FISSION PRODUCT INVENTORY AND DISTRIBUTION AT POINT LEPREAU GENERATING STATION

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1. Introduction

Existing safety analysis for Point Lepreau has been based on predictions of releases of iodines and noble gases only. However, it has been recognized that there is some potential for other less volatile species to be released in high temperature accident transients that could play an important role in the dose consequences to the public and on the role of site evacuation. As well, the release of other isotopes may be important contributors to the radiation doses that equipment inside containment could be exposed to, or the radiation doses around equipment that a station operator may be exposed to in an attempt to operate equipment after such an event.

As well, improvements in understanding of fission product release behaviour and enhanced computational capabilities make it possible now to account for a larger range of chemical species and isotopes.

Point Lepreau has initiated a program to enable future safety assessments to account for the release of a wider range of isotopes by updating the calculation of the fission product inventories in the core. The tools and methodology used have been upgraded. This paper describes this development and illustrates some results.

2. Methodology

The following steps were followed:

1. select the isotopes and groupings to use,
2. select the computer code for nuclide inventory calculations,
3. select the tools to use to obtain the gain bound, grain boundary and gap inventories,
4. select tools to assess the differences for defect fuel,
5. determine the method for treating the fuel element power and burnup history,
6. select the method for treating the allowable range of core power and burnup distributions,
7. use tools and methods selected to determine fission product inventories.

2.1 Selection of Isotopes

There are over a thousand radionuclides in irradiated fuel. To make analysis tractable it is necessary to consider only those that are important to accident consequences. Work had been performed in 1993 on the significance of these isotopes to the predictions of public doses for a range of accident types, see Reference 1. In that analysis isotopes were ranked in relative importance and a cut-off criteria was used to select only those that were of relatively greater importance to all accident types considered. 96 isotopes of 26 elements were selected.

For the other considerations than public dose, the measure by which the isotopes are ranked was determined as follows:

$$M_{i,n} = I_i \cdot Rf_i \cdot E_{i,n}$$

where:

$M_{i,n}$ is the measure of the significance of a given isotope, i, for particle n (MeV/s), due to emission of particle n (which is either γ or β);

I_i is the inventory of the isotope i (Bq);

Rf_i is the fractional release from the fuel element expected in a LOCA;

$E_{i,n}$ is the energy of the γ or β particle released in the decay of isotope i (MeV).

To assess the importance of dose to the operator, the values for $E_{i,n}$ used is the maximum gamma energy associated with the decay, since these provided the greatest penetration through containment. For gamma doses to equipment, the value for $E_{i,n}$ was the total gamma energy released during the decay via all decay chains, since all emitted gammas could damage equipment. For beta doses to equipment, the value of $E_{i,n}$ was the highest β energy associated with the decay unless the particle intensity was less than 1%, since only the higher energy betas would be sufficiently penetrating.

A cutoff threshold of 10^{-4} was used, to be consistent with Reference 1, for the 3 additional nuclide lists (*i.e.* isotopes for operator dose, equipment dose by gammas and equipment dose by β particles). The combination of the four lists resulted in 120 isotopes of 29 elements for inclusion in the inventory calculations, see Table 1.

These elements were grouped into three chemical groupings:

1. Noble Gases (Xe and Kr)
2. Halogens (Br, I, Rb, Cs, Te, Sb, Cd)
3. Semi-volatiles/Non-volatiles (Sr, Ba, Mo, Tc, Ru, Rh, Ag, Y, Zr, Nb, La, Ce, Nd, Pm, Sm, Eu, Cm)

It was felt that there was not sufficient experimental information regarding free inventories and release behaviour to expand on these groupings.

2.2 Selection of Tools

The standard tool for performing nuclide depletion calculations is the ORIGEN-S code that is part of the SCALE 4.3 package. This package has been defined, verified and validated for use in CANDU reactor analysis, see References 2 and 3.

However, ORIGEN-S does not include models of the fission product distribution within the fuel. The available tools considered were SEREL-HTT 1.1, SOURCE 1.1 and ELESIM-II with the FREEDOM models of diffusion from the fuel grains.

SOURCE 1.1 and SEREL-HTT 1.1 have similar models, but since SEREL-HTT had been used by NB Power and code modifications were required to accommodate the larger number of nuclides, it was deemed to be a better choice. The validation of ELESIM-II with FREEDOM, see Reference 4, indicated that in its present state, it significantly and systematically mis-predicts the free inventory of isotopes for elements in the power range 40-60 kW/m, so it was not selected for use in inventory distribution calculations.

SEREL-HTT's model of fission product distribution calculates the distribution by calculating the gap and bound inventories and attributing the remainder as the grain boundary inventory. To extend the model for this task the following steps were taken:

1. The isotope groupings and selection of representative isotopes were reassessed.
2. The free inventory calculations were updated to account for the dependence on λ (*i.e.* reflect the results of sweep gas tests).
3. The uncertainty in the correlations used in temperature profiles with power were addressed.
4. The free inventory calculations were compared against more recent data.
5. The grain boundary inventory predictions were compared with recent experimental data.

A comparison of the gap inventory release model against sweep gas tests results for FIO-122, FIO-124 and FIO-141 revealed that the correlations, when corrected for the effect of half-life, resulted in an under-prediction of free inventory fractions for lower powered elements, see Figure 1. The reasons for this discrepancy were investigated and it was found that there were two difficulties with the original SEREL-HTT model: the correlations for free inventory as a function of temperature and the lookup tables used to determine the fuel temperature in the model.

A review of the original data on which the correlations for free inventory as a function of temperature are based, Reference 5, revealed that the correlations tend to maximize retained inventory for ^{85}Kr and ^{137}Cs. Note that this trend was not observed for ^{90}Sr. Since for safety analysis purposes it is intended to over-predict releases, the correlations for ^{85}Kr and ^{137}Cs were modified.

Fuel temperature measurements were only available for FIO-141. These indicated that the temperatures derived from the lookup tables in the SEREL-HTT model prediction of the sweep gas tests were 200°C higher than the measured values. An assessment was performed on the effect of using ELESIM-II predicted temperatures in place of the temperature correlations presently used in SEREL-HTT, with 80°C added to the ELESIM-II-predicted temperature to account for the effect of the axial grooves, providing a best-estimate of fuel temperatures in the tests. It was shown that gap inventory predictions would be somewhat over-predicted if this were done, see Figure 2. This over-prediction in gap inventory relative to the true values was determined to be by a factor whose value is 2.3±1.16.

The model of fission product distribution in intact elements used in the calculations reported in this paper was the original SEREL-HTT model with alterations to the correlations for free inventory as a function of temperature and using ELESIM-II-predicted temperatures. The uncertainty in ELESIM-II centre-line temperature predictions is considered to be ±143°C, Reference 6, exclusive of the effect of uncertainties in power. Therefore, an uncertainty of 150°C was applied to the central temperature with the uncertainty decreasing linearly to zero at the fuel surface for the calculations reported in this paper. Note that this accounting for temperature uncertainty will increase the expected value of the over-prediction in gap inventory to a value somewhat larger than the factor of 2.3 mentioned above, as the factor of 2.3 is based on best-estimate temperatures. The use of ELESIM-II temperatures in the SEREL-HTT model was accomplished most conveniently by incorporating the modified SEREL-HTT model into ELESIM-II MOD10 (VAX Version 1.2).

The groupings as a function of half-life values was unchanged from the original SEREL-HTT that used the following nine groups:

1. $t_{1/2} < 3$hr
2. 7 hr $> t_{1/2} >$ 3 hr
3. 10 hr $> t_{1/2} >$ 7 hr
4. 21 hr $> t_{1/2} >$ 10 hr
5. 4 d $> t_{1/2} >$ 21 hr
6. 6d $> t_{1/2} >$ 4d
7. 9 d $> t_{1/2} >$ 6d
8. 13 d $> t_{1/2} >$ 9d

9. $t_{½} > 13d$

There was limited data available on grain boundary inventories. Data from References 7 and 8 were used to compare the predicted values and the results are illustrated in Figure 3.

Overall, it was concluded that the comparisons to experimental data indicate that the sum of the gap and grain boundary inventories would be over-predicted , and that the probability of over-predicting the free inventory was 97.5% if best-estimate fuel temperatures were used.

2.3 Accounting for Defected Fuel

In a defected fuel element, the distribution of fission products is altered due to the oxidation of UO_2 by steam which can gain access via the defect. Oxidized UO_2 releases fission products at a faster rate than unoxidized UO_2. Experiments performed at Chalk River Laboratories have been analyzed, see Reference 9, and indicate that the effective diffusion coefficient is dependent only on element power for mature defects. An uncertainty of 10% in powers was allowed for based on measured powers reported in Reference 10. The functional form of the correlations was:

$$D_I' = \begin{cases} P^{8.875391} \cdot e^{51.9978} & P \geq 20.7 \text{ kW/m} \\ 1.25134 \cdot 10^{-11} & P \leq 20.7 \text{ kW/m} \end{cases}$$

$$D_N' = \begin{cases} P^{8.183015} \cdot e^{50.1084} & P \geq 20.7 \text{ kW/m} \\ 1.01583 \cdot 10^{-11} & P \leq 20.7 \text{ kW/m} \end{cases}$$

where:

D_I' is the diffusion coefficient from the grain to the free volume for iodine (s^{-1})
D_N' is the diffusion coefficient from the grain to the free volume for noble gases (s^{-1})
P is the element power (kW/m)

With this the fractional free inventory can be determined using:

$$f = 3 \cdot \sqrt{\frac{D'}{\lambda}}$$

where:

f is the fractional free inventory
D' is the effective diffusion coefficient (s^{-1})
λ is the decay constant of the isotope (s^{-1})

For the purpose of this work, the reduction of the gap inventory by losses through the defect hole is neglected. These models were incorporated into the modified version of SEREL-HTT's fission product distribution model, which was incorporated into ELESIM-II as discussed above. The version of ELESIM-II with the modified SEREL-HTT fission product distribution model is called ELESIM-II MOD10 (VAX Version 1.2).PLGS1.

2.4 Operating Envelope for Fuel Bundles and Channels

To calculate the inventory and distribution for a fuel bundle, ORIGEN-S, SEREL-HTT, and ELESIM-II MOD10 (VAX Version 1.2).PLGS1 are run for the four element histories, one for each pitch circle. To maximize the releases, the fuel is modeled with a maximum mass and with fuel parameters that maximize fuel temperatures. The analysis is performed with a UO_2 mass of 19.65 kgU/bundle - this is somewhat larger than presently permitted - with parameters chosen from the study of Reference 11 to maximize temperatures.

A wide range of operating parameters can affect both the inventories and the distributions of fission products. The impact of the following variations were considered.

1. Power reductions
2. Trips and restarts
3. Fuel shifting and the time of the shifts
4. High burnup fuel
5. Power variations due to fuelling neighboring channels
6. Reduced or accelerated fuelling rates
7. Defect fuel

For channel inventory calculations, analysis using powers at the bundle or channel power limits tends to maximize predicted inventories. It was decided that an allowance of a bundle dwell time of 1.5 years for a maximum bundle burnup of 450 MW·h/kgU should be allowed for. If a channel could not be accessed for fuelling then it is expected that the problem would be rectified in the next maintenance outage. In general, other effects were addressed by making bounding assumptions or by performing sensitivity analyses. For example, it was recommended that it be assumed that all the elements of the bundle with the largest gap + grain boundary inventory be assumed to be defected, up to twice the number of defects possible under our defect control procedures for those cases in which defects are assumed to be present. This allows for the possibility of existing defects plus incipient defects.

2.5 Operating Envelope for the Core

For the nominal equilibrium core without a tilt, a snapshot of RFSP calculated powers and burnups was selected. Each bundle was placed in a power/burnup bin and represented by four ORIGEN-S, ELESIM-II and SEREL-HTT runs. Burnups were incremented to use up the core excess reactivity, *i.e.* to represent burnup before onset of shim operation, and powers were incremented by 3% to allow for reactor power uncertainties. For bundles in positions 1 to 8, a history proportional to the reference overpower history is assumed. For bundles in positions 9 to 12, the power change due to the fuel shift was modelled for each position. As for the channels, the possibility of a number of defects up to twice the controlled limit is allowed for. The defects are assumed to be in the bundles that result in the largest increase in release.

At Point Lepreau, the maximum side-to-side tilt allowed is 15%. However, it was not possible to tilt the nominal equilibrium core by 15% and still respect the channel and bundle power limits. Therefore, two different flux tilt scenarios were considered. In the first, a tilt is imposed by raising powers on one side of the core and reducing powers correspondingly on the other side such that no channel or bundle power limit is exceeded, resulting in a flux tilt which is less than 15%, but which is as large as is possible at full power. The other method is to impose a 15% tilt and then reduce reactor power to conform to the full power channel and bundle power limits.

In addition, methods were developed to assess the impact of other operating states such as:

1. shim operation
2. power maneuvers
3. trips with prompt restarts
4. startups after long outages

5. accelerated fuelling rates

3. Ensemble of Codes Used

In order to determine the fission product distribution, a modification to ELESIM-II MOD10 called ELESIM-II MOD10 (VAX Version 1.2) PLGS1 was used. This version of ELESIM-II is identical to ELESIM-II MOD10 (VAX Version 1.2), and gives nearly identical calculational results (there are some slight differences due to compiler options). The modified version adds the model for fission product distribution from SEREL-HTT, altered as described in this paper. The new version uses a new input card to control the fission product distribution calculations, and prints the results of these calculations to a new output file, which has the extension .FPD.

The fission product inventory was calculated using ORIGEN-S from the SCALE 4.3 code suite, using CANDU-specific cross-section libraries.

To ensure consistency between the inputs for the ORIGEN-S and the ELESIM-II runs, it was decided to prepare a utility code that would generate both input files. This code was called INPGEN.

To generate the binning of the RFSP output, a code called WRTHIST was used. And finally to collect the results of the total inventory data and the distributions and combine them to give core inventories, the program MAXBUILD was used. This process is illustrated in Figure 4.

4. Results

As an example of half-core fission product inventories for all of the isotopes considered Table 2 shows the results for the nominal equilibrium non-tilted case. Table 3 shows the effect of various defected fuel scenarios on the fission product inventory distribution of selected isotopes for the same equilibrium core.

Table 4 compares results from the current assessment with those which were reported in the 1993 Safety Report (*i.e.* the comparison is to the values used in previous analyses) for a nominal equilibrium core with no defects. In general, the total fission product inventories are similar between the new and the old analyses, which is as expected. The predicted gap inventories for the full core cases are significantly different, due primarily to the modelling of the effect of λ on free inventory in the current assessment, although the impact of the new correlations of free inventory fraction to temperature can be seen in the higher free inventory of ^{137}Cs in this analysis compared to the 1993 Safety Report numbers.

Table 5 compares results from the current assessment with those which were reported in the 1993 Safety Report for a few single channel cases with no defects. The channels are at slightly different powers. In this comparison, the total inventories are once again quite similar, but the free inventories are significantly different. The case from this analysis which is most similar to the 1994 Safety Report case is the 7.3 MW channel with 8 bundle sifting. The differences for ^{131}I and ^{137}Cs are both understandable on the same basis as was the case for the comparison of the core inventory distributions. However, the free inventories for ^{106}Ru and for ^{89}Sr and ^{90}Sr are quite more puzzling. The difference is most likely due to the impact of using ELESIM-II fuel temperatures with a 150°C temperature uncertainty rather than the temperature lookup tables which were used in the CURIES calculations in the Safety Report.

5. References

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Table 1
Isotopes Selected for Fission Product Inventory Calculations

Element	Isotopes
As	77, 79
Se	83
Br	82, 83, 84, 87
Kr	85, 85m, 87, 88, 89, 90
Rb	86, 88, 89, 90, 90m, 91
Sr	89, 90, 91, 92
Y	90, 91, 91m, 92, 93, 94, 95, 96
Zr	95, 97
Nb	95, 97
Mo	99, 101, 102, 104
Tc	99m, 101, 102, 104, 105
Ru	103, 105, 106
Rh	105
Pd	109
Ag	110m, 111, 112, 113
Cd	113m, 115, 115m
Sb	122, 124, 125, 126, 127, 128, 128m, 129, 130, 130m, 131, 132, 132m, 133
Te	127, 127m, 129, 129m, 131, 131m, 132, 133, 133m, 134
I	130, 131, 132, 133, 134, 135, 136, 136m
Xe	131m, 133, 133m, 135, 135m, 137, 138, 139
Cs	134, 136, 137, 138, 139, 140
Ba	139, 140, 141, 142
La	140, 141, 142
Ce	141, 143, 144
Nd	147
Pm	147
Sm	153
Eu	154, 155, 156, 157
Cm	242

Table 2
Half Core Fission Product Inventory For Nominal Equilibrium Core

Isotope	Inventory (TBq)	Isotope	Inventory (TBq)	Isotope	Inventory (TBq)
KR-85	2.202E+03	SB-131	8.981E+05	ZR-95	1.554E+06
KR-85M	3.124E+05	SB-132	5.415E+05	ZR-97	1.899E+06
KR-87	6.252E+05	SB-132M	4.966E+05	NB-95	1.231E+06
KR-88	8.715E+05	SB-133	7.139E+05	NB-97	1.857E+06
KR-89	1.095E+06	TE-127	8.841E+04	MO-99	2.140E+06
KR-90	1.164E+06	TE-127M	8.979E+03	MO-101	1.920E+06
XE-131M	1.283E+04	TE-129	3.433E+05	MO-102	1.782E+06
XE-133	2.278E+06	TE-129M	6.195E+04	MO-104	1.262E+06
XE-133M	7.138E+04	TE-131	9.681E+05	TC-99M	1.907E+06
XE-135	2.115E+05	TE-131M	2.126E+05	TC-101	1.921E+06
XE-135M	4.894E+05	TE-132	1.641E+06	TC-102	3.568E+04
XE-137	2.139E+06	TE-133	1.281E+06	TC-104	1.338E+06
XE-138	2.021E+06	TE-133M	1.068E+06	TC-105	1.083E+06
XE-139	1.495E+06	TE-134	2.078E+06	RU-103	1.442E+06
AS-77	2.598E+03	I-130	5.705E+05	RU-105	1.076E+06
AS-79	1.533E+04	I-131	1.141E+06	RU-106	1.717E+05
SE-83	7.004E+04	I-132	1.686E+06	RH-105	9.047E+05
BR-82	8.807E+02	I-133	2.366E+06	PD-109	3.125E+05
BR-83	1.474E+05	I-134	2.633E+06	AG-110M	2.962E+02
BR-84	2.732E+05	I-135	2.238E+06	AG-111	5.142E+04
BR-87	4.890E+05	I-136	9.948E+05	AG-112	2.553E+04
RB-86	2.643E+02	I-136M	5.077E+05	AG-113	1.421E+04
RB-88	8.973E+05	CS-134	9.416E+03	BA-139	2.124E+06
RB-89	1.155E+06	CS-136	1.426E+04	BA-140	2.079E+06
RB-90	1.055E+06	CS-137	2.425E+04	BA-141	1.912E+06
RB-90M	3.423E+05	CS-138	2.195E+06	BA-142	1.809E+06
RB-91	1.415E+06	CS-139	2.042E+06	LA-140	2.115E+06
CD-113M	5.007E+00	CS-140	1.827E+06	LA-141	1.941E+06
CD-115	7.957E+03	SR-89	1.030E+06	LA-142	1.868E+06
CD-115M	2.812E+02	SR-90	1.752E+04	CE-141	1.759E+06
SB-122	1.261E+02	SR-91	1.513E+06	CE-143	1.816E+06
SB-124	6.385E+01	SR-92	1.585E+06	CE-144	5.485E+05
SB-125	2.139E+03	Y-90	1.885E+04	ND-147	7.287E+05
SB-126	2.953E+02	Y-91	1.250E+06	PM-147	6.594E+04
SB-127	9.547E+04	Y-91M	8.764E+05	SM-153	1.811E+05
SB-128	1.718E+04	Y-92	1.595E+06	EU-154	4.420E+02
SB-128M	1.756E+05	Y-93	1.192E+06	EU-155	5.580E+02
SB-129	3.679E+05	Y-94	1.898E+06	EU-156	6.278E+04
SB-130	1.311E+05	Y-95	1.998E+06	EU-157	1.863E+04
SB-130M	4.985E+05	Y-96	1.775E+06	CM-242	9.180E+02

Table 3
Fission Product Distribution for Some Key Isotopes for an Entire Nominal Equilibrium Core Under Various Defect Scenarios

Isotope	Total Inventory (TBq)	Distribution with All Fuel Intact (TBq)			Distribution with 756 Defects in 30-40 kW/m range (TBq)		
		Free	Grain Boundary	Grain Bound	Free	Grain Boundary	Grain Bound
KR-85	4.406E+03	1.539E+02	0.000E+00	4.252E+03	1.943E+02	0.000E+00	4.212E+03
KR-88	1.742E+06	3.985E+02	2.156E+05	1.526E+06	4.752E+02	2.285E+05	1.513E+06
XE-133	4.548E+06	6.116E+03	9.672E+03	4.532E+06	7.161E+03	9.676E+03	4.531E+06
XE-137	4.273E+06	4.321E+02	5.275E+05	3.745E+06	4.516E+02	5.490E+05	3.724E+06
I-131	2.277E+06	2.746E+03	1.122E+03	2.273E+06	3.149E+03	1.122E+03	2.273E+06
CS-137	4.855E+04	2.058E+03	0.000E+00	4.649E+04	2.571E+03	0.000E+00	4.598E+04
SR-89	2.052E+06	2.175E+02	6.950E+02	2.051E+06	1.143E+03	1.805E+03	2.049E+06
SR-90	3.507E+04	5.409E+00	6.806E+00	3.506E+04	3.301E+02	6.785E+00	3.473E+04
RU-106	3.440E+05	3.723E+01	6.746E+01	3.439E+05	9.211E+02	5.547E+02	3.425E+05

Isotope	Total Inventory (TBq)	Distribution with 76 Defects in 40-50 kW/m range (TBq)			Distribution with 22 Defects in 50-60 kW/m range (TBq)		
		Free	Grain Boundary	Grain Bound	Free	Grain Boundary	Grain Bound
KR-85	4.406E+03	1.572E+02	0.000E+00	4.249E+03	1.545E+02	0.000E+00	4.252E+03
KR-88	1.742E+06	4.076E+02	2.171E+05	1.524E+06	4.014E+02	2.161E+05	1.525E+06
XE-133	4.548E+06	6.236E+03	9.778E+03	4.532E+06	6.153E+03	9.763E+03	4.532E+06
XE-137	4.273E+06	4.346E+02	5.301E+05	3.743E+06	4.329E+02	5.284E+05	3.744E+06
I-131	2.277E+06	2.788E+03	1.122E+03	2.273E+06	2.758E+03	1.129E+03	2.273E+06
CS-137	4.855E+04	2.095E+03	0.000E+00	4.646E+04	2.064E+03	0.000E+00	4.649E+04
SR-89	2.052E+06	3.296E+02	2.207E+03	2.049E+06	2.508E+02	1.002E+03	2.051E+06
SR-90	3.507E+04	3.550E+01	6.782E+00	3.503E+04	1.092E+01	6.806E+00	3.505E+04
RU-106	3.440E+05	1.174E+02	4.152E+02	3.434E+05	4.781E+01	9.676E+01	3.438E+05

Table 4
Comparison of Fission Product Inventories from This Analysis (Nominal Equilibrium Core with no Defects) to Values in the 1993 Safety Report

Isotope	This Analysis' Inventory		1993 Safety Report Inventory	
	Total (TBq)	Free (TBq)	Total (TBq)	Free (TBq)
I-131	2.277E+06	2.746E+03	2.337E+06	3.755E+04
Ru-106	3.440E+05	3.723E+01	4.033E+05	4.033E+02
Cs-137	4.855E+04	2.058E+03	4.481E+04	4.921E+02
Sr-89	2.052E+06	2.175E+02	1.607E+06	1.607E+03
Sr-90	3.507E+04	5.409E+00	3.120E+04	3.134E+01

Table 5
Fission Product Inventories for Selected Channel Cases from This Analysis and from the 1993 Safety Report

Isotope	This Analysis' Inventory (7.286 MW 12 B/S Channel)		This Analysis' Inventory (7.3 MW 8 B/S Channel)		1993 Safety Report Inventory (7.14 MW Channel)	
	Total (TBq)	Free (TBq)	Total (TBq)	Free (TBq)	Total (TBq)	Free (TBq)
I-131	8.143E+03	2.395E+01	7.370E+03	2.520E+01	7.722E+03	4.070E+02
Ru-106	1.717E+03	9.191E+00	8.313E+02	8.005E-01	9.457E+02	9.620E-01
Cs-137	2.040E+02	3.400E+01	1.112E+02	3.038E+01	9.620E+01	5.032E+00
Sr-89	7.250E+03	1.077E+01	5.368E+03	8.002E+01	4.906E+03	4.921E+00
Sr-90	1.375E+02	3.181E+00	7.885E+01	1.444E+01	6.734E+01	7.400E-02

Figure 1
Comparison of SEREL-HTT Model Results for Free Inventory Against Sweep Gas Test Results

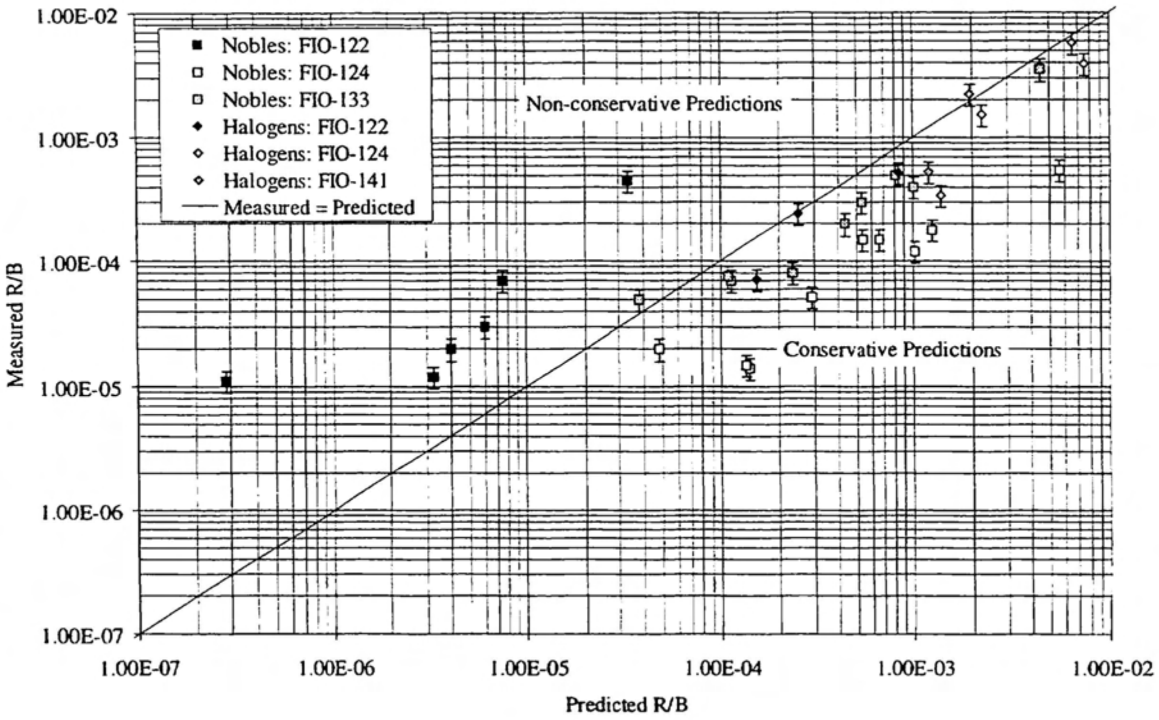

Figure 2
Comparison of SEREL-HTT Model Results with Modified Free Inventory Correlation and Using ELESIM-II MOD10 (VAX Version 1.2) Temperatures with 80°C Added to Account for Axial Grooves Against Sweep Gas Test Results

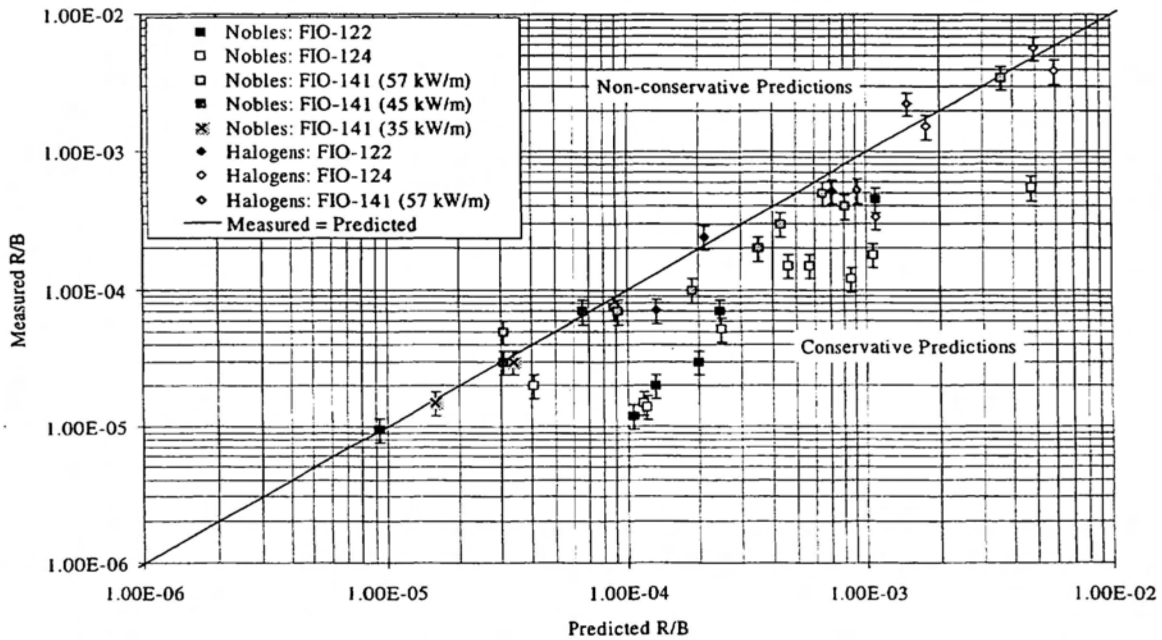

Figure 3
Measured Grain Boundary Inventories vs. Those Calculated using Technique for this Analysis

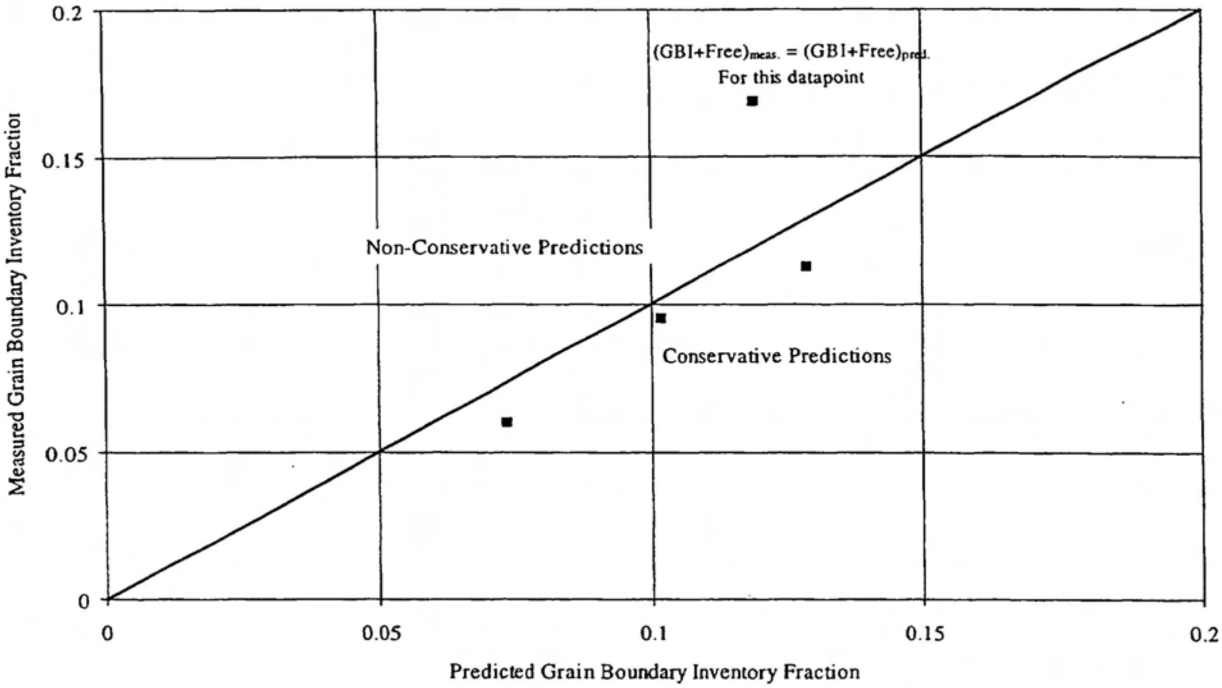

Figure 4
Process For Core Inventory Calculations