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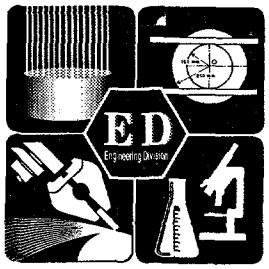

Using the TREAT Reactor in Support of Boron Neutron Capture Therapy (BNCT) Experiments: A Feasibility Analysis

by G.L. Grasseschi and
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USING THE TREAT REACTOR IN SUPPORT OF BORON NEUTRON CAPTURE THERAPY (BNCT) EXPERIMENTS: A FEASIBILITY ANALYSIS

by

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ABSTRACT

The technical feasibility of using the TREAT reactor facility for boron neutron capture therapy (BNCT) research was assessed. Using one-dimensional neutronics calculations, it was shown that the TREAT core neutron spectrum can be filtered to reduce the undesired radiation (contamination) dose per desired neutron more effectively than can the core spectra from two prominent candidate reactors. Using two-dimensional calculations, it was demonstrated that a non-optimized filter replacing the TREAT thermal column can yield a fluence of desired-energy neutrons more than twice as large as the fluence believed to be required and, at the same time, have a contamination dose per desired neutron almost as low as that from any other candidate facility. The time, effort and cost required to adapt TREAT for a mission supporting BNCT research would be modest.

INTRODUCTION

Boron neutron capture therapy (BNCT) is currently a promising treatment for certain malignancies. Attention is focused particularly on glioblastoma multiforme, a type of brain cancer not amenable to surgery since some of the tumor cells are inextricably intertwined among healthy tissue cells. The advantage of BNCT is that it is able to kill individual tumor cells without excessively damaging neighboring healthy tissue. In this procedure, the patient is infused with boron compounds preferentially absorbed by tumor cells, then is exposed to a neutron beam where the (n,α) reaction in the ^{10}B isotope provides an energy deposition of about 2.3 MeV of kinetic energy over a distance comparable to the diameter of a cell.

New developments have revived interest in BNCT in the United States. Interest declined when early BNCT trials conducted around 1960 at Brookhaven National Laboratory (BNL) and the Massachusetts Institute of Technology (MIT) were determined to be unsuccessful. [1] Since then, BNCT has been used with some success in Japan. New boron compounds are being developed that concentrate better in tumor cells. Neutron/gamma filters are being used both to reduce radiation damage to healthy tissue and to obviate the need to expose the tumor site surgically. These developments have led to the resumption of experimental human trials at BNL [2] and at MIT. [3] They have also resulted in proposals from several reactors and accelerators in the United States that they be developed into BNCT experiment or treatment facilities.

The purpose of this report is to present a technical feasibility study on using the Transient Reactor Test Facility (TREAT) reactor for BNCT experiment support. TREAT is an air-cooled, graphite moderated (thermal), transient reactor located at Argonne National Laboratory-West in Idaho. It has served fast reactor development for many years irradiating fast reactor test fuels under simulated normal operations and severe-accident conditions, TREAT has a number of features that appear to make it amenable to a BNCT application, including : 1) potential for a very large neutron fluence, deliverable over any time interval of practical interest, 2) ease and economy of facility modification, and 3) ease and economy of operation.

This feasibility study consists mostly of scoping neutronics analyses. The neutronics question addressed is whether TREAT can be operated to deliver a neutron beam with a high fluence of neutrons in the desired energy epithermal range, with a minimum fluence of neutrons and gamma rays harmful to healthy tissue. The study was conducted by adopting neutron filter designs suggested in the BNCT literature for other reactors; no attempt was made to design an optimum filter for TREAT. The cost and time estimates to modify TREAT are addressed in the concluding section.

NEUTRONICS ANALYSIS

1.1 Performance Criteria

The success of BNCT depends on whether all the tumor cells can be killed without excessive attendant damage to healthy tissue. Accordingly, performance evaluation requires as a minimum, a measure of the tumor-killing dose and a measure of the healthy-tissue damage dose. Simple, conventional performance measures of dose were deemed most appropriate for a feasibility study.

The epithermal flux level (intensity) to which the patient is exposed is the most common simple measure of tumor-destruction ability cited in the BNCT literature. The epithermal energy range is taken to be 0.5 eV to 10 keV, in accordance with the ICRU definition. The basis for this range is that incident neutrons in this energy range are most effective at inducing the ^{10}B (n,α) reaction at a typical tumor depth of 2-3 cm, [4] since they thermalize as they penetrate to this depth. In this study, the epithermal range was taken to be 0.4 eV to 15 keV, as these boundaries are the closest available in the adopted neutron cross section set.

Epithermal intensity is an appropriate quantity for reactors operating at steady state, as virtually all proposed BNCT reactor facilities other than TREAT are expected to do. An issue for these reactors is whether they can deliver an adequate dose in an acceptably short time. It appears that exposure durations under an hour are considered essential and durations around 10-15 minutes are considered good. Note that beam intensity is an essentially arbitrary quantity for TREAT operating in transient mode; the dose delivered by TREAT is limited by the energy deposited in the core, regardless of whether it occurs in milliseconds or tens of minutes. To put the intensity from TREAT on a comparable basis with that from steady state reactors, the assumption in the following discussion is for a 15 minute, steady state shaped transient, producing a maximum authorized integrated energy of 2.2 GJ (2.4 MW).

Epithermal fluence (flux x time) was also computed, as an alternative to epithermal intensity. Fluence is a more natural measure for a transient facility, with epithermal fluence most directly related to the beneficial dose delivered to the target. An epithermal fluence of $5x10^{12}$ appears to be about what is needed to destroy a tumor. [1]

The measure of healthy-tissue damage is a ratio defined by Nigg [5] called beam purity. The numerator of this quantity contains a therapeutically positive attribute, with the harmful components in the denominator. The definition is:

$$\text{purity} = \frac{(J/\phi)_{epi}}{4k_n/\phi_{epi} + k_\gamma/\phi_{epi}} \quad ,$$

where J is magnitude of the net current vector, ϕ is scalar flux, subscript epi indicates the epithermal neutron energy range and k is a kerma dose rate (integral of flux times kerma factor). The k_γ is the gamma dose rate from all gamma energies using the five-element approximation of tissue shown in Table I. The k_n is the neutron dose rate from all neutron energies above thermal, computed with just the hydrogen kerma at the Table 1 atom density, as recommended by Nigg. [5]. The neutron dose rate is about 6% higher if all five elements are included.

1.2 Models, Data, and Computer Codes

The TREAT reactor is described in detail in Ref. 6. The TREAT core is constructed from 10.16 cm square, zircaloy clad elements in a 19x19 square grid. The elements have chamfered edges, which form coolant air flow channels when the elements are assembled in the grid. The fuel portion of the core grid is 122 cm long, and about 190 cm across, with the typical core cross section a square with rounded corners of graphite dummy elements. Fuel elements are composed of reactor grade graphite with 0.009 atom percent finely divided uranium (UO_2) enriched in ^{235}U to 93 weight percent. The C : ^{235}U atom ratio is 10000 : 1 resulting in a neutron spectrum that is quite flat in lethergy units, with roughly 1/3 of the neutrons in each of the fast (> 10kev), thermal (< 1 ev) and epithermal ranges. The large, dilute core has sufficient heat capacity to allow a transient releasing as much as 2.2 GJ of energy.

Most of the BNCT performance calculations were performed using RZ-geometry models of TREAT, similar to the depiction in Fig. 1. The models include the core surrounded by the graphite reflector and part of the concrete shield. A filter plus collimator extends from the

core surface to the end of the model along the Z axis. Filters studied consist of at least three layers: at least 50 cm of materials to slow fast neutrons into the epithermal range, a thin layer to absorb thermal neutrons (usually Cd), and about 10 cm of material to absorb gamma rays (Pb or Bi). The radial extent of the filter was varied during the study. A reflective boundary condition was used at the axial midplane to reduce the computation time (implying the presence of two filters). The axial mesh spacing was 4-5 cm in the interior reflector and core, about 1.7 cm in the filter and collimator, with the radial mesh spacing 2.5 cm or smaller to model the conical collimator adequately. The performance parameters were monitored at various axial distances from the core edge through the filter assembly; the values at the exit of the collimator are reported here.

The RZ models are analogues of the three-dimensional (XYZ) representation of TREAT shown in Fig. 2. The XYZ model was used to design a core loading with nominal excess reactivity, power peaking and control rod worths. These calculations were performed with finite-difference diffusion theory and a 70 group cross section set generated specifically for TREAT. A graphite central reflector region was modelled to shift the neutron flux towards four of the core faces to anticipate an experimental configuration with a beam port at each face. The reactivity effect of replacing the reflector with a filter at one core face was computed to be 1-2 $\%\Delta k$.

Because a BNCT filter would be installed along either the X axis or the Y axis of the reactor, the Z axis of the RZ model is orthogonal to the Z axis of the XYZ model. The volumes and the distances to the core face where the filter was placed were preserved for both the internal reflector and the core. Similarly, the reflector and shield thicknesses along the axis of the filter were preserved. All compositions were preserved except that control elements were replaced by fuel elements rather than creating a mix of fuel and control elements in a thin annulus.

The Bugle 80 cross section set [7] was used in all the one- and two-dimensional calculations reported here. While collapsed for a light water reactor concrete shield, Bugle 80 is the most widely used set in the BNCT literature. The set features 47 neutron groups coupled with 20 gamma groups and includes both neutron and gamma kerma factors. The representation of the

thermal neutron energy range is not very flexible (no explicit upscattering and only two groups below 0.4 eV), but it allows an adequate prediction of the TREAT neutron spectrum at the energies of interest for filter evaluation. Three isotopes--Cd, Bi and ^{2}H--were copied from the more recent Bugle 93 [8] set and added to the Bugle 80 file.

The TWODANT code [9] was used for all the one- and two-dimensional calculations. The standard S_8 quadrature set was found to give nearly the same results at the filter exit as the S_{12} set. Similarly, the P_1 scattering approximation was found to give about the same results as P_3 scattering. Accordingly, most of the RZ calculations were done with S_8 and P_1. The one-dimensional calculations were performed with S_{12} and P_3 as the running time penalty was slight. The spatial mesh for the 1-D calculations was at least as fine as that of the RZ calculations. For all models, the convergence criteria were set to 10^{-5} or tighter. Most calculations solved the eigenvalue problem for the full model, but some solved the fixed source problem for just the filter, or just the collimator, by extracting position, angle and energy-dependent boundary sources from previously obtained eigenvalue flux solutions. Epithermal intensity and beam purity were obtained via utility code postprocessing of the TWODANT flux solutions.

1.3 One-Dimensional Calculations

The initial RZ calculations were performed with a model where the filter area was limited by the desire to gain access to the core via the hodoscope port, minimizing the effort and cost of the facility modifications by obviating the need to remove any of the TREAT reflector or shielding. The hodoscope access port is a roughly 60 cm square gap in the north reflector and shield which allows direct observation and radiography of test fuel during irradiation. Initial performance predictions were disappointing, especially for beam purity, with the predicted purity comparable to that of the poorest performers in the published literature and more than a factor of five smaller than that of the best. It was noted that the small cross sectional area of the filter compared to that of the core face provides a significant neutron transport medium, allowing neutrons from the core face radially outward from the filter to enter the filter assembly from the sides. Attempts to shield against the side entry of fast neutrons within the 60 cm constraint

proved only marginally effective in improving beam purity. To investigate this and other issues, a series of one-dimensional (slab geometry--effectively radially infinite) calculations were performed.

To test that the TREAT core neutron spectrum is not inherently less well suited for BNCT than the core spectra of alternative reactors, a consistent comparison was made of the beam purity and relative intensity from three different reactors with potential as BNCT facilities-- the Power Burst Facility (PBF), a standard-fuel TRIGA reactor, and TREAT. The remainder of this subsection deals with this study.

A simple calculational approach was used, the slab model shown in Fig. 3 used for each reactor type. No buckling was imposed, with the core thickness adjusted to give an eigenvalue near unity. The reflector had the composition appropriate for each reactor and was effectively infinite. Five different filter designs were tried with each reactor type. The purity and intensity of the beam emitted at the vacuum surface of the filter were computed and compared for the various core and filter options.

The core compositions are given in Table II. The TRIGA composition is for a fuel element cell with 8.5 wt % U enriched in ^{235}U to 20 wt % (20/8.5 fuel). The TREAT composition is for standard TREAT fuel. The PBF composition was derived from References 10, 11 and 12. The PBF core was assumed to be made entirely from the 7x7 canister type with 48 fuel pins and 1 steel pin; the Al fuel pin spacers were volume averaged.

The filter designs used here are depicted in Fig. 4. The proportions shown there are volume percents. A 15 cm Bi region is included against the core for the 330 Al/D_2O filter and optionally for the 302 AlF_3/Al filter. This layer was considered because the PBF configuration described in Ref. 10 has a Bi "reflector" between the core and the filter. Although labeled there as a reflector, it is viewed here as a filter layer because it has a considerable effect on the beam purity. The 302 AlF_3/Al filter design is the one used in the initial RZ calculations and came from an early study of BNCT with TREAT. The 310 AlF_3/Al design is an improvement on the 302 design. The 320 Al/Al_2O_3 design is similar to a filter proposed for a 20/8.5 fuel TRIGA reactor by Liu.[13] The Al/D_2O design is from a PBF description in Ref. 10. Together, these designs provide a broad test bed for evaluating the core spectrum influence on beam purity.

A basic issue addressed was that an adequate approximation to the core neutron spectrum for each of the reactors be produced with the Bugle 80 cross sections. These cross sections were collapsed with the spectrum in an LWR concrete shield and the actinide cross sections do not account for resonance self shielding or cell heterogeneity. The most serious problem with this occurs in the PBF core, where the infinitely dilute ^{238}U capture cross section causes k_∞ to be 0.9 instead of 1.4. To estimate the resulting spectral distortion, two sets of 20 neutron group cross sections were generated with the WIMS code, one based on the PBF fuel pin cell and the other based on the same concrete composition as used for Bugle 80. The asymptotic core spectrum was computed with each of these cross sections and the two results were found to differ little compared to the differences among the spectra of the three cores as computed with Bugle 80 cross sections. As shown in Fig. 5, the PBF core spectra computed with the three cross section sets are similar, and agreement is closest for the two spectra produced with concrete-based cross sections.

Additional confirmation of adequacy was obtained by adjusting the ^{238}U atom density. A search was made for the ^{238}U atom density that, when used with the 20 group concrete spectrum microscopic cross sections, gave the same eigenvalue as when the PBF fuel cell microscopic cross sections were used with the true atom densities. This adjustment corrects the spectrum well except below 0.4 eV, which is below the range of interest. Then a beam purity calculation was run twice with Bugle 80 cross sections, once using the true atom density and once using the adjusted atom densities. The beam purity differed by only 3%, evidence that core spectrum distortion caused by using Bugle 80 cross sections is not important for this study.

A compilation of numerical results is given in Table III. The table has five filter types for each of the three cores. Variations in the J/ϕ component are negligible and expected since it is not possible to include a collimator in a slab model. The fast neutron dose is the controlling purity component in all cases. For every filter type this component is largest with the TRIGA core and smallest with the TREAT core. Correspondingly, the purity is lowest with the TRIGA core and highest with the TREAT core. This is consistent with the fast flux fraction, which is always highest with the TRIGA core and lowest with the TREAT core. The spread in the purity among core cases is about a factor of two and is as low as 26% in one case (Al/D_2O filter).

Relative intensity values are also given in Table III. It is not possible to compare different cores using the slab model but, for a given core, the relative intensity emerging from different filters can be evaluated. The intensity from the 302 AlF_3/Al filter was arbitrarily set to unity. Although not the point of this exercise, it is clear that some filter designs are better than others from both purity and intensity perspectives. The ranking of filter options on the basis of purity or intensity is virtually the same for all cores, another indication that the core spectrum, while significant, does not make a vast difference.

Figures 6 through 9 are comparisons of neutron spectra from the three reactors. Fig. 6 shows that the core center spectrum is flattest in TREAT, the thermal component is smallest in PBF and the component above 1 MeV is about the same in TRIGA and PBF. Comparing Figures 6 and 7, note that the spectra at the filter entrance have somewhat lower values at the energy extremes but the spectra are similar to those at core center. The spectra emerging from two of the filter types are shown in Figures 8 and 9. Both filter types are seen to be very effective in producing spectra predominantly in the epithermal range. The residual flux in the high energy tail is largest for TRIGA and smallest for TREAT, in accordance with the fast neutron dose and beam purity results.

1.4 Multidimensional Calculations

With it apparent that virtually all of the neutrons from a core face would need be passed through a moderator or shielded, the next easiest access to the core is at the thermal column on the east side of the reactor. Here, an entire core face can be readily exposed by withdrawing shield plugs and removing the thermal column graphite. Figure 10 shows a conceptual filter and collimator occupying this east face thermal column access port; the results reported below are based upon this arrangement. The effect of extending the filter further to span also the entire reflector width at this face was explored but little performance advantage was observed. Note that the transient and control/shutdown rods banks have been interchanged.

RZ calculations were run for four similar filter designs. The same collimator was used in each case, approximating a cone with a diameter stepping down 10 cm for every axial 10 cm distance. The inner diameter of the cone is 125 cm at the filter exit and 20 cm at the collimator aperture. There are two radial annuli, an inner thermal neutron absorbing liner of 2.5 cm, 5% density LiF, and a 20 cm-thick wall of Bi. Likewise, all the filters have their three outermost axial layers in common: a 2 cm-thick layer of 1% density LiF at the filter exit, preceded by a 9 cm-thick layer of Bi, preceded by a 1 cm-thick layer of 5 % density Cd. The filters differ only in the material or materials used in the 65 cm-thick neutron moderating section. These are described in Table IV. All the filter layers are 152 cm in diameter, shielded from side contamination by a radial layer of Bi 20 cm thick .

The performance results for these four cases are given in Table V. In all cases, the beam purity is acceptable and the epithermal fluence (or intensity) is quite a bit greater than appears to be necessary. The substantial range of performance results show the sensitivity to filter design. For example, changing the proportions of Al and Al_2O_3 (Cases 1 and 2) increases the intensity by 70% while decreasing the purity by less than 1%. There is clearly a large potential to make substantial improvements in performance via optimization in filter design.

Three normalized neutron spectra, demonstrating the effectivness of the filters are compared in Fig. 11. The relatively flat profile is the core center spectrum, the other two taken from the exit of the collimator in Cases 2 and 4. The spectral shift and attenuation due to a filter assembly (Case 4) is shown in Fig. 12. The roughly 2 decade drop near the 10 Kev epithermal boundary is evident and commensurate with that of Figures 8 and 9. The attenuation in the total epithermal flux through the filters due to cross section, and the geometric attenuation through the collimator to the beam aperture were consistently calculated to be on the order of 1 decade each.

In Fig. 13, the Case 4 results are compared with the performance of other reactor facilities, as compiled by Nigg [5]. The TREAT intensity is significantly higher than that from any other reactor, and the TREAT purity value is within 10% of the highest value. It seems clear from the sensitivity demonstrated in Table V that the beam purity from TREAT could be improved much more than 10% while maintaining a high intensity. Thus, the BNCT performance potential of TREAT is at least competitive with that of the best of the candidate reactor facilities.

DISCUSSION

2.1 Neutronics Feasibility

This study has shown that the TREAT reactor is capable of producing a beam for BNCT whose performance characteristics are at least as good as those of eight other reactors that have been studied for this application. Without any attempt at filter optimization, the TREAT beam purity is within 10% of the best value in the literature and the maximum beam fluence is far more than seems to be required. This fluence can be delivered over essentially any time history that may be desired, a unique feature among candidate facilities.

It was determined, using one-dimensional calculations, that the core neutron spectrum of TREAT offers a modest advantage in producing a high purity beam. Consistent calculations compared TREAT, PBF and TRIGA reactors using five different filters. In every case, the TREAT reactor produced the highest beam purity. Only the 20/8.5 TRIGA fuel was tested but it seems unlikely that using another TRIGA fuel, e.g., 20/45 fuel, would alter the hierarchy. Although purity variations among the reactors differed by as much as a factor of two, this advantage is of only modest importance because differences in filter design can produce much larger changes.

The excess fluence capability of TREAT allows flexibility in operation and design. The energy of the transient could be reduced, which would allow a significant reduction in the cooldown time required between maximum energy transients (about 4 hours, the cooldown time roughly proportional to the total energy deposited). Alternatively, in a design optimization, fluence could be traded off for improvements in beam purity--increasing the forward directed component of the beam (larger J/ϕ) and decreasing the contamination doses.

The TREAT performance could almost certainly be improved significantly by optimizing the filter design. One obvious issue to address is a core flux tilt away from the filter due mostly to a hardening of the spectrum near the core edge. It may be possible to put a material at the core-filter interface that would reduce this tilt and increase the beam fluence. The geometry of the core, in particular that of the central reflector could also be altered to shift power towards

the interface. Within the neutron moderating section of the filter, there are many choices of material type, sequence and thickness. As the filter alternatives that have been calculated so far show (see for example Table III and Figures 8 and 9), these choices can have a large impact upon epithermal intensity and beam purity. Collimation of the beam from TREAT is an area that has received almost no attention so far. It is anticipated that it would be possible, with alternative geometry and materials, to increase the forward directed component of the beam without an inordinate sacrifice in intensity.

One caveat is that the beam purity measure used here was chosen because it is simple and has been used in the literature to compare the merits of different reactors and filters. Although it brings together into one quantity all the parameters of interest--the forward directed component, and the neutron and gamma ray damage doses per epithermal neutron--it is not clear that it accounts appropriately for the relative importance of these quantities. One observation is that all the neutrons in the epithermal range are given equal importance whereas neutrons at the high end of the range (8-10 Kev) are actually more effective than those at the low end. [5] Examination of Figures 8 and 9 with this in mind suggests that the true beam purity advantage offered by TREAT is likely less than the simple purity measure would indicate for some experiments or treatment protocols.

2.2 Cost and Schedule

Having established the neutronics feasibility, questions of cost and schedule for making TREAT functional as a BNCT facility become relevant. Note that TREAT has no water tank or pressure barrier, has easy access to the core and is above grade, making the necessary modifications relatively simple. Note also that there is no fuel cycle associated with the reactor operating in transient mode, with attendant long term savings of cost and a simplified regulatory environment. The reactor is in good condition, due in part to a recent control system upgrade.

Preliminary cost and schedule estimates have been made assuming that an aluminum/aluminum oxide filter would replace the thermal column [14]. The schedule, shown in Fig. 14, indicates that the analysis, modifications to the facility, modifications to documents

for safety and operations, and personnel training would take about six months to complete. The cost estimates for this work, shown in Fig. 15, total to just over one million dollars. The cost for operating TREAT in a program dedicated to the support of BNCT experiments would be approximately two million dollars per year. [15]

2.3 Mission Planning

Given the established flexibility in varying the core loading, the space available at the thermal column access port, and the ability to deliver an intense epithermal neutron beam at distances in the range of 1-2 meters from the core face, among the experiments might be:

- the testing of competitive filter designs
- the testing of beam collimation geometry and materials
- investigations into treatment rate effects and optimum fractions
- the testing of filter assembly detectors and instrumentation
- the development of control and data aquisition software
- investigations into the potential for designing and using graphite moderated, gas cooled, transient reactors as dedicated patient treatment facilities.

CONCLUSION

TREAT has long served as one of the tools in the research efforts of Argonne National Laboratory. The facility is currently available for a new kind of mission. It is not envisioned that TREAT would be used as a production-type patient irradiation facility. [16] It has been shown here, however, that a role in support of BNCT experiments is technically feasible, cost effective. and that the facility is uniquely suited for experiments supporting BNCT research and development.

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TABLE I. Five-Element Approximation of Tissue

Isotope	Atom Density (atoms/barn-cm)
H	0.06011000
C	0.01153000
N	0.00111800
O	0.02296000
Cl	0.00003397

TABLE II. Homogenized Core Compositions

Isotope	TRIGA	PBF	TREAT
H	0.0568420	0.0176390	0.0
B-10	0.0	0.0	0.0000002
C	0.0	0.0	0.0762014
O	0.0108860	0.0320290	0.0000165
Mg	0.0	0.0000640	0.0
Al	0.0	0.0059330	0.0
Si	0.0000301	0.0000330	0.0
Ca	0.0	0.0022920	0.0
Cr	0.0006360	0.0018310	0.0
Mn	0.0000320	0.0001820	0.0
Fe	0.0021870	0.0061790	0.0000144
Ni	0.0002750	0.0008510	0.0
Zr	0.0222860	0.0089890	0.0009861
U-235	0.0001540	0.0002610	0.0000077
U-238	0.0006190	0.0011470	0.0000006

TABLE III. Beam Characteristics From Filters For Three Cores; 1-D S12/P3 Solutions

Filter Design 1	Reactor	Current / Flux	Neutron Dose 2	Gamma Dose	Beam Purity Absolute	Beam Purity Relative	Relative Intensity	Flux Fraction Fast	Flux Fraction Epithml	Flux Fraction Thermal
302	TRIGA	0.598	6.70E-11	3.90E-12	2.29E+09	1.00	1.00	0.054	0.946	0.000
AlF_3+Al	PBF	0.599	5.66E-11	3.39E-12	2.60E+09	1.18	1.00	0.046	0.954	0.000
no Bi	TREAT	0.602	3.68E-11	3.63E-12	3.99E+09	1.81	1.00	0.027	0.973	0.000
302	TRIGA	0.600	3.31E-11	2.62E-12	4.44E+09	1.00	0.69	0.024	0.976	0.000
AlF_3+Al	PBF	0.601	2.95E-11	2.50E-12	4.99E+09	1.12	0.73	0.021	0.979	0.000
w Bi	TREAT	0.602	2.28E-11	3.01E-12	6.39E+09	1.44	0.93	0.015	0.985	0.000
310	TRIGA	0.582	3.42E-11	6.18E-12	4.07E+09	1.00	3.01	0.027	0.973	0.000
AlF_3+Al	PBF	0.582	2.80E-11	5.30E-12	4.96E+09	1.22	3.10	0.023	0.977	0.000
	TREAT	0.583	1.51E-11	6.72E-12	8.68E+09	2.13	3.72	0.011	0.989	0.000
320	TRIGA	0.584	1.71E-11	7.10E-12	7.72E+09	1.00	0.93	0.014	0.986	0.000
Al+Al_2O_3	PBF	0.584	1.34E-11	6.49E-12	9.69E+09	1.26	0.88	0.011	0.989	0.000
	TREAT	0.584	6.91E-12	8.95E-12	1.60E+10	2.07	1.19	0.005	0.995	0.000
330	TRIGA	0.579	1.03E-11	8.11E-12	1.17E+10	1.00	1.46	0.018	0.976	0.006
AlD_2O	PBF	0.579	9.64E-12	7.71E-12	1.25E+10	1.07	1.58	0.017	0.977	0.006
w Bi	TREAT	0.579	7.37E-12	9.88E-12	1.47E+10	1.26	2.27	0.013	0.981	0.007

1 Filter Designs from Figure 4.
2 Dose - cGy/epithermal neutron
Relative purity compares the three reactor types for a given filter
Relative intensity compares filter types for a given reactor

TABLE III. Beam Characteristics From Filters For Three Cores; 1-D S12/P3 Solutions

Filter Design 1	Reactor	Current / Flux	Neutron Dose 2	Gamma Dose	Beam Purity Absolute	Beam Purity Relative	Relative Intensity	Flux Fraction Fast	Flux Fraction Epithml	Flux Fraction Thermal
302	TRIGA	0.598	6.70E-11	3.90E-12	2.29E+09	1.00	1.00	0.054	0.946	0.000
AlF_3+Al	PBF	0.599	5.66E-11	3.39E-12	2.60E+09	1.18	1.00	0.046	0.954	0.000
no Bi	TREAT	0.602	3.68E-11	3.63E-12	3.99E+09	1.81	1.00	0.027	0.973	0.000
302	TRIGA	0.600	3.31E-11	2.62E-12	4.44E+09	1.00	0.69	0.024	0.976	0.000
AlF_3+Al	PBF	0.601	2.95E-11	2.50E-12	4.99E+09	1.12	0.73	0.021	0.979	0.000
w Bi	TREAT	0.602	2.28E-11	3.01E-12	6.39E+09	1.44	0.93	0.015	0.985	0.000
310	TRIGA	0.582	3.42E-11	6.18E-12	4.07E+09	1.00	3.01	0.027	0.973	0.000
AlF_3+Al	PBF	0.582	2.80E-11	5.30E-12	4.96E+09	1.22	3.10	0.023	0.977	0.000
	TREAT	0.583	1.51E-11	6.72E-12	8.68E+09	2.13	3.72	0.011	0.989	0.000
320	TRIGA	0.584	1.71E-11	7.10E-12	7.72E+09	1.00	0.93	0.014	0.986	0.000
Al+Al_2O_3	PBF	0.584	1.34E-11	6.49E-12	9.69E+09	1.26	0.88	0.011	0.989	0.000
	TREAT	0.584	6.91E-12	8.95E-12	1.60E+10	2.07	1.19	0.005	0.995	0.000
330	TRIGA	0.579	1.03E-11	8.11E-12	1.17E+10	1.00	1.46	0.018	0.976	0.006
AlD_2O	PBF	0.579	9.64E-12	7.71E-12	1.25E+10	1.07	1.58	0.017	0.977	0.006
w Bi	TREAT	0.579	7.37E-12	9.88E-12	1.47E+10	1.26	2.27	0.013	0.981	0.007

1 Filter Designs from Figure 4.
2 Dose - cGy/epithermal neutron
Relative purity compares the three reactor types for a given filter
Relative intensity compares filter types for a given reactor

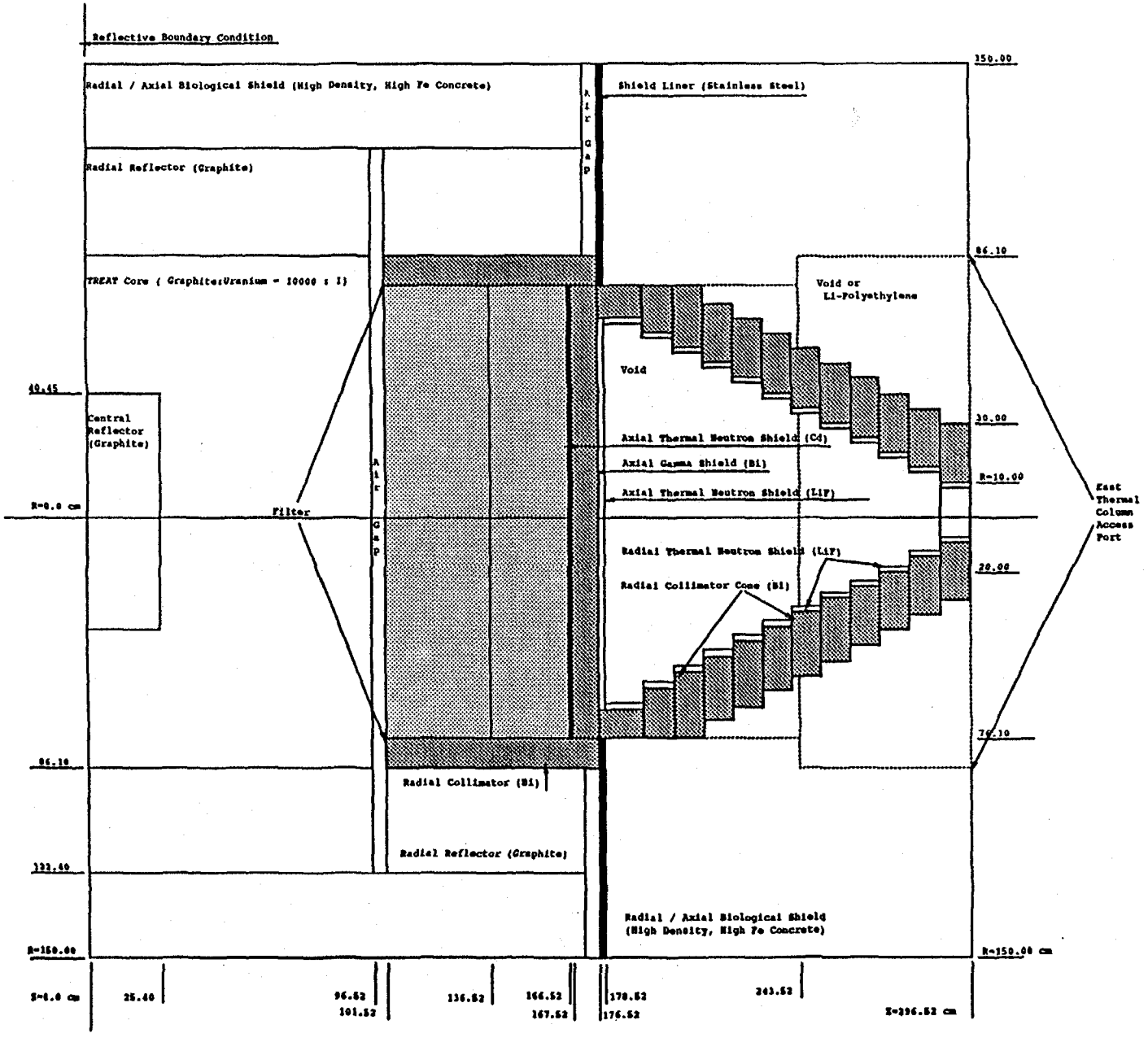

Fig. 1. RZ Model of TREAT with a BNCT Filter Assembly Replacing East Thermal Column.

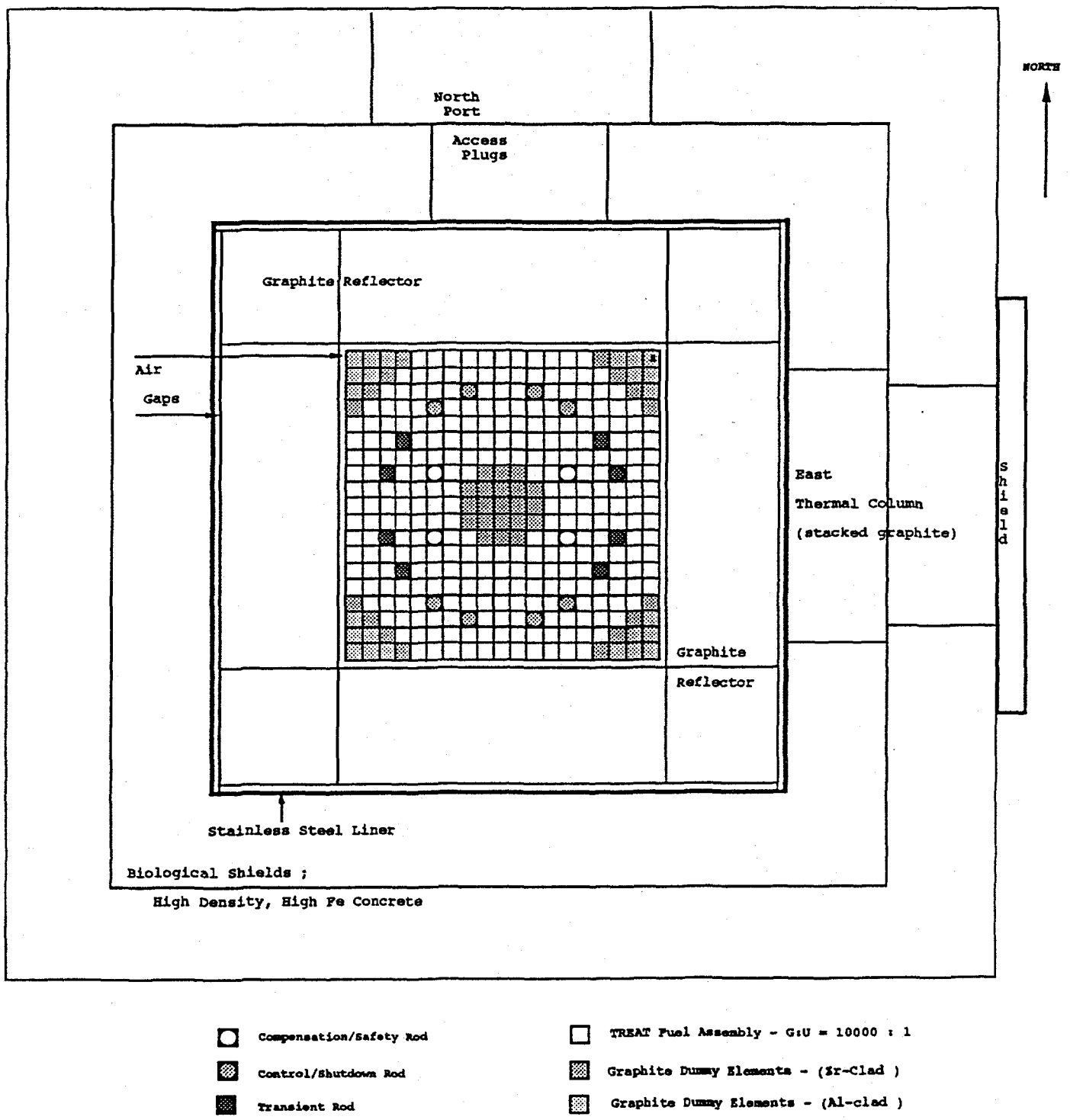

Fig. 2. XY Plane of 3-Dimensional TREAT Model.

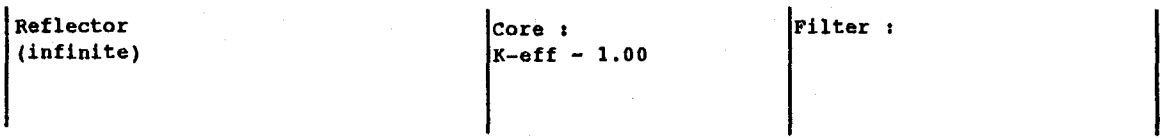

Fig. 3. Slab Model for Beam Purity Calculations.

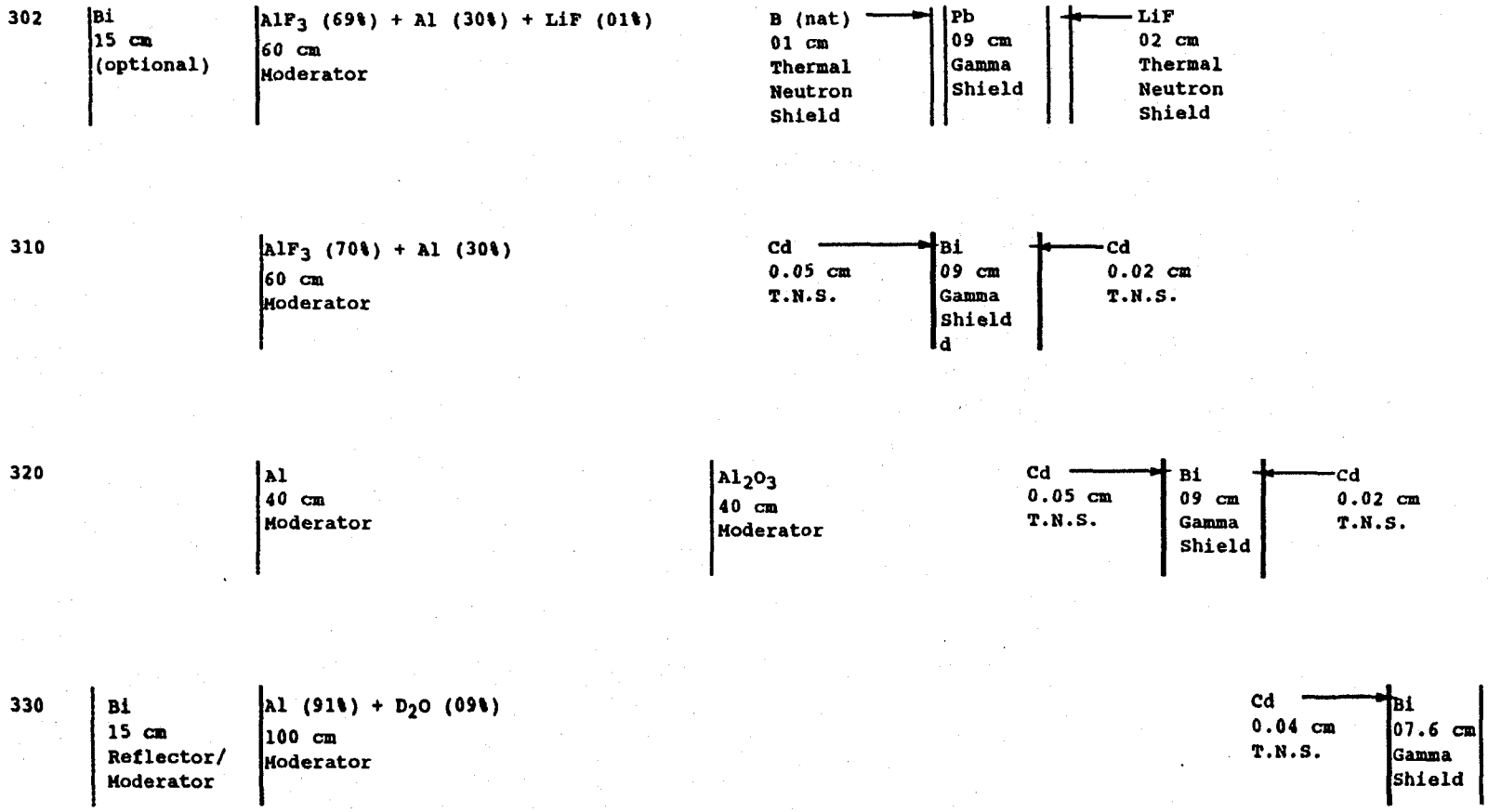

Fig. 4. Slab Filter Designs.

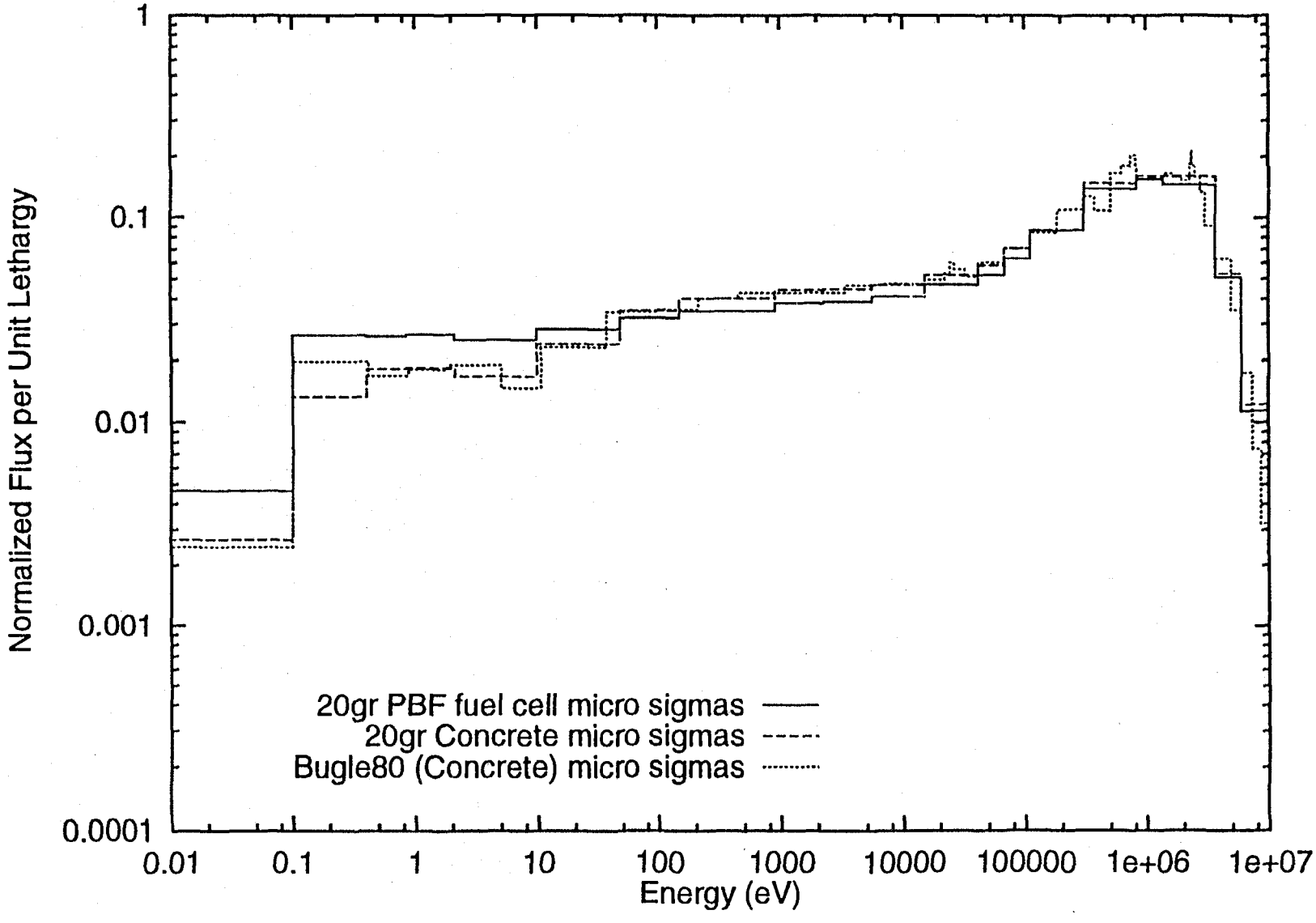

Fig. 5. Effect of Microscopic Cross Sections Upon PBF Core Spectrum.

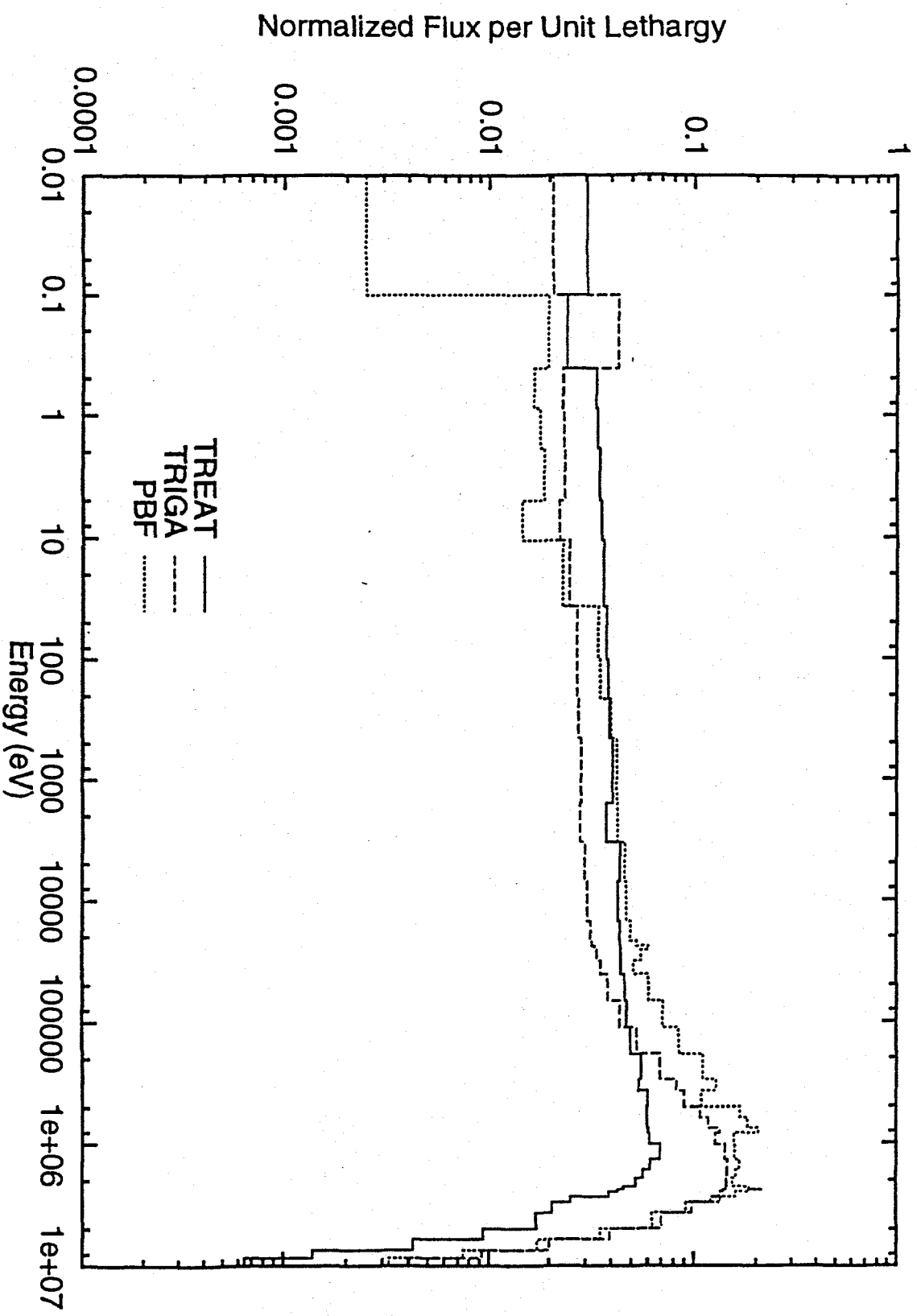

Fig. 6. Core Center Neutron Spectra From TREAT, TRIGA & PBF.

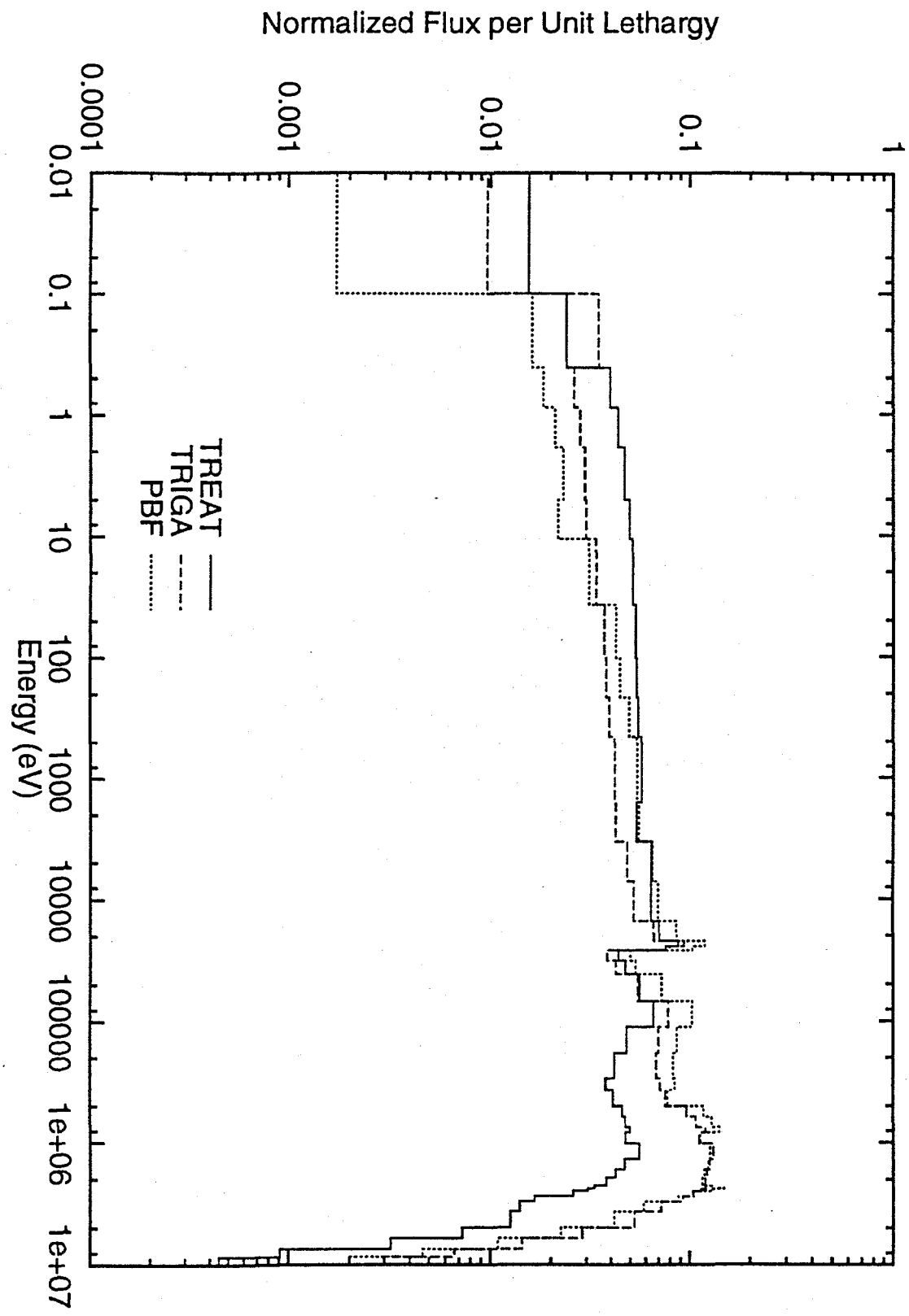

Fig. 7. 302 Filter Entrance Neutron Spectra From TREAT, TRIGA & PBF.

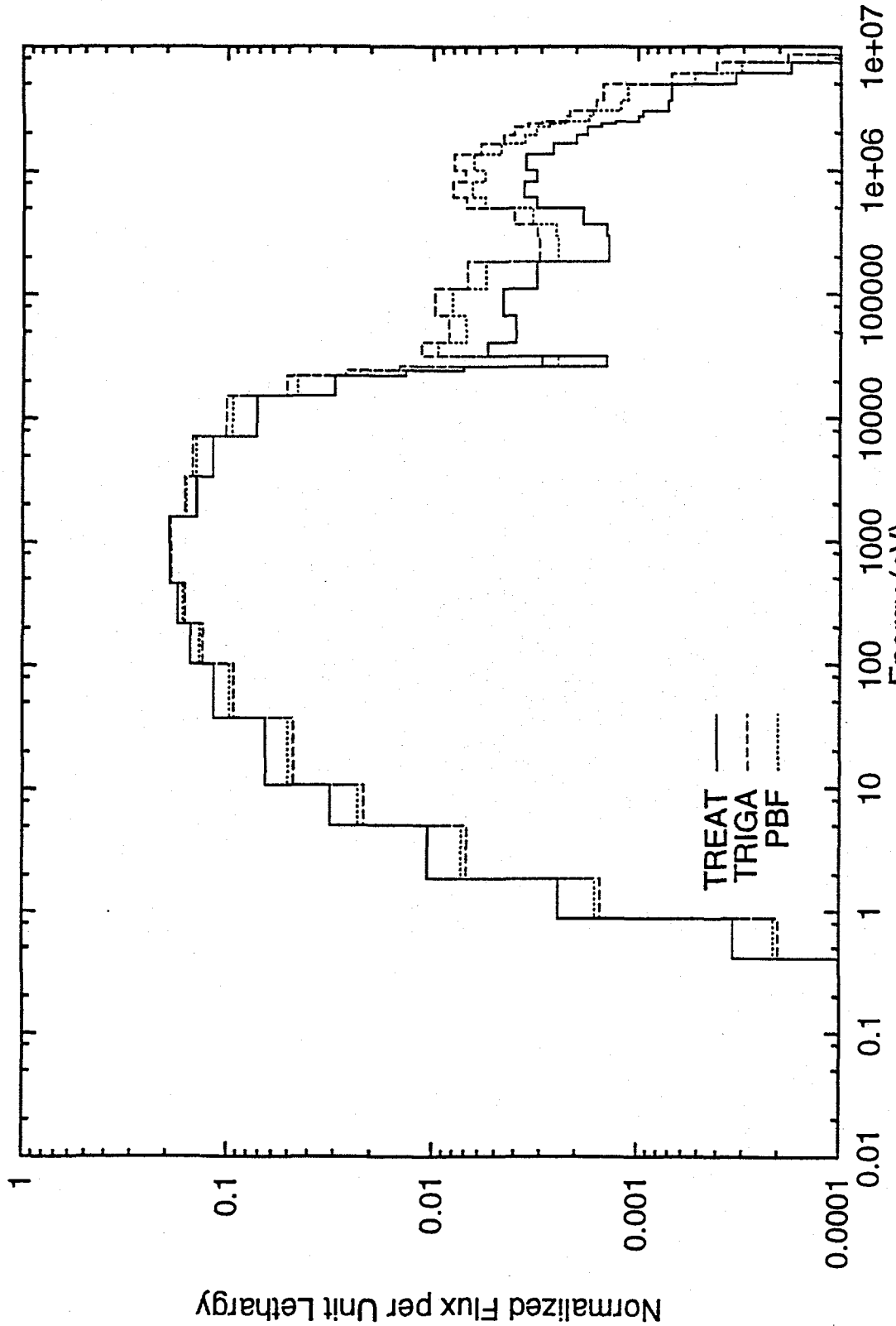

Fig. 8. 302 Filter Exit Neutron Spectra From TREAT, TRIGA & PBF.

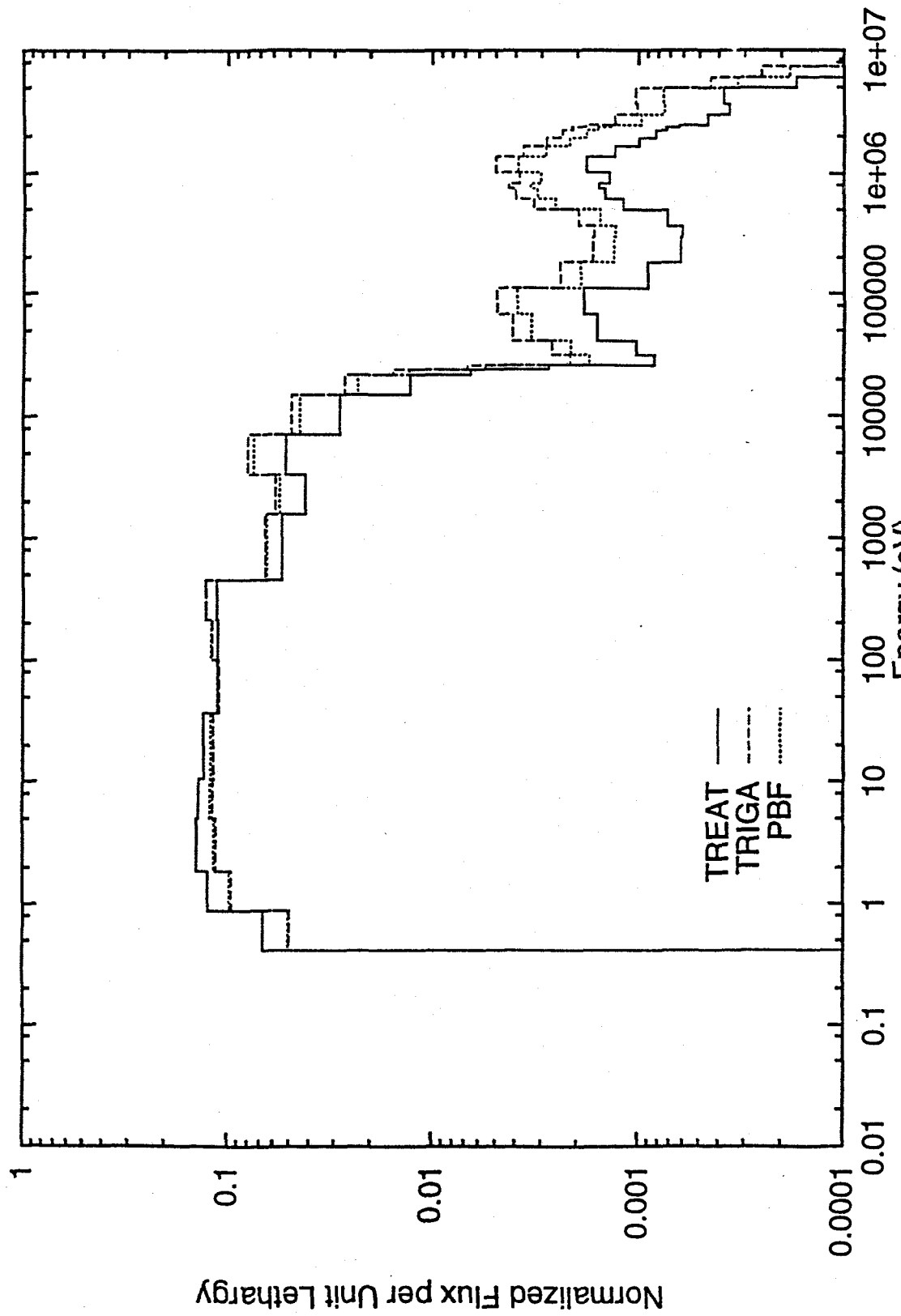

Fig. 9. 310 Filter Exit Neutron Spectra From TREAT, TRIGA & PBF.

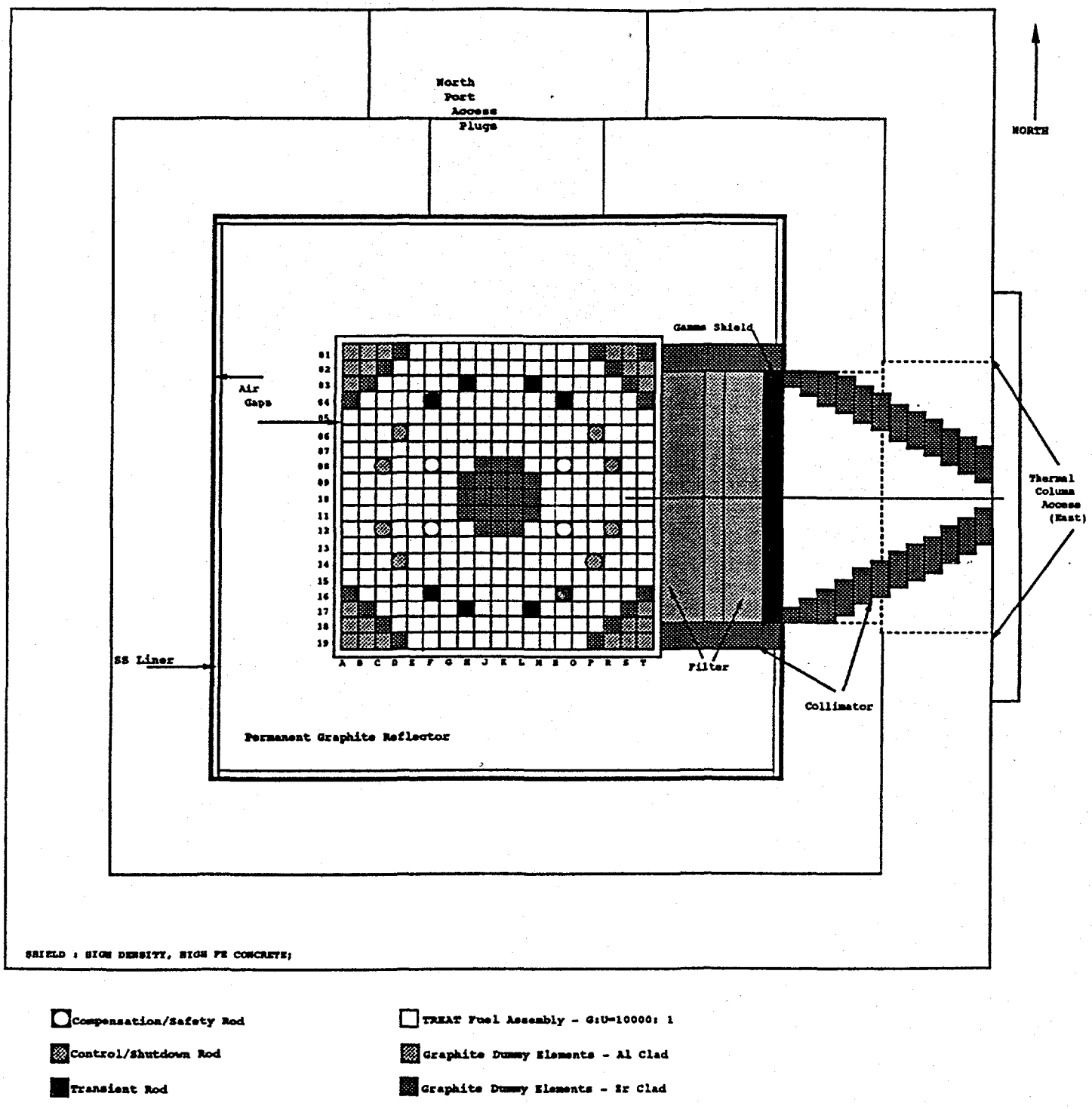

Fig. 10. XY Midplane View: TREAT with BNCT Experiment Replacing East Thermal Column.

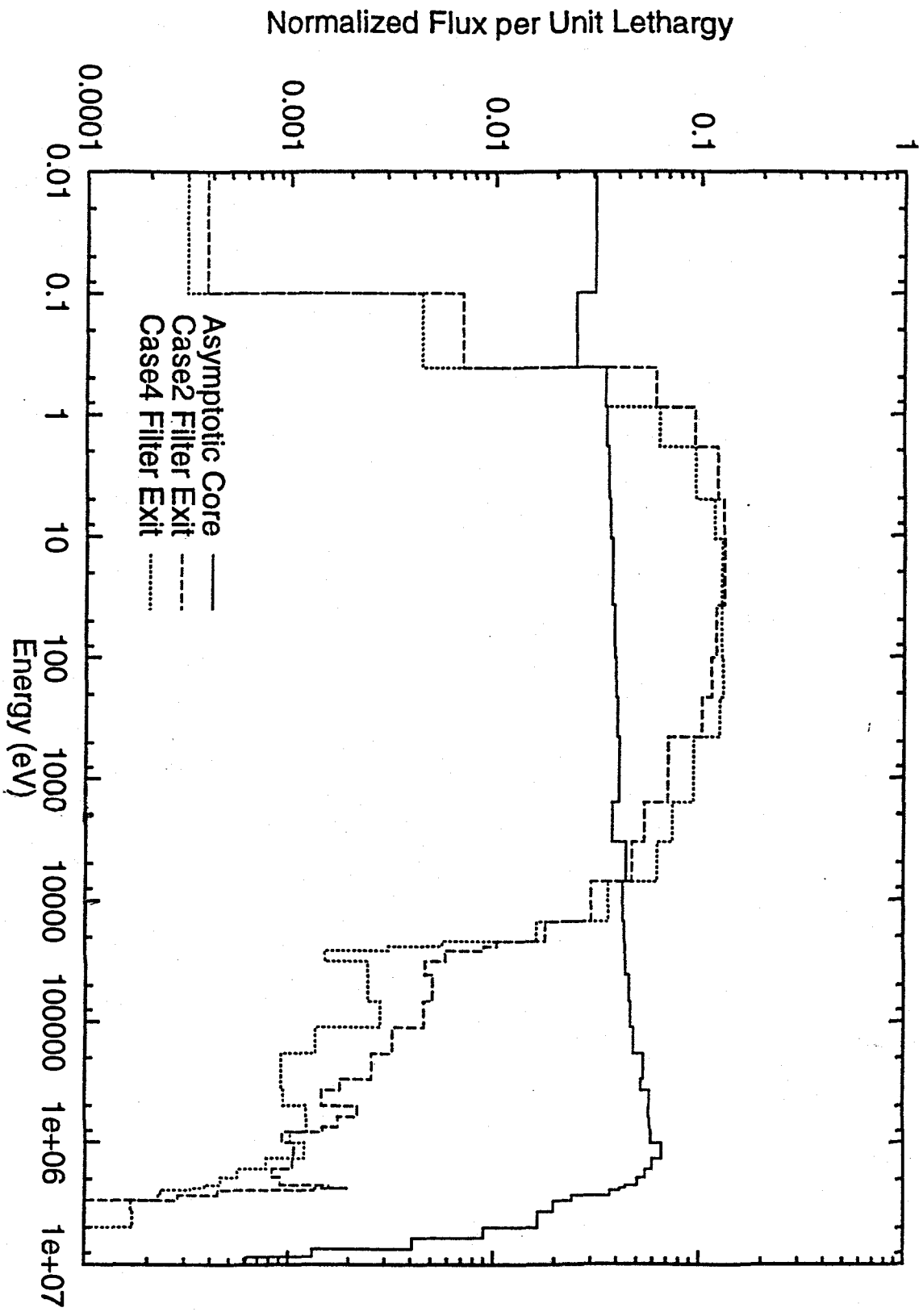

Fig. 11. TREAT Neutron Spectrum Alteration by Two Filters.

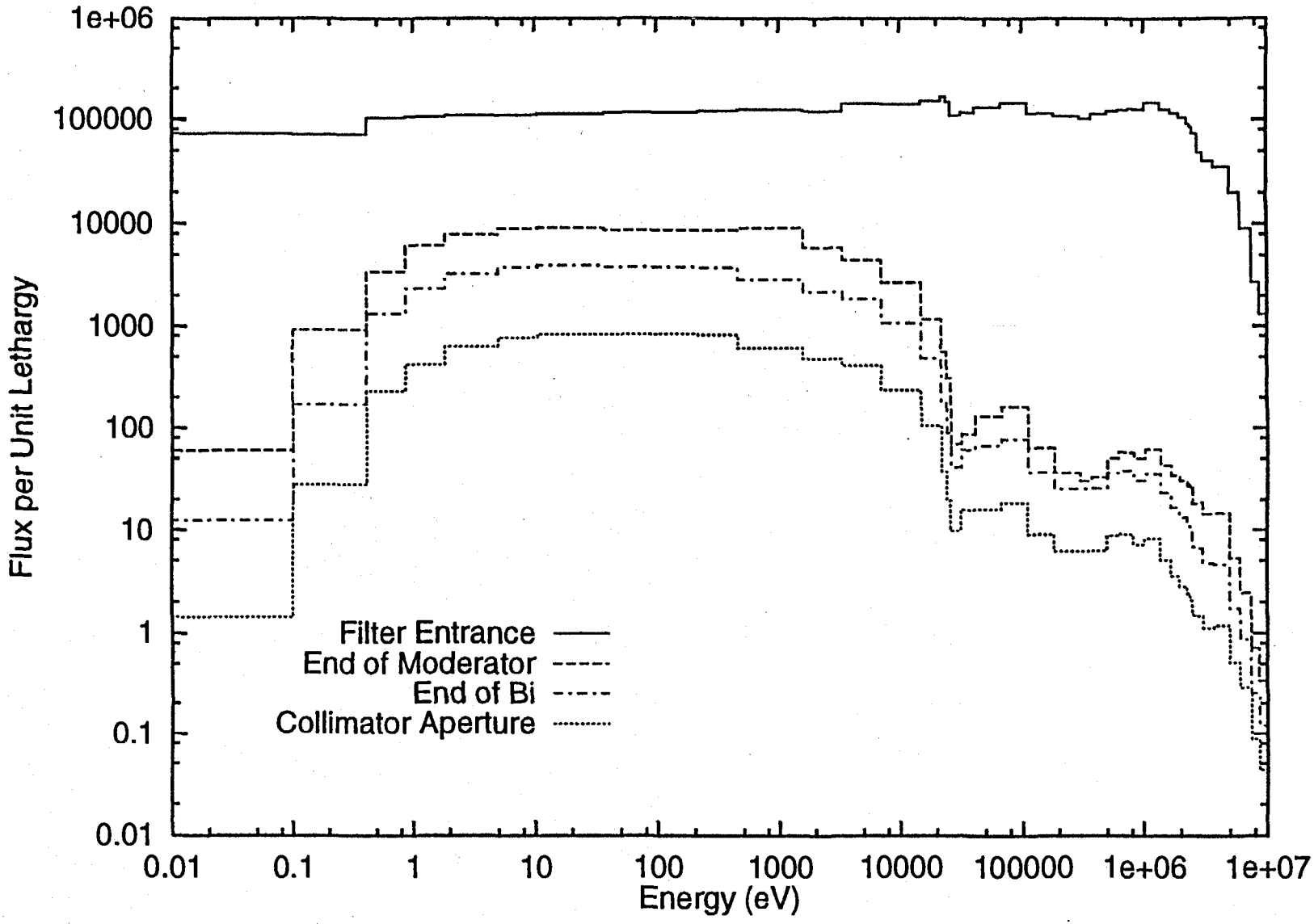

Fig. 12. TREAT Case 4 Flux Attenutation and Spectral Shift.

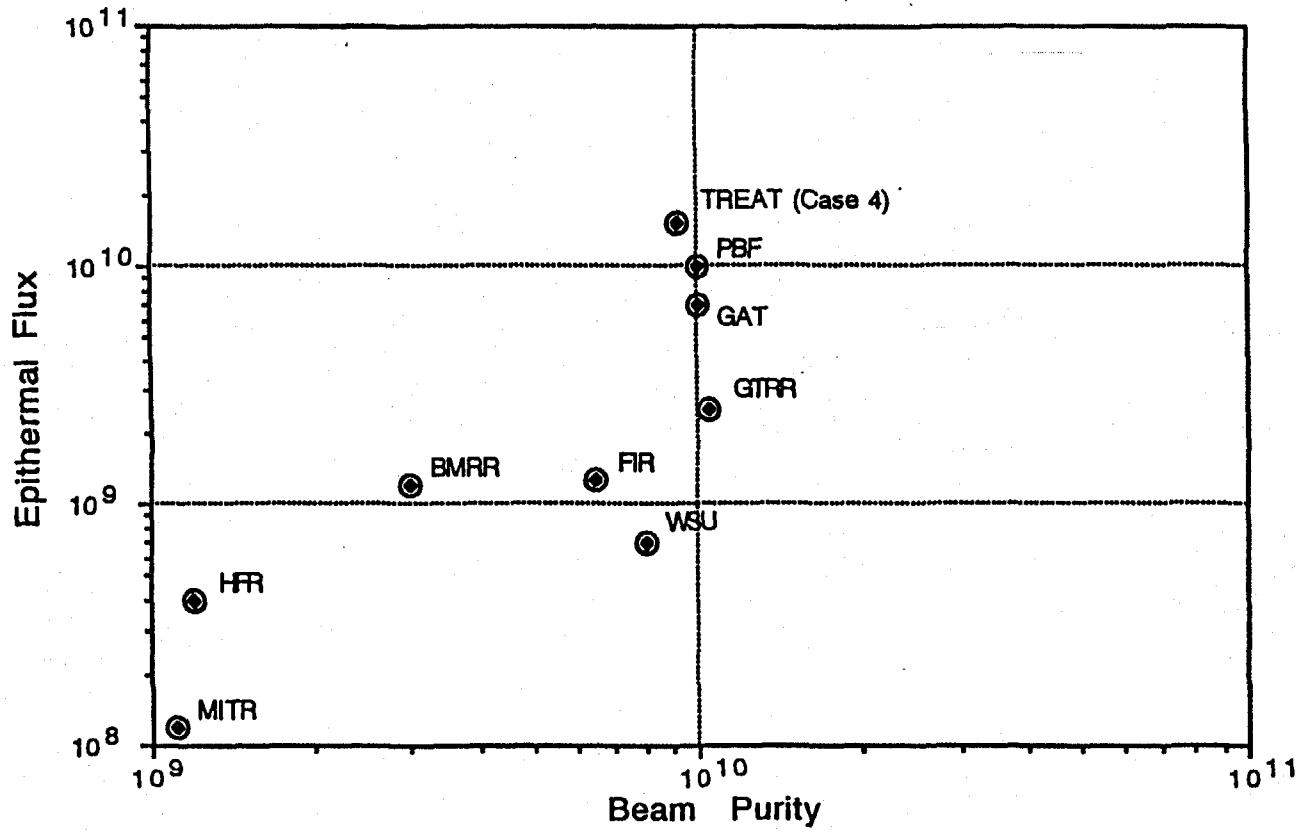

Fig. 13. Comparison of Reactor-Based Epithermal Neutron Beams.

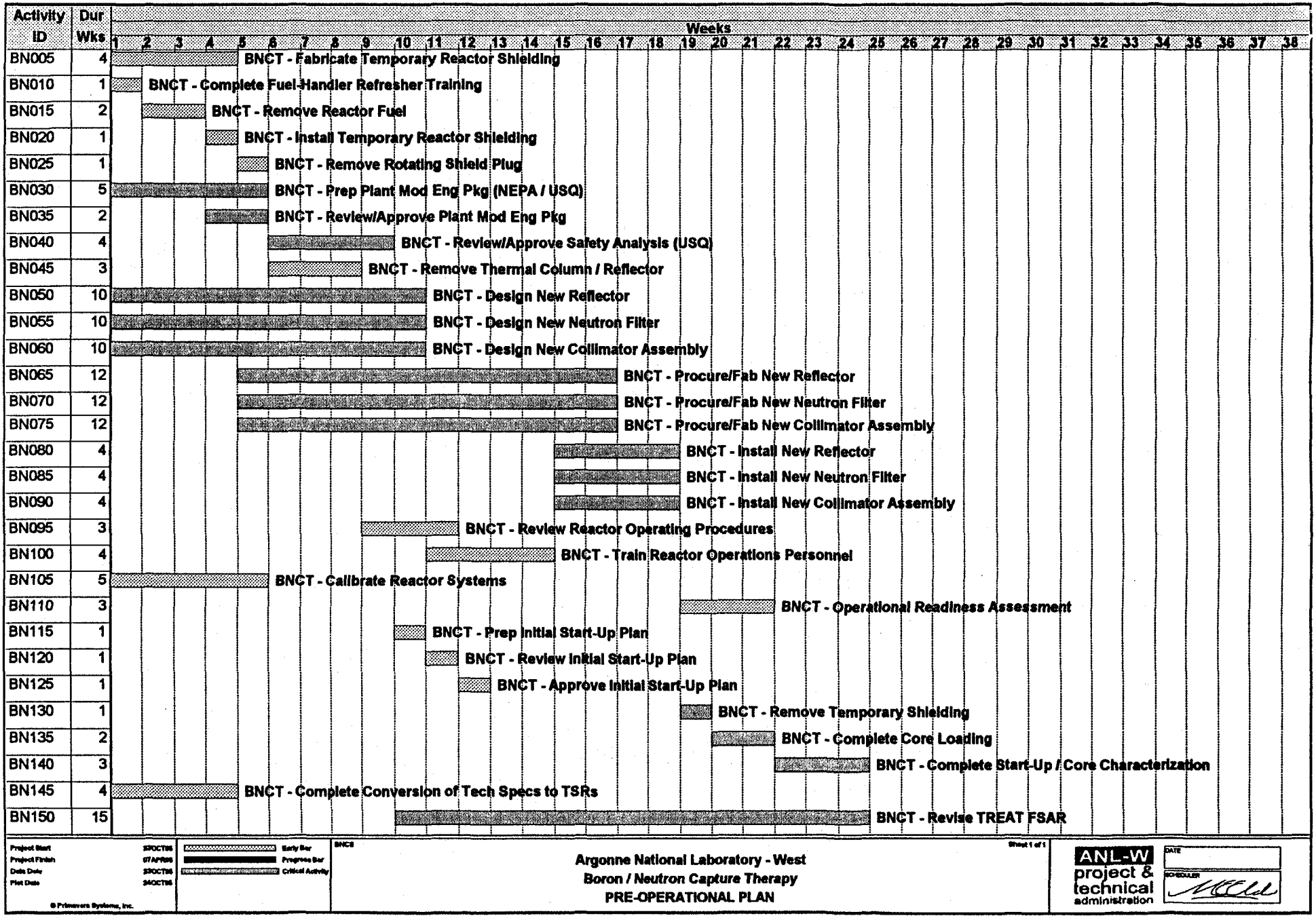

Fig. 14. Schedule to Prepare for a TREAT BNCT Mission.

COST ESTIMATE FOR PRE-OPERATIONAL PLAN
BORON/NEUTRON CAPTURE THERAPY AT TREAT
ARGONNE NATIONAL LABORATORY - WEST

DATE: 10/24/95

PAGE: 1 OF 4

ITEM NO.	ITEM AND DESCRIPTION	MANPOWER COSTS			OTHER COSTS		TOTAL COST
		DISCIPLINE	HOURS	RATE	ITEM	COST	
1.	FABRICATE TEMPORARY REACTOR SHIELDING.	ANL-W ENGINEER	40	$50/HR	MATERIALS	$5,000	$11,500
		ANL-W MACHINE SHOP	100	$45/HR			
2.	COMPLETE FUEL-HANDLER REFRESHER TRAINING.	ANL-W TRAINER	40	$45/HR			$8,400
		ANL-W REACTOR OPERATOR	80	$45/HR			
		ANL-W SUPERVISOR	40	$50/HR			
		ANL-W SUPERVISOR-IN-CHARGE	20	$50/HR			
3.	REMOVE REACTOR FUEL, INSTALL TEMPORARY REACTOR SHIELDING, AND REMOVE ROTATING SHIELD PLUG.	ANL-W FUEL HANDLER	80	$45/HR			$5,600
		ANL-W SUPERVISOR-IN-CHARGE	20	$50/HR			
		ANL-W ENGINEER	20	$50/HR			
4.	PREPARE PLANT MODIFICATION ENGINEERING PACKAGE. MUST INCLUDE NEPA AND USQ DOCUMENTATION.	ANL-W ENGINEER	400	$50/HR			$20,000
5.	REVIEW AND APPROVAL OF PLANT MODIFICATION ENGINEERING PACKAGE.	ANL-W ENGINEER	40	$50/HR			$2,000
6.	REVIEW AND APPROVAL OF SAFETY ANALYSIS ASSOCIATED WITH USQs.	ANL-W ENGINEER	40	$50/HR			$2,000

Fig. 15. Costs to Prepare for a TREAT BNCT Mission.

COST ESTIMATE FOR PRE-OPERATIONAL PLAN
BORON/NEUTRON CAPTURE TIIERAPY AT TREAT
ARGONNE NATIONAL LABORATORY - WEST

DATE: 10/24/95

PAGE: 2 OF 4

ITEM NO.	ITEM AND DESCRIPTION	MANPOWER COSTS			OTHER COSTS		TOTAL COST
		DISCIPLINE	IIOURS	RATE	ITEM	COST	
7.	REMOVAL OF TIIERMAL COLUMN AND REFLECTOR FROM EAST SIDE OF REACTOR.	ANL-W RADIATION WORKER	360	$45/IIR	WASTE BOXES	$7,500	$46,500
		ANL-W SUPERVISOR	120	$50/HR			
		ANL-W HEALTH PHYSICS TECHNICIAN	240	$45/HR			
		ANL-W ENGINEER	120	$50/IIR			
8.	DESIGN OF NEW REFLECTOR, NEUTRON FILTER, AND COLLIMATOR ASSEMBLY, INCLUDING STRESS ANALYSIS.	ANL-W NUCLEAR ENGINEER	400	$50/IIR			$29,500
		ANL-W STRUCTURAL ENGINEER	100	$50/IIR			
		ANL-W DRAFTER	100	$45/IIR			
9.	PROCUREMENT AND FABRICATION OF NEW REFLECTOR, NEUTRON FILTER, AND COLLIMATOR ASSEMBLY.	ANL-W MACIIINE SIIOP	200	$45/IIR	ALUMINUM	$150,000	$436,200
		ANL-W ENGINEER	240	$50/IIR	BISMUTII	$200,000	
		ANL-W MAINTENANCE SUPERVISOR	240	$50/HR	MISC. MATERIALS	$10,000	
		ANL-W MAINTENANCE TECHNICIAN	960	$45/IIR			
10.	INSTALLATION OF NEW REFLECTOR, NEUTRON FILTER, AND COLLIMATOR ASSEMBLY.	ANL-W RADIATION WORKERS	480	$45/IIR	LIFTING AND IIANDLING EQUIPMENT	$50,000	$102,000
		ANL-W SUPERVISOR	160	$50/HR			
		ANL-W HEALTH PIIYSICS TECIINICIAN	320	$45/IIR			
		ANL-W ENGINEER	160	$50/IIR			

COST ESTIMATE FOR PRE-OPERATIONAL PLAN
BORON/NEUTRON CAPTURE THERAPY AT TREAT
ARGONNE NATIONAL LABORATORY - WEST

DATE: 10/24/95

ITEM NO.	ITEM AND DESCRIPTION	MANPOWER COSTS			OTHER COSTS		TOTAL COST
		DISCIPLINE	HOURS	RATE	ITEM	COST	
11.	REVIEW OF REACTOR OPERATING PROCEDURES.	ANL-W SUPERVISOR-IN-CHARGE	120	$50/HR			$12,000
		ANL-W ENGINEER	120	$50/HR			
12.	TRAINING OF REACTOR OPERATIONS PERSONNEL.	ANL-W TRAINER	120	$45/HR			$16,200
		ANL-W OPERATORS	240	$45/HR			
13.	CALIBRATION OF REACTOR SYSTEMS.	ANL-W MAINTENANCE TECHNICIAN	200	$45/HR			$19,000
		ANL-W MAINTENANCE SUPERVISOR	200	$50/HR			
14.	OPERATIONAL READINESS ASSESSMENT.	ANL-W ENGINEER	120	$50/HR			$12,000
		ANL-W SUPERVISOR-IN-CHARGE	120	$50/HR			
15.	PREPARATION, REVIEW, AND APPROVAL IF INITIAL STARTUP PLAN.	ANL-W SUPERVISOR-IN CHARGE	120	$50/HR			$6,000
16.	REMOVE TEMPORARY SHIELDING AND COMPLETE CORE LOADING.	ANL-W FUEL HANDLERS	240	$45/HR			$22,800
		ANL-W SUPERVISOR	120	$50/HR			
		ANL-W SUPERVISOR-IN-CHARGE	60	$50/HR			
		ANL-W ENGINEER	60	$50/HR			

COST ESTIMATE FOR PRE-OPERATIONAL PLAN
BORON/NEUTRON CAPTURE THERAPY AT TREAT
ARGONNE NATIONAL LABORATORY - WEST

DATE: 10/24/95

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ITEM NO.	ITEM AND DESCRIPTION	MANPOWER COSTS			OTHER COSTS		TOTAL COST
		DISCIPLINE	HOURS	RATE	ITEM	COST	
17.	COMPLETE INITIAL STARTUP AND CORE CHARACTERIZATION.	ANL-W REACTOR OPERATOR	240	$45/HR			$34,200
		ANL-W SUPERVISOR	120	$50/HR			
		ANL-W SUPERVISOR-IN-CHARGE	120	$50/HR			
		ANL-W ENGINEER	120	$50/HR			
		ANL-W HEALTH PHYSICS TECHNICIAN	120	$45/HR			
18.	COMPLETE CONVERSION OF TECH SPECS TO TSRs.	ANL-W SUPERVISORE	160	$50/HR			$16,000
		ANL-W ENGINEER	160	$50/HR			
19.	REVISION OF TREAT FSAR.	ANL-W SUPERVISOR-IN-CHARGE	600	$50/HR			$60,000
		ANL-W ENGINEER	600	$50/HR			
	SUBTOTALS		9,200			$422,500	$861,900
	25% CONTINGENCY		2,300	$48/HR		$105,700	$216,100
		TOTALS	11,500			$528,200	$1,078,000