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THE FAST MIXED SPECTRUM REACTOR CONCEPT*

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INTRODUCTION

The Fast-Mixed Spectrum Reactor (FMSR) is a new concept in fast reactors for the production of electric power. The design and its limitations, possibilities, and effects of uncertainties are presently being explored in a feasibility study. Analysis so far bears out the validity and feasibility of the concept, though there are still significant design and operating problems requiring solution.

The concept has been tailored to offer excellent non-proliferation characteristics, and at the same time to achieve good utilization of uranium resources. Though in important operating characteristics the FMSR would be a substantial departure from conventional fast breeder designs, it is closely related to breeders in fundamental technology. As a result, only extensions of current fast breeder R&D programs, rather than new R&D programs, would be needed to establish feasibility and prepare for demonstration of the reactor. The cost of electric power produced using FMSR should be about equivalent to that from comparable fast breeder reactors. Fuel cycle costs of an FMSR should be less than those of a fast breeder.

FMSR has several features which differentiate it from fast breeders. It would operate on a once-through-and-store fuel cycle, with no fuel reprocessing being required. After the first core, and in equilibrium operation, the new fuel charged at reload time would consist only of natural or depleted uranium, with no added fissile values. The plutonium burned in the reactor would be produced in situ by neutron capture, as the result of a high breeding ratio or conversion ratio. Fuel would remain in the reactor a very long time (about 17 years according to current design studies), and the burnup of heavy metal that would be achieved in this period is substantial (about 13-15%). The combination of refueling with natural or depleted uranium and the high burnup would make the FMSR substantially more efficient in uranium utilization than a once-through light water reactor (measured in terms of energy per unit mass of natural uranium).

The reactor could be started up on medium enriched uranium, at an average enrichment of about 7% and a maximum enrichment of about 11%. These are well below guideline values commonly used to measure concern over proliferation. The combination of the low initial enrichment of fuel and the lack of need for chemical reprocessing, at least for many decades, make FMSR a very attractive concept for longer term reduction of the possibility that the commercial fuel cycle might be used as a springboard for proliferation of nuclear weapons. It would also reduce concern over possible subnational threats, because only the spent fuel would contain weapons-usable material, and the high fission product inventory would cause this spent fuel to be unattractive for long times.

FMSR would depend only on technology developed for the fast breeder program. In most respects this is main line LMFBR or GCFR technology, though in some important respects the technology chosen is the more advanced FBR technology. The non-nuclear parts of the plant could be identical to those of the corresponding fast breeder, though a gas-cooled version of FMSR would more closely resemble European designs of a GCFR.

As stated previously, the FMSR has been tailored to operation on the once-through fuel cycle. Nevertheless, the discharged fuel would contain substantial amounts of plutonium - about 600 kg each year for a 1000 MW(e) plant. This plutonium would be produced over and above any need for continuation of the FMSR fuel cycle. It would therefore be available for use in burner reactors in a symbiotic fuel cycle if this were desired.

PRINCIPAL DESIGN FEATURES

To achieve the characteristics discussed above requires high breeding gain and good neutron economy. To make these possible, the FMSR concept uses metal fuel. This one feature almost doubles the number of fertile atoms per unit volume of the core, significantly increases the fast fission contribution of U-238 and Pu-240, reduces the capture-to-fission ratio of fissile isotopes, and because of the relatively hard neutron spectrum, leads to reduced reactivity loss from fission products.

Fuel design is being developed in cooperation with Argonne National Laboratory. The design duplicates as closely as possible the performance features of the highly successful Mark II Metal Driver Fuel, which has been operated in EBR-II to a heavy metal burnup greater than 13%.

The physics analysis implies that designs would be acceptable with either sodium or helium as the coolant. For engineering reasons, we have somewhat higher confidence in the design based on helium cooling.

The reactor can be made to operate with any of several fuel shuffling strategies. In each case, however, it appears highly desirable to surround the central hard spectrum region of the core by a zone containing some moderator. This moderator consists of graphite or beryllium. The role of the moderator differs somewhat in different fuel shuffling strategies, but it is used in general for power flattening and for reactivity management. Its presence provides some boost in reactivity, and it can be used to reduce the reactivity swing during intervals between fuel shuffling. It must be remembered that this swing for FMSR consists of a gain in reactivity, because of the large breeding ratio.

The FMSR is compatible in design with the corresponding fast breeder in most respects. The one significant departure affecting the non-nuclear part of the plant is the current choice of high pressure (about 140 bars) for the gas-cooled version. This corresponds more closely to European designs of GCFR's, rather than American designs. The reason for this tentative choice is the desire to reduce pumping power, which tends to be high because of the denseness of fuel packing.

Figure 1 is a diagram of the core. Each hexagon represents a subassembly containing fuel or moderator. The diagram should be considered as generic rather than a picture of a specific design layout. In the several loading and shuffling strategies that have been explored, the same general features have been used. The hexagonal subassemblies contain fuel, moderator, or steel. The non-shaded hexagons contain steel, serving as thermal shield. The hexagons with dots in the center contain moderator. Hexagons marked "F" are locations of fine control rods, while those marked "S" are locations of shutdown rods. All other hexagons represent fuel-bearing subassemblies. Those marked with a "1" are in the moderated zone; those marked with a "2" are in the hard spectrum region, and those marked "3" are in a transition region where spectrum softening by the presence of surrounding moderator is apparent.

Subassemblies would have the cross-sectional appearance shown in Figure 2. Fueled subassemblies would contain nominally 271 fuel pins in a hexagonal array within the hexagonal duct walls that confine the coolant flow. The approximate distance between flats of the duct wall is approximately 20 cm. The moderator-filled subassemblies would be identical in the external dimensions.

NEUTRON PHYSICS CALCULATIONS

Most of the reactor physics and fuel cycle calculations performed so far have been done using the 2DB computer code, with the (r,z) geometry option. Most calculations have used a 50-group neutron cross-section set which was generated from the ENDF-B-IV set. The LIB-IV library of LASL was used along with the IDB code to account for the effects of regional differences in spectrum and isotopic concentrations. The validity of the cross-section set, and of use of diffusion theory in the analysis, were checked in a calculation of the criticality and fission distribution of an old Argonne critical experiment, where a coupled fast-thermal reactor concept was studied. Agreement with measured results in that case was excellent.

Sensitivity studies are underway to provide further checks on the diffusion theory results, to test dependence of results on the cross-sections, and to explore other details of the calculations. In addition, the question of power peaking in the transition zone is being explored more carefully using transport methods.

Figure 3 shows typical flux spectra calculated for the fast and the moderated zones. These are curves of flux integrated over the two regions of the reactor, and are thus spectral distributions of total flux. The distribution in the fast zone is extremely hard. As a result, about 25% of the fission rate in the fast region is the result of direct burning of U-238. Pu-240 also becomes a moderately useful fuel in this spectrum.

The flux in the moderated region is degraded in energy, but is far from well-moderated. There are few neutrons below 100ev. A spectrum of this kind would be termed "intermediate"; it even resembles the spectra in some oxide-fueled breeder designs.

METALLIC FUEL

Metallic uranium fuel was used in the first American fast breeder cores: EBR-I, EBR-II, Fermi-I. The decision to use uranium oxide and uranium-plutonium oxides was made because of severe dimensional changes in metallic fuel carried to above about 1% burnup of the heavy element. In the intervening years, Argonne has continued study of metallic fuel because of its desirability as driver fuel in EBR-II, and has developed a metallic fuel which has repeatedly undergone successful exposure to >10% heavy atom burnup in EBR-II, though still with large volume increase. This is the so-called Mark II fuel.

A Mark II fuel pin consists of a thin rod of metallic fuel, in an oversized tube of steel cladding, with the space between filled with sodium. As burnup proceeds in the reactor, the metal fuel swells because of retained fission products, principally fission gases. At higher exposures, retention of the fission gas in the fuel decreases. The fuel swells radially until it fills the volume formerly occupied by the sodium, which is squeezed out. Growth then continues axially, with the fuel becoming more spongy as a greater volume is occupied by gas bubbles.

Because of the successful history of Argonne's Mark II fuel, this is the choice as reference fuel for the sodium-cooled version of FMSR. It will probably be necessary to develop methods of limiting or preventing the axial growth of the metallic fuel at higher fuel exposure, because this will lead to reactivity loss.

It is preferable, however, to avoid use of sodium as bonding agent in the helium-cooled version of FMSR; sodium liberated by fuel failure could have undesirable effects on the primary system. We have, therefore, proposed, with Argonne's concurrence, that the reference fuel in this case consist of a vibratory compacted uranium metal powder, at a smear density of about 75% of theoretical. This would have built into it at the outset the space needed for the interconnected porosity that develops under neutron irradiation of solid metal fuel. Extensive development and testing of this fuel are required, but there is high expectation that this fuel should perform in the same general way as Argonne's Mark II fuel.

CLADDING AND DUCT WALLS

The fuel cladding and duct walls would be exposed to very high fluences in the fourteen years of fuel residence time in the reactor. Fluences of about $8x10^{23}$ neutrons >0.1MeV would be typical. The Type 316 cold worked steel currently proposed for fast reactor use would not withstand such high radiation exposure without undergoing significant dimensional changes and loss of strength.

Argonne and HEDL have suggested the possible use of some relatively new steel alloys for these applications. These are alloys which were developed under the LMFBR program, to withstand high values of fluence. Two of these alloys are low-nickel ferritic steels, (D-57, HT-9), and two are austenitic steels containing about 35% nickel by weight.

Argonne has suggested that if a high nickel alloy is used for cladding, it would be advisable to have a thin diffusion barrier between the cladding and the fuel. This would prevent diffusion of the nickel into the uranium. A barrier of a few mils of vanadium or titanium has been suggested.

The choice of materials for use as fuel cladding and duct walls is clearly crucial to the reactor concept. Materials development and radiation performance studies are necessary components of the development program. One question of special importance is pressure driven creep of duct walls. This will in time drive duct walls into contact with each other. It is necessary to ensure that this phenomenon will not lead to interference between subassemblies during reloading operations. The present view of Argonne staff, based on EBR-II experience, is that contact develops during operation, but thermal contraction with cooling loosens up the structure sufficiently to prevent the interference.

SOME FEATURES OF THE GAS-COOLED VERSION

Most of the analysis so far has been devoted to the helium-cooled version of FMSR. An attempt has been made to retain design parameters that do not depart too much from those of the GCFR, so as to ensure engineering reality. This is illustrated in Table 1, which shows a comparison of some of the principal design parameters with those of the General Atomics design of a demonstration plant, in GA-130450.

One principal difference is the choice of metallic fuel, the basis for which has already been discussed. The use of metallic fuel, with its relatively high heat conductivity, permits use of a larger diameter fuel pin. The reference fuel design for FMSR is vented, as is that for GA's GCFR. Core volume fractions of constituents depart somewhat from GA's choices, as FMSR's fuel content is denser. But the gas space assigned to coolant flow is approximately the same in the two cases.

The core height for FMSR is 1.6 meters, compared to the 1.0 meter height of the core of the GCFR demonstration plant. However, the GCFR Demo is designed to produce only 300 MW(e); commercial designs of GCFR's have a core height of 1.5 meters, which is closer to the FMSR value.

A second important difference exists between the FMSR reference design and that of GA's GCFR's. For reasons of reducing pumping power, the gas pressure of FMSR is selected as 140 bars. GA designs are based on gas pressure of about 100 bars. The FMSR choice is essentially that made for some European designs of GCFR. We have made this choice following discussions with and advice from members of the GA reactor analysis staff.

FUEL SHUFFLING STRATEGIES

Several strategies for fuel shuffling have been explored. In one of these, fresh fuel as natural or depleted uranium is inserted first into locations near the center of the hard spectrum zone. Here it displaces fuel which in turn is moved to a next position radially further out. In turn, fuel from that position is moved to a next position farther out, etc. Thus fuel moves in successive shuffling steps from the center of the fast spectrum region to the transition zone, into the moderated region, and outward there until it is discharged. Calculations indicate that this strategy would satisfy neutronic requirements of breeding and criticality in the steady state mode of operation, but it would have the disadvantage that the variation in plutonium content and therefore power generation would be high for fuel in its initial location at the center of the fast spectrum zone. The radial power peaking factor in this strategy would also be high.

A second strategy resembles that developed at Argonne by Avery, in his studies of coupled fast-thermal reactor cores a number of years ago. The fresh fuel would be placed first in the transition zone at the outside of the fast spectrum region. Its low initial plutonium content would offset the tendency toward power peaking in this location. After some period of residence the fuel would then be moved to the central zone of the fast region. From this point on it would be moved in succession through the second and third radial zones of the fast spectrum region, would skip over the transition zone, and would move outward through the two radial zones of the moderated region. This version of the reactor would also satisfy the neutron physics requirements.

The plutonium buildup is shown in Figure 4, where plutonium concentration is plotted vertically and time from first introduction into the core is plotted horizontally, for each of the six successive fuel residence periods of this strategy. The value of plutonium concentration in each case is that at the end of the indicated period of residence, just before moving to the next. There is a small tendency for plutonium burnup to occur in the outermost region of the reactor.

Corresponding power densities are shown in Figure 5. The power generated in the moderated region is about a third of the total. The moderated region contributes importantly to reactivity.

A third strategy is based on loading fresh fuel first into the outermost ring of the moderated region. After some period of residence, it is moved to the inner ring of the moderated region. In these locations, the plutonium content is low, so the contributions to total power and reactivity are relatively low. The objective is to reduce neutron leakage and to provide an initial plutonium buildup before fuel is moved into the fast spectrum region.

The subsequent history of fuel in the fast spectrum region is seen best from Figure 6, which shows plutonium concentration in each of 20 subzones. Fuel brought in from the moderated zone is first loaded into one of the subzones marked "1". After a residence there of two fuel shuffling cycles, its plutonium content has grown from an initial value of about 3% to a value of about 4%. It is then moved to one of the subzones marked "2". After a residence time of four shuffling cycles, the plutonium content has grown to about 6%. Fuel is then moved to one of the subzones marked "3". A further growth to an average plutonium content of about 7% occurs during a residence period of six shuffling cycles in these subzones. Fuel is then shifted to a subzone marked "4". Growth in plutonium concentration is not large in these subzones, even though the residence period is eight shuffling cycles, because the plutonium is essentially at its equilibrium concentration by this time.

The corresponding power distribution is shown in Figure 7. The fraction of power generated in the moderated region is not high, and only generation in the fast spectrum region is shown.

FURTHER FEATURES OF THE GAS-COOLED VERSION OF FMSR

Table 2 lists further features of the gas-cooled FMSR. The tentative design following the third of the fuel shuffling strategies discussed above has 408 fueled subassemblies, in 34 subzones of 12 subassemblies each. The subzones are grouped into six zones, the number of subzones differing from zone to zone. Zones 1 and 2 are located in the moderated region, and the remainder are located in the fast spectrum region. At each shutdown for fuel movement, the 12 subassemblies in one subzone of zone 6 are removed for cooling and storage, 12 subassemblies from one subzone of each zone are moved to the just-vacated subzone locations of the next higher numbered zone, and 12 new subassemblies of natural or depleted uranium are moved into the just vacated subzone of Zone 1. Each fuel subassembly would be shifted in location six times in the course of its 17-year residence in the reactor.

The reactivity would increase during a cycle by 2.1%, as a consequence of the increase in fissile material concentration everywhere in the reactor. This increase would have to be compensated for by withdrawal of fueled control rods.

The breeding ratios of the six zones are shown in the table at some time during the cycle. In Zone 1, where little plutonium has been built in, the fission density is low, and plutonium production is mostly due to capture of leakage neutrons. Therefore, the local conversion ratio is very high. In Zone 6, the plutonium concentration approaches its equilibrium value, and the ratio is near unity.

The overall breeding ratio is 1.65. This unusually high value is the result of use of metallic fuel.

Table 3 lists information on the composition of fuel in the gas-cooled FMSR. The core at equilibrium contains 5.38 tonnes of plutonium in 126 tonnes of fuel. The 24 subassemblies discharged each year contain 0.62 tonnes of plutonium in 8.3 tonnes of fuel. Therefore, the discharged fuel has a plutonium concentration of 7.4% on the average. The discharged plutonium has a lower Pu-240 content than is characteristic of spent fuel from a light water reactor. This results from the direct burning of Pu-240 in the hard reactor spectrum. The peak fluence at the burnup contemplated is calculated to be 8×10^{23} (neutrons >0.1MeV).

Initial startup of the reactor has been explored only tentatively. Startup could, of course, be made using plutonium from such a source as spent fuel from LWR's. We have not considered this option, and have instead analyzed some aspects of startup on medium-enriched uranium (MEU). Table 4 lists information pertinent to startup on medium enriched uranium with enrichment distributed throughout the fuel in the same profile as that of plutonium in the equilibrium core. It is recognized that this would pose an unrealistic manufacturing problem, but the case was calculated as interesting. In this strategy of initial loading, the average enrichment of fuel would be 6.7% U-235. The maximum enrichment would be about 11%.

THE SODIUM-COOLED VERSION

Tables 5 and 6 show corresponding characteristics of the sodium-cooled version of FMSR. It is apparent that the features affecting breeding ratio and plutonium production are very similar.

A conscious decision was made to assume fuel volume fractions higher and coolant volume fractions lower than those common for the current designs of LMFBR's. It is generally agreed that these choices for present LMFBR designs are conservative, and as confidence is built up through successful operation, coolant passages will be reduced in area in order to increase breeding gain. We have assumed from the outset that the tighter packing of fuel is possible, because the high breeding gain is necessary to the FMSR concept. Preliminary thermal-hydraulic analysis supports the choice we have made.

ADVANTAGES OF FMSR

We summarize the principal advantages of the FMSR concept.

No fuel reprocessing facility would be needed for the FMSR fuel cycle. Of course, fuel could be reprocessed, if desired, but FMSR operation does not require the use of plutonium in feed fuel.

No enrichment capacity would be needed for the fuel cycle, apart from that to supply the MEU for the startup core and perhaps fissile material for control elements.

As a result of these features, production of electricity could take place without accompanying fuel cycle facilities that are widely regarded as increasing the ease of proliferation of nuclear weapons, or of subnational diversion of fissile material.

The FMSR would be much more efficient in use of uranium resources than are LWR's. In the LWR fuel cycle, only about 15% of the uranium mined is used in reactors; the remainder ends up as tails at an isotope separation plant. The FMSR would use all uranium, because no enrichment is needed. It would even burn the tails from the LWR fuel cycle, after the fashion of a true breeder. The high burnup, combined with the use of natural uranium, would lead to a factor substantially greater than that of the LWR. If stored fuels were eventually reprocessed, fuel efficiency would be essentially that of the FBR.

The reliance on FBR technology should lead to plant capital costs essentially the same as for FBR's, but the FMSR should have lower fuel cycle costs. The use of natural or depleted uranium feed would permit fuel to be made using hands-on methods, with no criticality control restraints. Fuel inventory costs after the first core would be low. Reprocessing would not be required and the corresponding costs would be avoided.

The concept depends almost entirely on FBR technology. This is completely true for balance of plant. Some technology for the nuclear parts of the plant are not main-line FBR technology, but they are advanced developments of the FBR program. Therefore, the concept does not require opening up new areas of investigation of no interest to FBR development generally. Rather, it requires projecting FBR studies into areas where higher performance is needed.

DISADVANTAGES OF THE FMSR CONCEPT

The concept requires very long fuel residence times and subjects fuel components to high fluence. The effects of this mode of operation require materials to behave satisfactorily under conditions not yet explored experimentally. Though materials with the desired properties are believed to be known, a substantial period of development and testing is needed. It cannot at present be ruled out that some breakthrough will be required.

The dense packing of fuel in the reactor core that is required to achieve high breeding ratio has an effect on cooling which has not been fully explored. The pumping power of the gas-cooled reactor tends to be high, and studies are underway to improve estimation of pumping power and to reduce it. The implication of the narrow passages for coolant in the sodium-cooled version must be reviewed in light of whatever dimensional changes in cladding may be found to occur.

The half-year fuel shuffling cycle is almost certainly too short. A longer time between fuel shuffling may be used, but the tendency is then for the reactivity swing and the change in power distribution to be larger.

Both the gas-cooled and the sodium-cooled versions have such high burnup that without the use of vented fuel, gas pressure in the fuel pins may become excessive. The concept of vented fuel is not new, but the tendency has been to avoid it if possible. Tests of the effects of fuel venting would be needed, both with gas and sodium environments.

The gas-cooled reactor has a high design pressure, compared to current U.S. designs for GCFR's. This would require developing components for operation under conditions not presently contemplated in the United States.

AREAS REQUIRING INVESTIGATION

As pointed out at the beginning of this paper, FMSR is at present a reactor concept and not a reactor. To produce a reactor will require successful development programs in several areas.

It will be necessary to develop vibratory compacted fuel for the helium-cooled reactor, and to test it to high burnup in EBR-II, FFTF, or both. It will be necessary to develop a means to restrain the tendency for metallic fuel to develop excessive density of gas-filled pores at high burnup. This development is needed both for Mark II fuel and vibratory compacted fuel.

Further study of materials for cladding and duct walls must be undertaken. More extensive irradiation of candidate materials is required.

A program of critical experiments is needed to check the calculations. This may involve experiments in which some fuel has previously been heavily burned in a fast reactor, to test the fission product cross-sections and their impact on criticality and breeding.

Analytical studies are needed in several areas. Further exploration of fuel shuffle strategy is required. Startup strategy remains to be investigated. Development of control methodology is required. Tentative consideration of safety questions must be developed further into full safety review.

A number of engineering analyses are required, the chief of which is a stress analysis of the duct walls of fuel assemblies.

These are the essential components of a development program which is now being structured for consideration by the Department of Energy.

SUMMARY

The Fast Mixed Spectrum Reactor is a highly promising concept for a fast reactor with improved features of proliferation resistance, and excellent utilization of uranium resources. In technology, it can be considered to be a branch of fast breeder development, though its operation and implications are different from those of FBR's in important respects. Successful development programs are required in several areas to bring FMSR to reality. But the payoff from a successful program can be high.

DESIGN PARAMETERS

	EMSR	GA DEMO (GA-130450)
FUEL	METAL	OXIDE
FUEL VENT	GA VENTED DESIGN	GA VENTED DESIGN
FUEL PIN DIAMETER	.916 CM	.74 CM
CORE VOLUME FRACTIONS		
FUEL	.39	.29
STAINLESS STEEL	.16	.19
HELIUM	.45	.52
CORE HEIGHT	1.6 METERS	1.0 METERS (1.5 METERS 1000 MW)

TABLE 1

HELIUM-COOLED FMSR SELECTED REACTOR PARAMETERS

TOTAL NUMBER OF FUEL SUBASSEMBLIES = 408

NUMBER OF FUEL S.A/ZONE SHUFFLED PER CYCLE = 12

CYCLE DURATION = 170 FPD

ΔK DURING CYCLE = 2.1%

ZONAL CONVERSION RATIOS:

ZONE 1 = 5.68
ZONE 2 = 3.15
ZONE 3 = 2.27
ZONE 4 = 1.50
ZONE 5 = 1.19
ZONE 6 = 1.08

OVERALL BREEDING RATIO = 1.65

TABLE 2

HELIUM-COOLED FMSR MATERIAL INVENTORIES

	Pu (TONNES)	HEAVY METAL (TONNES)
CORE INVENTORY: (BOC)	5.38	126.05
DISCHARGE/YR*	0.62	8.3

AVERAGE DISCHARGE ENRICHMENT = 7.4%

DISCHARGE Pu COMPOSITION (%)
(239/240/241/242) : : (82.4/15.3/2.0/0.3)

CORE BURNUP (MWD/T):
AVG. = 133,000
PEAK = 161,570

PEAK FLUENCE (E > 0.1 MeV) = 8.0 x 10^{23})

*80% LOAD FACTOR

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.

TABLE 3

FIRST CORE FUEL NEEDS

ENRICHED U-235 NEEDED	6840 KG
U-235 IN NAT U OF CORE	890 KG
U-235 IN NAT U OF AXIAL BLANKET	275 KG
TOTAL U-235	8005 KG

EQUILIBRIUM CORE COMPOSITION

PU-239	5225 KG
PU-241	110 KG
U-235 (NAT)	565 KG
	5900 KG

TABLE 4

SODIUM-COOLED FMSR SELECTED REACTOR PARAMETERS

TOTAL NUMBER OF FUEL SUBASSEMBLIES = 408

NUMBER OF FUEL S.A/ZONE SHUFFLED PER CYCLE = 12

CYCLE DURATION = 185 FPD

ΔK DURING CYCLE = 2.65%

ZONAL CONVERSION RATIOS:

ZONE 1 = 4.37
ZONE 2 = 3.65
ZONE 3 = 2.82
ZONE 4 = 1.69
ZONE 5 = 1.33
ZONE 6 = 1.16

OVERALL BREEDING RATIO = 1.7

TABLE 5

SODIUM-COOLED FMSR MATERIAL INVENTORIES

	Pu (TONNES)	HEAVY METAL (TONNES)
CORE INVENTORY: (BOC)	6.33	173.70
DISCHARGE/YR*	0.69	10.57

AVERAGE DISCHARGE ENRICHMENT = 6.5%

DISCHARGE Pu COMPOSITION (%)
(239/240/241/242) : : (83.8/14.4/1.6/0.2)

CORE BURNUP (MWD/T):
AVG. = 110,500
PEAK = 163,000

PEAK FLUENCE (E > 0.1 MeV) = 7.98×10^{23}

*80% LOAD FACTOR

TABLE 6

FAST-MIXED SPECTRUM REACTOR CONCEPT

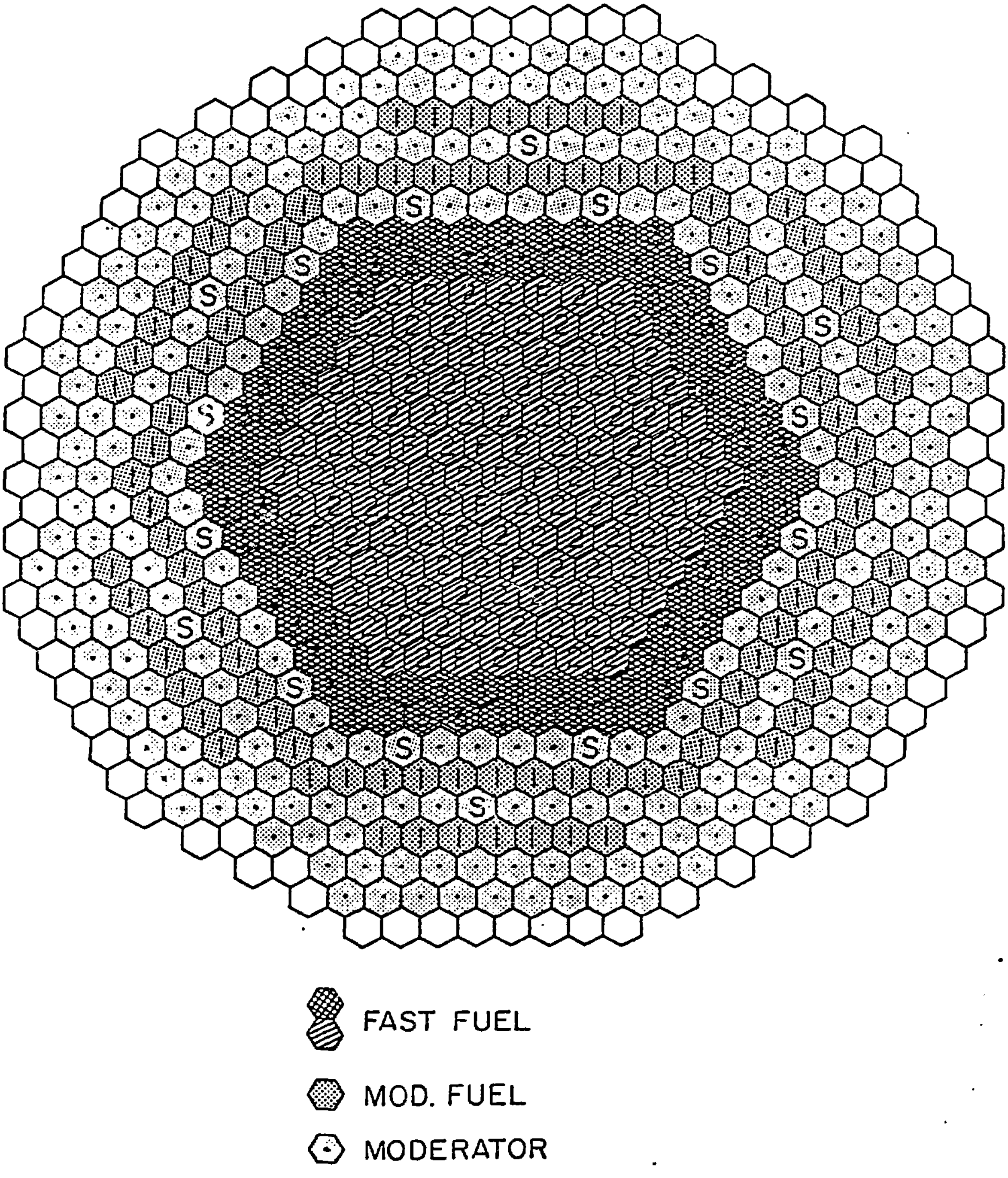


FIGURE 1

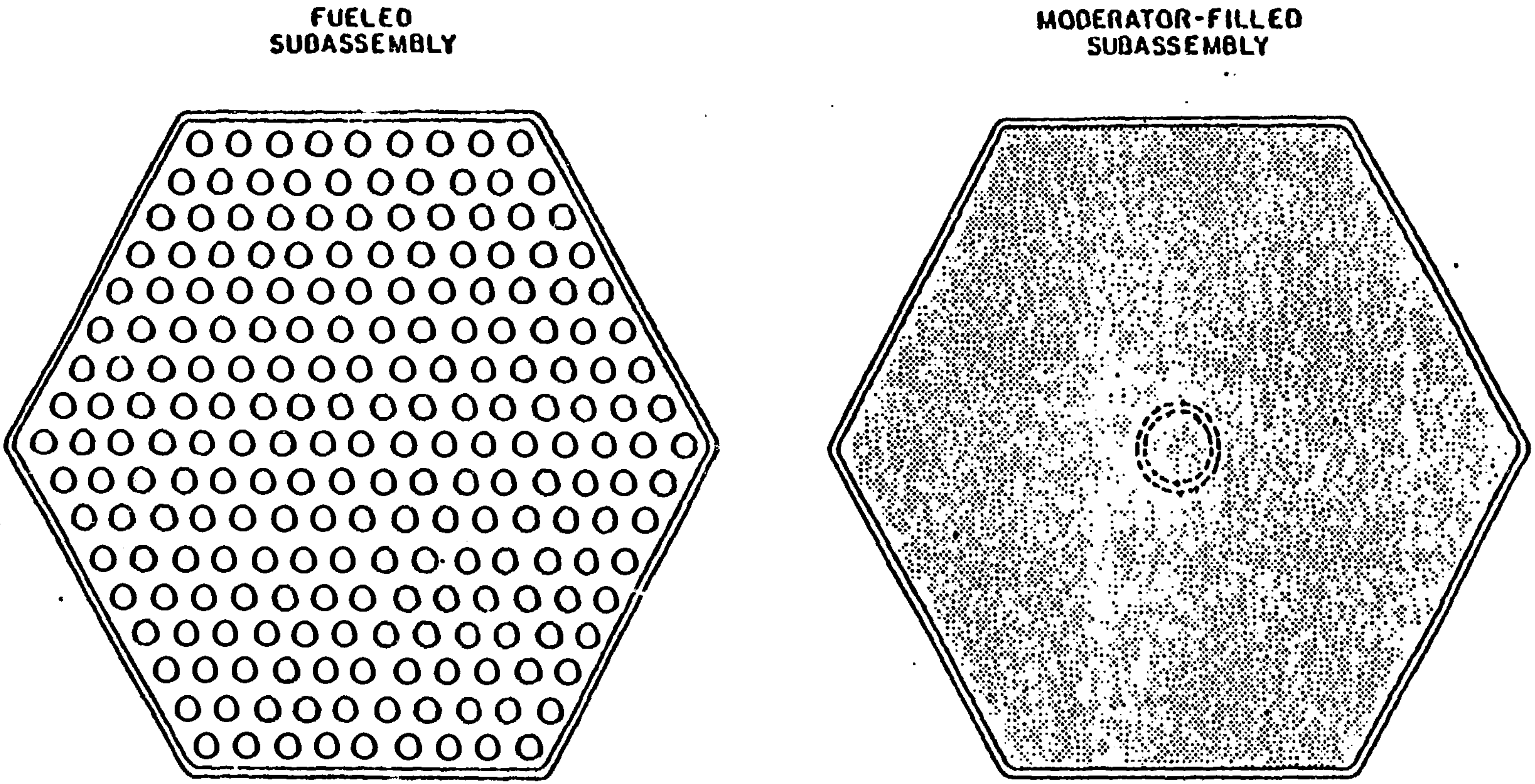
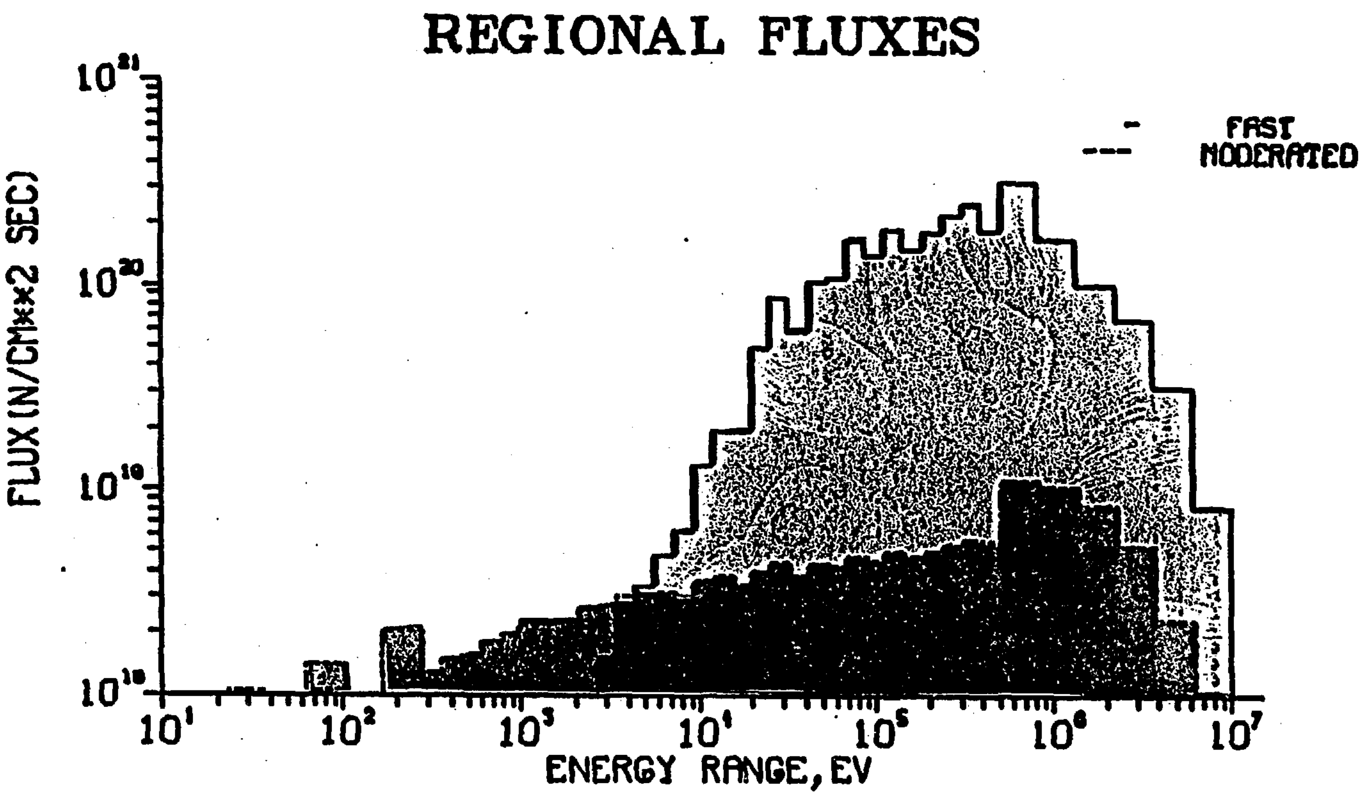


FIGURE 2



REGIONAL FLUXES
FAST
MODERATED
FLUX (N/CM**2 SEC)
ENERGY RANGE, EV

FIGURE 3

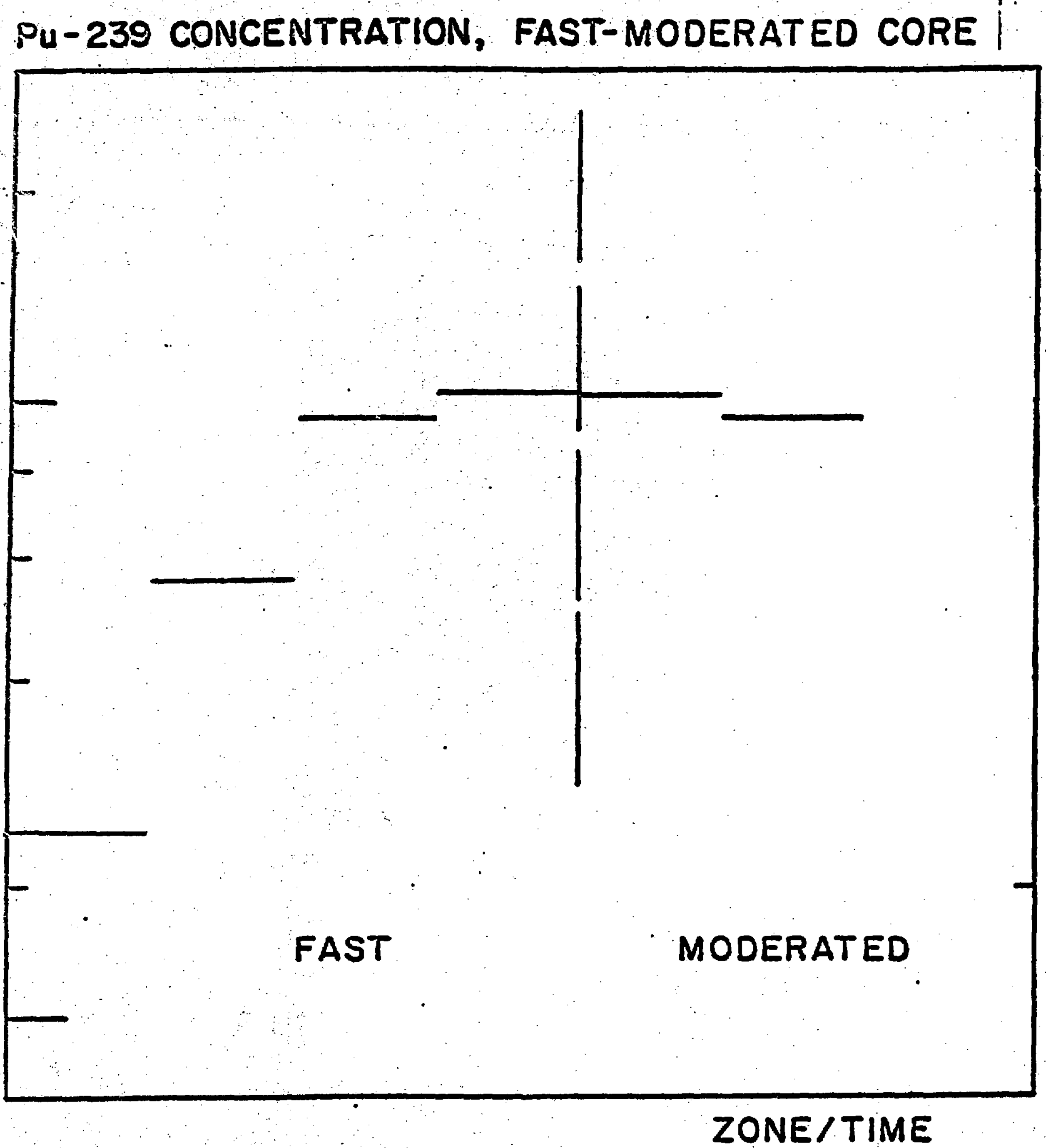

Pu-239 CONCENTRATION, FAST-MODERATED CORE
FAST
MODERATED
ZONE/TIME

FIGURE 4

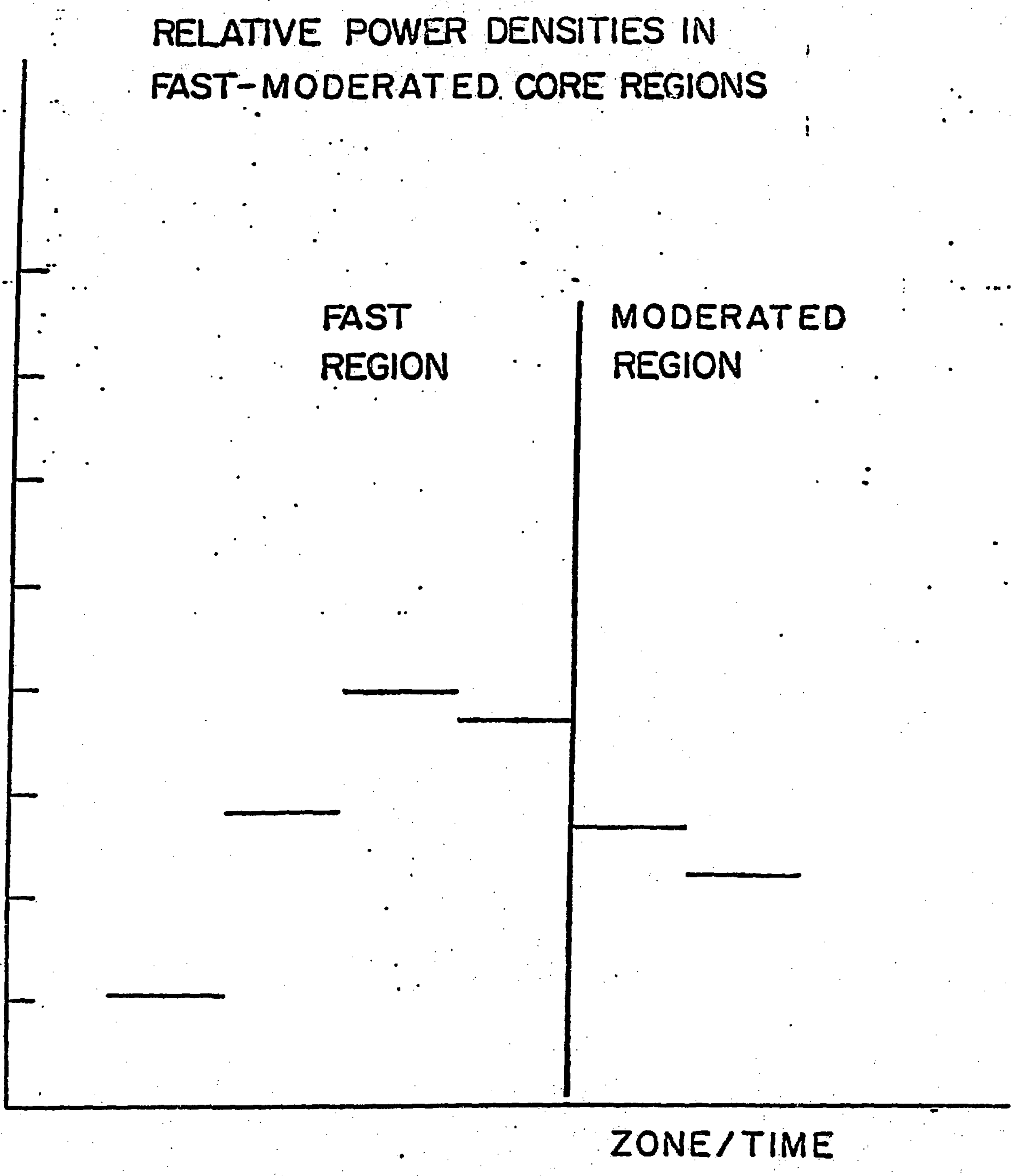

RELATIVE POWER DENSITIES IN
FAST-MODERATED CORE REGIONS
FAST
REGION
MODERATED
REGION
ZONE/TIME

FIGURE 5

PU-239 CONCENTRATION VARIATION
OVER FUEL RESIDENCE IN SUB-ZONES,
HE-COOLED FMSR

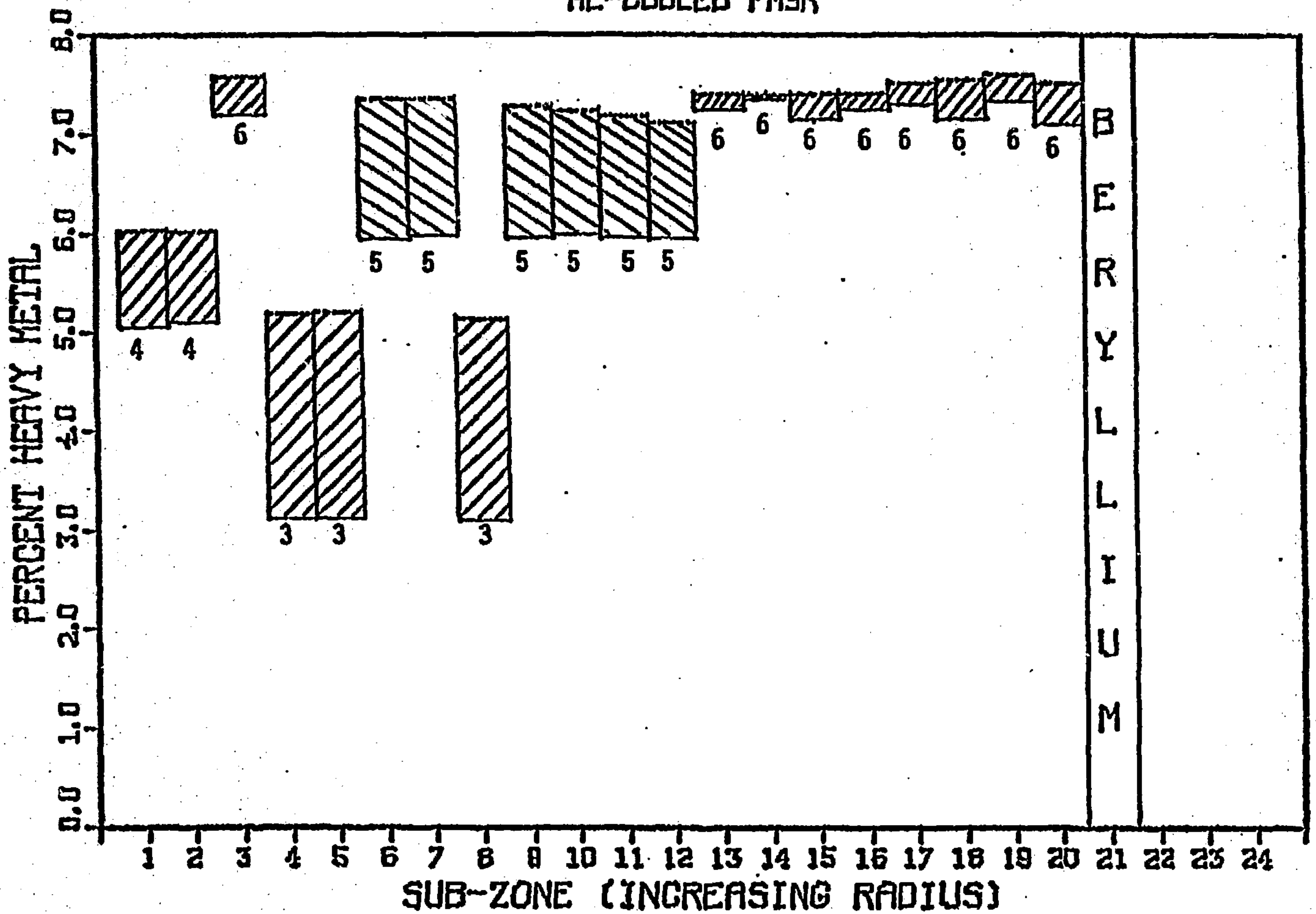
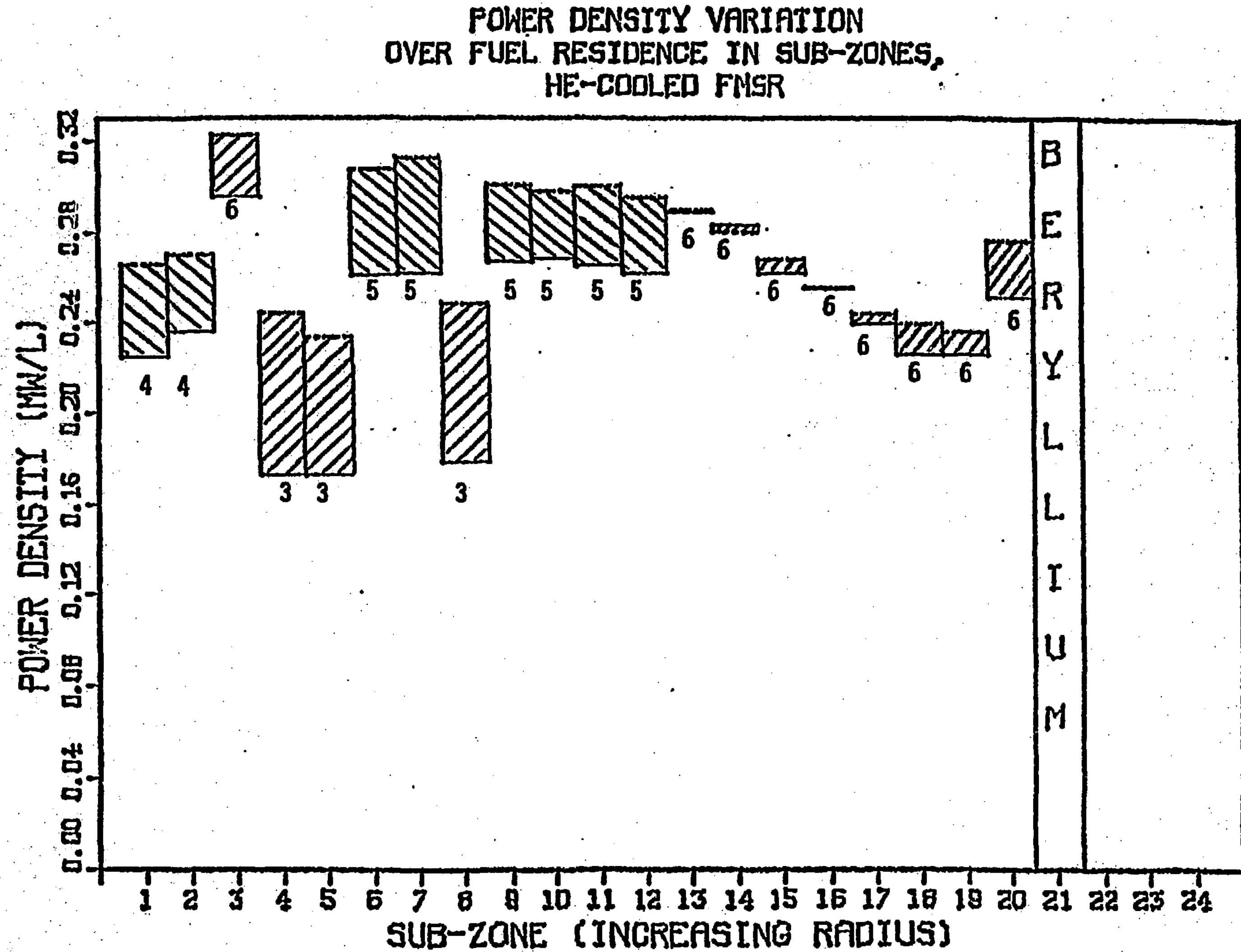


FIGURE 6



POWER DENSITY VARIATION
OVER FUEL RESIDENCE IN SUB-ZONES,
HE-COOLED FNSR
POWER DENSITY (MW/L)
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.32
SUB-ZONE (INCREASING RADIUS)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
4 4 6 3 3 5 5 3 5 5 5 5 6 6 6 6 6 6 6 6
BERYLLIUM

FIGURE 7