Simulation of the In-core Distribution of Decay Energy From Fuel, Following Shutdown of the CANDU-6 Reactor

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Abstract

This paper describes how innovative analytical techniques, centred around Monte Carlo radiation transport analysis, were used to obtain upper and lower bound estimates of the in-core distribution of decay energy released from fuel, following the shutdown of the CANDU-6 reactor. The ORIGEN-S/BETA-S codes and the Integrated Tiger Series (ITS) of Electron/Photon Monte Carlo radiation transport codes were employed in this investigation for gamma-ray/beta particle source term calculations and electron/photon radiation transport simulations, respectively.

Introduction

Following reactor shutdown, the spatial and temporal distribution of fuel decay energy that is absorbed in-core (and hence the decay heat produced), has important economic implications, in terms of defining when certain reactor maintenance operations can be initiated. It has generally been assumed that the spatial distribution of fuel decay energy deposited in-core is the same following shutdown, as it is while the reactor is at full-power. This assertion is not intuitively obvious, since the types and energy spectra of radiation emitted by fuel undergoing fission are different from those of decaying irradiated fuel. In this paper, we describe the work that was done to simulate both the temporal and spatial distribution of the energy deposited in-core, from the radioactive decay of fuel, following reactor shutdown.

Calculation of Source Terms

After reactor shutdown, the irradiated fuel undergoes radioactive decay, emitting primarily energetic gamma-rays and beta particles. This is the main source of energy liberated in the reactor core, as neutron production and neutron induced reactions rapidly subside. In order to calculate the gamma-ray spectrum emitted by a single fuel bundle, as a function of time, the ORIGEN-S code [1] was used, in conjunction with CANDU-6 specific data libraries [2]. The ORIGEN-S code is a module in the widely used SCALE 4.3 code suite [3]. To calculate the beta decay spectra from the fuel, the BETA-S code [4] was employed, in conjunction with the ORIGEN-S code.

In this initial study, for the sake of simplicity, the reactor was assumed to be loaded entirely with fuel having a uniform irradiation history. To obtain upper and lower bounding estimates of the decay energy released and absorbed in-core, either a typical high or low rate of fuel burn-up was assumed. For both cases of uniform fuel loading, the beta and gamma-ray decay energy spectra were calculated (for a single fuel bundle) for a total of 10 time steps, up to 3 weeks after shutdown (i.e. a total of 11 spectra were calculated for both betas and gamma-rays). The duration of each consecutive time interval was selected so that there was approximately equal beta+gamma-ray decay energy released over the duration of each time period.

In this study, the complexity of the physically accurate core/fuel modelling used in our Monte Carlo radiation transport analysis, coupled with our analytical approach (both discussed subsequently), necessitated the use of a relatively fast computer platform. This was a prerequisite to enable statistically significant simulation data to be obtained in a reasonable time period. As a consequence, we were motivated to try to minimize the number of energy bins used for both the gamma-ray and beta decay spectra, in order to reduce the computational burden. As part of our analytical approach, it was desired to keep the source term energy groupings fixed for the analysis of all gamma-rays spectra and similarly for all beta spectra. This applied to all decay spectra that were calculated over the 3 week decay period, for both high and low-power fuel bundles. An objective method for selecting the source term energy groupings was devised. The lower and upper energy limits for each energy group were numerically selected, so that no more than 10% of the total decay energy (in any given energy spectrum) would reside in any particular energy bin. A computer program was written to calculate the energy groupings required for both gamma-rays and beta particles, so that our 10% rule would apply to *all* source term energy spectra. For the majority of both beta and gamma-ray decay energy spectra, we were able to attain this criteria via the use of two sets of 10 energy groups; one set for beta particles and the other for gamma-rays.

Figure 1 illustrates the results of the ORIGEN-S calculations for gamma-ray decay spectra from a high power fuel bundle, calculated at time t=0.0 days and t=21.0 days after shutdown. Shown are energy spectra consisting of 10 energy groups, which were used in our analysis and a much finer resolution energy spectra, shown for comparison. [The finer energy resolution data was used to determine the 10 coarse energy bins used in our gamma-ray and beta particle source terms, via the procedure described previously.] The corresponding beta spectra for the high power fuel bundle, calculated using the ORIGEN-S/BETA-S codes, are shown in Figure 2. Spectra calculated using 10 energy groups are shown, along with much finer resolution data. The results for the calculation of the total energy release rate as a function of time, from a single high and low power fuel bundle, is shown in Figure 3.

Monte Carlo Electron/Photon Radiation Transport Analysis

The distribution of energy deposited in-core, by beta and gamma-ray emissions from decaying fuel, was calculated via a three-dimensional (3-D) Monte Carlo radiation transport simulation. The 3-D Accept code, a member of the Integrated Tiger Series (ITS v3.0) [5] of electron/photon Monte Carlo radiation transport codes, was used for this purpose. As it was not feasible to model the entire reactor core, a method was devised to simulate a small portion of the reactor core, the results of which could be accurately applied to the remainder of the reactor core.

In our simulation work, the physical model of the CANDU-6 reactor core used consisted of a 5x5 array of fuel channels, with 5 fuel bundles per channel. In our model, only the central fuel bundle is an 'active source'; one can calculate the contribution of other fuel bundles to the in-core energy deposition by the principal of superposition of sources (neglecting 'edge effects' at the periphery of the reactor core). A 5x5x5 fuel bundle geometry was selected for this work, as it was found (via Monte Carlo Analysis) that >99% of the energy was absorbed in this geometry, for the highest gamma-ray energy group in the source term (10 MeV). Larger physical models, in terms of the number of fuel channels and fuel bundles present, would not improve the accuracy of the simulation, but would greatly increase the computational time.

The physical modelling (both compositional and dimensional) of the reactor geometry used in our work is fuel-pin based, that is, it does not rely on the use of a 'smeared bundle composition' for simulation purposes. Each fuel bundle is modelled with 37 separate fuel elements, each composed of a stack of UO_2 fuel pellets, encased by zircaloy fuel cladding. The central fuel bundle in our 5x5x5 matrix of bundles (i.e. the active source bundle) is, therefore, composed of 37 separate cylindrical sources, each representing a separate fuel element in the bundle. In our modelling, we included the ability to simulate the effect of variation in burn-up across the various rings of fuel elements within the bundle.

The consequence of using a physically accurate geometry model, for describing the reactor core, is the complexity of the modelling required for the Monte Carlo analysis. In our simulations, the 5x5x5 bundle geometry requires the specification of approximately 10,000 geometrical bodies. The geometrical bodies are defined using the combinatorial geometry system (CGS). The ITS/ACCEPT code expects to find this geometrical description in the input data file for a given simulation. To ensure the accuracy of our modelling, a computer program (an automated CAD tool) was developed to automatically generate the CGS data, including body and material definitions. The data generated by our CAD tool was formatted so that it could be imported directly into the ITS/ACCEPT simulation input file, without any modification. Figure 4 illustrates the basic physical 'building block' used by our CAD tool to generate the core geometry. It is composed of a section of a single fuel channel and a fuel bundle, surrounded by moderator. The length of the section of fuel channel is equal to that of a single fuel bundle. By stacking this modelling 'primitive' axially, a fuel single fuel channel with any desired number of fuel bundles can be obtained. Similarly, any number of fuel channels can be built up, in array fashion. This physical modelling approach was necessary to ensure that we could obtain energy deposition data along each fuel channel and so that we could also compare energy deposition on a channel-by-channel basis. The ITS/ACCEPT code will automatically score energy deposition for each distinct physical volume defined in the geometry specification portion of the input file.

Monte Carlo simulations were carried out for 10 energy groups of gamma-rays and 10 energy groups of beta particles, spanning the energy range of 0-10 MeV. Separate simulations were carried out for each energy group of beta particles and gamma-rays. The number of source particle histories used in each energy group were selected to be large enough to yield less that a 1% error in the energy deposition for the entire 5x5x5 bundle geometry. The spatial energy deposition results for each energy group, obtained from the Monte Carlo analysis, were normalized to one source particle (for each energy group). This methodology has the advantage that it effectively 'decouples' the source spectrum from the Monte Carlo analysis, requiring the Monte Carlo analysis to be performed only once for a given energy group. If the energy groupings are maintained, the source spectrum can change without having to repeat the Monte Carlo analysis. This approach was necessitated by the large computational requirements of the simulations, coupled with the requirement for calculation of both the spatial *and* temporal distribution of energy in-core, following shutdown.

To calculate the rate of energy deposited (MeV/s) in our model, for the j'th reactor component, due to the i'th energy group (i.e. $(\Delta E)_{ij}$) of either beta particles ors or gamma-rays, the following was used

$$(\Delta E)_{ij} = \bar{R}_j(E_i)\,\varphi(E_i) \quad . \tag{1}$$

$\bar{R}_j(E_j)$ is the average rate of energy per source particle (from the i'th energy group), which is absorbed in the j'th reactor component and $\varphi(E_i)$ is the particle flux for the i'th energy group (either beta particles or gamma-rays). Analysis software was developed, which combined the Monte Carlo analysis results with the various beta and gamma-ray source spectra (from ORIGEN-S and BETA-S analysis), to obtain the in-core spatial distribution of energy deposition, as a function of time after reactor shutdown. Data is summarized in terms of MeV/s (either from gamma-rays, beta particles, or both) deposited in the various reactor components, such as fuel, coolant, moderator, pressure tube zircaloy, calandria tube zircaloy, etc. Along a given fuel channel, the spatial resolution of the energy deposition calculations is the length of a fuel bundle.

The results of the analysis of the Monte Carlo data, for the in-core energy deposition rates from a single fuel bundle, are illustrated in Figures 5 and 6, for a high and low power fuel bundle, respectively. In our 5x5x5 fuel bundle model, this represents the summation of all energy deposited in the various reactor components by the central (active) fuel bundle . Using the principle of superposition of sources, and by virtue of the physical symmetry present in our model, this data is equivalent to the following: all fuel bundles in our 5x5x5 geometry are active fuel bundles and the data shown in Figures 5 and 6 represent the energy deposited to the reactor components surrounding our central fuel bundle, as defined by the modelling primitive of Figure 3. The statistical uncertainty in our simulation data was <1% for the total energy deposited in our model.

Discussion

During full power operating conditions, about 96% of the nuclear energy is deposited in the fuel, coolant and pressure tubes. Some information exists regarding the energy deposition at the instant of shutdown, when the primary energy source derives from delayed beta particles and gamma rays. However, the available information does not examine the variation in energy deposition with time after shutdown, nor with the influence of a given bundle on its radial and axial neighbours. In this exercise we have examined these two effects. The primary aim was to provide information which may be useful in making decisions on the times at which various reactor maintenance activities could be performed after shutdown.

The temporal variation is shown in Figures 7 and 8. Figure 7 shows the short term nature of shut-down energy distribution, in terms of the proportion of decay energy which is deposited in the fuel, coolant and pressure tube, for the low-power and high-power bundles examined in this study. At the moment of shutdown, the percentage of decay heat in the fuel, coolant and pressure tube is about 90%, with about 86% going directly into the fuel. There is a small peak over the course of the first day, the cause of which we have not yet established. There is then a gradual decrease to about 88-89% (fuel, coolant pressure tube) or 83-85% (fuel only). This decrease "bottoms out" after about 10-14 days. The minimum is more obvious in Figure 8, which shows the shutdown extended to 200 days. The minimum occurs as a result of two competing effects - the gradual softening of the gamma spectrum with time after shutdown, and the increase in UO_2 mass attenuation coefficient, as photon energy reduces. Thus, as would be expected, as the outage proceeds to 200 days, an increasing proportion of the decay heat is deposited in the fuel.

The other effect we wished to examine was the spatial distribution of decay energy emanating from one bundle. As noted earlier, we learned that more than 99% of the total beta and gamma energy emitted from a single bundle was deposited in a 5x5x5 matrix of fuel bundles, where the central bundle represented the source. This type of geometrical distribution information may prove useful in assessing whether certain activities may take place adjacent to others.

The analytical techniques presented in this work allow detailed, physically accurate simulation of the spatial and temporal distribution of decay beta and gamma-ray energy following shutdown. We have explicitly avoided the use of 'smeared' core compositional models of fuel channels, which obviously lead to less accurate simulation results. Our approach to the physical modelling and simulation of energy deposition in-core was necessary to avoid the unwieldy computational burden, that normally would have been a problem using other modelling techniques. The exploitation of the physical symmetry present the reactor core, coupled with the principle of superposition of sources, has permitted the simulations to be carried out on relatively fast, current computer platforms (several 300 to 400 MHz DEC Alphas) in several weeks of dedicated CPU time, instead of months.

Conclusions

In our work, we have used state-of-the-art computational tools and analysis techniques to model the temporal and spatial distribution of decay energy absorbed in-core, for a CANDU-6 reactor following shutdown. The modelling techniques developed in this work, coupled with the accurate and detailed reactor core model used, will be applicable to other problems in reactor physics, as well as in the study of decay heat.

In particular, we have learned how the decay energy deposition varies after shutdown, both in terms of its temporal, and spatial variation. This information will prove useful in assessing the appropriate time after shutdown to perform certain reactor maintenance activities.

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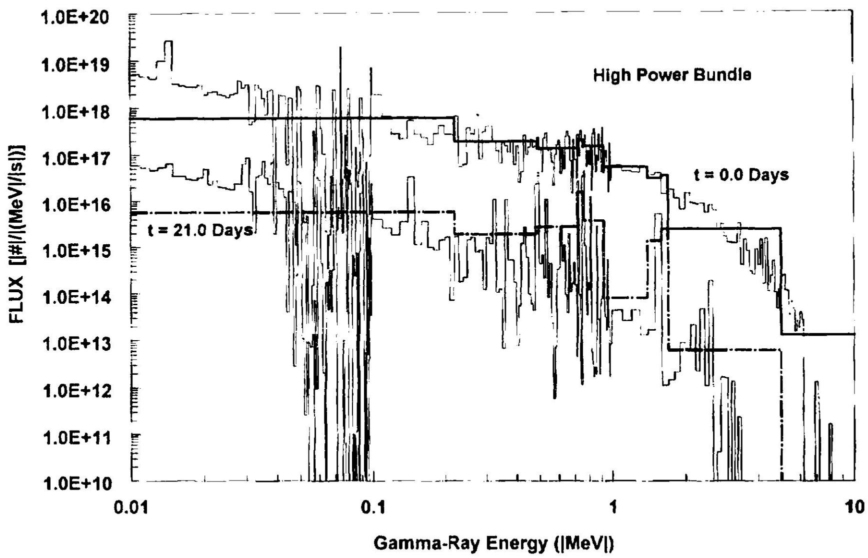

Figure 1. Decay gamma-ray spectra for a high power fuel bundle, calculated by the ORIGEN-S code, using fine energy binning and the 10 energy groups used in the analysis. The change in the gamma-ray spectra is quite evident between t=0.0 days and t=21.0 days after shutdown. The high energy gamma-rays can be seen to drop off quite rapidly, as does the overall gamma activity, with increasing decay time.

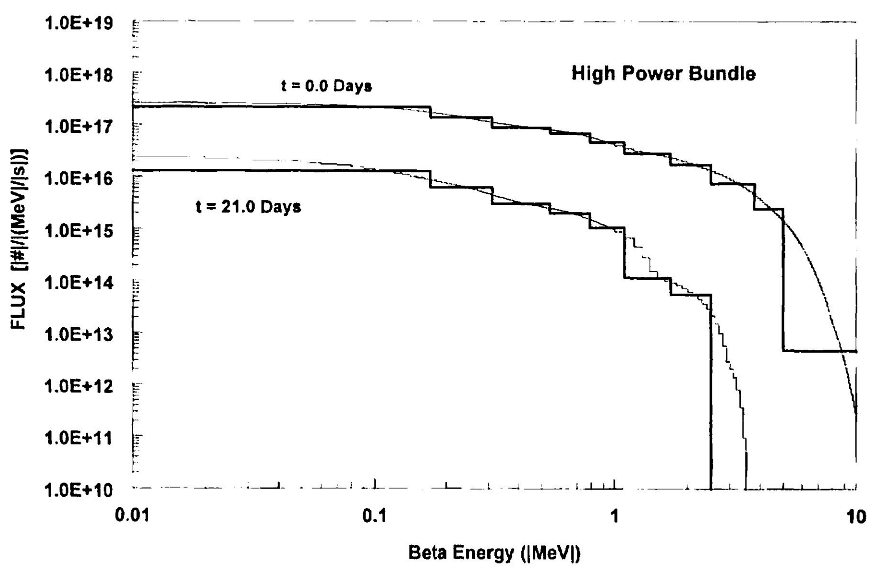

Figure 2. Decay beta spectra for a high power fuel bundle, calculated by ORIGEN-S/BETA-S, using fine energy binning and the 10 energy groups used in the analysis. The change in the beta spectra is quite evident between t=0.0 days and t=21.0 days after shutdown. The high energy betas can be seen to drop off quite rapidly, as does the overall beta activity, with increasing decay time.

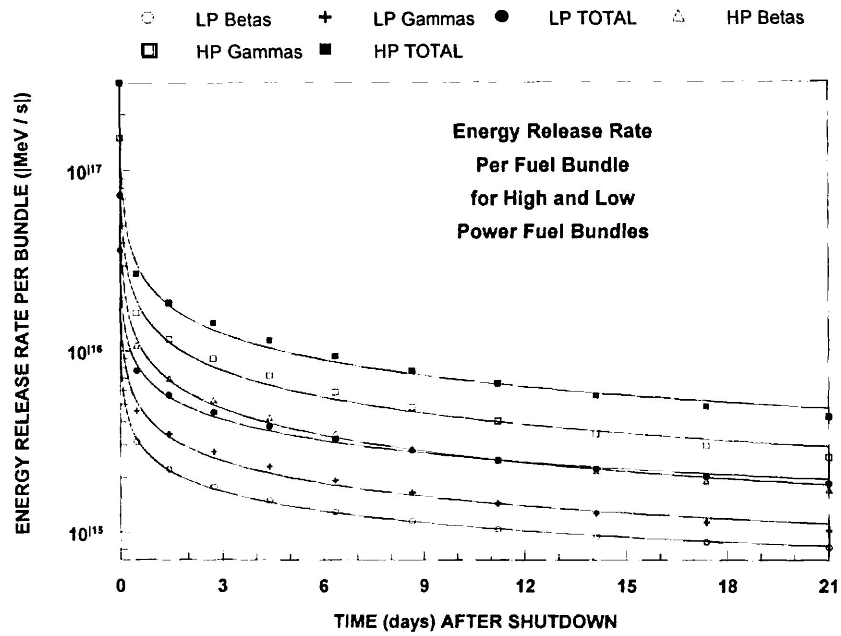

Figure 3. Energy release rates, from a single fuel bundle (high and low power), as calculated by the ORIGEN-S and BETA-S computer codes.

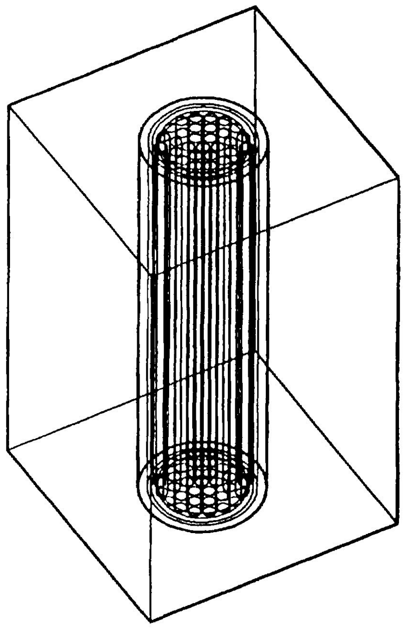

Figure 4. A three-dimensional wire-frame view of the 'modelling primitive' used to construct a 5x5x5 array of fuel bundles, for the ITS/ACCEPT Monte Carlo analysis.

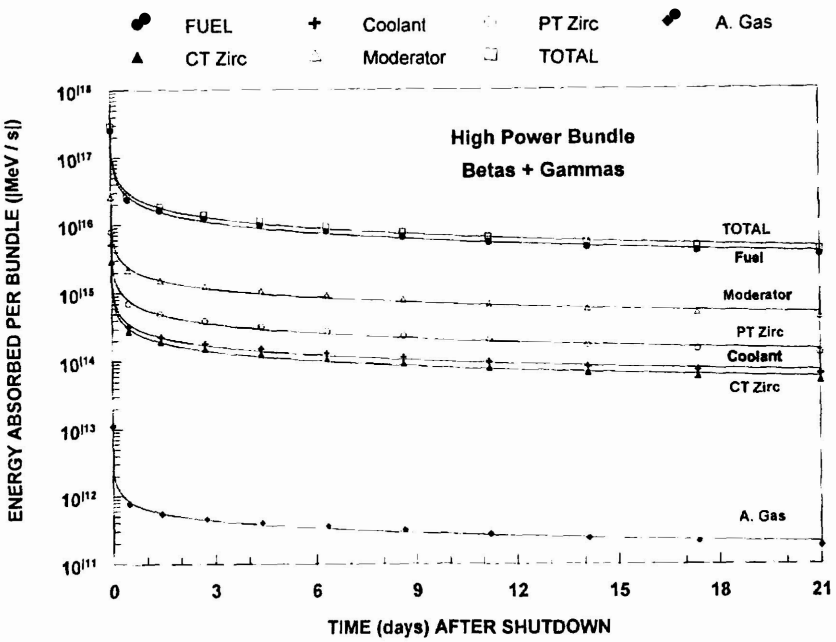

Figure 5. Results of analysis for in-core energy deposition by gamma-rays and beta particles originating from a single "high power" fuel bundle. This energy deposition rate is also equivalent to the energy deposited to the central fuel bundle and its immediate surroundings by an entire 5x5x5 matrix of high power fuel bundles.

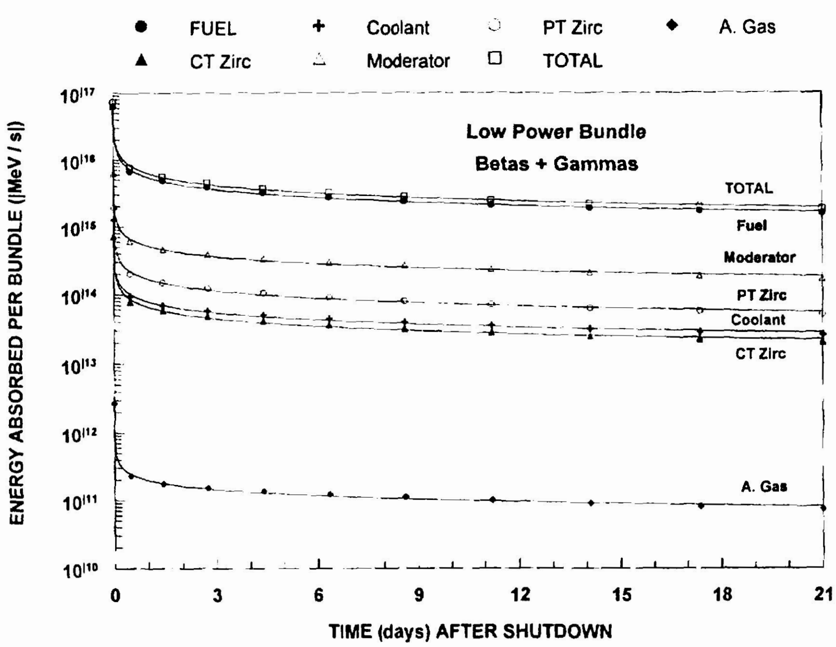

Figure 6. Results of analysis for in-core energy deposition by gamma-rays and beta particles originating from a single "low power" fuel bundle. This energy deposition rate is also equivalent to the energy deposited to the central fuel bundle and its immediate surroundings by an entire 5x5x5 matrix of low power fuel bundles.

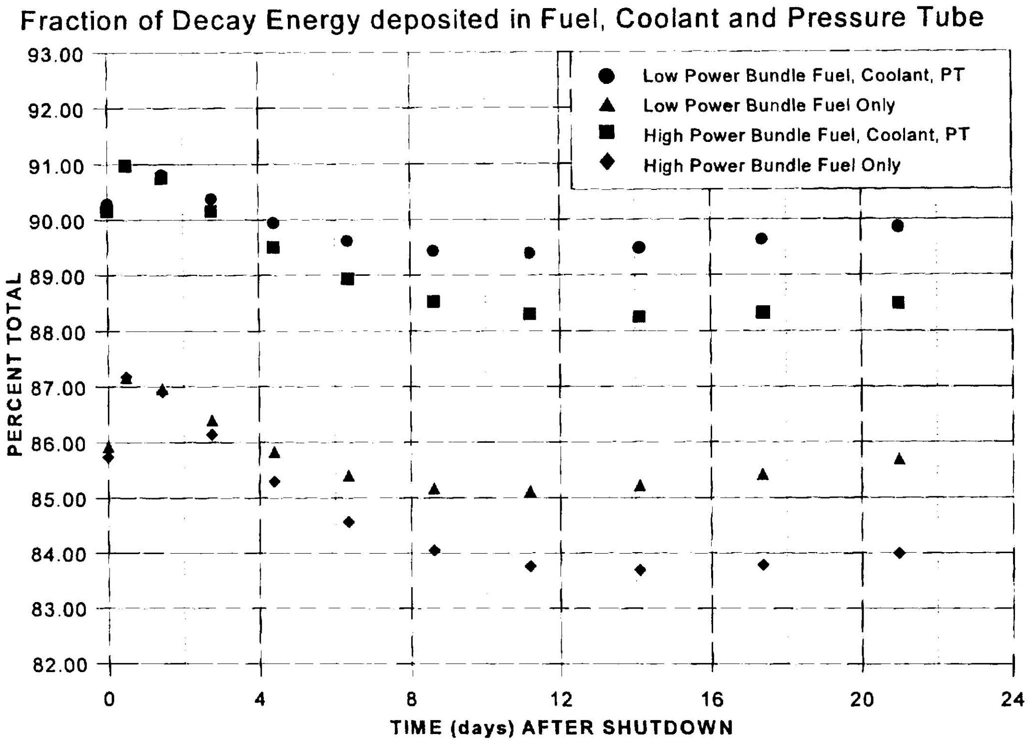

Figure 7 Short term variation in the fraction of decay energy which is deposited in the fuel, and adjacent components

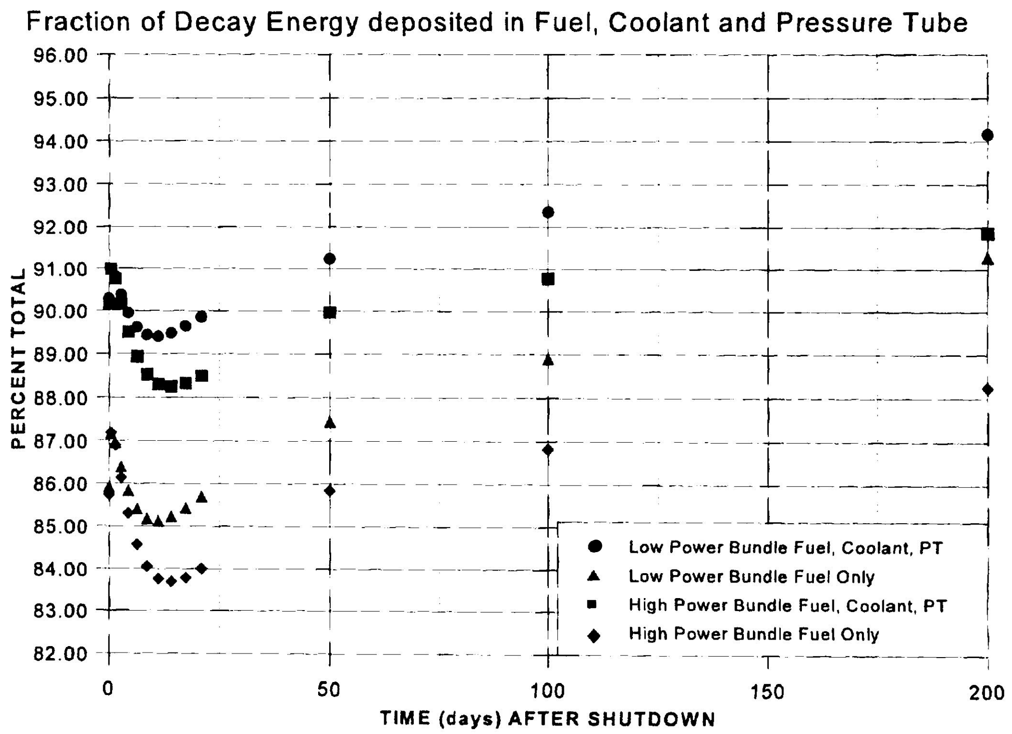

Figure 8 Longer term variation in the fraction of decay energy *which is deposited* in the fuel, and adjacent components