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Feasibility Study for an Epithermal Neutron-Beam Facility at the Washington State University Radiation Center

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ABSTRACT

A feasibility study has been performed to investigate modifications of the Washington State University Research Reactor facility to provide an epithermal-neutron beam for Neutron Capture Cancer Therapy. This facility, originally a General Electric concept, has since been converted to utilize TRIGA-type fuel elements. Results of calculations using the two-dimensional DORT discrete-ordinates computer code show that, assuming availability of appropriate materials, it will be possible to modify the facilities and obtain an epithermal beam of sufficient intensity with low contaminant and favorable directional properties. Two concepts were investigated, both requiring utilization of a reconfigured thermal column. These were: (1) a beam exit port interior to the existing thermal column cavity, and; (2) a beam exit port exterior to the thermal column, or brought out flush with the outer shield wall for better access. With the interior beam, a high intensity (2-5x10^9 n/cm^2 s) beam with excellent purity can be achieved with an AlF_3/Al composite material and, using Al_2O_3, a beam comparable to the epithermal-neutron beam at the Brookhaven Medical Research Reactor (presently the best epithermal beam in the world) can be achieved. With the exterior beam, an intensity adequate for therapy (6x10^8 to 10^9 n/cm^2 s) and excellent purity can be achieved using the AlF_3/Al material. Facility modifications would consist of removing the graphite, lead shielding and H_2O tank presently located in the thermal column and installing new materials to provide the epithermal beam. In addition to the neutron filtering material, bismuth and lead gamma shields and collimators would be required as well as lithiated polyethylene or equivalent materials. Shield walls about the thermal-column opening would also be required to restrict access and minimize radiation dose to occupied areas around the thermal column. This study did not consider the use of fission plates to enhance the beam. Studies underway at another institution indicate a beam with superior characteristics to the results herein quoted can be obtained with fission plates or perhaps other convertor concepts. Additional regulatory and operational concerns would have to be addressed if the convertor concept is used.

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ACRONYMS

BMRR	Brookhaven Medical Research Reactor
BNCT	Boron Neutron Capture Therapy
eV	Electron volts
GTRR	Georgia Institute of Technology Research Reactor
HFR	High Flux Reactor
KERMA	Kinetic Energy Released in Matter
keV	Kilo-electron volts
K_f	Fast-neutron KERMA factor
K_g	Gamma KERMA factor
MITR-II	Massachusettes Institute of Technology Research Reactor
NCT	Neutron Capture Therapy
PBF	Power Burst Facility
RBE	Relative biological effectiveness
R_j	Ratio of neutron current to neutron flux
TRIGA	Transient Reactor Irradiator-General Atomics
WSU	Washington State University

Feasibility Study for an Epithermal Neutron-Beam Facility at the Washington State University (WSU) Radiation Center

1. INTRODUCTION

Neutron Capture Therapy (NCT) is experiencing renewed interest as a treatment modality for brain (and other) cancer patients. Required for NCT are both an effective drug and an appropriate neutron beam. The only NCT now being performed is in Japan using thermal-neutron beams and the borocaptate sodium compound. It is the thermal-neutron flux that is most effective in generating therapeutic dose to tissue. With an incident thermal-neutron beam however, it is necessary to surgically displace the scalp and skull during therapeutic radiation to avoid surface tissue damage and to be able to deliver dose to the cancer cells that are deep inside the brain. In the United States as well as in Europe, researchers are concentrating on neutron beams with incident neutron energies predominantly in the epithermal [0.5 electron volts (eV) to 10 kilo-electron volts (keV)] energy range. Epithermal neutrons are surface sparing, they penetrate a few centimeters into tissue before producing the peak thermal-neutron flux. With epithermal neutrons it is hoped to avoid surgery during radiation therapy, thus providing a much safer and more acceptable procedure.

The characteristics of an epithermal beam important for therapy are:

1) Intensity: Dose delivery rate is directly proportional to the intensity of the neutron current in the beam. Also, as the beam is shaped and otherwise tailored to an individual irradiation, intensity is lessened so it is advantageous to start with an inherent, high intensity. For a well-designed epithermal beam having incident flux intensity 10^9 (n/cm^2 s), a single-fraction relative biological effectiveness (RBE) dose rate of about 20 cGy/min to healthy tissue (with 50 ppm ^{10}B) at peak depth will be achieved. If a tolerance dose of 14 Gy (Eq) for peak healthy-tissue dose is targeted, then total irradiation time would be about 70 minutes. If fractionation is used, total treatment time may be somewhat more, but time per fraction would then be about 20-30 minutes.

2) Contaminant: Neutrons with energies above 10 keV are very damaging to healthy tissue due to the recoil protons produced when neutrons undergo elastic scatter reactions with hydrogen. Therefore, it is important to design the neutron beam such that the relative intensity of above-10 keV neutrons is low. It is possible to design a beam where this component is negligible. Also, there are incident gamma rays in any neutron beam due to neutron capture events in structure and it is necessary to minimize this component. Finally, the thermal-neutron flux in the free beam should be minimized to reduce surface-tissue damage. The magnitudes of the fast-neutron and gamma components are often expressed as Kinetic Energy Released in Matter (KERMA) factors. For a therapeutic beam, the gamma KERMA factor (K_g) should be reduced to order 10^{-11}, and the fast-neutron KERMA factor (K_f) should be reduced to a few times 10^{-11}.

3) Collimation: A well-collimated beam is desirable, although not entirely necessary for effective therapy. A perfectly-collimated (forward directed) beam will have a ratio of neutron current to neutron flux (R_J) of 1.0 since current is the forward component of flux. A 2π isotropic beam has neutrons emanating randomly in the forward direction and has an R_J equal to 0.5. The collimated beam is more efficient at generating thermal flux in tissue and as a result, reduces K_f and K_g relative to peak thermal flux. Also, an isotropic beam diverges rapidly with distance and positioning error becomes large.

There are currently three facilities in the world that have epithermal beams. These are the Brookhaven Medical Research Reactor (BMRR), the Massachusetts Institute of Technology Research Reactor (MITR-II), and the High Flux Reactor (HFR) at Petten, The Netherlands. Some characteristics of these beams are shown in Table 1.

Table 1. Characteristics of Actual Epithermal Beams[1]

Reactor	Epithermal-Flux Intensity (10^9 n/cm^2 s)	Fast-Neutron KERMA K_f (10^{11} cGy/n-cm^2)	Gamma KERMA K_g (10^{11} cGy/n-cm^2)	Collimation R_j (Neutron Current/Flux)[1]
HFR (45 MW)	0.33	10.4	8.40	0.95
MITR-II (5 MW)	0.20	13.0	14.0	-
BMRR (3 MW)	1.80	4.3	1.30	~0.60

Note: [1] Except for R_j, these data are taken from Reference 1.

Human clinical trials are proposed for the HFR (Glioma Multiforme), for the MITR-II (Metastatic Melanoma of the extremities) and for the BMRR (Glioma Multiforme and Ocular Melanoma). It is believed by some that the existing epithermal beams are good enough for early studies but researchers almost unanimously agree that better beams must be developed for clinical applications. The predicted (calculated) characteristics of selected beam concepts now being proposed are shown in Table 2.

The proposed reactor concepts offer significant advantage in beam intensity and quality compared to existing beams. The accelerator concepts require further development, particularly in target cooling and beam current. There are other concepts and reactor upgrades proposed that are not listed in Table 2.

Figure 1 presents a comparison of existing and conceptual epithermal-neutron sources. Here intensity and purity are compared with purity defined as:

$$BeamPurity = \frac{R_j}{(4K_f + K_g)}$$

Here; R_j is a measure of the beam collimation, K_f is the fast-neutron component (here weighted by 4 to account for RBE) and K_g is the incident gamma component. Others may have a different quantification formula for beam purity but this definition is certainly adequate for comparison.

Table 2. Calculated Characteristics of Proposed Epithermal-Beam Concepts.

Reactor	Epithermal-Flux Intensity (10^9 n/cm^2 s)	Fast-Neutron KERMA K_f (10^{-11} cGy/n-cm^2)	Gamma KERMA K_g (10^{-11} cGy/n-cm^2)	Collimation R (Neutron Current/Flux)
Power Burst Facility (20 MW)	10.0	2.0	1.0	0.95
Georgia Institute of Technology Research Reactor (5 MW)	2.5	1.5	1.0	0.85
FIR 1[1] (TRIGA) (0.25 MW)	3.5	2.6	1.0	0.60
RFQ Accelerator[2] (10 mA)	1.1	4.7	-	0.61
TC Accelerator[3] (4 mA)	0.16	-	-	~0.6
WSU Facility[4] (1 MW)	0.6-5.0	1.5-4.0	~1.0	0.6-0.9

Notes: [1] Reference 2, page 5.
[2] Reference 3.
[3] Reference 4.
[4] WSU - Results indicated that beam characteristics in the listed ranges can be obtained, however, there are trade-offs in design goals.

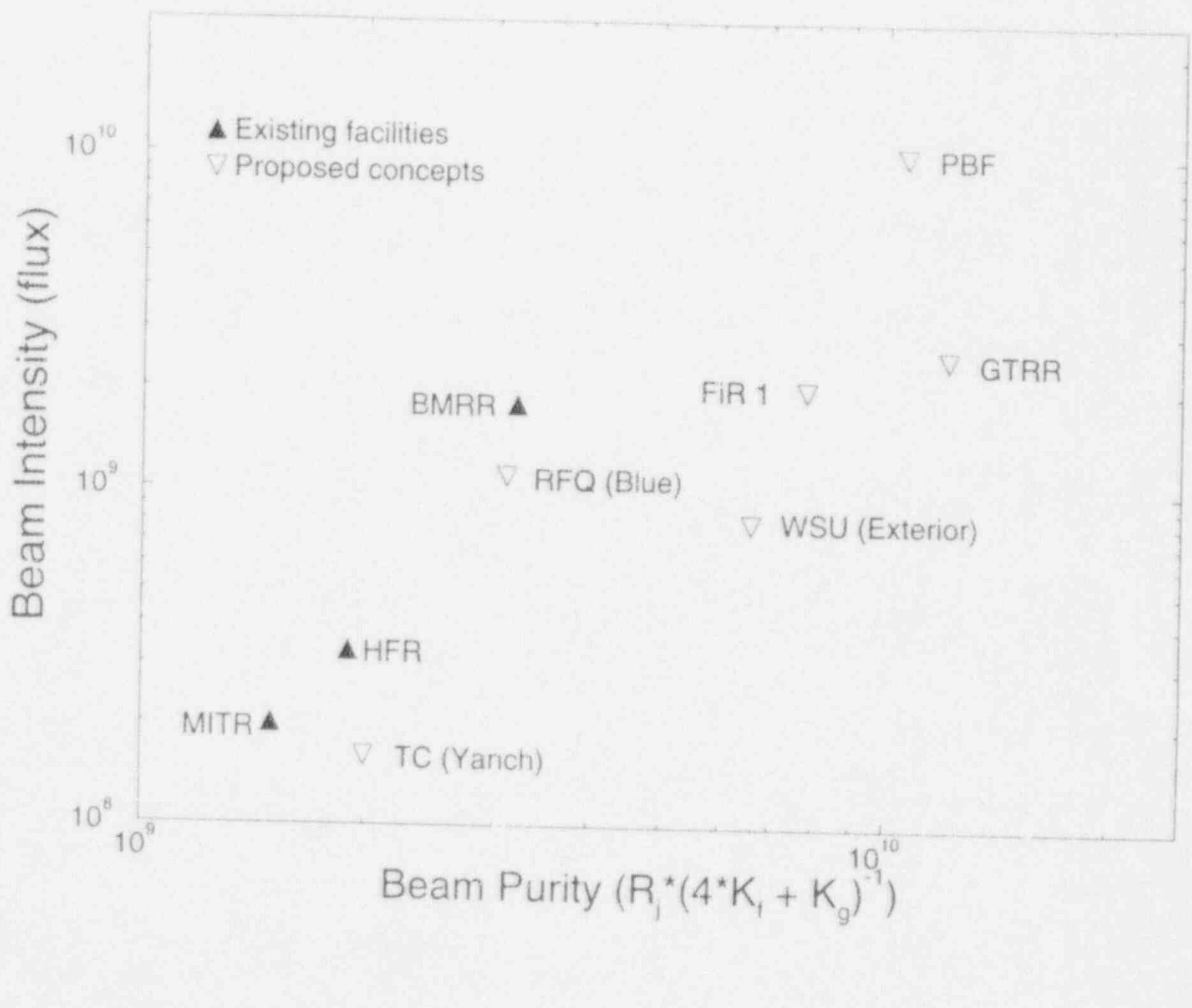


Figure 1. Comparison of Epithermal-Neutron Beams.

2. WSU FACILITY DESCRIPTION

2.1 Reactor

The Radiation Center at WSU houses a 1 MW convectively-cooled reactor. The reactor building sits on a hill and is isolated from the WSU campus and any residential areas. The reactor facility was originally a General Electric concept but was later modified to utilize Transient Reactor Irradiator-General Atomics (TRIGA) fuel elements and is recently referred to as a TRIGA facility. The reactor core resides in a large pool of ordinary water and is presently licensed to operate at 1 MW. A bridge over the pool is used to configure the core, insert experiments etc. and a reactor operator can safely occupy the bridge while the reactor is in operation. Figure 2 shows a sketch of an elevation plan showing the relationship of the pool, core and bridge, thermal column, and beam room. Figure 3 shows a view into the pool below the reactor bridge looking toward the core at the bottom of the pool. Figure 4 shows a reactor operator atop the bridge (moving the core). The TRIGA fuel in the core consists of standard elements and FLIP fuel. The reactor is inherently safe since the fuel elements contain a large amount of zirconium hydride which, when heated, decreases core reactivity, preventing reactor runaway. Figure 5 shows a sketch of the thermal column and reactor core. The core is mounted on tracks and can easily be moved when in shutdown mode. The core can be positioned immediately adjacent to the thermal-column wall providing a large leakage flux into the thermal column.

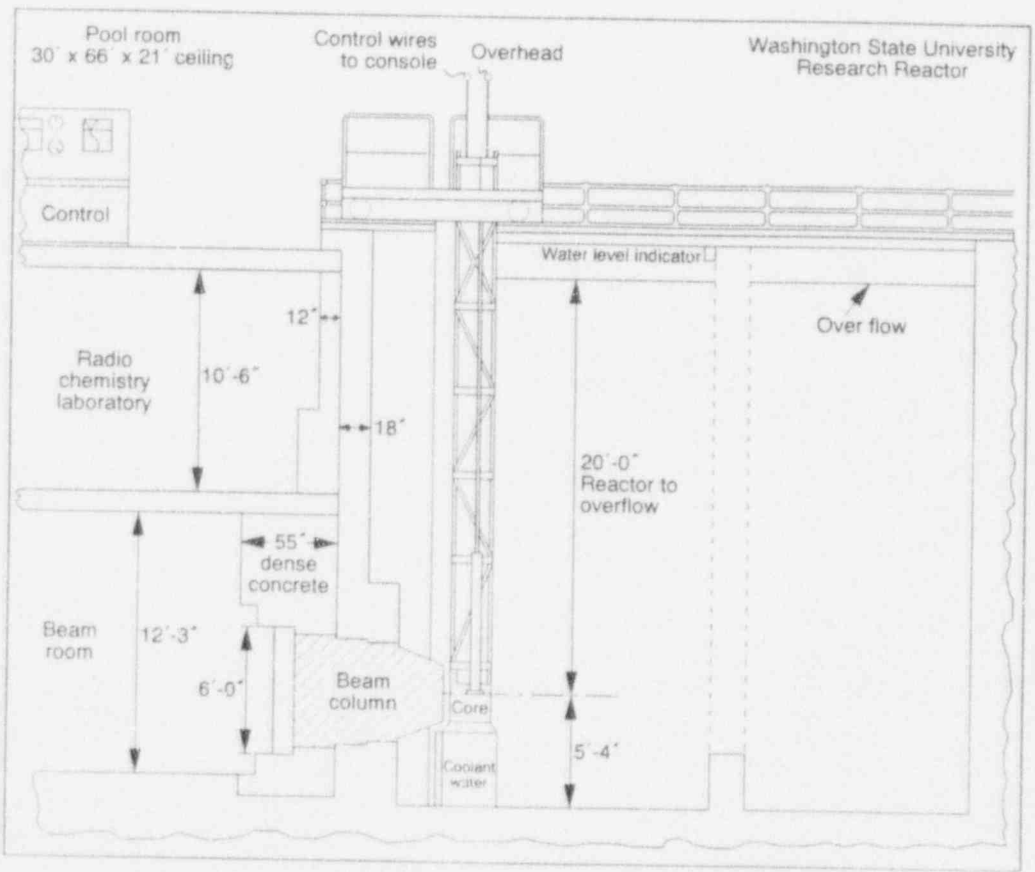


Figure 2. Elevation Plan Sketch.

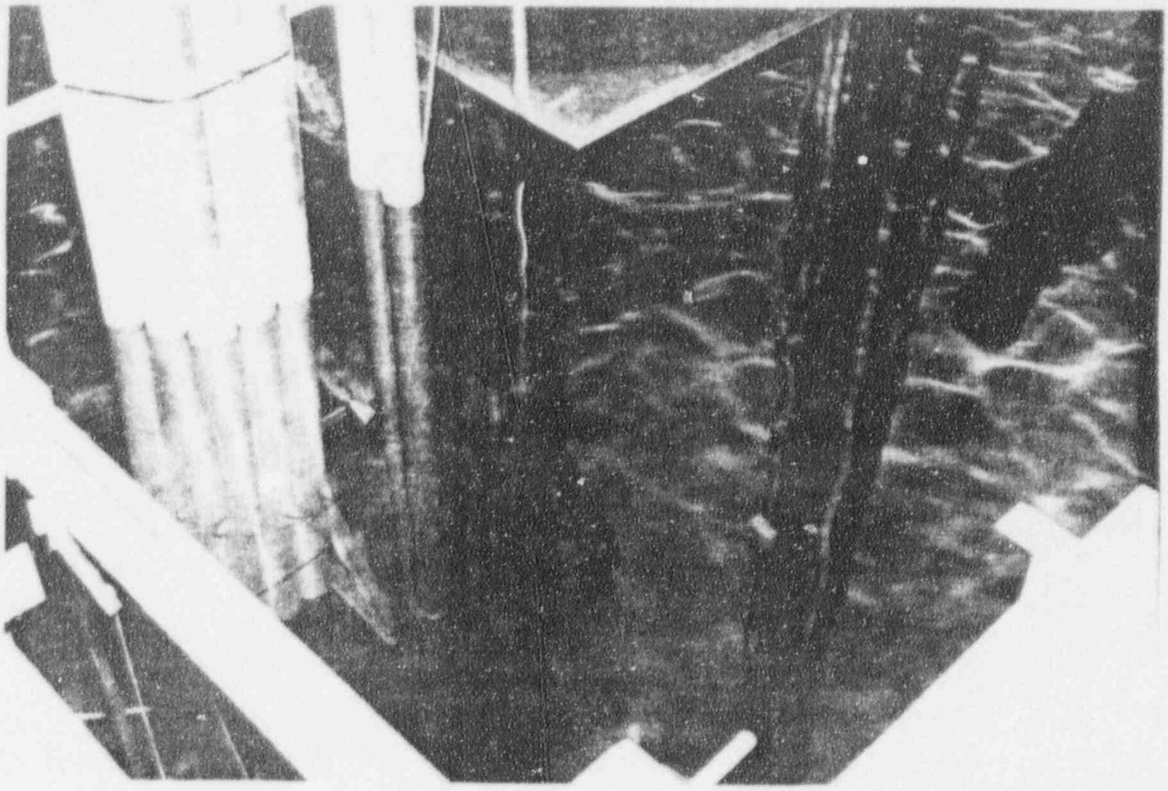


Figure 3. A view into the reactor pool below the bridge.

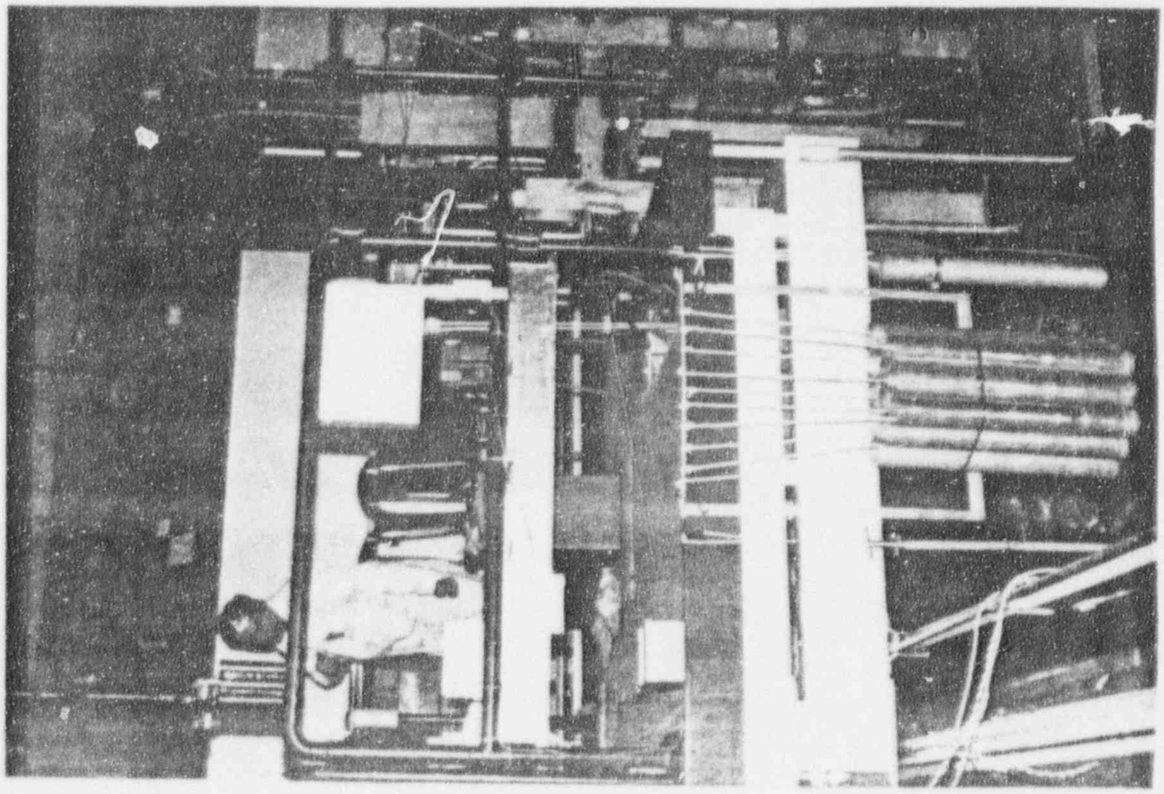
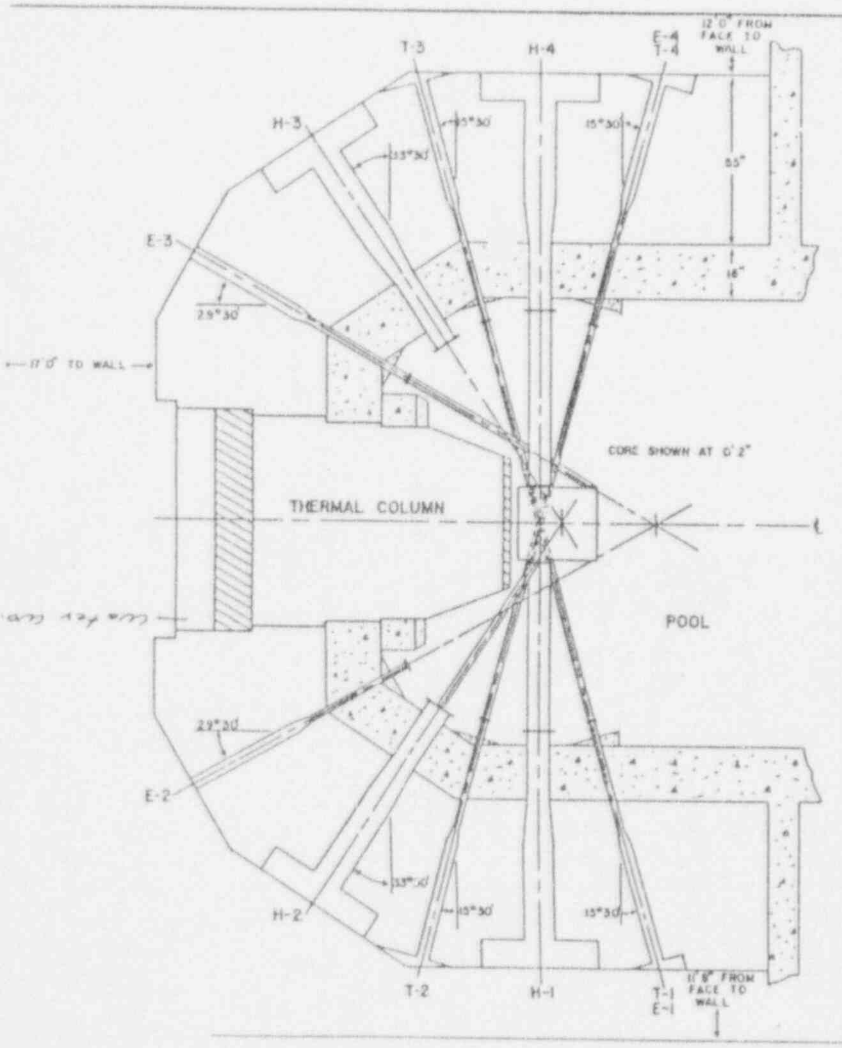


Figure 4. Reactor operator moving the core and bridge.

A cross section of a typical core layout is provided in the next section (Figure 9). The core contains standard (20% enriched) fuel elements as well as FLIP (70% enriched with erbium as a burnable poison) fuel elements. There are several possible loading patterns for the fuel. For maximum leakage flux into the thermal column, the graphite reflector pieces near the thermal column can be replaced with fuel elements.



BEAM PORT SCHEDULE							
	LENGTH, INCHES				℄ HEIGHT, INCHES		
BEAM PORT	10" I.D. SECTION	10" to 8" REDUCER	8" I.D. SECTION	EXTENSION	FROM CORE ℄	FROM POOL FLOOR	FROM BEAM RM FLOOR
H-1	31.50	15.50	21.75	55.13	-0.75	60.50	33.50
H-2	31.50	15.50	21.75	56.00	8.25	69.50	42.50
H-3	31.50	15.50	21.75	- - - -	8.25	69.50	42.50
H-4	31.50	15.50	21.75	54.63	-0.75	60.50	33.50
BEAM PORT	4" I.D. SECTION	4" to 2" REDUCER	2" I.D. SECTION	EXTENSION	FROM CORE ℄	FROM POOL FLOOR	FROM BEAM RM FLOOR
E-1	38.40	4.50	37.00	55.38	-5.75	55.50	28.25
E-2	39.19	4.50	37.00	69.75	-10.25	51.00	23.63
E-3	39.19	4.50	37.00	70.50	-10.25	51.00	24.13
E-4	38.40	4.50	37.00	54.50	-5.75	55.50	28.13
T-1	38.40	4.50	37.00		-25.25	36.00	9.00
T-2	38.40	4.50	37.00		-20.25	41.00	13.75
T-3	38.40	4.50	37.00		-25.25	36.00	9.25
T-4	38.40	4.50	37.00		-20.25	41.00	13.87

NOTES:
1. THE H-1 EXTENSION IS 5.50" I.D., 0.25" WALL THICKNESS.
2. THE H-2 EXTENSION IS 2.067" I.D., 2.375" O.D.
3. THE H-4 EXTENSION IS TAPERED WITH AN INNER DIMENSION OF 5.00" SQ. AT THE CORE END & 3.625" SQ. AT 53.00" FROM THE END. THE SIDES ARE 0.50" PLATE AND THE END IS 0.25" PLATE.
4. THE E-SERIES AND T-SERIES EXTENSIONS ARE 2.067" I.D., 2.375" O.D.
5. THE ℄ OF H-1 & H-4 IS 9.50" FROM THE THERMAL COLUMN FACE.
6. THE POINT WHERE THE ℄'S OF E-2 & E-3 CROSS THE POOL ℄ IS 48.00" FROM THE THERMAL COLUMN FACE.
7. THE POINT WHERE THE ℄'S OF H-2 & H-3 CROSS THE POOL ℄ IS 17.00" FROM THE THERMAL COLUMN FACE.

NUCLEAR RADIATION CENTER
WASHINGTON STATE UNIVERSITY
PULLMAN, WASHINGTON

TITLE: PLAN VIEW OF BEAM PORT FACILITIES		
SCALE: 1/4"=1'	DRAWN BY: J. OGREN	DRAWING NO.
DATE: 5/25/71	CK'D. BY: W. HENDRICKSON	

Figure 5. Plan view of WSU reactor beam port facilities.

2.2 Thermal Column

Figure 6 shows the evacuated cavity of the thermal column and Figure 7a shows the room outside the pool as presently configured. There is a large-vehicle door opposite the thermal column and there is ample room outside the thermal column for shielding, patient manipulation and equipment associated with the irradiations. There is a 10-inch ordinary-concrete ceiling above the room. The thermal column contains many stringers of graphite, then lead shielding bricks, and a final light-water tank which is recessed about 6 inches into the heavy-concrete wall. Figure 7b shows the outer portion of the water tank as viewed from the room.

Essentially, the thermal column consists of a column of graphite in a sealed container which will withstand the pressure of the water. The container is made up of an aluminum transition section near the core and steel sections in the shielding wall. This aluminum section is tapered on the sides so as to not interfere with the beam ports (Figures 8a and 8b). The front plate (facing the reactor) is 1/2" thick 2S aluminum which is reinforced with eight 1" x 8" aluminum ribs. These ribs are welded together to form a grid designed to withstand the water head with minimum deflection. The tapered walls of the transition transfer this load to aluminum walls of the column. The aluminum walls extend outward to a point opposite the actual pool wall. The aluminum section of the container rests on a concrete pad on the pool floor and is encased by about 1 foot of reinforced concrete which restrains the forces at this depth tending to collapse the column. Sections of aluminum I-beam have been welded to the aluminum walls and imbedded in the reinforced concrete. This I-beam will withstand the forces tending to push the entire column out of the pool. Circuiting the entire aluminum transition is a seepage collector. Any seepage into this collector will be collected in the common drain. The plate on the water side of the column is separated from the core by 3/8" to 1/2" of water. The support angles protruding from the grid plate provide this clearance. Water convection currents in this space will provide cooling for heat produced in the thermal shield when the reactor is operated at high power levels.

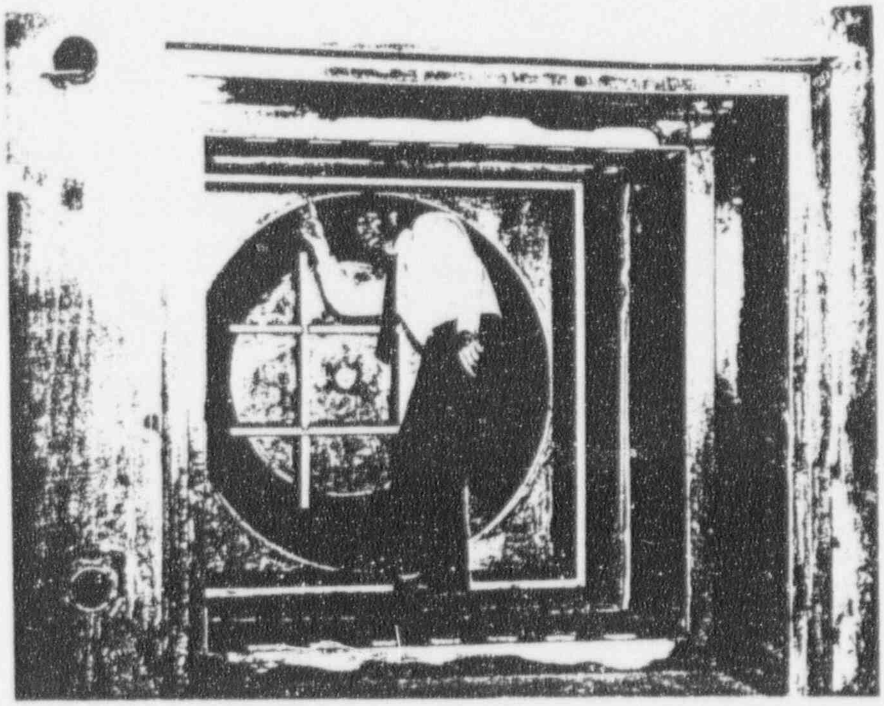


Figure 6. A view into the evacuated thermal column.

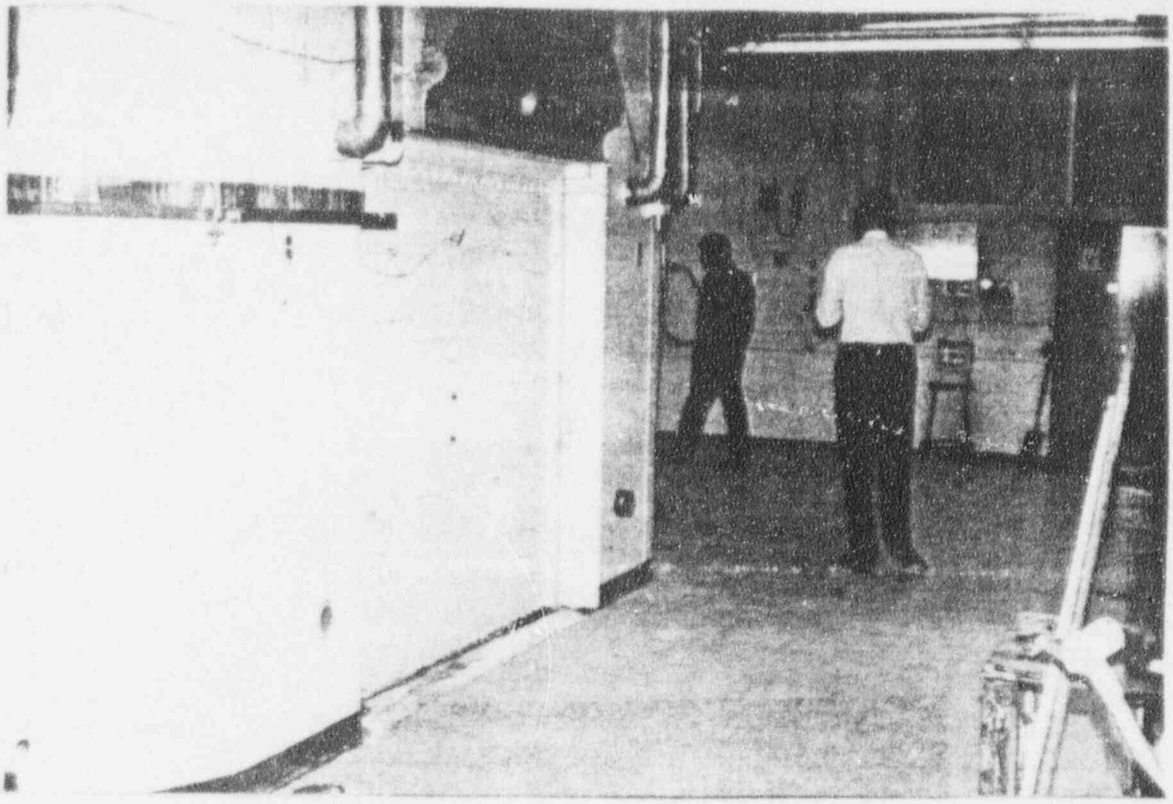


Figure 7a. A view of the room just outside the present thermal column.

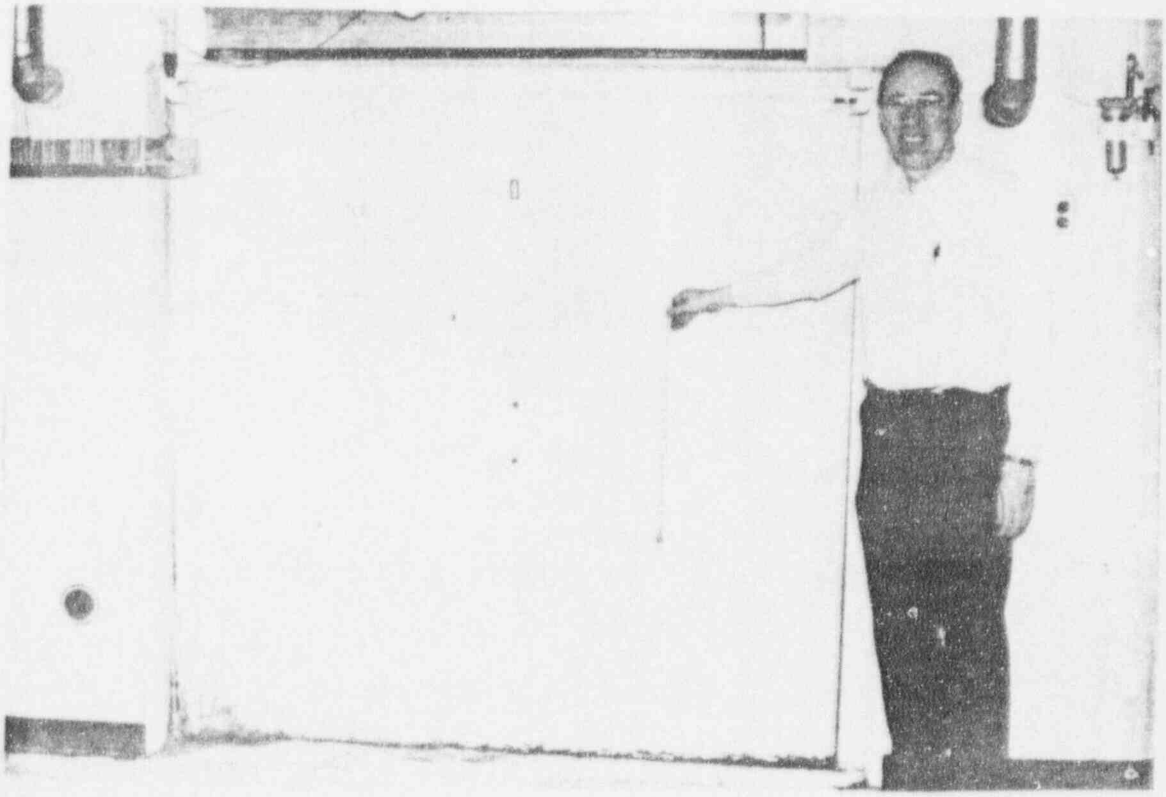


Figure 7b. A view of the front of the enclosed thermal column.

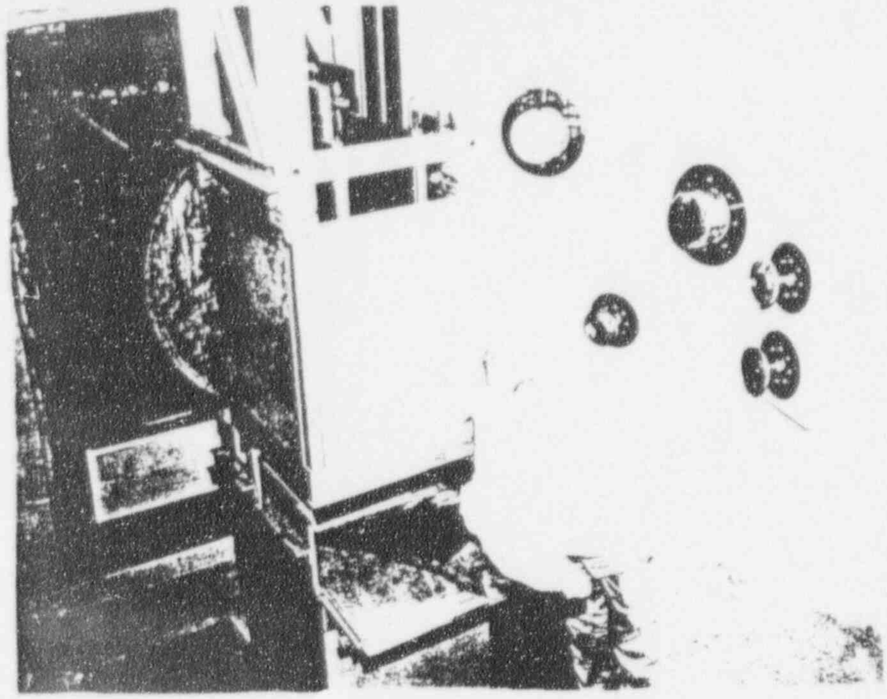


Figure 8a. A mockup of the core adjacent to the protruding core of the thermal column.

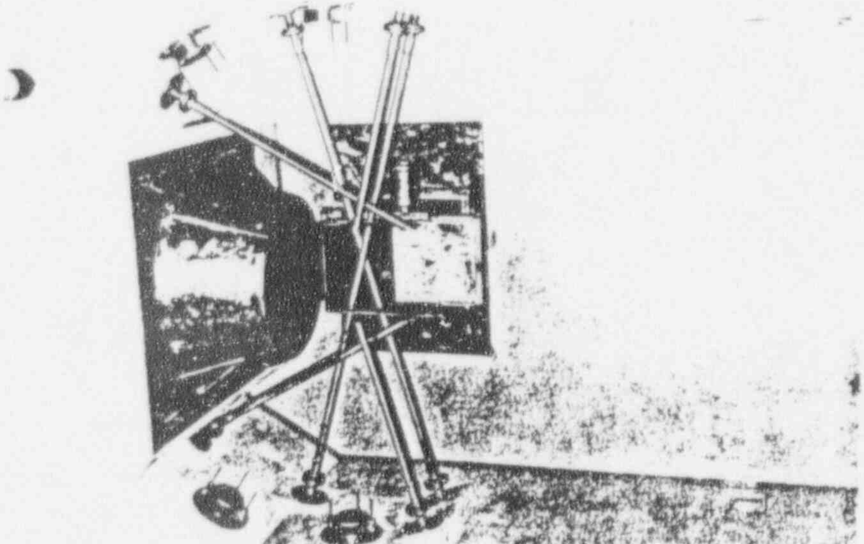


Figure 8b. A view of beam ports and thermal column core.

The thermal shield consists of 2.75" of lead brick. This also assists in shielding the column during shutdown and removes a large percent of the low-energy core gammas during operation. Around the outer perimeter of the aluminum section there is welded a small angle. The steel section of the column is bolted to this angle. This joint is not sealed but merely serves to align the two sections of the column. At this point the column is 2" wider in each direction. This extra space is occupied by 1" of shielding lead on all walls. There is another similar step 18" farther out. Here the additional space is occupied by 2" of lead. The outer end of the column is 6' x 6' and is occupied by lead brick and a final water tank. The inner walls of the column are lined with 1/4" sheets of Boral. These sheets are mounted on the walls with flush fasteners. They are mounted so that no abrupt steps exist on the column's inner surface to interfere with placing of the graphite logs. These sheets of high neutron absorbing material are placed on the walls to reduce activation of the concrete and the column container. Also by providing a surface which is black to thermal neutrons, the desired cosine flux distribution can be more nearly approached. Although cadmium would be a much cheaper neutron absorber, Boral has been used because of its shorter half life and because access to the pool is desired. Fast neutrons escaping the column will be slowed down and captured in the concrete. This effect will only be significant for radiation dose near the inner end of the column and substantially decays out within 24 hours.

3. ANALYSIS

The two-dimensional DORT[5] deterministic (Sn) code was used to determine estimated beam parameters. The locally-extended BUGLE80[6] cross section library was used in the DORT model. The reactor core and filter were represented as horizontal, cylindrical regions in the calculational model. This cylinder model will not be good for fluxes in and near the core but past studies for the BMRR and GTRR ... ign show that it provides quite good results for the beam predictions. Future calculations will employ three-dimensional calculations and independent physics data for verification of results.

3.1 Calculations for Standard Core Layout (Interior Beam)

Figure 9 shows a non-Boron Neutron Capture Therapy (BNCT) core layout for core 33X (Jan. 1993) provided by WSU personnel. DORT calculations were performed to estimate beam performance with this core placed at the 0' 0" location (next to the thermal column).

Figure 10 shows a sketch of the evacuated thermal column. Calculations were performed for both AlF_3/Al (70/30) and Al_2O_3 as a primary neutron spectrum shaping material. The AlF_3/Al material is being developed by investigators in Helsinki Finland[5]. The Al_2O_3 material is presently employed for the BMRR epithermal-neutron facility. Figure 11 shows a sketch of an assumed configuration for the calculations. Here the beam exit port is located 1-1.2 meters from the core side of the thermal column. Table 3 lists the thicknesses of the components assumed inside the thermal column.

Table 3. DORT Cases With Current Fuel Loading Pattern.

Case	Filter Material	Filter Thickness (cm)	Bismuth Gamma Shield Thickness[2] (cm)	^{6}Li/poly Thickness[2] (cm)
I1	$A1F_3$/A1[1] (70/30)	85.0	10.0	6.0
I2	$A1F_3$/A1 (70/30)	70.9	11.4	6.3
I3	$A1F_3$/A1 (70/30)	62.2	11.0	6.8
I4	$A1_2O_3$	70.9	11.4	6.3

Note: 1. assumes 100% theoretical density for the $A1F_3$ with a matrix consisting of 70% $A1F_3$ and 30% A1.
2. varies because of available mesh spacing in model.

Figure 12 shows the predicted performance for intensity and fast-neutron KERMA for these four cases. The one case for Al_2O_3 demonstrates the superior performance of the AlF_3/Al composite. For this thickness (71 cm), the $A1F_3$/A1 beam intensity is five times that with Al_2O_3 and the fast KERMA is nearly a factor of two less.

It must be pointed out that this model will likely underestimate the fast-neutron KERMA, probably by about 20%. Therefore, a calculated K_f of $2x10^{11}$ will likely increase to $2.4x10^{11}$ for the actual beam. Also, no optimization was done for the incident gamma dose nor the thermal flux.

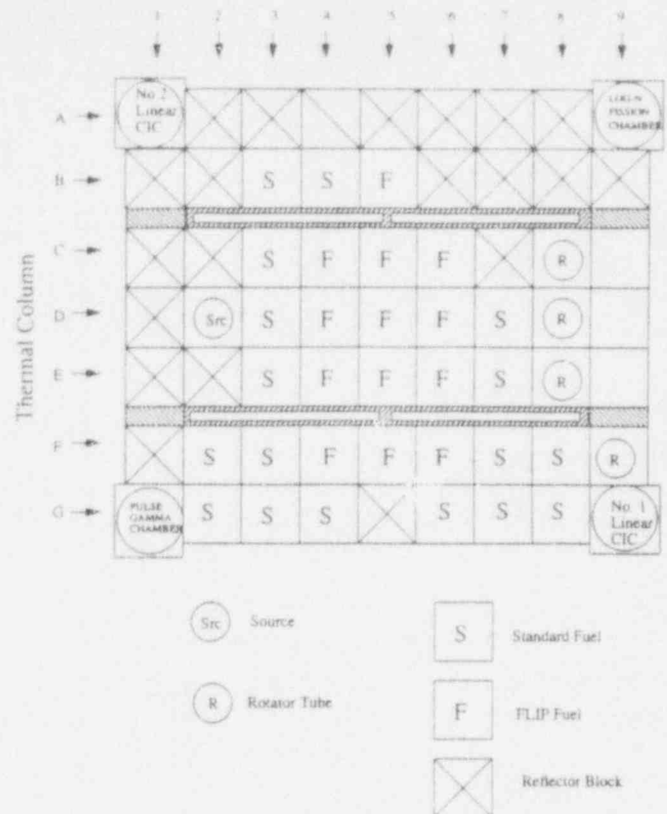


Figure 9. Core 33X layout, January 13, 1993.

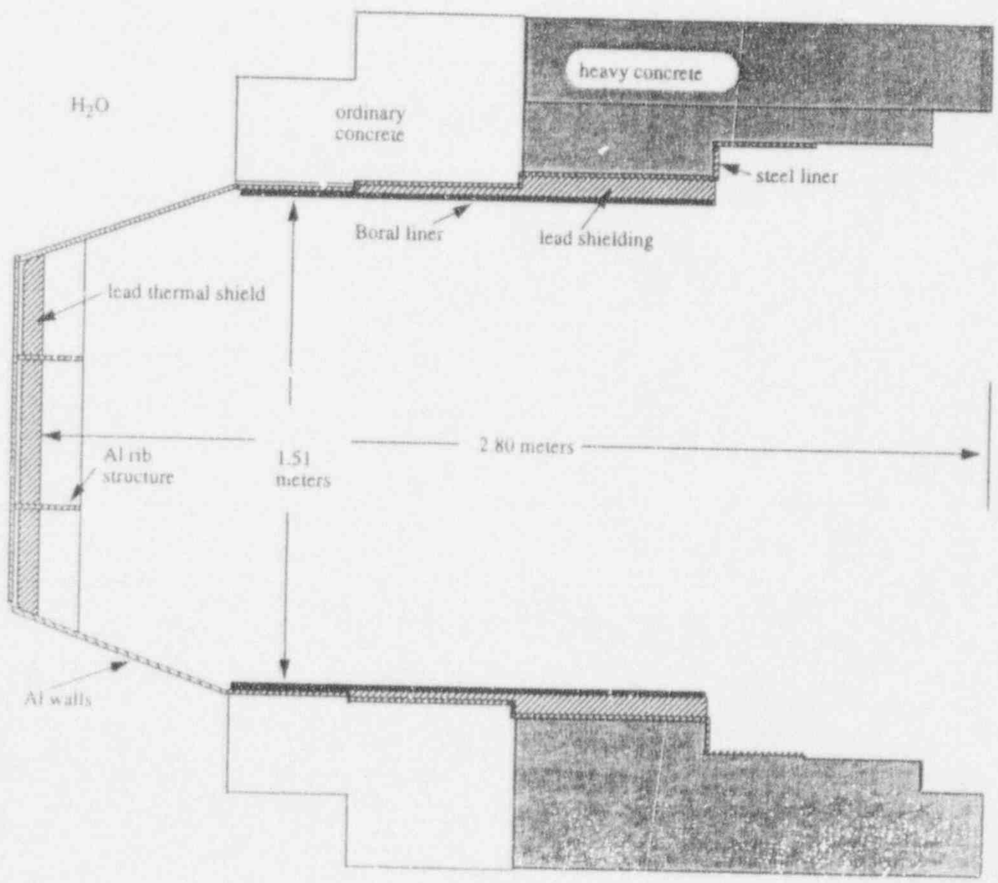


Figure 10. Thermal column assembly (evacuated).

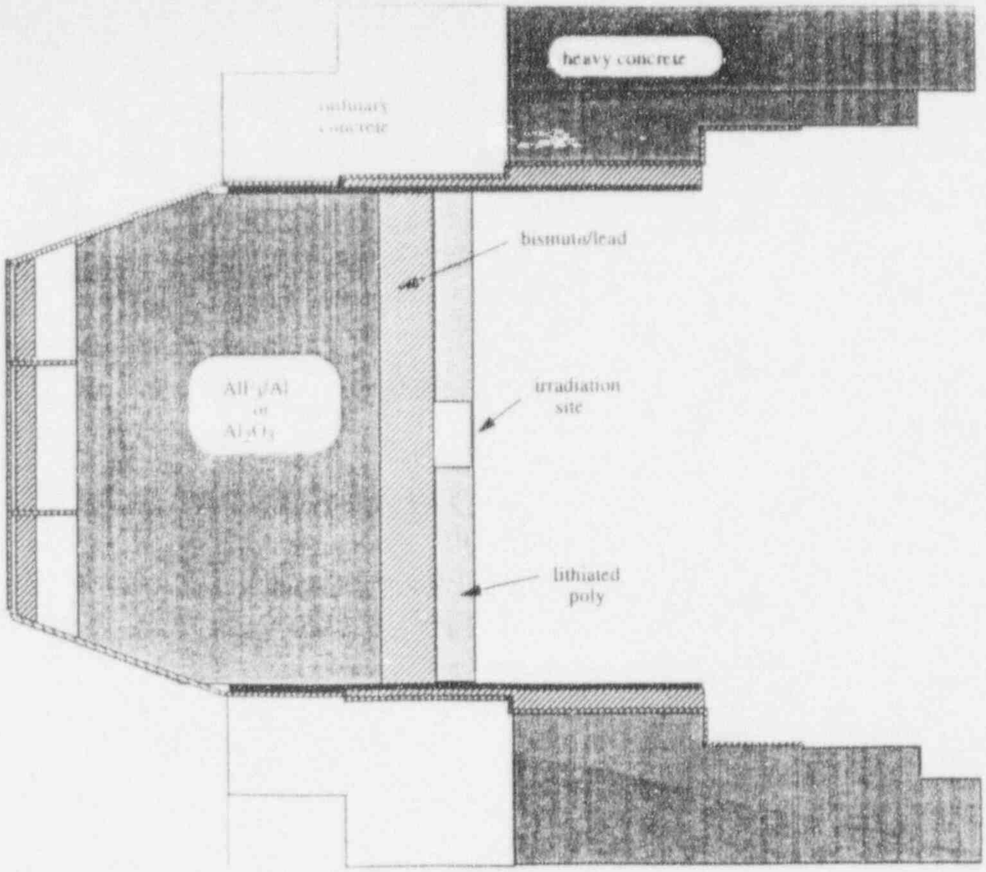


Figure 11. Thermal column assembly for interior beam-port studies.

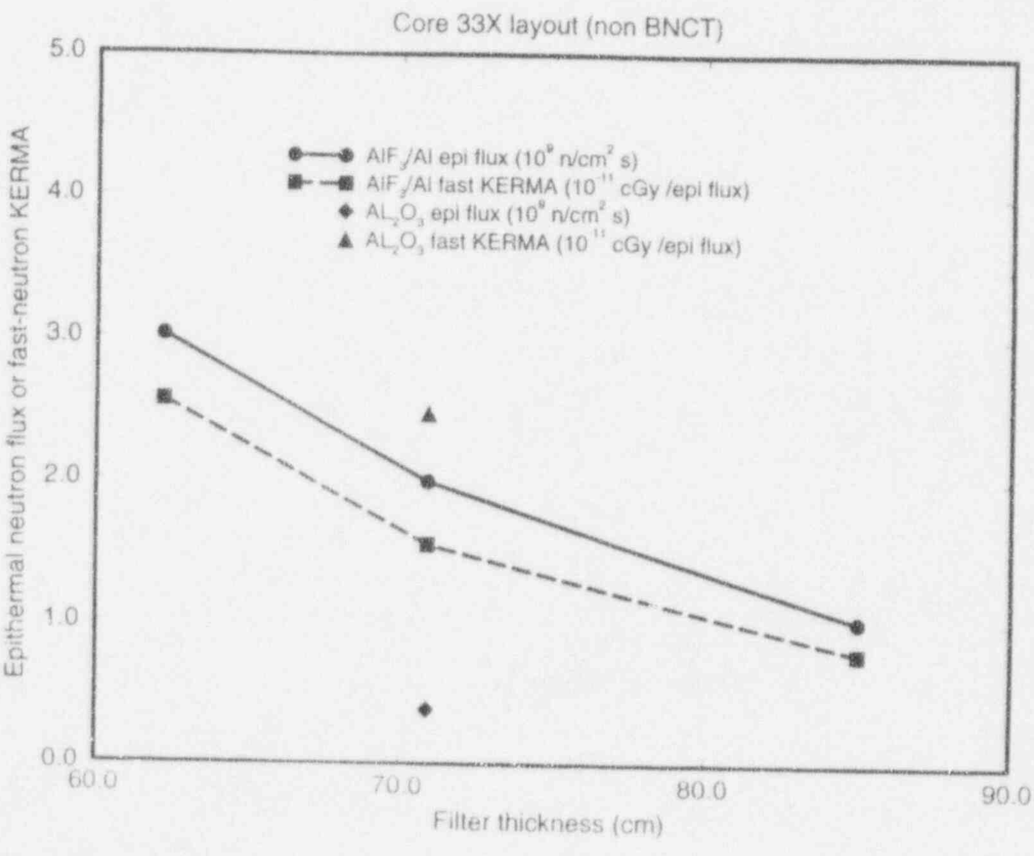


Figure 12. WSU TRIGA: performance versus filter thickness.

3.2 Calculations for BNCT Core Layout (Interior Beam)

Figure 13 shows a layout provided by WSU personnel for BNCT. This layout (core 34 BNCT) is designed to enhance leakage from the core to the thermal column. One calculation was performed for the interior beam using this layout and the filter configuration of case I2 (71 cm AlF_3/Al). Table 4 shows the change in beam performance when the new core layout is chosen.

Calculations were also pe 'ormed with FLIP (high enriched) fuel placed in the row nearest the thermal column. For this core loading, beam intensity increased very significantly ($\sim 10^{10}$) but results are not reported here because loading FLIP fuel at the core edge is not allowed in the reactor technical specifications.

Table 4. Calculated Increase in Beam Performance with BNCT Core Layout; Interior Beam, 71-cm AlF_3/Al (70/30).

Quantity	Core Layout 33X (January 1993) Case I2	Core Layout 34 (BNCT) Case I5	% Change
Epithermal Neutron Flux Intensity (n/cm^2 s) at 1 MW	1.99×10^9	2.84×10^9	+43%
Fast-Neutron KERMA (cGy/Epithermal Flux)	1.55×10^{-11}	1.56×10^{-11}	~0

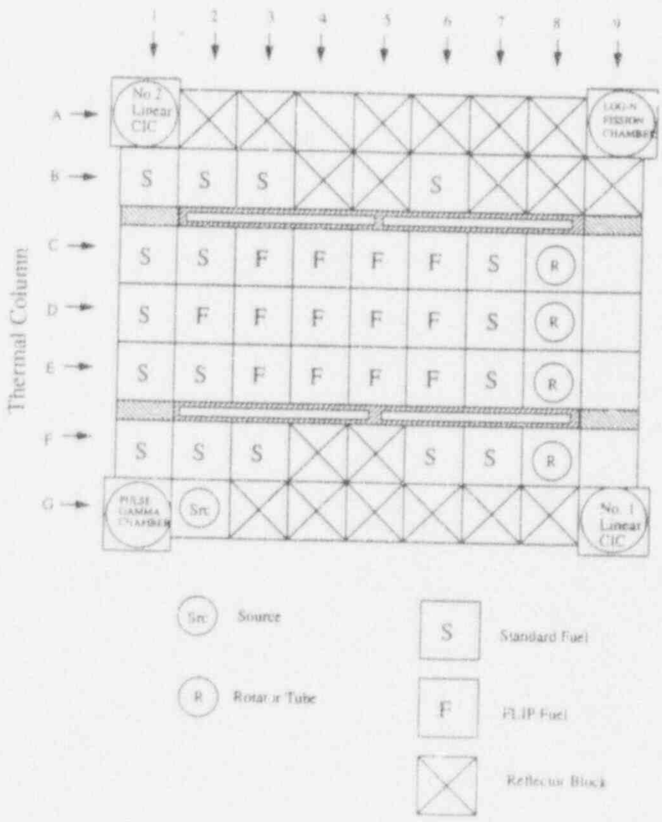


Figure 13. Core 34 BNCT

3.3 Calculations for BNCT Core Layout (Exterior Beam)

The DORT calculations indicate that an excellent beam can be obtained interior to the thermal column. There are two significant disadvantages however to the interior beam: (1) positioning capability, and (2) higher background-dose exposure to patient and therapist.

Therefore, a model was constructed to investigate beam characteristics obtainable when the beam exit port is brought out to the end of the thermal column where access is excellent (Figure 7). A sketch of this concept is shown in Figure 14 and an alternate concept is shown in Figure 15. For this model, 65-cm of AlF_3/Al (70/30) was assumed as the primary filter material. Variations in materials in regions interior to the thermal column were made to investigate the effect on beam characteristics.

Calculated results for these cases are shown in Table 5.

Table 5. Beam Characteristics for Exterior Beam Port with BNCT Core Layout; 65 -cm AlF_3/Al (70/30) as Primary Filter Material.

Case	Filter Perimeter	Collimator	Side Reflector	Flux Intensity[1] (n/cm2 x) @ 1 MW	Fast-Neutron KERMA (cGy/flux)	Gamma[2] KERMA (cGy/flux)
E1	AlF_3/Al	Bismuth	Borax[3]	8.16×10^{8}	2.65×10^{-11}	8.7×10^{-12}
E2	AlF_3/Al	Bismuth	Al_2O_3	1.00×10^{9}	2.43×10^{-11}	8.1×10^{-12}
E3	AlF_3/Al	Al_2O_3	Al_2O_3	8.00×10^{8}	2.17×10^{-11}	8.9×10^{-11}
E4	Al_2O_3	Bismuth	Al_2O_3	8.46×10^{8}	2.24×10^{-11}	1.2×10^{-11}
E5	AlF_3/Al	Lead	Borax	8.42×10^{8}	2.46×10^{-11}	1.04×10^{-11}

Note: 1. an alternate core representation of core layout 34 gave intensitites about 20% less than listed here.
2. not including gammas from thermal-flux suppression mechanism (if any)
3. $Na_2B4O_7 10H_2O$

The gamma KERMAs listed in Table 5 mean little in these cases because there is nothing yet in the design to remove thermal flux. There are three ways the thermal flux can be suppressed and the way this is done will affect the collimator design and perhaps the filter thickness. One way would be to place a cadmium sheet (~30 mils) at the end of the filter. This would eliminate the thermal neutrons without diminishing the epithermal flux but would cause the generation of hard gammas which might affect the shield/collimator designs. Another way would be to incorporate lithium (~1%) into the AlF_3/Al composite. This would diminish epithermal flux somewhat but would beneficially suppress gamma production and might reduce the thickness of bismuth (or lead) shielding required. A third way could be to use lithium sheeting built into the flux tailor (described later) region. The first two methods would produce a good epithermal beam but would reduce the thermal-flux intensity if one wants the capability to convert to a thermal beam for cell/murine experiments. The third method would produce a good epithermal beam and a much stronger thermal beam should it be desirable to convert.

Materials used at the filter perimeter should be further investigated. For example, the use of a very common (inexpensive) material (Al_2O_3) at the sides of the collimator instead of a flux suppressor (borax) increases beam intensity by 20% and decreases the fast KERMA by 10%. This would be a no cost option to improve the beam. Figure 16 shows the calculated neutron spectrum for a typical run (case E4).

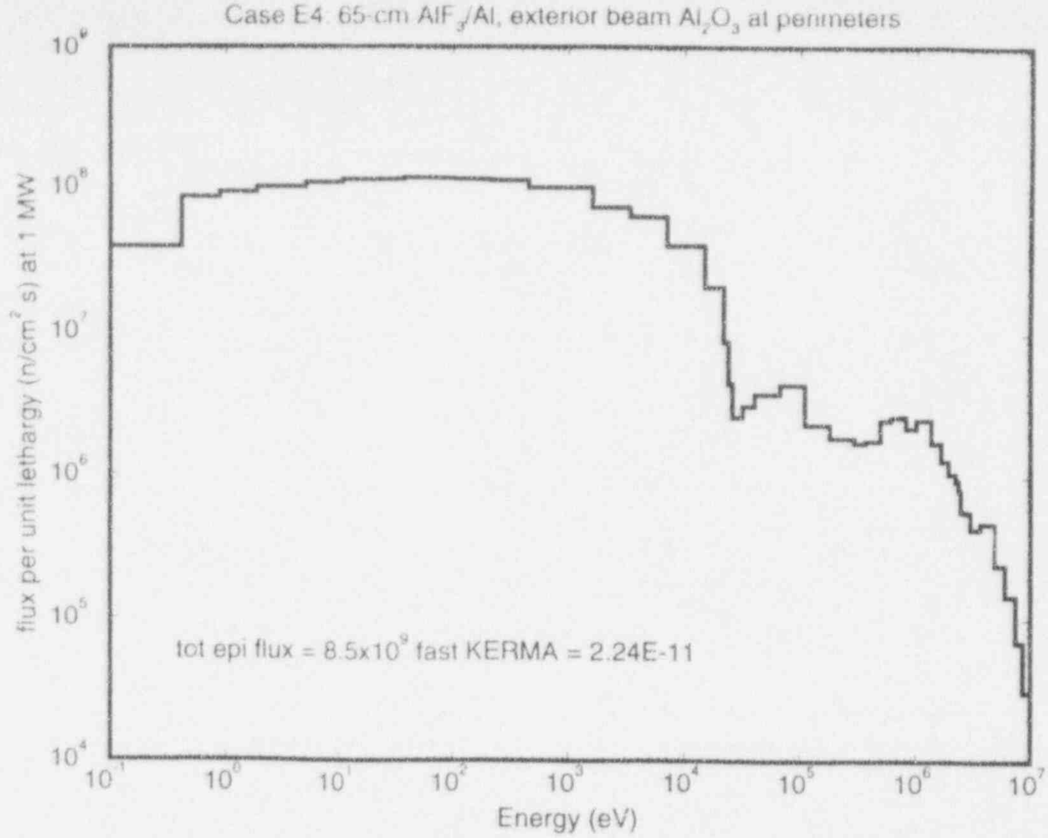


Figure 16. Calculated neutron flux spectrum for BNCT Case E4.

Case E3 shows that no gain is achieved by replacing the collimator with Al_2O_3 and, as might be expected, the gamma KERMA is dramatically increased. Case E4 was run to determine if less AlF_3/Al could be used by placing Al_2O_3 at the outer perimeter of the filter. For this case the outer 25 cm of the cylindrical representation was assumed to be the oxide. The effect (compare with case E1) is to reduce the intensity by about 15%. This configuration should be investigated further since it reduces the AlF_3/Al requirements by more than one half (saves ~20K). For a configuration with the same fast KERMA, the intensity may not be that much different. This result needs verification however since it is not clear why the fast KERMA is less with this configuration.

Case E5 is also a cost saving configuration since there is already an existing supply of lead and bismuth is more expensive. The beam is actually a little better with lead except for the gamma KERMA which may not be a problem anyway.

3.4 Beam Tailor

The beam tailor, alluded to previously, could be removable sections defining the last portion of the beam-tailoring system. Potentially, several beam tailors could be constructed and the beam could rapidly be changed from a large field to a small field or perhaps from an epithermal beam to a thermal beam for cell/murine research or as a prompt gamma facility.

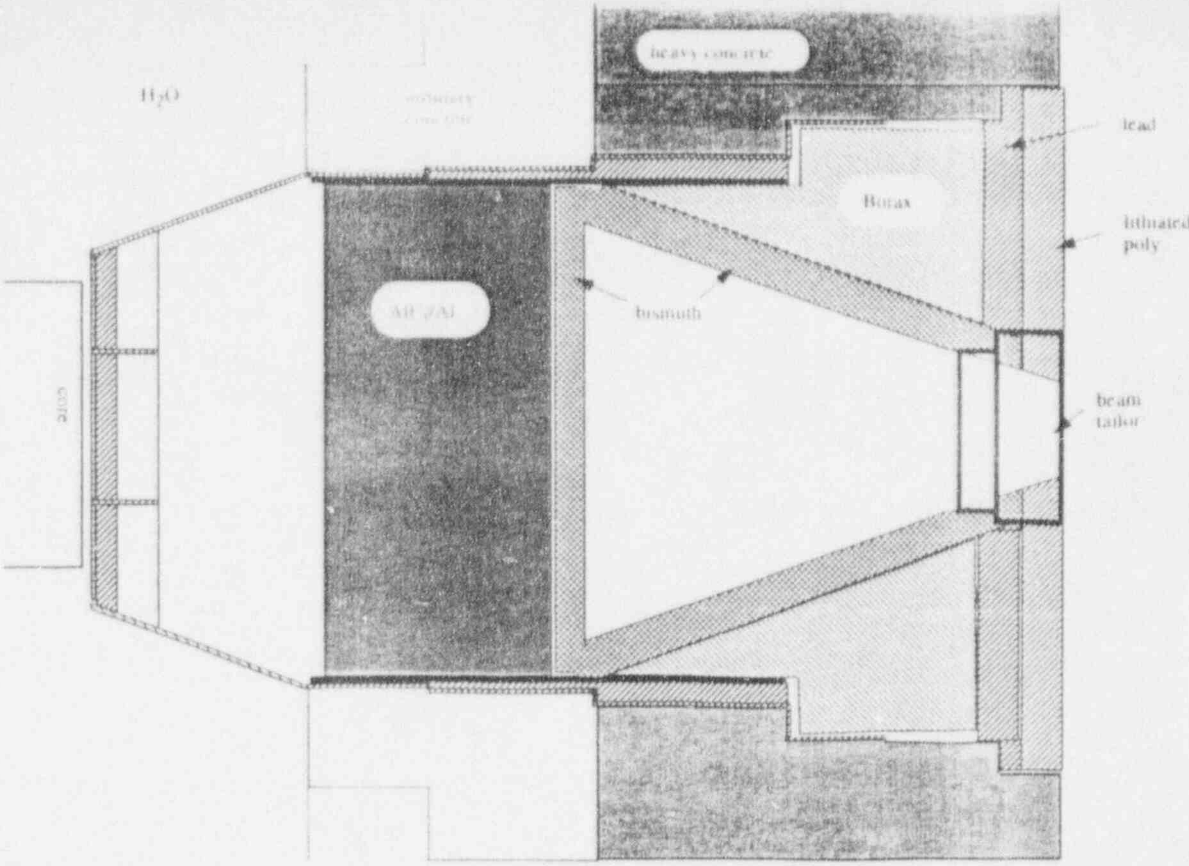


Figure 14. Thermal column assembly with $A1F_3/A1$ filter (not to scale).

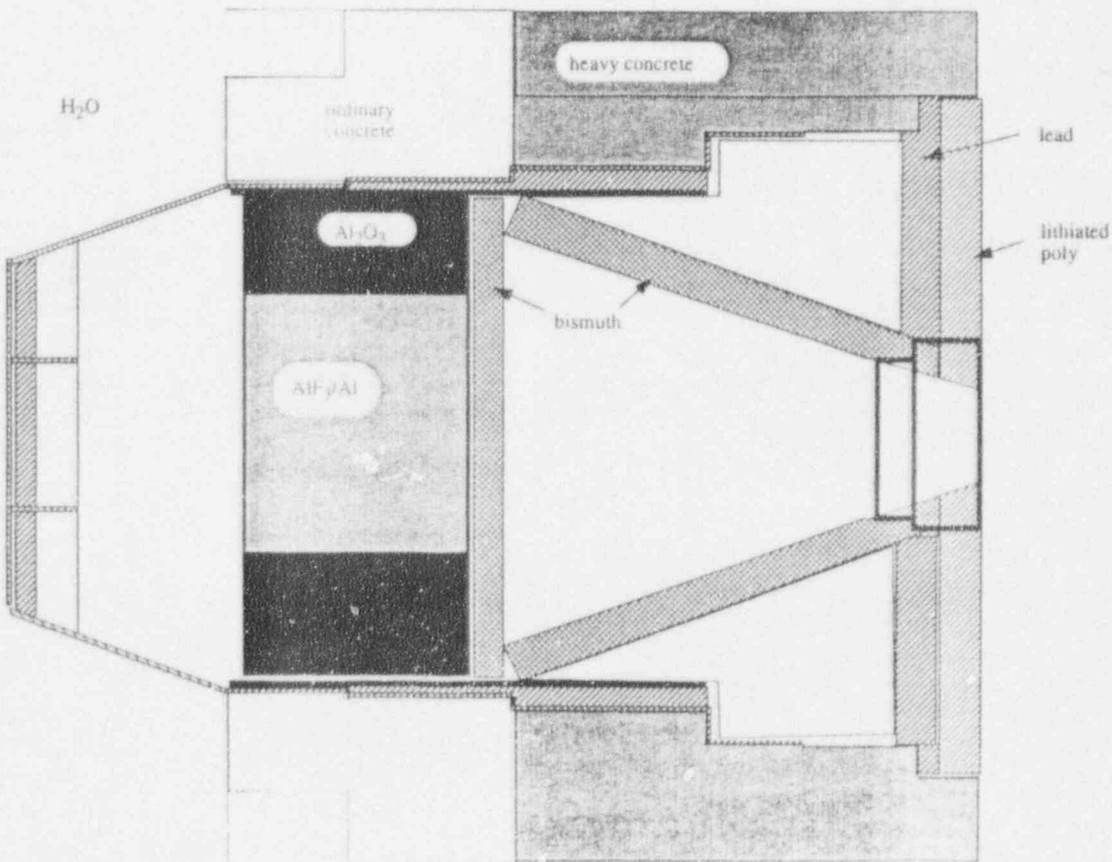


Figure 15. Thermal column assembly with $A1F_3/A1$ and $A1_2O_3$ filter (not to scale).

3.5 Beam Shutter

There is no beam shutter in the present facility and it would be a major campaign to construct a large shutter such as is in place at the BNL and the GTRR facilities. It is not necessary to have a shutter for the WSU concept since the reactor can be scrammed to a small percentage of full power in a matter of seconds. The reactor core then can be manually retracted several feet back into the center of the pool and away from the thermal column in just a few seconds to reduce the gamma field even more. With the exterior beam, it would be possible to incorporate an external shutter for further protection. This could be a slab that moves up to position the beam tailor and moves down to position neutron and gamma shielding in front of the collimator opening for further protection.

3.6 Patient Treatment Room

It will be necessary to construct a room around the beam facility to isolate the radiation field and reduce radiation to an acceptable level in all other areas of the facility. This room would have walls of heavy concrete (or equivalent) with thickness of ~200 grams/cm^3 that would be lined with lithiated or borated polyethylene. A heavy door at the entrance would also be required.

4. CONCLUSIONS

The results of these studies indicate that a useful epithermal beam can be obtained with a modified reactor facility. The exterior concept has lower intensity than the interior concept; however, it is more desirable because of excellent access to the beam port. Except for changing the fuel loading pattern, no core or control-system modifications are required. A treatment room with thick concrete (or equivalent) walls and ceiling would have to be constructed to keep the radiation dose to staff at an acceptable level. A preliminary study based on non-seismic issues has concluded that the present structure could accommodate the weight of the walls and ceiling. Design studies for the treatment room are now underway at WSU.

5. REFERENCES

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