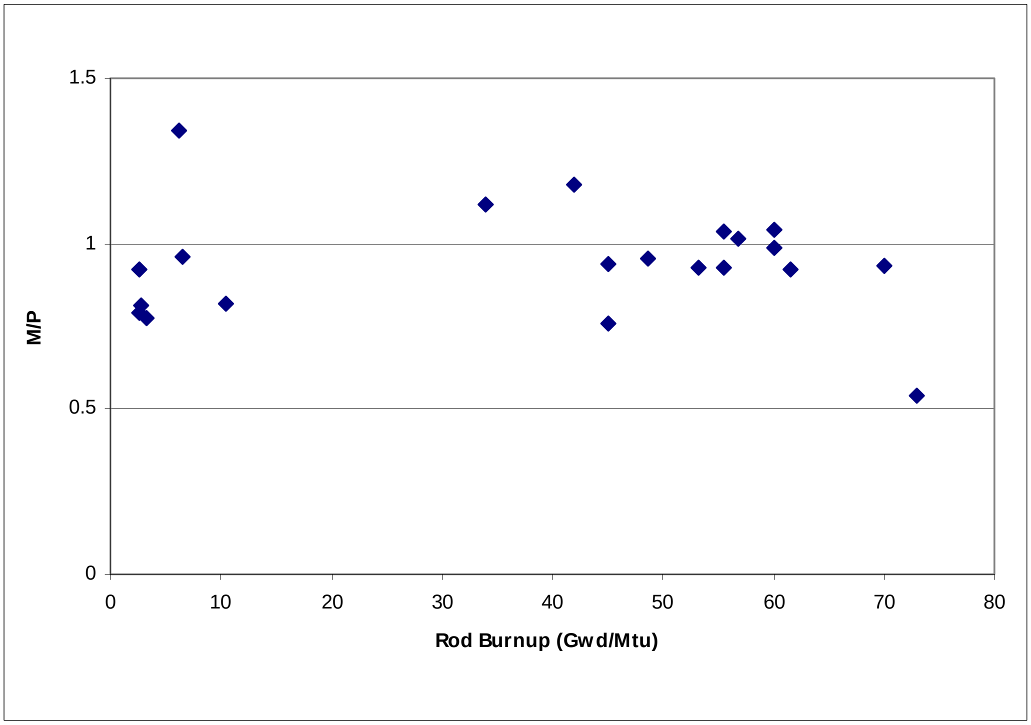

Figure 2 – Steady-state stable fission gas release measured-to-predicted ratios vs. burnup

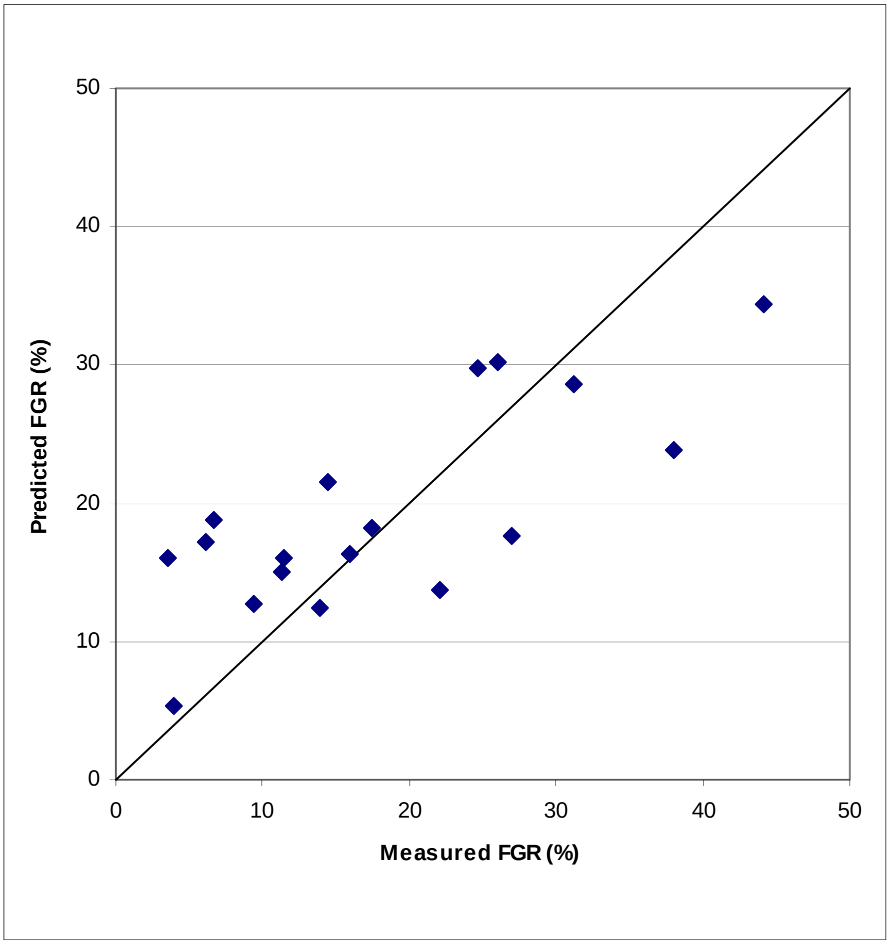

Figure 3 – Transient overpower stable fission gas release measured vs. predicted comparison

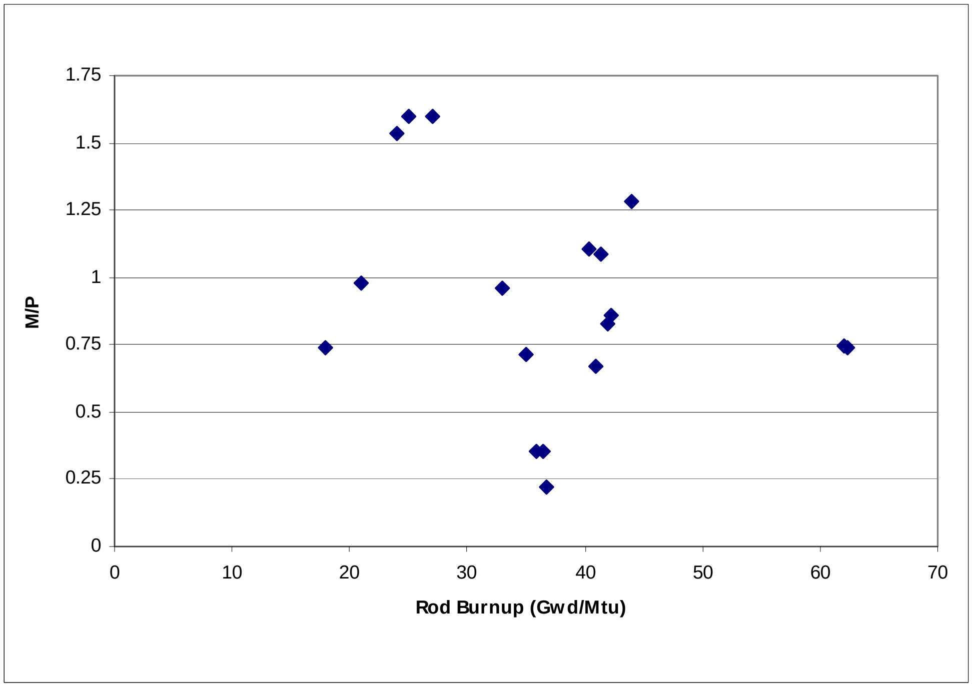

Figure 4 – Transient overpower stable fission gas release measured-to-predicted ratios vs. burnup

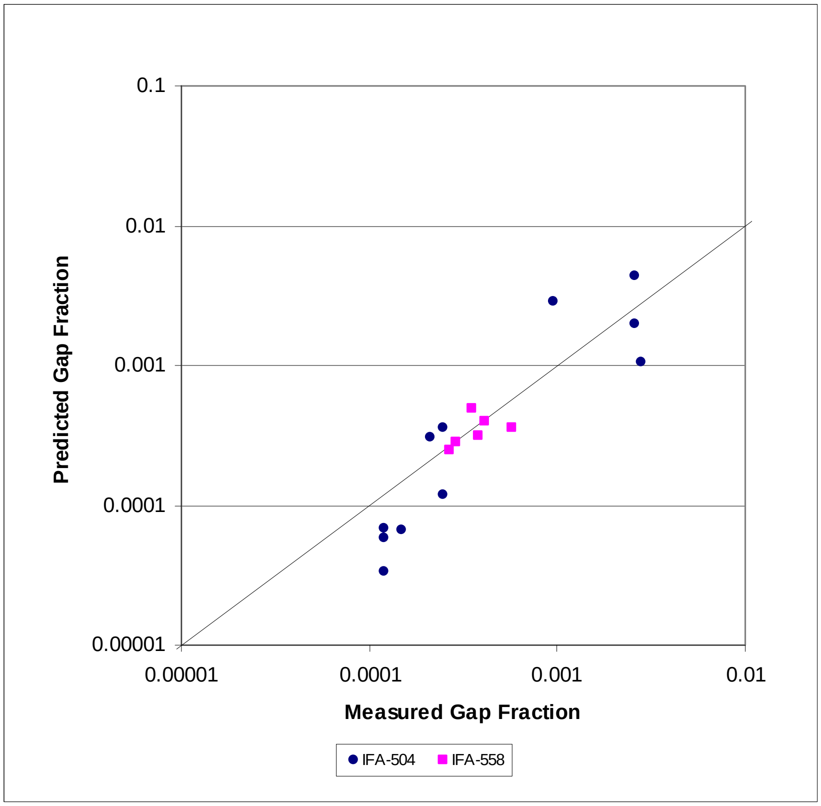

Figure 5 – ^{131}I release data predicted vs. measured comparison

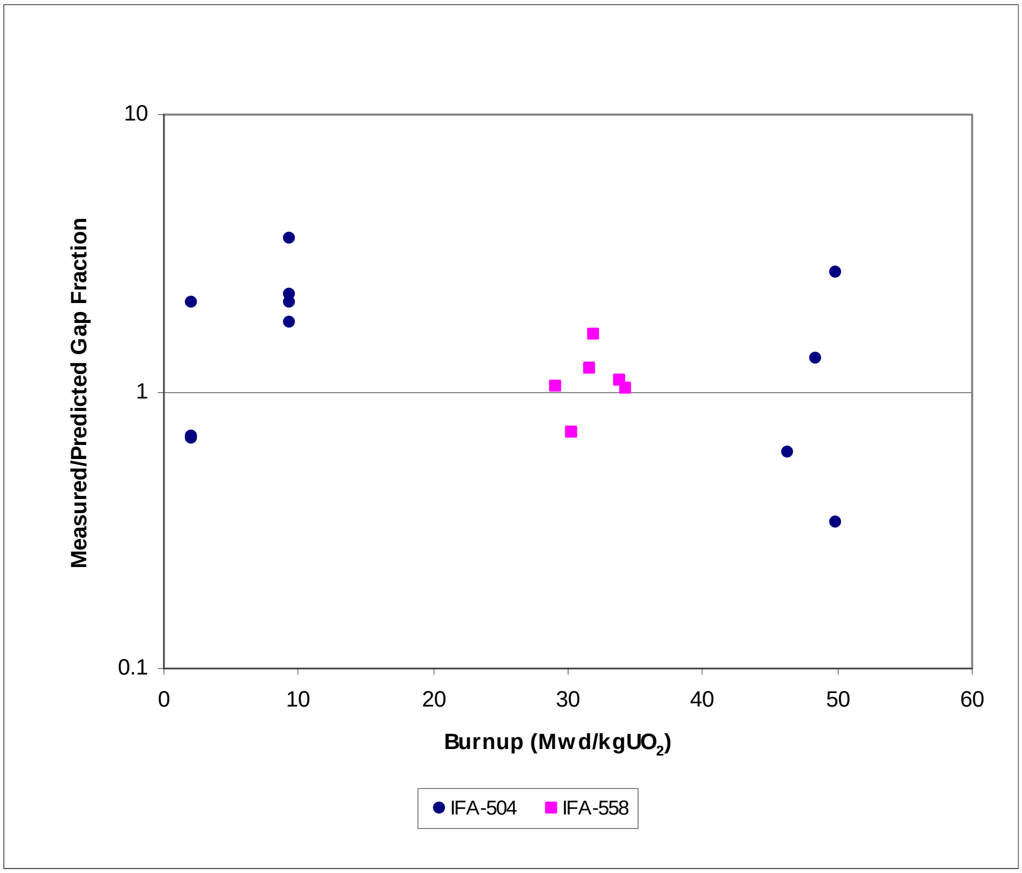

Figure 6 – ^{131}I release data measured/predicted ratios vs. burnup

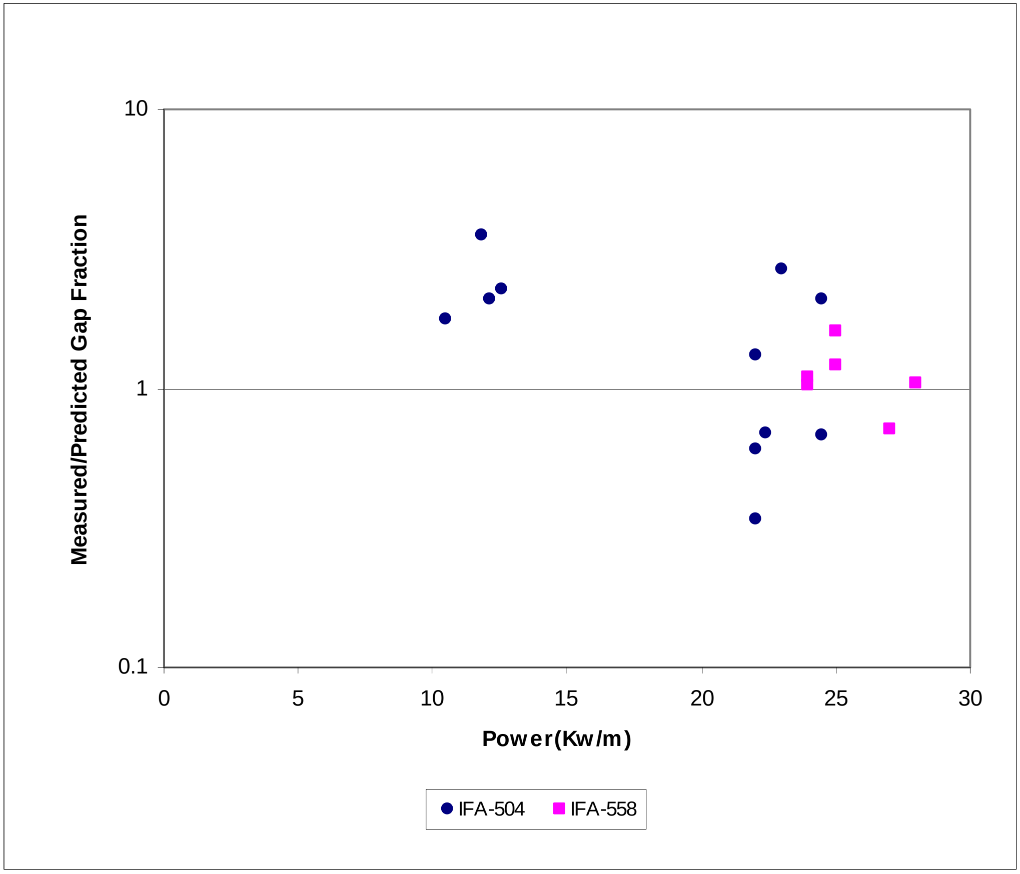

Figure 7 – ^{131}I release data measured/predicted ratios vs. power

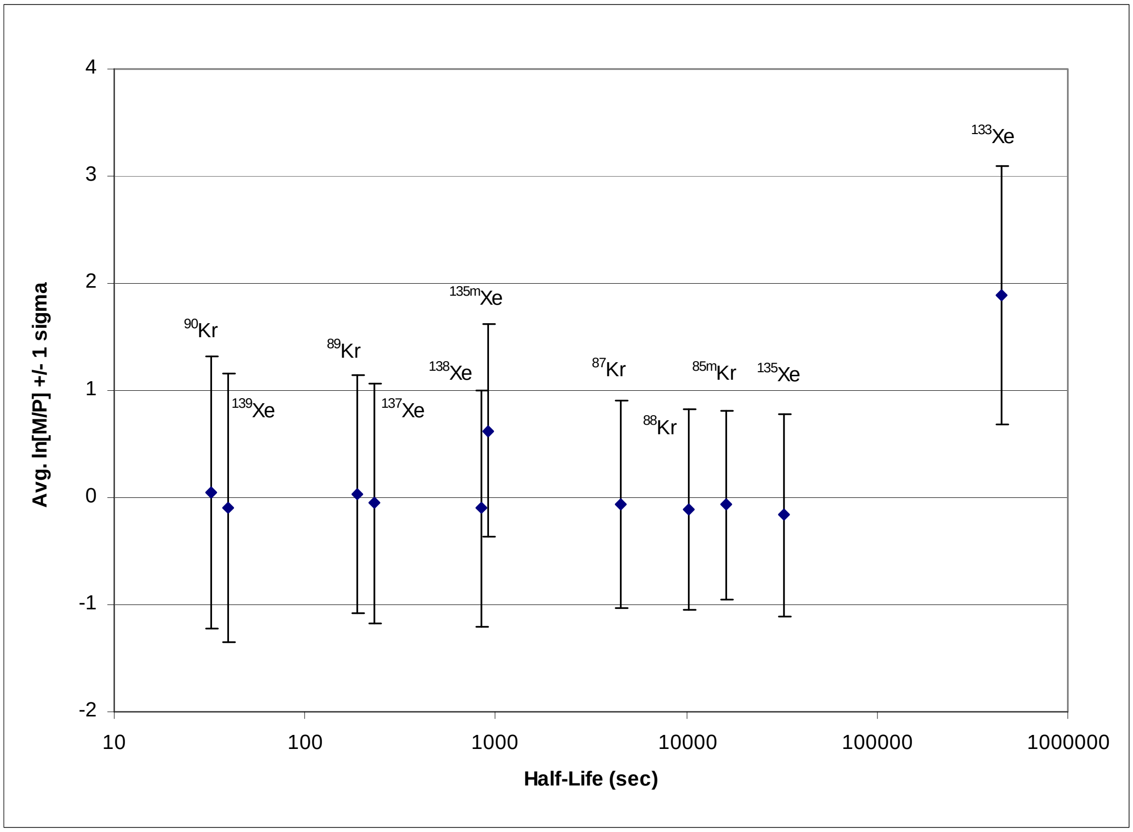

Figure 8 – IFA-504 and IFA-558 unstable isotope measured-to-predicted ratio data

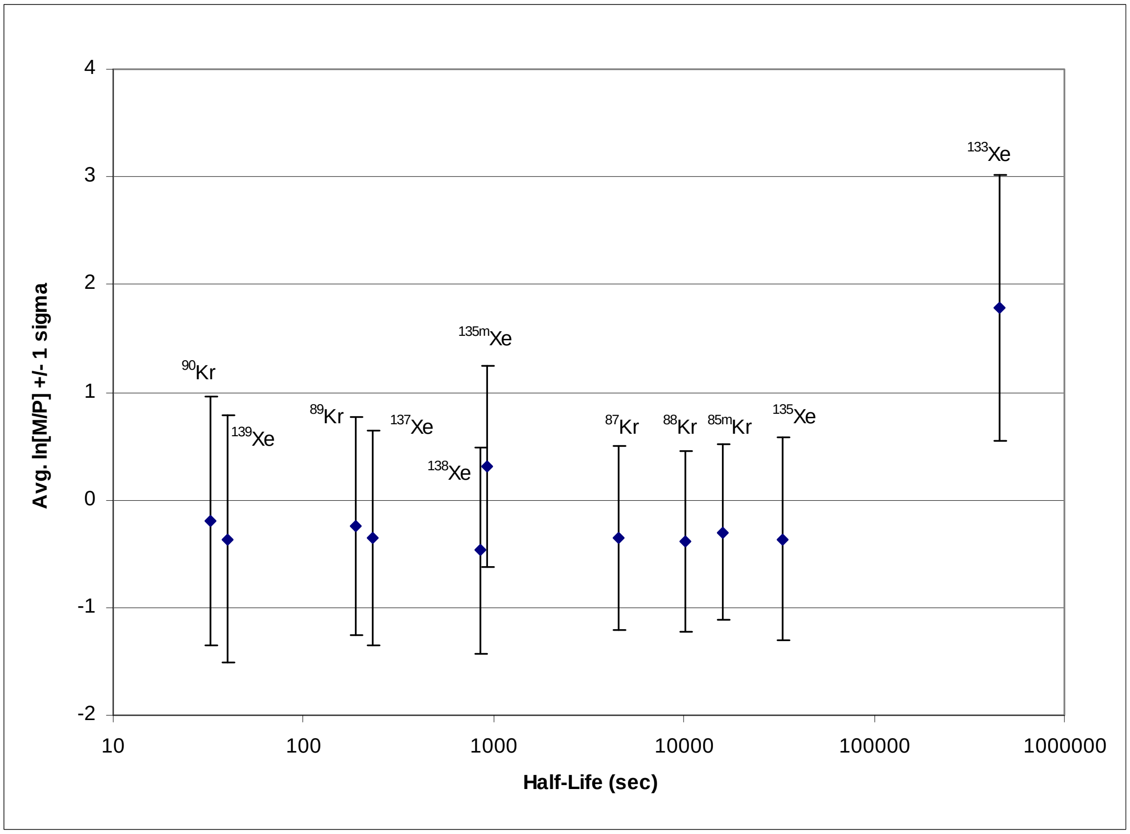

Figure 9 – IFA-504 and IFA-558 unstable isotope measured-to-predicted ratio data prior to grain boundary bubble interlinkage

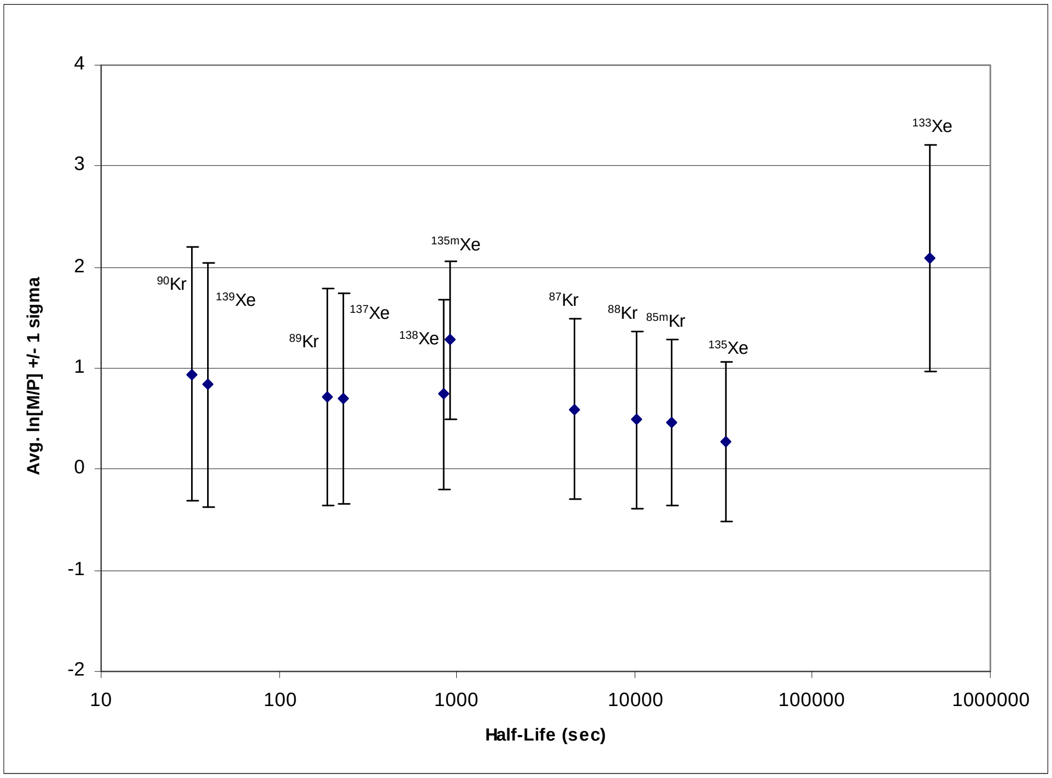

Figure 10 – IFA-504 and IFA-558 unstable isotope measured-to-predicted ratio data after initial grain boundary bubble interlinkage