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Sensitivity Analysis of Fabrication Parameters for Dry Process Fuel Performance Using Monte Carlo Simulations

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Abstract

This study examines the sensitivity of several fabrication parameters for dry process fuel, using a random sampling technique. The in-pile performance of dry process fuel with irradiation was calculated by a modified ELESTRES code, which is the CANDU fuel performance code system. The performance of the fuel rod was then analyzed using a Monte Carlo simulation to obtain the uncertainty of the major outputs, such as the fuel centerline temperature, the fission gas pressure, and the plastic strain. It was proved by statistical analysis that for both the dry process fuel and the UO_2 fuel, pellet density is one of the most sensitive parameters, but as for the fission gas pressure, the density of the UO_2 fuel exhibits insensitive behavior compared to that of the dry process fuel. The grain size of the dry process fuel is insensitive to the fission gas pressure, while the grain size of the UO_2 fuel is correlative to the fission gas pressure. From the calculation with a typical CANDU reactor power envelop, the centerline temperature, fission gas pressure, and plastic strain of the dry process fuel are higher than those of the UO_2 fuel.

Key Words : dry process fuel, ELESTRES, monte marlo simulation

1. Introduction

International research programs, such as generation IV international Forum (GIF) have investigated, and will soon begin to develop, new concepts for fuels and fuel cycles [1]. At the Korea Atomic Energy Research Institute, dry process fuel has been developed and studied for over 10 years [2, 3]. Dry process fuel cycle technology provides high proliferation resistance and a better utilization of uranium, because there is no separation of isotopes from the spent PWR fuel during the dry fabrication process. In addition, this fuel cycle has the merit of producing the lowest amount of radioactive waste. The fabrication of a dry process fuel pellet employs the OREOX (oxidation and reduction of oxide fuel) process, followed by compaction and sintering [3]. Nearly all the fission

products, except the volatile elements in the spent fuel, remain after fabrication. Thus, the performance of dry process fuel is expected to be quite different from that of UO_2 fuel. The performance code system for UO_2 fuel must be modified and expanded to evaluate dry process fuel. Simulated fuel demonstrates behavior analogous to that of dry process fuel that is fabricated from spent fuel [4]. Using the simulated fuel, thermal and mechanical material properties were obtained to predict the in-reactor behavior of dry process fuel. The thermal performance of dry process fuel was previously evaluated under light water reactor conditions with a modification of the existing fuel performance code system.

Sensitivity analysis (SA) for the dry process fuel design parameters was performed to observe which parameters significantly affect fuel performance. Sensitivity analysis is the study of how a variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variations, and of how the given model depends upon the information fed into it [5]. Among several methods of sensitivity analyses and uncertainty analyses, suitable sampling techniques are adopted to find the optimal design parameters of dry process fuel. In this study, a random sampling approach [6] is used to obtain the fabrication parameters, with the design criteria, and is given in Ref. 7. The results are analyzed using a statistical method, and the correlation coefficients are also obtained to find the relationship between the input and output variables.

2. Calculation Model

Among the thermal models of dry process fuel used for the experiments, the thermal conductivity and thermal expansion models are used for the calculation of fuel performance.

Thermal conductivity of the fuel is one of the most important parameters, because it is directly related to fuel temperature increase. The thermal conductivity model of dry process fuel, which can be applied for up to 3000K, was developed using simulated dry process fuel pellet. The basic model referred to the UO_2 solid density from Harding and Martin [8]. Figure 1 shows the thermal conductivity for both dry process fuel and UO_2 fuel.

Thermal expansion is another important property of the fuel; it affects the pellet and cladding mechanical interaction, as well as the gap conductivity and other characteristics. The thermal expansion model of dry process fuel shows larger results than that of UO_2 fuel and the difference becomes greater as the fuel temperature increases. The thermal expansion model of dry process fuel is described in Ref. 8. Figure 2 shows the thermal expansion for both dry process fuel and UO_2 fuel.

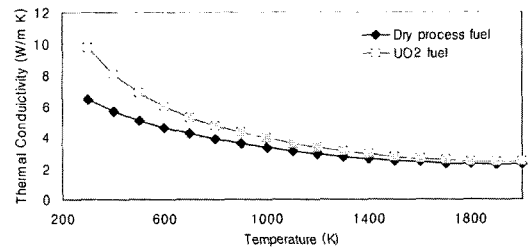

Fig. 1. Thermal Conductivity for Dry Process Fuel and UO_2 Fuel

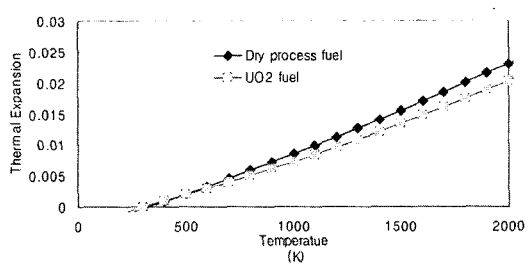

Fig. 2. Thermal Expansion for Dry Process Fuel and UO_2 Fuel

Table 1. Variation of Fabrication Parameters for Simulation

Parameters	Variation Values
Theoretical Density of Pellet (%)	95 ~ 98
Axial Gap (mm)	0.5 ~ 3.5
Diametral Clearance (mm)	0.08 ~ 0.12
Grain Size (μm)	7 ~ 15

For this study, the ELESTRES code [9, 10] is chosen, considering its ease of application and the original target of the dry process fuel. The ELESTRES is a computer program designed to predict the behavior of CANDU fuel under normal operating conditions. It takes into account the fuel geometry, material properties, and the operating conditions, and predicts the percentage of fission gas release, internal gas pressure, radial temperature distribution, and the percentage of the elastic and plastic sheath strains in a given fuel element [9]. To evaluate the performance of dry process fuel, we modified the ELESTRES code with the thermal calculation models. Specifically, the thermal conductivity and thermal expansion models of the dry process fuel are added, and minor parameters are changed to be appropriate for dry process fuel.

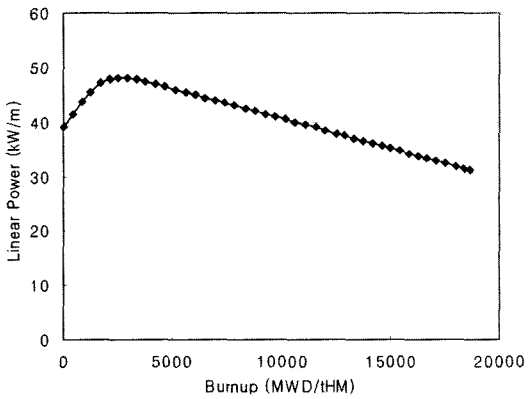

Fig. 3. Linear Power Envelop of CANDU 6 Reactor for Simulation

The input for the ELESTRES code system is based on a typical CANDU 6 reactor, the power envelope for which is given in Fig. 3. The concerned fabrication parameters are pellet density, axial gap, diametral clearance, and grain size. Table 1 shows the variation of the selected parameters, which are given in the design manual [7]. The other input values followed the specifications of a typical CANDU 6 fuel rod.

3. Sensitivity Analysis

3.1. Basic Statistical Analysis

In general, probabilistic distribution functions are classified into two categories: nonparametric distributions and parametric distributions. The parametric distribution is based on a mathematical function, the shape and range of which are determined by one or more of the distribution parameters, such as the lognormal, the Weibul, or the Beta distributions. These parameters often have little obvious or intuitive relation to the distribution shape to which they belong. Nonparametric distribution, on the other hand, has its shape and range determined by the respective parameters in a direct, obvious, and intuitive manner. According to modeling experts, nonparametric distributions, such as uniform, triangular, and discrete distributions, are far more reliable and flexible [10]. In this study, a uniform distribution (nonparametric distribution) was chosen that takes into account the fabrication environment of fuel rod. The outlayers of the fabrication specification are withdrawn in the fabrication process.

A sensitivity analysis on the fuel fabrication parameters can be performed with the results of a random sampling. In general, the purpose of a sensitivity analysis is to determine the change of a response to the changes of the model parameters

and specifications. In this study, the Spearman rank correlation method is used for the sensitivity analysis.

The input matrix (X), obtained by the random sampling, and the output matrix (Y) can be expressed as follows:

$$X=\begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix}, \quad Y=\begin{pmatrix} y_{11} & y_{12} & \cdots & y_{1k} \\ y_{21} & y_{22} & \cdots & y_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mk} \end{pmatrix}, \quad (1)$$

where m, n, k are the number of samplings, the number of input variables, and the number of output variables, respectively. The quantitative measure of the linear relationship between X and Y is provided by the Pearson correlation coefficient, as follows:

$$Pear(Y_i,X_j)=\frac{\sum_{l=1}^{m}(X_{lj}-\bar{X}_j)(Y_{li}-\bar{Y}_i)}{\left(\sum_{l=1}^{m}(X_{lj}-\bar{X}_j)^2\sum_{l=1}^{m}(Y_{li}-\bar{Y}_i)^2\right)^{1/2}}, \quad (2)$$

where $\bar{X}_j$ and $\bar{Y}_i$ are the sample means. The Spearman coefficient is a preferred measure of correlation for nonlinear models; it is essentially the same as the Pearson method, but it uses the ranks of both Y_i and X_j instead of the raw values, as follows:

$$Spear(Y_i,X_j)=Pear(R(Y_i),R(X_j)), \quad (3)$$

where $R(Y_i)$ and $R(X_j)$ are the ranks of Y_i and X_j, respectively. If the value of the coefficient approaches -1 or 1, it is an indication that the variables are highly correlated.

3.2. Simulation Results

Table 2 shows the results of the sampling frequency for 100, 1000, and 10000 trials of the ELESTRES for both dry process fuel and UO_2 fuel. For 1000 simulations, the centerline temperatures of the pellet are 2302.3±19.5 K and 2011.4±34.6 K at the burnup of 5800 MWd/tHM for the dry process fuel and the UO_2 fuel, respectively. The fission gas pressures are 13.002±0.811 MPa and 8.26±61.621 MPa at the burnup of 5600 MWd/tHM for the dry process fuel and the UO_2 fuel, respectively. The sheath plastic strains are 1.173±0.392 % and 0.318±0.313 % at the burnup of 18600 MWd/tHM for the dry process fuel and the UO_2 fuel, respectively. The burnups of each output variables are chosen from where the maximum values are observed. It is shown that the dry process fuel performs slightly worse robustness of fuel rod than that of UO_2 fuel, due to higher values of centerline temperature, fission gas pressure, and sheath plastic strain.

Table 3 shows the results of the sensitivity calculation using Eq. (3) for dry process fuel and UO_2 fuel. The coefficients provide an alternative measure of the relative importance of each input to the observed output variation of the fuel rod performance. The rank correlation coefficients of the same output parameter provide similar results as the variation of simulation numbers. The results indicate that the pellet density is the most sensitive among the input variables. The centerline temperature has an inverse proportional to the pellet density, which results from the increased thermal conductivity and an increased gap conductance, due to an increased pellet density. However, in the case of the dry process fuel, the density is more sensitive to the internal gas pressure than the UO_2 fuel. In general, a critical concentration of the fission gas is strongly dependent on the fuel temperature, the grain size, and the fission rate [11]. As the density increases, the swelling of the dry process fuel is much higher than that of the UO_2 fuel, thus the internal gas pressure increases. With the UO_2 fuel, however,

Table 1. Results of Monte Carlo Simulation for the Uncertainty Analysis of Fuel Rod Performance (1000 simulations)

	Centerline Temperature (K)		Fission Gas Pressure (MPa)		Plastic Strain (%)	
	Dry Process	UO_2	Dry Process	UO_2	Dry Process	UO_2
Minimum	2255.4	1943.7	10.751	5.037	0.271	-0.355
Maximum	2361.3	2148.4	16.032	12.756	2.246	1.223
Mean	2302.3	2011.4	13.002	8.266	1.173	0.318
STD	19.5	34.6	0.811	1.621	0.392	0.313
Variance	380.5	1198.0	0.657	2.627	0.154	0.098
Skewness	-0.016	0.786	0.466	0.232	0.162	0.268
Kurtosis	-0.620	0.693	-0.088	-0.808	-0.512	-0.424
Percentile						
5 %	2269.1	1962.5	11.898	5.839	0.536	-0.171
10%	2275.6	1971.4	12.039	6.224	0.657	-0.072
15%	2280.2	1976.3	12.161	6.424	0.764	-0.009
20%	2284.2	1982.1	12.253	6.670	0.808	0.035
25%	2287.9	1987.0	12.343	6.935	0.864	0.087
30%	2290.9	1991.0	12.457	7.159	0.941	0.135
35%	2294.0	1994.9	12.567	7.406	1.008	0.181
40%	2297.0	1999.1	12.687	7.656	1.055	0.221
45%	2300.0	2003.0	12.813	7.880	1.114	0.258
50%	2302.9	2006.2	12.936	8.175	1.167	0.298
55%	2306.2	2010.5	13.046	8.466	1.219	0.337
60%	2308.8	2015.2	13.168	8.687	1.273	0.379
65%	2311.4	2019.9	13.296	8.994	1.313	0.430
70%	2313.7	2025.3	13.416	9.216	1.373	0.477
75%	2316.2	2031.5	13.571	9.505	1.449	0.521
80%	2319.4	2038.5	13.732	9.835	1.516	0.579
85%	2323.2	2046.1	13.871	10.127	1.610	0.668
90%	2328.1	2058.4	14.079	10.484	1.707	0.767
95%	2334.4	2076.5	14.417	10.941	1.827	0.871

the density does not greatly affect the internal gas pressure, because of lower fuel temperature and less pellet swelling. Shown in Figs. 4 to 6 are the distribution of fuel centerline temperature, the fission gas pressure, and the plastic strain with density, for a case with 1000 simulations. The axial gap and the diametral gap within the design variations do not provide significant effects on the fuel performance. In the case of a larger grain size, as the diffusion length of the fission gas increases, the fission gas released from the grain boundary decreases. From the simulation, the grain size effect of the dry process fuel is less sensitive to the internal gas pressure than that of the UO_2 fuel. This is because the higher fuel temperature allows the grain growth to accommodate the released fission gas. Figure 7 depicts the distribution of the internal fission gas

Table 3. Comparison of Rank Correlation Coefficients

Number of Simulation	Centerline Temperature	Centerline Temperature		Fission Gas Pressure		Plastic Strain	
		Dry process	UO_2	Dry process	UO_2	Dry process	UO_2
100	Pellet Density	-0.827	-0.719	0.927	-0.005	0.802	0.665
	Axial Gap	-0.175	-0.318	-0.093	-0.375	-0.072	-0.141
	Diametral Clearance	-0.290	-0.290	-0.175	-0.198	-0.601	-0.744
	Grain Size	-0.210	-0.390	-0.144	-0.898	-0.035	-0.030
1000	Pellet Density	-0.653	-0.754	0.766	-0.072	0.891	0.603
	Axial Gap	-0.152	-0.149	-0.098	-0.215	-0.009	-0.034
	Diametral Clearance	-0.306	-0.407	-0.129	-0.290	-0.606	-0.698
	Grain Size	-0.213	-0.445	-0.197	-0.912	-0.092	-0.104
10000	Pellet Density	-0.853	-0.701	0.900	-0.006	0.766	0.651
	Axial Gap	-0.165	-0.141	-0.070	-0.226	-0.003	-0.044
	Diametral Clearance	-0.314	-0.327	-0.113	-0.315	-0.596	-0.733
	Grain Size	-0.216	-0.433	-0.160	-0.899	-0.052	-0.132

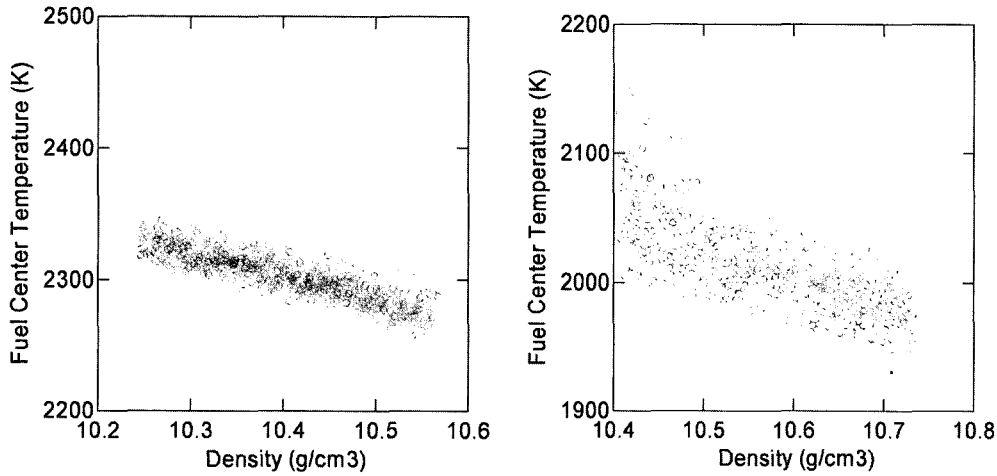

Fig. 4. Distribution of Internal Gas Pressure as a Function of Density

pressure as a function of grain size for a case with 1000 simulations.

4. Conclusions and Recommendations

Several fuel fabrication parameters are chosen from the CANDU fuel design manual for the sensitivity analysis. A Monte Carlo simulation with a random sampling technique is performed for both dry process fuel and UO_2 fuel, and various statistical results are obtained from the simulations. Among the fuel fabrication parameters, the pellet density is the most sensitive parameter for the fuel irradiation performance for both dry process fuel

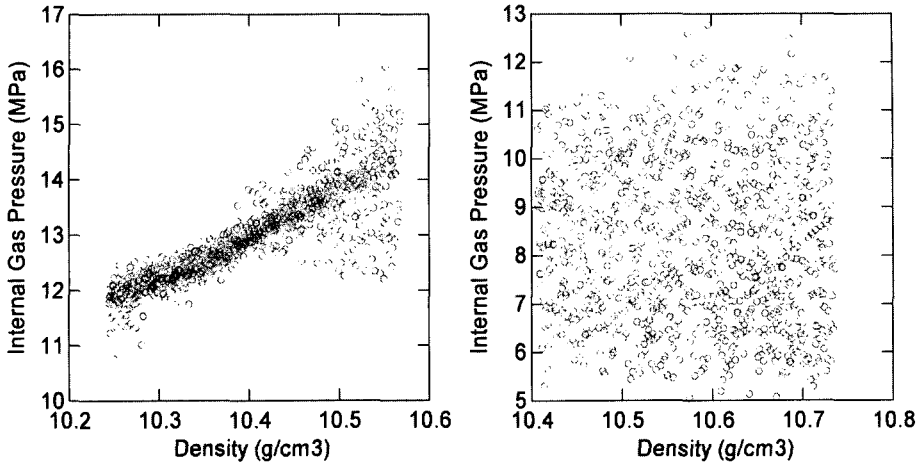

Fig. 5. Distribution of Internal Gas Pressure as a Function of Density

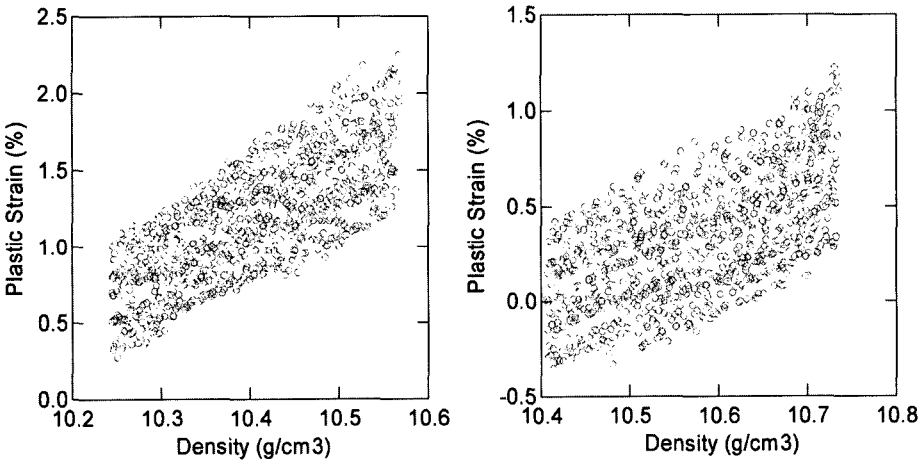

Fig. 6. Distribution of Plastic Strain as a Function of Density

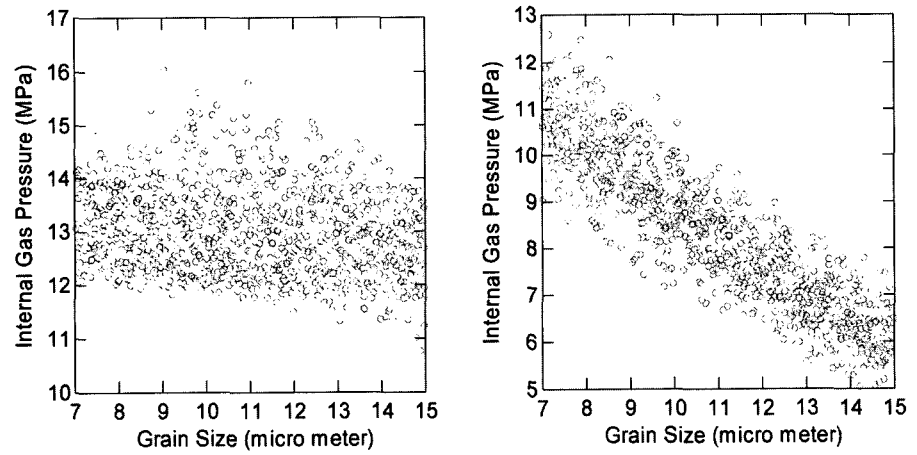

Fig. 7. Distribution of Internal Fission Gas Pressure as a Function of Grain Size

and UO_2 fuel. For UO_2 fuel, however, the density is less sensitive to the internal gas pressure, due to a lower fuel temperature.

For dry process fuel, it is recommended that the pellet density should be decreased to within the fuel design criterion, to decrease the internal gas pressure and strain rate, even though the fuel center temperature increases, assuming that the three outputs (internal gas pressure, strain, and fuel center temperature) are all the same importance for the fuel rod safety. Detailed calculations with more input and output variables should be done to determine the optimal fuel fabrication parameters for dry process fuel. Such a study would be helpful in obtaining the sensitivities of fuel fabrication parameters and would be useful in obtaining optimal fabrication parameters from the results of simulation.

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