CANDU TYPE FUEL BEHAVIOR EVALUATION - A PROBABILISTIC APPROACH

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ABSTRACT

In order to realistically assess the behavior of the fuel elements during in-reactor operation, probabilistic methods have recently been introduced in the analysis of fuel performance. The present paper summarizes the achievements in this field at the Institute for Nuclear Research (INR), pointing out some advantages of the utilized method in the evaluation of CANDU type fuel behavior in steady state conditions. The Response Surface Method (RSM) has been selected for the investigation of the effects of the variability in fuel element computer code inputs on the code outputs (fuel element performance parameters). A new developed version of the probabilistic code APMESRA based on RSM is briefly presented. The examples of application include the analysis of the results of an in-reactor fuel element experiment and the investigation of the calculated performance parameter distribution for a new CANDU type extended burnup fuel element design.

1. INTRODUCTION

Nuclear fuel element performance evaluation has usually relied upon the use of complex computer codes. In the codes used for this purpose, all mechanisms being important for the fuel element behavior have to be modeled in sufficient details, and these codes need a sound data base so they really cover the range of application. Such a code simulates in a deterministic way fuel element behavior for various configurations of its input data. Each run of the code produces a single set of output values that describe the fuel performance.

Fuel behavior analyses are, however, subject to various levels of uncertainties due to different factors such as statistical uncertainty on material behavior, tolerances on dimensions and uncertainties with respect to operating conditions and power history. These uncertainties are usually taken into account by a conservative approach, method that may result in unrealistic assumptions in some cases. The necessity for improving fuel performance has recently raised the problem of cutting excess conservatism, especially for the new fuel designs.

Another type of approach, that can offer an adequate answer for the above problem, is based on probabilistic analyses and permits rigorous evaluation of the uncertainties of calculated fuel element performance parameters. The principles of the probabilistic methodology of analysis are well established and frequently used in many other areas. It offers a variety of practical instruments for quantifying the conservatism. Information provided by this approach is more extensive and reliable and, depending on the particular probabilistic method utilized, consists of probability functions, statistical moments, fractiles, etc.

The most important inconvenient of the probabilistic methods has been considered to be the great amount of deterministic computer runs requested by a usual analysis. The availability and the performances of the new generation of computers offer now the possibility of currently utilizing these methods in our field. The present paper summarizes the experience gained in INR [1, 2] during the introduction and utilization of the probabilistic methodology in CANDU type fuel performance analyses, pointing out the main features and advantages of the selected methods and giving illustrative examples of application.

2. DESCRIPTION OF THE METHOD

The method selected for the probabilistic analysis of calculated fuel element behavior was the response surface method (RSM). It provides techniques for studying general problems in which a response variable (dependent variable) varies in some pattern according to the different values (levels) assumed by one or more independent variables [3, 4].

The objective of employing response surface techniques in nuclear fuel behavior analysis is to model the code response, in a delimited region of the input parameter space, by a simple smoothing function. The equation representing the variation of the code computed result as a function of the perturbed inputs is called the response surface equation. The second-order polynomial has been preferred as fitting function on account of its simplicity. It is important to note that the coefficients of second-order response equation are directly proportional to the partial derivatives of a truncated Taylor series expansion of the response about the nominal value. Thus, the response surface method can produce (a) the sensitivity coefficients for each input variable, (b) each second-order cross product between inputs, (c) a mechanism for mapping the response surface. The fact that in deriving the response equation no assumptions are made about the probability distribution functions of the input variables permits an analytical estimation of the response statistical moments by the technique of error propagation [4]. From these moments, the characteristic of the probability density function of the investigated response variable can be estimated by moment matching methods [5].

The application of the probabilistic response surface method to a fuel element behavior modeling code is a multi-stage process. We describe here the key-steps, pointing out the particularities of the implemented techniques and methods:

i) Selection of the response surface independent variables; Up to now, in similar analyses, the input variables that do not or slightly affect the code output are singled out by engineering judgment. During the code running, they are maintained at their nominal values or arbitrarily assigned to other values in their range. Using a more rigorous approach, a systematic procedure to pick out and certify the variables to be included in the response surface model has been developed. It includes a rank ordering of the input variables, normalized to a variable taken as a reference, via RSM sensitivity analysis. Another interesting feature of the implemented methodology is the possibility of randomization of the variables not included in the final response surface model. This procedure is able to give a figure of merit of the neglected variables through an independent analysis of residuals.

ii) Choice of the experimental design; This design is simply a pattern for perturbing the selected input variables of the problem. The deterministic code is run as many times the design dictates, varying each time the input variable perturbation according to the pattern. An efficient experimental design allows to obtain a maximum of information from a reasonable number of runs. In our analyses, the most used experimental design is the central composite design(CCD) on five levels [3]. Also the technique of sequential design has been utilized in problems with a large number of input variables.

iii) Determination of response surface equation; This step is performed by using standard step-wise regression analysis. An important aspect at this stage is to determine the adequacy of fit of the response surface equation. This is done by directly comparing the predictions obtained via response surface equation with independent deterministic code runs for random combinations of input variable values. Thus, possibly important terms that might bias the response equation may be determined through this independent residual analysis. If the determined response equation is found to be inadequate for the analyzed region, a simple probabilistic analysis can be performed by using the classic Monte Carlo method on the deterministic code.

iv) Estimation of the probability density function of the response; The characteristics of the probability density of the investigated output variable are obtained by treating the obtained second order polynomial response equation with the second order error propagation technique. Specific theoretical equations were developed in order to obtain the first four statistical moments of the probability density function of the response utilizing the known statistical moment of each perturbed input variable. Further, by using moment matching methods, the probability density function of the response can be fully determined. The matching methods selected for this stage are Gram-Charlier series and Johnson distributions [5]. An alternative of the above mention method, which is adequate when the statistical moments of the input variables are not available, is the utilization of Monte Carlo sampling on response equation, method that can offer only an indication of the statistical properties of the investigated response variable . The method can also be utilized in parallel with moment matching in order to additionally verify the final results.

All the above mentioned techniques and methods have been implemented in a sequence of computer routines that are combined in a flexible computer code called APMESRA 3.1 [1, 2]. The last version of this code has been developed for PC environment, being fully portable. The implemented structure of the code allows the analyst control in all the above mentioned stages

3. EXAMPLES OF APPLICATION. DISCUSSION

3.1 Application to fuel element behavior modeling codes assessment

The first example is related to the process of comparison between code predictions and experimental data performed during a recent international blind comparison exercise (FUMEX) organized by IAEA .

In the context of intended extension of burnup of nuclear fuel (including CANDU type fuel) the requirements on fuel element modeling codes have increased during recent years. Better models and data for calibration are necessary because more accurate predictions are required since the margins to certain design criteria become smaller with increasing burnup. In this respect, IAEA FUMEX blind comparison exercise has been proved to be an important step in exploring the existing predictive capabilities at extended burnup for a large number of nuclear fuel behavior modeling codes. IAEA has provided a consistent set of well-qualified experimental data obtained on various fuel rods irradiated to high burnups in Halden reactor [6].

An additional requirement of the exercise was the probabilistic uncertainty analysis of the calculated results with respect to the three main sources of uncertainty: irradiation conditions (considered parameter- power history), fuel rod characteristics (considered parameter - diametral gap) and code material data (considered parameter - UO2 thermal conductivity). INR has participated in the exercise with an updated version of ROFEM code [7]. Significant illustrative results of the probabilistic uncertainty analysis performed for two of the most challenging experiments (rod 3.1-He filled and rod 3.3 -Xe filled) are presented in figure 3 and 4. A summary of the rod characteristics is included in table 1 and the power histories are illustrated in figure 1 and 2. The rods were instrumented with high accuracy thermocouples for in- reactor centre temperature measurements. The evolution of the centre temperature with burnup for a given linear power level (20 kW/m) is figured for measured values and blind predictions of ROFEM. The figures also include the limits of the uncertainty band obtained by means of the probabilistic methodology. The considered input parameters have been assumed to follow a normal distribution with a standard deviation of 1.66 % relative to nominal value for linear power and thermal conductivity and 1.7 µm for diametral gap. It can be noticed that the uncertainty bands follow the trend of the measured values suggesting the code capability in simulating the most important phenomena that took place in these complex experiments. The uncertainty band covers adequately the blind predictions and measured values, giving a valuable indication that there are no sistematic differences to be taken into account.

Another example of probabilistic approach application was taken from the results obtained during the process of steady state fuel behavior modeling code validation, performed by utilizing the experimental data generated in the experimental program on CANDU type fuel fabricated and irradiated in INR [7, 8]. The selected cases comprise an enriched fuel element - A24 (see table 1) that supported without defect a significant ramp at relatively high burnup (figure 5). Due to the particular irradiation device utilized in this test, the uncertainties on irradiation conditions were higher than usual. In order to realistically asses the influence of these uncertainties on code calculations, a probabilistic analysis has been performed, taking into account the known uncertainties on irradiation conditions and also on fuel element constructive characteristics. A total of 21 input variables has been considered into this analysis. In figure 6 the probability distribution of ROFEM code calculated values of fission gas released volume is plotted together with the measured value and its error interval. This approach was utilized in assessing the code predictions versus the validation criterion (in this case: multiply/divide 2 band). The contributions of each input variable uncertainty on code calculations have been evaluated by using response surface equation coefficients, allowing a rank ordering of the input variable importance for all the performance parameters investigated. For the fission gas released volume , the input variables with significant contribution on variance were found to be: linear power (input standard deviation $\sigma = 2.3\%$), coolant temperature (input $\sigma = 1\%$) and pellet grain size (input $\sigma = 0.4\ \mu m$). This example has revealed a part of the advantages of the probabilistic approach in fuel element performance evaluation : availability of the probability density function for any calculated performance parameter, estimation of the sensitivity coefficients and rank ordering of the input variables investigated. The separate contribution of the input sources of uncertainties on performance parameters can be evaluated, allowing to identify the areas in which the deterministic code needs further improvements. Also, this type of information can constitute a basis for refining validation criteria and for improvements in designing new experiments.

3.2 Application to fuel design development process

Burnup extension is a process in continuing progress. Parallel investigations and experimental programs have accompanied this process and knowledge has increased about potential performance affecting phenomena associated with increased burnup. Fuel design analyses using current methodology often only allow limited burnup increases. Therefore effort has to be spent in order to find solutions that permit further increase of burnup. Besides fuel bundle and fuel element design improvements, the removal of excess conservatism from design criteria and from design calculations can contribute to this goal [9]. The main means for eliminating excess conservatism from design calculations at extended burnup are : refining the models, improving the data base and utilization of probabilistic design methods.

An example of the probabilistic methodology application to the evaluation of a particular CANDU type fuel design is presented in the following. An essential prerequisite for such an analysis is a best-estimate fuel element behavior modeling code that must incorporate an update of knowledge about potential performance limiting phenomena at extended burnup. The above mentioned version of ROFEM code includes such developments (e.g. burnup dependent degradation of UO_2 thermal conductivity [10], burnup dependence of radial heat generation rate) and has demonstrated good prediction capabilities in FUMEX blind comparison exercise [11].

The case under study was that of a 43 element fuel bundle design with two size fuel elements containing 1.2 wt% enriched UO_2 pellets [12]. The design includes modifications of internal fuel element geometry (e.g. pellet length, land width, axial gap, dish depth) in order to reduce the detrimental effects on fuel behavior at extended burnups. The probabilistic methodology has been applied for evaluating the effect of variation of fuel element design data within their tolerances on calculated fuel performance parameters. The outer elements linear power histories utilized in this set of calculations were deduced from the envelope bundle power history presented in figure 7, which was calculated from core management simulations involving a 2-bundles shift refueling scheme .

Figure 8 includes a series of succesive results obtained in evaluating the evolution of outer fuel element internal pressure for three different situations. The curve denoted "37 nominal" represents the evolution of calculated internal pressure in the outer element of a standard geometry CANDU 37 bundle containing enriched UO2 (1.2 wt%). It can be noticed that the internal pressure for this nominal case is permanently very close to the coolant pressure. The "worst case" conservative calculation produced significantly higher values and was not figured.

This curve was included as a reference for the next results. In the same figure are presented the calculated uncertainty band limits for the outer elements of the new 43 elements bundle design (noted 43a). A version of this design, containing UO_2 pellets with a different grain size range (25-45 μm) was investigated using the same approach. The calculated uncertainty band limits for this version are also figured (43b), showing a significant reduced range for internal pressure values. Other important additional results have been selected and included in figures 9. It shows the probability density function of EOL internal pressure for the 43b design, calculated using the two available methods on response surface equations. It also includes cumulative probability calculated for the same parameter, function that can be used directly for evaluating the probability of exceeding a given value (threshold). In figure 10 is presented the contribution to the variance of calculated EOL internal pressure (43b case) from 5 input parameters that have been selected in a RSM preliminary sensitivity analysis.

Another important advantage of this approach is the possibility of correctly establishing the "worst case" combination of the input variables for a given case and finding the associated probability of occurrence. This is the practical way of quantifying the conservatism of design calculations and also the basis for designs comparison.

4. SUMMARY AND CONCLUSION

The features and advantages of the probabilistic methodology developed and currently applied at INR to CANDU type fuel behavior evaluation are briefly described and some illustrative examples of application are presented.

The methodology has proved to be a powerful tool for identifying the main sources of uncertainties in fuel behavior modeling code calculations in order to give a perspective on current code predictions.

The probabilistic approach is also extremely useful in the process of new fuel design development and comparison. It can give a quantitative measure for the design differences and a measure for the importance of the tolerances specified for the fuel. This approach has also the capability of characterizing the degree of conservatism within fuel design analysis by making statements about the probability of occurrence of extreme values

The examples presented point out the flexibility of the method, allowing its utilization in areas of maximum interest for the CANDU fuel type development .

Future work is expected to introduce this approach in a more realistic evaluation of fuel element failures during steady state operation (SCC related failures) by coupling specific failure models presently under development with the techniques of the methodology.

5. REFERENCES

(1) D. R. MOSCALU, G. HORHOIANU, "CANDU Type Fuel Element Performance Analysis by the Probabilistic Response Surface Method", Rev. Roum. Phys., Tome 35, Nos. 5-6, 463-469, Bucarest, 1990

(2) G. HORHOIANU, D.R. MOSCALU, "Calculation Study of the CANDU Type Fuel Performance at Extended Burnup", Proc. IAEA Tech. Comm. Meeting on Fuel Performance at High Burnup for Water Reactors, Studsvik, Sweden, 1990, IWGFPT/36

(3) R. H. MYERS, "Response Surface Methodology", Allyn and Bacon, N.Y.,1975

(4) I.D. PALMER, "Probabilistic Performance Analysis Using the SLEUTH Fuel Modelling Code", Proc. IAEA Spec. Meeting on Water Reactor Fuel Element Performance Computer Modelling, Bowness on Windermere, UK, 1984

(5) G.J.HAHN, S.S. SHAPIRO, "Statistical Models in Engineering", John Wiley and Sons, New York, 1967

(6) IAEA - IWGFPT/43, "Fuel Modelling at Extended Burnups - FUMEX", IAEA, Vienna, 1995

(7) D.R. MOSCALU, M. TITA, E. GHEORGHIU, "CANDU Type Fuel Element Behaviour Modelling Codes Validation", INR Internal Report 4381, 1994

(8) C. GHEORGHIU, M. CIOCANESCU, "Irradiation Test Programme Aimed to Check Romanian Fuel Behaviour", Proc. Third Int. Conf. on CANDU Fuel, Chalk River, Canada, 1992

(9) R.EBERLE, L. HEINS, F. SONTHEIMER, "Fuel Rod Analysis to Respond High Burnup and Demanding Loading Requirements", Proc. IAEA Tech. Comm. Meeting on Water Reactor Fuel Element Modelling at High Burnup and its Experimental Support, Bowness on Windermere, UK, 1994

(10) D. R. MOSCALU, "On the Role of UO2 Thermal Conductivity Degradation at Extended Burnup In PHWR Fuels", Trans. Int. KTG/ENS Topical Meeting on Nuclear Fuel, Wurzburg, Germany, 1995

(11) G. HORHOIANU, D. R. MOSCALU, I. A. POPESCU, "Fuel Rod Behaviour Analysis using ROFEM Fuel Performane Code", Trans. Int. KTG/ENS Topical Meeting on Nuclear Fuel, Wurzburg, Germany, 1995

(12) G. HORHOIANU, D. R. MOSCALU, G. OLTEANU, "Preliminary Design of an Advanced SEU-1.2% 43 Fuel Element Bundle", INR Internal Report 3457, 1992

TABLE 1. FUEL ELEMENT CARACTERISTICS AND IRRADIATION CONDITIONS

Fuel Element NO.		FUMEX 3.1	FUMEX 3.3	A24
Pellet Radius, inner	mm	0.9	0.9	0
Radius, outer	mm	5.35	5.375	6.076
Length	mm	12.7	12.7	13.3
End geometry		One end dished		Double end dished
Dishing volume	mm^3	22.8	22.8	
Dish depth	mm			.25
Land width	mm	1.5	1.5	.55
Surface roughness, Ra	µm	1	1	.5
Density	%TD	95.	95.	95.9
Grain size	µm	3.4	3.4	9.4
Enrichment U^{235}	% W/O	10	10	5.00
Cladding Radius, inner	mm	5.4	5.4	6.11
Radius, outer	mm	6.25	6.25	6.53
Surface roughness, Ra	µm	0.5	0.5	0.5
Material type		Zy-2	Zy-2	Zy-4
Pin Fuel stack length, enriched	mm	140	140	187.3
Filling gas		He	Xe	He
Filling gas pressure	bar	1	1	1
Gap, diametral	µm	100	50	70
Coolant / moderator		D_2O, HBWR conditions		H_2O
Coolant pressure	MPa	3.36	3.36	10.4
Coolant temperature	°C	240	240	300

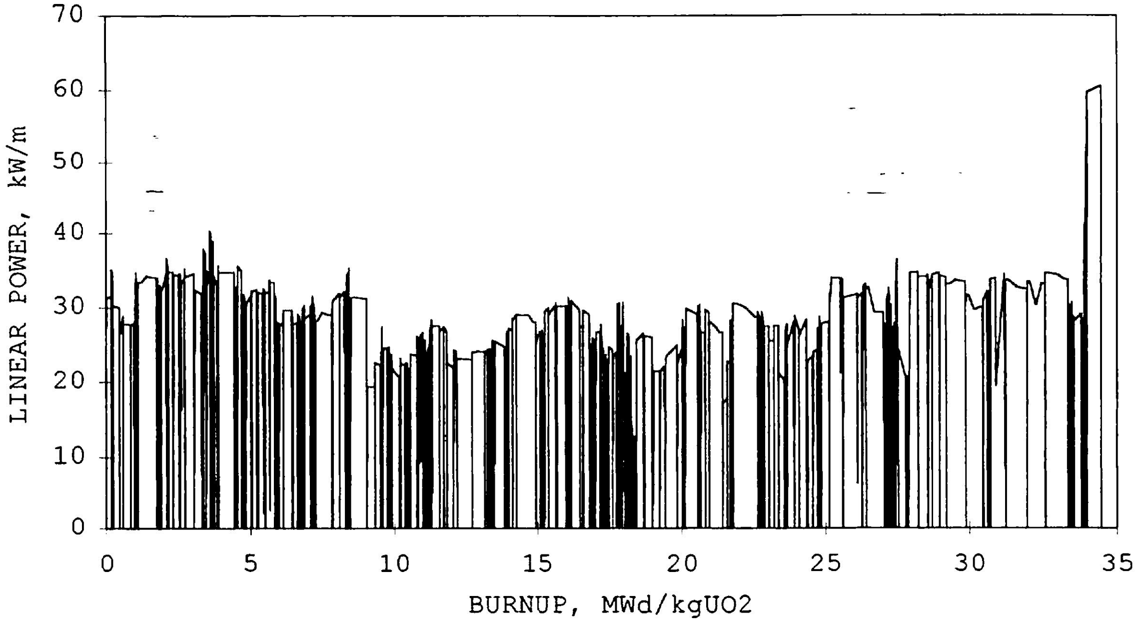


FIGURE 1. POWER HISTORY - FUEL ROD 3.1

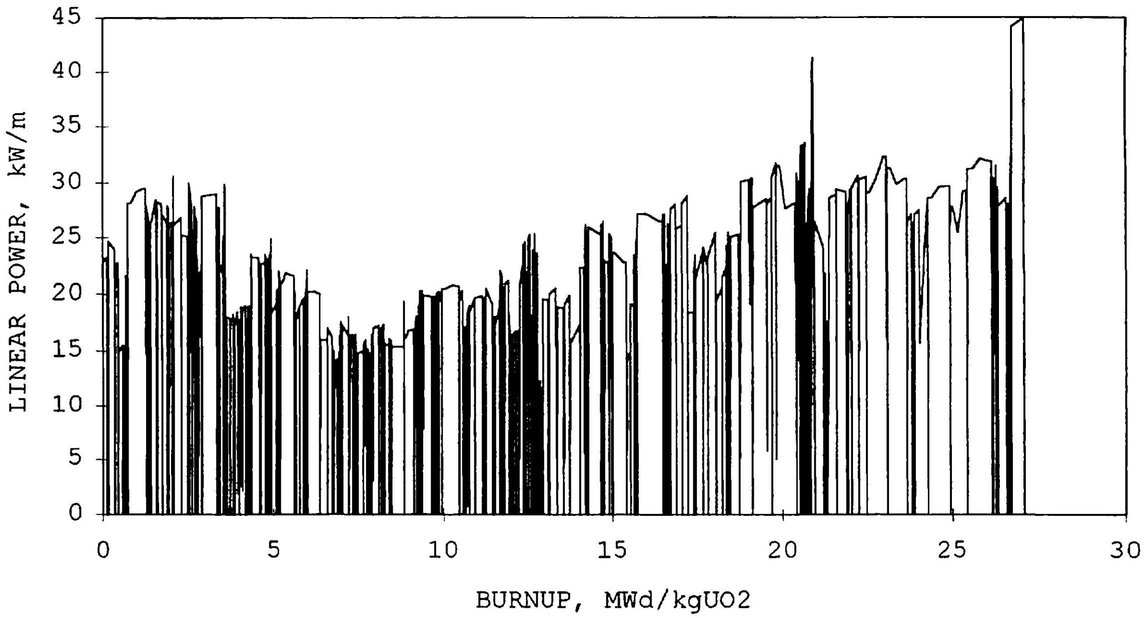


FIGURE 2. POWER HISTORY - FUEL ROD 3.3

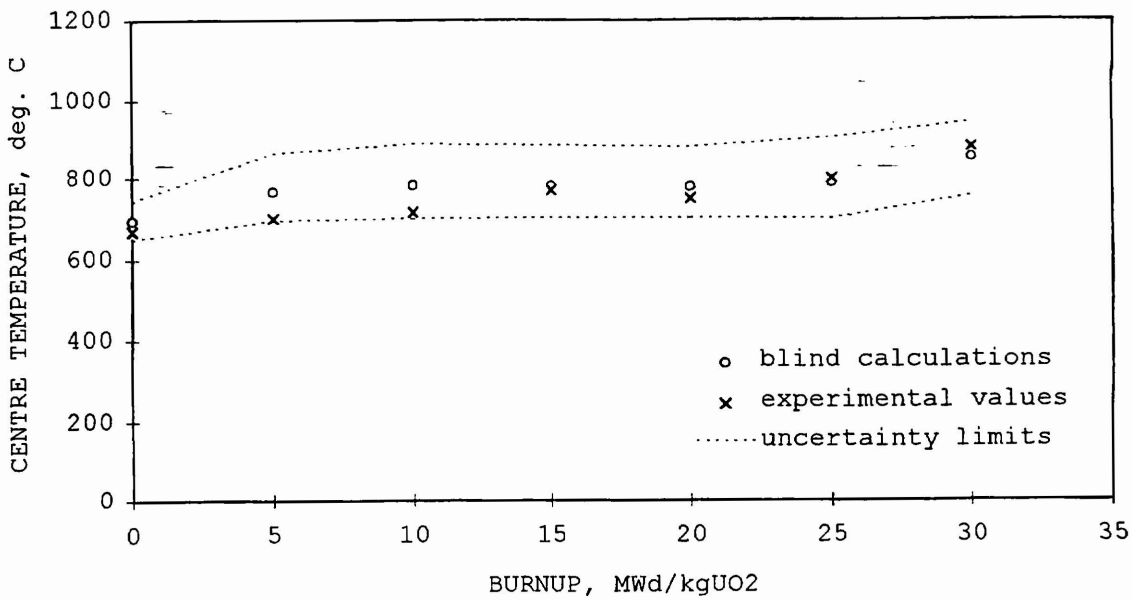


FIGURE 3. ROD 3.1 - FUEL CENTRE TEMPERATURE AT 20 KW/M VS. BURNUP

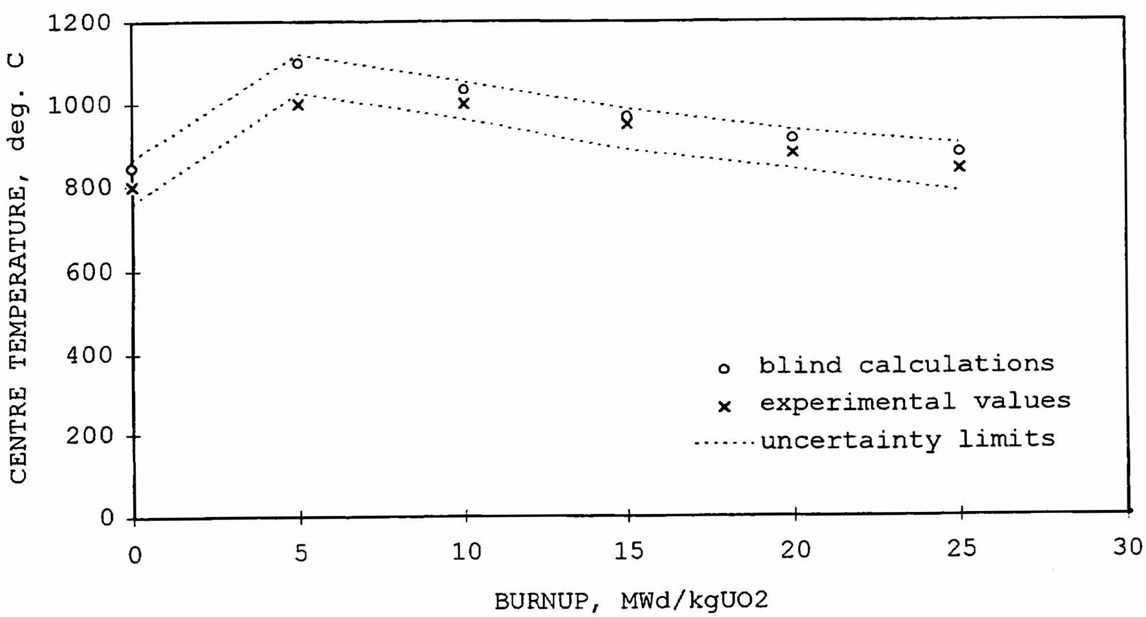


FIGURE 4. ROD 3.3 - FUEL CENTRE TEMPERATURE AT 20 KW/M VS. BURNUP

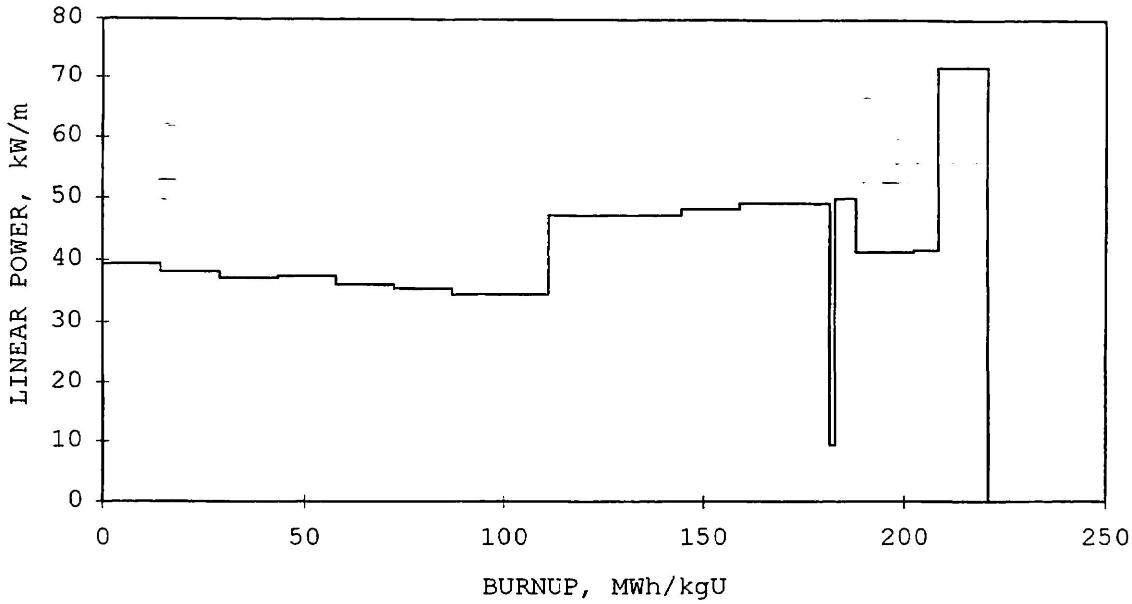


FIGURE 5. POWER HISTORY - FUEL ELEMENT A24.

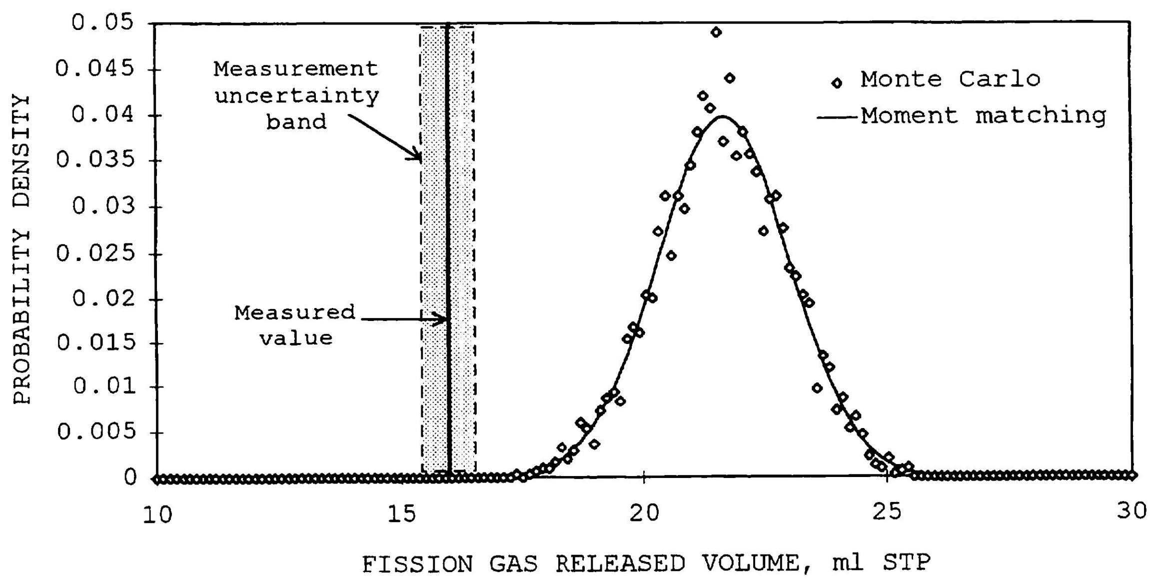


FIGURE 6. CALCULATED PROBABILITY DISTRIBUTION FUNCTION FOR FISSION GAS RELEASED VOLUME - A24 FUEL ELEMENT

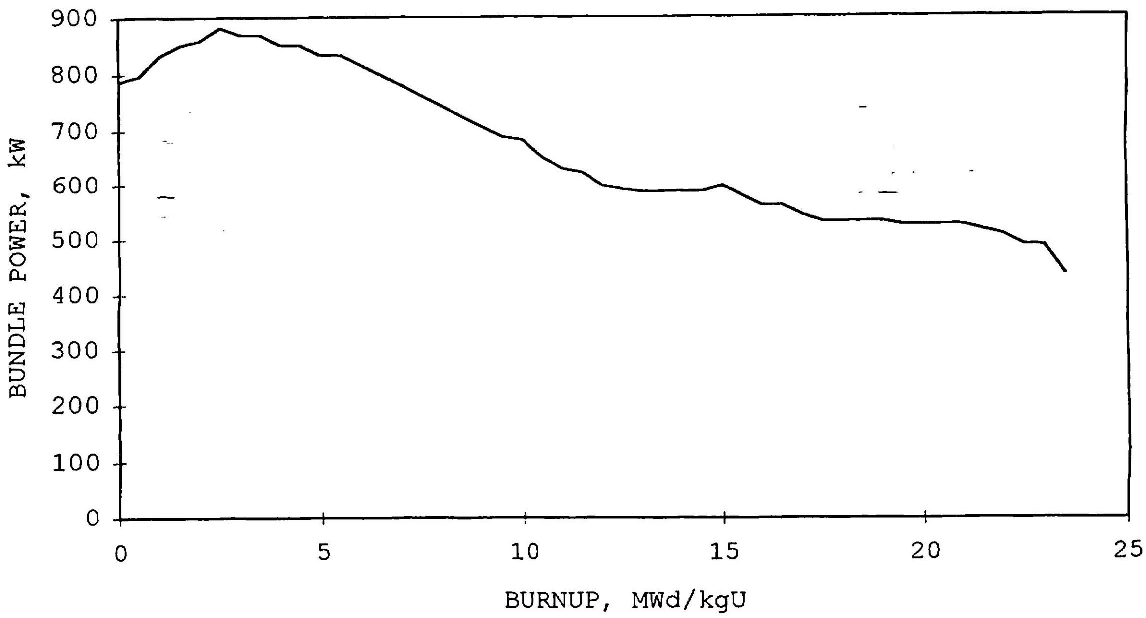


FIGURE 7. UTILIZED BUNDLE POWER ENVELOPE - ENRICHED CANDU TYPE FUEL (1.2 wt % U235)

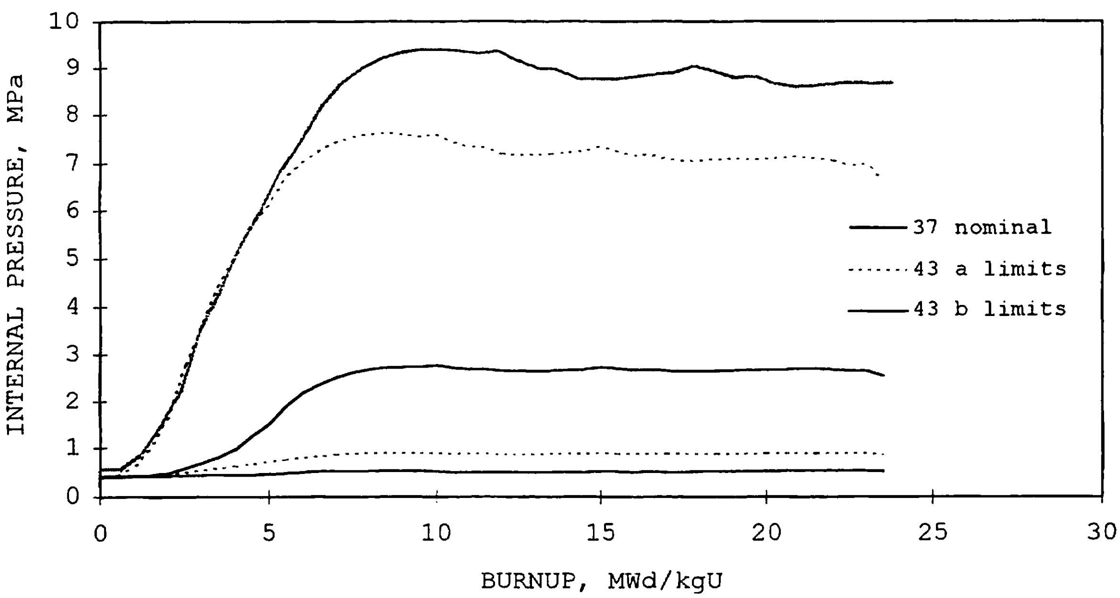
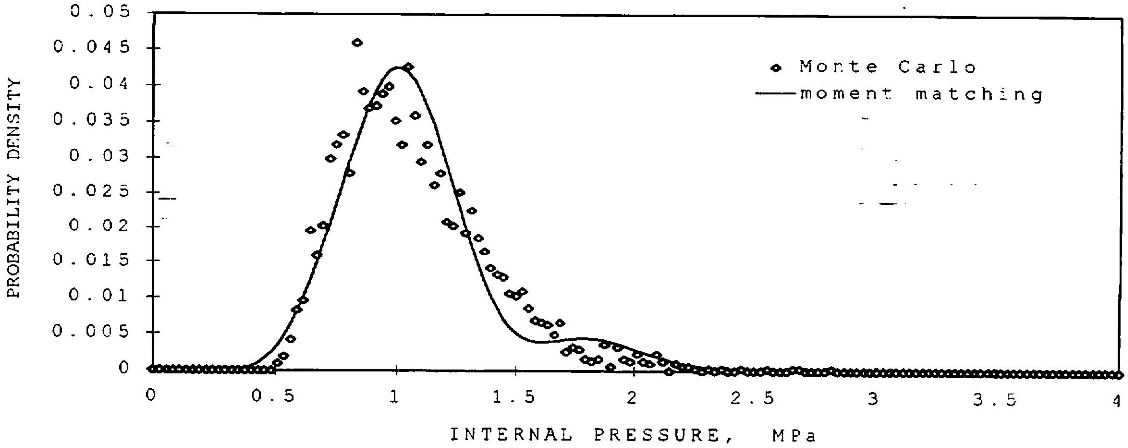


FIGURE 8. CALCULATED UNCERTAINTY BANDS OF INTERNAL PRESSURE FOR TWO FUEL ELEMENT DESIGNS



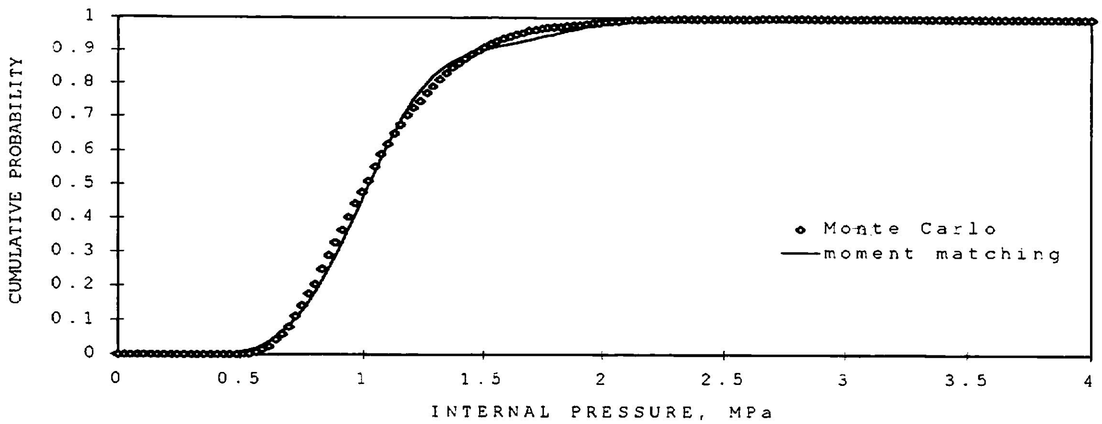


FIGURE 9. CALCULATED PROBABILITY DENSITY FUNCTION AND CUMULATIVE PROBABILITY FOR EOL INTERNAL PRESSURE - 43b FUEL ELEMENT DESIGN

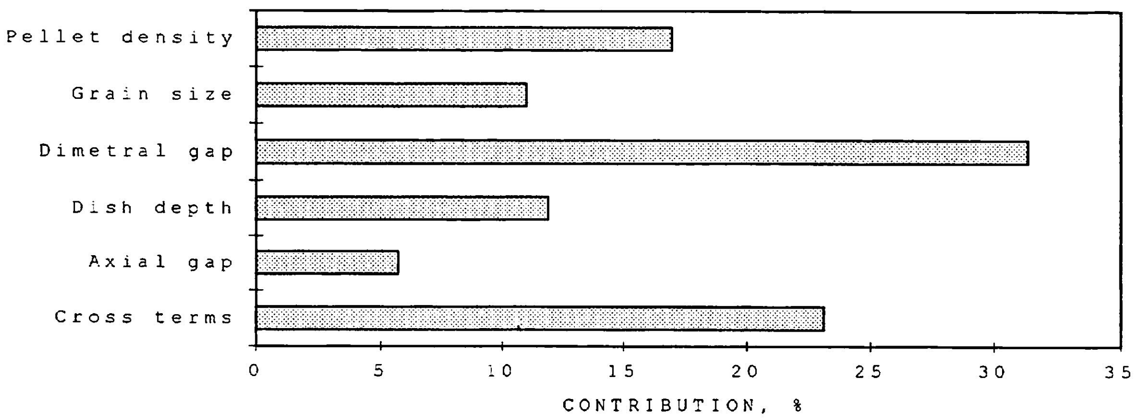


FIGURE 10. CONTRIBUTION TO EOL INTERNAL PRESSURE VARIANCE - 43b FUEL ELEMENT DESIGN