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NEEDS FOR EVALUATED COVARIANCE DATA FOR REACTOR PRESSURE VESSEL DOSIMETRY*

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R. E. Maerker and B. L. Broadhead
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

J. J. Wagschal
Racah Institute of Physics
The Hebrew University
Jerusalem, Israel

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NEEDS FOR EVALUATED COVARIANCE DATA FOR REACTOR PRESSURE VESSEL DOSIMETRY

R. E. Maerker and B. L. Broadhead
Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
and
J. J. Wagschal
Racah Institute of Physics, The Hebrew University, Jerusalem, Israel

A new methodology for quantifying and then reducing uncertainties in the calculated pressure vessel fluences of a pressurized water reactor (PWR) is reviewed. The technique involves combining the integral results of the calculated and measured PWR surveillance dosimetry activities with the differential data used in the calculations, along with covariances of all the quantities, into a generalized linear least-squares adjustment procedure. Based on analysis of both PWRs and test reactor benchmarks, substantial evidence now exists to support the conclusion that, of all the nuclear as well as non-nuclear differential data considered, ENDF/B-V values of the total inelastic iron cross sections and their covariances are the most important data controlling the outcome of the adjustment procedure. Predicted adjustments in these cross sections provided the stimulus for new measurements, the results of which impacted the ENDF/B-VI evaluation of iron 56.

I. INTRODUCTION

The lifetime of a PWR is usually determined by embrittlement of the pressure vessel (PV) that is caused by neutron-induced displacements of the atoms constituting the steel. This decrease in the fracture toughness reduces the ability of the PV to withstand cracking from effects caused by a rapid change in temperature followed by application of pressure such as would occur in response to a loss of coolant accident (pressurized thermal shock), as well as to arrest the propagation of a flaw inward (end-of-life rupture). Updated estimates of the state of the PV have been based in the past on analysis of passive dosimetry and metallurgical specimens extracted from capsules located in the downcomer region in front of the PV. Recently, however, the depletion of these capsules and the desire to extend the lifetime of these reactors have created a need for the installation of additional dosimetry in the reactor cavity behind the PV. This location has the advantage of being readily accessible but the disadvantage of not being able to provide an accelerated monitoring of the accumulated PV damage. For either the in-vessel or ex-vessel dosimetry, the information concerning the spectrum and fluence at these surveillance locations must be translated to the PV, both in space and in time, to determine the accumulated fluence on it and project the time when the PV begins to exceed the screening criteria. After this point is reached, the reactor is then decommissioned or subjected to some form of annealing process.

It is apparent that this procedure for determining a plant's lifetime can be subject to rather large uncertainties and that because of these uncertainties the conservatism required by imposing safety margins may shorten the lifetime considerably. Each step in this prescribed procedure introduces a non-trivial uncertainty - the measurements of the activities, the flux calculations at the dosimetry locations and throughout the PV, the flux adjustments at the dosimetry locations, extrapolation of the adjustments to the PV in space and to future exposures in time, the determination of the fluence level beyond which embrittlement is severe enough to necessitate shutdown - and each of these makes its own contribution to the penalties of a premature reactor shutdown.

Historically, adjustment methods (which are also referred to as unfolding or data combination processes depending on the particular direction of emphasis) have not considered effects of uncertainties in the calculation of the trial spectrum, in the dosimetry measurements, or in the final results. An example is the SAND-II code(1), still used by a large fraction of the international dosimetry community. Although later versions of this code contain some "error" estimation procedures, they are not central to the method. More recently, the codes LSL-M2 (2), STAYS'L (3), and FERRET (4), to name a few, have appeared and which possess the potential for consideration of not only standard deviations but correlations as well. Even for these codes, however, nonrigorous methods for covariance estimation must be employed, since no appropriate methodology is developed

to supply them. In addition, none of these more sophisticated codes, with the exception of LSL-M2, is capable of unfolding fluxes at other than a dosimetry location without resorting to the use of simplifying assumptions which break down completely for ex-vessel dosimetry.

This paper reviews a methodology that has been packaged into a computer software system called LEPRICON (5), which can be used to quantify and subsequently reduce uncertainties in several of the steps in the surveillance dosimetry procedure, namely, in those steps linking the measurements with the determination of PV flux and spectral information. A successful implementation of this method would then leave as the only remaining major source of uncertainty the one involving the prediction of existing PV damage susceptibility from analysis of in-vessel capsules and/or reference to the latest revision of the U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.99, which gives the relationships between fast fluence and several measures of radiation-induced damage in low-alloy steels for various concentrations of residual elements such as copper and nickel (6).

Taking full advantage of the theory reviewed in the next section, the LEPRICON system has the following capabilities that render it unique in the field of few-channel unfolding:

1. It solves the extrapolation problem necessitated by use of ex situ measurements.
2. It is capable of unfolding spectral fluences simultaneously at both a PV location and one or two dosimetry locations, and the dosimetry locations can be either in-vessel, ex-vessel, or a combination. However, if two, they must have been performed at the same time.
3. It unfolds PWR dosimetry measurements in conjunction with measurements previously performed and analyzed using simpler geometries. These benchmarks were calculated with the same cross section library and transport methods and approximations used in the PWR analysis. Thus the PWR multi-location unfolding procedure is performed simultaneously using all available PWR dosimetry data pertinent to a given cycle along with the data for the "cleaner" benchmarks.
4. In order to satisfy the requirement of using a transport procedure common to both the analysis of PWRs and benchmarks, and the desirability of making it as accurate as possible so that method uncertainties can be reduced to a minimum, the LEPRICON system provides a state-of-the-art capability for calculating the dosimeter activities and PV spectral fluences.
5. It incorporates the basic sensitivity and covariance data necessary for estimates of the flux uncertainties. These data are included as part of the default data base, along with the calculated and measured values of the benchmarks. Uncertainties in the mandatory transport method from various approximations are also part of the covariance data base.
6. It produces adjustments to the calculated fluxes along with covariances that are reduced by factors of between two and four from preadjusted values for the PV group fluxes.

In Section II the main features of the theory are reviewed.

Section III describes the benchmark experiments and agreement between the calculations using ENDF/B-IV and -V data and the measurements. In Section IV a description of the methods used in developing the covariances and flux sensitivities of the differential data is presented, including the manner in which flux uncertainties from approximations in the transport methods and in the as-built reactor geometry are defined and evaluated. The results from applying the entire LEPRICON procedure to an analysis of the H. B. Robinson-2 reactor are summarized in Section V. The important role played by the iron total inelastic cross section and its covariance is discussed in Section VI.

II. THEORY

We define a data combination process as one in which various types of data used to define a database are altered in such a fashion as to produce a more consistent data base. The general types of data involved in our present application can be integral measurements (e.g., dosimeter reaction rates or end of irradiation activities, spectrum-averaged cross sections or ratios of these cross sections) or differential data (e.g., dosimetry cross sections, partial cross sections involved in neutron transport, fission spectra, source distributions, and correction factors that account for methods approximations and geometrical assumptions in the transport modeling, i.e., "flux bias factors"). Any or all of these data types can be used to define the data base. The combination procedure must make use of calculations of the experiments using the differential data, have a criterion that defines "consistency" in a mathematical sense, and operate within the limitations imposed by estimated uncertainties of the data.

The particular adjustment procedure adopted for this study is a generalized linear least-squares technique introduced by Gandini (7) and others, and more recently refined and expanded by Wagschal and Yeivin (8) and Bahren (9). In this method, the consistency is expressed mathematically as maximizing the joint probability distribution of the data base subject to the relationships between the differential and integral data. Our problem to be solved is: Given a series of dosimetry experiments performed at an accessible (i.e., surveillance) PWR location, together with a calculation of the group fluxes and activities at this location and the group fluxes at another location that is inaccessible to dosimetry (i.e., in the PV), what are the "best" estimates of these PV group fluxes, and what are the "best" estimates of their corresponding uncertainties?

The adaptation of the least-squares technique to the problem of dosimetry unfolding is originally due to Petilli (10) and to Perey (11), who derived expressions for the flux unfolding at the surveillance location. With these identifications as points of departure, elaboration of the method to include effects of any correlations between the differential and integral data, to accommodate simultaneously in the PWR unfolding the results of earlier analyses of existing benchmarks that take advantage of simpler geometries and better known sources to provide more

definitive testing of sensitive differential data, and finally but most importantly, how to calculate the correlations between the fluxes at two locations such as at the dosimeter and in the PV, or what amounts to the same thing, the relative adjustments in the group fluxes at the two locations.

The following formulation and derivation of the expressions for the adjustment procedure are necessarily incomplete because of space limitations. For a more detailed presentation, the interested reader is referred to the literature (12,13). Let the column vector $r=(r_i)$, $i=1,2,..,I$ represent a series of dosimetry measurements in various fields, i.e., at a PWR surveillance location or at locations in standard or reference benchmark fields, Crr its corresponding IxI covariance matrix, and $\bar{r}=(\bar{r}_i)$ represent the calculations of these same experiments. Let the column vector $p=(p_n)$, $n=1,2,..,N$, with its corresponding NxN covariance matrix Cpp, represent the differential data (i.e., energy dependent parameters) used in the calculations, where $N=PG$, the product of the number of parameter types and number of groups used to define the energy dependence. Any covariances between the integral measurements and the differential data are denoted by the NxI matrix Cpr. If we denote the sensitivities of the calculated responses $\bar{r}$ to each of the parameters p by a IxN matrix $Sr=(d\bar{r}_i/dp_n)$, and impose the linearity restriction

$$\bar{r}(p+\delta p)=\bar{r}(p)+\bar{r}=\bar{r}(p)+(Sr)(\delta p), \qquad (1)$$

then the covariance matrix of the calculated responses becomes

$$C\bar{r}\bar{r}=(Sr)(Cpp)(Sr)^{\top}, \qquad (2)$$

where "δ" in Eq.(1) represents a finite difference and "T" in Eq.(2) the transpose. If the deviations of the measured and corresponding calculated responses are denoted by $d=(d_i)=\bar{r}-r$, then Cdd, the covariance matrix for d, becomes

$$Cdd=(Sr)(Cpp)(Sr)^{\top}+Crr-(Sr)(Cpr)-(Crp)(Sr)^{\top}, \qquad (3)$$

where Crp is the transpose of Cpr. Let the (unknown) adjusted parameter vector be $p'=(p_n')$ and adjusted calculated response vector be $\bar{r}'(p')$. By imposing the condition $r'=\bar{r}'(p')$, where r' is the adjusted measured response, the adjusted values p' and r' are forced to be consistent. If we further denote the actual adjustments by $x=p'-p$ and $y=r'-r$, Eq.(1) becomes

$$r'=\bar{r}+(Sr)(x), \qquad (4)$$

leading to

$$y=d+(Sr)(x). \qquad (5)$$

The generalized linear least-squares procedure involves minimizing the quadratic loss function

$$Q(x,y)=(y,x)^{\top}\begin{pmatrix} Crr & Crp \\ Cpr & Cpp \end{pmatrix}^{-1}(y,x), \qquad (6)$$

where $(y,x)^{\top}\equiv(y_1,\ldots,y_I,x_1,\ldots,x_N)$, subject to the constraint expressed in Eq.(5). Adopting the procedures in Refs. 7, 8, and 9, this formulation is equivalent to unconditionally minimizing the function R(x,y), where

$$R(x,y)=Q(x,y)+(2\lambda^{\top})[(Sr)(x)-(y)] \qquad (7)$$

and 2λ is a column vector of Lagrange multipliers. After some matrix algebra manipulations, the solution for x and y becomes

$$x=[(Cpr)-(Cpp)(Sr)^{\top}]\lambda, \qquad (8a)$$

and

$$y=[(Crr)-(Crp)(Sr)^{\top}]\lambda, \qquad (8b)$$

reflecting the driving influence of the vector λ. Substitution

of these values of x and y into Eq.(4) yields

$$\lambda=(Cdd)^{-1}(d), \qquad (9)$$

with

$$C_{\lambda\lambda}=(Cdd)^{-1}. \qquad (10)$$

The adjusted values p' and r' are found from Eqs.(8) to be

$$p'=p+[(Cpr)-(Cpp)(Sr)^{\top}](Cdd)^{-1}(d) \qquad (11a)$$

and

$$r'=r+[(Crr)-(Crp)(Sr)^{\top}](Cdd)^{-1}(d), \qquad (11b)$$

where $(Cdd)^{-1}$ is obtained by taking the inverse of Eq.(3) and is a matrix of dimensions IxI. The covariances of the adjusted differential and integral data are obtained from Eqs.(11) to be

$$Cp'p'=Cpp-[(Cpr)-(Cpp)(Sr)^{\top}](Cdd)^{-1}[(Crp)-(Sr)(Cpp)] \qquad (12a)$$

and

$$Cr'r'=Crr-[(Crr)-(Crp)(Sr)^{\top}](Cdd)^{-1}[(Crr)-(Sr)(Cpr)]. \qquad (12b)$$

Since the term following the first minus sign on the R.H.S. of these equations is positive, the conclusion can be drawn that the uncertainties in both the measurements and the differential data are reduced by the combination procedure. Furthermore, the cross covariances between all the adjusted data become

$$Cp'r'=Cpr-[(Cpr)-(Cpp)(Sr)^{\top}](Cdd)^{-1}[(Crr)-(Sr)(Cpr)]. \qquad (13)$$

Thus, even if no <u>á priori</u> correlations between the differential and integral data exist, an <u>á posteriori</u> correlation does exist by virtue of the combination procedure.

The minimum value of Q in Eq.(6), found by substituting the expressions for x and y from Eqs.(8), is denoted by the symbol χ^2, which is a measure of the adjustments made in units of the (combined) <u>á priori</u> standard deviations summed over the all the participating integral and differential data:

$$\chi^2=Qmin(x,y)=(d)^{\top}(Cdd)^{-1}(d). \qquad (14)$$

Values of χ^2/I, named chi-square per degree of freedom, should lie near unity for a meaningful adjustment (i.e., adjustments in each integral experiment and each participating differential datum should lie within one standard deviation with about a two thirds probability). This quantity, which can be considered a figure of merit of the adjustment, can perhaps surprisingly be calculated without actually performing the adjustment, since all the ingredients in Eq.(14) are known beforehand and merely reflect the consistency of the available data. For the case of a single measurement in which there is no correlation between the integral and differential data, Eq.(14) reduces to

$$\chi^2_{no}=(\bar{r}-r)^2/[(Crr)+(Sr)(Cpp)(Sr)^{\top}], \qquad (15)$$

which is just the square of the discrepancy between the measured quantity r and the calculated quantity $\bar{r}$ using the differential data p expressed in units of the combined variances of r and $\bar{r}$.

In the particular application to the dosimetry problem under consideration, the only adjusted data at the dosimetry location necessary for the PV flux adjustments are the differential data determined from Eq.(11a). For if we denote by the column vector $\Phi=(\phi_g)$, $g=1,2,..,G$ the calculated PV flux and by $S_\phi=d\phi_g/dp_n$ the GxN sensitivity matrix of the group fluxes to the differential data, then again to within the limits of a linear approximation

$$\Phi'=\Phi+(S_\phi)(p'-p)=\Phi+(S_\phi)[(Cpr)-(Cpp)(Sr)^{\top}](Cdd)^{-1}(d). \qquad (16)$$

Eq.(16) applies equally well to adjusted fluxes at dosimetry as well as PV locations, providing, of course, that sensitivities appropriate to the particular location are used. The importance of Eq.(16) lies in the fact that it reveals as the cause of the PV flux adjustments just those sources of uncertainty in the

differential data that the dosimetry and PV fluxes share common sensitivities to. These sensitivities need not be the same at the two locations, only large enough to be able to affect both the S_ϕ and $(p-p')$ terms in Eq.(16). The sharing of mutual sources of data uncertainty is what gives rise to correlations between the fluxes at the two locations A and B:

$$C_{\phi_A \phi_B} = (S_{\phi_A})(Cp'p')(S_{\phi_B})^T, \qquad (17)$$

and without the existence of these correlations the dosimetry would not provide any useful information about the PV fluences. Since, for either location, the adjusted flux covariances are

$$C_{\phi'\phi'} = (S_\phi)(Cp'p')(S_\phi)^T, \qquad (18)$$

then substituting from Eq.(12a) leads to

$$C_{\phi'\phi'} = (S_\phi)\{(Cpp) - [(Cpr) - (Cpp)(Sr)^T](Cdd)^{-1}[(Crp) - (Sr)(Cpp)]\}(S_\phi)^T. \qquad (19)$$

Although Eqs.(1-19) have been developed using absolute quantities, they remain unchanged and are far more useful if relative quantities are substituted instead. Hence, covariances may be replaced by relative covariances, sensitivities by such normalized quantities as $(p/\bar{r})(d\bar{r}/dp)$, and the corresponding adjustments become $(p'/p)-1$ and $(\bar{r}'/\bar{r})-1$.

III. THE BENCHMARK INTEGRAL EXPERIMENTS

One of the advantages of this methodology is its capability for simultaneously combining the results of simpler dosimetry-oriented benchmark experiments with those performed in the PWR. The advantage in including these data is that, if properly chosen, the benchmark and PWR calculations will be sensitive to some of the same differential data, but the less complicated benchmark experiments, having fewer sources of uncertainties, will tend to establish these data adjustments more accurately. This procedure thus leaves the PWR measurements primarily with the task of determining the adjustments in the data that are unique to the reactor calculations such as, for example, in the as-built dimensions and physical properties of the various reactor components and the spatial distributions of the source.

The differential data usually shared by the benchmarks are nuclear in nature, and an early exploratory analysis indicated the most important data to be, in order, the total inelastic cross sections of iron, the spectrum above 6 MeV arising from thermal-neutron induced fission in U235, and the cross sections for the dosimetry reactions. These data were determined to be the most influential in affecting the accuracy of the transport calculations because of their relatively large uncertainties and the high sensitivities of the measurements to them.

Table I identifies the 34 experiments adopted as benchmarks together with descriptive information of each measurement and its calculation. Eight were performed in Cf252 driven fields (14,15,16), four in the Intermediate-energy Standard Neutron Field (17), eight in a prototypic PCA mockup of pressure vessel transport geometry (18), and 14 in the prototypic PSF "startup" mockup of another pressure vessel transport geometry (19,20). The PCA and PSF experiments included measurements inside the simulated pressure vessel as well as at surveillance locations,

thus providing invaluable information not normally available in PWR dosimetry. These supplementary PV dosimetry sites included one-quarter depth (T/4) locations in both mockups and a (3T/4) location in the PSF mockup.

TABLE I

Integral Experiment Data Base Adopted for the LEPRICON Adjustment Procedure

Reaction	Field	Measured Quantity	Values		$E/C-1$ (%)	Standard Deviations		
			E	C		E[a] (%)	C (%)	Combined (%)
$^{235}U(n,f)$	^{252}Cf	$\bar{\sigma}$ (b)[b]	1.205	1.236	−2.51	2.05	1.54	2.56
$^{237}Np(n,f)/^{235}U(n,f)$	^{252}Cf	$\bar{\sigma}/\bar{\sigma}$	1.105	1.094	1.01	2.10	9.31	9.54
$^{240}Pu(n,f)/^{235}U(n,f)$	^{252}Cf	$\bar{\sigma}/\bar{\sigma}$	1.500	1.447	3.66	1.38	2.03	2.45
$^{238}U(n,f)/^{235}U(n,f)$	ISNF	$\bar{\sigma}/$[a]	0.0919	0.0910	0.99	0.69	4.24	4.30
$^{238}U(n,f)/^{235}U(n,f)$	ISNF	$\bar{\sigma}/\bar{\sigma}$	0.0926	0.0910	1.76	1.41	4.24	4.47
$^{237}Np(n,f)/^{235}U(n,f)$	ISNF	$\bar{\sigma}/\bar{\sigma}$	0.510	0.513	−0.58	2.02	10.28	10.48
$^{240}Pu(n,f)/^{235}U(n,f)$	ISNF	$\bar{\sigma}/\bar{\sigma}$	1.155	1.143	1.05	1.29	2.67	2.97
$^{27}Al(n,\alpha)$	^{252}Cf	$\bar{\sigma}$ (mb)	1.006	0.984	2.24	2.19	8.70	8.97
$^{58}Ni(n,p)$	^{252}Cf	$\bar{\sigma}$ (mb)	118	114.3	3.24	2.43	3.82	4.53
$^{115}In(n,n')$	^{252}Cf	$\bar{\sigma}$ (mb)	196.4	182.8	7.44	2.45	4.64	5.25
$^{46}Ti(n,p)$	^{252}Cf	$\bar{\sigma}$ (mb)	138	129	6.98	2.54	6.45	6.93
$^{63}Cu(n,\alpha)$	^{252}Cf	$\bar{\sigma}$ (mb)	0.709	0.689	2.90	2.44	8.43	8.78
$^{27}Al(n,\alpha)$	PCA SP	RR[c]	3.06−34[d]	2.90−34	5.52	7.99	11.31	13.85
$^{58}Ni(n,p)$	PCA SP	RR	2.40−32	2.36−32	1.69	7.70	7.83	10.98
$^{115}In(n,n')$	PCA SP	RR	3.64−32	3.51−32	3.70	7.85	7.48	10.84
$^{237}Np(n,f)$	PCA SP	RR	2.88−31	2.75−31	4.73	7.93	10.58	13 22
$^{58}Ni(n,p)$	PCA T/4	RR	5.45−33	4.92−33	10.77	7.70	11.12	13.53
$^{115}In(n,n')$	PCA T/4	RR	1.07−32	1.02−32	4.90	7.29	9.93	12.32
$^{237}Np(n,f)$	PCA T/4	RR	1.16−31	1.14−31	1.75	7.36	12.74	14.71
$^{238}U(n,f)$	PCA T/4	RR	1.80−32	1.63−32	10.43	10.14	9.03	13.58
$^{63}Cu(n,\alpha)$	PSF SSC	RR	1.33−33	1.12−33	18.75	6.34	14.22	15.57
$^{46}Ti(n,p)$	PSF SSC	RR	2.65−32	2.16−32	22.69	6.34	13.53	14.94
$^{54}Fe(n,p)$	PSF SSC	RR	2.02−31	1.76−31	14.77	5.85	12.22	13.55
$^{58}Ni(n,p)$	PSF SSC	RR	2.79−31	2.41−31	15.77	8.29	12.17	14.75
$^{63}Cu(n,\alpha)$	PSF T/4	RR	9.08−35	8.21−35	10.60	5.91	16.40	17.43
$^{46}Ti(n,p)$	PSF T/4	RR	1.75−33	1.43−33	22.38	6.33	16.15	17.35
$^{54}Fe(n,p)$	PSF T/4	RR	1.19−32	1.05−32	13.33	5.78	14.69	15.79
$^{58}Ni(n,p)$	PSF T/4	RR	1.69−32	1.45−32	16.55	6.14	14.49	15.74
$^{237}Np(n,f)$	PSF T/4	RR	6.05−31	5.80−31	4.31	7.84	15.32	17.21
$^{238}U(n,f)$	PSF T/4	RR	6.74−32	6.01−32	12.15	10.55	13.12	16.84
$^{63}Cu(n,\alpha)$	PSF 3T/4	RR	1.21−35	1.06−35	14.15	6.10	20.09	21.00
$^{46}Ti(n,p)$	PSF 3T/4	RR	2.29−34	1.73−34	32.37	6.84	20.23	21.36
$^{54}Fe(n,p)$	PSF 3T/4	RR	1.62−33	1.29−33	25.58	6.41	18.27	19.36
$^{58}Ni(n,p)$	PSF 3T/4	RR	2.40−33	1.86−33	29.03	6.80	17.76	19.02

[a]Experimental standard deviations have been multiplied by E/C to put them on the same relative basis as those of the calculation.

[b]The symbol $\bar{\sigma}$ should not be confused with the symbols σ_i and σ_o introduced later, which represent input and output standard deviations.

[c]Units of reaction rates are reactions per second per atom per source neutron per second.

[d]Read 3.06×10^{-34}

Inspection of Table I reveals that all but two experiments are undercalculated using the ELXSIR library (21) which was derived from ENDF/B-IV for the cross sections involved in the transport process and from an update of the ENDF/B-V dosimetry cross sections (22), with a strong implication that similar underpredictions of PWR measurements and PV fluxes probably would occur as well. It is also evident from Table I that the uncertainties in the calculations are significantly higher than those of the measurements, particularly for those experiments involving transport through iron. If this were not the case, then there would obviously be little need for the measurements.

The covariances of the benchmark measurements are shown in Table II in the form of a correlation matrix. The covariances of the benchmark calculations are developed in the next section.

IV. DEVELOPMENT OF THE DIFFERENTIAL DATA BASE

The benchmark data base, in addition to the data presented in Tables I and II, also must contain a selection of parameters determined to be of particular importance to the calculations, their values, covariances, flux sensitivities, and ultimately, the covariances of the calculated benchmark responses. For the benchmarks as well as for subsequent PWR calculations, these parameters consist of two basic types: nuclear data that is differential in the energy, and non-nuclear data that involves geometric and physical properties of the reactor components, source distributions, and transport method approximations. The propagation of nuclear data uncertainties through the transport calculations to uncertainties in the dosimetry responses and/or fluxes was handled by means of sensitivities [viz., Eq.(2) in Section II] which were calculated using the FORSS code. (23) The non-nuclear data assume the form of group-dependent flux bias factors. These bias factors provide a means for correcting the calculations for a given datum perturbation or a method approximation. Often the values of these bias factors may be assumed originally to be unity, since the most probable values of the data are used in the reference calculation, but their uncertainties will dictate, in general, values different from unity after adjustment. The sensitivities no longer need to be calculated, however, for if a corrected flux is written as

$$(\phi c)g = \phi g \prod_j (BFj')g, \qquad (20)$$

then

$$S=[d(\phi c)g/(\phi c)g]/[d(BFj')g/(BFj')g]=1. \qquad (21)$$

The benchmark parameters consist of three spectral shapes, i.e., normalized fission spectra for U235, Cf252, and the ISNF, two types of flux bias factors of unit magnitude (the first is due to the effect of a finite core height in the PCA and PSF 2-D calculations, the second arises from the magnitude of the PSF source as calculated by diffusion theory), and 13 partial cross sections (three total inelastic cross sections for the major components in stainless steel and ten dosimetry reaction cross sections). Most of these parameters are uncorrelated, the exceptions being the ISNF field which contains a U235 component, the spatial correlations among the bias factors of a given type,

TABLE II

Correlation Matrix of the Measurements in the LEPRICON Dosimetry Benchmark Data Base*

Reaction	PSD (%)	^{252}Cf			ISNF				^{252}Cf					PCA 12/13 SP				PCA 12/13 T/4				PSF SSC				PSF T/4						PSF 3T/4			
		25	37/25	49/25	28/25	28/25	37/25	49/25	Aluminum	Nickel	Indium	Titanium	Copper	Aluminum	Nickel	Indium	37	Nickel	Indium	37	28	Copper	Titanium	Iron	Nickel	Copper	Titanium	Iron	Nickel	37	28	Copper	Titanium	Iron	Nickel
^{252}Cf																																			
25	2.10	100																																	
37/25	2.08	-9	100																																
49/25	1.33	-19	32	100																															
ISNF																																			
28/25	0.68	14	9		100																														
28/25	1.39	2	15	3	7	100																													
37/25	2.03	-14	98	32	4	14	100																												
49/25	1.28	-21	32	95		4	33	100																											
^{252}Cf																																			
Aluminum	2.14								100																										
Nickel	2.35								75	100																									
Indium	2.28								77	70	100																								
Titanium	2.37								74	68	70	100																							
Copper	2.37	34											100																						
PCA SP																																			
Aluminum	7.57													100																					
Nickel	7.57													75	100																				
Indium	7.57													75	75	100																			
37	7.57													75	75	75	100																		
PCA T/4																																			
Nickel	6.95													64	90	64	64	100																	
Indium	6.95													64	64	90	64	70	100																
37	7.23													62	62	62	86	67	67	100															
28	9.18													49	49	49	49	53	53	60	100														
PSF SSC																																			
Copper	5.34													13	13	13	13	14	14	14	11	100													
Titanium	5.17													14	14	14	14	15	15	14	11	79	100												
Iron	5.10													14	14	14	14	15	15	14	11	80	82	100											
Nickel	7.16													33	58	33	33	63	36	34	27	56	58	58	100										
PSF T/4																																			
Copper	5.34													13	13	13	13	14	14	14	11	82	79	80	56	100									
Titanium	5.17													14	14	14	14	15	15	14	11	79	84	82	58	79	100								
Iron	5.10													14	14	14	14	15	15	14	11	80	82	83	58	80	82	100							
Nickel	5.27													13	16	13	13	17	14	14	11	77	79	80	59	77	79	80	100						
37	7.52													9	9	9	11	10	10	19	16	56	56	56	40	56	56	56	55	100					
28	9.41													7	7	7	7	8	8	17	49	44	45	45	32	44	45	45	44	40	100				
PSF 3T/4																																			
Copper	5.34													13	13	13	13	14	14	14	11	82	79	80	56	82	79	80	77	56	44	100			
Titanium	5.17													14	14	14	14	15	15	14	11	79	84	82	58	79	84	82	79	56	45	79	100		
Iron	5.10													14	14	14	14	15	15	14	11	80	82	83	58	80	82	83	80	56	45	80	82	100	
Nickel	5.27													13	16	13	13	17	14	14	11	77	79	80	59	77	79	80	81	55	44	77	79	80	100

*Matrix is symmetric; only the lower half is shown. Values of zero can be assumed if no entry is given. All correlations have been multiplied by 100.

and the dosimetry cross sections of Ref. 22. Inelastic cross-section covariances for iron, chromium, and nickel were taken from ENDF/B-V using the PUFF code (24), as were fission cross-section covariances for Np237 and Pu239. Covariances for the fission spectra were developed from suggestions by Perey and Marable (25), and covariances for the two types of bias factors were estimated by Maudlin and Maerker in Reference (26).

The sensitivities of the dosimeter reaction rates to the bias factors, dosimetry cross sections, and calculated fluxes at the dosimeter location are all identical. For dosimeter d, since

$$\bar{r}d = \sum_g (\sigma d)g\ (\phi g) \prod_j (BFj)g = \sum_g (\bar{\sigma} d)g\ (\phi c)g, \qquad (22)$$

it follows that, for each of the three terms $(X)g$ in Eq.(22),

$$S = d(\bar{r}d)/(\bar{r}d)/[d(X)g/(X)g] = (\sigma d)g\ (\phi c)g/(\bar{r}d). \qquad (23)$$

These reaction rate sensitivities are thus the fractional contributions of each group to the corrected reaction rate. By invoking the chain rule for sensitivities, these dosimeter sensitivities to nuclear data $(p)g$ used in the transport become

$$S[\bar{r}d \text{ to } (p)g] = S[\bar{r}d \text{ to } (\phi c)g'] \cdot S[(\phi c)g' \text{ to } (p)g],\ g' \geq g. \qquad (24)$$

By combining the sensitivities and covariances for each of the parameters involved in each benchmark and summing, the resulting correlation matrix of the calculated values may be obtained and is shown in Table III. Comparison of corresponding entries in Tables II and III shows that more of the experiments are correlated (albeit rather weakly) in the calculations and that the correlations among the calculated responses are also generally higher. However, as was pointed out earlier, the most significant difference lies in the fact that the uncertainties in the calculations are also consistently higher. For the PCA and PSF experiments in the pressure vessel, the differences become even more apparent, and suggest that the increasing contribution from uncertainties in the inelastic cross sections of iron are beginning to dominate. Since the data in Table I indicate a growing tendency of the calculations to underpredict the measurements as more iron is penetrated, a conclusion that is difficult to avoid is that the iron ENDF/B-IV inelastic data (and also that of ENDF/B-V, since there is very little if any difference between them) is deficient and should be remeasured. An application of the LEPRICON methodology to the on-line PWR H.B. Robinson-2, the results of which will be summarized in the following section, reinforces this tentative conclusion with additional data on the size of the adjustments in this cross-section that are required to effect agreement with measurement.

V. APPLICATION TO CYCLE 9 OF H.B. ROBINSON-2

The entire LEPRICON procedure has been applied to the first cycle of an older PWR in which the distribution of fresh and burned fuel was altered from that of previous cycles in order to provide lower leakage from the core to reduce the rate of accumulated PV fluence. (27) This PWR contains a 24.15cm-thick pressure vessel which is thicker than average and should serve as a severe test of the accuracy of the iron cross sections since dosimetry was located in the cavity behind the vessel as

TABLE III

Correlation Matrix of the Calculations in the LEPRICON Dosimetry Benchmark Data Base*

Reaction	PSD (%)	^{252}Cf			ISNF				^{252}Cf					PCA 12/13 SP				PCA 12 13 T/4				PSF SSC				PSF T/4						PSF 3T/4			
		25	37/25	49/25	28/25	26/25	37/25	49/25	Aluminum	Nickel	Indium	Titanium	Copper	Aluminum	Nickel	Indium	37	Nickel	Indium	37	28	Copper	Titanium	Iron	Nickel	Copper	Titanium	Iron	Nickel	47	28	Copper	Titanium	Iron	Nickel
^{252}Cf																																			
25	1.54	100																																	
37/25	9.31	-17	100																																
49/25	2.03	21	-3	100																															
ISNF																																			
28/25	4.24	5	1	4	100																														
28 25	4.24	-5	1	4	100	100																													
37/25	10.28	11	93	-1	33	33	100																												
49/25	2.67	10	2	59	55	55	20	100																											
^{252}Cf																																			
Aluminum	8.70	1	6	4					100																										
Nickel	3.82	19	1	-10	-3	-3	-1	4	72	100																									
Indium	4.64		1	1					19	14	100																								
Titanium	6.45	1	5	3					87	77	17	100																							
Copper	8.43	1	6	4					91	71	19	86	100																						
PCA SP																																			
Aluminum	11.31				50	50	10	6	7	3		3	1	100																					
Nickel	7.83	7	-1	-6	42	42	8	3	3	22		7	2	87	100																				
Indium	7.48				33	33	7	3			59			69	74	100																			
37	10.58		82		23	23	82	2						48	51	44	100																		
PCA T/4																																			
Nickel	11.12	5	1	-4	29	29	6	2	2	15		5	1	68	86	65	44	100																	
Indium	9.93				24	24	5	2			45			57	66	85	40	82	100																
37	12.74		72		19	19	73	2						44	49	43	91	60	59	100														
28	9.03	10	2	3	28	28	5	5						66	75	55	45	93	88	66	100														
PSF SSC																																			
Copper	14.22				34	34	7	4	1	2		2	6	63	60	46	31	53	41	31	48	100													
Titanium	13.53				28	28	6	3	2	7		11	1	54	58	43	29	55	41	30	47	95	100												
Iron	12.22	3	-1	-2	22	22	4	2	2	7		4	1	44	50	37	25	49	38	28	44	93	96	100											
Nickel	12.17	5	-1	-4	21	21	4	1	2	15		4	1	42	51	36	25	50	37	27	42	92	95	98	100										
PSF T/4																																			
Copper	16.40				31	31	6	4	1	2		1	5	66	65	51	35	62	49	36	57	96	91	88	87	100									
Titanium	16.15				26	26	5	3	1	6		9	1	57	65	50	33	67	50	36	58	90	96	91	90	94	100								
Iron	14.69	3		-2	21	21	4	1	2	6		3	1	48	60	47	32	64	50	36	57	88	93	95	93	91	97	100							
Nickel	14.49	4	-1	-3	20	20	4	1	1	12		4	1	47	61	46	31	64	50	36	57	88	93	94	96	90	96	99	100						
37	15.32		61		12	12	60	1						27	31	28	71	33	32	70	36	66	68	72	72	65	66	71	71	100					
28	13.12	7	-1	2	18	18	3	3						40	46	40	28	50	47	35	54	85	87	92	92	85	88	94	94	77	100				
PSF 3T/4																																			
Copper	20.09				26	26	5	3	1	2		1	4	64	64	51	35	70	57	42	66	88	83	80	78	95	89	85	84	58	78	100			
Titanium	20.23				22	22	4	2	1	4		7	1	55	66	51	34	77	60	42	68	82	88	83	81	89	95	92	91	59	80	93	100		
Iron	18.27	2		-2	17	17	3	1	1	5		2	1	46	61	49	33	75	62	44	70	79	85	87	85	85	92	95	94	64	87	88	96	100	
Nickel	17.76	3	-1	-2	17	17	3	1	1	10		3	1	45	62	48	33	75	62	45	70	79	85	86	87	84	91	94	95	66	89	87	95	99	100

*Matrix is symmetric; only the lower half is shown. Values of zero can be assumed if no entry is given. All correlations have been multiplied by 100.

well as in front of it.

The bias factors invoked for this PWR appear in Table IV, only one of which (BF 5) is common to the benchmark data base. Covariances of these bias factors were based on uncertainties in geometric and materials data estimated from our own limited experience, discussions with others qualified in the field, and as a result of an ad hoc specialists meeting convened in 1980. (28) Table V presents the flux uncertainties at the in-vessel dosimeter location arising from both the nuclear data and the pertinent bias factors, and Tables VI and VII show similar information for the cavity dosimeter and PV locations.

TABLE IV

Flux Bias Factors Assumed in the Calculations

Bias Factor	Source of Bias Factor Uncertainty	Locations
1	Dosimetry capsule location	Downcomer only
2	Finite capsule perturbation	Downcomer only
3	Pressure vessel out-of-roundness	Cavity and pressure vessel
4	Coolant density	Downcomer, cavity, and pressure vessel
5	Three-dimensional flux synthesis	Downcomer, cavity, and pressure vessel
6	Steel density	Downcomer, cavity, and pressure vessel

TABLE V

Standard Deviations in the Fluxes at the Downcomer Dosimeter Location Arising from Parameter Uncertainties

Flux Group	Lower Energy (MeV)	Standard Deviation (%)							
				Bias Factor					
		χ_{25}	$\sigma_{steel}(n,n')$	1	2	4	5	6	Total
1	11.1	14.1	13.2	10.9	1.0	3.1	1.5	3.0	22.7
2	8.2	10.6	13.7	12.1	1.0	3.4	1.5	3.1	21..
3	6.1	8.1	13.3	13.3	1.0	3.8	1.5	3.4	21.2
4	4.1	6.4	14.3	14.7	1.0	4.2	1.5	3.6	22.3
5	3.0	6.1	13.2	17.0	2.0	5.0	1.5	3.5	23.3
6	2.6	5.5	9.7	17.8	2.5	5.3	1.5	3.3	22.1
7	2.1	5.1	9.5	18.0	3.0	5.7	1.5	3.2	22.2
8	1.8	5.2	9.2	18.3	3.5	6.0	1.5	3.1	22.5
9	1.5	5.2	8.8	19.3	3.5	6.3	1.5	3.0	23.3
10	1.2	5.1	8.9	19.5	4.0	6.5	1.5	2.9	23.5
11	0.9	5.2	8.0	20.3	4.5	6.9	1.5	2.6	24.1
12	0.6	5.1	5.4	20.5	5.0	7.2	1.5	2.4	23.7
13	0.4	5.1	5.4	20.2	5.5	7.6	1.5	2.1	23.6
14	0.2	5.1	5.4	19.8	6.0	7.7	1.5	1.9	23.4
15	0.1	5.1	5.3	18.4	6.5	7.5	1.5	1.9	22.3

TABLE VI

Standard Deviations in the Fluxes at the Cavity Dosimeter Location Arising from Parameter Uncertainties

Flux Group	Lower Energy (MeV)	Standard Deviation (%)						
				Bias Factor				
		χ_{25}	$\sigma_{steel}(n,n')$	3	4	5	6	Total
1	11.1	14.1	29.6	6.7	3.7	2.5	5.5	34.3
2	8.2	10.6	30.8	7.3	4.0	2.5	5.8	34.3
3	6.1	8.1	29.8	7.9	4.4	2.5	6.3	32.9
4	4.1	6.4	32.2	8.6	4.9	2.5	6.6	35.0
5	3.0	6.1	29.8	9.2	5.5	2.5	6.4	33.0
6	2.6	5.5	21.8	9.6	5.7	2.5	6.2	26.0
7	2.1	5.1	21.3	9.9	6.0	2.5	6.0	25.6
8	1.8	5.2	20.6	9.9	6.0	2.5	5.8	25.0
9	1.5	5.2	19.9	10.1	6.2	2.5	5.5	24.5
10	1.2	5.1	20.0	10.2	6.3	2.5	5.2	24.6
11	0.9	5.2	18.0	10.3	6.5	2.5	4.5	22.9
12	0.6	5.1	12.0	10.5	6.4	2.5	3.8	18.5
13	0.4	5.1	12.0	10.6	6.9	2.5	3.4	18.7
14	0.2	5.1	12.2	10.7	6.9	2.5	2.8	18.7
15	0.1	5.1	12.0	10.7	7.1	2.5	2.8	18.7

TABLE VII

Standard Deviations in the Fluxes at the Critical LCW and T/4 Pressure Vessel Locations Arising from Parameter Uncertainties

Flux Group	Lower Energy (MeV)	Standard Deviation (%)										
			$\sigma_{cross}(n,n')$		Bias Factor					Total		
							5					
		χ_{ss}	LCW	T/4	3	4	LCW	T/4	6	LCW	T/4
1	11.1	14.1	11.4	15.9	6.8	3.7	5.0	1.5	3.0	20.6	22.9
2	8.2	10.6	11.9	16.5	7.4	4.1	5.0	1.5	3.1	19.0	21.7
3	6.1	8.1	11.5	16.0	7.9	4.5	5.0	1.5	3.4	17.8	20.4
4	4.1	6.4	12.4	17.3	8.6	5.0	5.0	1.5	3.6	18.2	21.3
5	3.0	6.1	11.4	15.9	9.5	5.7	5.0	1.5	3.5	18.1	20.7
6	2.6	5.5	8.4	11.7	10.0	6.0	5.0	1.5	3.3	16.5	17.8
7	2.1	5.1	8.2	11.4	10.2	6.3	5.0	1.5	3.2	16.5	17.7
8	1.8	5.2	8.6	11.0	10.3	6.3	5.0	1.5	3.1	16.5	17.5
9	1.5	5.2	7.7	10.7	10.5	6.5	5.0	1.5	3.0	16.5	17.4
10	1.2	5.1	7.7	10.7	10.6	6.5	5.0	1.5	2.9	16.5	17.5
11	0.9	5.2	6.9	9.6	10.6	6.6	5.0	1.5	2.6	16.2	16.9
12	0.6	5.1	4.7	6.5	10.9	6.5	5.0	1.5	2.4	15.5	15.4
13	0.4	5.1	4.7	6.5	10.9	7.0	5.0	1.5	2.1	15.7	15.6
14	0.2	5.1	4.7	6.6	10.9	7.0	5.0	1.5	1.9	15.6	15.6
15	0.1	5.1	4.6	6.4	10.9	7.2	5.0	1.5	1.9	15.7	15.6

The LCW location refers to the lower circumferential weld in Table VII above. These tables show that the contribution from the iron inelastic uncertainty is significant at the in-vessel location, a major contributor at the critical PV locations, and dominates in the reactor cavity. The advantages of cavity over downcomer dosimetry are apparent since the cavity activities possess higher sensitivities to the same sources of uncertainty that influence the PV fluxes, such as the iron cross sections and the PV out-of-roundness, and at the same time no sensitivity to the location of the downcomer dosimetry to which the PV flux is also insensitive.

The complete correlation matrix of the calculated activities is shown in Table VIII, where high degrees of correlation are seen to exist both among the activities at a given dosimetry location (the auto-correlations) and between the activities at different locations (the cross-correlations). This is primarily

TABLE VIII

Complete Correlation Matrix of the Calculated Activities*

Target Atom	Standard Deviation (%)	Downcomer Location						Cavity Location					
		^{63}Cu	^{46}Ti	^{54}Fe	^{58}Ni	^{238}U	^{237}Np	^{63}Cu	^{46}Ti	^{54}Fe	^{58}Ni	^{238}U	^{237}Np
Downcomer Location													
^{63}Cu	19.7	100[a]											
^{46}Ti	20.3	96	100										
^{54}Fe	20.9	93	98	100									
^{58}Ni	21.0	93	97	99	100								
^{238}U	21.2	89	92	96	97	100							
^{237}Np	23.9	79	82	86	87	90	100						
Cavity Location													
^{63}Cu	30.6	87	82	76	75	69	59	100					
^{46}Ti	31.7	84	87	83	82	74	62	95	100				
^{54}Fe	32.0	80	86	87	86	80	68	87	96	100			
^{58}Ni	31.4	80	86	88	87	82	69	86	95	100	100		
^{238}U	30.0	78	83	86	86	86	74	80	88	95	96	100	
^{237}Np	29.0	76	80	83	83	83	89	73	80	85	87	89	100

*Matrix is symmetric; only the lower half is given.

[a]All elements have been multiplied by 100.

due, of course, to the significant uncertainties in the iron inelastic data that are propagated to all flux groups by the transport process, and hence represent a strong source of correlation among the calculated fluxes.

Covariances of the 12 dosimeter measurements were estimated with the help of the experimentalists. (29) Four sources of uncertainty were identified and quantified: random counting statistics, gamma-ray counter efficiency calibrations, bias factors arising from contributions of competing reactions, and normalization of the measured activities during exposure to one core neutron/second as required by the LEPRICON adjustment module. The major contributors were the counter calibration and source normalization, both of which produce correlations among the measurements. The complete correlation matrix of the measured activities appears in Table IX below.

TABLE IX

Complete Correlation Matrix of the Measured Activities*

Target Atom	Standard Deviation (%)	Downcomer Location						Cavity Location					
		^{63}Cu	^{46}Ti	^{54}Fe	^{58}Ni	^{238}U	^{237}Np	^{63}Cu	^{46}Ti	^{54}Fe	^{58}Ni	^{238}U	^{237}Np
Downcomer Location													
^{63}Cu	6.72	100[a]											
^{46}Ti	6.16	31	100										
^{54}Fe	6.16	31	64	100									
^{58}Ni	6.16	31	55	72	100								
^{238}U	8.00	24	26	26	26	100							
^{237}Np	6.65	29	32	32	32	78	100						
Cavity Location													
^{63}Cu	6.72	54	31	31	31	24	29	100					
^{46}Ti	6.16	31	64	44	42	26	32	31	100				
^{54}Fe	6.16	31	44	64	47	26	32	31	64	100			
^{58}Ni	6.16	31	42	47	64	26	32	31	55	72	100		
^{238}U	11.79	16	18	18	18	26	24	16	18	18	18	100	
^{237}Np	7.93	24	27	27	27	29	46	24	27	27	27	84	100

*Matrix is symmetric; only the lower half is given.

[a]All elements have been multiplied by 100.

Comparison of Tables VIII and IX again shows that both the standard deviations and the correlations of the calculations are higher than corresponding values of the measurements, thus increasing the covariances of the calculations in two ways. The similarity to the comparisons obtained in Section IV for the PCA and PSF benchmarks reinforces the earlier conclusion that the dosimetry is of critical importance in directing the course of the adjustment procedure.

As a final illustration of the results of the procedure for estimating the a priori covariances for this reactor, the cross-correlation matrix between both sets of important PV fluxes and both sets of dosimeter activities is presented in Table X. As has been already mentioned in Section II in the derivation of Eq.(17), the effectiveness of the adjustment procedure (i.e., of the dosimetry) is determined by the elements of just such a matrix as the one shown here. Reasonably high values for these cross-correlations are sine qua non to the success of the whole methodology. The entries in Table X are in the vicinity of 0.5, which, while not overwhelming, are deemed adequate. It should also be noted that the cavity location is clearly superior in

providing information about the PV flux levels.

TABLE X

Cross-Correlation Matrix Between the Calculated Critical Pressure Vessel Fluxes and the Dosimeter Activities

Flux Group	Lower Energy (MeV)	Downcomer Location						Cavity Location					
		^{63}Cu	^{46}Ti	^{54}Fe	^{58}Ni	^{238}U	^{237}Np	^{63}Cu	^{46}Ti	^{54}Fe	^{58}Ni	^{238}U	^{237}Np
1	11.1	58[a] (59)[b]	46 (46)	36 (35)	35 (34)	31 (31)	25 (24)	67 (72)	53 (56)	40 (41)	40 (40)	37 (37)	33 (31)
2	8.2	56 (56)	44 (43)	33 (32)	33 (32)	29 (28)	23 (22)	69 (74)	54 (57)	40 (40)	40 (40)	38 (37)	33 (31)
3	6.1	59 (62)	61 (66)	57 (62)	56 (60)	47 (49)	36 (38)	69 (74)	76 (82)	75 (82)	73 (80)	65 (69)	57 (60)
4	4.1	53 (55)	58 (62)	56 (60)	55 (59)	45 (48)	35 (36)	64 (67)	74 (79)	76 (82)	74 (80)	65 (69)	58 (60)
5	3.0	51 (54)	56 (60)	54 (59)	53 (57)	44 (47)	34 (36)	62 (66)	71 (77)	73 (80)	72 (78)	64 (69)	58 (60)
6	2.6	44 (48)	46 (51)	45 (51)	45 (50)	42 (47)	32 (36)	55 (60)	59 (66)	63 (71)	64 (72)	64 (72)	54 (58)
7	2.1	41 (44)	42 (46)	42 (46)	41 (46)	40 (45)	31 (34)	51 (56)	54 (61)	59 (66)	60 (67)	63 (70)	52 (56)
8	1.8	42 (45)	43 (47)	42 (48)	42 (47)	41 (45)	32 (35)	52 (57)	55 (62)	59 (67)	60 (68)	63 (70)	53 (57)
9	1.5	42 (45)	42 (47)	42 (47)	42 (47)	40 (45)	32 (35)	52 (57)	55 (62)	58 (66)	60 (67)	62 (70)	53 (57)
10	1.2	42 (46)	43 (48)	42 (48)	42 (47)	40 (45)	32 (35)	52 (58)	55 (62)	59 (67)	60 (68)	62 (70)	53 (57)
11	0.9	43 (48)	44 (50)	43 (49)	43 (48)	40 (45)	32 (35)	53 (60)	57 (65)	59 (68)	60 (68)	60 (68)	54 (58)
12	0.6	39 (44)	40 (47)	39 (45)	38 (44)	34 (39)	28 (32)	47 (54)	51 (59)	52 (61)	52 (61)	51 (57)	51 (56)
13	0.4	39 (44)	40 (46)	39 (45)	38 (44)	34 (39)	28 (32)	47 (53)	51 (59)	52 (61)	52 (60)	51 (57)	50 (55)
14	0.2	39 (44)	41 (47)	39 (45)	38 (44)	34 (39)	28 (32)	47 (54)	51 (59)	52 (61)	53 (61)	51 (58)	50 (55)
15	0.1	39 (43)	40 (46)	38 (44)	38 (43)	34 (38)	28 (31)	47 (53)	51 (59)	52 (61)	52 (60)	51 (57)	50 (55)

[a]All elements have been multiplied by 100.

[b]The LCW flux cross correlations appear first, followed by the T/4 flux cross correlations in parentheses.

A summary of the comparisons between measured and calculated activities before any adjustment (cols. 2 and 4) and between the measured and adjusted activities (cols. 3 and 5) are shown in Table XI. The important things to observe are the magnitudes of the disagreement in cols. 2 and 4, the close proximity of the adjusted to the measured values, and the reductions by factors of about 4 in the standard deviations of the pre- and post-adjusted differences. It is also of interest to observe that the disagreements between calculations and measurements in the cavity exceed the standard deviations by about 50%, thus suggesting a possible underestimate in the iron uncertainties. Combining all 12 HBR-2 measurements and the 34 benchmarks leads to a value of chi-square per degree of freedom of 1.15. When the Np237 cavity measurement is "deactivated" (i.e., prevented from being included in the adjustment procedure), the resulting value of chi-square per degree of freedom for the remaining 45 measurements becomes, almost unbelievably, 1.00 - a dramatic and significant change. Consequently, until this discrepancy is eventually resolved, adjustments are based on only 11 of the HBR-2 experiments.

TABLE XI

Comparison of Calculated C and Adjusted A HBR-2 Activities with Measurement E

Reaction	Downcomer Dosimeter		Cavity Dosimeter	
	$(C/E-1) \pm \sigma_r$[a]	$(A-E)/E \pm \sigma_0$	$(C/E-1) \pm \sigma_r$	$(A-E)/E \pm \sigma_0$
$^{63}Cu(n,\alpha)^{60}Co$	−17.3% ± 17.6%	−3.6 4.2[b]	−27.9 ± 23.1	−3.7 ± 5.2
$^{46}Ti(n,p)^{46}Sc$	−19.2 ± 17.5	0.6 ± 4.2	−34.5 ± 21.7	−1.1 ± 4.5
$^{54}Fe(n,p)^{54}Mn$	−17.4 ± 18.3	0.0 ± 4.5	−32.2 ± 22.6	2.8 ± 5.0
$^{58}Ni(n,p)^{58}Co$	−13.3 ± 19.2	5.5 ± 4.7	−33.9 ± 21.7	−0.3 ± 4.8
$^{238}U(n,f)^{137}Cs$	−20.0 ± 18.8	−7.1 ± 4.8	−34.8 ± 22.8	−8.7 ± 5.7
$^{237}Np(n,f)^{137}Cs$	−15.0 ± 21.4	−4.3 ± 5.4	−39.0 ± 19.4	−18.5 ± 5.8[c]

[a]The values of σ_r, the relative standard deviations of $(C-E)$, are calculated as $(\sigma_E^2 + \sigma_C^2 C^2/E^2)^{1/2}$, where σ_E and σ_C are the standard deviations of the measured and calculated activities, respectively.

[b]Read as −3.6% with a relative standard deviation in A of 4.2%.

[c]This experiment was adjusted on the basis of sensitivity to the adjusted parameters only. It did not actively participate in the adjustment procedure and is included only for completeness.

The covariances of the adjusted activities appear in Table XII. Comparison of the correlations with those in Tables VIII and IX shows that they are smaller than those of the original calculations, but larger than those of the measurements. The standard deviations, of course, are smaller than either.

TABLE XII

Complete Correlation Matrix of the Adjusted Activities*

Target Atom	Standard Deviation (σ_a)	Downcomer Location						Cavity Location					
		^{63}Cu	^{46}Ti	^{54}Fe	^{58}Ni	^{238}U	^{237}Np	^{63}Cu	^{46}Ti	^{54}Fe	^{58}Ni	^{238}U	^{237}Np
Downcomer Location													
^{63}Cu	4.2	100[a]											
^{46}Ti	4.2	90	100										
^{54}Fe	4.5	82	91	100									
^{58}Ni	4.7	81	91	96	100								
^{238}U	4.8	73	74	84	87	100							
^{237}Np	5.4	67	68	76	79	90	100						
Cavity Location													
^{63}Cu	5.2	73	62	54	54	50	46	100					
^{46}Ti	4.5	67	76	68	67	53	49	85	100				
^{54}Fe	5.0	57	67	75	72	62	55	65	87	100			
^{58}Ni	4.8	56	65	71	74	66	59	64	84	97	100		
^{238}U	5.7	47	48	56	59	74	63	53	60	78	85	100	
^{237}Np	5.8	40	44	50	52	53	65	43	53	66	70	73	100

*Matrix is symmetric; only the lower half is given. The ^{237}Np cavity dosimeter was deactivated.
[a]All elements have been multiplied by 100.

Table XIII presents a summary of the flux adjustments with their reduced uncertainties at the LCW pressure vessel location for several combinations of active HBR-2 experiments but always including the benchmarks. The column headed "none" represents the a priori standard deviations. The last four columns give results of the adjustment when (a) only the in-vessel dosimetry is activated, (b) only the cavity dosimetry including Np237 is activated, (c) only the cavity dosimetry but excluding Np237 is activated, and (d) both the in-vessel and cavity dosimetry save for the Np237 cavity are simultaneously activated. Comparison of the a priori column with the last column (the most consistent combination) shows the standard deviations are about halved for fluxes above 3 MeV. Adjustments are observed to be considerable.

TABLE XIII

Flux Adjustments and Standard Deviations at the Critical LCW Pressure Vessel Location as Functions of HBR-2 Measurements Activated

Flux Group	Lower Energy (MeV)	None	34 Benchmarks +			
			6 Downcomer Only	6 Cavity Only	5 Cavity Only	6 Downcomer + 5 Cavity
1	11.1	0 ± 20.6[a]	−0.5 ± 12.5	4.5 ± 11.2	5.7 ± 11.3	8.2 ± 11.0
2	8.2	0 ± 19.0	−3.5 ± 12.4	2.1 ± 10.9	3.3 ± 10.9	6.3 ± 10.5
3	6.1	0 ± 17.8	22.9 ± 12.1	26.7 ± 10.8	27.5 ± 10.8	29.9 ± 10.3
4	4.1	0 ± 18.2	25.3 ± 12.9	29.0 ± 11.4	29.5 ± 11.4	32.0 ± 10.8
5	3.0	0 ± 18.1	23.2 ± 13.5	27.3 ± 12.1	27.4 ± 12.1	30.1 ± 11.5
6	2.6	0 ± 16.5	12.2 ± 13.8	15.5 ± 12.4	16.7 ± 12.4	20.3 ± 11.8
7	2.1	0 ± 16.5	9.2 ± 14.2	12.4 ± 12.7	13.9 ± 12.7	17.9 ± 12.1
8	1.8	0 ± 16.5	9.9 ± 14.1	13.5 ± 12.7	14.6 ± 12.7	18.4 ± 12.2
9	1.5	0 ± 16.5	9.7 ± 14.2	13.5 ± 12.9	14.6 ± 12.9	18.4 ± 12.3
10	1.2	0 ± 16.5	9.6 ± 14.3	13.8 ± 12.9	14.5 ± 12.9	18.3 ± 12.3
11	0.9	0 ± 16.2	10.4 ± 14.1	15.9 ± 12.8	15.2 ± 12.8	18.7 ± 12.3
12	0.6	0 ± 15.5	11.4 ± 13.9	19.0 ± 12.8	15.5 ± 12.9	18.2 ± 12.5
13	0.4	0 ± 15.7	11.5 ± 14.1	18.8 ± 13.0	15.5 ± 13.1	18.3 ± 12.7
14	0.2	0 ± 15.6	11.6 ± 14.0	18.5 ± 13.0	15.7 ± 13.0	18.5 ± 12.7
15	0.1	0 ± 15.7	11.4 ± 14.1	18.2 ± 13.0	15.5 ± 13.1	18.5 ± 12.7

[a]Read as a change of 0% with a standard deviation of 20.6%.

VI. CONCLUSIONS

It has been demonstrated that PWRs are amenable to prediction of pressure vessel fluence and its uncertainties by an in-depth analysis of the differential data used in the calculations in conjunction with an uncertainty analysis of existing dosimetry. Although not all bias factors were considered in the present analysis (for example, uncertainties in the composition of the concrete biological shield, in particular its water content and whether or not a steel liner is used, both of which might affect the cavity measurements, and in the radial source distributions which would affect all flux levels in the reactor beltline), subsequent consideration of these omissions in HBR-2 have not altered the main conclusions to be drawn from this paper.

The first of these important conclusions is that the use of ad hoc cavity dosimetry is preferable to the earlier more conventional in-vessel location where it was placed along with metallurgical specimens for early monitoring of any PV damage. In the determination of damaging fluence within the pressure vessel, the proximity of this latter location to the PV is outweighed by the greater sensitivity to the iron penetration afforded by the cavity location.

The second important conclusion is that accuracy in the iron total inelastic cross section is a requirement for an adequate estimate of the PV fluence, and this accuracy is not available in either the ENDF/B-IV or ENDF/B-V evaluations. Worse, these data underestimate the PV fluences, necessitating the use of conservative safety margins. The consistency of the benchmark and HBR-2 analyses in estimating the adjustments to these data in the important energy region between 3 and 8 MeV is shown in Table XIV below of the results from sequential addition of the iron-sensitive measurements. Notice should be taken of the reduction in the uncertainties as more of the experiments are considered.

TABLE XIV

Summary of Present and Past Adjustments in the Total Inelastic Cross Section of Iron in the 3- to 8-MeV Region

Energy Group	Energy Range (MeV)	ENDF/B[a]	PCA	+ PSF	+ HBR-2[b]
3	6.1 to 8.2	0.0 ± 5.4[c]	−8.9 ± 3.7	−8.7 ± 2.7	−9.4 ± 2.2
4	4.1 to 6.1	0.0 ± 5.5	−9.0 ± 3.7	−9.2 ± 2.7	−9.7 ± 2.2
5	3.0 to 4.1	0.0 ± 5.6	−8.9 ± 3.9	−9.0 ± 2.8	−9.7 ± 2.3

[a]The *a priori* values were taken from ENDF/B-V.
[b]The HBR-2 results include approximate contributions from chromium and nickel as well.
[c]Read as an adjustment of 0% with a standard deviation of 5.4%.

Expectations are high that the use of updated inelastic iron data in ENDF/B-VI, the need for which was first suggested as a consequence of these LEPRICON analyses, will result in improved agreement between calculation and measurement with the eventual adoption of less restrictive margins. Some preliminary evidence using an update to Mod-3 of ENDF/B-V (30) of such an improvement has been encouraging. (31)

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