Performance characteristics for optimized core module of liquid metal fast breeder reactor

Satoshi Minakuchi
Iowa State University

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Performance characteristics for optimized core module of liquid metal fast breeder reactor

by

Satoshi Minakuchi

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Approved:

In Charge of Major Work

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For the Graduate College

Iowa State University
Ames, Iowa
1972
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GLOSSARY OF PRINCIPAL SYMBOLS

The section numbers give the location of a more detailed definition or of the main use of a recurring symbol.

English letters

\( A \) area in the \( \gamma-\theta \) space II-A

\( A_i \) absorption rate for fissile isotope \( i \) II-B

\( A_i^n \) absorption rate of nuclide \( i \) in region \( n \) II-B

\( A_{i,j} \) exponents of \( D_i \) involved in a physical quantity \( x_j \) II-C

\( B^2 \) geometrical buckling III-B

\( B_{i,n} \) individual breeding ratio in region \( n \) II-B

\( BR \) total breeding ratio II-B, IV-A, B

\( C \) evaluated coefficient of the prediction function II-C

\( c \) coefficient of numerical solution II-A

\( C_j \) capture rate for fertile isotope \( J \) II-B

\( C_{i-1}^n \) capture rate of nuclide \( i-1 \) in region \( n \) (i.e., production rate of nuclide \( i \)) II-B

\( c \) any components involved IV-B

\( c' \) any components except fuel enrichments IV-B

\( D \) diffusion coefficient II-A, III-B

\( D_g \) diffusion coefficient for group \( g \) II-A

\( D_i \) basic dimension II-C

\( d \) extrapolation distance III-B

\( d \) direction unit vector II-D

\( e_i \) critical enrichment of fuel in region I (inner core) IV-B
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</tr>
<tr>
<td>( \nu^* )</td>
<td>average number of neutrons produced per fertile fission</td>
<td>II-B</td>
</tr>
<tr>
<td>( \nu_g )</td>
<td>average number of neutrons related per fission occurring in group ( g )</td>
<td>II-A</td>
</tr>
<tr>
<td>( \xi )</td>
<td>outer iteration index (superscript)</td>
<td>XI-B</td>
</tr>
<tr>
<td>( \pi )</td>
<td>non-dimensional parameter</td>
<td>II-C</td>
</tr>
<tr>
<td>( \pi_1 )</td>
<td>= BR</td>
<td>IV-B</td>
</tr>
<tr>
<td>( \pi_2 )</td>
<td>= ( \lambda_1 / H )</td>
<td>IV-B</td>
</tr>
<tr>
<td>( \pi_3 )</td>
<td>= ( \lambda_2 / H )</td>
<td>IV-B</td>
</tr>
<tr>
<td>( \pi_4 )</td>
<td>= ( \lambda_3 / H )</td>
<td>IV-B</td>
</tr>
<tr>
<td>( \pi_5 )</td>
<td>= 4( \theta )</td>
<td>IV-B</td>
</tr>
<tr>
<td>( \pi_6 )</td>
<td>= ( e_{\Gamma} )</td>
<td>IV-B</td>
</tr>
<tr>
<td>( \pi_7 )</td>
<td>= ( e_{\Pi} )</td>
<td>IV-B</td>
</tr>
<tr>
<td>( \Sigma_a )</td>
<td>macroscopic absorption cross section</td>
<td>II-A</td>
</tr>
<tr>
<td>( \Sigma_c )</td>
<td>macroscopic capture cross section</td>
<td>II-B</td>
</tr>
<tr>
<td>( \Sigma_f )</td>
<td>macroscopic fission cross section</td>
<td>II-B, XI-B</td>
</tr>
</tbody>
</table>
Greek letters (Continued)

$\Sigma_{g'\to g}$ macroscopic transfer cross section from group $g'$ to group $g$  

$\Sigma^r_g$ group $g$ averaged macroscopic removal cross section  

$\Sigma_m$ macroscopic cross section for mixture $m$  

$\Sigma_s$ macroscopic scattering cross section  

$\Sigma_t$ macroscopic total cross section  

$\Sigma_{tr}$ macroscopic transport cross section  

$\sigma$ any cross section of materials involved  

$\sigma_i$ microscopic cross section for material $i$  

$\phi$ neutron flux  

$\phi_g$ group $g$ scalar flux  

$\psi(x,K)$ penalty function  

$\zeta$ any pertinent angle  

$\chi_g$ fraction of fission neutron born in group $g$  

Abbreviations

BR breeding ratio  

CBBR core and radial blanket breeding ratio  

Den denominator  

EBR external breeding ratio  

IB inner radial blanket  

IBR internal breeding ratio  

IC inner core
### Abbreviations (Continued)

- **LHS** left hand side  
  - IV-B
- **Num** numerator  
  - IV-B
- **OB** outer radial blanket  
  - all over
- **OC** outer core  
  - all over
- **RHS** right hand side  
  - IV-B
- **SB** separating blanket  
  - all over

### Conventional symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>( \bar{\pi}_1 )</td>
<td>upper-bar denotes constant value</td>
<td>II-C, IV-C</td>
</tr>
<tr>
<td>( \hat{\pi}_1 )</td>
<td>under-bar of the subscript denotes only ( \pi_1 ) be variable</td>
<td>IV-C</td>
</tr>
<tr>
<td>( \nabla F(\hat{x}) )</td>
<td>gradient vector</td>
<td>II-D</td>
</tr>
<tr>
<td>( \langle f \rangle )</td>
<td>bracket function means ( \langle f \rangle = f ) for ( f \geq 0 ) or ( \langle f \rangle = 0 ) for ( f &lt; 0 )</td>
<td>II-D</td>
</tr>
<tr>
<td>( \langle \hat{u}, \hat{v} \rangle )</td>
<td>inner product of two vectors</td>
<td>II-D</td>
</tr>
<tr>
<td>( \approx )</td>
<td>test the equivalence</td>
<td>II-C</td>
</tr>
<tr>
<td>( \equiv )</td>
<td>dimensional equivalence</td>
<td>II-C</td>
</tr>
<tr>
<td>( (\ )_{NxN} )</td>
<td>NxN matrix</td>
<td>II-A</td>
</tr>
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</table>
I. INTRODUCTION

A. Review of LMFBR

Before the overall potential and the unique features of fast breeders were evaluated with PuO₂-UO₂ as fuel around 1960, such reactors were in effect the "first generation" of fast breeders [43]. The historical descriptions for fast reactor developments presented by Hafele [43] and Wensch [92] are significant. According to these references, we are now in the "second generation" of fast breeders, and a tremendous amount of technology has been developed in the past 10 years. Some of the main events during the developing process are, for example, the fast reactor ceramic fuel which received world-wide attention after the Vienna Conference of 1961, and the subject of the Doppler coefficient which led to major undertakings by many research groups resulting in the sodium void coefficient becoming one of the most important subjects. Many problems like these have appeared during the time in which breeders were developed; however, many of these were solved through international cooperation.

Now the time has arrived in which one can say, "The breeder is the nation's highest priority energy program" [26], "Fast reactors should and could be economically available by the end of the 1970's" [43], or "It will be possible to have breeder reactors generating electric power on a commercial scale by 1984" [79]. From these powerful slogans, the "second
generation" developing period might be over. When President Nixon stated, "Our best hope today for meeting the nation's growing demand for economical clean energy lies with the fast breeder reactor", in 1971 [26], the "third generation", fast breeders' construction epoch, had to begin.

In the "first generation", the physical concepts of breeding in fast reactors had been confirmed with the research reactors such as EBR-I and -II, EFPBR (above three USA), DFR (UK), and BR-1, -2, -5 (USSR). In the "second generation" large scale fast reactors may be designed as a result of the successful tests of materials and developing of highly accurate calculation techniques. And then, in the "third generation", commercial scale fast breeder reactors will be constructed.

In 1965, the USAEC proposed the Liquid Metal Fast Breeder Reactor (LMFBR) Program, using sodium coolant as the priority effort which would lead to large-scale commercial acceptance of the breeder [26]. The details of the LMFBR program plan are stated by the AEC [58, 59, 60, etc.]. At this moment, one question - why LMFBR were selected for this nation-wide research project instead of other fast breeder reactors such as gas-cooled reactors or steam-cooled reactors - naturally arises.

A highly qualified choice for the best type of fast breeder reactor is still not concluded even in the Fourth International Geneva Conference [78]. The U.S. development
programs of High Temperature Gas-cooled Reactor (HTGR), Molten Salt Breeder Reactor (MSBR) and some other advanced power reactors were reported in the Geneva Conference by Shaw [82]. Shaw also simply mentioned that the LMFBR produces plutonium with low doubling times, operates at high thermal efficiencies, and inherently possesses capabilities to significantly reduce radioactive releases while producing much needed electricity. Another article [79] also mentioned that the sodium coolant can be used at a fairly low pressure, even though it emerges from the reactor at a temperature (above 500°C) compared with coolants such as water and gas. These advantages and many years of experience with liquid metal heat transfer system have made LMFBR the choice in the most advanced and technically possible fast breeder reactor. Comparison among the different types of fast breeder reactors is discussed in more detail by Simnad [85].

As mentioned earlier, techniques for sodium coolant have been tremendously developed, and a large amount of necessary data has been obtained. However, many problems are still existent which must be solved before the final construction. The solutions will result from high quality standards and well understood technical bases of the design, construction, and operation of reactor plants, thereby assuring the highest possible reliability and safety [72], and/or certain prerequisites including basic program success, validation of economic attractiveness, plutonium availability, a viable
competitive industry, established licensing procedures, and strong well-established quality assurance practices to assure success and economic reproducibility of the final product [82].

Since the LMFBR program plan was established, the development of fast reactors has conspicuously advanced. The nuclear community, including the AEC, reactor designers, component manufacturers and the utilities, who have been occupied principally with the development and marketing of the light water reactors, turned their effort to the breeder as a result of the U.S. LMFBR program. These groups reported their original design of the LMFBR program plant in the International Conference on Sodium Technology and Large Fast Reactor Design on 1968 [6]. As a direct consequence of nuclear safety characteristics and power economics considerations, nine different fast reactor designs have resulted from six independent studies. Summaries of these design data are comparatively shown in Appendix A and some typical core arrangements of each concept are shown schematically in Figs. 1 to 3. Summaries of the nuclear design philosophy of each follow-on study of the 1000 MW(e) LMFBR plant program are as follows:

1. **Japan Atomic Energy Research Institute (JAERI) [2,6,52]**

   The nuclear characteristics associated with engineering safety devices were considered as a main procedure in establishing the general design criteria for safety in fast reactor
Figure 1. Core arrangement of the JAERI 1000 MWe LMFBRs (units of all values are in feet)

1. core (zone 1), 2. core (zone 2), 3. axial blanket, 4. radial blanket, 5. reflector, and 6. sodium coolant only
Figure 2. Core arrangement of the AI 1000 MWe LMFBRs (units of all values are in feet)

1 core region, 2 axial blanket region, 3 inner radial blanket region (1 row), and 4 outer radial blanket region (1 row)
Figure 3. Core arrangement of the WARD 1000 MWe LMFBRs (units of all the values are in feet)

1 core region, 2 radial blanket region, and 3 axial blanket region
(A) 7 - MODULE REACTOR

(B) 4 - MODULE REACTOR
operation. Two different reactors were comparably designed. In the first design, the reactivity increment was estimated when a sodium void propagated radially like a concentric cylinder from the center channel. The second design was analyzed by taking account of the reactivity due to the sodium void, which should not be much larger than the allowable upper limit ($1.5$) even if the geometry of the sodium void gave the most pessimistic value.

The shape of the core in the first design was flat cylindrical, and that in the second design was hollow cylindrical (or annular), as shown in Fig. 1. The main objectives of each reactor design were to analyze a core for which the internal breeding ratio was close to unity for the first reactor and to make the sodium void coefficient as small as possible under the worst conditions for the second design.

As the conclusion of their follow-on study, they mentioned that the sodium void effect, Doppler effect, internal breeding ratio and power peaking factor were shown to be rather good for the annular core of the second design compared with those of the first design.

2. **Atomics International (AI) Group** [6, 8]

Their overall objectives of the LMFBR Follow-on Study Program were to identify the research and development (R & D) necessary to lead to safe, reliable, and competitive LMFBR central-station power plants in the 1980's and to establish
the relative ranking of the needed R & D. Also, the specific primary objective of their study was to define the technical and economical characteristics of a 1000-MW(e) LMFBR plant design that would represent a direct extrapolation of the AI demonstration plant and would thus require a minimum of R & D beyond that planned for the demonstration plant.

They reported two different reactor designs which were called "preliminary reference design" and "final reference design". Major changes from the "preliminary" to the "final" designs were increasing the reactor outlet temperature, increasing the fuel pin diameter, and decreasing the core height.

Their trade studies and parametric analyses are unique and interesting for expensive and systematic projects. The research also served to evaluate the economic improvements associated with the proposed changes.

3. Babcock & Wilcox Group (BAW) [6,9,10]

The major objectives for their follow-on study of 1000 MW(e) LMFBR were: (1) to reduce power-generation cost directly by developing nuclear power plants that are more efficient and economical than those now in use, and (2) to protect the large investment in light-water reactor plants by minimizing the effects of increase in uranium ore costs through efficient use of natural uranium and the plutonium produced in the light-water reactors. They found some
advantages of their reference design as follows: (1) The primary-system design is compact. (2) The plant-control problems are eased because of the large primary sodium heat sink. (3) Vented fuel improves power-generation cost and reduces fuel-handling and shipping problems. (4) Solid fuel cans reduce the probability of sodium-void propagation. The most remarkable point of their follow-on study is the optimization of the power generation cost with the effect of the intermediate heat exchanger (IHX).


They were primarily concerned with the three subjects which bear most directly on reactor performance: safety, the fuel system, and core optimization. The considerations for the subject of the safety were included with the void effect and spoiled geometries, containment of Bethe-Tait excursions, protective systems, factors relating to the inherent stability of the core, and special effects related to sodium-bonded fuel. In the fuel area, three systems with sodium-bonded carbide fuel, gas-bonded carbide fuel, and gas-bonded oxide fuel were tested. The core optimization was taken by a systematic method that involved extensive thermal, hydraulic, and economic calculations.

They finally arrived at the following conclusions:

1. A stable core with high-reliability protective and cooling system is the principal requirement for
LMFBR safety. If a sufficiently negative Doppler coefficient can be achieved, a moderately positive sodium-void effect does not significantly compromise safety.

2. Hyperstoichiometric sodium-bonded, mixed plutonium-uranium carbide is the preferred fuel system for LMFBR's.

3. The preferred core configuration for large (1000 MW(e)) LMFBR's is a moderately pancaked cylinder of height-to-diameter ratio of about 1 to 4.

5. General Electric (GEAP) Group [6, 34, 35]

The detailed description of the GEAP's design procedure is in a practical manner and its summary may be worth special mention. To perform the consequent design, two main steps were taken as follows:

1. The desirable core geometry and composition were determined using a set of fixed, but reasonable, assumptions for the fuel-pin design and for limits on clad temperature and pressure drop.

2. The fuel-pin dimensions, clad temperatures, and burnup were considered using the geometry and composition (except insofar as affected by changes in fuel-pin design) as determined from the first step. Their interesting tentative conclusions are:

1. The fuel cost optimization incentives to reduce
structure in the core are consistent with fabrication and corrosion considerations.

2. The uncertainties in fuel-fabrication and reprocessing costs are caused mostly from optimizing pin dimensions and clad temperature and fuel cost estimation.

3. The optimum value of the maximum bulk clad temperature is between 1250 and 1300°F.

4. Vented fuel has a slightly significant economic advantage over sealed-pin plenum fuel.

5. From the economical point of view, the optimal fuel-pin diameter is less than 0.25 in.

6. Westinghouse (WARD) Group [6, 33, 80, 84, 85, 93]

   To achieve the goal of a safe, reliable, and economically viable LMFBR system, they completed the four tasks by 1969. In their report of Task II and Task III [84], their unique design features with some reasons are discussed. These design features may be corrected or modified by the future studies; however, these practical and unique design features are highly worthy of consideration at the moment of developing LMFBR. Some of them due to the core design are:

   1. (U,Pu)C fuel - The carbide fuel showed a superior economic promise over oxide. This economic promise hinges on the potential of carbide fuel for (a) harder neutron spectra, (b) higher heavy atom densities,
(c) higher linear power ratings, and (d) higher burnup.

2. Modular geometry - Compared with a pancake geometry, their several investigations on sodium void coefficient and fuel cycle cost showed that the modular geometry had better results. This subject will be discussed in detail in other sections.

3. Square lattice - A hexagonal lattice is very popular in fast reactors, but some qualified advances of the square lattice can not be neglected, such as on pressure drop, fabricability and fuel cycle cost.

4. Sodium bond - Since the swelling rate for carbide fuel is higher than that for oxide fuel, the carbide fuel requires a larger fuel-cladding gap. The larger gap must be filled with a material having high thermal conductivity such as sodium. The carbide-sodium combination thus provides a path of low thermal resistance.

5. 2640°F fuel centerline temperature limit - The melting point of (U,Pu)C fuel is much higher than this (~ 4180°F); however, the presence of Cr$_{23}$C$_6$ (which is added to tie-up free carbon) provides lower-melting phases.

6. 0.302-inch fuel pin diameter - The optimum fuel pin diameter gives the minimum fuel cycle cost.

The original large fast reactor studies done by these
groups were compared by Okrent et al. [68] and presented at the third Geneva Conference. After that, the greater part of their reference design data of the 1000 MWe LMFBR's has been modified; however, their results as reported by Okrent et al. [68] are still useful and the basis for fast reactor design.

B. Module Core Comparison

"Pancake" (or "flat cylinder"), "honeycomb", "hollow cylinder" (or "annulus") and "module" are names of geometrical shapes for fast reactor, and those examples are shown in Figs. 1 to 3. Geometrical shape is a highly weighted and basic factor which specifies the reactor characteristics, especially for a fast breeder reactor. Which is the best shape is a very interesting question, but not easy to answer. It is very difficult to compare the overall design of reactors with their unique features and different design tools; only individual characteristic parameters of the reactors can be compared with obvious way. In order to find how the geometrical reactor shape will affect the characteristics and/or to compare the different shapes on the characteristics, a systematic large scale research project is required and for a complicated reactor shape, a highly complex and accurate computation technique is also necessary. The result which can be contributed to this field by a small scale individual research is only a careful analysis of data given by each systematic research group and actual computations of parameters
for a few different simple shaped reactors.

Throughout Westinghouse's four tasks on the 1000 MW(e) LMFBR follow-on study, they concluded that the four-module reactor was better than a pancake - or a seven-module reactor in regard to the sodium void coefficient and the fuel cycle cost [6, 84]. Before the four-module reactor was selected as a reference design, three basic configurations - a seven-, four-, and one-module (pancake) reactor - were considered comparatively on four important parameters: sodium void effect, Doppler effect, fuel cycle cost, and doubling time. The results of these investigations are discussed in their Task I Final Report [93]. To review this discussion is useful for this research. Summary of their discussion is as follows:

1. Sodium void effect

From their comment, the reactivity effect of voids is a resultant of two effects: the spectrum hardening which increases reactivity, and the increase in neutron leakage which decreases it. The spectrum hardening is a function of enrichment, and the neutron leakage is a function of the core height-diameter ratio of the actual fuel region. In addition to the effect of the core height-diameter ratio, the void reactivity change is sensitive to the reactivity coupling between the modules (which may be a function of radial blanket thickness).

From their results shown in Fig. 4, a negative sodium
Figure 4. Sodium void effect of LMFBR vs. the core height. (The solid lines were drawn by WARD [93], and the dotted line was drawn by CEND [6].)

1 JAERI, First
2 JAERI, Second
3 BAW, Reference
7 CEND
8 GEAP, Advanced
9 GEAP, Conservative
11 WARD, 4-module
void coefficient is possible for core sizes considered in the three configurations; however, an acceptable core height is limited by the pressure drop effect due to sodium flow resistance.

2. Doppler effect

The reactivity temperature coefficient due to the Doppler effect was calculated from the difference in $k_{\text{eff}}$ of the whole reactor. The resulting temperature coefficient plotted in Fig. 5 is seen to be negative for all configurations.

3. Fuel economics

The evaluation of the fuel cycle economics was made on the basis of a three-year fuel cycle, with one-third of the core and blanket replaced and reprocessed each year. The resulting plot is copied in Fig. 6, and some comments on the results are: (1) The lowest fuel cycle costs are associated with designs having unacceptable sodium void coefficients. (2) The costs tend to increase with increasing blanket volume.

4. Doubling times

The simple doubling times for all configurations considered were calculated from the reactor inventories at the beginning of reactor operation and at the time the equilibrium cycle had been reached. A copy of the results is presented in Fig. 7. The results gave doubling times, as a function of the height-to-diameter ratio of the core, ranging
Figure 5. Doppler effect of LMFBR vs. the core height-diameter ratio [93]
Figure 6. Fuel cycle cost of LMFBR vs. the blanket-core volume ratio [93]
Figure 7. Simple doubling time vs. core height-diameter ratio [93]

1 JAERI, First
3 BAW, Reference
5 AI, Preliminary
7 CEND
8 GEAP, Advanced
9 GEAP, Conservative
11 WARD, 4-module
from 7 years to 11 years, with the four-module reactor configuration giving the lowest values.

The four-module design selected offers the best combination of economics of the fuel cycle, the lowest doubling time, nonpositive void coefficient, and a negative Doppler coefficient of reactivity.

Hummel and Okrent [47] pointed out the geometrical effects on the LMFBR design characteristics. The summaries are as follows:

1. Annular - A sodium region is provided above the core to enhance the negative leakage component for voids forming in this region.
2. Annular - a simple design free of complications arising from core coupling.
3. Pancake - simplest from an engineering design standpoint.
4. Pancake - an increase in reflector savings accompanying sodium voiding, which reduces the leakage component.
5. Modular - a feasible criterion of zero reactivity effect on complete voiding of core and axial blanket.
6. Modular - somewhat easier to create a prototype and straightforward on extension to larger sizes.

Hummel and Okrent [47] concluded their discussion on the geometrical effect with one sentence which might express a typical interpretation: "At the present time no clear-cut
advantage of one method of spoiling over another has been established."

In a study similar to that of Westinghouse, a comparison of modular and pancake core systems was conducted by Combustion Engineering [24]. In contrast to the Westinghouse conclusion of the modular core selection, the cylindrical core was selected as their reference design. Its superior fuel cycle costs and breeding performance are pointed out as main reasons for the cylindrical core selection.

The differences between the conclusions of these two study groups indicate the need for additional research directed toward the determination of the relative advantages of the different possible core configurations and the optimization of core design.

C. Techniques for Core Design

In order to accomplish a reactor core design, a strict procedure is required, such as that indicated in the following steps.

1. Select the appropriate calculation method (i.e., diffusion, transport, or Monte Carlo).
2. Establish a computer code including the selected calculation method.
3. Select the materials which are to be contained in the reactor.
4. Establish an accuracy for the results consistent
with the design objectives.

5. According to this determination, decide on a dimensional scale (i.e., one-, two-, or three-dimension), number of energy groups, and geometrical mesh size.

6. Take account of the engineering criteria (e.g., with respect to thermal-hydraulics, structural mechanics, and safety operation technique).

Except for some obvious engineering design procedures, each subject in the design process is discussed in some detail, particularly with respect to the LMFBR core design.

1. Reactor calculation for core design

Knowledge of neutrons behavior and distribution in a reactor core must be the starting point of all reactor calculations. Neutron "transport theory" is a mathematical theory which predicts this neutron behavior and takes into account the speed or energy, direction and time-dependence of the neutrons. To simplify the theoretical investigations, the neutrons are assumed to behave isotropically. The resulting equations, of which the approximation is called "diffusion theory", are then derived similarly to the equations obtained when considering the diffusion of heat in a body in the presence of heat sources. The diffusion theory, which is employed in this research, is discussed in Chapt. II in detail.

A detailed comparison of the transport and diffusion
theories was made by Rohan [77] on calculations of performance characteristics for large fast reactor assemblies. His results show generally good agreement between them, particularly in view of the relatively large size of the assemblies. This description must encourage fast reactor designers to employ the diffusion approximation theory to their design calculations, because the solutions of the diffusion equations are much easier than those of the transport equations.

There is a value in a design study to investigate a reactor core without considering short-term time effects. The time independent theory furnishes the mathematical model. Such calculations lead to critical calculations. Even at the design stage of reactor, however, a time-dependent approach on a computer is required to simulate the operation conditions and possible accidents.

To solve the transport problem, the Monte Carlo method may also be considered as a stochastic solution of a multidimensional integral equation. Although this concept is useful, the extensive Monte Carlo calculations are in general still expensive [11].

For the current large reactors, including fast breeder reactors, the high performance requirements demand an even more accurate knowledge of the power distribution and thermal conditions within the core. This is principally a problem of the large reactors, because the large size of these reactors increases sensitivity of the power distribution to small
changes in reaction rates in the various regions of the core [11].

2. **Computer code selection**

Modern design techniques for a complex large power reactor system can not be considered without application of a large-capacity computer. To begin with, the largest available computation machines are usually the best ones because of the lowest unit cost per computation and because of the more advanced software systems available. Some aspects of the digital computer and its price structure applied particularly to the reactor design field were discussed in detail by Bareiss [11]. Since the reactor designers, in general, consider an economical scale and an expected accuracy to make these calculations worthwhile, detailed information on the computer capacity and the available code are very useful.

To select the best suited code for the reactor design, the following points are pertinent to the choice:

1. Programming language in which the code is written.
2. Machine model with which the code was originally made.
3. Approximation method which is the main point in the code.
4. Combinations of multi-dimensional systems which can be used with the code.
5. Maximum number of energy groups for the
multi-group calculation.

6. Maximum number of mesh points for the design model.

7. Input data complexity and form which are required by the code.

8. Output form which indicates the convenient design and physical parameters.

9. Data transfer system which should be mechanized as far as possible.

10. Organization of the code programming in blocks or modules to check and modify some part of the code to increase simplicity.

11. Computation speed for standard calculations with codes.

General information on the computation systems used recently for reactor calculation objectives is given in Charnick's article, "Status of Reactor-Physics Calculations for U.S. Power Reactors" [22], along with his comments. The Argonne Code Center also gives overall information of the program packages indexed and distributed to the public by them [20].

3. Determination of feasible materials

Another important preparation for the reactor core design is determining the feasible materials of which the reactor will be composed. Fuel, coolant and structural materials are
the major components of the fast breeder reactor core. Besides these, control and reflector materials must be considered; however, only three main components will be discussed since a detailed discussion of the reactor materials is beyond the scope of this work.

In exchange for uranium, which has been the basis of thermal reactors, plutonium was selected as a highly efficient nuclear fuel to be used ultimately in fast breeder reactors. The present problems for utilization of plutonium and for its fabrication as a fuel are pointed out and discussed by Rippon [76]. A table, comparison of uranium and plutonium nuclear design characteristics, in this reference is very valuable for the basic fuel consideration.

In current practice, three uranium-plutonium ceramic compounds — oxides, carbides, and nitrides — all have high potential as fast breeder reactor fuels. The relative merits of these compounds has been tested and the results have been reported in many articles [39, 40, 46, 81, 89]. Comparison of these fast reactor ceramic fuels relative to their thermal properties, swelling behavior, and compatibility characteristics were reported by Goldsmith et al. [39], which is the most complete among the above articles. From their comments, the oxide fuel is most developed at the present; however, the carbide fuels have higher thermal conductivity and may provide higher breeding gains. Considerably more testing and evaluation of these materials are required to assess their
real worth. Availability of credible data which will be considered for the original design and also for its operation is one of the big factors in materials selection.

As mentioned in a previous section, sodium was selected as the best coolant for the fast breeder reactor by far, and the LMFBR nation-wide program was started. Studies of sodium have been reported by several writers, and conferences on sodium technology have been held [6]. In summary, the principal reasons for selecting sodium as a fast reactor coolant are its potential for high breeding ratios, high heat release rates, high thermal efficiencies, and its inherently favorable emergency cooling characteristics [38].

Selection requirements for fast reactor in-core structural materials correspond not only to individual structural material but also to the coupling with coolant, fuel and cladding-fuel bond material. The major cladding and can materials have been the stainless steels, types of 304, 316, 347, and 321. Adding to the SS, pure elements, Ti, V, Cr, Te, Ni, Zr, Nb, Mo, W, and Ta were tested for effect of cladding on nuclear performance, and the results were reported by Okrent et al. [68]. Preference among these possible materials as highly qualified structural materials also depends principally upon the availability of data that will permit design with a high degree of confidence [13].

For in-core components, this requires a definition not only of effects of temperature, fluence, and flux, but also
the effects of stress, stress relaxation, and neutron spectrum, as well as the influence of metallurgical structure, thickness, and compositional variations on irradiation-induced swelling and ductility loss in materials of interest [13]. Therefore, it seems reasonable to assume that the acquisition of more radiation tests and the determination of some of the basic information on the LMFBR's components are still required, prior to the construction of the Fast Flux Test Facility (FFTF) [41].

4. Engineering criteria on core design

The LMFBR Program Plan [58] states the major requirements which should be kept in mind by each designer. Summaries of the four major technical requirements for the initial commercial feasibility on the LMFBR Power Plant are as follows:

1. Safety is the most important requirement and a primary concern in the developing LMFBRs.

2. Operating reliability of the power plant components must be high in order to achieve commercial feasibility, requiring a reliable fuel development.

3. Net power cost must be as low as possible. For this requirement, a fuel-cycle cost target of 1 mill/kW-hr or less, a fuel burnup goal of 100,000 MWD/T, a higher breeding gain, a higher specific power, and a plutonium doubling time goal of 7 years will serve as helpful guides in planning.
4. Selecting a large plant size is paramount to the ultimate aim of a competitive capital cost for the plant. A 1000-MWe plant size was selected as a guide for technical program planning.

In addition to these major requirements, some standard design considerations are given by Hummel and Okrent [47], and these are:

5. A higher fuel concentration and low sodium content are required in order to obtain a high internal and total breeding ratio.

6. A high power density is desirable to minimize the core volume.

7. A short core (flat core) is necessary to avoid excessive temperature rise and pressure drop in the sodium.

8. Minimizing the core volume is helpful in making the sodium-void effect more negative.

D. Objectives of the Investigation

The ultimate purpose of this investigation is to obtain the optimized geometrical shape of a large-size liquid-metal cooled fast-breeder reactor (LMFBR) core and blanket system. In particular, breeding ratio, which will contribute directly to estimating a fuel cycle cost, is a criterion for the geometrical optimization of the core and blanket system.

Not according to the traditional optimization method of
reactor core design [45, 48], a simple and economical method is developed in this investigation. The diagram of this method is shown in Fig. 8, and its details are as follows:

1. The necessary number of data sets are obtained with reactor computation methods. In this investigation, values of the breeding ratio for different geometrical parameters are computed with use of the diffusion theory.

2. The data are plotted as a function of each non-dimensional variable, and one-independent-variable functions for the plotted curves are derived with the least square technique.

3. The most appropriate combination of the functions, derived in Step 2, to express the dependent variable with the all independent variables is presumed with a dimensional analysis technique, leading to an empirical function including all major variables.

4. The usual optimization method is applied to this empirical function as an objective function. A set of constraints is employed here, if it is necessary.

5. Using the optimized configuration as the new input, the optimized object calculated in Step 4 is reintroduced as Step 1 and examined as to its reliability, and other characteristics for the optimized
Figure 8. Logic diagram for developed optimization procedure
core are investigated at the same time.

After the feasibility of this method on the reactor core design optimization is substantiated, the optimized system is compared with two other standard core-blanket systems: pancake and 4-module. These three geometrically different systems are considered and their critical configurations are calculated using the same input data except for their geometrical data. The comparison is made, in particular, with regard to breeding ratio, critical enrichment, fuel load, and core-blanket volume ratio.

To keep the project within limits of time and expense as an individual thesis project, several ground rules were established.

1. Only a two-dimensional diffusion computational program was used.

2. Two energy groups were employed for the computation.

3. The traditional method for direct core design optimization was not examined.

4. Widely used optimization methods were to be employed, but their difference and feasibility were not to be considered.

5. The theoretical method of dimensional analysis was to be applied and improved as required.

6. Effects of different nuclear data sets were not to be considered.
7. Consideration of axial blanket availability was to be neglected because of its technical incompatibility with two-dimensional computation.

The basic ideas of the large size LMFBR core design come from the proceedings of three Argonne topical conferences [4, 5, 6], USAEC's LMFBR program plan [58, 59, 60], and many LMFBR follow-on study reports [8, 9, 10, 24, 25, 33, 34, 35, 75, 80, 84, 88, 93]. Several industrial organizations participated in the LMFBR program.

A two-dimensional, multigroup diffusion code, 2DB [57], was modified as required for the IBM 360/65 computer available for use in the fast reactor criticality and burnup analysis.

In the optimization project, the exterior penalty function method was applied to the constrained core design optimization problem. Its computation programming was composed for this research with two unconstrained optimization programs, FMCG (conjugate gradient method) and FMFP (Davidon's method), which are contained in IBM Science Subroutine Package [51].
II. MAIN THEORIES

Four theoretical fields are included in the research reported in this thesis. Numerical formulation of the two-dimensional diffusion equation is used for the computation of the neutron flux profile; the breeding ratio calculation method is very important especially for a breeder reactor; dimensional analysis is used for deriving an experimental or empirical function; and optimization techniques are widely used for engineering design. Discussion of these main theoretical tools for this research follows.

A. Formulation and Solution of Diffusion Equation

The starting point for the derivation is the set of forward multigroup diffusion equations for the steady state problem. For this objective, any nuclear reactor physics book may be useful, e.g., Refs. [19, 57, 63, 77, 90, 91]. As a summary, an interesting description of "the solution of reactor diffusion problems" was reported by McCallien [64].

The neutron flux diffusion equation in standard notation [55] is

$$\text{div } D \text{ grad } \phi - \Sigma_a \phi + S = \frac{1}{V} \frac{d \phi}{d t}, \quad (2-1)$$

where for simplicity all of the independent variables have been omitted. Nevertheless, this is the basic form of the diffusion equation; however, it is detailed formulation
according to its projected use. Borresen [16] started his derivation with the following equation, i.e., the fast-flux diffusion equation for a steady state thermal reactor problem.

\[-\nabla \cdot D \nabla \phi = S \cdot \phi, \quad (2-2)\]

where

\[S = \frac{1}{\lambda} \left( \nu \Sigma_f + \nu \Sigma_f \frac{\phi}{t} \right) - \Sigma_a - \Sigma_r. \quad (2-3)\]

Lorenzini and Robinson [61] described a different form of the diffusion equation and used it for their explanation of spectral-synthesis method; it was written in matrix notation as follows:

\[-D \nabla^2 \phi + \Sigma_t \phi = \Sigma_s \phi + \frac{1}{\lambda} M \phi, \quad (2-4)\]

where

\[\phi^{-1} = \{\phi_1, \phi_2, \phi_3, \ldots, \phi_N\}_{1 \times N}, \]
\[D = (D_{ij})_{N \times N}, \]
\[\Sigma_t = (\Sigma_{tij})_{N \times N}, \]
\[\Sigma_s = (\Sigma_{sij})_{N \times N}, \]
\[M = (\chi_i \nu \Sigma_{fj})_{N \times N}. \]

Particularly for this research which employed the diffusion theory with multigroup, in \(r-\theta\) geometry, and for steady state problem, the neutron balance equation can be written in a form,

\[\nabla \cdot D_{g}(r, \theta) \nabla \phi_{g}(r, \theta) - \Sigma^r_{g}(r, \theta) \phi_{g}(r, \theta) + S_{g}(r, \theta) = 0; \quad g = 1, 2, \ldots, G \quad (2-5)\]
where the source term is

\[ S_g(r, \theta) = \frac{\chi_g}{k_{eff}} \sum_{g'}^G \nu_{g'} \Sigma_{g'}^f(r, \theta) \phi_{g'}(r, \theta) + \sum_{g'=1}^{g-1} \Sigma_{g' \rightarrow g}^r(r, \theta) \phi_{g'}(r, \theta), \]

(2.6)

and

\[ g = \text{energy group index from 1 to } G, \text{ and } G \text{ is the number of energy groups or group index of the lowest energy}, \]

\[ \phi_g(r, \theta) = \text{group } g \text{ scalar flux with coordinates } r \text{ and } \theta, \]

\[ S_g(r, \theta) = \text{group } g \text{ scalar source at the point } (r, \theta), \]

\[ D_g(r, \theta) = \text{diffusion coefficient for group } g \text{ at the point } (r, \theta) \]

\[ = \frac{1}{3 \Sigma_{tr}^r(r, \theta)}, \]

\[ \Sigma_g^r(r, \theta) = \text{group } g \text{ averaged macroscopic removal cross section at the point } (r, \theta), \]

\[ = \Sigma_g^a(r, \theta) + \sum_{g'=g+1}^G \Sigma_{g' \rightarrow g}^r(r, \theta), \]

\[ \nu_g \Sigma_g^f(r, \theta) = \text{group } g \text{ average of product of macroscopic fission cross section times average number of neutrons related per fission occurring in group } g \text{ at the point } (r, \theta), \]

\[ \Sigma_{g' \rightarrow g}^r(r, \theta) = \text{macroscopic transfer cross section from group } g' \text{ to group } g \text{ at the point } (r, \theta), \]

\[ k_{eff} = \text{effective multiplication factor, and} \]
\( x_g = \text{fraction of fission neutron born in group } g. \)

The diffusion equations expressed in Eq. (2-5) are used for approximation in the multigroup with no upscatter. Considering more weight on energy-dependence of flux and/or higher accuracy on the flux computation, application of an advanced technique, such as "Space-Energy Factorization" [86, 87], "Successive Space-Energy Synthesis" [23], "Energy Model Synthesis Method" [53], and "Multiple Weighing Functions in Space-Energy Synthesis" [67], may be necessary.

In order to solve the spatial difference equations, the derivation should be started by rewriting Eq. (2-5) with simple notation as follows:

\[
V \cdot D V \phi - \Sigma^f \phi + S = 0 . \quad (2-6)
\]

From now on, the group index \( g \) is dropped for simplicity until it will be necessary again. The spatial difference equation is obtained by integrating Eq. (2-6) over the mesh area. Each mesh point is assumed to be at the center of its associated mesh area. The mesh point arrangement in \( r-\theta \) geometry is illustrated in Fig. 9 as an example; therefore, the \( r-\theta \) geometry can be easily replaced by other combinations of geometry (i.e., \( x-y \), \( r-z \), triangular).

For the \((1, j)\) mesh point, labeled 0 in Fig. 9, the radial integration is from \((r_1-\delta r_2/2)\) to \((r_1+\delta r_2/2)\), and the rotational integration is from \((\theta_j-\Delta \theta_2/2)\) to \((\theta_j+\Delta \theta_2/2)\), that
Figure 9. Mesh description in r-θ geometry
is given by

\[
\int_{r_1 - \delta r_o/2}^{r_1 + \delta r_o/2} \int_{\theta_j - \delta \theta_o/2}^{\theta_j + \delta \theta_o/2} [\nabla \cdot \nabla \phi - r \phi + S]dA = 0, \quad (2-7)
\]

where \(dA\) is the area element and is given by

\[
dA = r d\theta dr . \quad (2-8)
\]

The area integration of the leakage term in Eq. (2-7) is solved by first transforming to a circle integral using Green's theorem,

\[
\int_A \nabla \cdot \nabla \phi \, dA = \oint \nabla \phi \cdot \mathbf{\hat{n}} \, dl , \quad (2-9)
\]

where \(\mathbf{\hat{n}}\) represents a normal unit vector. To evaluate the circle integral, the flux gradients at the mesh area boundaries are approximated by using the two adjacent flux values, and then the integration could be solved by means of numerical analysis as follows:

\[
\text{Leakage} = \oint \nabla \phi \cdot \mathbf{\hat{n}} \, dl
\]

\[
= \int_{l_1, l_2, l_3, l_4} d[\frac{\partial \phi}{\partial r} + \frac{1}{r} \frac{\partial \phi}{\partial \theta}] \cdot \mathbf{\hat{n}} \, dl
\]

\[
= \overline{D}_1 \int_{l_1} \frac{\partial \phi}{\partial r} \, dl + \overline{D}_2 \int_{l_2} \frac{\partial \phi}{\partial r} \, dl
\]

\[
+ \overline{D}_3 \int_{l_3} \frac{1}{r} \frac{\partial \phi}{\partial \theta} \, dl + \overline{D}_4 \int_{l_4} \frac{1}{r} \frac{\partial \phi}{\partial \theta} \, dl , \quad (2-10)
\]

where \(l_1, l_2, l_3,\) and \(l_4\) are lengths of each circular boundary faced to the mesh points labeled 1, 2, 3, and 4,
respectively. By taking approximation of the flux gradients at the mesh boundaries,

\[
\text{Leakage} = \sum_{k=1}^{4} D_k \frac{\phi_k - \phi_0}{h_k} l_k, \quad (2-11)
\]

where \( h_k \) is a distance between the mesh point \( 0 \) and the mesh point \( k \), and \( D_k \) represents an effective diffusion coefficient associated with the mesh point \( 0 \) and \( k \), and is given by

\[
D_k = \frac{D_0 D_k (\delta X_0 + \delta X_k)}{\delta X_k + D_0 \delta X_0}, \quad (2-12)
\]

where \( \delta X_k \) is replaced with \( \delta \theta_1, \delta \theta_2, \delta r_3, \) or \( \delta r_4 \). To evaluate the integration for the second and the third terms, the flux, the removal cross section, the neutron source, and all values which are necessary in the complete diffusion equation are approximated as constants in each mesh region. The result of area integration of Eq. (2-6) for mesh point \( 0 \) (see Eq. (2-7) also) is thus

\[
\sum_{k=1}^{4} \frac{D_k l_k}{h_k} (\phi_k - \phi_0) - \Sigma^{F}_0 \phi_0 A_0 + S_0 V_0 = 0, \quad (2-13)
\]

where

- \( \Sigma^{F}_0 \) = macroscopic removal cross section associated with mesh point \( 0 \),
- \( S_0 \) = total neutron source rate associated with mesh point \( 0 \), and
\( A_o = \text{mesh area associated with mesh point } 0 = r_i \delta \theta_o \delta r_o \).

For calculational purposes, Eq. (2-13) can be written in the similar form

\[
\sum_{k=0}^{4} C_k \phi_k = S_o V_o ,
\]

where

\[
C_k = - \frac{D_{\theta} \phi_k}{h_{\theta}} ; \quad k = 1, 2, 3, 4 ,
\]

and

\[
C_o = \Sigma^r_r V_o - \sum_{k=1}^{4} C_k .
\]

These constants \( C_k \) are computed for the initial system and stored for use in the flux calculation. They must be recomputed whenever the material compositions and/or the mesh interval change.

For the next step of the derivation, various boundary conditions must be considered. The boundary of a system may be separated into three categories: reflective (or symmetric), vacuum (or extrapolated) and periodic boundaries. Fig. 10 represents a typical cylindrical reactor to clearly illustrate these terms. The reactor system illustrated in Fig. 10 could be calculated only with a quarter of the whole circle, if its four boundary-conditions are indicated correctly. In the flux calculation, the boundary conditions enter only through the computation of \( C_k \) values at the reactor
Figure 10. Vertical view of a cylindrical reactor with four boundaries
boundaries. To illustrate the boundary conditions, consider the one-dimensional slab reactor shown in Fig. 11 for reflective and vacuum boundaries and in Fig. 12 for periodic boundary.

1. **At reflective boundary**

Imagine that a pseudo mesh interval, labeled 0 in Fig. 11, has been added to the outside of the reflective boundary with the same compositions and thickness of interval with those in the mesh interval 1. Since \( \nabla \phi = 0 \) at the reflective boundary, then \( \phi_0 = \phi_1 \) or \( \phi_0 - \phi_1 = 0 \). Therefore, the coefficient \( C_0 \) of \( (\phi_0 - \phi_1) \) in Eq. (2-13) must be set equal to zero,

\[
C_0 = 0; \text{ at the reflective boundary, \quad (2-17)}
\]

and, thus, the imaginary flux \( \phi_0 \) does not contribute to Eq. (2-14).

2. **At a vacuum boundary**

To illustrate the vacuum condition, also imagine that a pseudo mesh interval, labeled \( I + 1 \) in Fig. 11, has been added to the outside of the vacuum boundary with the same compositions as the mesh interval \( I \) and the mesh thickness \( 2d \), where \( d \) is the extrapolation distance. Since \( \phi_I \neq 0 \) and \( \phi_{I+1} = 0 \), the coefficient, \( C_{I+1} \), of \( (\phi_I - \phi_{I+1}) \) in Eq. (2-13) cannot be zero and can be seen than
Figure 11. Slab reactor with reflective and vacuum boundaries

Figure 12. Slab reactor with periodic boundaries
where \( d = 0.71 \lambda^{tr} \) and \( \lambda^{tr} \) is the transport mean free path in the mesh interval \( I \).

3. At a periodic boundary

The periodic boundary conditions also enter into the computation of the constants \( C_k \) at the boundaries. Imaginary mesh intervals of 0 and \( J+1 \) have been added to the outside of the real mesh intervals of 1 and \( J \), respectively. The imaginary mesh interval 0 has the same composition and mesh thickness as interval \( J \) and, similarly, another imaginary mesh interval \( J+1 \) has the same composition and mesh thickness as interval 1. For a combination of two periodic boundaries, \( \phi_0 = \phi_J \) and \( \phi_{J+1} = \phi_1 \); then the coefficient \( C_1 \) and \( C_{J+1} \) can be given by

\[
C_1 = -\frac{D_o \lambda_0}{\frac{1}{2}(\delta X_1 + \delta X_J)}; \quad \text{at the periodic boundary, \hspace{1cm} (2-19)}
\]

\[
C_{J+1} = -\frac{D_{J+1} \lambda_{J+1}}{\frac{1}{2}(\delta X_1 + \delta X_J)}; \quad \text{at the periodic boundary, \hspace{1cm} (2-20)}
\]

where \( \lambda_0 = \lambda_{J+1} \),

and

\[
D_o = \frac{D_{J+1}}{D_1} = \frac{D_1 D_J (\delta X_1 + \delta X_J)}{D_1 \delta X_J + D_J \delta X_1}. \hspace{1cm} (2-21)
\]
Therefore, the two coefficients must be equal.

B. Definition of Breeding Ratio

The breeding ratio is a familiar term among fast reactor designers, and serves as a basis to making comparisons among reactors. Therefore, the breeding ratio is an important characteristic parameter for fast breeder reactors. The definition of breeding ratio has been discussed in various ways from general or conceptual definitions to approximate definitions.

Examples of the definitions are:

1. Glasstone and Sesonske [37] - "The ratio of the number of fissile atoms produced to the number of the same kind that have been consumed."

2. Lamarsh [55] - "The average number of fissile atoms produced in a reactor per fuel atom consumed either by fission or absorption."


4. Adkins' standard definition [1] - 
   \[
   BR = 1 + \frac{\text{surplus production rate of fuel}}{\text{destruction rate of fuel}}.
   \]

5. Wensch [92] - "The number of fissile nuclei created per fissile nucleus destroyed."

The simplified definitions of breeding ratio are very useful for understanding the important interrelationship among variables and the influence of the various reactor
parameters; however, the simplified definitions are not useful for actual design purposes [1]. Some reasons for the inapplicability of the simplified definitions might be low accuracy of its approximate calculation and difficulty of its use for actual complicated reactors.

From the recent articles, some interesting calculation methods for breeding ratio in addition to its standard definition have been discussed by Ott [69] and Adkins [1]. Adkins examined comparatively two methods: the method of $n$ weighting due to Ott [69] and the method of reactivity weighting due to Baker and Ross (British definition) [30].

It is also beneficial to study the various methods of calculating breeding ratio. A simple expression for the breeding ratio was derived by Glasstone and Sesonske [37] as follows:

The total breeding ratio, BR, is divided into two parts, namely, the internal breeding ratio, IBR, due to the seed region, and the external breeding ratio, EBR, due to the blanket region; this is given by

$$BR = IBR + EBR.$$  \hfill (2-22)

Since a complete expression for the total breeding ratio can be written as

$$BR = \frac{\int_{\text{seed}} \phi \Sigma_f \text{d}V + \int_{\text{blanket}} \phi \Sigma_f \text{d}V}{\int \phi \Sigma_{\text{fuel}} \text{d}V},$$  \hfill (2-23)
where $\Sigma^c$ and $\Sigma^a$ are macroscopic capture and absorption cross section, respectively. The first and the second terms divided separately by the common denominator give the internal and external breeding ratios. If the numerator of the external breeding ratio can be derived by assuming that all neutrons which have leaked from the seed region would be captured by fertile nuclei in the blanket and become fissile nuclei, the total breeding ratio is given by

$$BR = \frac{\int_{\text{seed}} \phi \Sigma^c_{\text{fertile}} dV + \int_{\text{seed}} \phi (\nu \Sigma^f_{\text{seed}} - \Sigma^c_{\text{seed}}) dV}{\int_{\text{seed}} \phi (\Sigma^f + \Sigma^c)_{\text{fuel}} dV}, \quad (2-24)$$

where $\nu$ is the number of neutrons produced per fission.

As the second assumption, if the spatial variations are neglected, Eq. (2-24) reduces to

$$BR = \frac{\Sigma^c_{\text{fertile}} + (\nu \Sigma^f_{\text{seed}} - \Sigma^c_{\text{seed}})}{(\Sigma^f + \Sigma^c)_{\text{fuel}}}, \quad (2-25)$$

or

$$BR = \frac{\Sigma^c_{\text{fertile}}/\Sigma^f_{\text{fuel}} + (\nu - 1 - \alpha^*)_{\text{seed}}}{1 + \alpha}, \quad (2-26)$$

where

$$\alpha^* = \frac{\Sigma^c}{\Sigma^f} \quad \text{for the seed region}$$

and

$$\alpha = \frac{\Sigma^c}{\Sigma^f} \quad \text{for the fuel (fissile) species only}.$$
Applying the third assumption, $a^* = a$, and $\eta$ which is equal to $v/(1+\alpha)$, Eq. (2-26) becomes

$$BR = \frac{\Sigma_c^{c\text{fertile}}/\Sigma_f^{c\text{fuel}}}{1 + \alpha} + \eta - 1.$$  \hspace{1cm} (2-27)

The external breeding ratio thus simply given by $\eta - 1$.

A more complicated expression compared with Eq. (2-27) is shown by Adkins [1] and Wensch [92] as

$$BR = \frac{(\eta^* - 1 + \alpha a^*)\delta - P - Q}{1 + \alpha} + \eta - 1,$$  \hspace{1cm} (2-28)

where

- $\alpha = $ capture to fission rate ratio for the fissile material only,
- $a^* = $ capture to fission rate ratio for all materials in the seed region,
- $P = $ number of neutrons captured (nonfissile and nonfertile materials) in parasitic absorbers per fission of primary fissile isotope,
- $Q = $ number of neutrons leaking from blanket per fission of primary fissile isotope,
- $\delta = $ fertile to fissile fission rate ratio,
- $\eta = $ neutron production to absorption rate ratio for fissile material, $\eta = v/(1+\alpha)$,
- $\eta^* = $ neutron production to absorption rate ratio for fertile material, $\eta^* = v^*/(1+\alpha^*)$. 

\[ v = \text{average number of neutrons produced per fissile fission, and} \]
\[ v^* = \text{average number of neutrons produced per fertile fission.} \]

The breeding ratio expressed by Eq. (2-28) is called "the conventional point-in-time breeding ratio".

As mentioned before, the simplified definitions of breeding ratio are not good enough for actual design purposes. In order to obtain a breeding ratio for a typical reactor using a simplified calculation method, a simpler model must be considered to satisfy the assumptions. However, this procedure for approximation calculation will be recognized by its technical difficulty for a complicated actual reactor such as multi-zoned system. The breeding ratio may be defined to conform with the conventional definition as

\[ \text{BR} = \frac{\sum \sum \gamma^n_1 C^n_{i-1}}{\sum \sum \gamma^n_1 A^n_1}, \quad (2-29) \]

where

- \( i \) = index of any particular nuclide,
- \( n \) = index of any particular reactor zone,
- \( C^n_{i-1} \) = capture rate of nuclide \( i-1 \) in region \( n \), (i.e., production rate of nuclide \( i \)),
- \( A^n_1 \) = absorption rate of nuclide \( i \) in region \( n \), and
- \( \gamma^n_1 \) = weighting factor dependent on nuclide \( i \) and zone \( n \).
Adkins [1] introduced two methods for calculating the reactor breeding ratio with breeding again. Those are called "standard BR" and "British BR"; however, both show the same form as Eq. (2-29). From the standard definition, it can be proved that the breeding ratio is equal to one plus the breeding gain, but this relationship is no more true in the British definition. In addition, Adkins also mentioned that the breeding gain is the quantity of physical interest affecting the doubling time and fuel cycle reactivity variation and, thus, the breeding ratio is of little physical interest.

The weighting factor, $\gamma^n_1$, by nuclide and zone, should be chosen to give the proper interpretation of the breeding gain and doubling time. Four different choices of weights were discussed by Adkins; these are listed below with the nuclide type (isotope) index: 1 = 5, 6, 8, 9, 0, 1, 2 denotes U-235, U-236, U-238, Pu-239, Pu-240, Pu-241, and Pu-242.

**Standard weighting:**

$$\gamma^n_1 = \begin{cases} 1 & i = 9, 1, 5 \text{ (fissile)} \\ 0 & i = 0, 2, 8 \text{ (fertile)} \end{cases}$$

**Ott \( n \) weighting:**

$$\gamma^n_1 = \begin{cases} \eta^n_1/\eta^n_9; & i = 9, 0, 1, 2 \\ 0; & i = 5, 8 \end{cases}$$

where $\eta^n_1 = \nu^{an}_i/\sigma^{an}_i$.

**Alternate \( n \) weighting:**

$$\gamma^n_1 = \begin{cases} \eta^n_1/\eta^n_9; & i = 9, 1, 5 \\ 0; & i = 0, 2, 8 \end{cases}$$
British reactivity weighting:

\[
\gamma_i^n = \frac{(\nu \sigma_f - \sigma_a)^n}{(\nu \sigma_f - \sigma_a)_g} - \frac{(\nu \sigma_f - \sigma_a)_g}{(\nu \sigma_f - \sigma_a)^n} ; \quad \text{all } i
\]

Using the standard weights, the breeding ratio as a form for this research use is derived as follows:

\[
BR = \sum_n B_n ,
\]

(2-30)

where \( B_n \) is the individual breeding ratio in region \( n \) and given by

\[
B_n = \frac{\sum_j c_j^n}{\sum_{n1} A_i^n} .
\]

(2-31)

The capture rate, \( c_j^n \), for the fertile isotope \( j \), and the absorption rate, \( A_i^n \), for the fissile isotope \( i \) are calculated with

\[
c_j^n = \sum_g \int V_n \phi^g \Sigma_c^g \phi^g dV ,
\]

(2-32)

\[
A_i^n = \sum_g \int V_n \phi^g (\Sigma_f + \Sigma_c)_i \phi^g dV ,
\]

(2-33)

By solving the integrals with numerical analogy,

\[
c_j^n = \sum_g \sum_{m_n} \phi^g \Sigma_c^g_{j,m_n} V_{m_n} ,
\]

(2-34)

\[
A_i^n = \sum_g \sum_{m_n} \phi^g (\Sigma_f + \Sigma_c)_i \phi^g_{1,m_n} V_{m_n} ,
\]

(2-35)
where \( m_n \) is the index for the mesh volume in region \( n \).

The individual breeding ratio in region \( n \), thus, becomes

\[
B_n = \frac{\sum_j \sum_i \sum_g \phi_{m_n}^g (\Sigma_f + \Sigma_c)^{g}_{j,m_n} V_{m_n}}{\sum_j \sum_i \sum_g \phi_{m_n}^g (\Sigma_f + \Sigma_c)^{g}_{i,m_n} V_{m_n}} \tag{2-36}
\]

and the total breeding ratio is finally given by

\[
BR = \frac{\sum_j \sum_i \sum_g \phi_{m_n}^g (\Sigma_f + \Sigma_c)^{g}_{j,m_n} V_{m_n}}{\sum_j \sum_i \sum_g \phi_{m_n}^g (\Sigma_f + \Sigma_c)^{g}_{i,m_n} V_{m_n}} \tag{2-37}
\]

where

- \( n \) = index for the reactor region,
- \( i \) = fissile nuclide index,
- \( j \) = fertile nuclide index,
- \( g \) = energy group index,
- \( m_n \) = index for a mesh point,
- \( \phi_{m_n}^g \) = neutron flux of group \( g \) at the mesh point labeled by \( m_n \), and
- \( V_{m_n} \) = mesh volume due to the mesh point \( m_n \).

These expressions for calculating the reactor breeding ratio are involved in the subroutine AVERAG of the computer code 2DB shown in Appendix B, and the total breeding ratio and the individual breeding ratio, fission rate, capture rate, and absorption rate are printed out with the region index and material index.
C. Dimensional Analysis

The dimensional analysis, which will be discussed in this section and employed for deriving an empirical function of the breeding ratio, is mentioned with its usefulness and proposed by some articles [12, 18, 27, 66]. Principles of the dimensional analysis could be explained by the following: dimensional analysis gives certain information about the relationships between the measurable quantities associated with various physical phenomena [12, 18]; dimensional analysis as a powerful analytical tool is developed from a consideration of the dimensions in which each of the pertinent quantities involved in a phenomenon is expressed and gives qualitative rather than quantitative relationship [66]; formulation of the dimensional analysis is started with defining a particular physical quantity as

\[ X_1 = f(X_2, X_3, X_4, \ldots, X_n), \quad (2-38) \]

where \( X_1, X_2, \ldots, X_n \) denote the values which are measures of the physical quantity. Each physical quantity involves a number of basic dimensions such as time, length, mass, and so on; therefore, the \( X \)'s can be expressed as follows:

\[
X_1 = (D_{11}^{a_{11}}, D_{21}^{a_{21}}, \ldots, D_{m1}^{a_{m1}}),
\]

\[
X_2 = (D_{12}^{a_{12}}, D_{22}^{a_{22}}, \ldots, D_{m2}^{a_{m2}}),
\]

\[
\vdots
\]

\[
\vdots
\]

\[
(2-39)
\]
where \( D_1 \) \((i = 1, 2, \cdots, m)\) designate the basic dimensions involved and \( \alpha_{ij} \) \((j = 1, 2, \cdots, \lambda)\) are exponents of \( D_1 \) involved in a physical quantity \( X_j \).

The number of dimensionless groups, or \( \Pi \) terms, required to express a phenomenon may be determined from the so-called Buckingham \( \Pi \) Theorem. The nondimensional terms are of great utility in design, more particularly when a complete quantitative theory is lacking and the data on which the design is based are derived from experiments [27].

1. **The Buckingham \( \Pi \) Theorem**

The number of dimensionless and independent quantities required to express a relationship among the variables in any phenomenon is equal to the number of quantities involved, minus the number of dimensions in which those quantities may be measured [66]. The \( \Pi \) Theorem is restated in equation form as

\[
\pi = \lambda - m , \quad (2-40)
\]

where

\[
\begin{align*}
\pi &= \text{number of nondimensional terms (\( \pi \)-terms)}, \\
\lambda &= \text{total number of quantities involved} \quad (\text{\( X \)-terms}), \text{ and} \\
m &= \text{total number of basic dimensions involved}
\end{align*}
\]
The proof of this theorem is given by Murphy [66]. Thus, Eq. (2-38) can be written in \( \pi \)-terms as

\[
\pi_1 = F(\pi_2, \pi_3, \pi_4, \ldots, \pi_n).
\]

This expression is very useful in technical physics, as well as being important in theoretical investigations; however, there is the important restriction mentioned by Murphy [66], that the \( \Pi \) terms be dimensionless and independent.

2. Application of dimensional analysis

The formulation of a suitable type of equation will be the next step of the dimensional analysis. The nature of the prediction equation which may be formulated must be established first. This may be done from an analysis of laboratory observations rather than by dimensional analysis. For convenience, \( \pi_1 \) will be called the dependent variable and \( \pi_i \) \((i = 2, 3, \ldots, n)\) will be called independent variables. At first, a series of relationships between \( \pi_1 \) and each of the \( \Pi \) terms in the function must be established in a form

\[
(\pi_1)_i = f_i(\pi_1) = F(\pi_2, \pi_3, \ldots, \pi_i, \ldots, \pi_n); \quad i = 2, 3, \ldots, n \quad (2-42)
\]

in which the upper bar denotes constant values and \( \pi_i \) denotes
values depending only on $\pi_1$. How these functions based on each $P_1$ term would contribute to the general function shown in Eq. (2-41) in separate or in combinational form may be investigated through some tests. The investigation, however, is not always simple, and increases in complexity with increasing $P_1$ terms involved in the general function like Eq. (2-41).

Each individual function, $f_1(\pi_1)$, may contribute to the list of the function in one of the three cases; those are

(i) $\pi_1 = f_1^{(1)}(\pi_1) + F(\pi_2, \pi_3, \ldots, \overline{\pi}_1, \ldots, \pi_n) + C$, (2-43)

(ii) $\pi_1 = C f_1^{(1)}(\pi_1) F(\pi_2, \pi_3, \ldots, \overline{\pi}_1, \ldots, \pi_n)$, (2-44)

(iii) neither of these two,

where $C$ represents a constant which will be evaluated from test data.

Case i (additive contribution): Presumably the general function has a form

\[ F(\pi_2, \pi_3, \ldots, \pi_1, \ldots, \pi_j, \ldots, \pi_n) = f_1^{(1)}(\pi_1) + F(\pi_2, \pi_3, \ldots, \overline{\pi}_1, \ldots, \pi_j, \ldots, \pi_n) + C, \]

(2-45)

where $C$ is a constant and given by

\[ C = -F(\pi_2, \pi_3, \ldots, \overline{\pi}_1, \ldots, \overline{\pi}_j, \ldots, \overline{\pi}_n). \]
For the first test option, one could investigate if the \( \pi_1 \) function would contribute to the general function in additive form.

**Test 1:**

\[
F(\pi_2, \pi_3, \ldots, \pi_1, \ldots, \pi_j, \ldots, \pi_n) + F(\pi_2, \pi_3, \ldots, \pi_1, \ldots, \pi_j, \ldots, \pi_n) + F(\pi_2, \pi_3, \ldots, \pi_1, \ldots, \pi_j, \ldots, \pi_n).
\] (2-47)

**Case ii (function separable):** If the general function would be in a form

\[
F(\pi_2, \pi_3, \ldots, \pi_1, \ldots, \pi_j, \ldots, \pi_n) = C f_1(\pi_1) \cdot F(\pi_2, \pi_3, \ldots, \pi_1, \ldots, \pi_j, \ldots, \pi_n)
\] (2-48)

where \( C \) is a constant and given by

\[
C = \frac{1}{F(\pi_2, \pi_3, \ldots, \pi_1, \ldots, \pi_j, \ldots, \pi_n)}.
\] (2-49)

For the second test, whether the \( \pi_1 \) function would contribute to the general function in a product form, the test function is

**Test 2:**

\[
\frac{F(\pi_2, \pi_3, \ldots, \pi_1, \ldots, \pi_j, \ldots, \pi_n)}{F(\pi_2, \pi_3, \ldots, \pi_1, \ldots, \pi_j, \ldots, \pi_n)} \cdot \frac{F(\pi_2, \pi_3, \ldots, \pi_1, \ldots, \pi_j, \ldots, \pi_n)}{F(\pi_2, \pi_3, \ldots, \pi_1, \ldots, \pi_j, \ldots, \pi_n)}.
\] (2-50)

If the function of \( \pi_1 \) terms does not satisfy either
of Test 1 or Test 2, it might contribute to the general equation in some other form, such as

\[
F(\pi_2, \pi_3, \ldots, \pi_i, \ldots, \pi_j, \ldots, \pi_n) \\
= F(\pi_2, \pi_3, \ldots, \pi_i, \ldots, \pi_j, \ldots, \pi_n) \cdot F(\pi_2, \pi_3, \ldots, \pi_i, \ldots, \pi_j, \ldots, \pi_n) \\
+ F(\pi_2, \pi_3, \ldots, \pi_i, \ldots, \pi_j, \ldots, \pi_n) + C .
\] (2-51)

In the third case given by Eq. (2-51) as an example, there is no simple way to find the most probable combination of \(\pi_i\) and \(\pi_j\) functions, particularly for a general function involving many \(\pi\) terms. Nevertheless, by enforcing the previous two tests all through \(\pi\) terms, the \(\pi\) terms of which the function could pass either of the tests could be taken aside from the general function to make the following analysis somewhat easier. The combination of four independent variables will be considered for further discussion. The general function for four independent \(\pi\) terms is given by

\[
\pi_1 = F(\pi_2, \pi_3, \pi_4, \pi_5) .
\] (2-52)

Four sets of the experimental data generate the individual \(\pi\) function, and one experiment is carried out by varying \(\pi_2\) and holding \(\pi_3, \pi_4\) and \(\pi_5\) constants to obtain the \(\pi_2\) function, that is

\[
(\pi_1)_2 = f_2(\pi_2) = F(\pi_2, \pi_3, \pi_4, \pi_5) ,
\] (2-53)
in which all notations are of the same type as in the previous part in this section. Simultaneously, other individual Pi functions are obtained and given by

\[(\pi_1)_3 = f_3(\pi_3) = F(\pi_2, \pi_3, \pi_4, \pi_5), \quad (2-54)\]
\[(\pi_1)_4 = f_4(\pi_4) = F(\pi_2, \pi_3, \pi_4, \pi_5), \quad (2-55)\]
\[(\pi_1)_5 = f_5(\pi_5) = F(\pi_2, \pi_3, \pi_4, \pi_5). \quad (2-56)\]

The functional symbols \(f\) and \(F\) are being used for experimental and general functions, respectively, in this section.

The general function for the case with four independent Pi terms involved may be assumed to be any one of the following nine types of functions. If all of the \(f\)-functions would satisfy the first test, the \(F\)-function (or general function) might have a form

\[(1) \pi_1 = f_2(\pi_2) + f_3(\pi_3) + f_4(\pi_4) + f_5(\pi_5) + C. \quad (2-57)\]

On the other hand, if all of the \(f\)-functions would satisfactorily pass the second test, the \(F\)-function might be in a form

\[(2) \pi_1 = C f_2(\pi_2) f_3(\pi_3) f_4(\pi_4) f_5(\pi_5). \quad (2-58)\]

If only two of the four \(f\)-functions would satisfy the first test,

\[(3) \pi_1 = f_2(\pi_2) + f_3(\pi_3) + C_1 f_4(\pi_4) f_5(\pi_5) + C_2. \quad (2-59)\]
For the next, if only two of the f-functions would pass the second test,

(4) \( \pi_1 = c_1 f_2(\pi_2) f_3(\pi_3) [f_4(\pi_4) + f_5(\pi_5) + c_2]. \) (2-60)

If any one of the f-functions would pass the first test and the other three would not, the F-function might be of either of the following two forms:

(5) \( \pi_1 = f_2(\pi_2) + c_1 f_3(\pi_3) [f_4(\pi_4) + f_5(\pi_5) + c_2], \) (2-61)

(6) \( \pi_1 = f_2(\pi_2) + c_1 f_3(\pi_3) [f_4(\pi_4) + f_5(\pi_5) + c_2] + c_3. \) (2-62)

If only one of the f-functions would satisfy the condition of the second test, the F-function might be of either of the following two forms:

(7) \( \pi_1 = c_1 f_2(\pi_2) [f_3(\pi_3) + f_4(\pi_4) + f_5(\pi_5) + c_2], \) (2-63)

(8) \( \pi_1 = c_1 f_2(\pi_2) [f_3(\pi_3) + c_2 f_4(\pi_4) + f_5(\pi_5) + c_3]. \) (2-64)

For the worst case, namely none of the f-functions satisfy either of the two tests, the F-function might be in the following form or another not identified so far:

(9) \( \pi_1 = c_1 f_2(\pi_2) f_3(\pi_3) + c_2 f_4(\pi_4) f_5(\pi_5) + c_3. \) (2-65)
If one, at least, of the f-functions satisfies either of the two tests, the next analysis will be easier because the number of Pi-terms involved in the F-function can be reduced. If none of them, however, is proved as an additive or productive contribution to the F-function, the analysis becomes much more complicated. The worst type of the F-function involving four independent Pi terms will be considered by assuming that F-function is of the form like Eq. (2-65).

\[
F(\pi_2, \pi_3, \pi_4, \pi_5) = C_1f_2(\pi_2, \overline{\pi}_3, \overline{\pi}_4, \overline{\pi}_5) \cdot f_3(\overline{\pi}_2, \pi_3, \overline{\pi}_4, \overline{\pi}_5) \\
+ C_2f_4(\pi_2, \overline{\pi}_3, \pi_4, \overline{\pi}_5) \cdot f_5(\overline{\pi}_2, \overline{\pi}_3, \pi_4, \pi_5) \\
+ C_3 \tag{2-66}
\]

This is what one would call a presumable function, and then leads to the following four equations:

\[
F(\pi_2, \overline{\pi}_3, \pi_4, \overline{\pi}_5) = C_1f_2(\pi_2, \overline{\pi}_3, \pi_4, \overline{\pi}_5) \cdot f_3(\overline{\pi}_2, \overline{\pi}_3, \pi_4, \overline{\pi}_5) \\
+ C_2f_4(\pi_2, \overline{\pi}_3, \pi_4, \overline{\pi}_5) \cdot f_5(\overline{\pi}_2, \overline{\pi}_3, \pi_4, \overline{\pi}_5) \\
+ C_3 \tag{2-67}
\]

\[
F(\overline{\pi}_2, \pi_3, \pi_4, \overline{\pi}_5) = C_1f_2(\overline{\pi}_2, \pi_3, \overline{\pi}_4, \overline{\pi}_5) \cdot f_3(\overline{\pi}_2, \pi_3, \overline{\pi}_4, \overline{\pi}_5) \\
+ C_2f_4(\overline{\pi}_2, \pi_3, \pi_4, \overline{\pi}_5) \cdot f_5(\overline{\pi}_2, \pi_3, \pi_4, \overline{\pi}_5) \\
+ C_3 \tag{2-68}
\]
\[ F(\pi_2, \pi_3, \pi_4, \pi_5) = C_1 f_2(\pi_2, \pi_3, \pi_4, \pi_5) f_3(\pi_2, \pi_3, \pi_4, \pi_5) + C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) f_5(\pi_2, \pi_3, \pi_4, \pi_5) + C_3 \]  

(2-69)

\[ F(\pi_2, \pi_3, \pi_4, \pi_5) = C_1 f_2(\pi_2, \pi_3, \pi_4, \pi_5) f_3(\pi_2, \pi_3, \pi_4, \pi_5) + C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) f_5(\pi_2, \pi_3, \pi_4, \pi_5) + C_3 \]  

(2-70)

And then, from these:

\[ f_2(\pi_2, \pi_3, \pi_4, \pi_5) \]  

(2-71)

\[ = \frac{F(\pi_2, \pi_3, \pi_4, \pi_5)}{C_1 f_3(\pi_2, \pi_3, \pi_4, \pi_5)} - C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) f_5(\pi_2, \pi_3, \pi_4, \pi_5) - C_3, \]

(2-72)

\[ f_3(\pi_2, \pi_3, \pi_4, \pi_5) \]  

(2-73)

\[ = \frac{F(\pi_2, \pi_3, \pi_4, \pi_5)}{C_1 f_2(\pi_2, \pi_3, \pi_4, \pi_5)} - C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) f_5(\pi_2, \pi_3, \pi_4, \pi_5) - C_3, \]

(2-74)

\[ f_4(\pi_2, \pi_3, \pi_4, \pi_5) \]  

(2-75)

\[ = \frac{F(\pi_2, \pi_3, \pi_4, \pi_5)}{C_1 f_2(\pi_2, \pi_3, \pi_4, \pi_5)} - C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) f_5(\pi_2, \pi_3, \pi_4, \pi_5) - C_3, \]

(2-76)

\[ f_5(\pi_2, \pi_3, \pi_4, \pi_5) \]  

(2-77)

\[ = \frac{F(\pi_2, \pi_3, \pi_4, \pi_5)}{C_1 f_2(\pi_2, \pi_3, \pi_4, \pi_5)} - C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) f_5(\pi_2, \pi_3, \pi_4, \pi_5) - C_3. \]

(2-78)

By substituting these four equations into Eq. (2-66), the general F-function becomes
\[ F(\pi_2, \pi_3, \pi_4, \pi_5) \]
\[ = \frac{F(\pi_2, \pi_3, \pi_4, \pi_5) - C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) \cdot f_5(\pi_2, \pi_3, \pi_4, \pi_5) - C_3}{C_1 f_2(\pi_2, \pi_3, \pi_4, \pi_5) \cdot f_3(\pi_2, \pi_3, \pi_4, \pi_5)} \]
\[ \cdot \left[ F(\pi_2, \pi_3, \pi_4, \pi_5) - C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) \cdot f_5(\pi_2, \pi_3, \pi_4, \pi_5) - C_3 \right] \]
\[ + \frac{F(\pi_2, \pi_3, \pi_4, \pi_5) - C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) \cdot f_5(\pi_2, \pi_3, \pi_4, \pi_5) - C_3}{C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) \cdot f_5(\pi_2, \pi_3, \pi_4, \pi_5)} \cdot f_3(\pi_2, \pi_3, \pi_4, \pi_5) - C_3 \]
\[ + C_3, \quad (2-75) \]

or

\[ F(\pi_2, \pi_3, \pi_4, \pi_5) \]
\[ = \frac{F(\pi_2, \pi_3, \pi_4, \pi_5) \cdot F(\pi_2, \pi_3, \pi_4, \pi_5)}{C_1 f_2(\pi_2, \pi_3, \pi_4, \pi_5) \cdot f_3(\pi_2, \pi_3, \pi_4, \pi_5)} \]
\[ + \frac{F(\pi_2, \pi_3, \pi_4, \pi_5) \cdot F(\pi_2, \pi_3, \pi_4, \pi_5)}{C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) \cdot f_5(\pi_2, \pi_3, \pi_4, \pi_5)} \cdot f_3(\pi_2, \pi_3, \pi_4, \pi_5) - C_3 \]
\[ - \frac{C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) \cdot f_5(\pi_2, \pi_3, \pi_4, \pi_5) + C_3}{C_1 f_2(\pi_2, \pi_3, \pi_4, \pi_5) \cdot f_3(\pi_2, \pi_3, \pi_4, \pi_5)} \]
\[ \cdot \left[ F(\pi_2, \pi_3, \pi_4, \pi_5) + F(\pi_2, \pi_3, \pi_4, \pi_5) \right] \]
\[ - \frac{C_1 f_2(\pi_2, \pi_3, \pi_4, \pi_5) \cdot f_3(\pi_2, \pi_3, \pi_4, \pi_5) + C_3}{C_2 f_4(\pi_2, \pi_3, \pi_4, \pi_5) \cdot f_5(\pi_2, \pi_3, \pi_4, \pi_5)} \]
Contrasting Eq. (2-76) with Eq. (2-66), the third and the fourth terms should be eliminated by setting their coefficient to be zero, namely

$$\begin{align*}
C_2 f_4 (\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) \cdot f_3 (\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) + C_3 = 0, \\
C_2 f_4 (\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) \cdot f_5 (\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) + C_3 = 0.
\end{align*}$$

By combining these with Eq. (2-66), the following relationships are derived.

$$\begin{align*}
C_1 f_2 (\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) \cdot f_3 (\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) = F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5), \\
C_2 f_4 (\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) \cdot f_5 (\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) = F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5),
\end{align*}$$

and

$$C_3 = -F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5).$$
By substituting these into Eq. (2-78), the F-function thus becomes

\[ F(\pi_2, \pi_3, \pi_4, \pi_5) = \frac{F(\pi_2, \pi_3, \pi_4, \pi_5) \cdot F(\pi_2, \pi_3, \pi_4, \pi_5)}{F(\pi_2, \pi_3, \pi_4, \pi_5)} + \frac{F(\pi_2, \pi_3, \pi_4, \pi_5) \cdot F(\pi_2, \pi_3, \pi_4, \pi_5)}{F(\pi_2, \pi_3, \pi_4, \pi_5)} - F(\pi_2, \pi_3, \pi_4, \pi_5). \] (2-82)

In order to investigate the validity of this, the test 3 will be applied using the following test function, that is

Test 3:

\[ \frac{F(\pi_2, \pi_3, \pi_4, \pi_5)}{F(\pi_2, \pi_3, \pi_4, \pi_5)} \leq \frac{\text{Numerator}}{\text{Denominator}}, \] (2-83)

where

Numerator = \[ F(\pi_2, \pi_3, \pi_4, \pi_5) \cdot F(\pi_2, \pi_3, \pi_4, \pi_5) \]

\[ + F(\pi_2, \pi_3, \pi_4, \pi_5) \cdot F(\pi_2, \pi_3, \pi_4, \pi_5) \]

\[ - \left[ F(\pi_2, \pi_3, \pi_4, \pi_5) \right]^2, \]
Denominator = \[ F(\pi_2, \pi_3, \pi_4, \pi_5) \cdot F(\overline{\pi}_2, \pi_3, \pi_4, \pi_5) \]
\[ + F(\pi_2, \pi_3, \pi_4, \pi_5) \cdot F(\overline{\pi}_2, \overline{\pi}_3, \pi_4, \pi_5) \]
\[ - [F(\pi_2, \pi_3, \pi_4, \pi_5)]^2. \]

This test should be repeated for three different combinations, which are

1. \( f_2(\pi_2) \cdot f_3(\pi_3) + f_4(\pi_4) \cdot f_5(\pi_5), \)
2. \( f_2(\pi_2) \cdot f_4(\pi_4) + f_3(\pi_3) \cdot f_5(\pi_5), \)
3. \( f_2(\pi_2) \cdot f_5(\pi_5) + f_3(\pi_3) \cdot f_4(\pi_4), \)

and then the most suitable combination will be found.

D. Optimization Methods

Various optimization methods will be classified, and some of them will be discussed in detail in this section, however, a comparison of these methods and a consideration of which is the most feasible one is considered later.

In general, an optimization problem can be formulated as follows:

Find a point \( \hat{x} \) for which the relation

\[ F(\hat{x}) + \text{minimum}; \hat{x} = (x_1, x_2, \ldots, x_n)^T \]  

(2-84)
subject to

\[ f_i(\hat{x}) \{<, =, \geq\} 0; \quad i=1,2,\ldots,m. \quad (2-85) \]

Here \( \hat{x} \) is an \( n \)-dimensional vector, the components of which are the independent variables, and \( F(\hat{x}) \) and \( f_i(\hat{x}) \) are called the objective function and the constrained functions, respectively.

For the sake of definiteness, the objective function, \( F(\hat{x}) \), and the vector \( \hat{x} \) are all assumed to be in the \( n \)-dimensional Euclidean space \( \mathbb{R}^n \), and the constrained functions, \( f_i(\hat{x}) \) will be defined a subset of \( \mathbb{R}^n \). In order to succeed in the optimization, one must assume that \( F(\hat{x}) \) has a unique minimum in the space \( \mathbb{R}^n \) for the unconstrained problem or in the subset of \( \mathbb{R}^n \) for the constrained problem, and that all the partial derivatives of at least first order exist for every components of \( \hat{x} \) in \( \mathbb{R}^n \).

Any optimization problem can be classified strictly into two categories, those are unconstrained optimization and constrained optimization. If each of the variables \( x_1, x_2, \ldots, x_n \) could be allowed to assume any value between \(-\infty\) and \( +\infty \) in seeking the extremum points of the function, this problem is called the unconstrained optimization. While if the choice of values for the independent variables \( \hat{x} \) is restricted by \( m \) constraints given in Eq. (2-85),
this problem is called the constrained optimization. The constrained optimization problem is more practical, however its analysis might be more difficult. The constrained optimization problem is further classified by the type of its constrained functions involved, such as linear or nonlinear and equality or inequality.

Methods of solution of optimization problems are available in variety and discussed in detail by many authors, e.g., Aoki [3], Beveridge and Schechter [14], Daniel [28], Fox [32], Künzi et al. [54], Ladson [56], McMillan [65], Polak [71], Pun [73], and Wismer [94]. Names of the optimization methods are as follows:

Unconstrained optimization methods:

1. Gradient method (steepest descent method),
2. Conjugate direction method (Powell's method),
3. Conjugate gradient method, (Fletcher and Reeves method),
4. Newton-Raphson method,
5. Davidon's method (variable matrix method),
6. One-dimensional search method,
7. Direct search method,
8. Grid and random method,
Constrained optimization methods:

1. Converting methods
   a. Eliminate by transformation,
   b. Motivate by penalty functions.

2. Direct methods
   a. Gradient projection method,
   b. Reduced gradient method.

In recent publications, new methods are also proposed, for instance, "Sequential Search Method" for solving constrained optimization problems [36], "Stochastic Approximation Method" for nonlinear problems [83], a method for a nonlinear objective function with nonlinear constraints [42], "Simplex" and "Complex" methods for nonlinear function [17], and a method for a system of differential equation [74].

In this research, some optimization method needed to be employed for solving a constrained optimization problem. The penalty function method involving the Davidon's method or the conjugate gradient method is tried for the optimization of a core shape, which will be discussed in Chapter V. Why these methods were selected are simply because the penalty function method is very good for a beginner who starts to learn the optimization methods [70], and for the Davidon's and the conjugate gradient methods, they are very popular and also their computer programs written in
FORTRAN IV were found from Ref. [51].

a. **The penalty function method**  The penalty function method is one of the techniques for converting constrained problems into unconstrained problems. The objective function of the constrained problem is suitably modified by some functions of the constraint equations, and the optimized point in the constrained region can be obtained as the limit of a sequence of unconstrained optimized point of that modified objective function.

The penalty function method can be used to remove the constraint equations by incorporating them into the objective function of the inequality constrained problems. The penalty function formulations in general use can be divided into two categories: exterior penalty function method and interior penalty function method. The basic idea of the exterior method is to modify the objective function in such a way that the values of the modified objective function within the feasible region defined by the constraints are exactly or approximately equal to those of the objective function, while its value outside the feasible region is very large compared with those of the objective function. The interior penalty function method modifies the objective function by adding some multiple of the negative of the inverse of the constraint equations to form a new objective function.
If the constrained optimization problem can be given in Eq. (2-84) rewritten as

\[ F(\hat{x}) \rightarrow \text{minimize} \quad (2-86) \]

subjected to all negative inequality constraints as

\[ f_i(\hat{x}) \leq 0; \quad i = 1, 2, \ldots, m, \quad (2-87) \]

then the modified objective functions for use of the exterior and the interior penalty function methods are given by

\[ \text{Exterior: } \phi(\hat{x}, K) = F(\hat{x}) + K \sum_{i=1}^{m} (f_i(\hat{x}))^a, \quad (2-88) \]

\[ \text{Interior: } \phi(\hat{x}, K) = F(\hat{x}) - K \sum_{i=1}^{m} \frac{1}{f_i(\hat{x})}, \quad (2-89) \]

where \( K > 0 \), \( a \geq 1 \), and the bracket function (or bracket operator) \( < \cdot > \) means

\[ <f> = \begin{cases} 
  f, & \text{for } f \geq 0, \\
  0, & \text{for } f < 0. 
\end{cases} \]

The framework of the penalty function method for finding the solution to the inequality constrained problem is shown as a logic diagram in Fig. 13.
Figure 13. Logic diagram for the penalty function method
b. The conjugate gradient method

The conjugate gradient method was originally developed by Hestenes and Stiefel in 1952 to solve a set of simultaneous equations with a positive definite matrix of coefficients [3], but this method is also called "Fletcher and Reeves Method" in honor of the men who greatly developed this method [32].

The algorithm of the conjugate gradient method must be started by assuming that the objective function, \( F(\hat{x}) \), is quadratic with a positive definite matrix \( Q \) which is usually replaced by Hessian matrix

\[
H(x) = \begin{bmatrix} \frac{\partial^2 F(x)}{\partial x_i \partial x_j} \end{bmatrix}_{n \times n} \tag{2-91}
\]

Since \( \frac{\partial^2 F}{\partial x_i \partial x_j} = \frac{\partial^2 F}{\partial x_j \partial x_i} \), \( H(\hat{x}) \) is a real symmetric matrix.

Any descent method generates \( \hat{x}^k \) by

\[
\hat{x}^{k+1} = \hat{x}^k + t_k \hat{d}^k \tag{2-92}
\]

where \( \hat{d} \) is the direction unit vector and \( t \) is the step size. Any directions are feasible for unconstrained problems since there is no constraints to be violated, however not all directions are usable. For example, it is foolish to use a direction \( \hat{d} \) unless

\[
F(\hat{x} + t\hat{d}) < F(\hat{x}) \tag{2-93}
\]
for some sufficiently small \( t \), that is, unless the function value decreases in the direction \( d \), at least locally. Computation methods for the \( t \) and \( \hat{d} \) are different for each descent methods. In other words, the main characteristics of the methods are seen in these calculation techniques.

The original idea of the decent methods are derived by Taylor series expansion, and the direction \( \hat{d} \) vectors are generated as

\[
\hat{d}^k = \hat{r}^k + \beta_{k-1} \hat{d}^{k-1}, \quad k = 1, 2, \ldots \\
\hat{d}^0 = -\hat{r}^0
\]  

(2-94)

where \( \hat{r} \) is the gradient vector, i.e.,

\[
\hat{r}^k = \nabla F(x^k),
\]  

(2-95)

and \( \beta_{k-1} \) is chosen to make \( \hat{d}^k \) \( Q \)-conjugate to the previously generated \( \hat{d}^{k-1} \) and given by

\[
\beta_{k-1} = \frac{\langle \hat{r}^k, Q\hat{d}^{k-1} \rangle}{\langle \hat{d}^{k-1}, \hat{d}^{k-1} \rangle}.
\]  

(2-96)

The step size \( t_k \) is generated by the one-dimensional search in the direction of \( \hat{d}^k \), and given by

\[
t_k = \frac{\langle \hat{r}^k, \hat{d}^k \rangle}{\langle \hat{d}^k, Q\hat{d}^k \rangle},
\]  

(2-97)

or

\[
t_k = -\frac{\langle \hat{r}^k, \hat{r}^k \rangle}{\langle \hat{r}^k, Q\hat{d}^k \rangle}.
\]  

(2-98)
As a summary for the conjugate gradient method, its logical diagram is shown in Fig. 14, in which some equations are simplified by the relation \( \mathbf{d}^k = (\mathbf{r}^{k+1} - \mathbf{r}^k) / t_k \).

The advantages of the conjugate gradient method are as follows:

1. Rapidly convergent technique suitable for use when the gradient of the function is readily computed [32].
2. One of the most effective minimization techniques with careful application [32].
3. Particular advantages are its simplicity and its modest demands on storage, space for only three vectors being required [31].
4. Significant advantage when the number of variable is large [56].
5. The gradient methods appear to converge more rapidly than the direct search methods [14].
6. As compared with other gradient methods, much better and approximate the performance of second-order methods [94].

c. The Davidon's method  The Davidon's method was originally developed and modified from the Newton-Raphson method by Davidon [29]. To use the Newton-Raphson method, the Hessian matrix of the function must be derived, however,
Figure 14. Logic diagram for the conjugate gradient method.
in many optimization problems the Hessian matrices are not available, are very expensive to compute, or are available only numerically. The Davidon's method, which is now to be described, solves these difficulties.

To find a minimum point of $F(x)$ in $\mathbb{R}^n$ might be equivalent to find a root of $\dot{F}(x)=0$. A straightforward generalization of Newton's method of finding a root of a function of a scalar variable is applicable to finding a root of $\dot{F}(x) = 0$. The Taylor series expansion gives

$$0 = \dot{F}(x^{k+1}) = \dot{F}(x^k) + H(x^k)(x^{k+1} - x^k) \tag{2-99}$$

or the minimum point $x^{k+1}$ is generated by the formula

$$x^{k+1} = x^k - H^{-1}(x^k)\dot{F}(x^k), \tag{2-100}$$

where $H^{-1}(x^k)$ is an inversed Hessian matrix of $F(x)$ at the point of $x^k$.

Thus the algorithm of the Davidon's method can be summarized with following equations:

$$x^{k+1} = x^k - t_k H_k x^k, \tag{2-101}$$

$$H_{k+1} = H_k - \frac{H_k \hat{v}_k <H_k \hat{v}_k>}{<\hat{v}_k H_k \hat{v}_k>} + \frac{\hat{p}_k <\hat{p}_k>}{<\hat{v}_k, \hat{p}_k>}, \tag{2-102}$$

$k = 0, 1, ...$
where $H_0$ is chosen arbitrarily to be positive definite, the step size $t_k$ is given by

$$t_k = \frac{\langle \hat{r}^k, H_k \hat{r}^k \rangle}{\langle H_k \hat{r}^k, QH_k \hat{r}^k \rangle} \quad (2-103)$$

and a new vector $\hat{y}$ is defined as

$$\hat{y}^k = \hat{r}^{k+1} - \hat{r}^k. \quad (2-104)$$

The iteration for the Davidon's method proceeds as follows:

1. Start with an initial $\hat{x}^0$ and an initial positive definite symmetric matrix $H_0$ (e.g., the identity matrix), and set $\hat{d}^0 = -H_0 \hat{r}^0$
2. Compute $\hat{x}^{k+1} = \hat{x}^k + t_k \hat{d}^k$, where $t_k$ minimize $F(\hat{x}^{k+1})$.
3. Compute $H_{k+1}$ Eq. (2-102)
4. Compute $d^{k+1} = -H_{k+1} \hat{r}^{k+1}$, and repeat from step 2.

The characteristics of the Davidon's method have been pointed out by several articles [14, 32, 56, 70].

1. This method can be applied to find a local minimum of a general function of a large number of variables whose first derivatives can be evaluated quickly, even if only poor initial approximations to a solution are known.
2. Extremely powerful algorithm for a first-order method, quadratical convergence and very good stable possessing.

3. The Fletcher-Reeves algorithm is simple and fast, while the variable metric algorithms follow somewhat behind.
III. DESIGN OF CORE-BLANKET SYSTEM

A. Design Model Configuration

In order to study the geometrical effect of fast reactor characteristics and to find the "clear-cut" one, a particular design model is considered. The model is required to be applicable to many different shaped cores. In other words, the model needs to be adaptable to many geometrically different cores, i.e., pancake, 4-module, annular or any others, by changing its geometrical variable(s).

In this research, the two most popularly designed cores, pancake and 4-module, were comparatively studied, and a medium-shaped core model shown in Fig. 15 was developed. By giving a certain value to one of the geometrical variables indicated in Fig. 16, the model can be both shaped cores. If the radius, \( r_1 \), of the inner core region is given a value of zero, the model is a typical 4-module core. Similarly, if the width, \( l_3 \), of the outer core region is taken to be zero, or if the angle, \( \theta \), of the separating blanket region is 90°, the model has a typical pancake shape. The systematic convenience of the core analysis model is schematically shown in Fig. 17.

The model system is separated into five different zones; these are called inner core (IC), outer core (OC), inner radial blanket (IB), outer radial blanket (OB), and
Figure 15. Analysis model of core-blanket system
Figure 16. Mesh map of the quarter design model
Figure 17. Systematic analysis model of the core-blanket systems
separating blanket (SB). An axial blanket could not be involved because a 2-dimensional calculation was employed for this research as mentioned in Chapter I. In general, the outer core contains higher enriched fuel than the inner core to make the peaking ratio close to unity. In the core designed in this research, this different enriched fuel system was considered. The detail of the fuel components will be discussed in the next section.

The model has quarterly symmetry on the r-θ plane as shown in Fig. 15, therefore only one quarter of the system is taken for critical calculations with r-θ geometry. The mesh map and zones for the critical calculations are indicated in Fig. 16. As shown in Fig. 10, the four boundary conditions required by the calculations are vacuum boundary on the arc side, reflective boundary on the center point, and periodic boundaries on left and bottom plane face in Fig. 16.

Expecting acceptable accuracy on the computation results, the mesh sizes were selected as \( \sim 10 \text{ cm} \) for the r-mesh and \( \sim 5.6^\circ \) for the θ-mesh.

For this investigation, the bare core height (H) and the thickness \( (\ell_4) \) of the outer radial blanket were kept their common values of \( H = 100 \text{ cm} \) and \( \ell_4 = 30 \text{ cm} \). Thus \( \ell_1, \ell_2, \ell_3, \) and θ were considered as variables for the geometrical effect investigation.
Beside these homogenized core and blanket regions, any other material zones like reflector and only-coolant region were not involved for the critical calculations.

B. Input Data for Critical Calculations

In order to place great emphasis on the geometrical effect investigation, only input parameters which are necessary and indispensable to an LMFBR core-blanket assemblies are considered. If accurate results are desired in the critical calculation of actual cores, careful choice of its components and proper treatment of cross section data is essential. Ideally, a multigroup cross section set should be prepared for interest starting from a microscopic data file such as ENDF/B and using a cross section code such as MC² to produce the multigroup sets [22]. Such an undertaking is beyond the scope and resources of this thesis research.

Five main materials, U-238, Pu-239, C, Na, and Fe were selected as indispensable components of the LMFBR core-blanket system. Fertile isotope U-238 and fissile isotope Pu-239 are contained in carbide fuel. Sodium and iron are of course, main components of liquid metal coolant and stainless steel structure, respectively. These fuel, coolant and structure materials are contained in all regions with the same fractions as listed in Table 1. The volume
fraction parameters were taken, on the average, from the reference design studies discussed in Section I-A.

Table I. Components commonly contained in all regions and for all designed systems

<table>
<thead>
<tr>
<th></th>
<th>Fuel (U+Pu)(^a)</th>
<th>Coolant</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material compositions (wt. %)</td>
<td>79.4</td>
<td>4.5</td>
<td>16.1</td>
</tr>
<tr>
<td>Volume fractions (vol. %)</td>
<td>45.6</td>
<td>38.9</td>
<td>15.5</td>
</tr>
<tr>
<td>Atom densities (atoms/barns-cm)</td>
<td>0.0115</td>
<td>0.0166</td>
<td>0.0073</td>
</tr>
<tr>
<td>Geometrical buckling(^b), (B^2 = 0.00153 \text{ cm}^{-2})</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Fuel contains U\(^{238}\) and Pu\(^{239}\) isotopes only.

\(^b\)The buckling in z-direction only.

For the core design calculations described in this thesis, the cross section set for two energy groups was taken from BNWL's 2DB users manual [57]. Other cross section sets taken from Bondarenko's [15] and ANL-5800 [7] had been considered for use before the final decision was made. Since these two later sets do not involve a suitable two group cross section set, it had to be calculated from multigroup sets. Therefore some computational error obviously might exist in the derived cross section set. Any error caused by
Inaccurate cross section data could be checked by the code, 2DB. From these reasons, BNWL's 2-group cross section set was selected.

The two energy groups are separated at 0.1 MeV with their fission spectrogram listed in Table II. The microscopic cross sections of all interesting materials are tabulated in Table III.

<table>
<thead>
<tr>
<th>Table II. Energy group parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group index</td>
</tr>
<tr>
<td>Energy range (MeV)</td>
</tr>
<tr>
<td>Fission spectrum</td>
</tr>
<tr>
<td>Neutron velocity ($10^8$ cm/sec)</td>
</tr>
</tbody>
</table>

The input data which are required for the critical calculations with the computer code, 2DB, are discussed in Appendix B, but one of the input data should be described in detail, that is a geometrical buckling.

The geometrical buckling is an important input parameter particularly for calculation with r-θ coordinates. As a matter of fact, there is no input datum section in 2DB for a core-height information even in the r-θ geometric calculation of a cylindrical assembly (see Appendix B). Only the geometrical buckling input value takes a role of the third constant coordinate information. The buckling $B^2$ of
Table III. Microscopic cross sections of the core components$^a$

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_f$</th>
<th>$\sigma_c$</th>
<th>$\sigma_{tr}$</th>
<th>$\nu_\sigma_f$</th>
<th>$\sigma_{i+1}$</th>
<th>$\sigma_{i-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-238</td>
<td>1 1.0010E-1</td>
<td>2.3289E-1</td>
<td>2.8144E-1</td>
<td>6.3357E+0</td>
<td>6.0052E+0</td>
<td>9.7561E-2</td>
</tr>
<tr>
<td></td>
<td>2 0.0000E+0</td>
<td>5.3219E-1</td>
<td>0.0000E+0</td>
<td>1.3158E+1</td>
<td>1.2626E+1</td>
<td>-</td>
</tr>
<tr>
<td>Pu-239</td>
<td>1 1.7244E+0</td>
<td>1.8487E+0</td>
<td>5.1150E+0</td>
<td>6.6936E+0</td>
<td>4.7659E+0</td>
<td>7.9040E-2</td>
</tr>
<tr>
<td></td>
<td>2 2.2842E+0</td>
<td>3.2401E+0</td>
<td>6.4950E+0</td>
<td>1.3918E+1</td>
<td>1.0678E+1</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>1 0.0000E+0</td>
<td>8.3362E-6</td>
<td>0.0000E+0</td>
<td>2.6393E+0</td>
<td>2.4508E+0</td>
<td>1.8842E-1</td>
</tr>
<tr>
<td></td>
<td>2 0.0000E+0</td>
<td>4.5694E-11</td>
<td>0.0000E+0</td>
<td>4.4855E+0</td>
<td>4.4855E+0</td>
<td>-</td>
</tr>
<tr>
<td>Na</td>
<td>1 0.0000E+0</td>
<td>7.1301E-4</td>
<td>0.0000E+0</td>
<td>3.0902E+0</td>
<td>3.0005E+0</td>
<td>8.8955E-2</td>
</tr>
<tr>
<td></td>
<td>2 0.0000E+0</td>
<td>4.2342E-3</td>
<td>0.0000E+0</td>
<td>4.9846E+0</td>
<td>4.9803E+0</td>
<td>-</td>
</tr>
<tr>
<td>Fe</td>
<td>1 0.0000E+0</td>
<td>5.9178E-3</td>
<td>0.0000E+0</td>
<td>2.5576E+0</td>
<td>2.5175E+0</td>
<td>0.3424E-2</td>
</tr>
<tr>
<td></td>
<td>2 0.0000E+0</td>
<td>2.1543E-2</td>
<td>0.0000E+0</td>
<td>2.8214E+0</td>
<td>4.7999E+0</td>
<td>-</td>
</tr>
</tbody>
</table>

$^a$All cross sections in unit of barns.
where \( d \) is an extrapolation distance. Butler and Cook [19] gives an equation for \( d \) as

\[
d = \frac{2.131338D}{1 + 1.065669(aD)^{\frac{1}{r_R}}},
\]

at the external boundary, where \( a=0, 1, \) or \( 2 \) for plane, cylindrical, or spherical geometry, respectively, \( D \) is the diffusion coefficient, and \( r_R \) is radius of the geometry. At the plane boundary, \( d \) also can be expressed by

\[
d = 0.710446 \lambda_{tr},
\]

where \( \lambda_{tr} \) is a transport mean free path. The calculated results of \( B^2 \) are listed in Table I.

C. General Discussion of the Output

In order to investigate the geometrical effect on core-blanket systems of LMFBR, 15 different combinations of \( l_1, l_2, l_3, \) and \( \theta \) were considered. All these geometrical combinations are listed in Table A-II, and the ranges over which they were evaluated are described in Table IV.
Table IV. Descriptions of the geometrical parameters

<table>
<thead>
<tr>
<th>Parametric symbols&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Variable ranges or constants</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_1 ) (cm)</td>
<td>50-60-70</td>
</tr>
<tr>
<td>( l_2 ) (cm)</td>
<td>10-20-30</td>
</tr>
<tr>
<td>( l_3 ) (cm)</td>
<td>40-50-60</td>
</tr>
<tr>
<td>( l_4 ) (cm)</td>
<td>30</td>
</tr>
<tr>
<td>( \theta ) (arbit.)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.050-0.075-0.100</td>
</tr>
<tr>
<td>H (cm)</td>
<td>100</td>
</tr>
</tbody>
</table>

<sup>a</sup>See Fig. 16.

<sup>b</sup>Arbitrary unit is defined as 360° = 1.000 (arbit.).

Whole copy of the computer output produced by 2DB is listed in Appendix B. The output data are listed in the tables as follows:

1. Input variable definitions and their values,
2. Material components indication,
3. Miscellaneous input data,
4. Zone map,
5. Material mixture map,
6. Material components and its mixture instructions,
7. Information of eigenvalue search iterations,
8. Final neutron balance table,
9. Mesh points configuration,
10. Total flux profiles,
11. Thermal power distribution,
12. Material inventory for each zone,
13. Burnup data taking instruction,
14. Burnup output data for each zone,
15. Breeding ratio data.

In addition to these tables, macroscopic cross sections and groups fluxes are also printed out if they are desired.

The total flux profiles along the four-differently placed radial lines are shown in Fig. 18. The high enrichment of the fuel in the outer core contributes to the flux flattening. These data are from the computer output in Appendix B and this is just one example of the data utilization.

To produce the 15th output table of breeding ratio data, the instructing program was specially made in 2DB for use in this investigation. All breeding ratio data are tabulated in Table A-III and plotted in Figs. 19 to 22. These figures show the geometrical effects on breeding ratio in each region. Concept of the regional breeding ratio is important for management of fuel element and for modification of the core-blanket arrangements. Furthermore, consideration of breeding ratio density may become useful instead of the present concept of only internal and
Figure 18. Total flux distribution along the four radial lines.
Figure 19. Regional breeding ratios depending on the inner core radius.
Figure 20. Regional breeding ratios depending on the inner radial blanket thickness
Figure 7.1. Regional breeding ratios depending on the outer core thickness.
Figure 22. Regional breeding ratios depending on the separating blanket angle
external breeding ratios.

The output data with regard to material inventories and zone volume are due only to the calculation section and unit length on the third coordinate. If the calculation section is one quarter of a cylindrical assembly with a constant core height, $H$, the inventories and volumes of the entire actual assembly, therefore, are derived from the corresponding values in the output time $4H$. 
IV. GEOMETRICAL OPTIMIZATION

A. Preparation for New Optimization Procedure

1. Overall procedure

In order to investigate the best core-blanket configuration, the new technical optimization procedure described generally in Section I-D, was used. Optimization of the breeding ratio of the entire core-blanket system was an objective of the core-design. The four geometrical parameters, \( l_1, l_2, l_3, \) and \( \theta \) (see Fig. 16) are independent variables. The objective function is expected to be expressed as

\[
BR = f(l_1, l_2, l_3, \theta),
\]

(4-1)

where \( BR \) is the breeding ratio and the dependent variable.

Since there is no ready analytical way to express the breeding ratio as a function of these variables, its empirical function was derived by dimensional analysis. At least 15 values of the breeding ratio with different combinations of the 4 independent variables were required to obtain the function. These combinations are listed in Table A-II. The minimum necessary number of data points for the dimensional analysis will be discussed in the next section.

A three-point plotted curve was drawn for obtaining a second-order equation,
ax^2 + bx + c = y, \hspace{1cm} (4-2)

where a, b and c are the coefficients which are to be obtained, and x and y are independent and dependent variables, respectively. If a set of three data on x and y is obtained, the three unknown coefficients can be calculated with three equations.

The four functions of only one independent variable have been derived. Then, the entire function was subjected to the three tests, i.e., Eqs. (2-47), (2-50), and (2-83), to determine its form.

At the stage of applying the ordinary optimization procedures to the empirical function of breeding ratio, a set of constraints was imposed by requirement to the reactor core design. In order to reduce error as much as possible, effective ranges of the derived function were extended to both edges of the plotted data points. Then, linear inequality equations expressing these effective ranges could be the constraints.

The foregoing is only an overview of the procedure for optimizing design of the core-blanket assembly. Additional details are described in the following sections.
2. Variation of breeding ratio

Consideration of all parameters which might cause variation of breeding ratio is a very important preparation for dimensional analysis. All these quantitative parameters should be listed for application of the Buckingham Pi Theorem stated briefly in Section II-C. Thus an exact indication of the total number of quantities involved in the phenomenon (i.e., the breeding ratio variation) and the number of basic dimensions involved in the quantities is the most fundamental preparation required for the dimensional analysis.

The breeding ratio varies with following quantitative parameters of the reactor of interest:

1. Geometrically represented parameters including core height and diameter, fuel pin size, cladding thickness, blanket thickness, and so on;
2. All neutron reaction cross sections of all materials involved;
3. Identification of these materials, which is expressed with other terms, such as concentration, volume fraction, atom density, and enrichment of fuel.

Besides these, temperature effect on cross section and time consideration during the reactor operation might be important to describe the breeding ratio. For the initial core-
design objective only, however these parameters can be neglected.

As a check on the breeding ratio variation phenomenon, some references may be helpful. The breeding ratio variation types are listed with their reporting references as follows:

1. Core breeding ratio, CBR, vs. the ratio of blanket area-to-core area, $A_b/A_c$, taken at midplane [88]. The result shows that CBR decreases exponentially with increasing $A_b/A_c$ and then asymptotically becomes a constant value when $A_b/A_c = 3.0$ of the 2 ft.-diameter core. The curves rise with increasing core diameter.

2. Core and radial blanket breeding ratio, CBBR, vs. $A_b/A_c$ [88]. From the figure, CBBR is slightly increased with increasing $A_b/A_c$; CBBR changes, at most, 0.2 for 8.0 change of $A_b/A_c$.

3. External breeding ratio density, $EBR/V_b$, vs. blanket thickness, $t_b$ [62]. $EBR/V_b$ is exponentially decreased as

$$EBR/V_b \sim e^{-0.5 t_b}$$

4. Effect of clad or structure material on breeding ratio [68]. For the 5000-liter oxide-fueled spherical reactor, the breeding ratios of different structure materials are 1.29 (ss), 1.30 (Fe),
1.37 (Zr), 0.76 (W), and so on. A difference of only 0.01 between stainless steel and pure ion is highly significant for the research reported in this thesis.

5. Comparison of three cross section sets developed by different groups [68]. The deviation of about ± 0.1 on the breeding ratio calculation is reported in the reference. This much deviation might be caused by experimental error, however it also indicates the large effect of cross section in altering the breeding ratio.

6. Comparison of metal and oxide fueled systems on breeding ratio [68]. The breeding ratio of the metal fueled system is 0.45 higher than that of the oxide fueled system.

7. Breeding ratio for various compositions of Pu-isotopes [92].

<table>
<thead>
<tr>
<th>Pu-239</th>
<th>Pu-240</th>
<th>Pu-241</th>
<th>Pu-242</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.8</td>
</tr>
<tr>
<td>74.7</td>
<td>10.2</td>
<td>12.4</td>
<td>2.7</td>
<td>1.9</td>
</tr>
<tr>
<td>.40</td>
<td>10</td>
<td>25</td>
<td>25</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Similar work was reported by Ott [69]. At the very beginning of the period of reactor operation, it can be considered that the component of Pu-239 in the Pu fuel is very close to 100%.
8. Breeding ratio as a function of fuel volume fraction [35]. The results illustrate the smoothly increasing curve. About 0.07 increase results from an increased fuel volume fraction from 38% to 50%.

9. Breeding ratio as a function of sodium coolant volume fraction [88]. A decrease of about 0.2 in the breeding ratio occurs as a complex function of the sodium volume fraction during a change from 30% to 70%.

The first three types correspond to the first category of the parameter classification; the next three, to the second; and the last three, to the third category.

Studying detail of various characteristics of the phenomena may eliminate missing any quantities involved in a consideration of dimensional analysis. The actual derivation for this research is described in the next section.

B. Empirical Function of Breeding Ratio

1. Function of B.R. with Pi terms

Based on the concept of breeding ratio variation, the total breeding ratio is expressed as

\[BR = f(r, \zeta, z, h, \sigma, c).\] (4-3)

Each factor is defined as follows:

1. \(BR\) breeding ratio
2. \(r\) any pertinent distance in radial direction L
3. \( \zeta \) any pertinent angle
4. \( z \) any pertinent distance on axial direction
5. \( h \) a significant distance
6. \( \sigma \) any cross section of materials involved
7. \( c \) any components involved

in which \( L \) denotes the basic dimension of length.

From the Buckingham Pi Theorem, it is apparent that there are six \((7-1=6)\) Pi terms. They may be determined, establishing a possible general equation as

\[
BR = F\left(\frac{r}{h}, \zeta, \frac{z}{h^2}, \frac{\sigma}{h^2}, c\right). \tag{4-4}
\]

For the core-blanket system, this equation is changed by displacing each factor with the design factors (see Fig. 16) as follows:

\[
\begin{align*}
\tau &\rightarrow \lambda_1, \lambda_2, \lambda_3, \lambda_4, \\
\zeta &\rightarrow \theta, \\
z, h &\rightarrow H, \\
c &\rightarrow e_I, e_{II}, c',
\end{align*}
\]

where \( e_I \) and \( e_{II} \) are the critical enrichment of fuel in the region I (inner core) and the region II (outer core), and \( c' \) denotes any other components. Then Eq. (4-4) becomes

\[
BR = F\left(\frac{\lambda_1}{H}, \frac{\lambda_2}{H}, \frac{\lambda_3}{H}, \theta, e_I, e_{II}, \frac{\lambda_4}{H}, \frac{\sigma}{H^2}, c'\right), \tag{4-5}
\]
and with $\Pi$ terms Eq. (4-5) is rewritten as

$$\Pi_1 = F(\Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6, \Pi_7, \Pi_8, \Pi_9, \Pi_{10}),$$  \hspace{1cm} (4-6)

in which each $\Pi$ term corresponds to the non-dimensional factors of Eq. (4-5) in the same order.

As mentioned in the previous section, the outer radial blanket thickness, $d_4$, the core height, $H$, all cross sections, and all component concentrations except the enrichment of fuel in two core regions were taken as constants for the core arrangement optimization. From this fact, the last three $\Pi$ terms could be omitted from the variation terms set for simplicity.

Furthermore, $e_{II}$ term can be eliminated by taking it a constant or a function of $e_I$. From a point of view the critical search calculation, it is not desirable to fix the enrichment in either two core region with a certain value. The relationship between $e_I$ and $e_{II}$ was made as the ratio of U-238 concentration in the inner core to that in the outer core. This can be expressed as

$$\frac{(1-e_I)}{(1-e_{II})} = \text{constant.}$$  \hspace{1cm} (4-7)

The constant value of 1.05 was selected as an average from the references listed in Appendix A. Thus $e_{II}$ is described as
The critical enrichment of region I, $e_I$, also can be eliminated because it is computed with the input parameters. The quantity $e_I$ is one of the independent variables and simultaneously the dependent variable described with other independent variables, $l_1$, $l_2$, $l_3$, and $\theta$. The functional expression is

$$e_I = f(e_I) = 1 - \frac{1}{1.05} (1-e_I). \quad (4-8)$$

Thus the basic independent variables expressing the breeding ratio are $l_1$, $l_2$, $l_3$, and $\theta$, and Eqs. (4-5) and (4-6) are simplified as

$$BR = F\left(\frac{l_1}{H}, \frac{l_2}{H}, \frac{l_3}{H}, \theta\right), \quad (4-11)$$

or

$$\pi_6 = G(\pi_2, \pi_3, \pi_4, \pi_5). \quad (4-10)$$

At this moment the first step of the dimensional analysis was made. On the second step, four individual functions expressed with Eqs. (2-53) to (2-56) are derived from curves illustrated in Figs. 23 to 26, based on the following constants:
Figure 23. Breeding ratio as a function of $\pi_2$
Figure 24: Breeding ratio as a function of $\pi_3$. 

Breeding ratio ($\pi_1$, $\pi_2$, $\pi_3$) vs. $l_2/H$ for $\pi_5 = 0.40$ and $\pi_5 = 0.30$. 

- $\pi_5 = 0.40$ curve 
- $\pi_5 = 0.30$ curve
Figure 35. Breeding ratio as a function of \( \pi_4 \)
Figure 26. Breeding ratio as a function of $\pi_5$
\( \bar{\pi}_2 = 0.6, \)

\( \bar{\pi}_3 = 0.2, \)

\( \bar{\pi}_4 = 0.5, \)

\( \bar{\pi}_5 = 0.3. \)

The derived functions are as follows:

\[
(\pi_1)_{2} = F(\pi_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) = f_2(\pi_2) = 0.04496(\pi_2)^2 + 0.02455(\pi_2) + 0.8510, \quad (4-13)
\]

\[
(\pi_1)_{3} = F(\bar{\pi}_2, \pi_3, \bar{\pi}_4, \bar{\pi}_5) = f_3(\pi_3) = -0.1050(\pi_3)^2 + 0.04650(\pi_3) + 0.8768, \quad (4-14)
\]

\[
(\pi_1)_{4} = F(\bar{\pi}_2, \bar{\pi}_3, \pi_4, \bar{\pi}_5) = f_4(\pi_4) = 0.3400(\pi_4)^2 - 0.3890(\pi_4) + 0.9914, \quad (4-15)
\]

\[
(\pi_1)_{5} = F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \pi_5) = f_5(\pi_5) = 0.1106(\pi_5)^2 + 0.0007377(\pi_5) + 0.8717. \quad (4-16)
\]

2. **Dimensional analysis tests**

On the third step of the dimensional analysis, contribution modes of the individual functions are to be decided by passing through the two tests described in Eqs. (2-47)
and (2-50), and then combination mode of the all individual functions is finally decided by other tests such as Eq. (2-83).

In order to proceed with these tests, one more data set is required. With nine data points the four curves were drawn (see Table A-II), and the four functions were gained as Eqs. (4-13) to (4-16). In addition to the nine data points, at least three additional data points are required to complete the tests, however six or seven additional data points will be useful to check shapes of the previously drawn curves.

In this investigation, the total of 15 data points were prepared for the dimensional analysis. For the first three functions, a pair of curves was drawn in each graph as shown in Figs. 23 to 25. For the fourth function, seven curves were drawn as shown in Fig. 26, without newly collected data. Since six of the curves were drawn with two data points each, their credibility is, of course, lower than that for the three-point plotting curve, however, they are useful to indicate the characteristics of the designated curve.

Before entering the tests, Eqs. (2-47) and (2-50) are slightly modified as
\[ F(\pi_2, \pi_3, \pi_4, \pi_5) - F(\pi_2, \pi_3, \pi_4, \pi_5) = F(\pi_2, \pi_3, \pi_4, \pi_5) - F(\pi_2, \pi_3, \pi_4, \pi_5) \]  \hspace{1cm} (4-17)

and

\[ \frac{F(\pi_2, \pi_3, \pi_4, \pi_5)}{F(\pi_2, \pi_3, \pi_4, \pi_5)} = \frac{F(\pi_2, \pi_3, \pi_4, \pi_5)}{F(\pi_2, \pi_3, \pi_4, \pi_5)} \]  \hspace{1cm} (4-18)

The use of these equations conveniently corresponded to the pair of curves, namely Eq. (4-17) denotes the distance and Eq. (4-18) denotes the ratio between two curves at a certain place on the abscissa. Eqs. (4-17) and (4-18) are the tests only for the \( \pi_2 \)-function as an example. Other test equations also can be derived similarly.

The numerical results are listed in Table V. The results show that all of the functions appear to contribute both in addition and in multiplication. This also may mean that if the presumable function is constructed with the individual functions either in addition or in multiplication, their results will show not to be very much different. This must be caused from the small range of the variations involved, however in such a case, it is safer that the problem is continued to the third test described in Eq. (2-83).

Rewriting Eq. (2-83)
Table V. Results of the contribution mode tests

<table>
<thead>
<tr>
<th>Testing position</th>
<th>$f_2(\pi_2)$</th>
<th>$f_3(\pi_3)$</th>
<th>$f_4(\pi_4)$</th>
<th>$f_5(\pi_5)^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Addition mode)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>0.00613</td>
<td>0.00639</td>
<td>0.00678</td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>0.00781</td>
<td>0.00781</td>
<td>0.00781</td>
<td>0.00479</td>
</tr>
<tr>
<td>Right</td>
<td>0.00712</td>
<td>0.00736</td>
<td>0.00441</td>
<td>0.00566</td>
</tr>
<tr>
<td>Fluctuation$^b$</td>
<td>$\pm 0.00090$</td>
<td>$\pm 0.00100$</td>
<td>$\pm 0.00190$</td>
<td>0.00087</td>
</tr>
<tr>
<td><strong>Test 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Multiple mode)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>1.00701</td>
<td>1.00726</td>
<td>1.00759</td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>1.00886</td>
<td>1.00886</td>
<td>1.00886</td>
<td>1.00550</td>
</tr>
<tr>
<td>Right</td>
<td>1.00800</td>
<td>1.00835</td>
<td>1.00601</td>
<td>1.00638</td>
</tr>
<tr>
<td>Fluctuation$^b$</td>
<td>$\pm 0.00095$</td>
<td>$\pm 0.00090$</td>
<td>$\pm 0.00148$</td>
<td>0.00088</td>
</tr>
</tbody>
</table>

$^a$Average from the six values.

$^b$Deviation for the average of three values.
LHS = \frac{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)}{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)} = \text{Num} \frac{\text{Den}}{\text{Den}} = \frac{\text{Num}}{\text{Den}}, \quad (4-19)

where

\text{Num} = F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)
+ F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)
- [F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)]^2

\text{Den} = F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)
+ F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)
- [F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)]^2.

The similar test equations are derived for two other combinations. The three possible combinations are as follows:

(1) \quad \pi_1 = \frac{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)}{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)}
+ \frac{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)}{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)}
- F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5), \quad (4-20)

(2) \quad \pi_1 = \frac{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)}{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)}
+ \frac{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)}{F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5) F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5)}
- F(\bar{\pi}_2, \bar{\pi}_3, \bar{\pi}_4, \bar{\pi}_5), \quad (4-21)
The numerical results of Test 3 for every combination are tabulated in Table VI. From the last row of the table, the differences between the left-and right-hand sides are very small for any combination. Therefore any of these combinations can be selected as the breeding ratio empirical function. By way of trial, the first combination was used for the objective function of the optimization described in the next section. The numerically expressed function of the first combination is given by

\[
\pi_1 = \frac{F(\pi_2, \pi_3, \pi_4, \pi_5)F(\pi_2, \pi_3, \pi_4, \pi_5)}{F(\pi_2, \pi_3, \pi_4, \pi_5)} + F(\pi_2, \pi_3, \pi_4, \pi_5)F(\pi_2, \pi_3, \pi_4, \pi_5) - F(\pi_2, \pi_3, \pi_4, \pi_5). \tag{4-22}
\]

\[
\pi_1 = \{0.04496(\pi_2)^2 + 0.02455(\pi_2) + 0.8510\} \\
\times \{0.1050(\pi_3)^2 + 0.04650(\pi_3) + 0.8768\}/(0.88193) \\
+ \{0.3400(\pi_4)^2 - 0.3890(\pi_4) + 0.9914\} \\
\times \{0.1106(\pi_5)^2 - 0.0007377(\pi_5) + 0.8717\}/(0.88193) \\
-(0.88193). \tag{4-23}
\]
Table VI. Results of the combination tests

<table>
<thead>
<tr>
<th></th>
<th>Combination 1 $f_2^2 f_3 + f_4 f_5$</th>
<th>Combination 2 $f_2 f_4^5 + f_3 f_5^5$</th>
<th>Combination 3 $f_2 f_5 + f_3 f_4^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHS</td>
<td>0.99123</td>
<td>0.99123</td>
<td>0.99123</td>
</tr>
<tr>
<td>RHS = Num/Den</td>
<td>0.99596</td>
<td>0.99588</td>
<td>0.99582</td>
</tr>
<tr>
<td>Num</td>
<td>0.77304</td>
<td>0.77302</td>
<td>0.77311</td>
</tr>
<tr>
<td>Den</td>
<td>0.77618</td>
<td>0.77622</td>
<td>0.77635</td>
</tr>
<tr>
<td>LHS-RHS</td>
<td>0.00473</td>
<td>0.00465</td>
<td>0.00459</td>
</tr>
</tbody>
</table>

C. Application and Results of Optimization

As mentioned in Section II-D, constrained optimization is more common for any engineering design. The same detail of the reasons for constraints necessary for the design optimization is considered first, restricting on reactor core design.

Concepts of the optimization constraints may be derived from the following ground design rules:

1. All quantities involved are zero or positive values.
2. Overall geometrical size depends on the desired thermal output.
3. Almost all quantities involved are limited by technical ability and safety restraints.
4. Range of the fuel enrichment is decided by considering fuel cycle cost, burnup situation, technical
problems of fabrication and many others.

5. Volume fractions of materials contained are limited from 0 to 1, and their thermal and neutron characteristics are taken into account to decide the most suitable combination of the volume fractions.

For the geometrical optimization of the core-blanket system using the design model illustrated in Fig. 15, the constraints are possibly made from following considerations:

1. All geometrical parameters, $l_1$, $l_2$, $l_3$, and $\theta$ are greater than or equal to zero.

2. Overall diameter of the system is limited approximately from 2 m to 4 m by taking into account its total thermal output of around 2500 MW(e).

3. Fuel enrichment ranges from 8 to 25 Pu % for reasonable fuel cost.

4. The effective range of the empirical function of Eq. (4-23) must be inside extensions of the data taken for each parameter.

It would be ideal to consider the first three conditions at the same time. In order to include the first and second conditions, more data should be collected for a more extensive range for deriving the empirical equation, so that its credibility will be extended. For the third condition, another empirical function such as Eqs. (4-9) and (4-10) must
be obtained as briefly discussed in the next section.
Therefore, this ideal consideration for creating the con­
straints has technical complexity.

The fourth condition, thereafter, was taken into
account with its simplicity, and the linear constraints were
set up for the optimization as follows:

\[
\text{Set of the constraints}
\]
\[
y_1 = \pi_2 - 0.7 \leq 0,
\]
\[
y_2 = 0.5 - \pi_2 \leq 0,
\]
\[
y_3 = \pi_3 - 0.3 \leq 0,
\]
\[
y_4 = 0.1 - \pi_3 \leq 0,
\]
\[
y_5 = \pi_4 - 0.6 \leq 0,
\]
\[
y_6 = 0.4 - \pi_4 \leq 0,
\]
\[
y_7 = \pi_5 - 0.4 \leq 0,
\]
\[
y_8 = 0.2 - \pi_5 \leq 0.
\]

The objective function of the optimization is given
by Eq. (4-23), however the function is applied by changing
its sign, because, in general, all optimization techniques
are set for minimizing the objective, and the breeding ratio,
which is the objective of the optimization, must be maxi­
mized. By substituting the actual terms into Eq. (2-88)
with \( a = 2 \), the exterior penalty function is given by

\[
\phi(\pi_2, \pi_3, \pi_4, \pi_5, K) = -F(\pi_2, \pi_3, \pi_4, \pi_5) + K \sum_{i=1}^{8} y_i^2,
\]
where \( K \) is the penalty factor and is selected usually from a positive large number. In the actual calculation, the iteration was started with \( K=500 \), and \( K \) was increased by an increment factor 4.

The computation results with Davidon's method are listed in Appendix C. The computation with Davidon's method was completed successfully, however with the conjugate gradient method, many iterations were recorded until the optimized point was found. Since it is beyond the scope of this research to inquire deeply into the optimization methods themselves, the description about the difference between the two methods will not be continued.

The optimized core data are the inner core radius \( \ell_1=70.0 \text{ cm} \), the inner radial blanket thickness \( \ell_2=22.1 \text{ cm} \), the outer core radial length \( \ell_3=40 \text{ cm} \), the outer blanket thickness \( \ell_4=30 \text{ cm} \), and the separating blanket angle \( \theta=36^\circ \). The entire system breeding ratio was computed with the empirical function of Eq. (4-24) in the optimization code, and the value was \( \text{BR}=0.9063 \).

Thereafter, the critical computation was run with the above core data, and the characteristics of the optimized core-blanket system were obtained. By this method the breeding ratio was calculated as \( \text{BR}=0.90436 \). This value will be referred to as the "actual" breeding ratio for convenience.
In contrast with the approximately calculated value with the empirical equation, the difference is only 0.0019, which is equivalent to only 0.22% error. This estimated error percentage was calculated with the standard way, namely

\[
\text{Error} \, \% = \frac{|\text{Actual BR} - \text{Approximate BR}|}{\text{Actual BR}} \times 100. \quad (4-26)
\]

With only this estimated error percentage, it may not be adequate to evaluate the authenticity of the empirical function derived by dimensional analysis and given by Eq. (4-23), because the variation range of the variable breeding ratio is small. Consequently, the difference between the actual and approximate breeding ratios is measured as a percentage of the variation range. The formulated equation is given by

\[
\text{Coefficient} \, \% = \frac{|\text{Actual BR} - \text{Approximate BR}|}{\text{Highest BR} - \text{Lowest BR}} \times 100. \quad (4-27)
\]

This percentage may be an appreciation coefficient of the empirical equation.

With numerical values, the appreciation coefficient percentage of Eq. (4-23) is calculated as

\[
\frac{|0.9044 - 0.9063|}{0.90436 - 0.87450} \times 100 = 6.7\% , \quad (4-28)
\]

in which the highest breeding ratio is the actual breeding ratio of the optimized system, and the lowest breeding
ratio is found in Table A-III.

By these two small percentages of 0.22% error and 6.7% appreciation coefficient, the empirical equation for breeding ratio can be appreciated with its great high authenticity.

D. Treatment of Critical Enrichment as a Function

As described in Eq. (4-9), the critical enrichment of the inner core, \( e_1 \), is also varied as a function of the same geometrical parameters as those involved in the breeding ratio equation, Eq. (4-11). Data of the critical enrichments were computed with the critical search code 2DB, (see Appendix B), and the resulting values are listed in Table A-IV.

The starting point for the \( e_1 \) function estimation is rewriting Eq. (4-10) with Pi terms,

\[ \pi_6 \, = \, G(\pi_2, \pi_3, \pi_4, \pi_5). \quad (4-29) \]

The individual functions are defined as follows:

\[ (\pi_6)_2 \, = \, G(\pi_2, \pi_3, \pi_4, \pi_5) \, = \, g_2(\pi_2), \quad (4-30) \]

\[ (\pi_6)_3 \, = \, G(\pi_2, \pi_3, \pi_4, \pi_5) \, = \, g_3(\pi_3), \quad (4-31) \]

\[ (\pi_6)_4 \, = \, G(\pi_2, \pi_3, \pi_4, \pi_5) \, = \, g_4(\pi_4), \quad (4-32) \]
In which the under bar denotes the index of the variable Pi term.

The general second order function, such as 

\[ y = ax^2 + bx + c, \]

was assumed for estimating the breeding ratio function from three-point plotting. If any typical function for each curve is unknown, even this somewhat reckless approximation may be the best choice. If it can be assumed as a result of some theoretical consideration, it is appropriate, of course, to use the typical function for fitting the corresponding data points, and higher accuracy will be expected from the results derived from the more appropriate approximation.

In order to estimate the individual critical function described from Eq. (4-30) to Eq. (4-33), the typical functions corresponding to each of the functions were predicted by some reasonable consideration. The overall curves are schematically illustrated in Fig. 27. Descriptions for each case are as follows:

A function of \( \pi_2 \). As the inner core radius, \( l_1 \), is increased to infinity, the critical enrichment is decreased asymptotically to zero. When \( l_1 \) is decreased to a certain imaginary negative value, the entire system will disappear and an infinitely high enrichment will be required.
(a) \( g_2(\pi_2) = a_2/\sqrt{\pi_2 + b_2} \)  
(b) \( g_3(\pi_3) = -a_3 e^{-c_2 \pi_2^2} + b_2 \)  
(c) \( g_4(\pi_4) = a_4 e^{-c_4 \pi_4^2} \)  
(d) \( g_5(\pi_5) = -a_5 e^{-c_5 \pi_5^2} + b_5 \)  

Figure 27. Four curves of typical functions relative to the critical enrichment.
to keep the infinitesimal system criticality at the point of $l_1$. Thus the critical enrichment function of $\pi_2$ may be given by a form of

$$g_2(\pi_2) = \frac{a_2}{\sqrt{\pi_2 + b_2}}, \quad (4-34)$$

where $a_2$ and $b_2$ are coefficients to characterize the curve.

A function of $l_3$. When the inner radial blanket thickness, $l_2$, is zero, the critical enrichment is determined by both fix-sized inner and outer core regions. As $l_2$ is increased, the inner core critical enrichment is determined without any effect of the outer core. Thus the critical enrichment curve as a function of the inner radial blanket thickness may be like the curve (b) in Fig. 27. From the shape of the curve, an Inverted Gaussian distribution curve may be assumed, and the corresponding function is given by

$$g_3(\pi_3) = -a_3 e^{-c_3 \pi_3^2 + b_3}, \quad (4-35)$$

where $a_3$, $b_3$ and $c_3$ are coefficients having all positive value to be calculated by curve fitting.

The curve (c) and (d) are also associated in the same manner as a regular Gaussian curve and an Inverted Gaussian curve, respectively. The functions corresponding to these curves are given by
\[ g_4(\pi_4) = a_4 e^{-c_4 \pi_4^2}, \]

where \( a_4, c_4, a_5, b_5, \) and \( c_5 \) are also coefficients having all positive value to be calculated by the each curve fitting.

Eqs. (4-34) and (4-36) have two unknown coefficients, and Eqs. (4-35) and (4-37) have three unknown ones; however, \( b_3 \) and \( b_5 \) are given from \( a_4 \); hence, their relation can be easily found as

\[ a_4 = b_3 = b_5. \]

Thus these four equations have all two unknown coefficients to be calculated from the three-point fittings. In other words, there exist three equations with two unknown coefficients for each case. Therefore the coefficients were finally evaluated by taking the average over the three values which were calculated from three combinations of the three equations. The numerical values for all coefficients with their average fraction are listed as follows:

\[
\begin{align*}
  a_2 &= 0.1601 \pm 0.0005 \\
  b_2 &= 0.7047 \pm 0.0070
\end{align*}
\]
\[ a_3 = 0.02341 \pm 0.00356 \]
\[ b_3 = 0.1562 \]
\[ c_3 = 8.5709 \pm 3.2493 \]

\[ a_4 = 0.1562 \pm 0.0043 \]
\[ c_4 = 0.4459 \pm 0.1025 \]

\[ a_5 = 0.02188 \pm 0.00062 \]
\[ b_5 = 0.1562 \]
\[ c_5 = 3.3538 \pm 0.3543 \]

By substituting these numerical values into Eqs. (4-34) to (4-37), they become

\[ g_2(\pi_2) = \frac{0.1601}{\sqrt{\pi_2} + 0.7047} \quad (4-39) \]

\[ g_3(\pi_3) = -0.02341 e^{-8.5709\pi_3^2} + 0.1562 \]
\[ g_3'(\pi_3) = -0.4459\pi_4^2 \quad (4-40) \]

\[ g_4(\pi_4) = 0.1562 e^{-3.358\pi_5^2} \quad (4-41) \]

\[ g_5(\pi_5) = -0.02188 e^{-3.358\pi_5^2} + 0.1562 \quad (4-42) \]

In order to investigate the contribution mode of each functions to the prediction equation, the Tests 1 and 2 can be proceeded by the graphical representation instead of by the numerical calculations [66]. If a pair of curves is
parallel, the corresponding function contributes in additive mode. If the distance between the two curves increases proportionally to values of the abscissa, the function must contribute in multiplication mode.

The critical enrichment curves are illustrated in Figs. 28 to 31 with the supporting curves.

Since the prediction function for the critical enrichment of the inner core is not used for the main objective of the core module optimization, the final judgment for the combination mode will not be hesitantly left.
Figure 28. Critical enrichment as a function of $\pi_2$
Figure 29. Critical enrichment as a function of $\pi_3$
Figure 30. Critical enrichment as a function of $\pi_4$. 
Figure 31. Critical enrichment as a function of $\pi_5$
V. COMPARISON OF THREE CORES

Three geometrically different core-blanket systems illustrated in Fig. 32 were analyzed and compared by examining, in particular, their fuel load, critical enrichment, breeding ratio, and several more minor points. As briefly mentioned in the previous sections, several ground rules were established in undertaking the comparisons. The summary is as follows.

1. Components and their concentrations are the same (see Table I).
2. Common core height of 100 cm is used.
3. Geometrical configurations of pancake and 4-module system are designed similarly to the reference design studies (see Appendix A) as much as possible.
4. The outer most radial blanket thickness is constant at 30 cm.
5. All three systems have two core regions such as high and low enrichment fueled cores.
6. Critical calculations are undertaken with r-θ two-dimension diffusion code, 2DB.

All these ground rules are according to one of the main objectives of this investigation – that is to examine the effects caused by the different geometrical core-blanket arrangements.
Figure 32. Comparative three typical shapes of core-blanket system (Units in cm)
The configurations of these three systems are illustrated in Figs. 33 to 35 with their geometrical parameters. The pancake shape system was designed similarly to GEAP's and AI's reference designs, and the 4-module system to WARD's 4-module core (see Appendix A). Not all of the parameters involved, however, can be matched, because many of the design conditions are controlled by the above ground rules.

The overall dimensions and computed volume data are listed in Table VII. From the values of total volumes, the pancake is obviously the smallest, however the optimized system also has a fairly small size compared with the 4-module. The optimized system has almost the same volumes for inner and outer core region ($V_{\text{ic}}/V_{\text{oc}} \approx 0.9$); this may help to make fuel management easier. The volume ratio of the blanket to core region in the optimized system is quite large compared with other two. Any harmful effects which might be caused from this were not investigated in detail, however the higher blanket volume fraction will show the lower sodium void coefficient [88].

The criticality computation code, 2DB, also computes the flux (total, group or both) profiles. The highest fluxes and the average fluxes in each region of each system are listed in Table VIII. As also shown in Fig. 18, flux flattening in the optimized system is the worst; however,
Figure 33. Mesh map of the quarter pancake core-blanket system

IC = inner core region
OC = outer core region
RB = radial blanket region
Figure 34. Mesh map of the quarter 4-module core-blanket system

IC = inner core region
OC = outer core region
IB = inner radial blanket region
OB = outer radial blanket region
SB = separating blanket region
Figure 35. Mesh map of the quarter optimized core blanket system

IC = inner core region
OC = outer core region
IB = inner radial blanket region
OB = outer radial blanket region
SB = separating blanket region
Table VII. Overall dimensions and volume data of the core-blanket systems

<table>
<thead>
<tr>
<th>Description (unit)</th>
<th>Pancake</th>
<th>4-module</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core height (cm)</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Entire system diameter (cm)</td>
<td>260</td>
<td>356</td>
<td>324</td>
</tr>
<tr>
<td>Volume (liter)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner core zone, $V_{ic}$</td>
<td>1130.96</td>
<td>2261.92</td>
<td>1539.36</td>
</tr>
<tr>
<td>Outer core zone, $V_{oc}$</td>
<td>2010.60</td>
<td>3194.08</td>
<td>1688.92</td>
</tr>
<tr>
<td>Inner radial blanket zone, $V_{ib}$</td>
<td>-</td>
<td>166.19</td>
<td>1119.64</td>
</tr>
<tr>
<td>Outer radial blanket zone, $V_{ob}$</td>
<td>2167.68</td>
<td>3072.48</td>
<td>2770.88</td>
</tr>
<tr>
<td>Separating blanket zone, $V_{sb}$</td>
<td>-</td>
<td>1259.08</td>
<td>1125.96</td>
</tr>
<tr>
<td>$V_c = V_{ic} + V_{oc}$</td>
<td>3141.56</td>
<td>5456.00</td>
<td>3228.28</td>
</tr>
<tr>
<td>$V_b = V_{ib} + V_{ob} + V_{sb}$</td>
<td>2167.68</td>
<td>4497.75</td>
<td>5016.48</td>
</tr>
<tr>
<td>$V_c + V_b$</td>
<td>5309.24</td>
<td>9953.75</td>
<td>8244.76</td>
</tr>
<tr>
<td>$V_{ic} / V_{oc}$</td>
<td>0.5625</td>
<td>0.7082</td>
<td>0.9114</td>
</tr>
<tr>
<td>$V_b / V_c$</td>
<td>0.6900</td>
<td>0.8244</td>
<td>1.5539</td>
</tr>
</tbody>
</table>
Table VIII. Flux profiles in the core-blanket systems

<table>
<thead>
<tr>
<th>Description (unit)</th>
<th>Pancake</th>
<th>4-module</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average flux ((10^{17} \text{ n/cm}^2\text{-sec}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner core zone, (\bar{\phi}_{ic})</td>
<td>30.10</td>
<td>16.10</td>
<td>37.24</td>
</tr>
<tr>
<td>Outer core zone, (\phi_{oc})</td>
<td>22.29</td>
<td>11.37</td>
<td>8.49</td>
</tr>
<tr>
<td>Inner radial blanket zone</td>
<td>-</td>
<td>9.15</td>
<td>11.56</td>
</tr>
<tr>
<td>Outer radial blanket zone</td>
<td>4.76</td>
<td>2.27</td>
<td>1.35</td>
</tr>
<tr>
<td>Separating blanket zone</td>
<td>-</td>
<td>7.42</td>
<td>3.06</td>
</tr>
<tr>
<td>Highest flux, (\phi_{max}) ((10^{17} \text{ n/cm}^2\text{-sec}))</td>
<td>30.56</td>
<td>17.65</td>
<td>58.92</td>
</tr>
<tr>
<td>Peaking factor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\phi_{max}/\bar{\phi}_{ic})</td>
<td>1.015</td>
<td>1.096</td>
<td>1.582</td>
</tr>
<tr>
<td>(\phi_{max}/\phi_{oc})</td>
<td>1.371</td>
<td>1.552</td>
<td>6.940</td>
</tr>
</tbody>
</table>
this kind of problem can be solved by separating inner core region to lower and higher enriched regions and/or by increasing the difference in enrichment of the fuel between inner and outer core zones.

Comparisons on fuel load are highly significant, because of its direct effect on fuel cycle cost. All mass data are listed in Table IX. The total fissile mass and the critical fuel load data of the optimized system are placed between those of the pancake and 4-module systems. One of the disadvantages of modular system over pancake system, such as a great amount of fuel is required, is somewhat solved by setting the center core region like the optimized system. The critical enrichment computation results for all three systems were shown within the reasonable variable range. The most feasible ratio of higher to lower enrichments fueled in a critical system is selected by taking account of its fuel cycle management.

As might have been expected, the highest breeding ratio is of the optimized system, the next is of the 4-module, and the lowest is of the pancake. Since breeding ratio is a negative factor as plutonium credit on the fuel cycle cost estimation, nevertheless, the higher breeding ratio of a system will result in the lower fuel cycle cost under the general condition. The inner radial blanket
<table>
<thead>
<tr>
<th>Description (unit)</th>
<th>Pancake</th>
<th>4-module</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel mass data</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fissile masses (kg Pu)</td>
<td>2047</td>
<td>3665</td>
<td>2327</td>
</tr>
<tr>
<td>Inner core region</td>
<td>573</td>
<td>1290</td>
<td>972</td>
</tr>
<tr>
<td>Outer core region</td>
<td>1374</td>
<td>2376</td>
<td>1355</td>
</tr>
<tr>
<td>Radial blanket region</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Critical loading (kg Pu+U)</td>
<td>23639</td>
<td>52054</td>
<td>37483</td>
</tr>
<tr>
<td>Inner core region</td>
<td>5141</td>
<td>10286</td>
<td>7000</td>
</tr>
<tr>
<td>Outer core region</td>
<td>9146</td>
<td>14528</td>
<td>7684</td>
</tr>
<tr>
<td>Inner radial blanket</td>
<td>7552</td>
<td>5088</td>
<td></td>
</tr>
<tr>
<td>Outer radial blanket region</td>
<td>9352</td>
<td>13964</td>
<td>12596</td>
</tr>
<tr>
<td>Separate blanket region</td>
<td>5724</td>
<td>5116</td>
<td></td>
</tr>
<tr>
<td>Entire core region</td>
<td>14287</td>
<td>24814</td>
<td>14683</td>
</tr>
<tr>
<td>Entire blanket region</td>
<td>9352</td>
<td>27240</td>
<td>22800</td>
</tr>
<tr>
<td><strong>Critical enrichment</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e_I$</td>
<td>0.1115</td>
<td>0.1190</td>
<td>0.1389</td>
</tr>
<tr>
<td>$e_0$</td>
<td>0.1571</td>
<td>0.1556</td>
<td>0.1764</td>
</tr>
<tr>
<td>$e_0/e_I$</td>
<td>1.41</td>
<td>1.31</td>
<td>1.27</td>
</tr>
<tr>
<td>$(1-e_I)/(1-e_0)$</td>
<td>1.046</td>
<td>1.046</td>
<td>1.046</td>
</tr>
</tbody>
</table>
region with comparatively high breeding ratio may be useful for something like a conversion objective.

Comparative data of the breeding ratios for the three systems are listed in Table X.
<table>
<thead>
<tr>
<th>Breeding Ratio, BR</th>
<th>Pancake</th>
<th>4-module</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner core zone, BR&lt;sub&gt;ic&lt;/sub&gt;</td>
<td>0.32909</td>
<td>0.34106</td>
<td>0.52662</td>
</tr>
<tr>
<td>Outer core zone, BR&lt;sub&gt;oc&lt;/sub&gt;</td>
<td>0.39983</td>
<td>0.32142</td>
<td>0.12420</td>
</tr>
<tr>
<td>Inner radial blanket zone, BR&lt;sub&gt;ib&lt;/sub&gt;</td>
<td>-</td>
<td>0.01887</td>
<td>0.16125</td>
</tr>
<tr>
<td>Outer radial blanket zone, BR&lt;sub&gt;ob&lt;/sub&gt;</td>
<td>0.12681</td>
<td>0.08603</td>
<td>0.04667</td>
</tr>
<tr>
<td>Separate blanket zone, BR&lt;sub&gt;sb&lt;/sub&gt;</td>
<td></td>
<td>0.11414</td>
<td>0.04562</td>
</tr>
<tr>
<td>Core BR, BR&lt;sub&gt;ic&lt;/sub&gt; + BR&lt;sub&gt;oc&lt;/sub&gt;</td>
<td>0.72892</td>
<td>0.66248</td>
<td>0.65082</td>
</tr>
<tr>
<td>Radial blanket BR, BR&lt;sub&gt;ib&lt;/sub&gt; + BR&lt;sub&gt;ob&lt;/sub&gt; + BR&lt;sub&gt;sb&lt;/sub&gt;</td>
<td>0.12681</td>
<td>0.21904</td>
<td>0.25354</td>
</tr>
<tr>
<td>Total BR of core-radial blanket system</td>
<td>0.85573</td>
<td>0.88152</td>
<td>0.90436</td>
</tr>
</tbody>
</table>
VI. SUMMARY AND CONCLUSIONS

In this chapter the important points developed in the preceding chapters will be summarized, and the conclusions drawn from the whole investigation will be emphasized.

The geometrical optimization for a core-blanket system, roughly corresponding to a prototype or demonstration LMFBR in the 1000-MW(e) class, was made using a prediction equation derived by dimensional analysis. The intermediate geometrical system between pancake shape and 4-module reactors was analyzed for the investigation reported in this thesis. The geometrical effects on performance characteristics of reactors were examined by changing combinations of four geometrical parameters; those are the inner core radius $l_1$, the inner radial blanket thickness $l_2$, the outer core radial length $l_3$, and the separating blanket angle $\theta$. The types of systems studied in this thesis are (Pu, U)C fueled, sodium-cooled fast breeders.

In making a comparison of geometrically different core-blanket systems, it is crucial that the systems be handled equivalently in the geometrically different calculational models. The physical equivalence, which was taken to guarantee this, includes the composition, cross section sets, outermost radial blanket thickness, and core height. A different type of equivalence, numerical equivalence, is more difficult to achieve. Included in this term are the convergence of the
methods, the mesh sizes, and the estimated geometrical bucklings. Care was taken to insure that spurious differences in numerical results did not occur as a result of poor numerical treatment of the reactors. Once this equivalence is achieved, it becomes meaningful to investigate the effects arising only from geometrical differences of the reactors.

In particular, the breeding ratio variation was selected for an objective function of the geometrical core optimization. There is no theoretical way to express the breeding ratio variation as a mathematical function of the geometrical parameters. The breeding ratio must be computed by a reactor calculation code, unless a highly approximate value is satisfactory. In other words, the breeding ratio is a function of an individual reactor, and continuous, functional values of the breeding ratio variation can not be computed simply. Whenever the breeding ratio is required to be computed with certain parameters of a reactor, the criticality configuration must be determined at first; then the breeding ratio is calculated with the previously obtained critical conditions.

When not only breeding ratio, but also other significant parameters such as power cost and sodium void coefficient are optimized objectives of reactor core designs, the complicated calculations noted are required for each optimization iteration, greatly increasing the computation expense. If these parameters, which are to be optimization objectives, can be expressed as mathematical functions of any desired
input parameters, reactor core design optimization can be achieved without consuming excessive computation time.

In accordance with this requirement, the dimensional analysis method was utilized. The four-independent-variable case was particularly developed in this thesis. By deriving the combination mode test, application of the dimensional analysis was extended to a complicated combinations case. This derivation, to the best knowledge of the author, has not appeared in the literature.

Once the empirical equation of the breeding ratio is carefully derived as a function of nondimensional $P_i$ terms, this prediction equation can be used in a general optimization procedure. In general, engineering design optimization problems require a set of constraints. The reactor core optimization is not an exception to this general rule. A set of the constraints for this investigation was made corresponding to the effective ranges of the prediction equation. For this constrained optimization problem, the external penalty function method with the Davidon's method worked very well from a viewpoint of the convergence speed.

By calculating the critical configuration of the system with the optimized geometrical parameters adding to the previously discussed physical equivalent parameters as a set of the input of the reactor computation code, the optimization results are verified and the characteristics of the optimized system are computed at the same time. There is very close
agreement (0.2\% error) between the breeding ratios computed by the optimization code and the reactor critical search code. This close agreement also means that the prediction equation of the breeding ratio is proved to be highly accurate (6.7\% error) inside the constrained field.

In order for the optimized system to be appraised more correctly and be compared with other geometries, a pancake shaped and a 4-module system were analyzed under the previously discussed physical equivalence. The pancake shaped system corresponds very roughly to the AI's and GEAP's reference designs, and the 4-module corresponds to the WARD's 4-module reference design.

The comparisons among the three geometries are as follows:

1. The highest breeding ratio is for the optimized system.
2. The optimized system has an intermediate overall size.
3. The optimized system requires a critical fuel load less than the 4-module.
4. The peaking factor of the optimized system may be the worst, but this can be modified.
5. The critical enrichments of the three are all in the ranges from 10 to 20\%.
6. The volume ratio of blanket to core regions is the highest in the optimized system.
The overall conclusions drawn from the investigation are summarized again as follows:

1. The geometrically optimized reactor core was investigated to have the intermediate characteristics between pancake and 4-module geometries.

2. The possibility of applying certain dimensional analysis techniques to the determination of a prediction equation for the breeding ratio was proved with a high accuracy.

3. The newly developed core optimization process, combined with the prediction equation, was appraised with the computation time saving.
VII. REFLECTION TO FURTHER STUDY

In order to achieve higher accuracy, the computation tools must be improved. This includes a more accurate neutron balance equation, higher ordered dimensional calculations, reliable cross section sets with more multi-energy groups, and smaller mesh sizes. And, more careful selection of reactor components and increases of axial blanket and reflector should be taken into account for more practical studies. Once some or all of these are improved, it would be very interesting to see how much the results described in this thesis will be altered.

It would be also interesting to extend the dimensional analysis application to the prediction equation for another parameter such as sodium void coefficient and fuel cycle cost, or to a function of many variables. These variables may include an outer radial, top and bottom axial blanket, and variable concentrations of components.

The reflection and suggestions for further study, which are described in this chapter, are mostly for the author himself. If some of these insignificant suggestions can be shared by the reader, that will be a great pleasure to the author.


49. INTERNATIONAL ATOMIC ENERGY AGENCY, Fast Reactor Physics, Vol. 1 and 2, Vienna, Austria (1968).


70. B. L. PIERSO, Personal Communication (May, 1972).


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Finally, the author wishes to express his appreciation to his and his wife's parents, Mr. and Mrs. Shigeru Minakuchi and Mr. and Mrs. Naoyoshi Fujimoto, for their constant encouragement from Japan.
X. APPENDIX A: LMFBR PLANT REFERENCE DESIGN DATA
Table A-I. 1000 MW(e) LMFBR plant design for comparative reference study

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>JAERI</th>
<th>Babcock &amp; Wilcox</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>First</td>
<td>Second</td>
</tr>
<tr>
<td>Overall Reactor Performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total thermal output</td>
<td>MW(t)</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>Net electrical output</td>
<td>MW(e)</td>
<td>1000</td>
<td>1090</td>
</tr>
<tr>
<td>Net efficiency</td>
<td>%</td>
<td>40.0</td>
<td>43.6</td>
</tr>
<tr>
<td>Net heat rate</td>
<td>Btu/kWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam condition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superheat/re-heat temp</td>
<td>°F</td>
<td>950/950</td>
<td>900/900</td>
</tr>
<tr>
<td>Pressure</td>
<td>psig</td>
<td>2400</td>
<td>1800</td>
</tr>
<tr>
<td>Refueling cycle</td>
<td>yr.</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Fuel material</td>
<td></td>
<td>oxide</td>
<td>oxide</td>
</tr>
<tr>
<td>Coolant material</td>
<td></td>
<td>sodium</td>
<td>sodium</td>
</tr>
<tr>
<td>Cladding material</td>
<td></td>
<td>ss</td>
<td>ss 304</td>
</tr>
<tr>
<td>Reactor Geometry</td>
<td></td>
<td>flat</td>
<td>hollow</td>
</tr>
<tr>
<td>Reactor size</td>
<td></td>
<td>cyl.</td>
<td>cyl.</td>
</tr>
<tr>
<td>Seed (core) ht.</td>
<td>ft.</td>
<td>2.62</td>
<td>2.62</td>
</tr>
<tr>
<td>Seed (core) dia.</td>
<td>ft.</td>
<td>8.70</td>
<td>OD-10.62</td>
</tr>
<tr>
<td>Axial blanket thickness</td>
<td>ft.</td>
<td>1.31</td>
<td>1.31</td>
</tr>
<tr>
<td>Radial blanket thickness</td>
<td>ft.</td>
<td>1.31</td>
<td>1.31</td>
</tr>
<tr>
<td>Reactor Composition (Volume fluctuation)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seed region</td>
<td></td>
<td>vol.%</td>
<td>44</td>
</tr>
<tr>
<td>Fuel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coolant</td>
<td></td>
<td>vol.%</td>
<td>39</td>
</tr>
<tr>
<td>Structure</td>
<td></td>
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<td>kg(Pu+U)</td>
<td>86,300</td>
<td>83,000</td>
<td>100,000</td>
<td>80,000</td>
</tr>
<tr>
<td>Axial blanket region</td>
<td>kg(Pu+U)</td>
<td>86,300</td>
<td>83,000</td>
<td>100,000</td>
<td>80,000</td>
</tr>
<tr>
<td>Radial blanket region</td>
<td>kg(Pu+U)</td>
<td>86,300</td>
<td>83,000</td>
<td>100,000</td>
<td>80,000</td>
</tr>
<tr>
<td>Burnup, average</td>
<td>MWD/T</td>
<td>100,000</td>
<td>100,000</td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Maximum</td>
<td>MWD/T</td>
<td>100,000</td>
<td>100,000</td>
<td>100,000</td>
<td>100,000</td>
</tr>
</tbody>
</table>

**Thermal Power Data**

| Total thermal power          | 2500  | 2500  | 2450  | 2580     |
| Core region                  |       |       |       |          |
| Axial blanket region         |       |       |       |          |
| Radial blanket region        |       |       |       |          |
| Specific power               |       |       |       |          |
| Core av.                     | kw/kg(Pu+U) | 110  | 125   | 130      |
| Core peak                    | kw/kg(Pu+U) |       |       |          |
| Linear power                 |       |       |       |          |
| Core average                 | kw/ft | 9.5   | 8.3   | 7.75     | 8.36     |
| Core peak                    | kw/ft | 15.2  | 12.8  |          |
| Core power density           | kw/liter | 0.5  | 0.45  |          |

**Temperature Data**

<p>| Fuel highest temp. °F        | 4820  | 4633  |
| Clad highest temp. °F        | 1202  | 1333  |
| Av. sodium output temp. °F   | 1160  | 1301  | 1100  | 1050    |
| Sodium temp. Inc. Δ°F        | 302   | 392   | 300   | 350     |
| Max. heat flux M/Btu/hr-ft²  |       |       |       |          |</p>
<table>
<thead>
<tr>
<th>Atomics Combus-</th>
<th>General Electric</th>
<th>Westinghouse</th>
</tr>
</thead>
<tbody>
<tr>
<td>International</td>
<td>Advanced Engrg.</td>
<td>7-module</td>
</tr>
<tr>
<td>Preliminary</td>
<td>Conservative</td>
<td>4-module</td>
</tr>
<tr>
<td>Final</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------</td>
<td>-------------</td>
</tr>
<tr>
<td>98</td>
<td>176</td>
<td>622</td>
</tr>
<tr>
<td>331</td>
<td>377</td>
<td>51,244</td>
</tr>
<tr>
<td>13,339</td>
<td>19,090</td>
<td>15,261</td>
</tr>
<tr>
<td>7,463</td>
<td>13,132</td>
<td>17,052</td>
</tr>
<tr>
<td>15,365</td>
<td>15,688</td>
<td>18,926</td>
</tr>
<tr>
<td>67,000</td>
<td></td>
<td>112,200</td>
</tr>
<tr>
<td>2500</td>
<td>2400</td>
<td>2465</td>
</tr>
<tr>
<td>2250</td>
<td>2200</td>
<td>2128</td>
</tr>
<tr>
<td>80</td>
<td>75</td>
<td>286</td>
</tr>
<tr>
<td>170</td>
<td>125</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>121.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>170.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>16</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1060</td>
<td>1140</td>
<td>1095</td>
</tr>
<tr>
<td>300</td>
<td>360</td>
<td>298</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Unit</td>
<td>JAERI First</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Temperature Data (Cont)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Av. core heat flux</td>
<td>MBtu/hr-ft²</td>
<td></td>
</tr>
<tr>
<td>Hydraulic Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total coolant flow rate</td>
<td>lb/hr</td>
<td>9.76x10⁷</td>
</tr>
<tr>
<td>Total pressure drop</td>
<td>psi</td>
<td>142.2</td>
</tr>
<tr>
<td>Coolant velocity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>ft/sec</td>
<td>26.2</td>
</tr>
<tr>
<td>Maximum</td>
<td>ft/sec</td>
<td></td>
</tr>
<tr>
<td>Atomics International Preliminary</td>
<td>Combus-</td>
<td>General Electric Advanced Conservative</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>Final</td>
<td>Engrg.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.541</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.3x10^7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
</tr>
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<td></td>
<td></td>
<td>9.40x10^7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.46x10^7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12.85x10^7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>31.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>38.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>23.5</td>
</tr>
</tbody>
</table>
XI. APPENDIX B: COMPUTER PROGRAM, 2DB

A. Introduction

2DB is a two-dimensional (X-Y, R-Z, R-Θ, triangular), multigroup diffusion theory code. It was made by Battelle Memorial Institute, Pacific Northwest Laboratories group, and its instruction and summary were published by Little and Hardie [57], and the code is distributed by Argonne Code Center [20, p. 509]. This code was made for criticality and burnup analysis of fast nuclear reactors, and therefore, it can be used to compute $k_{\text{eff}}$ or to perform criticality searches on reactor composition, time absorption ($\alpha$), or reactor dimensions by either the regular or the adjoint flux equations. Material burnup, fission production and breeding ratio can be computed for specified time intervals, and the flexible material shuffling scheme is also useful for fuel managements.

The whole program was written in FORTRAN-IV, and originally made for use on a UNIVAC 1108. To use this code on an IBM 360, some modification and a special control deck are necessary. These points are discussed later in Section D of this chapter.

A description of the mathematical model is given in the body of this thesis and the above reference and follows closely the description given in the 3DB user's manual [44].
and 3DDT user's manual [90]. Some ideas for input instructions, storage requirements, a simplified logical flow diagram, a description of the variable-dimensioned arrays and nonsubscripted common variables are also given in these references.

With the IBM 360 control system a large memory area and a long compiling and computing time are required for common two-dimensional problems. For example a concentration search problem with 16x16 mesh points in R-θ dimension, using five materials in five material zones and two energy groups was accommodated on the machine with a 162K main memory area and required about one minute computing time passed through 15 outer iterations.

This code might be useful in following areas (not necessarily in order of priority):

1. Overall core design using concentration and/or boundary search options.

2. Fuel management with shuffling option (burnup information at any time step can be obtained).

3. Calculation of reactivity coefficients using adjoint flux.

4. Incorporation of the control rod problem (i.e., internary boundary conditions).

5. Computation on a hexagonal fuel assembly using a triangular geometry specification.
6. Computation of buildup of individual fission products such as xenon and samarium characterized by a single decay constant and a single cross-section set.

B. Computational Procedure

To compute eigenvalues and flux profiles, source iteration methods are used. The detail of this method is discussed by Butler and Cook [19]. Using an initial flux guess, an initial fission source distribution is calculated, and then, new flux profiles in each group are sequentially computed. This process is iterated until the flux profiles are converged and is called an "inner iteration", distinguishing it from the "outer iterations" which correspond to a fission source cycle, i.e., a complete pass through all the energy groups. The outer iteration process is continued until the fission source converges or until the maximum number of outer iterations subjected by input parameter, D05, is exceeded. After the fluxes in all groups have been calculated, a new fission source distribution is computed from the flux profiles and then is used for next computation of a new flux profile. In each step of the iteration, the multiplication ratio, λ, is obtained by taking the ratio of the new (current iteration) total fission source to the old (previous iteration) total fission source.
It is valuable to understand the iteration method in detail. This method is discussed by Carlson and Lathrop [21] in their chapter of transport theory. Their explanation of the iteration method with transport theory could be used for diffusion theory, which is used in 2DB, because the basic idea of the iteration method applied for solving the diffusion equation and the transport equation are identical. The outline of their discussion is as follows:

**Iteration cycle.** After the discrete ordinates equations are derived, and the principles for the evaluation of these solutions are enunciated, a strategy for the overall flow of solution evaluation must be determined, and then a criterion for determination of the solution is to be established. The solution strategy proceeds from the innermost portion of the problem at hand to the outermost portion. To obtain a complete solution, three levels of iteration, within a group, over all groups, and over system changes are required. Iterations within a group and over all groups are called inner iteration and outer iteration, respectively. Iteration over system changes is called "Parametric Eigenvalue Searches Method", which is discussed in the next section. To obtain a solution with satisfactory accuracy, the convergence criterion is established by corresponding to the expected accuracy.

**Inner iteration.** A calculation cycle in a given energy
group in which the within-group source is successively recomputed is called inner iteration. The iterative process is terminated when two successive within-group sources differ by some established criterion, by less than a prescribed amount, or the maximum number of inner iteration given with input parameter is exceeded. Convergence of the iteration can be accelerated by a process scaling which is given as one of the input parameters.

Outer iteration. Once inner iteration is converged in the first energy group, the calculation proceeds to the second group. A calculation cycle for all energy groups is called an outer iteration. The downscattering source can be computed for all energy groups, except the highest energy group, immediately after each inner iteration is finished, but the fission source cannot be computed until an outer iteration is finished, i.e., the total source must be recomputed after an outer iteration, and the outer iterative process must be continued until the total sources become stable.

As defined before, the multiplication ratio is calculated before the fission source and flux profiles are re-normalized to a specified level. The multiplication ratio, $\lambda$, is given by
\[ \lambda^\xi = S_f^\xi / S_f^{\xi-1}, \]  
\( (A-1) \)

where \( S_f \) is the total fission source and the superscript \( \xi \) is the outer iteration index. Since the fission spectrum is multiplied by \( 1/\lambda \), \( \lambda \) tends towards unity as the outer iteration proceeds. The effective multiplication factor, \( k_{\text{eff}} \), is given by the product of the sequence of \( \lambda \)'s,

\[ k_{\text{eff}} = (\lambda^\xi)(\lambda^{\xi-1}), \]  
\( (A-2) \)

which is equivalent to

\[ k_{\text{eff}} = (\sum_{g=1}^G \chi_g^\xi-1)/(\sum_{g=1}^G \chi_g^\xi), \]  
\( (A-3) \)

where \( \chi_g^\xi \) is the fission spectrum in group \( g \) computed in outer iteration index of \( \xi \).

Outer iteration convergence is terminated when both

\[ |1-\lambda^\xi| < \varepsilon_1, \]  
\( (A-4) \)

\[ |\lambda^\xi - \lambda^{\xi-1}| < \varepsilon_1, \]

where \( \varepsilon_1 \) is the lambda convergence input parameter. In order to accelerate the outer iteration convergence, so called "fission source over-relaxation" is employed. After the new fission source rate profile, \( \hat{S}_f^\xi \), is calculated, a second new value, \( S_f^\xi \), is computed by magnifying the difference between the new fission source rate and the old fission source rate, \( S_f^{\xi-1} \), according to
\[ S_f^\xi = S_f^\xi + \beta'(S_f^\xi - S_f^{\xi-1}) \]  
(A-6)

where \( \beta' \) is the fission source over-relaxation factor. 

\( S_f^\xi \) is then normalized to give the same total source as \( S_f^{\xi-1} \).

The group-fluxes are computed simultaneously on each vertical (or horizontal) line and then line-over-relaxed successively using the algorithm

\[ \phi^\xi = \phi^{\xi-1} + \beta(\phi^{\xi-1} - \phi^{\xi-1}) \]  
(A-7)

where \( \beta \) is the flux over-relaxation factor distinguished from \( \beta' \), and \( \beta \) is an input parameter. The fission source over-relaxation, \( \beta' \), is computed internally from the ad hoc expression

\[ \beta' = 1.0 + 0.6(\beta-1) \]  
(A-8)

The inner iteration process for each energy group is continued until either its convergence is achieved or the maximum number of inner iterations is exceeded. The maximum number of inner iteration is given by an input parameter as mentioned before, while for inner iteration convergence, two tests are employed. The first test requires that

\[ \frac{G \int \nu \Sigma g f \phi g \gamma \phi g \gamma^{-1} dV}{G \sum_{g=1} \nu \Sigma g f \phi g \xi^{-1} dV} \leq \varepsilon_1 \]  
(A-9)
where the integration is over the entire mesh, $\gamma$ is the inner iteration index, $\xi$ is the outer iteration index, and $\varepsilon_1$ is the same convergence criterion defined at lambda convergence. This is basically a convergence test on the total fission source. After the first test is satisfied, the second test then requires that

$$|\phi^\gamma_{g} - \phi_{g}^{\gamma-1}| \phi_{g}^{\gamma-1} \leq \varepsilon_2,$$

where $\varepsilon_2$ is the pointwise flux convergence input parameter and usually $\varepsilon_1 < \varepsilon_2 < 10\varepsilon_1$.

C. Eigenvalue Technique for Search Options

This computer code, 2DB, permits implicit eigenvalue searches for time absorption constant (alpha), material composition (concentration), or system dimensions (delta). Only the general eigenvalue search technique and concentration search option, which was specially used in this research, are discussed here.

Once an outer iteration cycle is converged, the system may be altered by adjusting suitable parameters, in an attempt to achieve a given multiplication level, usually criticality. In contrast to a $k_{eff}$ calculation, the fission spectrum keeps a constant value, and instead, the desired parameter is changed to make $\lambda$ approach unity. Subsequent
parameter changes are determined by either linear interpolation or by parabolic interpolation modified by precautionary safeguards. When the convergence is nearly complete, the numerical derivatives involved may become unreliable. This difficulty is overcome by fixing the slope when $\lambda$ is within a specified distance of unity. Eigenvalue search problems are thus basically a sequence of $k_{eff}$ calculations for several perturbations of the original systems [90].

The outer iteration for search option is continued with keeping the original system and the initial eigenvalue guess until $|\lambda^{\xi}-\lambda^{\xi-1}| < \varepsilon_1$, where $\xi$ is the outer iteration index and $\varepsilon_1$ is the lambda convergence criterion input parameter specified in a code variable, EPS. The original eigenvalue guess (input parameter with code variable, EV) is then modified with an eigenvalue modifier (input parameter with code variable, EVM) as follows:

$$EV \rightarrow EV - EVM; \text{ if } \lambda < 1 \text{ (subcritical)},$$

$$EV \rightarrow EV + EVM; \text{ if } \lambda > 1 \text{ (supercritical)}.$$

After $\lambda$ for the original system is converged to a precision of $|\lambda^{\xi}-\lambda^{\xi-1}| < \varepsilon_1$, subsequent values are converged to $|\lambda^{\xi}-\lambda^{\xi-1}| < \varepsilon_3$, where $\varepsilon_3$ is the eigenvalue search convergence criterion specified in the input (code variable, EPSA), and in general, $\varepsilon_3$ is larger than $\varepsilon_1$. The main
objective for using of $\varepsilon_3$ is to save time by requiring fewer outer iterations without sacrificing final accuracy. When the second converged value of $\lambda$, corresponding to the second value of eigenvalue, $\text{EV}$, is obtained, a straight line interpolation is employed to modify $\text{EV}$, provided that

$$\varepsilon_L \leq |1-\lambda| \leq \varepsilon_H,$$

where $\varepsilon_L$ and $\varepsilon_H$ are low and high limits on $|1-\lambda|$ specified in the input with code variables, $\text{LAL}$ and $\text{LAH}$ for $\varepsilon_L$ and $\varepsilon_H$, respectively, and these parameters are used to stabilize the search process. If $|1-\lambda| > \text{LAH}$, the straight-line interpolation proceeds as though $|1-\lambda|$ were equal to $\text{LAH}$. If $|1-\lambda| < \text{LAL}$, the search continues to completion using a straight-line interpolation with a fixed slope to prevent errors due to subtraction of nearly equal quantities. The slope of the line of straight-line interpolation is adjusted to either over- or under-predict by using the parameter oscillation damper specified in the input with code variable, $\text{POD}$.

After the third converged value of $\lambda$ corresponding to the third value of $\text{EV}$ is obtained, and if $|1-\lambda| \geq \text{LAL}$, parabolic interpolation is used to obtain the next value of $\text{EV}$. The root of the parabolic equation closest to the previous value of $\text{EV}$ is taken as the next $\text{EV}$. Let $\lambda^P$ and $\lambda^{PP}$ be the converged lambdas corresponding to $\text{EV}^P$ and $\text{EV}^{PP}$, where $\text{EV}^P$ is the previous eigenvalue and $\text{EV}^{PP}$ is two eigenvalues back. If the sign of $\lambda^{PP} - 1$ is different from the
sign of \( \lambda^P-1 \), the new value of \( EV \) must lie in the extreme range of the previous values \( EV^P \) and \( EV^{PP} \). If it does not, \( EV \) is set equal to \( (EV^P+EV^{PP})/2 \). If \( |1-\lambda| < \varepsilon_L \) and/or the two roots of the parabola are imaginary, the straight-line method is used again computing its slope from the parabolic search. Final convergence of the search is reached when both \( |1-\lambda| < \varepsilon_1 \) and \( |\lambda^P-\lambda^P-1| < \varepsilon_1 \) are satisfied.

Concentration searches: This computer code, 2DB, can perform an extremely flexible and comprehensive criticality search on material composition [57]. Any number of materials can simultaneously be added, depleted, or interchanged in any number of zones during a concentration search. Therefore, any concentration search problems can be constructed; the possibility may be limited by the ingenuity of the user.

Let it be supposed that the mixture specified by mixture index \( m \) is initially composed of materials 1, 2, 3, ... with atom densities of \( N_1, N_2, N_3, \ldots \), respectively. Now suppose that critical enrichment of material 2 will be found keeping the total concentration of materials 1 and 2 as a constant, say the material 1 and 2 must be fertile and fissile materials, respectively, while the rest of the materials in the \( m \) are not changed for the critical search. The \( I0, I1 \) and \( I2 \) tables for mixture \( m \) would then be illustrated in the
following tabulation.

<table>
<thead>
<tr>
<th>Mixture Index (I0)</th>
<th>Material Index (II)</th>
<th>Atom Density (I2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>m</td>
<td>1</td>
<td>N₁</td>
</tr>
<tr>
<td>m</td>
<td>2</td>
<td>-N₁</td>
</tr>
<tr>
<td>m</td>
<td>m</td>
<td>0.0</td>
</tr>
<tr>
<td>m</td>
<td>2</td>
<td>N₁+N₂</td>
</tr>
<tr>
<td>m</td>
<td>3</td>
<td>N₃</td>
</tr>
<tr>
<td>:</td>
<td>:</td>
<td>:</td>
</tr>
</tbody>
</table>

In the first row, the 0 entry in the II table instructs the code to clear a storage area for mixture m, therefore, in the first row of each mixture, the tables of II and I2 must be filled with zero entry. In the fourth row, the entry in the II table is the same as the mixture number and that in the I2 table is zero; that instructs that the current contents of mixture m is multiplied by the eigenvalue. These instructions are summarized by the expression as follows:

\[
\Sigma_m = (N_1\sigma_1 - N_1\sigma_2)EV + (N_1+N_2)\sigma_2 + N_3\sigma_3 + \ldots, \quad (A-11)
\]

where

- \(\Sigma_m\) = macroscopic cross section for mixture m,
- \(\sigma_1\) = microscopic cross section for material 1,
- \(N_1\) = atom density of material 1, and
- \(EV\) = eigenvalue.

The atom densities of materials 1 and 2 are modified with
eigenvalue as follows:

\[ N_1 \rightarrow N_1 \times EV, \]

\[ N_2 \rightarrow N_1(1-EV)+N_2. \]

Each atom density is changed, however the total atom densities are the same as \( N_1 + N_2 \).

D. Utilization on IBM 360

As mentioned before, the computer code, 2DB, was originally made for use on UNIVAC 1108 computer. In order to use the code on IBM 360/65 computer, modification of the entire code is required. Main part of the program written in FORTRAN-IV language is not necessary to be changed. Control systems between these computers are great different. The term of this control systems includes computation time, data memory, and input and output controls.

Before the details of these differences and the modification rules are discussed, brief general comparison of IBM machine with UNIVAC machine may be interesting and valuable to transfer a code from one to another. Bareiss wrote about such subjects in his article, "Computers and Reactor Design [11]". He compared UNIVAC 1108 with IBM 360/MODEL 75 instead of MODEL 65. These two IBM models are slightly different, such as the MODEL 75 runs a little faster than the MODEL 65 does. Since the IBM 360/65 is used for this investigation,
some comparison data between the UNIVAC 1108 and the IBM 360/65 are desired in practice. The Bareiss' comparison results of the IBM 360/75, however, will serve as a reference.

These UNIVAC 1108 and IBM 360/75 computers were originally produced approximately at the same time. The first UNIVAC 1108 was delivered in September of 1965, while IBM 360/75 in January of 1966. The computation speed of the IBM 360/75 is approximately 1.25 time faster than that of the UNIVAC 1108. However, the estimated monthly rental of the IBM 360/75 is $80,000 in contrast to $60,000 for the UNIVAC 1108. Considering these two factors, the running costs of the same problem with the same program on both computers would be very close, because IBM 360/75 has 1.25-time faster running speed and 1.33-time more expensive monthly rental as compared with UNIVAC 1108.

For a practical example, a $k_{eff}$ calculation problem involving standard fast reactor components, two energy groups, and 20x20 mesh size in r-z geometry took a running time of 1.5 minute with 2DB code used on the IBM 360/65, while 0.2 minute on UNIVAC 1108 [57]. This 0.2-minute running time on UNIVAC 1108 may be questionable, because the output of the same type problem reported in the same reference shows that the 11 outer iterations required for the $k_{eff}$ computation took 0.33 minute already. Therefore the running time required for the whole computation of this problem on the UNIVAC 1108
should be longer than 0.33 minute. Inconveniently, there is no method to get the detailed information of time during the computation period from the IBM 360/65.

The main difference of programmlings and control systems between for the UNIVAC 1108 and for the IBM 360 computers especially corresponded on the computer code, 2DB, are as follows:

**UNIVAC 1108**

- **INCLUDE statement for COMMON, INTEGER and REAL**
  - Possible to use for simplification

- **Computing time control**
  - Use special subroutines, ETIME and/or ETIMEF

- **To set up memory drum units**
  - Use special subroutine, SETDR, e.g., "CALL bSETDR (3,525000,520000, JLPTAB)"

**IBM 360**

- **INTEGER and REAL**
  - Cannot be used and no similar statement. All list of COMMON, INTEGER and REAL must be stated in each SUBROUTINE

- **Computing time control**
  - Use control cards. Stated as TIME=3, which means that the maximum running time is 3 minutes

- **To set up memory drum units**
  - By control cards, e.g., "PT03FO01bDDbNIT=SPool, SPACE=(TRK,(10,10)), 11bDCB=(RECfm=VBs, LRECL =796, BLKSIZE=800)

**Maximum number of alphameric characters for A-FORMAT**

- **A6**

**Output for E-FORMAT**

- **Necessary 3 spaces for power indication, e.g.,**
  - (E10.4); -0.3563+03

- **Necessary 4 spaces for power indication, e.g.,**
  - (E11.4); -0.3563E 03
E. Instruction for Data Input

The input data for 2DB used on IBM 360 computer are listed in the following pages. These input specifications are described exactly in the order which they are required by the code. The FORMAT for data read in through the generalized input subroutines, with the exception of the cross sections, must adhere to one of the two FORMATS: 6(I1, I2, E9.4) for reading floating point numbers and 6(I1, I2, I9) for reading integers. In these FORMATS, the integer in the first column, K(I1), indicates the option (described below), the integer in the next two columns, IN(I2), indicates the number of times to which the option is applied, and the number in the last nine columns, IV(I9) or V(E9.4) is the data associated with the field. The options for K(I1) are as follows:

<table>
<thead>
<tr>
<th>K(I1)</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (or blank)</td>
<td>Code reads data field and no special action is taken. IN(I2) must be blank.</td>
</tr>
<tr>
<td>1</td>
<td>Repeat the number, IV or V for IN times.</td>
</tr>
<tr>
<td>2</td>
<td>Do IN+1 linear interpolations between the number in this datum field and the number in the following datum field (allowed for V only).</td>
</tr>
<tr>
<td>3</td>
<td>Terminate reading of this datum field with previous datum entry. This option number, 3, must follow the last data field of each data block.</td>
</tr>
<tr>
<td>4</td>
<td>Repeat the previous numbers in the IV data fields IN times.</td>
</tr>
<tr>
<td>5</td>
<td>Ignore the number in this datum field.</td>
</tr>
<tr>
<td>Columns</td>
<td>Variable</td>
</tr>
<tr>
<td>---------</td>
<td>----------</td>
</tr>
<tr>
<td>Card 1  (To run a series of cases, repeat from this card), FORMAT (16A4, I6)</td>
<td></td>
</tr>
<tr>
<td>1-64</td>
<td>ID (16)</td>
</tr>
<tr>
<td>65-70</td>
<td>MAXT</td>
</tr>
<tr>
<td>Card 2  (Required for control), FORMAT (12I6)</td>
<td></td>
</tr>
<tr>
<td>1-6</td>
<td>AO2</td>
</tr>
<tr>
<td>7-12</td>
<td>IO4</td>
</tr>
<tr>
<td>13-18</td>
<td>SO2</td>
</tr>
<tr>
<td>19-24</td>
<td>IGM</td>
</tr>
<tr>
<td>25-30</td>
<td>NXCM</td>
</tr>
<tr>
<td>31-36</td>
<td>MCR</td>
</tr>
<tr>
<td>37-42</td>
<td>MO7</td>
</tr>
<tr>
<td>43-48</td>
<td>DO5</td>
</tr>
<tr>
<td>49-54</td>
<td>GO7</td>
</tr>
<tr>
<td>55-60</td>
<td>SO4</td>
</tr>
<tr>
<td>61-66</td>
<td>NPRT</td>
</tr>
<tr>
<td>67-72</td>
<td>NPUN</td>
</tr>
<tr>
<td>Card 3  (Required for control), FORMAT (12I6)</td>
<td></td>
</tr>
<tr>
<td>1-6</td>
<td>IGE</td>
</tr>
<tr>
<td>7-12</td>
<td>IM</td>
</tr>
<tr>
<td>13-18</td>
<td>JM</td>
</tr>
<tr>
<td>19-24</td>
<td>IZM</td>
</tr>
<tr>
<td>Columns</td>
<td>Variable</td>
</tr>
<tr>
<td>---------</td>
<td>----------</td>
</tr>
<tr>
<td>25-30 MT</td>
<td>Total number of materials including mixtures (i.e., MT=</td>
</tr>
<tr>
<td>31-36 MO1</td>
<td>Number of mixture specifications, i.e., the length of the &quot;I0,I1,I2&quot; table which specifies how mixtures are to be formed from the input cross sections.</td>
</tr>
<tr>
<td>37-42 BO1</td>
<td>Left boundary (at I=1) condition (0/1=vacuum/reflective).</td>
</tr>
<tr>
<td>43-48 BO2</td>
<td>Right boundary (at I=IM) condition (see BO1).</td>
</tr>
<tr>
<td>49-54 BO3</td>
<td>Top boundary (at J=JM) condition (0/1/2=vacuum/reflective/periodic).</td>
</tr>
<tr>
<td>55-60 BO4</td>
<td>Bottom boundary (at J=1) condition (see BO3).</td>
</tr>
<tr>
<td>61-66 IZ</td>
<td>Number of radial (R or X) mesh interval modifiers (&gt; 1 for δ option, 0 otherwise).</td>
</tr>
<tr>
<td>67-72 JZ</td>
<td>Number of axial (Z, Y or θ) mesh interval modifiers (see IZ).</td>
</tr>
</tbody>
</table>

Card 4 (Required for control), FORMAT (6E12)

1-12 EV | Initial eigenvalue guess (typical values are 1.0 for C calculations and 0.0 for all the rest). |
1-12 EVM | Initial eigenvalue modifier used in search calculation. Typical values are 1.0 for α, 0.1 for C and 0.05 for δ. |
25-36 S03 | Parametric eigenvalue (leave blank or zero if S02=0, otherwise =EV). |
37-48 BUCK | Approximated buckling (cm⁻²) due to finite extension in other than the direction of calculation. Used for searching calculation in X-Y, R-θ and triangular geometry, but for buckling search, BUCK should be zero. |
49-60 LAL | Lower limit on |1-λ| used in search options only. After LAL is reached, the eigenvalue slope is no longer altered. Suggested value is ≈ 0.005. |
61-66 LAH | Upper limit on |1-λ| used in search options only. If |1-λ| > LAH, LAH rather than |1-λ| is used in predicting the new eigenvalue. Suggested value is ≈ 0.5. |
<table>
<thead>
<tr>
<th>Columns</th>
<th>Variable</th>
<th>Description and Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Card 5</td>
<td>(Required for control), FORMAT (6E/2)</td>
<td></td>
</tr>
<tr>
<td>1-12 EPS</td>
<td>Convergence criterion on the total fission source rate (LAMBDA). Typical values are 0.00001 &lt; EPS &lt; 0.0001. The maximum error in $k_{eff}$ is actually about $3 \times$ EPS.</td>
<td></td>
</tr>
<tr>
<td>13-24 EPSA</td>
<td>Parametric eigenvalue convergence criterion. Used only in search calculations. Suggested value $EPS &lt; EPSA &lt; 10 \times EPS$.</td>
<td></td>
</tr>
<tr>
<td>25-36 GO6</td>
<td>Inner iteration pointwise flux convergence criterion. If zero, this flux convergence test is skipped. Suggested value $\approx EPSA$.</td>
<td></td>
</tr>
<tr>
<td>37-48 POD</td>
<td>Parameter oscillation damper used in search options only. Ratio of the computer eigenvalue change to the predicted eigenvalue change. POD is used to accelerate convergence or damp out oscillations. Suggested value is 0.5 for a calculation, 1.0 otherwise.</td>
<td></td>
</tr>
<tr>
<td>49-60 ORF</td>
<td>Over-relaxation factor. If instabilities arise, reduce ORF. Suggested value: 1.4.</td>
<td></td>
</tr>
<tr>
<td>61-72 SOI</td>
<td>Neutron source rate with positive sign, or expecting total thermal power in MWT with negative sign using the conversion factor of 215 MeV/fission. Used to normalize the fluxes.</td>
<td></td>
</tr>
<tr>
<td>Card 6</td>
<td>(Required for control), FORMAT (A4,2X,2E6,13A4)</td>
<td></td>
</tr>
<tr>
<td>1-4 HOLN(MCR)</td>
<td>Identification card for first material. Name.</td>
<td></td>
</tr>
<tr>
<td>7-12 ATW(MCR)</td>
<td>Atomic weight (a.m.u.) of first material (isotope).</td>
<td></td>
</tr>
<tr>
<td>13-18 ALAM(MCR)</td>
<td>Decay constant (days$^{-1}$) for first material. Used only in burnup calculations.</td>
<td></td>
</tr>
<tr>
<td>19-70 AA(13)</td>
<td>Miscellaneous additional identification.</td>
<td></td>
</tr>
<tr>
<td>Card 7</td>
<td>(Optional, required for positive MCR), FORMAT (6E12).</td>
<td></td>
</tr>
<tr>
<td>1-12 C(ITL,IGM,MCR)</td>
<td>Cross section data for first group of first material (isotope) in barns.</td>
<td></td>
</tr>
<tr>
<td>13-24 C(ITL,IGM,MCR)</td>
<td>$\sigma_f$</td>
<td></td>
</tr>
<tr>
<td>25-36 C(ITL,IGM,MCR)</td>
<td>$\sigma_a$</td>
<td></td>
</tr>
<tr>
<td>37-48 C(ITL,IGM,MCR)</td>
<td>$\nu \sigma_f$</td>
<td></td>
</tr>
<tr>
<td>49-60 C(ITL,IGM,MCR)</td>
<td>$\sigma_{t(g+g)}$</td>
<td></td>
</tr>
<tr>
<td>61-72 C(ITL,IGM,MCR)</td>
<td>$\sigma_{(g-l+g)}$</td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td>Variable</td>
<td>Description and Comment</td>
</tr>
<tr>
<td>---------</td>
<td>----------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Card 8</td>
<td>(Continue from Card 8)</td>
<td></td>
</tr>
</tbody>
</table>
| 1-12   | C(ITL,IGM,MCR) | $\sigma(g-2+g)$  
|        | ... | Repeat above sequence for all groups and all materials. Data for each new energy group must begin on a new card. The code checks the input data to insure that  
|        |        | $\sigma_{tr} = \sigma_a + \Sigma \sigma(g+g')$  

**Card 9** (Optional, required if M07=1), FORMAT(6E12.)  
**RF(IM)** Initial flux guess for radial (X) intervals. This flux profile is used for all energy groups.

**Card 10** (Optional, required if M07=1), FORMAT(6E12.)  
**ZP(JM)** Initial flux guess for axial (θ) intervals. This flux profile is used for all energy groups.

**Card 9'** (Optional, required if M07=2), FORMAT(6E12.)  
**NO(IMJM)** Initial flux guess in first energy group. Each new group begins on a new card.

**Card 11** (Optional, required if I04=0), FORMAT(6E12.)  
**SO(IMJM)** Extraneous source distribution for each energy group. Continues for all mesh points.

**Card 12** (Required), FORMAT(6(I1,I2,E9.))  
**RO(IM+1)** Radial (X) position of mesh boundary in cm. The entries must be ordered by magnitude and must begin with 0.0.

**Card 13** (Required), FORMAT(6(I1,I2,E9.))  
**ZO(JM+1)** Axial (Y,θ) position of mesh boundary. Dimensions should be in cm for Z-,X- and triangular-geometry options, and in fractions of a circle for θ (e.g., 0.25 for 90°).
### Card 14 (Required), FORMAT(6(I1,I2,I9))

**MO(IMJM)**  
Zone number specification for each mesh interval. Mesh intervals are sequence numbered beginning at the lower left (at the center for R-0) and then proceeding in radial direction through each row in order, i.e., in order of (1,1), (2,1),...(IM,1), (1,2),..., (IM,2),..., (1,JM),..., (IM,JM).

### Card 15 (Required), FORMAT(6(I1,I2,I9))

**M2(IZM)**  
Mixture numbers by zone starting with zone 1. M2(1)=|MCR|+1, M2(IZM)=MT.

### Card 16 (Optional, required if BUCK\neq 0 or if I04=5), FORMAT(6(I1,I2,E9.))

**GAM(IZM)**  
Zone dependent buckling modifier. The buckling in material zone IZM is given by $B^2(IZM) = \text{GAM}(IZM) \times \text{BUCK}$.

### Card 17 (Required), FORMAT(6(I1,I2,E9.))

**K7(IMG)**  
Fission spectrum ordered by group beginning with the highest energy group.

### Card 18 (Required), FORMAT(6(I1,I2,E9.))

**V7(IGM)**  
Neutron velocities (cm/sec) for each group beginning with the highest energy group.

### Card 19 (Optional, required if MO1 > 0), FORMAT(6(I1,I2,I9))

**I0(MO1)**  
Mixture number, corresponding to M2(IZM), in order to make an information table of mixing materials or concentration search direction.

### Card 20 (Optional, required if MO1 > 0), FORMAT(6(I1,I2,I9))

**II(MO1)**  
Mixture commands indicating which isotopes are to be used to make each mixture. The first entry for each mix must be 0. To indicate multiplication of eigenvalue to the previous entries, use the mixture number for II.
<table>
<thead>
<tr>
<th>Columns</th>
<th>Variable</th>
<th>Description and Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Card 21 (Optional, required if M01 &gt; 0), FORMAT(6(I1,I2,E9.))</td>
<td>I2(M01)</td>
<td>Atomic densities (concentration) (atoms/burn-cm) of the various components (isotopes) in each mixture. Volume fraction and enrichment must be taken into this value. The first entry for each mix is 0.0, corresponding to the 0 in the I1 table. The density for each material is followed in the order they are given in the I1 table, but in concentration searches, these tables are changed with their objectives.</td>
</tr>
<tr>
<td>Card 22 (Optional, required if I04=4), FORMAT(6(I1,I2,E9.))</td>
<td>R2(IM)</td>
<td>Radial mesh number to be modified in dimensional search calculations. These numbers indicate which mesh interval modifier (corresponding to R3 table) is to be used for each radial (R or X) interval.</td>
</tr>
<tr>
<td>Card 23 (Optional, required if I04=4), FORMAT(6(I1,I2,E9.))</td>
<td>R3(IZ)</td>
<td>Radial mesh interval modifiers used in dimensional search calculations. These factors are used with the eigenvalue to increase or decrease size of the radial (R or X) mesh intervals.</td>
</tr>
<tr>
<td>Card 24 (Optional, required if I04=4), FORMAT(6(I1,I2,E9.))</td>
<td>Z2(JM)</td>
<td>Axial mesh number to be modified in dimensional search calculations.</td>
</tr>
<tr>
<td>Card 25 (Optional, required if I04=4), FORMAT(6(I1,I2,E9.))</td>
<td>Z3(JM)</td>
<td>Axial mesh interval modifiers used in dimensional search calculations. The same idea with for R3.</td>
</tr>
<tr>
<td>Columns</td>
<td>Variable</td>
<td>Description and Comment</td>
</tr>
<tr>
<td>---------</td>
<td>----------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>Card 26</td>
<td>(Required for Burnup calculation, or preceding the other cases), FORMAT(4I6,E12.)</td>
<td></td>
</tr>
</tbody>
</table>
| 1-6     | NCON     | Burnup control:  
|         |          | =0: end of problem or read input data for next case. These two options are controlled with Card 29.  
|         |          | =N: read the data for burnup calculation of N burnable isotopes and take time step of DELT.  
|         |          | <0: take time step of DELT using burnup parameters from previous time step. |
| 7-12    | NPRT     | Print control:  
|         |          | =0: mini print. (partial print).  
|         |          | =1: midi print. (partial print).  
|         |          | =2: maxi print. (full print).  
|         |          | See the 11th word in Card 2. |
| 13-18   | NPUN     | Flux damp control: blank or zero for use in IBM. This option should be taken with IBM control card. |
| 19-24   | ITEMPL   | Material density punch option: blank or zero for use in IBM. This option should also be taken with IBM control card. |
| 25-36   | DELT     | Length (days) of time step (burnup calculation interval). If zero, but NCON=0, code has a burnup calculation at the time of zero, and then proceeds to next case. If negative, code shuffles mixture with data in Card 28. |
| Card 27 | (Optional, required if NCON>0, repeat for all burnable isotopes, i.e., N=1, NCON), FORMAT(12I6) |
| 1-6     | MATN(N)  | Material number of the burnable isotope. |
| 7-12    | NBR(N)   | Classification of the isotope:  
|         |          | =0, no effect (e.g., fission products),  
|         |          | =1, fertile isotope (e.g., U-238, Pu-240),  
|         |          | =2, fissile isotope (e.g., Pu-239, Pu-241). |
| 13-18   | LD(N)    | Decay source indication:  
|         |          | =0, no decay source,  
|         |          | =I, decay source from burnable isotope I. |
### Description and Comment

<table>
<thead>
<tr>
<th>Columns</th>
<th>Variable</th>
<th>Description and Comment</th>
</tr>
</thead>
</table>
| 19-24   | LCN(N,1) | Capture source No. 1:  
  =0, no capture source,  
  =I, capture source from burnable  
  isotope I.          |
| 25-30   | LCN(N,2) | Capture source No. 2:  
  Same options as LCN(N,1). |
| 31-36   | LPN(N,1) | Fission source No. 1:  
  =0, no fission source  
  =I, fission source from burnable  
  isotope I.          |
| 67-72   | LFN(N,7) | Fission source No. 7:  
  Same options as LFN(N,1). |

Card 28 (Optional required if DELT < 0, repeat for all mixture to be shuffled), FORMAT(3I6)

| 1-6     | ITEMP   | With this card, the densities of  
  materials in any mixture in IO table  
  can be replaced by the densities of  
  the same materials in another mixture  
  in this table.  
  =0, end of shuffling data,  
  =1, read shuffling data in this card. |
| 7-12    | ITEMP1  | Mixture number (IO) to be replaced. |
| 13-18   | ITEMP2  | Mixture number replacing ITEMP1. |

Card 29 (Required), FORMAT(F7.3)

| 1-7     | FINAL   | Stop or continuation control: This  
  card is placed at the end of the  
  data set of each case.  
  =9.999, final stop,  
  =0, proceed to the next case.  |

### F. Complete Control, Program, and Input Data Decks

The computer code, 2DB is very long programming  
(approximately 3000 cards), and has a very complicated sub-  
routine calling system as illustrated in Fig. A-1, so that to  
use 2DB on IBM 360, long compiling time is necessary (2.5  
mins.). In order to save this time, use of "Library Pack
Figure A-1. Simplified logical flow chart of 2DB
Usage Authorization" system might be convenient for use of the same and long programming with various input data sets. A sample of application form for this purpose is shown in Fig. A-2.

Two different combinations of control, source and data decks to be submitted into IBM 360 computer is listed in this section. The first deck listing is to be used for setting the program in the computer memory, for producing a new source deck for additional debuggings, and usual computation with the data input. Even after the program is submitted, each subroutine can be modified separately, in other words, whole program need not be submitted again in order to change and/or to add some subroutines. The second deck listing including the control cards and the input data cards only is to be used for successive computation with the program kept in the memory. The computer output under this control is just computation results only, but the program is not printed out.
Figure A-2. A sample of the pack usage application form
LIBRARY PACK USAGE AUTHORIZATION

LAST NAME: MINAYUCHI

SOCIAL SECURITY: 306-60-1618

ACCOUNT NUMBER: 14531

THE ABOVE ACCOUNT WILL BE BILLED FOR DISK SPACE ACTUALLY ALLOCATED FOR THE DATA SET NAMED BELOW. IF THE ACCOUNT EXPIRES OR RUNS OUT OF MONEY, THE DATA SET WILL BECOME DELINQUENT.

NEW REQUEST: X EXTENSION OR CORRECTION __ DELETION __

INDICATE ABOVE WHETHER THIS IS A REQUEST FOR A NEW DATA SET OR FOR ADDITIONAL SPACE AND/OR TIME FOR AN EXISTING DATA SET.

DATA SET NAME: PROG. 14531

FOR CPS USERS, THE DATA SET NAME MUST BEGIN WITH THE CPS NUMBER AND ACCOUNT NUMBER, FOR EXAMPLE "CP506.U9998".

FOR NON-CPS USERS, THE DATA SET NAME MUST BEGIN WITH "PSQ" FOR SEQUENTIAL DATA SETS, "PROG" FOR PARTITIONED DATA SETS (PROGRAM LIBRARIES), OR "DA" FOR DIRECT ACCESS DATA SETS. USE OF THE ACCOUNT NUMBER AS A SECOND LEVEL OF QUALIFICATION IS OPTIONAL.

AUTHORIZATION APPLIES COLLECTIVELY TO ALL DATA SETS WITH THE ABOVE NAME AS A LEADING QUALIFIER. THUS TWO 10 TRACK DATA SETS NAMED "PROG.U9998.A" AND "PROG.U9998.X" COULD BE AUTHORIZED WITH A SINGLE REQUEST FOR 20 TRACKS UNDER THE NAME "PROG.U9998".

PACK NAME: LIBPK2

CPS DATA SETS MUST RESIDE ON KJFPAK. NON-CPS DATA SETS MAY RESIDE ON THE RESIDENT PUBLIC PACKS (LIBPAK, LIBPK2, LIBPK1), OR ON THE MOUNTABLE PUBLIC PACK (PUBPK1).

MAXIMUM SPACE: 35 TRACKS

RETENTION PERIOD: 90 DAYS

THE DATA SET WILL BECOME DELINQUENT AT THE END OF THE RETENTION PERIOD OR AT ANY SUCH TIME THAT IT IS FOUND TO BE LARGER THAN THE AUTHORIZED SIZE.

I UNDERSTAND THAT THE ABOVE DESCRIBED DATA SET(S) WILL BE RENAMED IF THEY BECOME DELINQUENT, AND THAT THEY WILL BE SCRATCHED IF THEY ARE STILL DELINQUENT AFTER THREE WEEKS. I FURTHER UNDERSTAND THAT THE COMPUTATION CENTER BEARS NO RESPONSIBILITY FOR MAINTAINING BACK-UP FOR THIS DATA SET.

SIGNATURE: __________________________ DATE: 3/14/72

AUTHORIZATION:
(AN AUTHORIZING SIGNATURE IS NOT REQUIRED UNLESS THE DATA SET EXCEEDS 20 TRACKS OR THE RETENTION PERIOD EXCEEDS 90 DAYS.)

SIGNATURE: __________________________ DATE: 3/14/72
1. **Source deck listing I**

   (This deck is to be used for setting the program in the computer memory).
*** DESCRIPTION OF SUBROUTINES ***

**MAIN**
Main program – controls the overall of the problem. Main calls INP, INIT, FISCAL, $S8830$, ERR02, OUTER, CNNP, S8850, GRAM, INPB, AVERAG, MARCH, and SHUF.

**INP**
Controls the reading and printing of all input data except the burnup data and computes program constants and variable-dimension pointers. INP is called by MAIN and calls S860, S862, S864, REAG2, REAI2, MAPR, and ERR02.

**ERR02**
ERROR2 is used to print an error message. It is called by CALC, INP, REAI2, REAG2, INIT, and CNNP.

**S860**
Reads cross sections from cards and checks them for consistency, performs ADJOINT reversals of the cross sections if required. S860 is called by INP and calls ERR02.

**S862**
Reads input flux guess and prepares a flux tape. S862 is called by INP and calls REAG2.

**S864**
S864 reads input source and prepares a source tape. It is called by INP and calls REAG2.

**REAG2**
Intermediate subroutine used to read floating-point data. REAG2 is called by INP, S862 and S864 and calls ERR02.

**REAI2**
Intermediate subroutine used to read integer data. REAI2 is called by INP and calls ERR02.
SUBROUTINE TO PRODUCE A PICTURE BY ZONE AND MATERIAL. MAPR IS CALLED BY INP.

INIT PERFORMS ADJOINT REVERSALS (S006), MIXES CROSS SECTIONS (S007), MODIFIES GEOMETRY (S010), AND CALCULATES AREAS AND VOLUMES (S011), AND FISSION NEUTRONS (S021). INIT IS CALLED BY MAIN AND CALLS CLEAR AND ERROR.

CLEAR SETS AN ARRAY OF A SPECIFIED LENGTH TO A GIVEN CONSTANT. THE SUBROUTINE IS CALLED BY INIT AND GRAM.

CALCULATES FISSION SUMS (S022) AND PERFORMS NORMALIZATION (S023). FISCAL IS CALLED BY MAIN.

S8830 IS THE MONITOR PRINT SUBROUTINE—PRINTS EIGENVALUE, LAMBDA, ETC. AFTER EACH OUTER ITERATION. IT IS CALLED BY MAIN AND S8850.

PERFORMS A COMPLETE OUTER ITERATION. CALLS INNER1, INNER, AND INNERP. OUTER IS CALLED BY MAIN.

CALCULATES COEFFICIENTS FOR THE FLUX EQUATION. INNER1 IS CALLED BY OUTER.

CALCULATES COEFFICIENTS FOR THE FLUX EQUATION FOR TRIANGULAR GEOMETRY. INNERT IS CALLED BY OUTER.

CALCULATES THE FLUX IN SPECIFIED GROUP. IT IS CALLED BY OUTER AND CALLS IFLUXN.

CALCULATES THE FLUX IN SPECIFIED GROUP FOR PERIODIC B.C. IT IS CALLED BY OUTER AND CALLS IFLUXN.

SUBROUTINE TO NORMALIZE THE FLUXES BEFORE EACH
GROUP FLUX CALCULATION. IT IS CALLED BY INNER, INNER2, AND INNERP.

CNNP performs convergence tests (S851) and computes a new eigenvalue for search options (S852). CNNP is called by MAIN and calls ERRO2 and CLEAR.

S8850 FINAL PRINT SUBROUTINE—PRINTS THE MONITOR LINE, GROUP FLUXES, TOTAL FLUX, POWER DENSITY, AND FISSION SOURCE RATE. IT IS CALLED BY MAIN AND CALLS PRT, S8830, and S8847.

S8847 SUBROUTINE TO COMPUTE AND PRINT GROUP TOTALS. S8847 is called by S8850.

PRT SUBROUTINE TO PRINT ANY IM*JM ARRAY. IT IS CALLED BY S8850.

GRAM calculates and prints the mass of each material in each zone and the zone volume. IT IS CALLED BY MAIN AND CALLS CLEAR.

INPB SUBROUTINE TO READ AND PRINT THE INPUT BURNUP DATA. IT IS CALLED BY MAIN.

AVERAG AVERAG calculates zone averaged fluxes, fission cross sections, absorption cross sections, and breeding ratio. THE SUBROUTINE IS CALLED BY MAIN.

MARCH SUBROUTINE TO CALCULATE THE TIME DEPENDENT ISOTOPIC CONCENTRATIONS. MARCH IS CALLED BY MAIN.

SHUF SUBROUTINE TO SHUFFLE MIXTURES. SHUF IS CALLED BY MAIN.

*** INTERNAL VARIABLES ***
C NINP  READ STATEMENT NUMBER
C NOUT  WRITE STATEMENT NUMBER
C NCR1  CROSS SECTION TAPE
CNFLUX1 FLUX TAPE
C NSCRAT SCRATCH TAPE
C NSORCE SOURCE TAPE
C NCXS  FLUX CONSTANTS TAPE
C ALA   LAMBDA
C B07   USED FOR INTERNAL COMPUTATION IN FISCAL AND INIT
C CNT   CONVERGENCE TRIGGER FOR LAMBDA
C CVT   CONVERGENCE TRIGGER
C DAY   BURNUP TIME IN DAYS
C DELT  LENGTH (DAYS) OF TIME STEP—IF NEG, SHUFFLE MIXES
C E0(I GP) FISSION RATE
C E1(I GP) FISSION SOURCE
C E2(I GP) IN-SCATTER (AND EXTRANEOUS SOURCE)
C E3(I GP) OUT-SCATTER
C E4(I GP) ABSORPTIONS
C E5(I GP) LEFT LEAKAGE
C E6(I GP) RIGHT LEAKAGE
C E7(I GP) TOP LEAKAGE
C E8(I GP) BOTTOM LEAKAGE
C E9(I GP) TOTAL LEAKAGE
C E01   TEMPORARY
C E02   TEMPORARY
C E03   TEMPORARY
C EQ    TEMPORARY FOR S852 (CNNP)
C EVP   PREVIOUS EIGENVALUE
C EVPP  EIGENVALUE FOR TWO ITERATIONS BACK
C FEF   ENERGY RELEASED PER FISSION (=215 MEV)
C GBAR  GROUP INDICATOR FOR TAPE MOTION IN S824 (OUTER)
C GLH   MAXIMUM TIME IN SECONDS
C IGE P IGE + 1
C IGP   IGM + 1
C IGV   GROUP INDICATOR FOR INNER AND OUTER
C IHS   POSITION OF SIGMA SELF SCATTER
C IHT   POSITION OF SIGMA TRANSPORT
INNER ITERATION COUNT FOR A SINGLE GROUP

IMJM  IM*JM
IP    IM + 1
ITEMP TEMPORARY
ITEMP1 TEMPORARY
ITEMP2 TEMPORARY
ITL   CROSS SECTION TABLE LENGTH
IZP   IZM + 1
JP    JM + 1
KO7   NOT USED
KPAGE PAGE COUNTER FOR MONITOR PRINT
LAP   LAMBDA FOR PREVIOUS EIGENVALUE
LAPP  LAMBDA FOR TWO ITERATIONS BACK
LAR   LAMBDA FOR PREVIOUS ITERATION
LC    LOOP COUNT (TOTAL II IN A SINGLE OUTER ITERATION)
ML    MCR + MTP
NCON  NEG/ZERO/POS=TAKE TIME STEP OF DELT/END OF PROBLEM/
      TAKE TIME STEP OF DELT AND READ BURNUP DATA
NGOTO TEMPORARY
NINIT TEMPORARY
ORFP  ORF FOR 1 - LAMBDA LESS THAN 10*EPS
P02   OUTER ITERATION COUNT
PBAR  TEMPORARY
SBAR  TEMPORARY
SK7   SUM OF K7 OVER ALL GROUPS
T06   0/1=NOT DELTA/DELTA CALCULATION
T7    ALPHA/VELOCITY
T11   PREVIOUS FISSION TOTAL
TEMP  TEMPORARY
TEMP1 TEMPORARY
TEMP2 TEMPORARY
TEMP3 TEMPORARY
TEMP4 TEMPORARY
TI    TIME
TSD   (MW-SEC)/(FISSIONS)
V11   TOTAL SOURCE FOR THE GROUP
* * * * * INPUT VARIABLES * * * * *

ID(16) IDENTIFICATION CARD
MAXT MAXIMUM TIME IN MINUTES
A02 0/1=FLUX CALCULATION/ADJOINT CALCULATION
I04 EIGENVALUE TYPE (1/2/3/4/5=KEFF/ALPHA/CONCENTRATION/
DELTA/BUCKLING)
S02 PARAMETRIC EIGENVALUE TYPE (0/1/2=NONE/KEFF/ALPHA)
IGM NUMBER OF GROUPS
NXCM NUMBER OF DOWNSCATTERING TERMS
MCR NUMBER OF MATERIALS FROM CARDS
MTP NUMBER OF MATERIALS FROM TAPE
M07 FLUX GUESS 0/1/2/3=NONE/X(R)*X(Z)/X(R,Z,E)/X(R,Z,E)
FROM TAPE
D05 OUTER ITERATION MAX
G07 INNER ITERATION MAX PER GROUP
S04 INVERSION DIRECTION (0/1=NO EFFECT/ALTERNATE
DIRECTION)
NPRT 0/1=PARTIAL PRINT/FULL PRINT
NPUN FLUX DUMP (0/1/2/3=NONE/CARDS/TAPE+EOF/TAPE+EOF
+REWIND)
IGE GEOMETRY (0/1/2/3=X-Y/R-Z/R-THETA/TRIANGULAR)
IM NUMBER OF RADIAL INTERVALS
JM NUMBER OF AXIAL INTERVALS
IZM NUMBER OF MATERIAL ZONES
MT TOTAL NUMBER OF MATERIALS INCLUDING MIXES
M01 NUMBER OF MIXTURE SPECIFICATIONS
B01 LEFT BOUNDARY CONDITION (0/1=VACUUM/REFLECTIVE)
B02 RIGHT BOUNDARY CONDITION (0/1=VACUUM/REFLECTIVE)
B03 TOP BOUNDARY CONDITION (0/1/2=VAC/REFL/PERIODIC)
B04 BOTTOM BOUNDARY CONDITION (0/1/2=VAC/REFL/PERIODIC)
IZ RADIAL ZONES (DELTA-OPTION ONLY)
JZ AXIAL ZONES (DELTA-OPTION ONLY)
EV FIRST EIGENVALUE GUESS
EVM EIGENVALUE MODIFIER
S03 PARAMETRIC EIGENVALUE
BUCKLING

LAMBDA LOWER
LAMBDA UPPER
EIGENVALUE CONVERGENCE CRITERIA
POINTWISE CONVERGENCE CRITERIA
INNER ITERATION TEST (IF ZERO, NO TEST)
PARAMETER OSCILLATION DAMPER
OVER-RELAXATION FACTOR
NEG/POS=POWER (MWT)/NEUTRON SOURCE RATE

*** SUBSCRIPTED VARIABLES ***:

MATERIAL ATOMIC WEIGHT
MATERIAL NAME
DECAY CONSTANT (DAYS-1)
CROSS SECTION ARRAY FOR CURRENT GROUP
TOTAL FLUX (OLD)
TOTAL FLUX (NEW)
RADIAL AREA ELEMENT
AXIAL AREA ELEMENT
FISSIONS (OLD)
FISSIONS (NEW)
MIX NUMBER
MATERIAL NUMBER FOR MIX
MATERIAL DENSITY
MATERIAL DENSITIES FOR GRAM CALCULATION
FISSION SPECTRUM (EFFECTIVE)
FISSION SPECTRUM (INPUT)
ZONE NUMBERS
MATERIAL NUMBERS BY ZONE
INITIAL RADII
CURRENT RADII
RADIAL ZONE NUMBERS (DELTA CALCULATION ONLY)
RADIAL ZONE MODIFIERS (DELTA CALCULATION ONLY)
AVERAGE RADII
DELTA-R
S2(IM, JM)  FIXED SOURCE
V0(IM, JM)  VOLUME ELEMENTS
V7(IGM)  NEUTRON VELOCITIES
Z0(JP)  INITIAL AXII
Z1(JP)  CURRENT AXII
Z2(JM)  AXIAL ZONE NUMBERS (DELT CALCULATION ONLY)
Z3(JZ)  AXIAL ZONE MODIFIERS (DELT CALCS ONLY)
Z4(JM)  AVERAGE AXII
Z5(JM)  DELTA-Z
CXS(IM, JM, J3)  CONSTANTS INVOLVING CROSS SECTIONS FOR FLUX CALC.
VOL(IZM)  ZONE VOLUME (LITERS)
MASS(ML, IZM)  MATERIAL INVENTORY IN EACH ZONE
MATN(ML)  MATERIAL NUMBER FOR BURNABLE ISOTOPES
NBR(ML)  0/1/2=NO EFFECT/FERTILE/FISSION ISOTOPE
LD(ML)  SOURCE ISOTOPES FOR DECAY
LCN(ML, 2)  SOURCE ISOTOPES FOR CAPTURE
LFN(ML, 7)  SOURCE ISOTOPES FOR FISSION
PHIB(IZM)  ZONE AVERAGED FLUX
AXS(ML, IZM)  SPECTRUM AVERAGED ABSORPTION CROSS SECTION
FXS(ML, IZM)  SPECTRUM AVERAGED FISSION CROSS SECTION
MASSP(ML, IZM)  MATERIAL INVENTORY IN EACH ZONE (PREVIOUS)
CXR(JM)  CONSTANTS FOR RIGHT BOUNDARY
CXT(IM)  CONSTANTS FOR TOP BOUNDARY
HA(IM OR JM)  TEMP STORAGE FOR LINE INVERSION
PA(IM OR JM)  TEMP STORAGE FOR LINE INVERSION
GAM(IZM)  BUCKLING COEFFICIENTS

NOTE * * THESE COMMENT CARDS MUST BE TAKEN OFF FOR USE ON IBM360

THIS IS THE MAIN PROGRAM OF 2DB USED ON IBM360

COMMON  NSORCE, NCXS
COMMON  NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, BO7,
        CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
COMMON ID(11), MAXT, A02, I04, S02, IGM, NXCM,
1 MCR, M07, D05, G07, S04, NPRT, NPUN,
2 IGE, IM, JM, IZM, MT, M01, B01,
3 B02, B03, B04, IZ, JZ, EV, EVM,
4 S03, BUCK, LAL, LAH, EPS, EPSA, G06,
5 POD, ORF, S01
COMMON LATw, LHOLN, LALAM, LC0, LNO, LN2, LA0,
1 LA1, LF0, LF2, L10, L11, LI2, LI3,
2 LK6, LK7, LM0, LM2, LR0, LR1, LR2,
3 LR3, LR4, LR5, LS2, LV0, LV7, LZO,
4 LZ1, LZ2, LZ3, LZ5, LCXS, LV0L,
5 LMASS, LMATN, LMBR, LLD, LLCN, LLFN, LPHIB,
6 LAXS, LFXS, LMASSP, LCXR, LCXT, LHA, LPA,
7 LGAM
INTEGER A02, B01, B02, B03, B04, B07, CNT,
1 CVT, D05, G07, P02, S02, S04, T06,
2 R2, Z2
REAL I2, I3, K6, K7, LAH, LAL, LAP,
1 LAPP, LAR, NO, N2, MASS, MASSP

COMMON A(9000)

CONTINUE
REWWIND 3
REWWIND 4
REWWIND 8
REWWIND 9
REWWIND 10
CALL INP

CALL INIT(A(LK6), A(LK7), A(LIO), A(L11), A(LI2), A(LM0), A(LM2),
1 A(LNO), A(LRO), A(LR1), A(LR2), A(LR3), A(LR4), A(LR5),
A(LZ0), A(LZ1), A(LZ2), A(LZ3), A(LZ4), A(LZ5), A(LAO),
A(LA1), A(LFO), A(LCO), A(LVO), ITL, IM, A(LV7),
JM, MT, A(LGAM)
CALL FISCAL (A(LNO), A(LFO), A(LVO), A(LCO), A(LK6),
A(LMO), A(LM2), ITL, MT)
CALL MONITOR PRINT
GO TO (100, 106, 106, 107), NGOTO
CALL ERRO2 (4HM0NP, 106, 1)
PERFORM AN OUTER ITERATION
CALL OUTER (A(LAO), A(LA1), A(LCO), A(LFO), A(LK6),
A(LMO), A(LM2), ITL, MT)
PERFORM FISSION CALCULATION
CALL FISCAL (A(LNO), A(LFO), A(LVO), A(LCO), A(LK6),
A(LMO), A(LM2), ITL, MT)
PERFORM CONVERGENCE AND NEW PARAMETER CALCULATIONS
PERFORM FISSION CALCULATION
GO TO 102
190 CALL SHUF(A(LI0),A(LI1),A(LI2))
GO TO 102
1 READ(NINP,200) FINAL
200 FORMAT(F7.3)
IF(FINAL.NE.9.999) GO TO 2
STOP
END

C
C
SUBROUTINE INP
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
1 CNT, CVT, DAY, DELT, E01(51), E1(51), E2(51),
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3 E01, E02, E03, EQ, EVP, EVPP, FEF,
4 GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,
5 II, IMJM, IP, ITEMP, ITEMP1, ITEMP2, ITL,
6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
7 LC, ML, NCON, NGOTO, NINIT, ORFP, P02,
8 PBAR, SBAR, SK7, TO6, T7, T11, TEMP,
9 TEMPI, TEMP2, TEMP3, TEMP4, TI, TSD, V11
COMMON ID(11), MAXT, A02, I04, S02, IGM, NXCM,
1 MCR, M07, D05, G07, S04, NPR, NPUN,
2 IGE, IM, JM, IZM, MT, M01, B01,
3 B02, B03, B04, IZ, JZ, EV, EVM,
4 S03, BUCK, LAL, LAH, EPS, EPSA, G06,
5 PO0, QRF, S01
COMMON LATW, LHOLN, LALAM, LCO, LNO, LN2, LAO,
1 LA1, LFJ, LF2, LI0, LI1, LI2, LI3,
2 LK6, LK7, LM0, LM2, LRO, LRL, LR2,
3 LR3, LR4, LR5, LS2, LV0, LV7, LZ0,
4 LZ1, LZ2, LZ3, LZ4, LZ5, LCXS, LVOL,
5 LMASS, LMATN, LNBR, LLD, LLCN, LLFN, LPHIB,
6 LAXS, LFXS, LMASSP, LCXR, LCXT, LHA, LPA,
7 LGAM
INTEGER A02, B01, B02, B03, B04, B07, CNT,
COMMON A(9000)

C THIS SUBROUTINE CONTROLS THE READING OF ALL INPUT DATA

NCR1 = 3
NSCRAT = 4
NINP = 5
NOUT = 6
NFLUX1 = 8
NSORCE = 9
NCXS = 10
WRITE (NOUT, 5)
FORMAT (1H1)
WRITE(NOUT, 10)
FORMAT(42X,35H ** ** ** 2 DB ** ** ** /// )
READ(NINP,20) (ID(I),I=1,16), MAXT
FORMAT(16A4,2X,16)
WRITE(NOUT,30) (ID(I),I=1,16), MAXT
FORMAT(10X,1H ,16A4,16/)
READ(NINP,40) A02, I04, S02, IGM, NXCM, MCR, M07, D05, G07,
S04, NPRT, NPU, IGE, IM, J1, M1, MT, J01, B01, B02, B03, B04,
I2, JZ
WRITE(NOUT,60) A02, I04, S02, IGM, NXCM, MCR
FORMAT(192H A02 0/1=REGULAR CALCULATION/ADJOINT CALCULATION
2 19/)
392H I04 EIGENVALUE TYPE (0/1/2/3/4/5=SOURCE/KEFF/ALPHA/CON
4CENBRAT/DLTA/BUCKLING) 19/
592H S02 PARAMETRIC EIGENVALUE TYPE (0/1/2=NONE/KEFF/ALPHA)
6 19/
792H IGM NUMBER OF GROUPS
8 19/
992H NXCM NUMBER OF DOWNSCATTING TERMS
1 19/
MCR 30S WRITE(NOUT,70) M07, D05, G07, S04, NPRT, NPUN

\[392H \ M07\]
\[
392H \ D05\]
\[
392H \ G07\]
\[
392H \ S04\]
\[
392H \ NPRT\]
\[
392H \ NPUN\]

\[
WRITE(NOUT,80) IGE, IM, JM, IZM, MT, M01\]

\[192H \ IGE\]
\[
192H \ IM\]
\[
192H \ JM\]
\[
192H \ IZM\]
\[
192H \ MT\]
\[
192H \ M01\]

\[
WRITE(NOUT,90) B01, B02, B03, B04, IZ, JZ\]

\[192H \ B01\]
\[
192H \ B02\]
\[
192H \ B03\]

\[
LEFT\ \ BOUNDARY\ \ CONDITION\ \ (0/1=VACUUM/REFLECTIVE)\]
\[
RIGHT\ \ BOUNDARY\ \ CONDITION\ \ (0/1=VACUUM/REFLECTIVE)\]
\[
TOP\ \ BOUNDARY\ \ CONDITION\ \ (0/1/2=VACUUM/REFLECTIVE)\]

\[
NEGATIVE/POSITIVE=NUMBER\ \ OF\ \ MATERIALS\ \ FROM\ \ TAPE/CAR\]
\[
OUTER\ \ ITERATION\ \ MAX\]
\[
INNER\ \ ITERATION\ \ MAX\ \ PER\ \ GROUP\]
\[
INVERSION\ \ DIRECTION\ \ (0/1=NO\ \ EFFECT/ALTERNATE\ \ DIRECTIONS)\]
\[
PRINT\ \ OPTION\ \ (0/1/2=MINI/MIDI/MAXI\ \ PRINT)\]
\[
FLUX\ \ DUMP\ \ (0/1/2/3/4=NONE/CARDS/CARDS+I2/TAPE/TAPE+)\]
\[
GEOMETRY\ \ (0/1/2/3=X-Y/R-Z/R-\Theta/TRIANGULAR)\]
\[
NUMBER\ \ OF\ \ RADIAL\ \ INTERVALS\]
\[
NUMBER\ \ OF\ \ AXIAL\ \ INTERVALS\]
\[
NUMBER\ \ OF\ \ MATERIAL\ \ ZONES\]
\[
TOTAL\ \ NUMBER\ \ OF\ \ MATERIALS\ \ INCLUDING\ \ MIXES\]
\[
NUMBER\ \ OF\ \ MIXTURE\ \ SPECIFICATIONS\]

\[
FLUX\ \ GUESS\ \ (0/1/2/3=NONE/X(R)*X(Z)/X(R,Z,E)/X(R,Z,E)
4)\ \ FROM\ \ TAPE)\]
\[
OUTER\ \ ITERATION\ \ MAX\]
\[
INNER\ \ ITERATION\ \ MAX\ \ PER\ \ GROUP\]
\[
INVERSION\ \ DIRECTION\ \ (0/1=NO\ \ EFFECT/ALTERNATE\ \ DIRECTIONS)\]
\[
PRINT\ \ OPTION\ \ (0/1/2=MINI/MIDI/MAXI\ \ PRINT)\]
\[
FLUX\ \ DUMP\ \ (0/1/2/3/4=NONE/CARDS/CARDS+I2/TAPE/TAPE+)\]
\[
GEOMETRY\ \ (0/1/2/3=X-Y/R-Z/R-\Theta/TRIANGULAR)\]
\[
NUMBER\ \ OF\ \ RADIAL\ \ INTERVALS\]
\[
NUMBER\ \ OF\ \ AXIAL\ \ INTERVALS\]
\[
NUMBER\ \ OF\ \ MATERIAL\ \ ZONES\]
\[
TOTAL\ \ NUMBER\ \ OF\ \ MATERIALS\ \ INCLUDING\ \ MIXES\]
\[
NUMBER\ \ OF\ \ MIXTURE\ \ SPECIFICATIONS\]

\[
LEFT\ \ BOUNDARY\ \ CONDITION\ \ (0/1=VACUUM/REFLECTIVE)\]
\[
RIGHT\ \ BOUNDARY\ \ CONDITION\ \ (0/1=VACUUM/REFLECTIVE)\]
\[
TOP\ \ BOUNDARY\ \ CONDITION\ \ (0/1/2=VACUUM/REFLECTIVE)\]
6/PERIODIC) I9/
792H 804 BOTTOM BOUNDARY CONDITION (0/1/2=VACUUM/REFLECTIVE
8/PERIODIC) I9/
992H IZ RADIAL ZONES (DELTA-OPTION ONLY)
1 I9/
292H JZ AXIAL ZONES (DELTA-OPTION ONLY)
3 I9/
READ(NINP,100) EV, EVM, S03, BUCK, LAL, LAH, EPS, EPSA, G06,
1 POD, ORF, S01
100 FORMAT(6E12.5)
WRITE(NOUT,110) EV, EVM, S03, BUCK, LAL, LAH
110 FORMAT(
191H EV FIRST EIGENVALUE GUESS
2 1PE11.4/
391H EVM EIGENVALUE MODIFIER
2 1PE11.4/
591H S03 PARAMETRIC EIGENVALUE
2 1PE11.4/
791H BUCK BUCKLING (CM-2)
2 1PE11.4/
991H LAL LAMBDA LOWER
2 1PE11.4/
291H LAH LAMBDA UPPER
2 1PE11.4/)
WRITE(NOUT,120) EPS, EPSA, G06, POD, ORF, S01
120 FORMAT(191H EPS EIGENVALUE CONVERGENCE CRITERION
2 1PE11.4/
391H EPSA PARAMETER CONVERGENCE CRITERION
2 1PE11.4/
591H G06 INNER ITERATION TEST (IF ZERO, NO TEST)
2 1PE11.4/
791H POD PARAMETER OSCILLATION DAMPER
2 1PE11.4/
991H ORF OVER-RELAXATION FACTOR
2 1PE11.4/
291H S01 NEGATIVE/POSITIVE=POWER (MWT)/NEUTRON SOURCE RATE
IF(IZ + JZ) 230, 210, 230
210 IF(I04 - 4) 230, 220, 230
220 CALL ERROR2 (4H*I04, 220,1)
230 CONTINUE
240 IF(S02) 240, 260, 240
250 CALL ERROR2 (4H*S03, 250,1)
260 CONTINUE

FEF = 215.0
TSD = FEF*1.602*10.**(-19)
GLH = MAXI*60
KPAGE = 100
IHS = 5
ITL = NXCM + 5
IHT = 4
IZP = IZM + 1
IP = IM + 1
JP = JM + 1
ML = IAABS(MCR)
IGP = IGM + 1
IGEP = IGE + 1
IMJM = IM*JM
EQ = .0
LAP = .0
LAPP = .0
LAR = 0.0
DAY = 0.0
ALA = .0
LC = 0
PO2 = 0
CVT = 0
CNT = 0
NCON = 0
TJ6 = 0
300 IF(I04-4) 310, 300, 310
300 TO6 = 1
310 CONTINUE
ORFP = 1.0 * (ORF - 1.0) + 1.0
C COMPUTE DIMENSION POINTERS
LATW = 1
LHOLN = LATW + ML
LALAM = LHOLN + ML
LC0 = LALAM + ML
LNO = LC0 + ITL*MT
LN2 = LNO + IMJM
LA0 = LN2 + IMJM
LA1 = LA0 + IP
LF0 = LA1 + IM
LF2 = LF0 + IMJM
L10 = LF2 + IMJM
L11 = L10 + MO1
L12 = L11 + MO1
L13 = L12 + MO1
LK6 = L13 + MO1
LK7 = LK6 + IGM
LM0 = LK7 + IGM
LM2 = LM0 + IMJM
LR0 = LM2 + IZM
LR1 = LR0 + IP
LR2 = LR1 + IP
LR3 = LR2 + TO6*IM
LR4 = LR3 + TO6*IZ
LR5 = LR4 + IM
LS2 = LR5 + IM
LV0 = LS2 + IMJM
LV7 = LV0 + IMJM
LZ0 = LV7 + IGM
LZ1 = LZ0 + JP
LZ2 = LZ1 + JP
LZ3 = LZ2 + JM*TO6
LZ4 = LZ3 + JZ*TO6
LZ5 = LZ4 + JM
LCXS = LZ5 + JM
LVOL = LCXS + IMJM*3
LMASS = LVOL + IZM
LMATN = LMASS + ML*IZM
LNBR = LMATN + ML
LLD = LNBR + ML
LLCN = LLD + ML
LLFN = LLCN + ML*2
LPHIB = LLFN + ML*7
LAXS = LPHIB + IZM
LFXS = LAXS + ML*IZM
LMASSP = LFXS + ML*IZM
LCXR = LMASSP + ML*IZM
LCXT = LCXR + JM
LHA = LCXT + IM
LPA = LHA + MAX0(IM, JM)
LGAM = LPA + MAX0(IM, JM)
LAST = LGAM + IZM
ITEMP = 1 + 3*ML + IGP*ITL*MT
IF(LAST - ITEMP) 316,318,318
LAST = ITEMP
WRITE(NOUT,320) LAST
FORMAT(5H LAST,16)
READ CROSS SECTIONS AND WRITE CROSS SECTION TAPE
CALL S860(A(LN0),A(LCO),ITL,IGM,MT,A(LATW),A(LHOLN),A(LALAM))
DO 325 I=LCO, LAST
A(I) = .0
READ FLUXES AND WRITE FLUX TAPE
CALL S862(A(LN0), A(LRO), A(LZ0))
READ EXTERNAL SOURCE
IF (104) 328,326,328
WRITE (NOUT,327)
FORMAT (16H0EXTERNAL SOURCE)
CALL S864 (A(LS2))
CONTINUE
WRITE(NOUT,330)
FORMAT(51HOMESH BOUNDARIES (RO/20=RADIAL POINTS/AXIAL POINTS))
READ RADIAL INTERVALS
CALL REAG2(4H RO, A(LRO), IP)
C READ AXIAL INTERVALS
CALL REAG2(4H ZO, A(IZO), JP)
C READ ZONE NUMBERS
WRITE(NOUT,340)
340 FORMAT(30H ZONE NUMBERS BY MESH INTERVAL)
CALL REAI2(4H MO, A(1MO), 1MJM)
C READ MATERIAL NUMBERS
WRITE(NOUT,350)
350 FORMAT(25HMATERIAL NUMBERS BY ZONE)
CALL REAI2(4H M2, A(LM2), IZM)
C READ BUCKLING COEFFICIENTS
IF(I04 - 5) 351, 352, 358
351 IF(BUCK) 352, 358, 352
352 WRITE(NOUT,354)
354 FORMAT(30HBUCKLING COEFFICIENTS BY ZONE)
CALL REAG2(4H GAM, A(LGAM), IZM)
C READ FISSION FRACTIONS
WRITE(NOUT,360)
360 FORMAT(17H FISSION SPECTRUM)
CALL REAG2(4H K7, A(LK7), IGM)
C READ VELOCITIES
WRITE(NOUT,370)
370 FORMAT(17H NEUTRON VELOCITY)
CALL REAG2(4H V7, A(LV7), IGM)
IF(M01) 400, 400, 380
380 WRITE(NOUT,390)
390 FORMAT(82H MIXTURE SPECIFICATIONS (10/11/12=MIX NUMBER/MAT. NUMBER
1 FOR MIX/MATERIAL DENSITY))
CALL REAI2(4H 10, A(L10), M01)
CALL REAI2(4H 11, A(L11), M01)
CALL REAG2(4H 12, A(L12), M01)
400 CONTINUE
C CHECK FOR DELTA CALCULATION
IF(I04 - 4) 440, 410, 440
410 WRITE(NOUT,420)
420 FORMAT(85H DELTA OPTION DATA  [R2/Z2/R3/Z3=RADIAL/AXIAL ZONE NOS.]})
1/RADIAL/AXIAL ZONE MODIFIERS))
CALL REAI2(4H R2, A(LR2), IM)
CALL REAG2(4H R3, A(LR3), IZ)
CALL REAI2(4H Z2, A(LZ2), JM)
CALL REAG2(4H Z3, A(LZ3), JZ)
440 CONTINUE
C END OF INPUT DATA
CALL MAPR(A(LMO), A(LM2), IM, JM, A(LCO))
IF(LAST 9000) 470, 470, 450
450 WRITE(NOUT, 460)
460 FORMAT(26H PROGRAM CAPACITY EXCEEDED)
STOP
470 RETURN
END

SUBROUTINE ERROR( HOL, JBR, I)
COMMON NSORCE, NCXS, NINP, NOUT, NCR1, NFlUX1, NSCRAT
WRITE(NOUT, I) HOL, JBR
1 FORMAT(2H */llH ERROR IN**, A4, 3H AT, I6/2H */2H *)
GO TO (3, 4), I
3 STOP
4 RETURN
END
C
SUBROUTINE S860 (C, CO, JTL, JGM, JMT, ATW, HOLN, ALAM)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFlUX1, NSCRAT, ALA, B07,
1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3 E01, E02, E03, EQ, EVP, EVPP, FEF,
4 GBAR, GLH, IGE, IGP, IGV, IH, IHT,
5 IL, IMJ, IP, ITE, ITEMP1, ITEMP2, ITEMP3, ITL,
6 IZP, JP, KO7, KPAGE, LAR, LAPP,
7 LC, ML, NCON, NGOTO, NINIT, ORFP, PO2,
8 PBR, SBR, SK7, T06, T7, T11, TEMP,
9 TEMPI, TEMPI2, TEMP3, TEMP4, TI, TSD, V11
COMMON ID(I1), MAXT, A02, I04, SO2, IGM, NXCM,
COMMON LATW, LHOLN, LALAM, LCO, LNO, LN2, LAO, 1
LA1, LFO, LF2, LI0, LI1, LI2, LI3, 1
LK6, LK7, LMO, LM2, LRO, LR1, LR2, 3
LR3, LR4, LR5, LS2, LV0, LV2, LZ2, 4
LZ1, LZ2, LZ3, LZ4, LZ5, LCXS, LVOL, 5
LMASS, LMATN, LNV, LLD, LLFN, LPHIB, 6
LAXS, LFXS, LMASSP, LCXR, LCXT, LHA, LPA, 7
LGAM
INTEGER A02, B01, B02, B03, B04, B07, CNT, 1
CVT, D05, G07, P02, S02, S04, T06, 2
R2, Z2
REAL I2, I3, K6, K7, LAH, LAL, LAP, 1
LAPP, LAR, NO, N2, MASS, MASSP
DIMENSION C(JTL, JGM, JMT), CO(JTL, JMT), ATW(I), HOLN(I), ALAM(I)
DIMENSION AA(I)

C THIS SUBROUTINE READS CROSS SECTIONS, PERFORMS ADJOINT
C REVERSALS IF REQUIRED, AND WRITES CROSS SECTION TAPE
WRITE(N0UT,5) (IDII>, 1=1,16)
5 FORMAT(1H1,16A4,///)
10 WRITE (NOUT, 20 )
20 FORMAT (55H CROSS SECTIONS ARE READ-IN FOR THE FOLLOWING MATERIALS
1/
DO 50 I=1,ML
READ(NINP, 30) HOLN(I), ATW(I), ALAM(I), (AA(J), J=1,13)
ALAM(I) = ALAM(I) / (24.*3600.)
30 FORMAT(A4,2X,2E6.2,13A4)
IF(MCR) 35,35,40
35 READ(15) ((C(L,IIG,I), L=1,ITL), IIG=1,IGM)
GO TO 50
40 DO 45 IIG=1,IGM
45 READ(NINP,60) (C(L,IIG,I), L=1,ITL)
50 WRITE(NOUT, 55 ) I, HOLN(I), (AA(J), J=1,13)
CHECK ON CROSS SECTION CONSISTENCY AND ORDER
ITEMP = 0
IF(MCR) 70,70,90
REWIND 15
DO 140 J=1,ML
DO 140 I=1,IGM
G = C(2,I,J) + C(5,I,J)
DO 110 K = 1, NXCM
KK = I + K
M = 5 + K
IF(KK - IGM) 100, 100, 110
G = G + C(M,KK,J)
CONTINUE
IF(ABS((G - C(4,I,J))/C(4,I,J)) - .01) 135, 120, 120
ITEMP = 1
IFCABS((G - C(4,I,J))/C(4,I,J) ) - .0001) 140, 138, 138
WRITE(NOUT,130) J, I
CONTINUE
IF (ITEMP) 160,160,150
CALL EXIT
A02=0/1=FLUX CALCULATION/ADJOINT CALCULATION
IF(A02) 170, 280, 170
DO 190 II=1,IGM
IGBAR=IGM-II+1
DO 180 M=1,MT
DO 180 L = 1,IHS
TEMP=C(L,II,M)
C(L,II,M)=C(L,IGBAR,M)
C(L,IGBAR,M)=TEMP
IF (IGBAR - II - 1) 200, 200, 190
CONTINUE
CONTINUE
KK = ITL - IHS
IF (KK) 280, 280, 210
210 CONTINUE
DO 240 M = 1, MT
DO 240 IIG = 1, IGM
IGBAR = IGM - IIG + 1
DO 240 L = 1, KK
IF (L - IIG) 220, 240, 240
220 I = L + IHS
ITEMP = IGBAR + L
IF (IIG - ITEMP) 230, 230, 240
230 TEMP = C(I, IIG, M)
C(I, IIG, M) = C(I, ITEMP, M)
C(I, ITEMP, M) = TEMP
240 CONTINUE
C WRITE CROSS SECTION TAPE
280 DO 300 IIG = 1, IGM
DO 290 M = 1, MT
DO 290 L = 1, ITL
290 CO(L, M) = C(L, IIG, M)
300 WRITE (NCR1), ((CO(L, M), L = 1, ITL), M = 1, MT)
REWIND NCR1
RETURN
END
C
C SUBROUTINE S862(NO, RF, ZF)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07, 1
CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51), 2
E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51), 3
E01, E02, E03, EQ, EVP, EVPP, FEF, 4
GBAR, GLHu, IGEP, IGP, IGV, IHS, IHT, 5
II, IMJM, IP, ITEMP, ITEMP1, ITEMP2, ITL, 6
IZP, JP, K07, KPAGE, LAP, LAPP, LAR, 7
LC, ML, NCON, NGOTO, NINIT, ORFP, P02, 8
PBAR, SBAR, SK7, T06, T7, T11, TEMP, 9
TEMP1, TEMP2, TEMP3, TEMP4, TI, TSD, V11
COMMON IO(11), MAXT, A02, I04, SO2, IGM, NXCM,
THIS SUBROUTINE READS THE INPUT FLUXES AND PREPARES A FLUX TAPE WRITE(NOUT,5)

5 FORMAT(1H1)

C M07=0/1/2/3=NO FLUX INPUT/X(R)*X(Z)/X(R,Z,E)/TAPE
KK = M07 + 1
DO 1000 IIG = 1, IGM
GO TO (50, 60, 70, 120), KK

50 DO 99 I=1, IM
DO 99 J = 1, JM
ITEMP = (J - I)*IM + I
99 NO(ITEMP) = 1.0
GO TO 200

60 IF(IIG - 1) 62, 62, 64

62 WRITE(NOUT,63)
63 FORMAT(55HOFLUX GUESS (RF/ZF=TOTAL RADIAL FLUX/TOTAL AXIAL FLUX))
CALL REAG2H(RF, RF, IM)
CALL REAG2H(ZF, ZF, JM)
64 DO 69 I = 1, IM
DO 69 J = 1, JM
ITEMP = (J - 1)*IM + I
69 NOITEMP) = RF(I)*ZF(J)
GO TO 200
70 READ(NINP,100) (NO(I), I=1, IMJM)
100 FORMAT(6E12.6)
GO TO 200
120 READ(14) (NO(I), I=1, IMJM)
200 WRITE(NFLUX1) (NO(I), I=1, IMJM)
1000 CONTINUE
IF(MO7 - 3) 1020,1013,1020
1010 REWIND 14
1020 REWIND NFLUX1
RETURN
END

SUBROUTINE S864 (S2)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07, 
1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51), 
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51), 
3 E01, E02, E03, EQ, EVP, EVPP, FEF, 
4 GBAR, GLH, IGEP, IGP, IGV, IHS, IHT, 
5 II, IMJM, IP, ITMP,ITEMP1,ITEMP2, ITL, 
6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR, 
7 LC, ML, NCDN, NGOTO, NINIT, ORFP, P02, 
8 PBAR, SBAR, SK7, T06, T7, T11, TEMP, 
9 TEMP1, TEMP2, TEMP3, TEMP4, TI, TSD, V11 
COMMON ID(11), MAXT, A02, I04, S02, IGM, NXCM, 
1 MCR, MO7, D05, G07, S04, NPRT, NPUN, 
2 IGE, IM, JM, IZM, MT, MO1, B01, 
3 B02, B03, B04, JZ, JZ, EV, EVM, 
4 S03, BUCK, LAL, LAH, EPS, EPSA, G06, 
5 POD, ORF, S01 
COMMON LATW, LHOLN, LALAM, LCO, LNO, LN2, LAO, 
1 LAL, LF0, LF2, LI0, LII, L12, LI3,
INTEGER A02, B01, B02, B03, B04, B07, CNT,
1 CVT, D05, G07, PJ2, SJ2, SJ4, TJ6,
2 R2, Z2
REAL I2, I3, K6, K7, LAH, LAL, LAP,
1 LAPP, LAR, NO, N2, MASS, MASSP
DIMENSION S2(I)

C THIS SUBROUTINE READS THE EXTERNAL SOURCE AND PREPARES A SOURCE TA
DO 50 IIG = 1, IGM
CALL REAG2 (4H S0, S2, IMJM)
WRITE (NSORCE) (S2(I), I = 1, IMJM)
CONTINUE
REWIND NSORCE
RETURN
END
SUBROUTINE REAG2(4H H0LL, ARRAY, NCOUNT)
DIMENSION ARRAY(1), V(12), K(12), IN(12)
COMMON NSORCE, NCXS, NINP, NOUT, NCR1, NFLUX1, NSCRAT
JFLAG=0
J=1
10 IF(JFLAG)20,40,20
20 DO 30 JJ=1,6
K(JJ)=K(JJ+6)
IN(JJ)=IN(JJ+6)
V(JJ)=V(JJ+6)
JFLAG=0
GO TO 60
40 READ (NINP,50) (K(I), IN(I), V(I), I = 1, 6)
50 FORMAT(6(I1, I2, E9.4))
60 DO 140 I=1,6
L=K(I)+1
GO TO (70, 80, 100, 150, 132, 140, 62), L
C FILL

62 JJ=J
DO 65 M=JJ,NCCUNT
   ARRAY(J) = V(I)
65 J=J+1
   GO TO 150
C NO MODIFICATION
70 ARRAY(J)=V(I)
   J=J+1
   GO TO 140
C REPEAT
80 L=IN(I)
   DO 90 M=1,L
      ARRAY(J)=V(I)
      J=J+1
90 CONTINUE
   GO TO 140
C INTERPOLATE
100 IF(I-6) 120,110,110
110 READ (NINP,50) (K(JJ),IN(JJ),V(JJ),JJ=7,12)
   JFLAG=1
120 L=IN(I)+1
   DEL=(V(I+1)-V(I))/FLOAT (L)
   DO 130 M=1,L
      ARRAY(J)=V(I)+DEL*FLCAT (M-1)
      J=J+1
130 CONTINUE
   GO TO 140
C CYCLE
132 L = IN(I)
   N = INT(.00001+V(I))
   DO 135 LL=1,L
   DO 135 NN=1,N
      ARRAY(J) = ARRAY(J-N)
135 J=J+1
140 CONTINUE
   GO TO 10
C TERMINATE
150 J=J-1
WRITE (NOUT,160), HOLL,J, (ARRAY(I),I=1,J)
IF(J-NCOUNT)170,180,170
160 FORMAT(6X,A4,I6/(10E12.5))
170 CALL ERRO2(4HREAI, 170,1)
180 RETURN
END

SUBROUTINE REAI2(HOLL,IARRAY,NCOUNT)
DIMENSION IARRAY(I),IV(6),K(6),IN(6)
COMMON NSORCE, NCXS, NINP, NOUT, NCR1, NFLUX1, NSCRAT
J=1
READ(NINP,20) (K(I),IN(I),IV(I),I=1,6)
20 FORMAT(6(I1,I2,I9))
DO 70 I=1,6
L=K(I)+1
GO TO (30,40,60,80,62,70,22), L
C FILL
22 JJ=J
DO 25 M=JJ,NCOUNT
IARRAY(J) = IV(I)
25 J=J+1
GO TO 80
C NO MODIFICATION
30 IARRAY(J)=IV(I)
J=J+1
GO TO 70
C REPEAT
40 L=IN(I)
DO 50 M=1,L
IARRAY(J)=IV(I)
J=J+1
50 CONTINUE
GO TO 70
C INTERPOLATE
60 CALL ERRO2(4HREAI,63,1)
C CYCLE
DO 65 LL=1,L
DO 65 NN=1,N
IARRAY(J) = IARRAY(J-N)
J=J+1
CONTINUE
GO TO 10

C TERMINATE
J=J-1
WRITE (NOUT,90) HOLL,J,(IARRAY(I),I=1,J)
IF(J -NCOUNT)100,110,100
90 FORMAT(6X,45/12)
100 CALL ERR02(4HREADI, 100,1)
110 RETURN

END

C

SUBROUTINE MAPR (M0,M2, JIM,JJM, K)

COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3 E01, E02, E03, EQ, EVP, EVPP, FEF,
4 GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,
5 IM, IMJ, IP, ITEMP, ITEMP1, ITEMP2, ITL,
6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
7 LC, ML, NCON, NGOTO, NINIT, ORFP, P02,
8 PBAR, SBAR, SK7, T06, T7, T11, TEMP,
9 TEMPL, TEMP2, TEMPL, TEMP4, TI, TSO, V11
COMMON ID(11), MAXT, A02, I04, S02, IGM, NXCM,
1 MCR, M07, D05, G07, S04, NPRT, NPUN,
2 IGE, IM, JM, IZM, MT, M01, BJ1,
3 B02, B03, B04, IZ, JZ, EV, EVM,
4 S03, BUCK, LAL, LALM, EPS, EPSA, G06,
5 POD, ORF, S01
COMMON LATW, LHCLN, LALAM, LCO, LNO, LN2, LA0,
INTEGER A02, B01, B02, B03, B04, B07, CNT,
C
REAL I2, I3, K6, K7, LAH, LAL, LAP,
C
DIMENSION MO(JIM, JJM, M2(1), K(1)

SUBROUTINE INIT (K6, K7, I0, I1, I2, M0, M2, NO, RO, R1, R2,
C
R3, R4, R5, Z0, Z1, Z2, Z3, Z4, Z5, A0, A1,
C
FO, CO, VO, JTL, JIM, VT, JJM, JMT, GAM)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
   CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
   E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
   E0(52), E1(52), E2(52), E3(52), E4(52), E5(52), E6(52), E7(52),
   E8(52), E9(52),
   I2, IMJM, IP, ITMP, ITEM1, ITEM2, ITL,
   IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
   LC, ML, NCON, NGOTO, NINIT, ORFP, P02,
   PBAR, SBAR, SK7, T06, T7, T11, TEMP,
   TEMPE, TEMPP, TEMPS, TEMP3, TEMPM, T6,
   COMMON ID(11), MAXT, A01, 104, 502, IGM, NXCM,
   MCR, M07, DO5, GO7, SO4, NPRT, NPUN,
   IGE, IM, JM, IZM, MT, M01, B01,
   B02, B03, B04, IZ, JZ, EV, EVM,
   S03, BUCK, LAL, LAH, EPS, EPSA, G06,
   POD, ORF, S01
COMMON LAT, LHON, LAM, L0, L1, L2, LA0,
   LA1, LF0, LF1, L10, L11, L12, L13,
   LK6, LK7, LM0, L1M2, L1R0, L1R1, L1R2,
   LR3, LR4, LR5, LS2, LV0, LV7, M20,
   LZ1, LZ2, LZ3, LZ4, LZ5, LCXS, LVOL,
   LMASS, LMAIT, LNB, LLO, LNC, LLFN, LPHI,
   LAX, LFX, LMASSP, LCXR, LCA, LAH, LPA,
   LGAM
INTEGER A02, B01, B02, B03, B04, B07, CNT,
   CVT, DO5, GO7, PO2, S02, S04, T06,
   R2, Z2
REAL I2, I3, K6, K7, LAH, LAL, LAP,
   LAPP, LAR, N0, N2, MASS, MASSP
DIMENSION K6(1), K7(1), I0(1), I1(1), I2(1), RO(1), R1(1),
   R2(1), R3(1), R4(1), R5(1), Z0(1), Z1(1), Z2(1),
   Z3(1), Z4(1), Z5(1), A0(1), A1(1), CO(JM, JMT),
   V0(JM, JM), M0(1), M2(1), N0(1), FO(1), V7(1), GAM(1)

NINIT = 1
IF (P02) 20, 10, 20
WRITE(NOUT,15) DAY
CONTINUE
ADJOINT REVERSALS
IF(A02) 25, 45, 25
IF(P02) 45, 30, 45
IF(NCOND) 45, 35, 45
IIG=1
IGBAR=IGM
TEMP=K7(IIG)
K7(IIG)=K7(IGBAR)
K7(IGBAR)=TEMP
TEMP=V7(IIG)
V7(IIG)=V7(IGBAR)
V7(IGBAR)=TEMP
IIG=IIG+1
IGBAR=IGBAR-1
IF(IIG-IGBAR) 40, 45, 45
CONTINUE
MIX CROSS-SECTIONS
IF(P02) 50, 55, 50
GO TO (245,245,85,245,185), 104
IF(M31) 70, 70, 60
WRITE(NOUT, 65 ) (J, I0(J), I1(J), I2(J), J = 1, MOI)
FORMAT(/19H MATERIAL ATOMIC DENSITY/(I4,1X,I8,8X,I8,8X,E20.8))
IF(NPRT-l) 85, 85, 75
WRITE (NOUT,80 )
FORMAT(/19H1CROSS-SECTION EDIT)
REWIND NCR1
DO 180 IIG=1,IGM
READ (NCR1) ((C0(I,J),I=1,ITL),J=1,MT)
IF(M01) 90, 145, 90
DO 140 M=1,M01
IF(IO(M)-MT) 100, 100, 95
CALL ERR02(4HINIT, 95,1)
100 IF(Il(M)-MT) 105, 105, 95
105 N=IO(M)
     L=Il(M)
     E01=I2(M)
     IF(L) 125, 125, 110
110 IF(E01) 125, 115, 125
115 IF (N-L) 125, 120, 125
120 E01 = EV
     L = 0
125 DO 140 I=1,ITL
     IF (L) 130, 135, 130
130 CO(I,N)=CO(I,N)+CO(I,L)*E01
     GO TO 140
135 CO(I,N)=CO(I,N)*E01
140 CONTINUE
145 IF(P02) 175, 150, 175
150 IF(NPRT=1) 175, 175, 155
155 WRITE (NOUT,160 ) IIG K,
     FORMAT (6HOGROUP, 13, e4H SIGF SIGA NUSIGF SIGTR
     1 GXG G-1XG G-2XG ...)
     DO 165 N=1,MT
     WRITE (NOUT,170 ) N,(CO(I,N),I=1,ITL)
165 WRITE (NOUT,170 ) N,(CO(I,N),I=1,ITL)
165 WRITE (NOUT,170 ) N,(CO(I,N),I=1,ITL)
170 FORMAT(4H MAT,I3, (10E11.3))
175 WRITE (NSCRAT) ((CO(I,J),I=1,ITL),J=1,MT)
180 CONTINUE
     REWIND NCR1
     REWIND NSCRAT

C SWITCH TAPE DESIGNATIONS
     ITEMP=NSCRAT
     NSCRAT=NCR1
     NCR1=ITEMP
185 IF(104=5) 190, 205, 190
190 IF(BUCK) 200, 245, 200
200 TEMP = BUCK
     GO TO 220
205 IF(P02) 210, 210, 215
210 BUCK = 0.
TEMP = EV - BUCK
BUCK = EV

DO 240 IIG=1,IGM
READ(NCR1) ((CO(I,J), I=1,ITL),J=1,MT)
DO 235 MTZ = 1,MT
DO 230 KZ=1,IZM
IF(M2(KZ) - MTZ) 230, 225, 230
225 TEMP1 = (TEMP*GAM(KZ))/(3.*CO(4,MTZ))
CO(2,MTZ) = CO(2,MTZ) + TEMPI
CO(5,MTZ) = CO(5,MTZ) - TEMPI
GO TO 235
230 CONTINUE
235 CONTINUE
WRITE(NSCRAT) ((CO(I,J), I=1,ITL),J=1,MT)
CONTINUE
REWIND NCR1
REWIND NSCRAT
C SWITCH TAPE DESIGNATIONS
ITEMP = NSCRAT
NSCRAT = NCR1
NCR1 = ITEMP
240 CONTINUE
C
C MODIFY GEOMETRY
IF(P02)270, 250, 270
250 IF(NCON) 375, 255, 375
255 DO 260 I=1,IP
260 R1(I)=RO(I)
DO 265 J=1,JP
265 Z1(J)=Z0(J)
270 IF(104-4) 305, 275, 305
275 DO 280 I=1,IM
K=R2(I)
280 R1(I+1)=R1(I)+(RO(I+1)-RO(I))*((1.0+ EV*R3(K))
DO 285 J=1,JM
K=Z2(J)
285 Z1(J+1)=Z1(J)+(Z0(J+1)-Z0(J))*((1.0+ EV*Z3(K))
IF(IGE-2) 305, 290, 305
290 IF(ABS(Z1(IP)-1.0)-1.0E-04) 305, 305, 300
300 CALL ERR02(4HINIT, 300,1)
305 CONTINUE
C
C AREAS AND VOLUMES
PI2=6.28318
IF(P02) 310, 315, 310
310 IF(I04 - 4) 375, 315, 375
315 CONTINUE
DO 345 I=1,IM
R4(I)=(R1(I+1)+R1(I))*0.5
R5(I)=R1(I+1)-R1(I)
IF( R5(I) ) 320, 320, 325
320 CALL ERR02 (4HR(I), 320,1)
325 CONTINUE
GO TO (330,335,340,342), IGEP
330 A0(I)=1.0
A0(IP)=1.0
A1(I)=R5(I)
GO TO 345
335 A0(I)=PI2*R1(I)
A0(IP)=PI2*R1(IP)
A1(I)=PI2*R5(I)*R4(I)
GO TO 345
340 A0(I)=PI2*R1(I)
A0(IP)=PI2*R1(IP)
A1(I)=R5(I)
GO TO 345
342 A0(I) = 2.*R5(I)
A0(IP) = 2.*R5(I)
A1(I) = 2.*R5(I)
345 CONTINUE
DO 370 J=1,JM
Z4(J)=(Z1(J+1)+Z1(J))*0.5
Z5(J)=Z1(J+1)-Z1(J)
IF(Z5(J)) 350, 350, 355
CALL ERR02 (4HZ(J), 350, 1)
355 CONTINUE

DO 370 I=1, IM
GO TO (360, 365, 365, 360), IGEP
360 VO(I,J)=R5(I)*Z5(J)
GO TO 370
365 VO(I,J)=PI2*R5(I)*Z5(J)*R4(I)
370 CONTINUE
375 CONTINUE

C
C MATERIAL ADDRESSES
380 IF(P02) 405, 385, 405
385 SK7=J.
DO 400 IIG=1, IGM
IF(S02-1) 395, 390, 395
390 K6(IIG)=K7(IIG)/S03
GO TO 400
395 K6(IIG)=K7(IIG)
400 SK7=SK7+K7(IIG)
405 CONTINUE

C
C FISSION NEUTRONS
T11=E1(IGP)
410 CALL CLEAR(0.0, F0, IMJM)
DO 425 IIG=1, IGM
EO(IIG) = .0
READ (NFLUX1) (NO(I), I=1, IMJM)
READ (NCR1) ((CO(I,J), I=1, ITL), J=1, MT)
DO 425 J = 1, JM
DO 425 K = 1, IM
I = K + (J-1)*IM
ITEMP=M0(I)
ITEMP=M2(ITEMP)
EO(IIG) = EO(IIG) + VO(K, J)*NO(I)*CO(1, ITEMP)
IF(A02) 415, 423, 415
415 F0(I)=F0(I)+K7(IIG)*NO(I)
GO TO 425
420   F0(I)=F0(I)+CO(IHT-1,ITEMP)*NO(I)
425   CONTINUE
REWIND NFLUX1
REWIND NCR1
RETURN
END

SUBROUTINE CLEAR (X,Y,N)
DIMENSION Y(N)
DO 1 I=1,N
1   Y(I)=X
RETURN
END

C
C
SUBROUTINE FISCAL (NO, F0, VO, CO, K6, M0, M2, JTL,JMT)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
1   CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2   E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3   EO1, E02, E03, EQ, EVP, EVPP, FEF,
4   GBAR, GLH, IGEF, IGF, IGV, IH5, IHT,
5   II, IMJM, IP, ITEMP, ITEMP1, ITEMP2, ITL,
6   JZP, JP, KO7, KPAGE, LAP, LAPP, LAR,
7   LC, ML, NCON, NGOTO, NINIT, ORFP, PO2,
8   TBP, SBAR, SK, T06, T7, T11, TEMP,
9   TEF, TEF, TEF, TEF, TEF, TEF, TEF, TEF, TEF,
COMMON ID(11), MAXV, A02, I04, SO2, IGM, NXCM,
1   MCR, M07, D05, G07, SO4, NPRT, NPUN,
2   IGE, IM, JM, IJM, MT, M01, B01,
3   B02, B03, B04, IZ, JZ, EV, EVM,
4   S03, BUCK, LAL, LAH, EPS, EPSA, GO6,
5   POD, ORF, SO1
COMMON LATW, LHOln, LALAM, LC0, LN0, LN2, LAO,
1   LA1, LF0, LF2, LIO, LI1, LI2, LI3,
2   LK0, LK7, LM0, LM2, LR0, LR1, LR2,
3   LR3, LR4, LR5, LS2, LV0, LV7, L20,
4   LZ1, LZ2, LZ3, LZ4, LZ5, LCXS, LVOL,
C FISSION SUMS
IF(B07) 90,90,10
10 IF(A02) 20, 40, 20
20 DO 30 IIG=1,IGM
READ (NCR1) (((C0(I,J),I=1,ITL),J=1,MT)
E1(IIG)=0.
DO 30 I=1,IMJM
ITEMP=MO(I)
ITEMP=M2(IITEMP)
30 E1(IIG)=E1(IIG)+C0(IHT-1,ITEMP)*FO(I)*V0(I)
REWIND NCR1
GO TO 70
40 E01=0.
DO 50 I=1,IMJM
50 E01=E01+V0(I)*F0(I)
DO 60 IIG=1,IGM
60 E1(IIG)=K6(IIG)*E01
70 E1(IGP)=0.
E0(IGP)=0.
DO 80 IIG=1,IGM
E0(IGP)=E0(IGP)+E0(IIG)
80 E1(IGP)=E1(IGP)+E1(IIG)
IF(B07) 140, 90, 140
90 ALA = E1(IGP)/T11
TEMP=1.0/ALA
IF(IO4-1) 230, 100, 140
100 DO 110 IIG=1,IGM
E1(IIG) = E1(IIG) * TEMP
K6(IIG) = K6(IIG) * TEMP
E1(IGP) = E1(IGP) * TEMP
IF(A02) 120, 140, 120
DO 130 I = 1, IMJM
130 F0(I) = F0(I) * TEMP
140 CONTINUE
C
C NORMALIZATION
B07 = 0
150 IF(S01) 160, 230, 170
160 E01 = ABS(S01) / (E01(IGP) * TSD)
GO TO 180
170 E01 = S01 / E01(IGP)
180 DO 190 IIG = 1, IGP
190 E1(IIG) = E01 * E1(IIG)
DO 200 I = 1, IMJM
200 F0(I) = E01 * F0(I)
230 RETURN
END
C
C SUBROUTINE S8830
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3 E01, E02, E03, EQ, EVP, EVPP, FEF,
4 GBAR, GLH, IGEP, IGP, IGR, IHS, IHT,
5 II, IMJM, IP, ITEMP, ITEMP1, ITEMP2, ITL,
6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
7 LC, ML, NCON, NGOLO, NINIT, ORFP, P02,
8 PBAR, SBAR, SK7, T06, T7, T7, T7, TEMP,
9 TEMPI, EMP2, EMP3, EMP4, T1, TSD, V11
COMMON ID(11), MAXT, A02, I04, S02, IGM, NXCM,
1 MCR, M07, D05, GO7, S04, NPRT, NPUN,
2 IGE, IM, JM, IZM, MT, M01, B01,
3     B02,  B03,  B04,  IZ,  JZ,  EV,  EVM,
4     S03,  BUCK,  LAL,  LAH,  EPS,  EPSA,  G06,
5     POD,  ORF,  S01
COMMON  LATW,  LHQLN,  LALAM,  LCO,  LNO,  LN2,  LA0,
1     LAI,  LF0,  LF2,  LIO,  LI1,  LI2,  LI3,
2     LK6,  LK7,  LM0,  LM2,  LRO,  LR1,  LR2,
3     LR3,  LR4,  LR5,  LS2,  LVO,  LV7,  LZO,
4     LZ1,  LZ2,  LZ3,  LZ4,  LZ5,  LCXS,  LVOL,
5     LMASS,  LMATN,  LNBK,  LLD,  LLCN,  LLFN,  LPHIB,
6     LAXS,  LFXS,  LMASSP,  LCXR,  LCXT,  LHA,  LPA,
7     LGAM
INTEGER  A02,  B01,  B02,  B03,  B04,  B07,  CNT,
1     CVT,  D05,  G07,  P02,  S02,  S04,  T06,
2     R2,  Z2
REAL     I2,  I3,  K6,  K7,  LAH,  LAL,  LAP,
1     LAPP,  LAR,  NO,  N2,  MASS,  MASSP
C     MP  830  MCNITOR PRINT
C     TI = TI/60.
1     KPAGE = KPAGE + 1
160  IF(KPAGE - 40)  220,  160,  160
210  WRITE(NOUT,  213)
213  FORMAT(105H1  TIME  OUTER  IN.  IT.  EIGENVAL
1UE  EIGENVALUE  LAMBDA )
215  WRITE(NOUT,  215)
215  FORMAT(105H1  (MINUTES)  ITERATIONS  PER LOOP  SLOPE
1UE )
220  WRITE(NOUT,  225)  P02,  LC,  EQ,  EV,  ALA
225  FORMAT(20X,  I4,  11X,  I4,  6X,  E15.8,  E15.8,  E15.8)
230  P02=P02+1
1     LC=0
1     IF(P02-D05)430,430,330
330  NGOTO = 1
1     GO TO 630
430  NGOTO = 4
630  RETURN
END
SUBROUTINE OUTER(AO, A1, C0, F0, K6, M0, M2, NO, N2,  
  S2, V3, V7, Z5, F2, JTL, JMT, CXS,  
  JIM, JJM, R5, R4, Z4, CXR, CXT, HA, PA)  
DIMENSION AO(l), A1(l), F0(l), K6(l), M0(l), M2(l),  
  NO(l), N2(l), S2(l),  
  V0(l), V7(l), Z5(l), F2(l), C(J(TL, JMT), HA(l), PA(l),  
  CXS(JIM, JJM, 3), R5(l), R4(l), Z4(l), CXR(l), CXT(l)  
INTEGER GBAR, PBAR, SBAR  
COMMON NSORCE, NCXS  
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,  
  CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),  
  E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),  
  E01, E02, E03, EQ, EVP, EVPP, FEF,  
  GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,  
  I, IMJM, IP, ITMP, ITMP1, ITMP2, ITL,  
  IZP, JP, K07, KPAGE, LAP, LAPP, LAR,  
  LC, ML, NCON, NGOTO, NINIT, ORFP, P02,  
  PBAR, SBAR, SK7, TO6, T7, T11, TEMP,  
  TEMPI, TEMP2, TEMPS, T1, TSD, V11  
COMMON ID(11), MAXT, A02, I04, SO2, IGM, NXCM,  
  MCR, M07, D05, G07, SO4, NPRT, NPUH,  
  IGE, IM, JM, IMJ, MT, M01, B01,  
  B02, B03, B04, IZ, JZ, EV, EVM,  
  S03, BUCK, LAL, LAH, EPS, EPSA, G06,  
  POD, ORF, S01  
COMMON LATW, LHCLN, LALAM, LC0, LNO, LN2, LA0,  
  LAL, LFO, LF2, LI0, LII, LI2, L13,  
  LK6, LK7, LMO, LM2, LRO, LR1, LR2,  
  LRR, LRR, LR5, L52, LV0, LV7, L2O,  
  L21, L2Z, L3Z, L44, L54, LCXS, LVOL,  
  LMASS, LMATN, LNB, LLD, LLCN, LLFN, LPHIB,  
  LAX, LFXS, LMASSP, LCXR, LCXT, LHA, LPA,  
  LGAM  
INTEGER A02, BO1, BO2, BO3, BO4, BO7, CNT,  
  CVT, D05, G07, P02, S02, S04, T06,
REAL I2, I3, K6, K7, LAH, LAL, LAP,
1 LAPP, LAR, NO, N2, MASS, MASSP

IGV=1

C SOURCE CALCULATION
10 CONTINUE
READ(NCR1) ((CO(I,M),I=1,IMJM),M=1,MT)
IF (I04) 15,12,15
12 READ (NSORCE) (S2(I), I = 1,IMJM)
GO TO 30
15 DO 20 I=1,IMJM
20 S2(I)=0.
30 IF(A02) 60, 40, 60
40 DO 50 I=1,IMJM
50 S2(I)=S2(I)+K6(IGV)*F0(I)
GO TO 80
60 DO 70 I=1,IMJM
ITEMP1=M0(I)
ITEMP1=M2(ITEMP1)
70 S2(I)=S2(I)+CO(IHT-1,ITEMP1)*F0(I)
80 GBAR=IGV+IHS-ITL
IF(GBAR-1) 90, 100, 100
90 GBAR=1
100 PBAR = IHS + IGV - 1
IF(PBAR - ITL) 115, 115, 110
110 PBAR = ITL
115 IF(GBAR - IGV) 120, 140, 140
120 READ (NSCRAT) (N2(I),I=1,IMJM)
DO 130 I=1,IMJM
ITEMP1=M0(I)
ITEMP1=M2(ITEMP1)
ITEMP=ITEMP1
TEMP=CO(PBAR,ITEMP)
130 S2(I)=S2(I)+N2(I)*TEMP
GO TO 150
140 READ (NFLUX1) (N2(I),I=1,IMJM)
150 GBAR=GBAR+1
PBAR=PBAR-1
IF(GBAR - IGV) 120, 140, 160
160 IF(IGV - IGM) 180, 170, 180
170 REWIND NCR1
180 V11=0.
DO 190 I=1,IMJM
S2(I)=S2(I)*V0(I)
190 V11=V11+S2(I)
E2(IGV) = V11 - E1(IGV)
C SOURCE ALPHA
200 IF(I04 - 2) 210, 240, 210
210 IF(S02 - 2) 230, 220, 230
220 T7 = S03/V7(IGV)
GO TO 250
230 T7 = J.0
GO TO 270
240 T7 = E7/V7(IGV)
250 DO 260 K = 1, IZM
ITEMP1 = M2(K)
260 CO(IHS,ITEMP1) = CO(IHS,ITEMP1) - T7
270 CONTINUE
C GROUP FLUX CALCULATION
280 IF(V11) 282, 370, 282
282 GO TO 290
C TO STORE COEFFICIENTS, ADD COMMENT CARDS.
C 282 IF(NINIT) 295, 295, 290
290 IF(IGE - 3) 292, 294, 292
292 CALL INNER1(M0, M2, CXS, VO, CO, AO, Z5, R5, R4, Z4, A1, IM, JM, 1
ITL, CXR,CXT)
C WRITE(NCXS) (((CXS(KI,KJ,M),KI = l,IM),KJ=1,JM),M=1,3),
C 1 (CXT(KI),KI=1,IM),(CXR(KJ),KJ=1,JM)
GO TO 296
294 CALL INNER2(M0, M2, CXS, VO, CO, AO, Z5, R5, R4, Z4, A1, IM, JM, 1
ITL, CXR,CXT)
C WRITE (NCXS) (((CXS(KI,KJ,M),KI=1,IM),KJ=1,JM),M=1,3),
C 1 (CXT(KI),KI=1,IM), (CXR(KJ),KJ=1,JM)
GO TO 340
C 295 READ (NCXS) (((CXS(KI,KJ,M),KI=1,IM),KJ=1,JM),M=1,3),
C 1 (CXT(KI),KI=1,IM), (CXR(KJ),KJ=1,JM)
C IF (IGE - 3) 296, 340, 296
296 IF (S03 - 1) 310, 310, 300
300 CALL INNERP(NO, N2, CXS, S2, M0, M2, VO, CO, IM, JM, ITL, CXR, CXT,
1 HA, PA)
GO TO 350
310 IF (IGE - 2) 320, 330, 320
320 IF (S04 - 1) 325, 322, 325
322 IF (P02 - 2 * (P02/2)) 330, 330, 340
325 IF (IM - JM) 330, 330, 340
330 CALL INNER(NO, N2, CXS, S2, M0, M2, VO, CO, IM, JM, ITL, CXR, CXT,
1 HA, PA)
GO TO 350
340 CALLINNER2(NO, N2, CXS, S2, M0, M2, VO, CO, IM, JM, ITL, CXR, CXT,
1 HA, PA)
GO TO 350
350 DO 360 K = 1, IZM
ITEMPL = M2(K)
360 CO(IHS,ITEMPL) = CO(IHS,ITEMPL) + T7
GO TO 390
370 DO 380 I = 1, IMJM
N2(I) = 0.
380 NO(I) = 0.
390 CONTINUE
WRITE (NSCRAT) (N2(I), I = 1, IMJM)
C USE FOLLOWING OPTION IF BACKSPACING REQUIRES EXCESSIVE TIME
C REWIND NSCRAT
C SBAR = IGV - (ITL - IHS)
C IF (SBAR) 440, 440, 420
C 420 DO 430 IS = 1, SBAR
C 430 READ (NSCRAT)
SBAR = ITL - IHS
IF (SBAR) 440, 440, 420
420 DO 430 IS = 1, SBAR
430  BACKSPACE  NSCRAT
440  CONTINUE
   IF(V11)  450, 500, 450
450  IF(A02)  460, 480, 460
460  EO(IGV)=0.0
   DO 470  I=1,IMJM
      ITEMP1=M0(I)
      ITEMP1=M2(ITEMP1)
      EO(IGV)=EO(IGV) + CO(1,ITEMP1)*N2(I)*V0(I)
470  F2(I)=F2(I)+K6(IGV)*N2(I)
   GO TO 530
480  EO(IGV)=0.0
   DO 490  I=1,IMJM
      ITEMP1=M0(I)
      ITEMP1=M2(ITEMP1)
      EO(IGV)=EO(IGV) + CO(1,ITEMP1)*N2(I)*VI3(I)
490  F2(I)=F2(I)+CO(IHT-1,ITEMP1)*N2(I)
500  CONTINUE
   IGV=IGV+1
   IF(IGV-IGM)  10, 10, 510
510  TII = E1(IGP)
C  SWITCH  TAPE  DESIGNATIONS
   REWIND  NCR1
   REWIND  NSCRAT
   REWIND  NFLUX1
   REWIND  NCXS
   ITEMP  =  NSCRAT
   NSCRAT  =  NFLUX1
   NFLUX1  =  ITEMP
   NINIT  =  0
   IF (I04)  514, 512, 514
512  REWIND  NSORCE
514  CONTINUE
C  C  OVER-RELAX  FISSION  SOURCE
   ORFF  =  1.0 + .6*(ORF - 1.0)
   EO2  =  .0
IF(A02) 520,580,520

E1(IGP) = 0

C FOR ADJOINT CALCULATION, S2(I) STORES ORFED F2(I)

DO 522 I=1,IMJM

522 S2(I) = FO(I) + ORFF*(F2(I) - FO(I))

DO 540 IIG = 1,IGM

READ(NCR1) ((CO(I,J), I=1,ITL), J=1,MT)

E1(IIG) = 0

DO 530 I=1,IMJM

ITEMP = M0(I)

ITEMP = M2(ITEMP)

E1(IIG) = E1(IIG) + CO(IHT-1,ITEMP)*F2(I)*V0(I)

540 E02 = E02 + CO(IHT-1,ITEMP)*S2(I)*V0(I)

E1(IGP) = E1(IGP) + E1(IIG)

TEMP1 = E1(IGP)/E02

DO 550 I=1,IMJM

550 FO(I) = TEMP1*S2(I)

REWIND NCR1

GO TO 620

580 E01 = 0.0

DO 590 I=1,IMJM

E01 = E01 + V0(I)*F2(I)

F2(I) = FO(I) + ORFF*(F2(I) - FO(I))

590 E02 = E02 + V0(I)*F2(I)

TEMP1 = E01/E02

DO 600 I=1,IMJM

600 FO(I) = TEMP1*F2(I)

DO 610 IIG = 1,IGM

610 E1(IIG) = K6(IIG)*E01

IF(T11/E01 - .01) 620,611,620

IF (T11/E01 - 1./EV + .0001)) 613,613,620

C ACCELERATION FOR EXTRANEOUS SOURCE PROBLEMS

611 TEMP1 = (1.0 - EV*T11/E01)/(1.0 - EV)

IF (T11/E01 - .01) 620,620,612

612 IF (T11/E01 - 1./(EV + .0001)) 613,613,620

613 DO 614 I = 1,IMJM

614 FO(I) = TEMP1 * FO(I)

DO 616 IIG = 1,IGM
EO(IIG) = TEMP1*EO(IIG)
E1(IIG) = TEMP1*E1(IIG)
E1(IGP) = 0.0
EO(IGP) = 0.0
DO 640 IIG = 1, IGM
EO(IGP) = EO(IGP) + EO(IIG)
E1(IGP) = E1(IGP) + E1(IIG)
RETURN
END

C C
SUBROUTINE INNER
IM0, M2, CXS, V0, CO, A0, Z5, R5, R4, Z4, A1,
  JIM, JJM, JTL, CXR, CXT
DIMENSION M0(1), M2(1), CXS(JIM, JJM, 3), V0(1), CO(JTL, 1),
  A0(1), Z5(1), R5(1), R4(1), Z4(1), A1(1), CXR(1), CXT(1)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
  CNT, CVT, DAY, DELT, EO(51), E1(51), E2(51),
  E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
  E01, E02, E03, EQ, EVP, EVPP, FEF,
  GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,
  II, IMJM, IP, ITEMP, ITEMP1, ITEMP2, ITL,
  I2E, JP, K07, KPAGE, LAP, LAPP, LAR,
  LC, ML, NCON, NGOTO, NINIT, ORFP, PO2,
  PBAR, SBAR, SK7, T06, T7, T11, TEMP,
  TEMPI, TEMP2, TEMP3, TEMP4, TI, TS0, V1
COMMON ID(11), MAXT, A02, IO4, S02, IGM, NXCM,
  MCR, M07, D05, GO7, S04, NPRT, NPUN,
  IGE, IM, JM, IZM, MT, M01, B01,
  BO2, BO3, B04, IZ, JZ, EV, EVM,
  S03, BUCK, LAL, LAH, EPS, EPSA, G06,
  PO2, ORF, S01
COMMON LATW, LHOLN, LALAM, LCO, LNO, LN2, LAO,
  LAL, LF0, LF2, LI0, LI1, LI2, LI3,
  LK6, LK7, LMO, LM2, LRO, LR1, LR2,
  LR3, LR4, LR5, LS2, LV0, LV7, LZO,
  LZ1, LZ2, LZ3, LZ4, LZ5, LCXS, LVOL,
THIS SUBROUTINE CALCULATES COEFFICIENTS FOR THE FLUX EQUATION

PI2 = 6.28318

DO 45 KJ = 1, JM
  DO 45 Kl = 1, IM
    GO TO (10, 10, 5), IGEP
7    TEMP = PI2*(Z4(KJ) - Z4(KJ-1))*R4(KI)
     GO TO 15
10   TEMP = Z4(KJ) - Z4(KJ-1)
15   I = KI + (KJ-1)*IM
    ITEMPI = MO(I)
    ITEMP1 = M2(ITEMPI)
    CXS(KI,KJ,3) = VO(I)*(C0(IHT,ITEMP) - C0(IHS,ITEMPI))
    IF(I - 1) 45,45,18
18   ITEMPI1 = MO(I-1)
    ITEMP1 = M2(ITEMPI1)
    IF (ITEMP - ITEMP1) 25, 20, 25
20   CXS(KI,KJ,1) = AO(KI) * Z5(KJ)/(3.*C0(IHT,ITEMP)*(R4(KI)-R4(KI-1)))*
     ((R4(KI-1)*C0(IHT,ITEMP1) + R5(KI)*C0(IHT,ITEMP))))
     GO TO 30
     1 (3.*(R5(KI-1)*C0(IHT,ITEMPI) + R5(KI)*C0(IHT,ITEMP))))
30   IF(I - IM) 45,45,32
32   ITEMPI3 = MO(I - IM)
    ITEMP3 = M2(ITEMPI3)
    IF (ITEMP - ITEMP3) 40, 35, 40
35   CXS(KI,KJ,2) = A1(KI)/(3.*C0(IHT,ITEMP)*ITEMPI)
     GO TO 45
40   CXS(KI,KJ,2) = A1(KI) * (Z5(KJ-1) + Z5(KJ))/ITEMP*
     1 (3.*(Z5(KJ-1)*C0(IHT,ITEMPI) + Z5(KJ)*C0(IHT,ITEMP))))
45   CONTINUE
DO 200 KJ = 1, JM
DO 200 KI = 1, IM
GO TO (55, 55, 50), IGEP
50 TEMP = .5*PI2*Z5(KJ)*R4(KI)
GO TO 60
55 TEMP = .5*Z5(KJ)
60 I = KI + (KJ-1)*IM
ITEMP = MO(I)
ITEMP = M2(ITEMP)
TEMP1 = CXS(KI+1,KJ,1)
TEMP2 = CXS(KI,KJ+1,2)
IF(KJ - 1) 65, 65, 100
65 IF(B04 - 1) 90, 95, 70
70 GO TO (80, 80, 75), IGEP
75 TEMP3 = PI2*R4(KI)*.5*(Z5(KJ) + Z5(JM))
GO TO 85
80 TEMP3 = .5*(Z5(KJ) + Z5(JM))
85 ITEMP3 = I + IM*(JM - 1)
ITEMP3 = MO(ITEMP3)
ITEMP3 = M2(ITEMP3)
CXS(KI,KJ,2) = A1(KI)*(Z5(JM) + Z5(KJ))/(ITEMP3*
1/(3.*(Z5(JM)*CO(IHT,ITEMP3) + Z5(KJ)*CO(IHT,ITEMP3))))
GO TO 125
90 CXS(KI,KJ,2) = A1(KI)/(3.*CO(IHT,ITEMP)*( TEMP +.71/
1 CO(IHT,ITEMP)))
GO TO 125
95 CXS(KI,KJ,2) = .0
GO TO 125
100 IF (KJ - JM) 125, 125, 125, 105
105 IF (B03 - 1) 115, 120, 110
110 TEMP2 = CXS(KI,1,2)
CXT(KI) = TEMP2
GO TO 125
115 TEMP2 = A1(KI)/(3.*CO(IHT,ITEMP)*( TEMP +.71/
1 CO(IHT,ITEMP)))
CXT(KI) = TEMP2
GO TO 125
120  TEMP2 = .0
     CXT(KI) = TEMP2
125  IF (KI - 1) 130,130,145
130  IF (B01) 135,135,140
135  CXS(KI,KJ,1) = AO(KI) * ZS(KJ)/(3. * CO(IHT,ITEMP)) *  
10 (.5*R5(KI) + .71/CO(IHT,ITEMP))
     GO TO 165
140  CXS(KI,KJ,1) = .0
     GO TO 165
145  IF (KI - IM) 165,150,150
150  IF (B02) 155,155,160
155  TEMP1 = AO(KI+1) * ZS(KJ)/(3. * CO(IHT,ITEMP)) *  
1 (0.5*R5(KI) + .71/CO(IHT,ITEMP))
     CXR(KJ) = TEMP1
     GO TO 165
160  TEMP1 = .0
     CXR(KJ) = TEMP1
165  CXS(KI,KJ,3) = CXS(KI,KJ,3) + CXS(KI,KJ,1) + CXS(KI,KJ,2) *  
1 TEMP1 + TEMP2
200 CONTINUE
     RETURN
     END

C
C
SUBROUTINE INNERT(MO, M2, CXS, V0, CO, AO, Z5, R5, R4, Z4, A1,  
2 JIM, JJM, JL1, CXR, CXT)
DIMENSION MO(1), M2(1), CXS(JIM, JJM, 3), V0(1), CO(JTL,1),  
1 AO(1), Z5(1), R5(1), R4(1), Z4(1), A1(1), CXR(1), CXT(1)
COMMON NSORCE, NCXS
COMMON INP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,  
1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),  
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),  
3 E01, E02, E03, EQ, EVP, EVPP, FEF,  
4 GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,  
5 II, IMJM, IP, ITEMP, ITEMPL, ITMP2, ITL,  
6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,  
7 LC, ML, NCON, NGOTO, NINIT, ORFP, P02,
THIS SUBROUTINE CALCULATES COEFFICIENTS FOR TRIANGULAR GEOMETRY

DO 45 KJ = 1, JM
DO 45 KI = 1, IM
TEMP = KI - 2* (KI/2) - (KJ - KJ/2)
TEMP = ABS(TEMP)
I = KI + (KJ-1) *IM
ITEMP = MO(I)
ITEMP = M2(ITEMP)
CXS(KI,KJ,3) = VO(I)*(CO(IHT,ITEMP) - CO(IHS,ITEMP))
IF(I - 1) 45, 45, 18
18 ITEMPI = MO(I-1)
ITEMPI = M2(ITEMP)
IF(ITEMP - ITEMPI) 25, 20, 25
20 CXS(KI,KJ,1) = AO(KI)/(2.*CO(IHT,ITEMP)*Z5(1))
GO TO 30
25 CXS(KI,KJ,1) = AO(KI)/((CO(IHT,ITEMP1) + CO(IHT,ITEMP))*Z5(1))
GO TO 165
CXS(KI,KJ,1) = .0
GO TO 165
IF(KI - IM) 165, 150, 150
150 IF(BO2) 155, 155, 160
155 TEMP1 = AO(KI+1)/(3.*C)(IHT,ITEMP)*(Z5(1)/3.+71/C0(IHT,ITEMP))
CXR(KJ) = TEMP1
GO TO 165
160 TEMP1 = .0
CXR(KJ) = TEMP1
165 CXS(KI,KJ,3) = CXS(KI,KJ,3) + CXS(KI,KJ,1) + CXS(KI,KJ,2)
1 + TEMP1 + TEMP2
200 CONTINUE
RETURN
END

C
C SUBROUTINE INNER(NO, N2, CXS, S2, MO, M2, VO, CO,JIM,JJM, JTL,
1 CXR,CXT, HA, PA1

COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3 E01, E02, E03, EQ, EVP, EVPP, FEF,
4 GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,
5 II, IMJM, IP,ITEMP,ITEMP1,ITEMP2, I1T,
6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
7 LC, ML, NCON, NGOTO, NINIT, ORFP, P02,
8 PBAR, SBAR, SK7, T06, T7, T11, TEMP,
9 TEMP1, TEMP2, TEMP3, TEMP4, TI, TSD, V11
COMMON IO(11), MAXT, A02, IO4, S02, IGM, NXCM,
1 MCR, M07, D05, G07, S04, NPRT, NPUN,
2 IGE, IM, JM, IZM, MT, M01, B01,
3 B02, B03, B04, IZ, JZ, EV, EVM,
4 S03, BUCK, LAL, LAH, EPS, EPSA, G06,
5 POD, ORF, S01
COMMON LATW, LH0LN, LALAM, LC0, LNO, LN2, LAO,
INTEGER A02, B01, B02, B03, B04, B07, CNT,
1 CVT, D05, G07, P02, S02, S04, T06,
2 R2, Z2
REAL I2, I3, K6, K7, LAL, LAH, LAP,
1 LAPP, LAR, NO, N2, MASS, MASSP
DIMENSION NO(I), N2(I), CXS(JIM, JJM, 3), S2(I), MO(I), M2(I),
1 VO(I), CO(JTL, I), CXR(I), CXT(I), HA(I), PA(I)
CALL IFUXN(N2, CO, VO, CXS, NO, M2, ITL, IM, JM, CXR, CXT)
DO 4 I=1, IMJM
1 NO(I) = N2(I)
C BEGIN FLUX CALCULATION
IKB = IM - 1
JKB = JM - 1
C FLUX CALCULATION USING SOR WITH LINE INVERSION
C
C CALCULATION OF LEFT BOUNDARY FLUX
KI = 1
KJ = 1
I = KI + (KJ - 1)*IM
HA(KJ) = CXS(KI, KJ+1, 2)/CXS(KI, KJ, 3)
PA(KJ) = S2(I) + CXS(KI+1, KJ, 1)*N2(I+1)/CXS(KI, KJ, 3)
DO 5 KJ = 2, JKB
I = KI + (KJ - 1)*IM
HA(KJ) = CXS(KI, KJ+1, 2)/CXS(KI, KJ, 3) - CXS(KI, KJ, 2)*HA(KJ-1)
5 PA(KJ) = (S2(I) + CXS(KI+1, KJ, 1)*N2(I+1) + CXS(KI, KJ, 2)*PA(KJ-1))/
1 (CXS(KI, KJ, 3) - CXS(KI, KJ, 2)*HA(KJ-1))
KI = JM
I = KI + (KJ - 1)*IM
N2(I) = S2(I) + CXS(KI+1, KJ, 1)*N2(I+1) + CXS(KI, KJ, 2)*PA(KJ-1))/
1 (CXS(KI, KJ, 3) - CXS(KI, KJ, 2)*HA(KJ-1))
DO 10 KJJ = 2, JM  
KJ = JM - KJJ + 1  
I = KI + (KJ - 1)*IM  
10 N2(I) = PA(KJ) + HA(KJ) * N2(I+IM)  
DO 15 KJ = 1, JM  
I = KI + (KJ - 1)*IM  
15 N2(I) = NO(I) + ORF*(N2(I) - NO(I))  
C PRINCIPAL FLUX LOOP  
DO 40 KI = 2, IMB  
KJ = 1  
I = KI + (KJ - 1)*IM  
HA(KJ) = CXS(KI, KJ+1,2)/CXs(KI, KJ,3)  
PA(KJ) = (S2(I) + CXS(KI, KJ,1)*N2(I-1) + CXS(KI+1, KJ,1)*N2(I+1))/  
1 CXS(KI, KJ,3)  
DO 25 KJ = 2, JKB  
I = KI + (KJ - 1)*IM  
HA(KJ) = CXS(KI, KJ+1,2)/CXs(KI, KJ,3) - CXS(KI, KJ,2)*HA(KJ-1))  
PA(KJ) = (S2(I) + CXS(KI, KJ,1)*N2(I-1) + CXS(KI+1, KJ,1)*N2(I+1) +  
1 CXS(KI, KJ,2)*PA(KJ-1))/CXs(KI, KJ,3) - CXS(KI, KJ,2)*HA(KJ-1))  
KJ = JM  
I = KI + (KJ - 1)*IM  
N2(I) = (S2(I) + CXS(KI, KJ,1)*N2(I-1) + CXS(KI+1, KJ,1)*N2(I+1) +  
1 CXS(KI, KJ,2)*PA(KJ-1))/CXs(KI, KJ,3) - CXS(KI, KJ,2)*HA(KJ-1))  
DO 30 KJJ = 2, JM  
KJ = JM - KJJ + 1  
I = KI + (KJ - 1)*IM  
30 N2(I) = PA(KJ) + HA(KJ) * N2(I+IM)  
DO 35 KJ = 1, JM  
I = KI + (KJ - 1)*IM  
35 N2(I) = NO(I) + ORF*(N2(I) - NO(I))  
40 CONTINUE  
C CALCULATION OF RIGHT BOUNDARY FLUX  
KI = IM  
KJ = 1  
I = KI + (KJ - 1)*IM  
HA(KJ) = CXS(KI, KJ+1,2)/CXs(KI, KJ,3)  
PA(KJ) = (S2(I) + CXS(KI, KJ,1)*N2(I-1))/CXs(KI, KJ,3)
DO 45 KJ = 2, JKB
   I = KI + (KJ - 1)*IM
   HA(KJ) = CXS(KI,KJ+1,2)/(CXS(KI,KJ,3) - CXS(KI,KJ,2)*HA(KJ-1))
   PA(KJ) = (S2(I) + CXS(KI,KJ,1)*N2(I-1) + CXS(KI,KJ,2)*PA(KJ-1))/
   1 (CXS(KI,KJ,3) - CXS(KI,KJ,2)*HA(KJ-1))
   KJ = JM
   I = KI + (KJ - 1)*IM
   N2(I) = (S2(I) + CXS(KI,KJ,1)*N2(I-1) + CXS(KI,KJ,2)*PA(KJ-1))/
   1 (CXS(KI,KJ,3) - CXS(KI,KJ,2)*HA(KJ-1))
DO 50 KJJ = 2, JM
   KJ = JM - KJJ + 1
   I = KI + (KJ - 1)*IM
50  N2(I) = PA(KJ) + HA(KJ) * N2(I+IM)
DO 55 KJ = 1, JM
   I = KI + (KJ - 1)*IM
55  N2(I) = NO(I) + ORF*(N2(I) - NO(I))
   TEMP1 = .0
   DO 90 II = 1, IMJM
   TEMP2 = ABS (1.0 - NO(II)/N2(II))
   IF (TEMP1 - TEMP2) 80, 90, 90
80  TEMP1 = TEMP2
90  CONTINUE
C
C  INNER ITERATION CONTROL
133  LC = LC + 1
   II = II + 1
   IF (II - G07) 533, 1033, 1033
533  IF (TEMP1 - EPS) 633, 633, 2
633  IF (G06_) 733, 1033, 733
733  IF (TEMP1 - G06) 1033, 1033, 2
1033  CONTINUE
RETURN
END
C
C  SUBROUTINE INNER2(N0, N2, CXS, S2, MO, M2, VO, CO, JIM, JJM, JTL, 1
   CXR, CXT, HA, PA)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
 E01, E02, E03, EQ, EVP, EVPP, FEF,
 GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,
 II, IMJM, IP, ITEMP, ITEMP1, ITEMP2, ITL,
 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
 LC, ML, NCON, NGOTO, NINIT, ORFP, PO2,
 PBAR, SBAR, SK7, T06, T7, T11, TEMP,
 TEMP1, TEMP2, TEMP3, TEMP4, TI, TSD, V11
COMMON ID(11), MAXT, A02, IA4, S02, IGM, NXCM,
 MCR, M07, D05, G07, S04, NPRT, NPUN,
 IGE, IM, JM, IZM, MT, M01, BO1,
 B02, B03, B04, IZ, JZ, EV, EVM,
 S03, BUCK, LAL, LAH, EPS, EPSA, G06,
 POD, ORF, S01
COMMON LATW, LHOLN, LALAM, LC0, LN0, LN2, LA0,
 LA1, LFO, LF2, LI0, LI1, LI2, L13,
 LK6, LKT7, LMO, LM2, LR0, LR1, L22,
 LR3, LR4, LR5, LS2, LVO, LV7, LZ0,
 L21, L2Z, LZ3, L24, L25, LCXS, LVOL,
 LMASS, LMATN, LBPR, LLD, LLCN, LLFN, LPHIB,
 LAXS, LFXS, LMASSP, LCXR, LCXT, LHA, LPA,
 LGAM
INTEGER A02, B01, B02, B03, B04, B07, CNT,
 C0V, D05, G07, P02, S02, S04, T06,
 R2, Z2
REAL I2, I3, K6, K7, LAH, LAL, LAP,
 LAPP, LAR, NO, N2, MASS, MASSP
DIMENSION NO(1), N2(1), CXS(JIM, JM, 3), S2(1), M0(1), M2(1),
 V0(1), CO(IITL, 1), CXR(1), CXT(1), HA(1), PA(1)
CALL IFLUXN (N2, CO, VJ, CXS, M0, M2, ITL, IM, JM, CXR, CXT)
DO 4 I=1, IMJM
4 NO(I) = N2(I)
CALL FLUX CALCULATION
IK8 = IM - 1
JKB = JM - 1

C FLUX CALCULATION USING SOR WITH LINE INVERSION

C CALCULATION OF BOTTOM BOUNDARY FLUX

KI = 1
KJ = 1
I = KI + (KJ - 1)*IM
HA(KI) = CXS(KI+1,KJ,1)/CXS(KI,KJ,3)
PA(KI) = (S2(I) + CXS(KI,KJ+1,2)*N2(I+IM))/CXS(KI,KJ,3)
DO 5 KI = 2,JKB
I = KI + (KJ - 1)*IM
HA(KI) = CXS(KI+1,KJ,1)/CXS(KI,KJ,3) - CXS(KI,KJ,1)*HA(KI-1)
5 PA(KI) = (S2(I) + CXS(KI,KJ+1,2)*N2(I+IM) + CXS(KI,KJ,1)*PA(KI-1))/
1 (CXS(KI,KJ,3) - CXS(KI,KJ,1)*HA(KI-1))

KI = IM
I = KI + (KJ - 1)*IM
N2(I) = (S2(I) + CXS(KI,KJ+1,2)*N2(I+IM) + CXS(KI,KJ,1)*PA(KI-1))/
1 (CXS(KI,KJ,3) - CXS(KI,KJ,1)*HA(KI-1))
DO 10 KII = 2,IM
I = KI + (KJ - 1)*IM
10 N2(I) = PA(KI) + HA(KI) * N2(I+1)

DO 15 KI = 1,IM
I = KI + (KJ - 1)*IM
15 N2(I) = NO(I) + ORF*(N2(I) - NO(I))

C PRINCIPAL FLUX LOOP

DO 40 KJ = 2,JKB
KI = 1
I = KI + (KJ - 1)*IM
HA(KI) = CXS(KI+1,KJ,1)/CXS(KI,KJ,3)
PA(KI) = (S2(I) + CXS(KI,KJ+1,2)*N2(I+IM))/CXS(KI,KJ,3)
DO 25 KI = 2,JKB
I = KI + (KJ - 1)*IM
HA(KI) = CXS(KI+1,KJ,1)/(CXS(KI,KJ,3) - CXS(KI,KJ,1)*HA(KI-1))
25 PA(KI) = (S2(I) + CXS(KI,KJ+1,2)*N2(I+IM))/CXS(KI,KJ,3) - CXS(KI,KJ,1)*HA(KI-1))
KI = IM
I = KI + (KJ - 1)*IM
N2(I) = (S2(I) + CXS(KI,KJ,2)*N2(I-IM)+ CXS(KI,KJ+1,2)*N2(I+IM)+
1 CXS(KI,KJ,1)*PA(KI-1))/(CXS(KI,KJ,3) - CXS(KI,KJ,1)*HA(KI-1))
DO 30 KII = 2,IM
KI = IM - KII + 1
I = KI + (KJ - 1)*IM
30 N2(I) = PA(KI) + HA(KI) * N2(I+1)
DO 35 KI = 1,IM
I = KI + (KJ - 1)*IM
35 N2(I) = NO(I) + ORF*(N2(I) - NO(I))
40 CONTINUE
C CALCULATION OF TCP BOUNDARY FLUX
KJ = JM
KI = 1
I = KI + (KJ - 1)*IM
HA(KI) = CXS(KI+1,KJ,1)/CXS(KI,KJ,3)
PA(KI) = (S2(I) + CXS(KI,KJ,2)*N2(I-IM))/CXS(KI,KJ,3)
DO 45 KI = 2,KJ
I = KI + (KJ - 1)*IM
HA(KI) = CXS(KI+1,KJ,1)/CXS(KI,KJ,3) - CXS(KI,KJ,1)*HA(KI-1))
45 PA(KI) = (S2(I) + CXS(KI,KJ,2)*N2(I-IM)+ CXS(KI,KJ,1)*PA(KI-1))/
1 (CXS(KI,KJ,3) - CXS(KI,KJ,1)*HA(KI-1))
KI = IM
I = KI + (KJ - 1)*IM
N2(I) = (S2(I) + CXS(KI,KJ,2)*N2(I-IM)+ CXS(KI,KJ,1)*PA(KI-1))/
1 (CXS(KI,KJ,3) - CXS(KI,KJ,1)*HA(KI-1))
DO 50 KII = 2,IM
KI = IM - KII + 1
I = KI + (KJ - 1)*IM
50 N2(I) = PA(KI) + HA(KI) * N2(I+1)
DO 55 KI = 1,IM
I = KI + (KJ - 1)*IM
55 N2(I) = NO(I) + ORF*(N2(I) - NO(I))
TEMP1 = .0
DO 90 I = 1,IMJM
TEMP2 = ABS (1.0 - NO(I)/N2(I))

IF (TEMP1 - TEMP2) 80,90,90
80 TEMP1 = TEMP2
90 CONTINUE
C
C INNER ITERATION CONTROL
133 LC = LC + 1
II = II + 1
IF (II - G07) 533, 1033, 1033
533 IF (TEMP1 - EPS) 633,633,2
633 IF (G06) 733, 1033, 733
733 IF (TEMP1 - G06) 1033, 1033, 2
1033 CONTINUE
RETURN
END
C
C SUBROUTINE INNERP(NO, N2, CXS, S2, MO, M2, VO, CO, JIM, JJM, JTL, 1
CXR, CXT, HA, PA)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3 E01, E02, E03, EQ, EVP, EVPP, FEF,
4 GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,
5 II, IMJM, IP, ITEMP, ITEMP1, ITEMP2, ITL,
6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
7 LC, ML, NCON, NGOTO, NINIT, ORFP, P02,
8 PBAR, SBAR, SK7, T06, T7, T11, TEMP,
9 TEMP1, TEMP2, TEMP3, TEMP4, TI, TSD, V11
COMMON ID(11), MAXT, A02, I04, S02, IGM, NXCM,
1 MCR, M07, D05, G07, S04, NPRT, NPUN,
2 IGE, IM, JM, IZM, MT, M01, B01,
3 B02, B03, B04, IZ, JZ, EV, EVM,
4 S03, BUCK, LAL, LAH, EPS, EPSA, G06,
5 POD, ORF, SOI
COMMON LATW, LHOLN, LALAM, LCO, LNO, LN2, LA0,
1 LA1, LF0, LF2, LIO, LI1, LI2, LI3,
THIS SUBROUTINE CALCULATES THE FLUX FOR PERIODIC B. C.

CALL IFLUXN (N2, C0, VO, CXS, MO, M2, ITL, IM, JM, CXR, CXT)

DO 4 I=1, IMJM

4 NO(I) = N2(I)

BEGIN FLUX CALCULATION

IKB = IM - 1
JKB = JM - 1

FLUX CALCULATION USING SOR WITH LINE INVERSION

CALCULATION OF LEFT BOUNDARY FLUX

KI = 1
KJ = 1

I = KI + (KJ - 1)*IM

N2(I) = CXS(KI,1,2)/CXS(KI,KJ,3)

HA(KJ) = CXS(KI,KJ+1,2)/CXS(KI,KJ,3)

TEMP1 = N2(I)

TEMP = HA(KJ)

PA(KJ) = (S2(I) + CXS(KI+1,KJ,1)*N2(I+1))/CXS(KI,KJ,3)

TEMP2 = PA(KJ)

DO 5 KJ = 2, JKB

I = KI + (KJ - 1)*IM

HA(KJ) = CXS(KI,KJ+1,2)/CXS(KI,KJ,3) - CXS(KI,KJ,2)*HA(KJ-1)

N2(I) = CXS(KI,KJ,2) * N2(I-IM)/

1

{CXS(KI,KJ,3) - CXS(KI,KJ,2)*HA(KJ-1)}
TEMP1 = TEMP1 + TEMP*N2(I)
PA(KJ) = (S2(I) + CXS(K1+1,KJ,1)*N2(I+1) + CXS(K1,KJ,2)*PA(KJ-1))/
1  (CXS(K1,KJ,3) - CXS(K1,KJ,2)*HA(KJ-1))
TEMP2 = TEMP2 + TEMP*PA(KJ)
5
TEMP = TEMP*HA(KJ)
KJ = JM
I = KI + (KJ - 1)*IM
TEMP1 = (TEMP1 + TEMP)*CXs(K1,1,2) + CXS(K1,KJ,2)*N2(I-IM)
N2(I) = (S2(I) + CXS(K1+1,KJ,1)*N2(I+1) + CXS(K1,KJ,2)*PA(KJ-1)
1  + CXS(K1,1,2)*TEMP2 )/
1  (CXS(KI,KJ,3) - CXS(KI,KJ,2)*HA(KJ-1) - TEMP1)
DO 10 KJJ = 2, JM
KJ = JM - KJJ + 1
I = KI + (KJ - 1)*IM
KII = (JM-1)*IM + KI
10  N2(I) = PA(KJ) + HA(KJ) * N2(I+IM) + N2(I) * N2(KII)
DO 15 KJ = 1, JM
I = KI + (KJ - 1)*IM
15  N2(I) = NO(I) + ORF*(N2(I) - NO(I))
C
PRINCIPAL FLUX LOOP
DO 40 KI = 2, IKB
KJ = 1
I = KI + (KJ - 1)*IM
HA(KJ)= CXS(KI,KJ+1,2)/CXs(KI,KJ,3)
N2(I) = CXS(KI,1,2)/CXs(KI,KJ,3)
TEMP1 = N2(I)
TEMP = HA(1)
PA(KJ) = (S2(I) + CXS(KI,KJ,1)*N2(I-1) + CXS(KI+1,KJ,1)*N2(I+1))/
1  CXS(KI,KJ,3)
TEMP2 = PA(KJ)
DO 25 KJ = 2, JKB
I = KI + (KJ - 1)*IM
HA(KJ) = CXs(KI,KJ+1,2)/(CXs(KI,KJ,3) - CXS(KI,KJ,2)*HA(KJ-1))
N2(I) = CXS(KI,KJ,2) * N2(I-IM)/
1  (CXS(KI,KJ,3) - CXS(KI,KJ,2)*HA(KJ-1))
TEMP1 = TEMP1 + TEMP*N2(I)
PA(KJ) = (S2(I) + CXS(KI,KJ,1)*N2(I-1) + CXS(KI+1,KJ,1)*N2(I+1) +
1 \( \frac{\text{CXS}(K_I,K_J,2) \cdot \text{PA}(K_J-1)}{\text{CXS}(K_I,K_J,3)} - \frac{\text{CXS}(K_I,K_J,2) \cdot \text{HA}(K_J-1)}{\text{CXS}(K_I,K_J,3)} \) \\
\text{TEMP} = \text{TEMP} + \text{TEMP} \cdot \text{PA}(K_J) \\
\text{TEMP} = \text{TEMP} \cdot \text{HA}(K_J) \\
I = K_I + (K_J - 1) \cdot I_M \\
\text{TEMP1} = (\text{TEMP} + \text{TEMP} \cdot \text{CXS}(K_I,1,2) + \text{CXS}(K_I,K_J,2) \cdot N2(I-M) \\
N2(I) = (\text{S2}(I) + \text{CXS}(K_I,K_J,1) \cdot N2(I-1) + \text{CXS}(K_I+1,K_J,1) \cdot N2(I+1) + \\
1 \frac{\text{CXS}(K_I,1,2) \cdot \text{TEMP} \cdot \text{PA}(K_J-1)}{\text{CXS}(K_I,K_J,3)} - \frac{\text{CXS}(K_I,K_J,2) \cdot \text{HA}(K_J-1)}{\text{CXS}(K_I,K_J,3)} - \text{TEMP1} \\
\text{DO 30 KJJ = 2, JM} \\
\text{KJ} = J - KJJ + 1 \\
I = K_I + (K_J - 1) \cdot I_M \\
\text{KII} = (J-M-1) \cdot I_M + K_I \\
N2(I) = \text{PA}(K_J) + \text{HA}(K_J) \cdot N2(I+I_M) + N2(I) \cdot N2(KII) \\
\text{DO 35 KJ = 1, JM} \\
I = K_I + (K_J - 1) \cdot I_M \\
N2(I) = \text{NO}(I) + \text{ORF} \cdot (N2(I) - \text{NO}(I)) \\
35 \text{CONTINUE} \\
\text{C CALCULATION OF RIGHT BOUNDARY FLUX} \\
I = \text{IM} \\
K_J = 1 \\
I = K_I + (K_J - 1) \cdot I_M \\
\text{HA}(K_J) = \frac{\text{CXS}(K_I,K_J+1,2)}{\text{CXS}(K_I,K_J,3)} \\
N2(I) = \frac{\text{CXS}(K_I,1,2)}{\text{CXS}(K_I,K_J,3)} \\
\text{TEMP1} = N2(I) \\
\text{TEMP} = \text{HA}(I) \\
\text{PA}(K_J) = (\text{S2}(I) + \text{CXS}(K_I,K_J,1) \cdot N2(I-1)) / \text{CXS}(K_I,K_J,3) \\
\text{TEMP} = \text{PA}(K_J) \\
\text{DO 45 KJ = 2, JKB} \\
I = K_I + (K_J - 1) \cdot I_M \\
\text{HA}(K_J) = \frac{\text{CXS}(K_I,K_J+1,2)}{\text{CXS}(K_I,K_J,3)} - \frac{\text{CXS}(K_I,K_J,2) \cdot \text{HA}(K_J-1)}{\text{CXS}(K_I,K_J,3)} \\
N2(I) = \frac{\text{CXS}(K_I,K_J,2)}{\text{CXS}(K_I,K_J,3)} + N2(I-IM) / \\
1 \frac{\text{CXS}(K_I,K_J,3)}{\text{CXS}(K_I,K_J,3)} - \frac{\text{CXS}(K_I,K_J,2) \cdot \text{HA}(K_J-1)}{\text{CXS}(K_I,K_J,3)} \\
\text{TEMP1} = \text{TEMP} + \text{TEMP} \cdot \text{N2}(I) \\
\text{PA}(K_J) = (\text{S2}(I) + \text{CXS}(K_I,K_J,1) \cdot N2(I-1) + \text{CXS}(K_I,K_J,2) \cdot \text{PA}(K_J-1)) / \\
1 \frac{\text{CXS}(K_I,K_J,3)}{\text{CXS}(K_I,K_J,3)} - \frac{\text{CXS}(K_I,K_J,2) \cdot \text{HA}(K_J-1)}{\text{CXS}(K_I,K_J,3)}
\[
\text{TEMP2} = \text{TEMP2} + \text{TEMP} \cdot \text{PA(KJ)} \\
\text{TEMP} = \text{TEMP} \cdot \text{HA(KJ)} \\
\text{KJ} = \text{JM} \\
\text{I} = \text{KI} + (\text{KJ} - 1) \cdot \text{IM} \\
\text{TEMP1} = (\text{TEMP1} + \text{TEMP}) \cdot \text{CXs(KI,1,2)} + \text{CXs(KI,KJ,2)} \cdot \text{N2(I-IM)} \\
\text{N2(I)} = (S2(I) + \text{CXs(KI,KJ,1)} \cdot \text{N2(I-1)} + \text{CXs(KI,KJ,2)} \cdot \text{PA(KJ-1)} \\
\text{I} + \text{CXs(KI,1,2)} \cdot \text{TEMP2})/ \\
(\text{CXs(KI,KJ,3)} - \text{CXs(KI,KJ,2)} \cdot \text{HA(KJ-1)} - \text{TEMP1}) \\
\text{DO } 50 \text{ KJ} = 2, \text{JM} \\
\text{KJ} = \text{JM} - \text{KJ} + 1 \\
\text{I} = \text{KI} + (\text{KJ} - 1) \cdot \text{IM} \\
\text{KII} = (\text{JM-1}) \cdot \text{IM} + \text{KI} \\
\text{N2(I)} = \text{PA(KJ)} + \text{HA(KJ)} \cdot \text{N2(I+IM)} + \text{N2(I)} \cdot \text{N2(KII)} \\
\text{DO } 55 \text{ KJ} = 1, \text{JM} \\
\text{I} = \text{KI} + (\text{KJ} - 1) \cdot \text{IM} \\
\text{N2(I)} = \text{NO(I)} + \text{ORF} \cdot (\text{N2(I)} - \text{NO(I)}) \\
\text{CALCULATION OF ERROR CRITERION} \\
\text{TEMP1} = 0 \\
\text{DO } 90 \text{ I} = 1, \text{IM JM} \\
\text{TEMP2} = \text{ABS (1.0 - NO(I) / N2(I))} \\
\text{IF (TEMP1 - TEMP2) 80, 90, 90} \\
\text{80} \text{ TEMP1} = \text{TEMP2} \\
\text{90} \text{ CONTINUE} \\
\text{C} \\
\text{INNER ITERATION CONTROL} \\
\text{133} \text{ LC} = \text{LC} + 1 \\
\text{II} = \text{II} + 1 \\
\text{IF (II - GO7) 533, 1033, 1033} \\
\text{533} \text{ IF (TEMP1 - EPS) 633, 633, 2} \\
\text{633} \text{ IF (GO6) 733, 1033, 733} \\
\text{733} \text{ IF (TEMP1 - GO6) 1033, 1033, 2} \\
\text{1033} \text{ CONTINUE} \\
\text{RETURN} \\
\text{END} \\
\text{C} \\
\text{SUBROUTINE IFLUXN (N2, CO, VO, CXS, MO, M2, JTL, JIM, JM, CXR, CXT)}
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3 E01, E02, E03, EQ, EVP, EVPP, FEF,
4 GBAR, GLH, IGEF, IGP, IGV, IHS, IHF,
5 II, IMJM, IP, ITEMP, ITEMP1, ITEMP2, ITL,
6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
7 LC, ML, NCON, NGOTO, NINIT, ORFP, PO2,
8 PBAR, SBAR, SK7, T06, T7, T11, TEMP,
9 COMMON ID(11), MAXT, A02, I04, S02, IGM, NXCM,
10 MCR, MJ72, D05, G07, S04, NPRT, NPUN,
11 IGE, IM, JM, IZM, MT, MO1, BO1,
12 B02, B03, B04, IZ, JZ, EV, EVM,
13 S03, BUCK, LAL, LAH, EPS, EPSA, G06,
14 PCD, ORF, S01
COMMON LATW, LHOLN, LALAM, LC0, LNO, LN2, LA0,
1 LA1, LF0, LF2, L10, L11, L12, L13,
2 LK6, LK7, LM0, LM2, LR0, LR1, LR2,
3 LR3, LR4, LR5, LS2, LV0, LV7, LZ0,
4 LZ1, LZ2, LZ3, LZ4, LZ5, LEXS, LVOL,
5 LMASS, LMAXT, LN1R, LL, LC0, LLFN, LPHIS,
6 LAXS, LFXS, LMAXP, LCXR, LCTT, LHA, LPA,
7 LGAM
INTEGER A02, B01, B02, B03, B04, B07, CNT,
1 CVT, D05, G07, P02, S02, S04, T06,
2 R2, Z2
REAL I2, I3, K6, K7, LAH, LAL, LAP,
1 LAPP, LAR, NO, N2, MASS, MASSP
DIMENSION N2(1), CO(JTL,1), VO(1), CXS(JM, JJM, 3), MO(1), M2(1),
1 CXR(1), CXT(1)
C THIS SUBROUTINE NORMALIZES FLUXES BEFORE EACH INNER ITERATION
C ABSORPTION AND OUT-SCATTER
E3(IGV) = 0.0
E4(IGV) = 0.0
DO 10 I=1, IMJM
TEMP = V0(I)*N2(I)
ITEMP = M0(I)
ITEMP = M2(ITEMP)
E3(IGV) = E3(IGV) + (C0(4,ITEMP) - C0(5,ITEMP) - C0(2,ITEMP))*TEMP
E4(IGV) = E4(IGV) + C0(2,ITEMP)*TEMP
C
LEFT LEAKAGE
IF(B01) 20, 20, 40
E5(IGV) = 0.0
DO 30 KJ = 1, JM
I = (KJ - 1)*IM + 1
30 E5(IGV) = E5(IGV) + CXS(1,KJ,1)*N2(I)
GO TO 50
C
RIGHT LEAKAGE
IF(B02) 60, 60, 80
E6(IGV) = 0.0
DO 70 KJ = 1, JM
I = KJ*IM
70 E6(IGV) = E6(IGV) + CXR(KJ)*N2(I)
GO TO 90
C
TOP LEAKAGE
IF(B03) 120, 140, 100
E7(IGV) = 0.0
DO 110 KI = 1, IM
I = IMJM - IM + KI
110 E7(IGV) = E7(IGV) + CXS(KI,1,2)*(N2(I) - N2(KI))
E8(IGV) = -E7(IGV)
GO TO 190
C
BOTTOM LEAKAGE
IF(B04) 160, 160, 180
160  E8(IGV) = 0.0
    DO 170 KI = 1, IMJM
170  E8(IGV) = E8(IGV) + CXS(KI,1,2)*N2(KI)
    GO TO 190
180  E8(IGV) = 0.0
190  E9(IGV) = E5(IGV) + E6(IGV) + E7(IGV) + E8(IGV)
    TEMP = (E1(IGV) + E2(IGV))/(E3(IGV) + E4(IGV) + E9(IGV))
    DO 200 I = 1, IMJM
200  N2(I) = TEMP*N2(I)
    E3(IGV) = TEMP*E3(IGV)
    E4(IGV) = TEMP*E4(IGV)
    E5(IGV) = TEMP*E5(IGV)
    E6(IGV) = TEMP*E6(IGV)
    E7(IGV) = TEMP*E7(IGV)
    E8(IGV) = TEMP*E8(IGV)
    E9(IGV) = TEMP*E9(IGV)
    RETURN
END

SUBROUTINE CNNP (F2, K6)
DIMENSION F2(1), K6(1)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
1     CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2     E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3     E01, E02, E03, EQ, EVP, EVPP, FEF,
4     GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,
5     II, IMJM, IP,ITEMP,ITEMP1,ITEMP2, ITL,
6     IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
7     LC, ML, NCON, NGOTO, NINIT, ORFP, P02,
8     PBAR, SBAR, SK7, T06, T7, T11, TEMP,
9     TEMP1, TEMP2, TEMP3, TEMP4, TI, TSD, V11
COMMON ID(11), MAXT, A02, I04, S02, IGM, NXCM,
1     MCR, M07, D05, G07, S04, NPR, NPUN,
2     IGE, IM, JM, IZM, MT, MO1, B01,
3     B02, B03, B04, IZ, JZ, EV, EVM,
COMMON LATW, LHCLN, LALAM, LCO, LNO, LN2, LAO,
1 LA1, LF0, LF2, LIO, LI1, LI2, LI3,
2 LK6, LK7, LM3, LM2, LR0, LR1, LR2,
3 LR3, LR4, LR5, LS2, LVO, LV7, LZ0,
4 LZ1, LZ2, LZ3, LZ4, LZ5, LCXS, LVOL,
5 LMASS, LMATN, LNBR, LLD, LLCN, LLFN, LPHIB,
6 LAXS, LFXS, LMASSP, LCXR, LCXT, LHA, LPA,
7 LGAM
INTEGER A02, B01, B02, B03, B04, B07, CNT,
1 CVT, D05, G07, P02, S02, S04, T06,
2 R2, Z2
REAL I2, I3, K6, K7, LAH, LAL, LAP,
1 LAPP, LAR, N0, N2, MASS, MASSP
C CONVERGENCE TESTS
C IF (MAXT) 25, 25, 10
C10 IF (TEMP - GLH) 25, 15, 15
C15 NGOTO = 1
C WRITE (NOUT, 20)
C20 FORMAT (53H1 ** RUNNING TIME EXCEEDED--FORCED CONVERGENCE ** //)
C GO TO 135
C25 CONTINUE
30 E01 = 1.0 - ALA
IF (ABS (E01) - 10.0 * EPS) 40, 40, 45
40 ORF = ORFP
45 CONTINUE
E02 = ABS (E01)
50 IF (E1 (IGP)) 55, 130, 55
55 IF (E02 - EPS) 60, 60, 70
60 CVT = 1
70 CALL CLEAR (0.0, F2, IMJM)
GO TO 105
70 EV = EV + POD * EQ * E01
GO TO 170
C FINAL PRINT
90 NGOTO = 1
IF (I04 - 1) 135, 95, 80

95 EV=0.0
DO 100 I=1,IGM
100 EV=EV+K6(I)
EV=SK7/EV
GO TO 135

105 IF (CVT-1) 110, 90, 110
110 IF (I04-1) 115, 120, 140
C MONITOR PRINT
115 NGOTO=2
GO TO 135

120 EV=0.
DO 125 I=1,IGM
125 EV=EV+K6(I)
EV=SK7/EV
GO TO 115

130 CALL ERR02(4HCNNP, 130,1)
135 RETURN
140 CONTINUE
C
C CALCULATE NEW PARAMETERS FOR SEARCH CALCULATIONS

145 E03=ABS (ALA-LAR)

150 IF (LAPP) 270, 150, 270
155 IF (LAP) 230, 155, 230
160 IF (EQ) 200, 160, 200
C MONITOR PRINT.
165 NGOTO=2
RETURN
C FINAL PRINT EXIT.

170 NGOTO=1
RETURN
175 LAP=ALA
EVP=EV
IF (EO1) 185,185,180
180 EV=EV-EVM
GO TO 190
185 EV=EV+EVM
190 IF (104-2) 195, 165, 195
C MIX X-SECS.
195 NGOTO=3
RETURN
200 IF (CVT) 170, 205, 170
205 EV=EV+POD*EQ*E01
210 IF (((LAPP-1.0)/(LAP-1.0)) 215, 190, 190
215 TEMP1=AMIN1(EVP,EVPP)
IF (EV-TEMP1) 220, 225, 225
220 EV=(EVPP+EVP)/2.
GO TO 190
225 TEMP1=AMAX1(EVP,EVPP)
IF (EV-TEMP1) 190, 220, 220
230 IF (E03-EPSA) 235, 235, 165
235 EQ=(EVP-EV)/(LAP-ALA)
240 IF (CNT) 260, 245, 260
245 IF (E02-LAL) 265, 265, 250
250 IF (E02-LAH) 260, 260, 255
255 E01=SIGN (LAH,E01)
260 LAPP=LAP
LAP=ALA
EVPP=EVP
EVP=EV
GO TO 205
265 CNT=1
LAP=0.0
LAPP=0.0
GO TO 205
270 IF (E03-EPSA) 275, 275, 165
C CALCULATE QUADRATIC COEFFICIENTS.
275 TEMP1=EVP-EV
TEMP2=EVPP-EV
TEMP3=EVPP-EVP
TEMP4=TEMP1*(EVP+EVP)
TEMP5=-TEMP2*(EV+EVPP)
TEMP6=TEMP3*(EVPP+EVP)
DENOM = TEMP3*TEMP2*TEMP1
EQA = ((LAPP-1.0)*TEMP1*EVP*EV - (LAP-1.0)*TEMP2
1*EV*EVPP + (ALA-1.0)*TEMP3*EVPP*EVP)/DENOM
EQB = -(LAPP*TEMP4 + LAP*TEMP5 + ALA*TEMP6)/DENOM
EQC = (LAPP*TEMP1 - LAP*TEMP2 + ALA*TEMP3)/DENOM
DISCR = EQB*EQB - 4.0*EQA*EQC
IF (DISCR) 235, 280, 280
280 IF (E02 - LAL) 265, 265, 285
285 TEMP1 = EQC + EQC
TEMP = SQRT (DISCR)
EQ = 1.0/(E0B + EV*TEMP1)
LAPP = LAP
LAP = ALA
EVPP = EVP
EVP = EV
EV1 = (TEMP - EQB)/TEMP1
EV2 = -(TEMP + EQB)/TEMP1
EVA = ABS (EV - EV1)
EVB = ABS (EV - EV2)
IF (EVA - EVB) 290, 290, 295
290 EV = EV1
GO TO 210
295 EV = EV2
GO TO 210
END

C
C
SUBROUTINE S8850(F2,N2,R1,Z1,R4,Z4,JIM,JJM,FN2,
1 CO,N0,M0,M2,F0,JTL,JMT)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3 E01, E02, E03, EQ, EVP, EVPP, FEF,
4 GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,
5 II, IMJM, IP,ITEMP,ITEMP1,ITEMP2, ITL,
6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
COMMON ID(11), MAXT, A02, IO4, S02, IGM, NXCM,
1 MCR, M07, DO5, G07, S04, NPRT, NPUN,
2 IGE, IM, JM, IZM, MT, M01, B01,
3 B02, B03, B04, IZ, JZ, EV, EVM,
4 S03, BUCK, LAL, LAH, EPS, EPSA, G06,
5 POD, ORF, S01

COMMON LATW, LHCLN, LALAM, LC0, LNO, LN2, LA0,
1 L1, LF0, LF2, LI0, LI1, LI2, LI3,
2 LK6, LK7, LM0, LM2, LR0, LR1, LR2,
3 LR3, LR4, LR5, LS2, LV0, LV7, LZ0,
4 LZ1, LZ2, LZ3, LZ4, LZ5, LCXS, LVO,
5 LMASS, LMATN, LNBR, LLD, LLCN, LLFN, LPHIB,
6 LAXS, LFXS, LMASSP, LCXR, LCXT, LHA, LPA,
7 LGAM

INTEGER A02, B01, B02, B03, B04, B07, CNT,
1 CVT, D05, G07, P02, S02, S04, T06,
2 R2, Z2

REAL I2, I3, K6, K7, LAH, LAL, LAP,
1 LAPP, LAR, NO, N2, MASS, MASSP

DIMENSION F2(JIM, JJM), N2(JIM, JJM), R1(I1), Z1(I1), R4(I1), Z4(I1),
1 FLUX(6), F2N(1), CO(JTL, JMT), NO(JIM, JJM), MO(JIM, JJM),
2 M2(I1), FO(JIM, JJM)

C FP S850 FINAL PRINT
ICARD = 1
CALL S8830
IF(NPRT-1) 90, 10, 10
10 CALL S8847
J=IP
IF(IP-JP) 30, 30, 20
20 J=JP
30 WRITE (NOUT, 40 ) (I,R1(I),R4(I),Z1(I),Z4(I),I=1,J)
40 FORMAT(84H1 RADII AVG RADII//(14,4F20.4))
1 AXII AVG AXII//((I4,4F20.6))
J=J+1
IFIIP-JP) 50, 90, 70
50 WRITE (NOUT, 60) (I, Z1(I), Z4(I), I=J, JP)
60 FORMAT(I4, 40X, 2F20.4)
GO TO 90
70 WRITE (NOUT, 80) (I, R1(I), R4(I), I=J, IP)
80 FORMAT(I4, 2F20.4)
90 CONTINUE
DO 100 I=1, IM
  DO 103 J=1, JM
    NO(I, J) = 0.0
  100 F2(I, J) = 0.0
DO 220 IIG=1, IGM
  IF(NPRT-1) 115, 115, 105
105 WRITE (NOUT,110) IIG
110 FORMAT(1H1, 20X, 14HFLUX FOR GROUP, I3)
115 READ (NFLUX1)((N2(I, J), I=1, IM), J=1, JM)
  REAC(NCR1)((CO(I, J), I=1, IM), J=1, JM)
  DO 120 I=1, IM
    DO 120 J=1, JM
      NO(I, J) = NO(I, J) + N2(I, J)
      ITEMP = NO(I, J)
      ITEMP = M2(ITEMP)
120 F2(I, J) = F2(I, J) + CO(I, ITEMP)*N2(I, J)*1000.*TSO
IF(NPUN) 210, 210, 130
C PUNCH FLUXES
130 GO TO (150, 200, 200), NPUN
150 DO 180 I=1, IMJM, 6
160 FLUX(J) = 0.
  II = MIN(I+5, IMJM)
  JI = 1
170 DO 170 J=I, II
    FLUX(J) = FN2(J)
  170 JI = JI + 1
PUNCH 190 ,(FLUX(J), J=1, 6), ICARD
180 ICARD = ICARD + 1
190 FORMAT(1P6E12.6, 4HFLUX, I4)
GO TO 210
200 WRITE(16) ((N2(I,J), I=1,IM), J=1,JM)
210 IF(NPRT-1) 220, 220, 215
215 CALL PRN(IM,JM,N2,Z4,NOUT)
220 CONTINUE
225 WRITE(NOUT,230)
230 FORMAT(1H1, 19X, 11H TOTAL FLUX//)
235 CALL PRN(IM,JM,N0,Z4,NOUT)
240 WRITE(NOUT, 240)
245 IF(NPUN) 270, 270, 250
250 GO TO (270, 255, 260), NPUN
C PUT AN END OF FILE ON 16
255 END FILE 16
GO TO 270
C PUT AN END OF FILE AND REWIND 16
260 REWIND 16
270 REWIND NCR1
REWIND NFLUX1
280 RETURN
END

SUBROUTINE S8847
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRA, ALA, B07,
1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3 E01, E02, E03, EQ, EVP, EVPP, FEF,
4 GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,
5 II, IMJM, IP, ITEMP, ITEMP1, ITEMP2, ITL,
6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
7 LC, ML, NCON, NGOTO, NINIT, ORFP, P02,
8 PBAR, SBAR, SK7, T06, T7, T11, TEMP,
9 TEMPI, TEMP2, TEMP3, TEMP4, TI, TSD, V11
COMMON ID(11), MAXT, AO2, IO4, SO2, IGM, NXCM,
1 MCR, M07, D05, G07, S04, NPRT, NPUN,
2 IGE, IM, JM, IZM, MT, M01, B01,
3 B02, B03, B04, IZ, JZ, EV, EVM,
4 SO3, BUCK, LAL, LAH, EPS, EPSA, G06,
5 POD, ORF, S01
COMMON LATW, LHolN, LALAM, LCO, LNO, LN2, LAL,
1 LA1, LF0, LF1, L13, L11, L12, L13,
2 LK6, LK7, LM0, LM2, LRO, LR1, LR2,
3 LR3, LR4, LR5, LS2, LVO, LV7, LZO,
4 LZ1, LZ2, LZ3, LZ4, LZ5, LCXS, LVOL,
5 LMASS, LMATN, LNBR, LLD, LLCN, LLFN, LPHIB,
6 LAXS, LFXS, LMASSP, LCXR, LCXT, LHA, LPA,
7 LGAM
INTEGER A02, B01, B02, B03, B04, B07, CNT,
1 CVT, D05, G07, P02, SO2, S04, T06,
2 R2, Z2
REAL I2, I3, K6, K7, LAH, LAL, LAP,
1 LAPP, LAR, NO, N2, MASS, MASSP

E2(IGP) = .0
E3(IGP) = .0
E4(IGP) = .0
E5(IGP) = .0
E6(IGP) = .0
E7(IGP) = .0
E8(IGP) = .0
E9(IGP) = .0
DO 10 I = 1, IGM
E2(IGP) = E2(IGP) + E2(I)
E3(IGP) = E3(IGP) + E3(I)
E4(IGP) = E4(IGP) + E4(I)
E5(IGP) = E5(IGP) + E5(I)
E6(IGP) = E6(IGP) + E6(I)
E7(IGP) = E7(IGP) + E7(I)
E8(IGP) = E8(IGP) + E8(I)
E9(IGP) = E9(IGP) + E9(I)
10 WRITE(NCUT,20)
SUBROUTINE PRT (IIM, JJM, N2, Z4, NOUT)
DIMENSION N2(IIM, JJM), I4(1)
REAL N2
IM = IIM
JM = JJM
DO 50 I=1, IM, 5
I1=I
I2=I+4
IF(I2-IM) 20, 20, 10
10 I2=IM
20 WRITE ( NOUT,30 ) ( JJ, JJ=I1,I2)
30 FORMAT (5I20)
DO 50 JJ=1, JM
J=JJ
40 FORMAT(I5,E15.7,5E20.7)
50 WRITE(NOUT,40 ) J,(N2(K, J),K=I1,I2),Z4(J)
RETURN
END

C
C
SUBROUTINE GRAM(MASS, VOL, ATW, HOLN, JIM, JJM, MO, M2, VO, 1  IO, I1, I2, JML, I3)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
    CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
    E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
    E01, E02, E03, EQ, EVP, EVPP, FEF,
    GBAR, GLH, IGEPS, IGP, IGV, IHS, IHT,
    II, JM, IP, ITEMP, ITEMP1, ITEMP2, ITL,
    IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
    LC, ML, NCON, NGOTO, NINIT, ORFP, PO2,
    PBAR, SBAR, SK7, T06, T7, T11, TEMP,
    TEMP1, TEMP2, TEMP3, TEMP4, TI, TSD, V11
COMMON ID(11), MXT, A02, IO4, S02, IGM, NXCM,
    MCR, M07, D05, G07, S04, NRT, NPUN,
    IM, JM, IJM, MT, M01, B01,
    BO2, B03, B04, IZ, JZ, EV, EVM,
    SO3, BUCK, LAL, LAH, EPS, EPSA, GO6,
    POD, ORF, S01
COMMON LATW, LHoln, LAlam, LC0, LNO, L02, LAO,
    LAL, LF0, LF2, LI0, LI1, LI2, LI3,
    LK6, LK7, LMO, LM2, LR0, LR1, LR2,
    LR3, LR4, LR5, LS2, LV0, LV7, LZO,
    LZ1, LZ2, LZ3, LZ4, LZ5, LCXS, LVOL,
    LMASS, LMAP, LNR, LLD, LLCN, LLFN, LPHIB,
    LAXS, LFXS, LMASSP, LCXR, LCXT, LHA, LPA,
    LGAM
INTEGER A02, B01, B02, B03, B04, B07, CNT,
    CVT, D05, G07, P02, S02, S04, T06,
    R2, Z2
REAL I2, I3, K6, K7, LAH, LAL, LAP,
    LAPP, LAR, NO, N2, MASS, MASSP
DIMENSION MASS(JML,1), VOL(1), ATW(1), Holn(1), MO(JIM,JJM),
    M2(1), VO(JIM,JJM), I0(1), I1(1), I2(1), I3(1)
C THIS SUBROUTINE CALCULATES THE MASS OF THE VARIOUS MATERIALS
WRITE(NOUT,10) (ID(I), I=1,16)
10 FORMAT(1H1,16A4/>
WRITE(NOUT, 20)
20 FORMAT(45H MATERIAL INVENTORY (KILOGRAMS) FOR EACH ZONE / )
CALL CLEAR(0.0,VCL,IZM)
ITEMP = ML*IZM
CALL CLEAR(0.0,MASS,ITEMP)
DO 30 J = 1, JM
DO 30 I = 1, IM
K = MO(I,J)
30 VOL(K) = VOL(K) + VOL(I,J)*.001
DO 39 M=1,M01
I3(M) = I2(M)
IF(IO(M) - I1(M)) 39,35,39
IF(I2(M)) 39,36,39
36 DO 38 MM=1,M
IF(IO(M) - IO(MM)) 38,37,38
37 I3(MM) = I2(MM)*EV
38 CONTINUE
39 CONTINUE
DO 190 N =1, IZM
MM = M2(N)
DO 190 M = 1,M01
IF(IO(M) - NN) 190, 40, 190
40 L = I1(M)
IF(L - ML) 170, 170, 50
50 NNAA = L
IF(L - IO(M)) 130,190, 130
130 DO 160 MAA = 1, M01
IF(IO(MAA) - NNAA) 160, 140, 160
140 L = I1(MAA)
IF(L) 160, 160, 150
150 E01 = I3(MAA)*I3(M)
MASS(L,N) = ((E01*ATW(L)*VOL(N))/6.023) + MASS(L,N)
160 CONTINUE
GO TO 190
170 IF(L) 190, 190, 180
180 E01 = I3(M)
MASS(L,N) = ((E01*ATW(L)*VOL(N))/6.023) + MASS(L,N)
190 CONTINUE
CATA ZONE/4HZONE/
DO 260 L = 1, IZM, 5
   LL = L + 4
   IF(LL - IZM) 210, 210, 200
200   LL = IZM
210   WRITE(NOUT, 220) ((ZONE, K), K=L, LL)
220   FORMAT(/26H MATERIAL ATOMIC WT., 3X, 5(A4,2X,I2,12X))
   WRITE(NOUT, 230) (VOL(K), K = L, LL)
230   FORMAT(25X, 5(E8.3, 7H LITERS, 5X))
   DO 240 K = 1, ML
240   WRITE(NOUT, 250) K, HOLN(K), ATW(K),
                  (MASS(K, I), I = L, LL)
250   IF(LL - IZM) 260, 270, 270
   CONTINUE
260   RETURN
270   END

SUBROUTINE INPB(MATN, NBR, LD, LCN, LFN, ALAM, HOLN, JML, I2)
COMMON NSCORE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
1   CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2   E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3   E01, E02, E03, EQ, EVP, EVPP, FEF,
4   GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,
5   II, IMJM, IP, ITOP, ITEMP1, ITEMP2, ITL,
6   IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
7   LC, ML, NCON, NGOTO, NINIT, ORFP, P02,
8   PBAR, SBAR, SK7, T06, T7, T11, TEMP,
9   TEMP1, TEMP2, TEMP3, TEMP4, TI, TSD, V11
COMMON ID(11), MAXT, A02, I04, S02, IGM, NXCM,
1   MCR, M07, D05, G07, S04, NPRT, NPUN,
2   IGE, IM, JM, IZM, MT, MO1, B01,
3   B02, B03, B04, IZ, JZ, EV, EVM,
4   S03, BUCK, LAL, LAH, EPS, EPSA, G06,
5   POD, ORF, SO1
COMMON LATW, LHOLN, LALAM, LCO, LNO, LN2, LA0,
1   LA1, LF0, LF2, LI0, LI1, LI2, LI3,
THIS SUBROUTINE READS AND PRINTS THE BURNUP DATA
READ(NINP,10) ITEMP, NPRT, NPUN, ITEMP1, DELT
10 FORMAT(416, E12.0)
   IF(DELT) 14,14,12
12 DAY = DAY + DELT
14 CVT = 0
   CNT = 0
   P02 = 0
   ALA = 0.0
   LAP = 0.0
   LAPP = 0.0
   LAR = 0.0
   EQ = 0.0
   KPAGE = 100
   IF(ITEMP) 190, 15, 20
15 NCON = ITEMP
   GO TO 190
20 NCON = ITEMP
   DD 40 N = 1, NCCN
30 FORMAT(1216)
40 READ(NINP,30) MATN(N), NBR(N), LD(N), (LCN(N,K), K=1,2), (LFN(N,K),
   K=1,7)
   WRITE(NOUT,60)
60 FORMAT(12H1BURNUP DATA///)
WRITE(NOUT,70)
70 FORMAT(130H BURNABLE MATERIAL NAME LAMBDA)
      NBR * * * * * SOURCE ISOTOPE FOR * * * *
      *
      1 130H ISOTOPE NO. (DAYS-1) DECAY CAPTURE FISS
      *
      2 / *
      3 MOON /9H NO. )
      DO 90 N=1, NCN
      80 FORMAT(3X, I3, 12X, I3, 10X, A4,10X, E8.3, 19, 15X, I3, 13X, 2I3,
      1 10X, 7I3)
      ITEMP = MATN(N)
      ALAM(ITEMP) = 24.*3600.*ALAM(ITEMP)
      WRITE(NOUT,80) N, MATN(N), HOLN(ITEMP), ALAM(ITEMP), NBR(N),
      1LD(N), (LCN(N,K),K=1,2), (LFN(N,K),K=1,7)
      90 ALAM(ITEMP) = ALAM(ITEMP)/(3600.*24.)
      190 IF(ITEMP1) 230, 230, 200
      200 PUNCH 210, (12(1), I=1,M01)
      210 FORMAT(6(3X,E9.4))
      230 RETURN
      END

C

SUBROUTINE AVERAG(PHIB,AXS,FXS,MATN,MASS,ATW,VOL,CO,N2,M0,VO,
      1 HOLN, JML, JTL, NBR)
      DIMENSION PHIB(1), AXS(JML,1), FXS(JML,1), MATN(1), MASS(JML,1),
      1 ATW(1), HOLN(1), CO(JTL,1), N2(1), M0(1), VO(1), HOLN(1)
      2 COMMON NSORCE, NCXS
      COMMON NINP, NOUT, NCR1,NFLUX1, NSCRAT, ALA, B07,
      1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
      2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
      3 E01, E02, E03, EQ, EVPP, FEF,
      4 GBAR, GLH, IGP, IGV, IHS, IHT,
      5 II, IMJM, IP, ITEMP, ITEMP1, ITEMP2, ITL,
      6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
      7 LC, ML, NCON, NGOTO, NINIT, ORFP, P02,
      8 PBAR, SBAR, SK7, TO6, T7, T11, TEMP,
THIS SUBROUTINE CALCULATES ZONE AVERAGED FLUXES, FISSION CROSS SECTIONS, AND ABSORPTION CROSS SECTIONS.

DO 10 KZ = 1, IZM

RL(KZ) = 0.0
RC(KZ) = 0.0
PHIB(KZ) = 0.0
DO 10 KN = 1, NCON
AXS(KN,KZ) = 0.0
FXS(KN,KZ) = 0.0
LN = MATN(KN)

MASS(LN,KZ) = (MASS(LN,KZ) * 6023) / (ATW(LN) * VOL(KZ))

DO 100 IIG = 1, IGM
READ(NCR1) ((C0(I,I,J), I=1, ITL), J=1, MT)
READ(NFLUX1) (N2(I), I=1, IMJM)

DO 100 I = 1, IMJM
KZ = MO(i)
PHIB(KZ) = PHIB(KZ) + N2(I) * V0(I)
DO 100 KN=1,NCON
  LN = MATN(KN)
  AXS(KN,KZ) = AXS(KN,KZ) + CO(2, LN)*N2(I)*VO(I)
 100  FXS(KN,KZ) = FXS(KN,KZ) + CO(1, LN)*N2(I)*VO(I)
DO 250 KZ=1,IZM
  TEMP3 = PHI3(KZ)
  PHIB(KZ) = PHIB(KZ)/(VOL(KZ)*1000.)
WRITE(NOUT, 110) KZ
  110 FORMAT(1H1, 45X, 9H ZONE, 13/)  
WRITE(NOUT, 120)
  120 FORMAT(1H15H BURNABLE MATERIAL NAME ATOM)
  1 FISSION ABSORPTION SIGMA SIGMA /
  2 115H ISOTOPE NO. DENSITY /
  3 RATE RATE FISSION ABSORPTION/
  4 7H NC./)
  TEMP4 = 0.0
DO 200 KN=1,NCON
  LN = MATN(KN)
  TEMP1 = AXS(KN,KZ)*MASS(LN,KZ)
  TEMP2 = FXS(KN,KZ)*MASS(LN,KZ)
  TEMP4 = TEMP4 + TEMP2
  AXS(KN,KZ) = AXS(KN,KZ)/TEMP3
  FXS(KN,KZ) = FXS(KN,KZ)/TEMP3
  130 FORMAT(4X, I3, 11X, I3, 10X, A4, 4X, 1P5E15.3)
WRITE(NOUT, 130) KN, LN, HOLN(LN), MASS(LN,KZ), TEMP2, TEMP1,
  1 FXS(KN,KZ), AXS(KN,KZ)
  ITEMP = NBR(KN)
  IF(ITEMP -1) 200, 140, 160
  140 RC(KZ) = RC(KZ) + TEMP1 - TEMP2
  GO TO 200
  160 RL(KZ) = RL(KZ) + TEMP1
200 CONTINUE
  TEMP4 = TEMP4*TSD
WRITE(NOUT, 210) PHIB(KZ), TEMP4, VOL(KZ), RC(KZ), RL(KZ)
  210 FORMAT(/24H ZONE FLUX(N/CM+2*SEC) =1PE11.4/
    1  24H ZONE POWER(MW) =1PE11.4/
    2  24H ZONE VOLUME(LITERS) =1PE11.4/
250 CONTINUE
WRITE(NOUT,170)
170 FORMAT(1HI,30X,25H DATA FOR BREEDING RATIO //)
WRITE(NOUT,175)
175 FORMAT(20X,60H ZONE INDEX BREED RATIO CAPTURE RATE FISSION RATE)
1ON RATE /)
TRL=0.0
BRT=0.0
DO 300 KZ=1,IZM
TRL =TRL + RL(KZ)
DO 305 KZ=1,IZM
BR(KZ) = RC(KZ)/TRL
WRITE(NOUT,310) KZ, BR(KZ), RC(KZ), RL(KZ)
310 FORMAT(25X,13,7X, F10.5, 5X, 1P2E15.5)
BRT = BRT + BR(KZ)
305 CONTINUE
WRITE(NOUT,350) BRT
350 FORMAT(//20X,25H TOTAL BREEDING RATIO = F8.5 )
REIND NCR1
REIND NFLUX1
RETURN
END

SUBROUTINE MARCH(PHIB,MATN,FXS,AXS,VOL,MASS,MASSP,ALAM,LD,LCN,
LFN,JML,IO,II,I2,M2)
DIMENSION PHIB(1), MATN(1), FXS(JML,1), AXS(JML,1), VOL(1),
MASS(JML,1), MASSP(JML,1), ALAM(1), LD(1), LCN(JML,1),
LFN(JML,1), IO(1), II(1), I2(1), M2(1)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
E01, E02, E03, EQ, EVP, EVPP, FEF,
GBAR, GLH, IGEPI, IGP, IGV, IHS, IHT,
THIS SUBROUTINE Computes the Time Dependent Isotopic Concentration

\[
\text{TEMP} = \text{DELT} \times 24. \times 3600. / 10.
\]

TEMP1 = .0

DO 5 KZ = 1,IZM

\[
\text{PHIB(KZ)} = \text{PHIB(KZ)} \times 10.**(-24)
\]

DO 5 KN = 1,NCON

LN = MATN(KN)

5 TEMP1 = TEMP1 + FXS(KN,KZ)*PHIB(KZ)*MASS(LN,KZ)*VOL(KZ)

DO 200 KT = 1,10

TEMP3 = .0

DO 20 KZ = 1,IZM

DO 20 KN = 1,NCON

LN = MATN(KN)
DO 100 KZ = 1,IZM
DO 50 KKK = 1,5
DO 50 KN = 1,NCON
LN = MATN(KN)
TEMP2 = -(MASS(LN,KZ) + MASSP(LN,KZ))*(ALAM(LN) + AXS(KN,KZ)*PHIB(KZ))
IF (LC(KN)) 30, 30, 28
KK = LD(KN)
KK = MATN(KK)
TEMP2 = TEMP2 + ALAM(KK)*(MASS(KK,KZ) + MASSP(KK,KZ))
DO 32 K = 1,2
KK = LCN(KN,K)
KL = MATN(KK)
IF (KK) 32, 32, 31
TEMP2 = TEMP2 - AXS(KK,KZ)*PHIB(KZ)*
(MASS(KL,KZ) + MASSP(KL,KZ))
CONTINUE
DO 36 K = 1,7
KK = LFN(KN,K)
KL = MATN(KK)
IF (KK) 36, 36, 34
TEMP2 = TEMP2 + AXS(KK,KZ)*PHIB(KZ)*(MASS(KL,KZ) + MASSP(KL,KZ))
CONTINUE
MASS(LN,KZ) = MASSP(LN,KZ) + .5*TEMP*TEMP2
DO 100 KN = 1,NCON
LN = MATN(KN)
TEMP3 = TEMP3 + AXS(KN,KZ)*PHIB(KZ)*MASS(LN,KZ)*VOL(KZ)
IF(TEMP3) 200, 200, 110
110 DO 120 KZ = 1,IZM
PHIB(KZ) = PHIB(KZ) * TEMP1/TEMP3
CONTINUE
DO 500 KZ = 1,IZM
PHIB(KZ) = PHIB(KZ)*10.**24
DO 540 KZ=1,IZM
DO 540 M=1,M01
IF(10(M) = M2(KZ)) 540,520,540
DO 530 KN=1,NCON
LN = MATN(KN)
IF(LN = I1(M)) 530, 525, 530
525 I2(M) = MASS(LN, KZ)
530 CONTINUE
540 CONTINUE
RETURN
END

C
C
C
SUBROUTINE SHUF(I0, I1, I2)
COMMON NSORCE, NCXS
COMMON NINP, NOUT, NCR1, NFLUX1, NSCRAT, ALA, B07,
1 CNT, CVT, DAY, DELT, E0(51), E1(51), E2(51),
2 E3(51), E4(51), E5(51), E6(51), E7(51), E8(51), E9(51),
3 E01, E02, E03, EQ, EVP, EVPP, FEF,
4 GBAR, GLH, IGEP, IGP, IGV, IHS, IHT,
5 II, IMJM, IP, ITEMP, ITEMP1, ITEMP2, ITL,
6 IZP, JP, K07, KPAGE, LAP, LAPP, LAR,
7 LC, ML, NCON, NGOTO, NINIT, ORFP, P02,
8 PBAR, SBAR, SK7, TO6, T7, T11, TEMP,
9 TEMPI, TEMP2, TEMP3, TEMP4, TI, TSD, V11
COMMON ID(11), MAXT, A02, I04, SO2, IGM, NXCM,
1 MCR, M07, D05, G07, S04, NPRINT, NPUN,
2 IGE, IM, JM, IZM, MT, M01, B01,
3 B02, B03, B04, IZ, JZ, EV, EVM,
4 SO3, BUCK, LAL, LAH, EPS, EPSA, G06,
5 POD, CRF, S01
COMMON LATW, LHOLN, LALAM, LCO, LNO, LN2, LAO,
1 LAI, LF0, LF2, L10, LI1, L12, LI3,
2 LK6, LK7, LMO, LM2, LR0, LR1, LR2,
3 LR3, LR4, LR5, L52, LV3, L7V, LZ0,
4 LZ1, LZ2, LZ3, LZ4, LZ5, LCXS, LVOL,
5 LMASS, LMATN, LNB, LLD, LLCN, LLFN, LPHIB,
6 LAXS, LFXS, LMASSP, LCXH, LCXT, LHA, LPA,
7 LGAM
INTEGER A02, B01, B02, B03, B04, B07, CNT,
1 CVT, D05, G07, P02, S02, S04, TO6,
REAL I2, I3, K6, K7, LAH, LAL, LAP, LAPP, LAR, NO, N2, MASS, MASSP
DIMENSION I0(1), I1(1), I2(1)

C THIS SUBROUTINE SHUFFLES MIXTURES.

DELT = .0
WRITE(NOUT,10) CAY
10 FORMAT(1H1,10X,51H MIXTURES SHUFFLED AT TIME
       1 = ,F8.3,8H DAY S///)
I = 0
15 I = I + 1
READ(NINP,20) ITEMP,ITEMP1,ITEMP2
20 FORMAT(I6)
IF(ITEMP) 25,100,25
25 WRITE(NOUT,30) I,ITEMP1,ITEMP2
30 FORMAT(I6, 6X, 4H MIX,I6,19H IS REPLACED BY MIX, 16)
DO 90 II=1,M01
   IF(ITEMP2 - I0(II)) 90,40,90
40 DO 70 JJ=1,M01
   IF(ITEMP1 - I0(JJ)) 70,50,70
50 IF(I1(II) - II(JJ)) 70,60,70
60 I2(JJ) = I2(II)
   GO TO 90
70 CONTINUE
90 CONTINUE
GO TO 15
100 RETURN
END

C THE END OF THE PROGRAM

C

//LKD.SYSLMOD CD DSN=PROG.14531(TWODB),UNIT=2314,DISP=(NEW,CATLG),
// SPACE=(TRK,(35,,1),RLSE),VOL=SER=LIBPK2
//GO.FT03F001 DC UNIT=SPOOL,SPACE=(TRK,(10,10)),
// DCB=(RECFM=VBS,LRECL=796,BLKSIZE=800)
LMFBR MODULAR CORE DESIGN (ORIGINAL)

2

0  3  0  2  1  5  8  22  1  0  2  2  0  0
1.0  0.1  0.0  153.02  3.005  0.5
0.0001  0.001  0.001  1.0  1.4  -2500.

U238  238.05  0.0  FERTILE FUEL MATERIAL
.100100+00  .232887-00  .281437-00  .633569+01  .600524+01  .000000
.000000  .532188-00  .000000  .131583+02  .126261+02  .975608-01

Pu49  239.05  0.0  FISSILE FUEL MATERIAL
.172436+01  .184872+01  .511503+01  .669364+01  .476589+01  .000000
.228419+01  .324006+01  .649503+01  .139176+02  .106775+02  .790403-01

C  12.011  0.0  IN (PU+U)C FUEL
.000000  .833620-05  .000000  .263926+01  .245083+01  .000000
.000000  .456935-10  .000000  .448553+01  .448553+01  .188417-00

Na  22.991  0.0  COOLANT
.000000  .713006-03  .000000  .309019+01  .300053+01  .000000
.000000  .423424-02  .000000  .498455+01  .498031+01  .889546-01

Fe  55.847  0.0  STRUCTURE
.000000  .591775-02  .000000  .255761+01  .251745+01  .000000
.000000  .215431-01  .000000  .482144+01  .479990+01  .342399-01

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2. **Source deck listing II**

   (This deck is to be used after the program is submitted in the computer memory)
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//S1 EXEC PGM=TW0DB,REGION=176K,TIME=3
//STEPLIB DD DSNAME=PROG.I4531,DISP=SHR
//FT03F001 DD UNIT=SPOOL,SPACE=(TRK,(10,10)),
// DCB=(RECFM=VBS,LRECL=796,BLKSIZE=800)
//FT04F001 DD UNIT=SPOOL,SPACE=(TRK,(10,10)),
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//FT06F001 DD SYSOUT=A,SPACE=(CYL,(2,1)),
// DCB=(RECFM=FBA,LRECL=133,BLKSIZE=3325)
//FT05F001 DD *

LMFBR MODIFIED CORE (OPTIMIZED)

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2 16 16 16 5  0  22 1  0  2  2  0
1.0  0.1  0.0  0.153-02  0.005  0.5
0.0001 0.001 0.001 1.0  1.4 -2500.

U238 238.05 0.0  FERTILE FUEL MATERIAL
.100100+00 .232887-00 .281437-00 .633569+01 .600524+01 .000000
.000000 .532188-00 .000000 .131583+02 .126261+02 .975608-01

PU49 239.05 0.0  FISSILE FUEL MATERIAL
.172436+01 .184872+01 .511503+01 .669364+01 .476589+01 .000000
.228419+01 .324006+01 .649503+01 .139176+02 .106775+02 .790403-01

C  12.011 0.0  IN (PU+U)C FUEL
.000000 .833620-05 .000000 .263926+01 .245083+01 .000000
.000000 .456935-10 .000000 .448553+01 .448553+01 .188417-00

NA  22.991 0.0  COOLANT
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| 211 | 0.02 | 3 | .15 | .253 |
| 17  | 11.2 | 31.4 | 21.3 | 4411 | 1617 | 1 |
| 12  | 31.4 | 51.3 | 44.3 | 163 |
| 0.06| 0.71 | 3 | 083 |

| 15  | 1.03 |
| 7.63085+8 | .1133 |
| 108 | 0.61 | 8 | 071.6 | 083 |
| 0   | 1   | 2 | 6   | 2   | 3 |
| 4   | 5   | 0 | 1   | 2   | 7 |
| 2   | 3   | 4 | 5   | 0   | 1 |
| 2   | 3   | 4 | 53 |

| .0000 | .0092 | -.0092 | .0000 | .0115 | .0166 |
| .0073 | .0101 | .0000 | .0088 | -.0088 | .0000 |
| .0115 | .0166 | .0073 | .0101 | .0000 | .0115 |
| .0000 | .0166 | .0073 | .01013 |

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| 1   | 0   | 0 | 0   | 0   |
| 2   | 2   | 0 | 1   | 0   | 0   | 0   |

9.999
G. Complete Output of Optimized Core Calculation
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| Z0N6 NUMBERS BY MESH INTERVAL |
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| 3   | 1 1 2 2 3 2 3 2 |
| 4   | 4 4 4 4 4 4 4 4 |
| 5   | 1 1 1 1 1 1 1 1 |
| 6   | 2 2 2 2 2 2 2 2 |
| 7   | 3 3 3 3 3 3 3 3 |
| 8   | 4 4 4 4 4 4 4 4 |
| 9   | 5 5 5 5 5 5 5 5 |
| 10  | 6 6 6 6 6 6 6 6 |
| 11  | 7 7 7 7 7 7 7 7 |

**MATERIAL NUMBERS BY ZONE**

| 2   | 5 |
| 6   | 7 |

**BUCKLING COEFFICIENTS BY ZONE**

| GAM  | 5 |
| 6.10000E-01 0.10000E-01 0.10000E-01 0.10000E-01 0.10000E-01 0.10000E-01 0.10000E-01 |

**FISSION SPECTRUM**

| K7  | 2 |
| 0.98700E-01 0.10000E-01 |

**NEUTRON VELOCITY**

| V7  | 2 |
| 0.76200E-09 0.11636E-09 |

**MIXTURE SPECIFICATIONS**

| ID  | 22 |
| 6   | 6 6 6 6 6 6 6 6 |
| 7   | 7 7 7 7 8 8 8 9 |
| 8   | 8 8 8 8 8 8 8 8 |
### L4F3R MODIFIED CORE (OPTIMIZED)

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### LMFBR MODIFIED CORE (OPTIMIZED)

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**Notes:**

- The table entries include numerical data and possibly coordinates or parameters.
- The diagrams illustrate core configurations, likely with radial and axial orientations.
- The terms "MODIFIED CORE" and "OPTIMIZED" indicate specific adjustments or enhancements to the core design.

**Legend:**

- RADIAL: Orientation or direction of the core structure.
- AXIAL: Orientation or direction of the core structure.
**L4F3R MODIFIED CORE (OPTIMIZED)**

CROSS SECTIONS ARE READ-IN FOR THE FOLLOWING MATERIALS

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**Zone Flux (n/cm²·sec)** = 1.351E 17  
**Zone Power (MW)** = 2.111E 01  
**Zone Volume (Liters)** = 6.927E 00  
**Zone Capture Rate** = 3.369E 19  
**Zone Fission Rate** = 0.0

### Zone 5

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**Zone Flux (n/cm²·sec)** = 1.055E 17  
**Zone Power (MW)** = 1.868E 01  
**Zone Volume (Liters)** = 2.814E 00  
**Zone Capture Rate** = 3.098E 18  
**Zone Fission Rate** = 0.0

### Data for Breeding Ratio

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**Total Breeding Ratio** = 0.93436
XII. APPENDIX C: PROGRAMMING FOR OPTIMIZATION

A. List of Source Deck
THIS IS A FORTRAN IV COMPUTER PROGRAM FOR CONSTRAINED OPTIMIZATION WITH THE EXTERNAL PENALTY FUNCTION METHOD.

INPUT PARAMETERS

N   NUMBER OF VARIABLES
LIMIT  MAXIMUM NUMBER OF INNER ITERATIONS FOR PERFORMANCE OF UNCONSTRAINED OPTIMIZATION
ITOUT  MAXIMUM NUMBER OF OUTER ITERATIONS FOR PERFORMANCE OF CONSTRAINED OPTIMIZATION WITH PENALTY FUNCTION METHOD
EST  ESTIMATE OF THE MINIMUM FUNCTION VALUE
EPS  TEST VALUE REPRESENTING THE EXPECTED ABSOLUTE ERROR
WHERE A REASONABLE CHOICE IS SOMEWHAT GREATER THAN 10**(-D), WHERE D IS THE NUMBER OF SIGNIFICANT DIGITS IN FLOATING POINT REPRESENTATION.
CCNV  CONVERSION VALUE FOR OUTER ITERATION AND CORRESPONDED TO EPS FOR INNER ITERATION
KINP  INITIAL K-VALUE FOR EXTERNAL PENALTY FUNCTION
X(I)  N INITIAL VALUES REPRESENTING THE ITERATION STARTING POINT

MAIN VARIABLES

FUNCT  SUBROUTINE CONCERNING THE FUNCTION TO BE MINIMIZED
THIS SUBROUTINE MUST INCLUDE A SET OF CONSTRAINTS, THE OBJECTIVE FUNCTION WITH PENALTY FUNCTION, AND THEIR GRADIENT VECTOR, G, CONTAINING N ELEMENTAL FUNCTIONS.
G(I)  ELEMENTAL FUNCTIONS OF N-DIMENSIONAL GRADIENT VECTOR CORRESPONDING TO THE MINIMUM ON RETURN
H  WORKING STORAGE COMPUTED AUTOMATICALLY IN SUBROUTINE, FMFP, WITH REPRESENTATIVE N*(N+7)/2
Y(I)  CONSTRAINED FUNCTIONS STORED IN SUBROUTINE, FUNCT
NUMBER OF THE CONSTRAINTS CAN BE ADJUSTED IN FUNCT.
IER  ERROR INDICATION PARAMETER CAUSED FROM FMFP
IER = 0 MEANS CONVERGENCE WAS OBTAINED
IER = 1 MEANS NO CONVERGENCE IN LIMIT ITERATIONS
IER = -1 MEANS ERRORS IN GRADIENT CALCULATIONS
IER = 2 MEANS LINEAR SEARCH TECHNIQUE INDICATES IT IS LIKELY THAT THERE EXIST NO MINIMUM.

MAIN PROGRAM
INPUT AND OUTPUT INDICATIONS, CALLING FMFP, OUTER ITERATION CCNTRCL, AND CONVERSION TEST ARE INCLUDED IN MAIN.

EXTERNAL FUNCT
DIMENSION X(5),G(5),H(30)
REAL L,KINP
WRITE(6,1)
1 FORMAT(1H1)
WRITE(6,2)
2 FCRMAT(1C10,55H CONSTRAINT OPTIMIZATION WITH PENALTY FUNCTION METHO 1D ///)
READ(5,3) N,LIMIT,ITOUT
3 FCRMAT(3I10)
READ(5,4) EST,EPS,CONV,KINP
4 FCRMAT(4E10.3)
WRITE(6,5) N,LIMIT,ITOUT
5 FCRMAT(
153H N NUMBER OF VARIABLES I9/
253H LIMIT MAXIMUM NUMBER OF INNER ITERATION I9/
353H ITCLT MAXIMUM NUMBER OF OUTER ITERATION I9/)
WRITE(6,6) EST,EPS,CONV,KINP
6 FCRMAT(
153H EST ESTIMATE OF MINIMUM FUNCTION VALUE 1PE15.4/
253H EPS TEST VALUE REPRESENTING EXPECTED VALUE 1PE15.4/
353H CONV CONVERSION VALUE FOR OUTER ITERATION 1PE15.4/
453H KINP INITIAL VALUE FOR PENALTY FUNCTION 1PE15.4///)
REAC(5,7) (X(I),I=1,N)
7 FCRMAT(7E10.4)
L=KINP
CO 13 J=1,ITOUT
SUBROUTINE, FMFP, IS USED FOR UNCONSTRAINED OPTIMIZATION
WITH CAVIDON'S METHOD.

SUBROUTINE FMFP(FUNCT,N,X,F,G,EST,EPS,LIMIT,IER,H,KP)
DIMENSION H(1),X(1),G(1)
REAL KP
WRITE(6,200)
200 FORMAT('KOUNT',8X,'ITERATION NUMBER = ',I5,5X,'K-VALUE = ',E15.5)
CALL FMFP(FUNCT,N,X,F,G,EST,EPS,LIMIT,IER,H,KP)
WRITE(6,500) J,(X(I),I=1,N),F,(G(I),I=1,N)
500 FORMAT('0',14,9E13.4)
WRITE(6,17) IER
17 FORMAT('0','* * * IER = ',I5///)
IF(J-1)12,12,10
IF(F-FLAST) 11,14,14
IF(ABS(F-FLAST)-CONV) 14,14,12
10 FLAST=F
12 L=L*4.
13 CONTINUE
14 STOP
END
2 DO 3 L=1,NJ
   KL=K+L
3   H(KL)=0.
4   K=KL+1
5   KCUNT=KCUNT+1
   WRITE(6,500) KCUNT,(X(I),I=1,N),F, (G(I),I=1,N)
500  FCRMAT(15,9E13,4)
     OLDF=F
     DO 9 J=1,N
      K=N+J
      H(K)=G(J)
      K=K+N
      H(K)=X(J)
      K=J+N3
      T=0.
      DO 8 L=1,N
      T=T-G(L)*H(K)
      IF(L-J)6,7,7
6     K=K+N-L
     GO TO 8
7     K=K+1
8    CONTINUE
9   H(J)=T
     DY=0.
     HNRM=0.
     GNRM=0.
     DO 10 J=1,N
      HNRM=HNRM+ABS(H(J))
      GNRM=GNRM+ABS(G(J))
10    DY=DY+H(J)*G(J)
     IF(DY)11,51,51
11    IF(HNRM/GNRM-EPS)51,51,12
12    FY=F
     ALFA=2.*(EST-F)/DY
     AMBCA=1.
     IF(ALFA)15,15,13
13    IF(ALFA-AMBDA)14,15,15
14 AMBDA=ALFA
15 ALFA=0.
16 FX=FY
   DX=DY
   CO 17 I=1,N
17 X(I)=X(I)+AMBDA*H(I)
   CALL FUNCT(N,X,F,G,KP)
   FY=F
   DY=0.
   DO 18 I=1,N
18 DY=DY+G(I)*H(I)
   IF(DY)19,36,22
19 IF(FY-FX)20,22,22
20 AMBDA=AMBDA+ALFA
   ALFA=AMBDA
   IF(HNRM*AMBDA-1.E10)16,16,21
21 IER=2
   RETURN
22 T=0.
23 IF(AMBDA)24,36,24
24 Z=3.*(FX-FY)/AMBDA+DX+DY
   ALFA=MAX1(ABS(Z),ABS(DX),ABS(DY))
   CALFA=Z/ALFA
   CALFA=DALFA*DALFA-FX
   DALFA=DALFA*DALFA-DX/ALFA*DY/ALFA
   IF(DALFA)51,25,25
25 W=ALFA*SQRT(DALFA)
   ALFA=DX+DY+W+W
   IF(ALFA)250,251,250
250 ALFA=(DY-Z+W)/ALFA
   GO TO 252
251 ALFA=(Z+DY-W)/(Z+DX+Z*DY)
252 ALFA=ALFA*AMBDA
   DO 26 I=1,N
26 X(I)=X(I)+(T-ALFA)*H(I)
   CALL FUNCT(N,X,F,G,KP)
   IF(F-FX)27,27,28
27 IF(F-FY)36,36,28
28 CALFA=0.
   DO 29 I=1,N
29 DALFA=CALFA+G(I)+H(I)
   IF(DALFA)30,33,33
30 IF(F-FX)32,31,33
31 IF(DX-DALFA)32,36,32
32 FX=F
   CX=CALFA
   T=ALFA
   AMBDA=ALFA
   GO TO 23
33 IF(FY-F)35,34,35
34 IF(DY-DALFA)35,36,35
35 FY=F
   OY=DALFA
   AMBDA=AMBDA-ALFA
   GO TO 22
36 IF(OLCF-F*EPS)51,38,38
38 DO 37 J=1,N
   K=N+J
   H(K)=G(J)-H(K)
   K=N+K
37 H(K)=X(J)-H(K)
   IER=0
   IF(KCOUNT-N)42,39,39
39 T=0.
   Z=0.
   DO 40 J=1,N
      K=N+J
      W=H(K)
      K=K+N
      T=T+ABS(H(K))
39 Z=Z+W*H(K)
   IF(HNRM-EPS)41,41,42
41 IF(T-EPS)56,56,42
42 IF(KCOUNT-LIMIT)43,50,50
43 ALFA=0.
   DC 47 J=1,N  
   K=J+N3  
   W=0.  
   DC 46 L=1,N  
   KL=N+L  
   W=W+H(KL)*H(K)  
   IF(L-J)44,45,45
44 K=K+N-L  
   GO TO 46  
45 K=K+1  
46 CONTINUE  
   K=N+J  
   ALFA=ALFA+W*H(K)  
47 H(J)=W  
   IF(Z*ALFA)48,1,48  
48 K=N31  
   DO 49 L=1,N  
   KL=N2+L  
   DO 49 J=L,N  
   NJ=N2+J  
   H(K)=H(K)+H(KL)*H(NJ)/Z-H(L)*H(J)/ALFA  
49 K=K+1  
   GO TO 5  
50 IER=1  
   RETURN  
51 DO 52 J=1,N  
52 X(J)=H(K)  
   CALL FUNCT(N,X,F,G,KP)  
   IF(GNRM-EPS)55,55,53  
53 IF(IER)56,54,54  
54 IER=-1  
   GO TO 1  
55 IER=0  
56 RETURN
END
SUBROUTINE, FUNCT, MUST BE CHANGED BY DIFFERENT OBJECTIVE FUNCTION.
PRESENT *FUNCT* WAS MADE FOR LMFBR CORE MODULE OPTIMIZATION.

SLBRUTE FUNCTION(N,X,F,G,L)
DIMENSION Y(8),X(1),G(1)
REAL L
Y(1)=X(1)-0.7
Y(2)=0.5-X(1)
Y(3)=X(2)-0.3
Y(4)=0.1-X(2)
Y(5)=X(3)-0.6
Y(6)=0.4-X(3)
Y(7)=X(4)-0.4
Y(8)=0.2-X(4)
F=-(0.06496*X(1)**2+0.02455*X(1)+0.8510
1 *(-0.1050*X(2)**2+0.04650*X(2)+0.8768)/0.88193
2 +{0.34000*X(3)**2-0.38900*X(3)+0.9914
3 *(0.11060*X(4)**2+0.0007377*X(4)+0.8717)/0.88193
4 -0.88193
DO 1 I=1,8
IF(Y(I).LT.0.) Y(I)=0.
1 F=F+L*Y(I)*Y(I)
G(1)=-(C.08992*X(1)+0.02455)
1 *(0.1050*X(2)**2+0.04650*X(2)+0.8768)/0.88193
2 +L*2.0*(Y(1)-Y(2))
G(2)=-(C.0496*X(1)**2+0.02455*X(1)+0.8510)
1 *(0.21000*X(2)+0.0465)/0.88193
2 +L*2.0*(Y(3)-Y(4))
G(3)=-(C.68000*X(3)+0.38900)
1 *(0.11060*X(4)**2+0.0007377*X(4)+0.8717)/0.88193
2 +L*2.0*(Y(5)-Y(6))
G(4)=-(C.34000*X(3)**2-0.38900*X(3)+0.9914)
1 *(C.22120*X(4)+0.0007377)/0.88193
2 +L*2.0*(Y(7)-Y(8))
RETURN
END
B. Output of Geometrical Optimization
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<td>Test Value Representing Expected Value</td>
<td>1.0000E-04</td>
</tr>
<tr>
<td>CONV</td>
<td>Conversion Value for Outer Iteration</td>
<td>1.0000E-04</td>
</tr>
<tr>
<td>KINP</td>
<td>Initial Value for Penalty Function</td>
<td>5.0000E 02</td>
</tr>
<tr>
<td>Iteration Number</td>
<td>K-Value</td>
<td>X1</td>
</tr>
<tr>
<td>------------------</td>
<td>---------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>0.7000E00</td>
<td>0.2214E00</td>
</tr>
<tr>
<td>2</td>
<td>0.7000E00</td>
<td>0.2214E00</td>
</tr>
<tr>
<td>3</td>
<td>0.7000E00</td>
<td>0.2214E00</td>
</tr>
<tr>
<td>4</td>
<td>0.7000E00</td>
<td>0.2214E00</td>
</tr>
</tbody>
</table>

**Core Usage**
- Object Code: 10600 Bytes
- Array Area: 192 Bytes
- Total Area Available: 38912 Bytes

**Diagnostics**
- Number of Errors: 0
- Number of Warnings: 0
- Number of Extensions: 0

**Compile Time:** 0.64 Sec.
**Execution Time:** 1.79 Sec.

*Note: This document appears to be a report or output from a computer program, detailing results of iterative calculations or simulations.**
XIII. APPENDIX D: LIST OF GENERAL DATA
Table A-II. Various combinations of geometrical parameters for core-blanket system designs

<table>
<thead>
<tr>
<th>Design No.</th>
<th>$l_1$(cm)</th>
<th>$l_2$(cm)</th>
<th>$l_3$(cm)</th>
<th>$l_4$(cm)</th>
<th>$\theta^a$</th>
<th>H(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>20</td>
<td>50</td>
<td>30</td>
<td>0.075</td>
<td>100</td>
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<tr>
<td>2</td>
<td>50</td>
<td>20</td>
<td>50</td>
<td>30</td>
<td>0.075</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>20</td>
<td>50</td>
<td>30</td>
<td>0.075</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>20</td>
<td>40</td>
<td>30</td>
<td>0.075</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>20</td>
<td>60</td>
<td>30</td>
<td>0.075</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>10</td>
<td>50</td>
<td>30</td>
<td>0.075</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>60</td>
<td>30</td>
<td>50</td>
<td>30</td>
<td>0.075</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>60</td>
<td>20</td>
<td>50</td>
<td>30</td>
<td>0.050</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>20</td>
<td>50</td>
<td>30</td>
<td>0.100</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>20</td>
<td>50</td>
<td>30</td>
<td>0.100</td>
<td>100</td>
</tr>
<tr>
<td>11</td>
<td>70</td>
<td>20</td>
<td>50</td>
<td>30</td>
<td>0.100</td>
<td>100</td>
</tr>
<tr>
<td>12</td>
<td>60</td>
<td>20</td>
<td>40</td>
<td>30</td>
<td>0.100</td>
<td>100</td>
</tr>
<tr>
<td>13</td>
<td>60</td>
<td>20</td>
<td>60</td>
<td>30</td>
<td>0.100</td>
<td>100</td>
</tr>
<tr>
<td>14</td>
<td>60</td>
<td>10</td>
<td>50</td>
<td>30</td>
<td>0.100</td>
<td>100</td>
</tr>
<tr>
<td>15</td>
<td>60</td>
<td>30</td>
<td>50</td>
<td>30</td>
<td>0.100</td>
<td>100</td>
</tr>
<tr>
<td>Optimized</td>
<td>70</td>
<td>22.1</td>
<td>40</td>
<td>30</td>
<td>0.100</td>
<td>100</td>
</tr>
</tbody>
</table>

$^a$Angle of the separating blanket in unit of arbitrary one, i.e., 360°=1.000.
Table A-III. Complete output data for breeding ratio

<table>
<thead>
<tr>
<th>Design No.</th>
<th>Inner Core</th>
<th>Outer Core</th>
<th>Inner blanket</th>
<th>Outer blanket</th>
<th>Separating blanket</th>
<th>Entire region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.26068</td>
<td>0.31439</td>
<td>0.14249</td>
<td>0.09738</td>
<td>0.06700</td>
<td>0.88193</td>
</tr>
<tr>
<td>2</td>
<td>0.17973</td>
<td>0.36350</td>
<td>0.14253</td>
<td>0.11611</td>
<td>0.08264</td>
<td>0.87450</td>
</tr>
<tr>
<td>3</td>
<td>0.36069</td>
<td>0.26227</td>
<td>0.13815</td>
<td>0.07627</td>
<td>0.05282</td>
<td>0.89020</td>
</tr>
<tr>
<td>4</td>
<td>0.40051</td>
<td>0.19443</td>
<td>0.16906</td>
<td>0.07550</td>
<td>0.05171</td>
<td>0.89121</td>
</tr>
<tr>
<td>5</td>
<td>0.17730</td>
<td>0.40792</td>
<td>0.11728</td>
<td>0.10098</td>
<td>0.07688</td>
<td>0.88036</td>
</tr>
<tr>
<td>6</td>
<td>0.29961</td>
<td>0.31479</td>
<td>0.09084</td>
<td>0.09301</td>
<td>0.08214</td>
<td>0.88039</td>
</tr>
<tr>
<td>7</td>
<td>0.22040</td>
<td>0.32928</td>
<td>0.16986</td>
<td>0.10426</td>
<td>0.05749</td>
<td>0.88129</td>
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<tr>
<td>8</td>
<td>0.22620</td>
<td>0.35355</td>
<td>0.13823</td>
<td>0.10610</td>
<td>0.05218</td>
<td>0.87627</td>
</tr>
<tr>
<td>9</td>
<td>0.31418</td>
<td>0.26279</td>
<td>0.14918</td>
<td>0.08360</td>
<td>0.0800</td>
<td>0.88974</td>
</tr>
<tr>
<td>10</td>
<td>0.20934</td>
<td>0.31259</td>
<td>0.14912</td>
<td>0.10768</td>
<td>0.10190</td>
<td>0.88063</td>
</tr>
<tr>
<td>11</td>
<td>0.41847</td>
<td>0.21238</td>
<td>0.14151</td>
<td>0.06275</td>
<td>0.06220</td>
<td>0.89732</td>
</tr>
<tr>
<td>12</td>
<td>0.44024</td>
<td>0.15937</td>
<td>0.17199</td>
<td>0.06377</td>
<td>0.06260</td>
<td>0.89797</td>
</tr>
<tr>
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<td>0.36873</td>
<td>0.12139</td>
<td>0.09526</td>
<td>0.09472</td>
<td>0.88477</td>
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<tr>
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<td>0.27072</td>
<td>0.09360</td>
<td>0.08303</td>
<td>0.10191</td>
<td>0.88678</td>
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<tr>
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<td>0.27925</td>
<td>0.17825</td>
<td>0.09112</td>
<td>0.06735</td>
<td>0.88865</td>
</tr>
<tr>
<td>Pancake</td>
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<td>0.39983</td>
<td>-</td>
<td>0.12681</td>
<td>-</td>
<td>0.85573</td>
</tr>
<tr>
<td>4-module</td>
<td>0.34106</td>
<td>0.32142</td>
<td>0.01887</td>
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<td>0.11414</td>
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<tr>
<td>Optimized</td>
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<td>0.12420</td>
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<td>0.04667</td>
<td>0.04562</td>
<td>0.90436</td>
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</table>
### Table A-IV. Critical fuel load in the seed region

<table>
<thead>
<tr>
<th>Design No.</th>
<th>Inner Core Region</th>
<th>Outer Core Region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^2$U$^{238}$ (kg)</td>
<td>$^{239}$Pu (kg)</td>
</tr>
<tr>
<td>1</td>
<td>4424</td>
<td>721</td>
</tr>
<tr>
<td>2</td>
<td>3051</td>
<td>521</td>
</tr>
<tr>
<td>3</td>
<td>6056</td>
<td>946</td>
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<tr>
<td>4</td>
<td>4400</td>
<td>744</td>
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<tr>
<td>5</td>
<td>4464</td>
<td>679</td>
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<tr>
<td>6</td>
<td>4456</td>
<td>686</td>
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<tr>
<td>7</td>
<td>4404</td>
<td>740</td>
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<tr>
<td>8</td>
<td>4440</td>
<td>704</td>
</tr>
<tr>
<td>9</td>
<td>4408</td>
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