OSR 24-A117
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DPST-71-566-TL

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SAVANNAH RIVER LABORATORY
AIKEN, SOUTH CAROLINA 29801

(TWX: 810-771-2670, TEL: 803-824-6331, WU: AUGUSTA, GA.)

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A. A. Johnson, Wilm.
S. A. McNeight
C. H. Ice - L. H. Meyer, SRL
G. Dessauer - P. L. Roggenkamp
S. W. O'Rear - TIS File

January 24, 1972

Mr. N. Stetson, Manager
Savannah River Operations Office
U. S. Atomic Energy Commission
Aiken, South Carolina 29801

Dear Mr. Stetson:

Attached are 33 copies of DPST-71-566, One-Dimensional Axial Xenon Oscillation Calculations. This is the final report of the work we have done for the Division of Reactor Licensing on xenon oscillations in power reactors. As indicated on the distribution of the report, 30 copies are for the Division of Reactor Licensing for redistribution.

The report shows that one-dimensional calculations can be used to derive xenon oscillation characteristics with adequate precision if the reduction of the applicable three-dimensional flux shape to a one-dimensional shape is made with the suggested procedure.

Very truly yours,

Original signed by
C. H. Ice

C. H. Ice, Director

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CC: L. C. Evans - J. W. Croach -
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December 8, 1971

Mr. A. F. Westerdahl, Chief
Patent Branch
Savannah River Operations Office
U. S. Atomic Energy Commission
Aiken, SC 29801

Dear Mr. Westerdahl:

REQUEST FOR PATENT REVIEW

Please review for patent matter:

DPST-71-566, "One-Dimensional Axial Xenon Oscillation Calculations" by V. D. Vandervelde.

This paper reports work done for the Division of Reactor Licensing, USAEC, and will be sent through SROO to DRL for further distribution.

If any technical clarification is needed please call H. S. Hilborn, whose Document Review is attached.

Please telephone your comments to the TIS office (ext. 3598) and notify me by signing and returning to TIS the original of this letter. A copy is provided for your file.

If you decide to pursue a patent on any development covered, I shall be happy to supply additional information required such as appropriate references and the names of persons responsible for the development.

Very truly yours,

J. W. Croach, Director
Technical Division

By: [redacted]
H. S. Hilborn

The above item is approved for release.

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P. L. Roggenkamp, Research Manager
Theoretical Physics Division
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Author(s): **V. D. Vandervelde**

Contractual Origin: AT(07-2)-1

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December 10, 1971

Mr. N. Stetson, Manager
Savannah River Operations Office
U. S. Atomic Energy Commission
Aiken, South Carolina 29801

Dear Mr. Stetson:

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The report shows that one-dimensional calculations can be used to derive xenon oscillation characteristics with adequate precision if the reduction of the applicable three-dimensional flux shape to a one-dimensional shape is made with the suggested procedure.

Very truly yours,

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C. H. Ice, Director

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by

V. D. Vandervelde

Approved by

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Theoretical Physics Division

December 1971

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CONTRACT AT(07-2)-1 WITH THE
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INTRODUCTION

Many large reactors may be subject to spatial oscillations in the power distribution caused by redistribution of xenon poison. To enable a power reactor to operate, the susceptibility of the reactor core to xenon oscillations must be determined, and, if the core is susceptible to undamped oscillations, a control mechanism and strategy must be available.

Susceptibility and control strategy can be determined by calculation. Precise calculation of a reactor core requires a three-dimensional (3-D) representation. A 3-D calculation is very expensive in computer time, and this expense is multiplied by several orders of magnitude to follow a xenon oscillation. If a one-dimensional (1-D) calculation could be used, the computer time saving would be great and in many cases oscillation characteristics, determined without calculating the actual flux oscillations, would be useful.

In 1958, Randall and St. John[1] derived equations in one dimension that yield the flux at which sustained oscillations occur with flat flux shapes over the central region of the reactor. These equations were expanded in DPST-68-372[2] to include growing and damped oscillations and flux shapes, which are "dished" or "humped." The results are presented as a series of curves dependent upon the neutron flux level and the flux shape factor as well as a number of reactor parameters that account for material composition and reactor size. It is desired to determine the degree to which these curves are applicable.

A series of xenon oscillation experiments[3] were designed and conducted at the Savannah River Plant (SRP) to determine the accuracy of various calculational techniques. The results of the axial experiments were found to be adequately reproduced with 3-D calculations.[4] The starting equilibrium axial flux shape, during the experiments, differed appreciably with radius and exemplified the problem of finding a single axial flux shape for a 1-D calculation. Although specific spatial detail may be obtained with 3-D xenon oscillation calculations, it is often desirable to obtain approximate results quickly with 1-D calculations. Because the shape is very important to the 1-D calculations, a study was initiated to determine if some simple scheme could be found to reduce the 3-D nonseparable flux to a single 1-D flux for assessing susceptibility to xenon oscillations.

Although xenon oscillations can occur in any dimension of space, this discussion will be limited to the first harmonic in the axial dimension of cylindrical reactors.

SUMMARY

A series of axial xenon oscillation calculations were made using similar 3-D and 1-D models. Cases were chosen to include a variety of 3-D flux shapes where the axial shape changed as a function of radius. 1-D axial flux shapes were obtained by averaging the flux at each axial layer by two methods, volume weighting and flux-volume weighting.

For H_2O reactors, the simple volume weighting ($W = 1$) gave slightly more accurate results than the flux-volume weighting ($W = \phi$). For the shapes considered, the 1-D calculations with either weighting indicated a greater degree of instability than the 3-D calculations.

For D_2O reactors, the two weightings are equally good, although the $W = \phi$ weighting gave a better result for a very unstable system.

These results can be used to apply the xenon oscillation calculations graphed parametrically in Reference 2 by following the procedure on page 9.

DISCUSSION

3-D xenon oscillation calculations adequately reproduce experimental results.[4] In this report, 3-D calculations are the standard against which 1-D calculations are compared. XHERC, a Savannah River Laboratory (SRL) code described in Appendix A for calculating xenon oscillations in 1, 2, or 3 dimensions, was used for the study. The calculational procedure involved obtaining a 3-D equilibrium flux shape assumed to exist before a perturbation is applied. A 3-D xenon oscillation was calculated with XHERC to obtain the flux behavior with time and the associated damping factor. The 3-D equilibrium flux shape was then reduced to the 1-D fluxes with two weighting functions. A xenon oscillation was calculated for each of the 1-D shapes, and the damping factor was compared with the 3-D results.

The damping factor is defined as the ratio of the change in flux from equilibrium at the peak of an oscillation to the change in flux from equilibrium at the peak one cycle later. Oscillations with damping factors less than 1.0 grow with time, and damping factors greater than 1.0 represent damped oscillations.

To reduce the 3-D flux shape to a 1-D shape, the flux at each axial layer $\phi(z)$ was obtained from the equation:

$$\phi(z) = \frac{\int_V \phi(r,z) \cdot W(r) dv}{\int_V W(r) dv}$$

where ϕ is the pointwise 3-D flux, and W is the weighting function. Since the volume element can be expressed in terms of $\Delta z \cdot 2\pi r \cdot dr$,

$$\phi(z) = \frac{\int_R \phi(r,z) \cdot W(r) \cdot rdr}{\int_R W(r) \cdot rdr}$$

Two functions were chosen for evaluation. The simple volume weighted flux is obtained when all W(r) = 1

$$\phi_V(z) = \frac{\int_R \phi(r,z) \cdot rdr}{\int_R rdr}$$

and the flux-volume weighted flux is obtained when each $W(r) = \phi(z,r)$

$$\phi_{\phi V}(z) = \frac{\int_R \phi^2(z,r) \cdot rdr}{\int_R \phi(z,r) \cdot rdr}$$

The study was made by repeating the above procedure with several radial power shapes chosen to accentuate the worth of the weighting functions, for two reactor types. Figure 1 shows the relative powers for each of five cases. The first three cases have material properties and dimensions that represent a D_2O-moderated reactor; the power level was constant among the three cases. The last two cases have material properties, dimensions, and power level, which are appropriate to a present generation PWR. Figure 2 shows the plots of the 1-D equilibrium axial fluxes using the two weighting functions.

A sixth case was calculated using the same flux shape as Case 5 but with the total reactor power (and therefore the flux level at every point) reduced 5/8 to produce an oscillation nearer the threshold.

Table 1 contains the results, a comparison of the damping factors from the 3-D calculation and 1-D calculations using volume weighted fluxes (W = 1), and flux-volume weighted fluxes ($W = \phi$). The 1-D damping factors agree reasonably well with the 3-D damping factors except for Case 3, W = 1. $W = \phi$ gave the better agreement for D_2O-moderated reactors whereas W = 1 gave better agreement for H_2O-moderated reactors.

A comparison of the damping factors does not necessarily convey a meaningful understanding of the accuracy of the 1-D calculations. To examine the accuracy further, changes in two parameters, the reactor power and the flux shape factor (Λ),* that would produce agreement of the 1-D with the 3-D calculations were determined. The changes were evaluated from the curves in Reference 2 and are listed in Table 1. For the weightings cited in the preceding paragraph as giving better results, the changes are ≤10%. In an operating core, the precision with which the power is known and the flux can be determined from the power is smaller than this change. However, in the case of the flux shape factor, the 10% change is smaller than the precision with which the parameter is known for an operating reactor core.

TABLE 1

CALCULATED DAMPING FACTORS

Case	Reactor Type	Radial Power Shape	3-D Damping[a] Factor	1-D; W = 1 Damping[a] Factor	1-D; W = 1 % Change[b] Power	1-D; W = 1 % Change[b] Λ	1-D; W = φ Damping[a] Factor	1-D; W = φ % Change[b] Power	1-D; W = φ % Change[b] Λ
1	SRP	Flat	0.88	1.01	+7	-3	0.78	-6	+3
2	SRP	Dished	2.12	1.85	-8	+3	1.98	-5	+1
3	SRP	Humped	0.15	0.44	+73	-15	0.12	-7	+2
4	PWR	Humped	0.42	0.30	-7	+7	0.13	-26	+24
5	PWR	Flat	0.32	0.18	-11	+12	0.09	-21	+28
6	PWR	Flat	1.54	1.03	-10	+11	0.63	-19	+24

a. Damping factor is the ratio of the change in flux from equilibrium at the peak of an oscillation to the change in flux from equilibrium at the peak one cycle later.

b. Percent change in the indicated parameter required to make the 1-D damping factor agree with the 3-D damping factor.

* Λ is the factor that multiplies the geometric buckling to obtain the added buckling for the first harmonic of the fundamental flux shape (see Reference 2).

To utilize the curves of Reference 2 to estimate the xenon stability of a reactor core, the following procedure will give a conservative result:

- Determine the expected 3-D equilibrium flux shape and reduce it to the corresponding 1-D flux shape with the appropriate weighting function.
- From the power and the 1-D shape determine the flux as per Reference 2.
- From the 1-D shape determine Λ per Reference 2. Arbitrarily reduce Λ by 10%.
- Determine the necessary parameters and enter the curves of Reference 2 to obtain the damping factor.

REFERENCES

1. D. Randall and D. S. St. John. "Xenon Spatial Oscillation." *Nucleonics 16(3)*, 82 (1958).
2. V. D. Vandervelde. *Xenon Oscillation Dependence on Reactor Parameters*. E. I. du Pont de Nemours and Co., Savannah River Laboratory, Aiken, S. C. DPST-68-372 (May 1968).
3. S. V. Topp, R. F. Byars, and R. P. Germann. "Xenon Oscillation Experiments in a Production Reactor." *Nucl. Sci. Eng. 42*, 239 (1970).
4. V. D. Vandervelde. *Analysis of Xenon Oscillation Experiments*. E. I. du Pont de Nemours and Co., Savannah River Laboratory, Aiken, S. C. DP-1251 (August 1971).

EQN/shc

Case 1
SRP Flat

764 764 757 764

828 828 831 746 749 816 743 672

932 926 837 835 808 764 703 720 664

886 883 900 889 865 826 761 763 721

935 924 920 915 904 900 862 892 814 757 695

951 944 939 932 922 904 869 934 869 781 717

960 955 952 945 935 921 902 885 823 815 749

971 967 963 959 953 949 943 950 918 841

977 974 971 967 964 962 958 961 916

982 980 977 974 974 969 959

988 987 984 981 978 976 967

992 990 987 984 979

995 992 989 984

998 996 993

999 998 996

1000

Case 2
SRP Dished

895 885 860 853

943 935 922 798 795 887 822 761

1000 983 859 848 827 797 756 816 777

869 858 869 863 855 841 811 868 848

856 838 832 834 840 863 864 960 924 888 830

800 790 793 804 822 843 857 992 969 906 853

728 727 750 772 802 836 869 904 884 934 885

676 671 680 701 733 786 835 896 918 893

622 626 642 670 714 777 832 891 907

581 593 616 652 712 767 818

544 552 569 598 639 699 752

519 532 554 586 628

503 520 545 580

483 495 516

472 480 495

468

Case 3
SRP Humped

261 265 270 280

298 301 310 293 297 311 275 239

371 374 354 356 340 312 274 257 226

405 409 418 407 385 352 303 273 244

474 473 470 461 442 421 379 351 295 259 230

539 538 527 507 480 443 394 379 325 273 239

615 608 583 553 516 471 424 383 328 291 252

685 684 669 640 601 549 500 462 409 341

754 744 721 684 635 574 522 479 415

812 793 761 716 652 592 534

870 857 831 791 737 669 605

910 890 856 809 751

937 910 869 817

972 951 917

993 979 951

1000

FIGURE 1 Radial Power Shapes

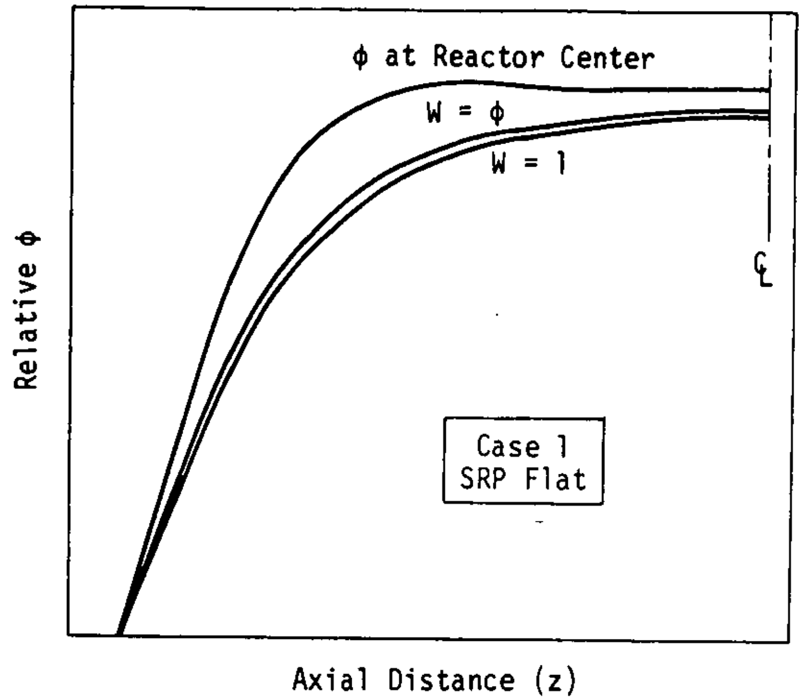
Case 4
PWR Humped

200 199 185 151
339 346 338 314 272 224 174 123
482 484 470 441 398 345 284 211 124
602 598 588 555 509 450 376 286 180
704 708 700 678 642 599 533 450 350 239 128
794 793 781 755 715 660 588 507 402 286 164
855 850 842 813 770 710 635 543 435 319 190
906 906 897 877 845 807 746 667 572 461
944 941 928 906 872 824 761 690 593
962 955 948 924 889 840 777
980 977 968 952 927 899 851
990 985 975 958 934
990 984 978 962
995 992 986
999 996 992
1000

Case 5
PWR Flat

312 317 301 249
502 524 526 499 440 369 291 207
677 697 699 676 625 555 465 349 205
759 775 825 805 762 694 592 457 289
828 844 855 853 834 844 774 671.534 369 199
898 907 909 898 876 833 766 713 582 427 251
938 942 944 928 898 849 782 692 578 467 291
965 969 968 958 938 911 862 794 709 608
987 987 982 970 947 913 865 810 734
992 991 990 976 953 921 878
998 997 994 987 974 959 930
1000 999 996 989 977
997 996 996 991
997 996 996
997 997 997
997

FIGURE 1 (Continued)



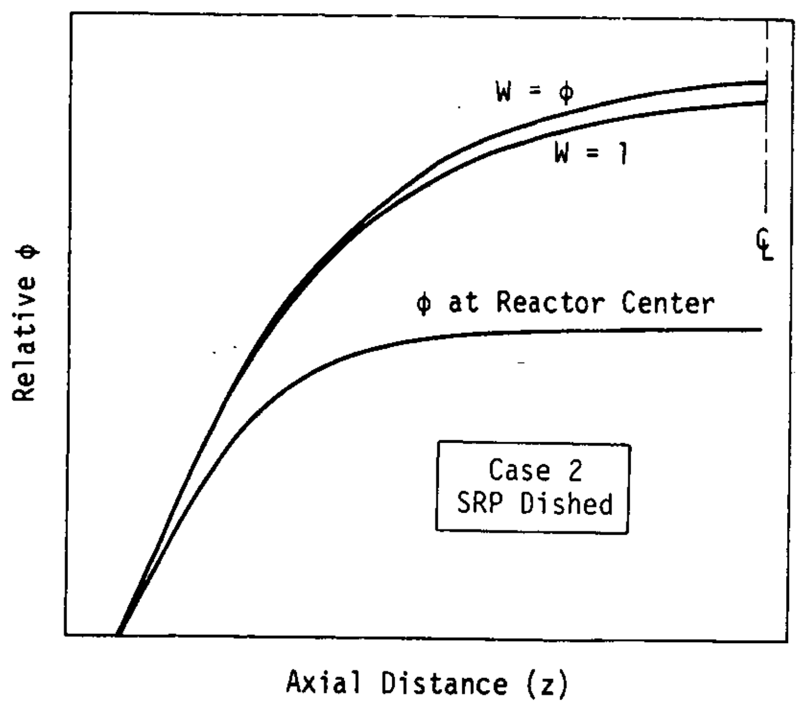


FIGURE 2 1-D Axial Flux Shapes

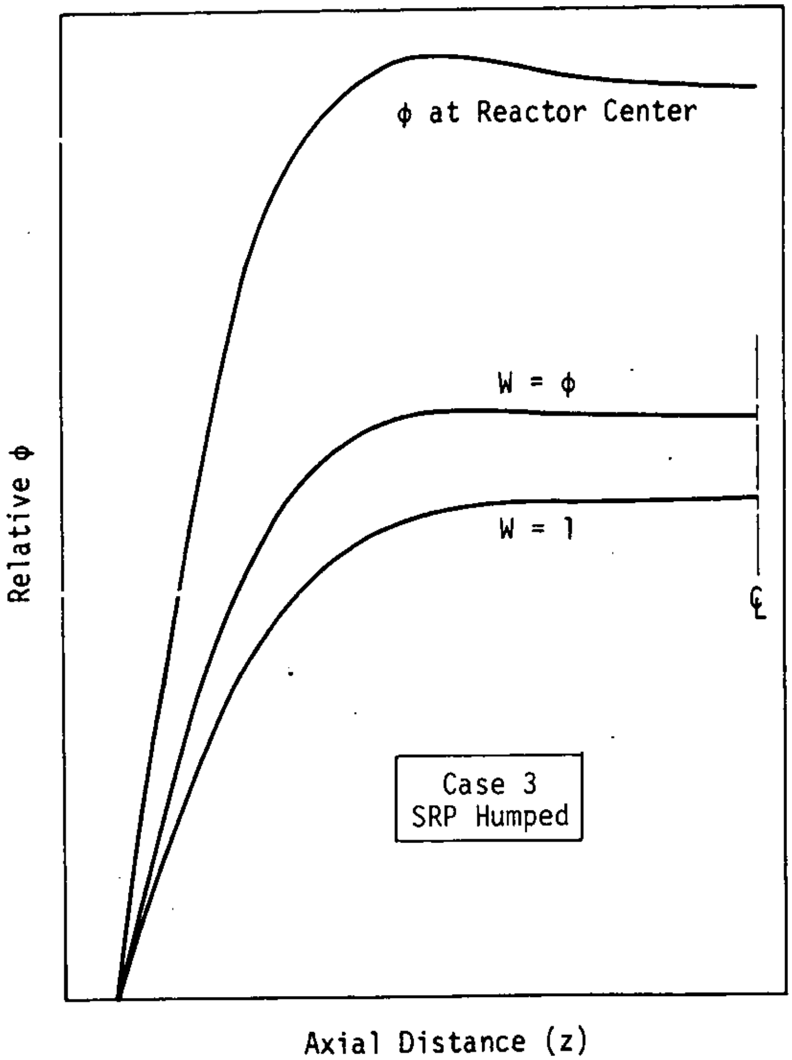
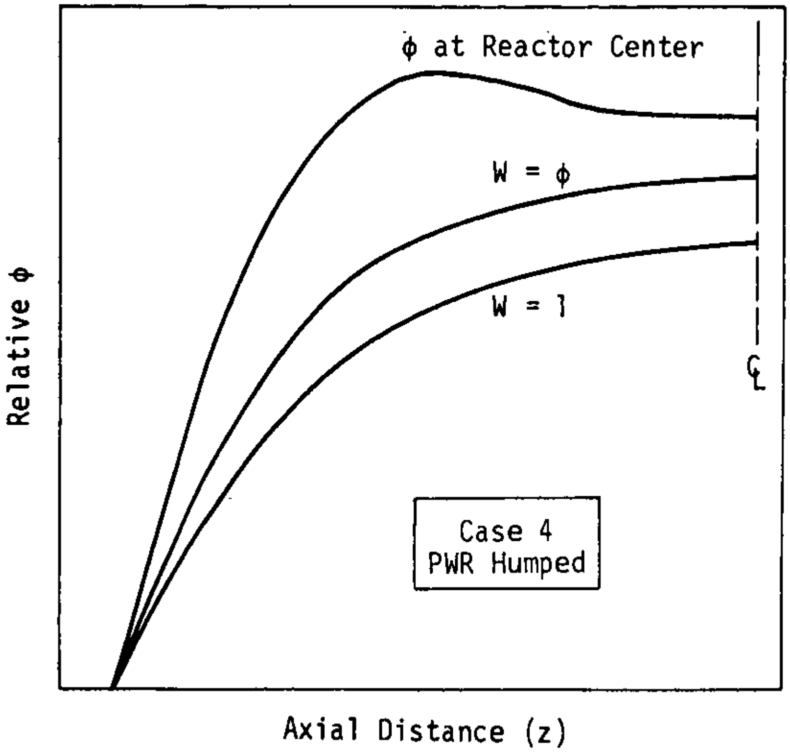


FIGURE 2 (Continued)



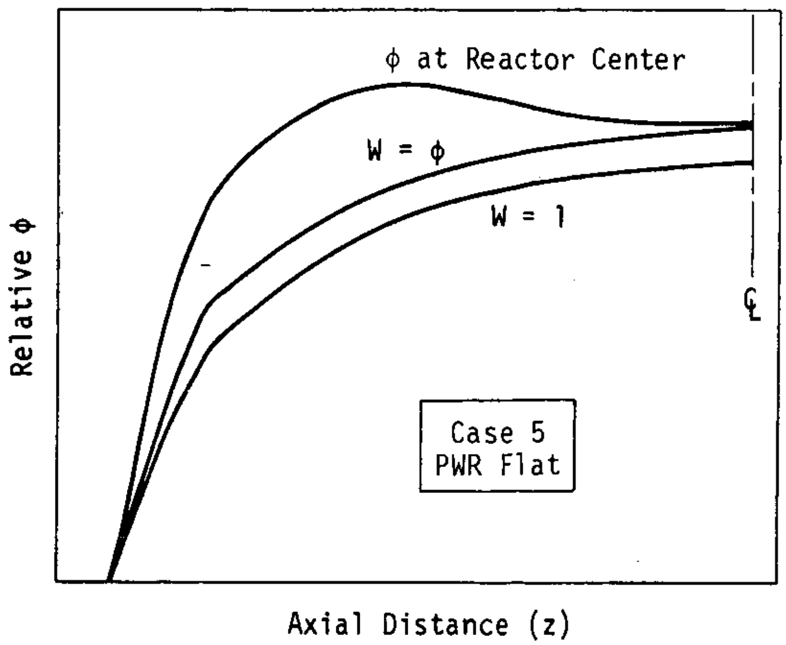


FIGURE 2 (Continued)

APPENDIX A

XHERC is a code that calculates three-dimensional xenon oscillations in SRP reactors. HERC (Appendix B) is used as a subroutine to calculate the neutron flux distribution. The code first calculates the equilibrium neutron flux and the ^{135}Xe and ^{135}I concentrations. This initial reactor state is perturbed by changing the material properties in any number of regions, and a new neutron flux distribution is calculated. The code then steps through time calculating xenon and iodine with constant flux during a time interval and, using the revised concentrations, calculates a new flux shape for each time step.

A second perturbation may be introduced after some number of time steps. For the present set of calculations, this perturbation was applied after six time steps (each time step was 0.25 hr) for the purpose of returning all material properties to their initial value. The first perturbation changed the material properties to be axially nonsymmetric, and the second perturbation returned the properties to the initial symmetric distribution.

The number of iterations required for the flux to converge during a HERC calculation is dependent upon the accuracy of the flux guess for the first iteration. XHERC contains a subroutine which examines the flux after successive time steps and uses, as a guess for the next time step, an extrapolated shape based on the relative change in flux at an arbitrary point for the last three time steps. The total running time was significantly reduced by using this procedure.

In the present version, HERC has been modified to accept feedback through the thermal absorption cross section, which changes at every mesh point proportional to the changing xenon concentration. The prompt temperature coefficient is simulated by a change in thermal absorption cross section proportional to the change in neutron flux from the initial value.

Total reactor power was held constant during each set of calculations, and the radial power shape was observed to stay constant (within 0.1%) throughout an oscillation. The eigenvalue was held constant at unity by a uniform poison search for all calculations.

APPENDIX B

HERC is a three-dimensional, few-group neutron diffusion code in hexagonal geometry which calculates the space dependent, steady state neutron flux in a reactor. The code assumes a hexagonal mesh in the X-Y plane with constant mesh spacing and a single mesh point at the center of each hex. The axial dimension assumes a number of such layers, one precisely below the other, separated by a constant distance.

The solution may be either an eigenvalue problem or a poison search. If a poison search is desired, it is made on the thermal absorption cross section of either a selected material or all materials uniformly.

The geometric model allows the calculation to be performed over only those azimuthal sectors and those axial layers of interest when azimuthal or axial symmetry exists. If, for instance, it is desired to calculate a case which has 60° azimuthal symmetry, only one sector need be calculated and the running time is reduced accordingly. The scheme allows flexibility in the amount of detail one may calculate for a given problem. If fine detail in the axial flux shape is desired (many axial layers), it may be obtained at the sacrifice of the number of sectors (and/or energy groups) used. The size limitation of the version being discussed here is that the product of the number of layers times the number of sectors times the number of energy groups must be less than 49.

The calculations discussed in this report all used 24 axial layers, 1 sector, and 2 energy groups. The material properties were initially placed axially symmetric with respect to the midplane (between layers 12 and 13) to yield axially symmetric equilibrium flux shapes.