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EFFECTS OF CROSS-SECTION UNCERTAINTIES
IN COMPACT SPACE POWER REACTORS

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EFFECTS OF CROSS-SECTION UNCERTAINTIES IN COMPACT SPACE POWER REACTORS*

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Abstract

The effects of cross-section uncertainties have been studied in compact (20 kWe to 10 MWe) space power reactors. Three systems were considered having core sizes of 12, 78, and 525 liters and median fission energies of 560, 380, and 200 keV, respectively. Each core contained UN fuel, W-Re-Mo alloy cladding, and Li coolant within a Ta pressure vessel and BeO reflector. The cross sections of each material were perturbed 10%, and downscatter terms of each scattering matrix were increased 50%. Reactivity effects were computed for these perturbations with the ZOOM diffusion code with tight convergence. The size of perturbations was varied to demonstrate linearity. Because of hardness of the spectra, the perturbations had significant effects only above 10 keV. The additivity of groupwise and materialwise cross-section changes was examined to determine interaction between the various perturbations. Calculations were done to determine the sensitivity of the spectrum shape, fission ratios, reactivity worths, and neutron lifetime to cross-section uncertainties, and to evaluate whether measurement of such parameters in critical experiments can be useful in testing cross-section data.

Introduction

Lawrence Radiation Laboratory is studying several space reactor designs with power levels ranging from 20 kWe to 10 MWe. Because of low allowable burnups, operational reactivity losses will be small; hence, it is not planned to provide much variable reactivity control, possibly as little as 1%. The amount of shim reactivity that can be provided may be limited, and it is therefore desirable to predict criticality to high accuracy. In fact, it appears that some of the smaller systems may be criticality limited, even with fully enriched U²³⁵ fuel. This study was undertaken to determine how cross-section uncertainties affect the neutronics of the reactors under consideration.

Core volumes differ by more than an order of magnitude among the various systems. It is therefore necessary to study a range of core sizes. Three reactors were considered in this study (Table I). Each contains UN fuel, clad with an alloy of 45 a/o tungsten, 25 a/o rhenium, and 30 a/o molybdenum. The cylindrical cores are contained in tantalum pressure vessels and are reflected radially with BeO, 5 cm thick. Lithium is the coolant.

Method

Reactivity and other effects were evaluated by comparing tightly converged ZOOM [1] computations using perturbed and unperturbed cross sections. ZOOM is a diffusion code that was found to calculate values of k_{eff} differing from transport results by only a few percent, even for the smallest system considered. It was estimated that ZOOM would be sufficiently accurate for calculating the various effects of cross-section

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perturbations, including those involving changes in leakage.

The following cross-section perturbations were made: 10% reductions in σ_a , σ_f , ν , and the average cosine of the scattering angle $\bar{\mu}$; 10% increase in σ_s , and a 50% increase in the off-diagonal terms of the transfer matrix $\mu_{i \rightarrow j}$ (balanced by a decrease in the diagonal term $\mu_{i \rightarrow i}$ to preserve normalization to unity). When smaller perturbations were made, the results were found to be quite linear, thus permitting interpolation for smaller changes and extrapolation for reasonably larger changes. The cross sections were obtained from the Howerton Evaluated Library [2] and were weighted into the 16-group Hansen-Roach [3] structure using a single fast reactor spectrum typical of the three reactors.

The additivity of groupwise and materialwise perturbations on a given cross section was generally found to be quite good (~10%). Likewise, the additivity of perturbations among the different cross sections was found to be good even when all the cross sections were perturbed simultaneously. The major non-additive effects were encountered when downscatter was increased 50%, thereby affecting the shape of the spectrum appreciably.

Results

Space does not permit listing the individual effects of cross section perturbations in each material. However, the reactivity effects of perturbing the macroscopic cross sections over the entire energy range are given in Table II. The trends are as expected, the effects of $\Delta\Sigma_c$ being greatest in the large reactor with the softest spectrum and the effects of $\Delta\Sigma_s$ and $\Delta\bar{\mu}$ being greatest in the small reactor with the highest leakage. The $\mu_{i \rightarrow j}$ perturbation may have a positive or negative effect, as explained below.

The energy dependent effects of the above macroscopic perturbations are given in Table III. Owing to hardness of the neutron spectra, the lower eight groups contributed negligibly to the neutron balance, and cross section perturbations had appreciable effects only above about 10 keV. Hence, only the upper eight groups are listed. The results have been divided by the group lethargy widths to provide a better picture of the energy trends. The trends are consistent with what might be expected from perturbation theory expressions, and from the behavior of the regular spectra (Fig. 1) and adjoint fluxes (Fig. 2) in the three reactors. The groupwise reactivity effects of $\Delta\Sigma_c$ correspond approximately to the shape of $\phi(u)$, with the importance of the lower groups enhanced by the increase of Σ_c with decreasing energy. Two peaks in the $\Delta\nu$ and $\Delta\Sigma_f$ values are evident in the larger reactors, one corresponding to U^{235} , the other to U^{238} fissions. The reactivity effects of $\Delta\Sigma_s$ are generally positive because of a decrease in leakage. However, in some groups the Δk_{eff} is negative since increasing the value of Σ_s increases the scatter of neutrons to an energy of lower importance. The negative result occurs in more groups in the large reactor, where the leakage is relatively small and the adjoint spectrum decreases more rapidly with decreasing energy. The reactivity effects of increasing the $\mu_{i \rightarrow j}$ from each group i are positive or negative, depending upon the sign and relative magnitude of the difference $(\phi_j^+ - \phi_i^+)$ for downscatter to group j . Because of the adjoint spectrum shapes, the total effect (all groups i at once) can be positive or negative (Table II). The effects of perturbing $\bar{\mu}$ are especially big in the

upper groups where the scattering is highly anisotropic.

Estimates have been made of the actual cross-section uncertainties and their possible effects. It appears that over the energy range of importance in the three reactors, representative pointwise uncertainties for these materials are of the order of $\pm 20\%$ in σ_c , $\pm 2\%$ in ν , $\pm 3\%$ in σ_f , $\pm 20\%$ in σ_s , and $\pm 30\%$ in $\bar{\mu}$. In regard to uncertainties in energy transfer, it is estimated that the $\Delta\mu_{i \rightarrow j}$ is about $\pm 10\%$ for elastic scattering (corresponding to the $\pm 30\%$ uncertainty in $\bar{\mu}$). For inelastic scattering, a $\pm 50\%$ uncertainty in nuclear temperature θ is assumed. Hand perturbation calculations have shown that a 50% decrease in θ produces almost the same reactivity effect as a 50% increase in the inelastic $\mu_{i \rightarrow j}$ in the small reactor, and the same effect as a 6% increase in $\mu_{i \rightarrow j}$ in the large reactor. The reason for the different relationship between $\Delta\theta$ and $\Delta\mu_{i \rightarrow j}$ in the two reactors is attributable to the different adjoint spectrum shapes.

Using the above representative uncertainties, the absolute values of all groupwise and materialwise effects have been added to give a maximum effect for each cross section and for all cross sections combined (Table IV). It should be noted that in Table IV, inelastic scattering accounts for over 80% of the uncertainty in $\mu_{i \rightarrow j}$ in the large and medium reactors, and about 65% in the small reactor.

The results in Table IV are rather extreme and unrealistic in that no credit has been taken for cancellation of effects among the materials, different cross sections, or energy groups. Assuming no correlation of effects among materials, cross sections or energy groups, and assuming the groupwise and pointwise cross section uncertainties to be the same, the individual groupwise and materialwise reactivity effects have been statistically averaged by taking the square root of the sum of the squares (Table V). In reality it is not legitimate to take so much credit for cancellation of effects, since some compounding of errors should occur because of normalization of cross section data amongst materials and between different cross sections, or incorrectly normalizing a cross section curve at a particular energy. On the other hand, the uncertainties in group cross sections should be smaller than the pointwise uncertainties. The approach one uses to characterise such uncertainties is highly subjective, and if desired, the results in Table V can be scaled up or down for other assumed uncertainties. The uncertainties used in Tables IV and V are representative of the "average" uncertainties that might be encountered for the materials considered. Admittedly, it would be better to estimate the uncertainty at each energy for each material cross section; however, the amount of labor involved would be about as great as that in setting up an evaluated library.

Several conclusions may be drawn from Table V. First, none of the reactors is particularly sensitive to uncertainties in the downscatter matrix. This is not surprising since the adjoint spectra do not vary much over the energy range of importance in the three reactors. When the results are treated statistically, inelastic scattering accounts for about 97% of the uncertainty in $\mu_{i \rightarrow j}$ in the small and medium reactors and 71% in the large reactor. The biggest source of uncertainty in the small reactor is scattering (a leakage effect). The biggest source of uncertainty in the medium and large reactors, which have softer spectra and a higher concentration of materials which capture neutrons, is capture. The uncertainty in k_{eff} resulting from the combined estimated

cross section uncertainties is about $\pm 2\%$ for all three reactors (or $\pm 4\%$ within 95% confidence limits). A considerable improvement in the accuracy of the cross section data would be needed to reduce the uncertainty in a calculated k_{eff} to below one percent, irrespective of uncertainties from computational methods.

The signs of the macroscopic changes described above (Table II) were chosen to produce softer spectra. The resultant effects of these changes on median fission energy (MFE) are given in Table VI. It is apparent that large perturbations in scattering (Σ_s and $\mu_{i \rightarrow j}$) have an appreciable effect on the spectrum. Fission ratios were also found to be very sensitive to these perturbations, with the various threshold fission ratios changing by 20 to 40% when all the reactor cross sections were simultaneously perturbed. If actual cross section uncertainties are used and allowance is made for cancellation of effects, the sensitivity of the fission ratios (and MFE's) will be appreciably less. Their measurement could, however, be used to verify that gross errors in the cross section data (particularly inelastic scattering) do not exist. It is interesting to note that with all cross sections (except ν) perturbed as in Table VI, the reactivity effects in the small, medium, and large reactors are only 0.002, -0.0137, and -0.0424, respectively. Thus, although the spectrum may be in considerable error, the value of k_{eff} is changed only a small amount.

The uncertainty in neutron lifetime ℓ resulting from the combined estimated cross section uncertainties (Table V) is less than $\pm 5\%$ for the three reactors. This uncertainty is small compared to the disagreements that are usually reported for fast reactor lifetime measurements, possibly because this study deals with thinly reflected systems. The main change in ℓ comes from σ_s uncertainties in the small reactor (a leakage effect), from σ_c and σ_s uncertainties in the medium reactor, and from σ_c uncertainties in the large reactor. Uncertainties in energy transfer appear to have relatively little effect on ℓ .

The reactivity worths of various materials were found to be very sensitive to spectrum changes resulting from cross section perturbations in the reactor materials, as well as to perturbations in the cross sections of the reactivity samples themselves. It will be very difficult to determine whether the discrepancy between calculation and experiment is due to an incorrectly calculated spectrum or to sample cross section errors. Furthermore, if the error is definitely due to sample cross sections, it may be impossible to determine which cross sections are incorrect, except for a few cases in which one cross section contributes almost entirely to the reactivity worth (e.g. a strong absorber or fissile material).

Conclusions

Some of the major conclusions to be drawn from this study are: (1) Using "estimated" cross-section uncertainties, the value of k_{eff} can be calculated on the average to about $\pm 2\%$ for these small systems; (2) Cross-section uncertainties below about 10 keV have negligible effect; (3) The primary sources of error are scattering in the smaller systems and capture in the larger systems; (4) Because of flatness of the adjoint spectra, uncertainties in elastic and inelastic downscatter have relatively little effect; (5) The spectrum may be grossly in error, and yet the value of k_{eff} may be exact in view of the way reactivity errors cancel;

(6) Neutron lifetimes and fission ratios are not very sensitive to the estimated cross-section uncertainties. The value in measuring these quantities would be to verify the absence of gross errors in the data; (7) It will be difficult, if not impossible, to determine the source of discrepancies between calculated and measured reactivity worths.

Acknowledgment

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1. E. H. Canfield, et al., "ZOOM-II, One-Dimensional, Multi-Group, Neutron Diffusion Theory Reactor Code with Linearly-Anisotropic Corrections to Neutron Leakage for the CDC-3600 and CDC-6600 Computers," to be published.
2. R. J. Howerton, Lawrence Radiation Laboratory, unpublished.
3. Reactor Physics Constants, ANL-5800, Table 7-2 (1963).

Table I. Description of Reactors.

	Small	Intermediate	Large
Core volume (liters)	12.2	78.0	524.9
Fuel volume fraction	0.74	0.60	0.45
Fuel enrichment (a/o-U ²³⁵)	83.0	53.0	31.5
Median fission energy (keV)	560	380	200

Table II. Δk_{eff} Due to Macroscopic Cross-Section Perturbations.

Reactor size	$\Sigma_c(-10\%)$	$\nu(-10\%)$	$\Sigma_f(-10\%)$	$\Sigma_s(+10\%)$	$\mu_{i \rightarrow j}(+50\%)$	$\bar{\mu}(-10\%)$
Small	0.01308	-0.09690	-0.06291	+0.03354	+0.00667	+0.00949
Medium	0.02959	-0.09932	-0.06404	+0.02005	-0.00780	+0.00598
Large	0.03867	-0.10123	-0.06521	+0.00885	-0.02781	+0.00308

Table III. $\Delta k_{\text{eff}}/\Delta u$,^a Effects of Group Macroscopic Cross-Section Changes.

Gp	$\Sigma_c(-10\%)$	$\nu(-10\%)$	$\Sigma_f(-10\%)$	$\Sigma_s(+10\%)$	$\mu_{i \rightarrow j}(+50\%)$	$\bar{\mu}(-10\%)$	E_{lower}
Small							
1	.000701	-.00866	-.00628	.002492	-.002241	.002027	3 MeV
2	.001316	-.02211	-.01534	.009400	.002996	.003272	1.4 MeV
3	.001412	-.02304	-.01553	.009999	.003587	.002605	900 keV
4	.002494	-.02498	-.01643	.010909	.005801	.002550	400 keV
5	.003387	-.01686	-.01186	.005952	.001538	.000585	100 keV
6	.001662	-.00749	-.00309	.000429	-.000830	.000042	17 keV
7	.000441	-.00084	-.00044	-.000062	-.000150	.000010	3 keV
8	.000042	-.00004	-.00002	-.000006	-.000006	.000000	550 eV
Intermediate							
1	.000930	-.00765	-.00517	.000160	-.006510	.001100	
2	.002056	-.01910	-.01239	.002771	-.009116	.001956	
3	.002664	-.01769	-.01154	.005246	-.001756	.001340	
4	.005107	-.02216	-.01445	.007022	.001386	.001782	
5	.009527	-.02228	-.01420	.005516	.005719	.000517	
6	.003800	-.00952	-.00546	-.000677	-.001038	.000052	
7	.000664	-.00111	-.00069	-.000028	-.000137	.000001	
8	.000039	-.00007	-.00003	.000000	-.000003	.000000	
Large							
1	.00082	-.00566	-.00369	-.001150	-.00746	.00042	
2	.00165	-.01375	-.00854	-.001273	-.01336	.00079	
3	.00224	-.01032	-.00652	-.000194	-.00265	.00052	
4	.00472	-.01507	-.00890	.004080	.00095	.00092	
5	.01034	-.02476	-.01559	.004070	.00016	.00053	
6	.00786	-.01637	-.01029	.000570	-.00332	.00007	
7	.00146	-.00212	-.00154	-.000030	-.00033	.00000	
8	.00006	-.00007	-.00006	.000000	.00000	.00000	

^aResults normalized to equal lethargy widths.

Table IV. Maximum Effects (Δk_{eff}) of Estimated Cross-Section Uncertainties.

Reactor size	σ_c (20%)	ν (2%)	σ_f (3%)	σ_s (20%)	$\mu_{i \rightarrow j}$ (see text)	$\bar{\mu}$ (30%)	Combined Δk_{eff}
Small	0.0262	0.0194	0.0189	0.0671	0.01365	0.0285	0.174
Medium	0.0592	0.0197	0.0192	0.0410	0.01525	0.0179	0.172
Large	0.0773	0.0202	0.0196	0.0241	0.00433	0.0090	0.155

Table V. Statistically Averaged Effects (Δk_{eff}) of Estimated Cross-Section Uncertainties.

Reactor size	σ_c (20%)	ν (2%)	σ_f (3%)	σ_s (20%)	$\mu_{i \rightarrow j}$ (see text)	$\bar{\mu}$ (30%)	Combined Δk_{eff}
Small	0.00702	0.00784	0.00786	0.01206	0.00316	0.00660	0.0193
Medium	0.01572	0.00814	0.00777	0.00736	0.00354	0.00351	0.0213
Large	0.01726	0.00900	0.00834	0.00466	0.00116	0.00192	0.0218

Table VI. Values of Median Fission Energy (keV) with Various Macroscopic Cross-Section Perturbations.

Reactor size	Unpert.	Σ_f (-10%)	Σ_c (-10%)	Σ_s (+10%)	$\mu_{i \rightarrow j}$ (+50%)	$\bar{\mu}$ (-10%)	All Σ 's changed
Small	560	545	545	525	408	560	347
Medium	380	358	362	340	253	380	209
Large	200	190	186	178	133	200	105

Figure Captions

Figure 1. Neutron spectra in the small, intermediate, and large reactors.

Figure 2. Adjoint group fluxes in small, intermediate, and large reactors.

Figure 1 Brown

Figure 2 Brown

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