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FTR Tag Burnup

R. B. Kidman*

Los Alamos Scientific Laboratory, University of California,
Theoretical Division, Los Alamos, New Mexico 87544

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I. Introduction

Control and fuel pins for the Fast Test Reactor (FTR) are designed and fabricated to perform satisfactorily throughout their expected lifetime. Nonetheless, with about 17,000 fuel and poison control pins undergoing irradiation in the reactor at the same time, it is possible that cladding failures might occur prior to attainment of goal exposure. Cladding failure would result in the release of the contained gas from the pin. Although pin depressurization will not necessarily impair the operating capabilities of the pin, it was deemed desirable to include a system for detecting the existence of a cladding failure, and a system for identifying or locating the assembly, in order that it might be removed if operating experience indicates such action to be prudent. The failure of fuel cladding will be detected by monitoring the reactor cover gas for the presence of noble gas fission products.

The following procedure is being implemented on the FTR to rapidly locate failed fuel subassemblies. Each subassembly will be fabricated with a small amount ($\sim$2cc/pin) of a unique ratio of noble gas isotopes (tag) in its plenum. Once a subassembly failure has been detected, a sample of the reactor cover gas will be analyzed with a mass spectrometer to determine which tag or tags are present. The tags identified will then be used in conjunction with burnup and loading charts to locate the failed fuel or absorber subassembly.

Previous work[1] has recognized and investigated the fact that the tag in a subassembly will change due to differential burnup of the constituents of the noble gas ratio. However, the single volume-averaged flux spectrum used in that study was expeditiously based on a simplified, two-dimensional model of

the FTR plenum which did not include the perturbing effects of control rods, test loops, and other reactor components. In the present study, neutron spectra generated from a detailed, three-dimensional model of the FTR are utilized to calculate the gas tag burnup changes for each fuel and control subassembly.

The fuel subassembly exhibiting the worst combination of tag burnup changes, burnup uncertainties, mass spectrometer uncertainties, and uncertainties in indirect noble gas production was used to compute the minimum spacing of tags that would still allow the tags to be unambiguously identified.

II. Calculational Procedure

The overall strategy in this study is to volume average appropriate regions of a three-dimensional neutron flux distribution to obtain plena-averaged spectra for each individual FTR subassembly. These plena-averaged spectra are then combined with noble gas cross sections to obtain reaction rates that can be used to predict the burnup of noble gases (tags) initially placed in the subassembly plena. The Figure shown is a more detailed outline of the calculational procedure followed in this study.

The basic neutron cross section library used is FTR Set-300S[6]. This is an ETOX[7]-generated, 42-group library based on ENDF/B[8] Version II data with modifications to achieve better agreement with integral critical assembly results. The library was chosen because it has been successfully evaluated[2] and because it has a reasonable number of groups in the intermediate energy range where the noble gas isotopes exhibit most of their reaction rates. Since the library does not contain the noble gas isotopes, it was necessary to use the cross section parameters and methods employed in Reference 1 to obtain 42-group noble gas cross sections for this study. Although effective group cross sections and reaction rates for the noble gas isotopes are spectra dependent, a useful awareness of their general shape and magnitude can be gained by studying their behavior for the plenum-averaged spectrum of the central subassembly. This in-

formation is provided in the Figure which includes plots of the central subassembly plenum spectrum, the resulting noble gas cross sections, the flux breakdown by group, and the noble gas reaction rate breakdowns by group.

Two 1DX[9] runs were required to generate 42-group effective resonance shielded neutron cross sections for the radial and axial regions of the FTR.

In order to realistically predict the neutron spectra that are likely to exist in the fuel and control assembly plena, it is necessary to perform three-dimensional calculations with 3DB[11] utilizing a detailed beginning-of-life (BOL) model of the FTR that adequately accounts for all important material perturbations such as test loops, control rods, and positioning of control rods. The geometric model and zone compositions are indicated in the Figure.

The resulting three-dimensional distribution of neutron spectra can now be used to compute an average spectrum for each fuel and control subassembly plenum. In the following two sections, volume averaging is done separately for the fuel and control rods since their plena are dissimilar and occupy grossly different locations in the reactor. Subsequent sections make use of the resulting plena-averaged spectra and reaction rates to compute production of noble gases.

III. Fuel Rod Tag Burnup

Each FTR fuel pin is fabricated with a 42-inch-long expansion chamber for the purpose of containing fission product gases produced by fission in the fuel. Into this same chamber (gas plenum) will go the noble gas isotopes that constitute a subassembly's unique combination of tags. As can be seen in the Figure, this 42-inch region above each subassembly has been specifically included in the three-dimensional FTR model. This makes it a simple matter to obtain the volume-averaged plenum flux, VAPF(i,s), for each group, i, and for each subassembly, s, that will be used to determine tag burnup changes for each subassembly:

$$VAPF(i,s) = \sum_{n=1}^{72} F(i,n) * V(n) / \sum_{n=1}^{72} V(n).$$

In this equation, the sum is over the 72 spatial meshes comprising the plenum volume of subassembly s, V(n) is the volume of spatial mesh n, and F(i,n) is the group flux at spatial mesh n. The noble gas capture cross sections, $\sigma(i,m)$, for group i, and isotope m, can now be combined with the above spectra to obtain a plena-averaged atom reaction rate, $\overline{\phi\sigma(s,m)}$, for each subassembly s, and each isotope m:

$$\overline{\phi\sigma(s,m)} = \sum_{i=1}^{42} VAPF(i,s) * \sigma(i,m).$$

Derivation of the tag burnup equations is straightforward and has been done in Reference 1. For the sake of completeness, the final equation is repeated here:

$$R(t) \pm U_R^{\pm} = R_o e^{\left\{(\phi\sigma)_y - (\phi\sigma)_x \pm [(U_x^{\pm})^2 + (U_y^{\pm})^2]^{\frac{1}{2}}\right\}t}$$

where:

$R(t)$	=	Ratio of the number of x-atoms to the number of y-atoms, at time t
R_o	=	Initial ratio (set equal to 1 for this study)
$U_R^{\pm}$	=	Upper (+) and lower (-) 1σ uncertainties in the ratio at time t
$(\phi\sigma)_x, (\phi\sigma)_y$	=	Atom reaction rates for isotopes x and y
$U_x^{\pm}, U_y^{\pm}$	=	1σ uncertainties in the reaction rate for isotopes x and y.

FTR fuel subassemblies are scheduled to remain in place (no fuel reshuffling) for at least three 100-day cycles. Therefore, the above equation, with T=300 days and R_o=1, can be applied to each subassembly to obtain an upper bound (with uncertainties) on the tag changes expected during any subassembly's lifetime. Results are summarized in Table shown for the three tags currently accepted as being the most desirable (Kr-78/Kr-80, Xe-126/Xe-129, and Kr-82/Kr-80).

The results show that as one approaches a control rod the tag burnup change becomes less. This is, of course, caused by the severe flux depression within a control rod. Even more interesting, however, is the fact that these tag changes are significantly less than the tag changes calculated previously[1]. It is obvious that the presence of the withdrawn safety and control rods is globally depressing and hardening the flux in the fission gas plenum, yielding the desirable result of smaller gas tag burnup changes.

IV. Control Rod Tag Burnup

Control rod pins are fabricated with expansion chambers for the purpose of containing helium gas produced by neutron capture in the boron. As with the fuel pins, these chambers will contain tags for which we wish to determine burnup changes.

Unlike the fuel rod pins, which have a single 42-inch plenum above the fuel, the control rod pins have plenums above and below the poison section. The Figure shows the length and position of the control rod plenum regions as deduced from HEDL engineering drawings.

Volume-averaged atom reaction rates for the control rod plena are obtained after the same fashion as was done for the fuel rod plena. However, since the control rod plena were not specifically included in the three-dimensional FTR model, some of the volume averaging had to be done over partial spatial meshes

in order to accommodate the actual control rod plenum dimensions. As long as gases can communicate between the upper and lower plenum regions, as was assumed in this study, only the combined plenum results are pertinent. However, the upper and lower plenum results exist so one can fathom the consequences of noncommunication. Results are shown in the Table.

Since safety rods are scheduled to remain in the reactor for three cycles, control rods for four cycles and peripheral shim rods for six cycles, their tags must be burned for 300, 400, and 600 days, respectively, in order to ascertain maximum tag changes expected during the lifetime of any control subassembly. The peripheral shim rods exhibit the greatest tag changes because the tags are irradiated for 600 days and because the peripheral shim rods are located where the low energy neutron flux is greater than for the other tagged subassemblies.

V. Indirect Noble Gas Production

None of the noble gases currently being considered for use as tags is produced directly as a fission product. However, Kr-82 and Xe-128 are produced when Br-81 and I-127, which are fission products, capture neutrons and subsequently decay.

The equation describing the Kr-82 buildup from this process is

$$N^{Kr}(t) = \lambda F[1-EXP(-R^{Kr}t)]/[(\lambda+R^{82})R^{Kr}]$$
$$- \lambda F[EXP(-R^{81}t)-EXP(-R^{Kr}t)]/[(\lambda+R^{82}-R^{81})(R^{Kr}-R^{81})]$$
$$- \lambda F[1/(\lambda+R^{82})-1/(\lambda+R^{82}-R^{81})][EXP(-\lambda t-R^{82}t)-EXP(-R^{Kr}t)]/(R^{Kr}-\lambda-R^{82})$$

where:

$N^{Kr}(t)$ = number of Kr-82 atoms at time t

F = number of Br-81 atoms/sec produced from fission

λ = decay constant of Br-82

R^{Kr} = atom capture reaction rate for Kr-82 = $\overline{\phi\sigma}$

R^{81} = atom capture reaction rate for Br-81 = $\overline{\phi\sigma}$

R^{82} = atom capture reaction rate for Br-82 = $\overline{\phi\sigma}$.

The Xe-128 buildup is described by an exactly analogous equation.

If we assume that the central subassembly produced 7.27 MW power, and 2.9×10^{16} fissions/sec is equal to 1 MW, and the Br-81 and I-127 yields[3] are .00178 and .0043, respectively, then 3.75×10^{14} Br-81 and 9.07×10^{14} I-127 atoms/sec are produced in the "hot" subassembly. These are the F-factors for the previous equation.

The Br-82 and I-128 decay constants[4], λ, are 5.45×10^{-6} and 4.62×10^{-4} sec^{-1}, respectively.

It is assumed that any Br-81 and I-127 produced in the fuel will be a gas which rises to the fission plenum. Therefore, the volume-averaged plena flux, VAPF(i,s), previously calculated, can be combined with the Br-81 and I-127 42-group capture cross sections (as generated from data in Reference 5) to obtain the maximum atom capture reaction rates, $R^{81}=1.19 \times 10^{-10}$ and $R^{127}=7.28 \times 10^{-10}$. The factors $R^{Kr}=1.07 \times 10^{-9}$ and $R^{Xe}=1.90 \times 10^{-10}$ were previously calculated. Capture cross sections for Br-82 and I-128 are unknown so it was assumed $R^{82}=R^{81}$ and $R^{128}=R^{127}$.

Finally, using the above parameters and equation, after 300 days exposure, it is found that the "hot" subassembly will have produced $1.46 \times 10^{19}/217=6.73 \times 10^{16}$ Kr-82 atoms/pin and $2.20 \times 10^{20}/217=1.01 \times 10^{18}$ Xe-128 atoms/pin.

Now, if it is assumed that a nominal fuel pin tag contains ~0.06 ml of Xe-128 or about 1.61×10^{18} atoms, then Xe-128 production from fission is 63% of this, which simply makes Xe-128 unacceptable for a gas tag.

A nominal fuel pin tag will contain ~0.25 ml of Kr-82 or about 6.72×10^{18} atoms. Production from fission is seen to be only about 1% of this initial load. The values used in the design (Kr-82/Kr-80 ratios for each subassembly) have <u>not</u> been corrected for Kr-82 production.

VI. Spacing

Since all subassemblies will contain the same tag isotopes to form their unique tags, one must be concerned about how close the initial ratios (tags) can be spaced before uncertainties in burnup and measurement, in conjunction with different subassembly residence times, render tag identification ambiguous. On the other hand, minimum spacing is desired to reduce the cost of the enriched gases employed and to assure an adequate number of unique tags.

It has been arbitarily assumed that if the initial ratios are spaced such that, after maximum exposure, the worst case ratio ±.5% for mass spectrometer measurement uncertainty and ±3σ for burnup uncertainty, does not include any other ratio (e.g., the initial ratio of new subassembly), then the tags can be unambiguously identified. If the initial tag ratio is R_o and the final (maximum exposure) ratio is R, the spacing criterion is given by:

$$\text{Spacing} = \frac{\text{MAX } (R_o,\ 1.005R+3\sigma)}{\text{MIN } (R_o,\ 0.995R-3\sigma)}$$

The symbol MAX (a,b) indicates that only the larger of the values a or b will be employed, whereas MIN (a,b) indicates that only the smaller of a or b will be used.

This calculation was performed for the tags of every subassembly. The characteristics of the worst case subassemblies are summarized in the Table, used to establish tag spacings. As an example, if one manufactures an initial tag of Kr-78/Kr-80=0.8 for one subassembly, then the initial tag for another subassembly would have to be Kr-78/Kr-80=1.079 x .8-0.863 or greater (or Kr-78/Kr-80=.8/1.079= .741 or less) to meet the criterion.

It is interesting to note that the decision to tag the control rods considerably increases the required minimum spacings (compare the control rod spacings with the fuel rod spacings).

VII. Discussion and Summary

The gas tag burnup changes investigated in this report were limited to the three tags (Kr-78/Kr-80, Xe-126/Xe-129 and Kr-82/Kr-80 currently accepted as being the most desirable. Tags containing Xe-124 would change too dramatically with exposure due to the high Xe-124 capture cross section. Tags containing Xe-128 were eliminated because the rather uncertain production of Xe-128 via fission would be too large a fraction of the proposed initial Xe-128 charge, thus resulting in unacceptable uncertainties in the ratio changes.

On the other hand, Kr-82 production from neutron capture by a fission product is a small fraction of the initial Kr-82 charge. In fact, since the Kr-82 reaction rate is less than the Kr-80 reaction, this indirect production of Kr-82 will always act to improve Kr-82/Kr-80 ratio changes and lessen the tag gas ratio spacings for fuel pins. As a conservative measure, the Kr-82/Kr-80 results of this study were not modified to account for this effect.

Control rod tag burnup was significantly greater than fuel rod tag burnup. This occurs because control rods stay in the reactor longer and occupy positions of greater low-energy flux. Thus, minimum tag spacings were set by the control rods as 1.079 for Kr-78/Kr-80, 1.189 for Xe-126/Xe-129 and 1.134 for Kr-82/Kr-80.

Finally, uncertainties are nothing better than extremely tentative estimates. Lacking any recent and rigorous evaluation of noble gas cross sections and uncertainties, the cross sections and uncertainties of Reference 1 were also used in this study. However, after considering the experimental and calculated reaction rate comparisons made on the FTR/EMC[2], it was decided to use a flux uncertainty of ±25% rather than the optimistic ±15% used in Reference 1.

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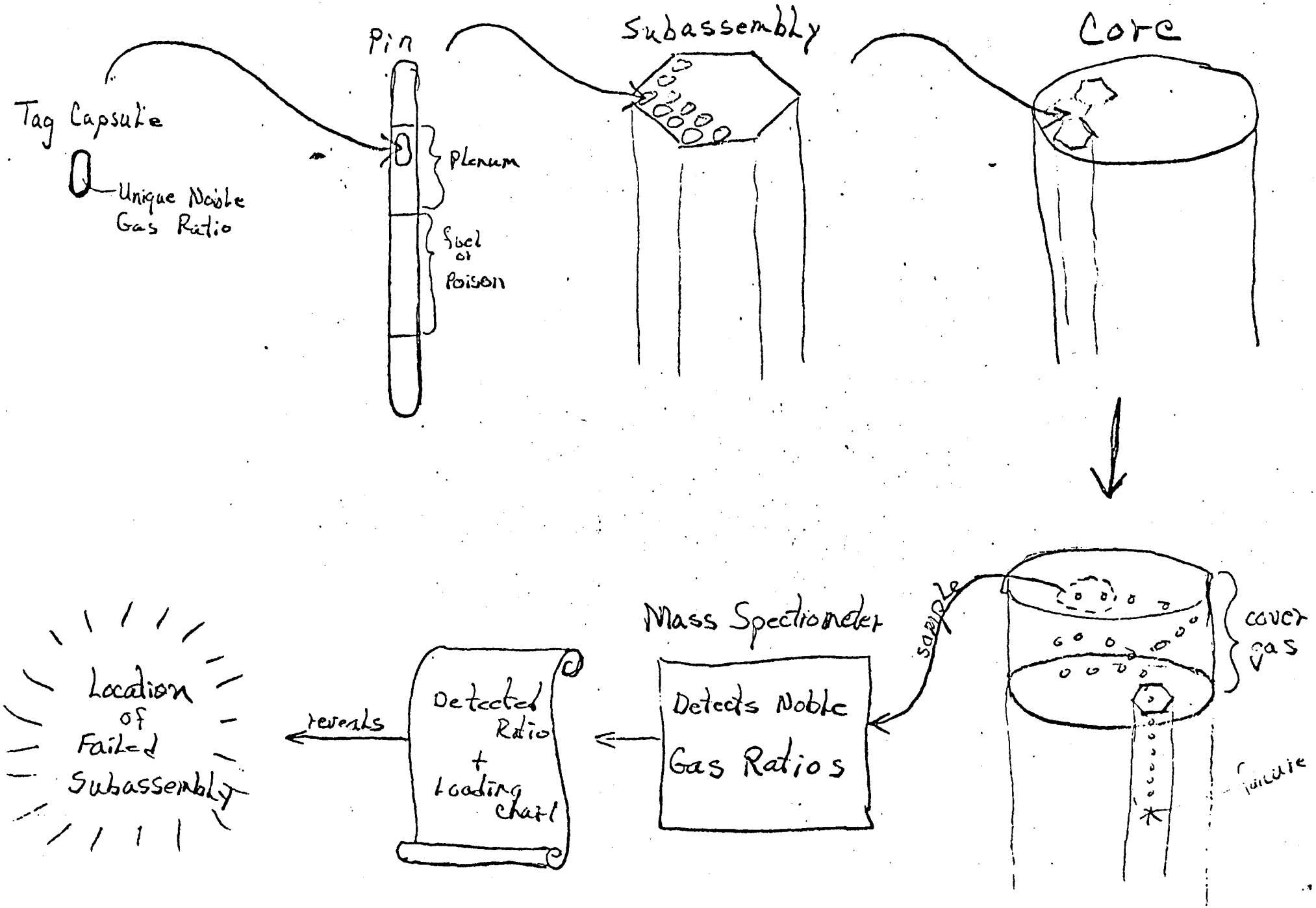
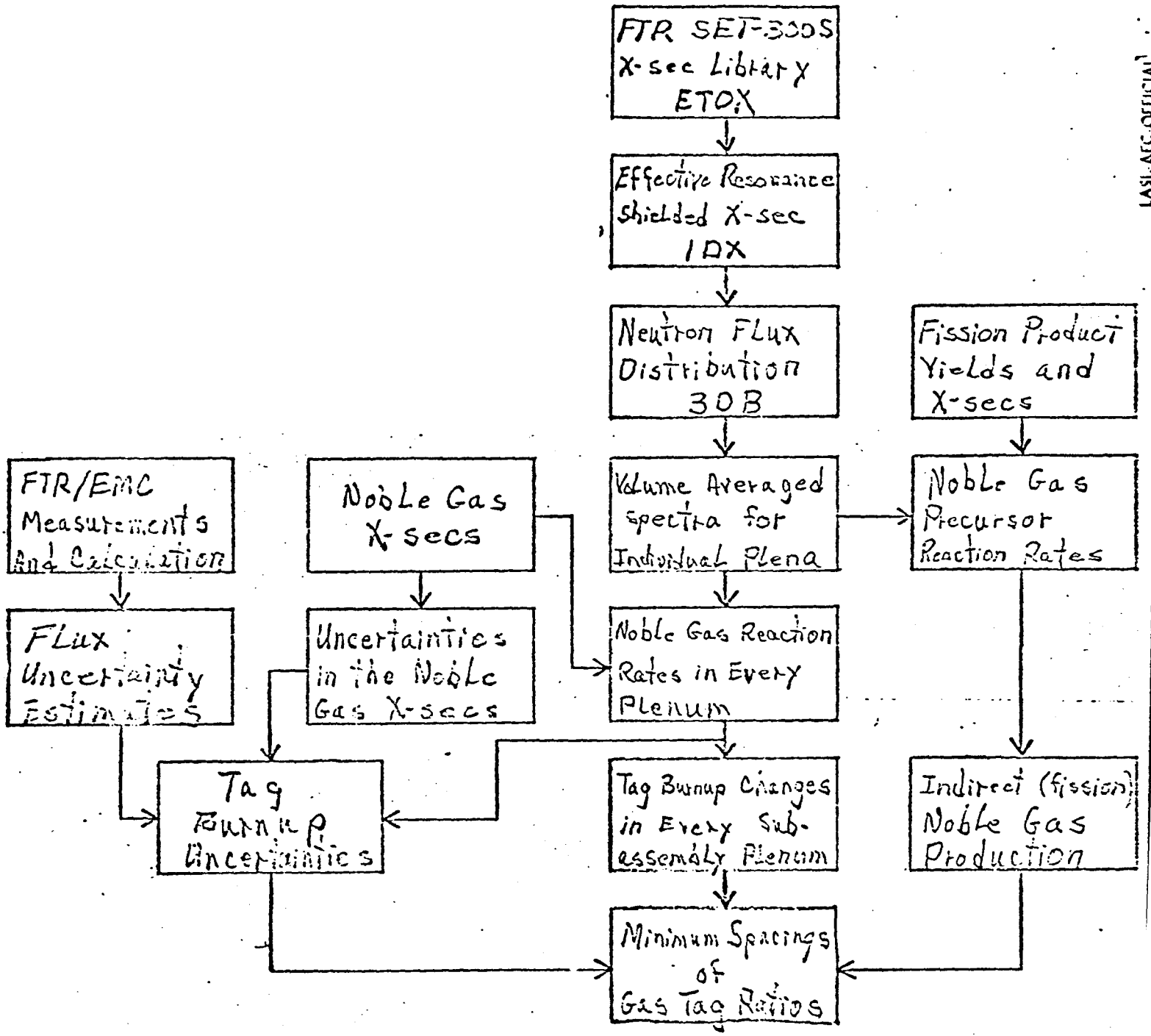
TAGGING - CONCEPT



Schematic of Tag Burnup Computations



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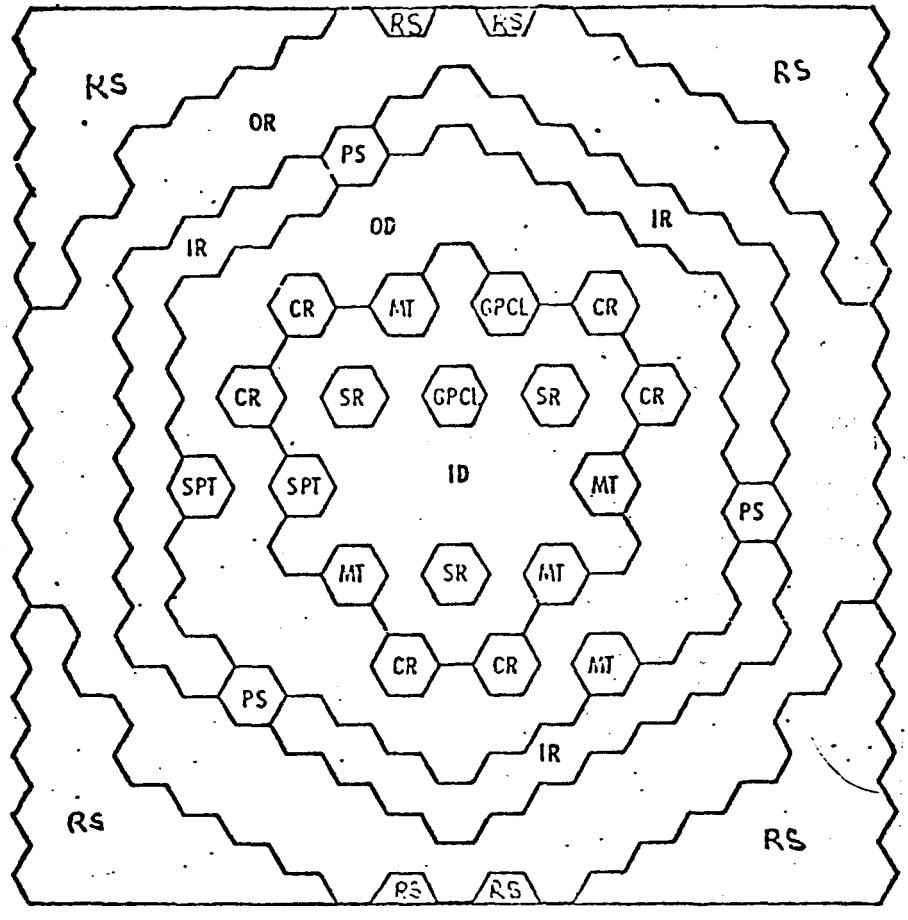
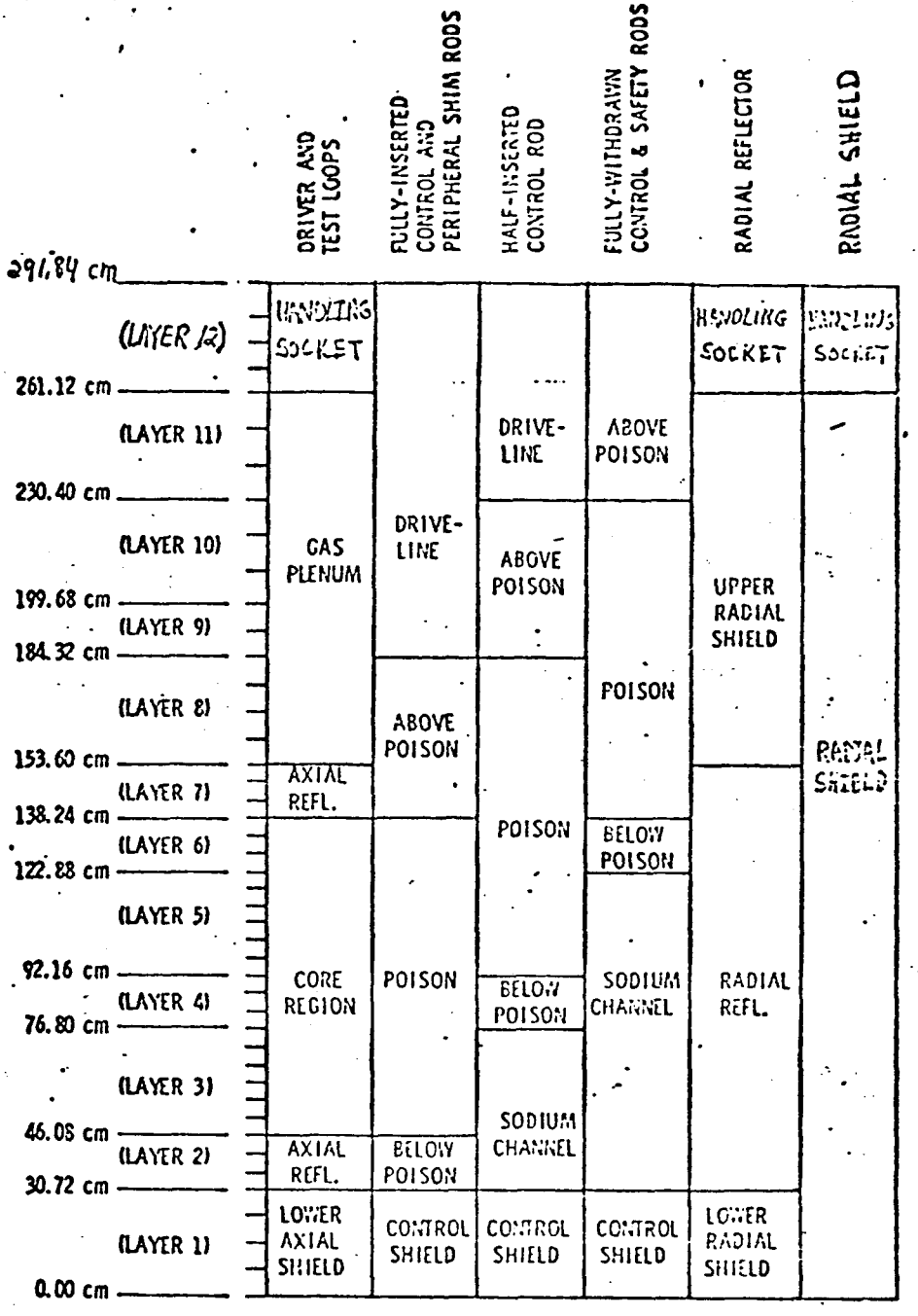
TOP VIEW OF FTR MODEL



ID	INNER DRIVER	SR	SAFETY ROD (WITHDRAWN)
OD	OUTER DRIVER	PS	PERIPHERAL SHIM ROD (INSERTED)
IR	INNER RADIAL REFLECTOR	MT	MATERIAL TEST LOOP
OR	OUTER RADIAL REFLECTOR	GPCL	GENERAL PURPOSE CLOSED LOOP
CR	CONTROL ROD (1/2 INSERTED)	SPT	SPECIAL PURPOSE TEST LOOP
		RS	RADIAL SHIELD

Axial View of FTR Subassemblies



BURNUP EQUATION

$$R(t) \pm U_R^{\pm} = R_0 \, e^{\left\{ (\phi\sigma)_y - (\phi\sigma)_x \pm \left[(U_x^{\mp})^2 + (U_y^{\pm})^2 \right]^{1/2} \right\} t}$$

where:

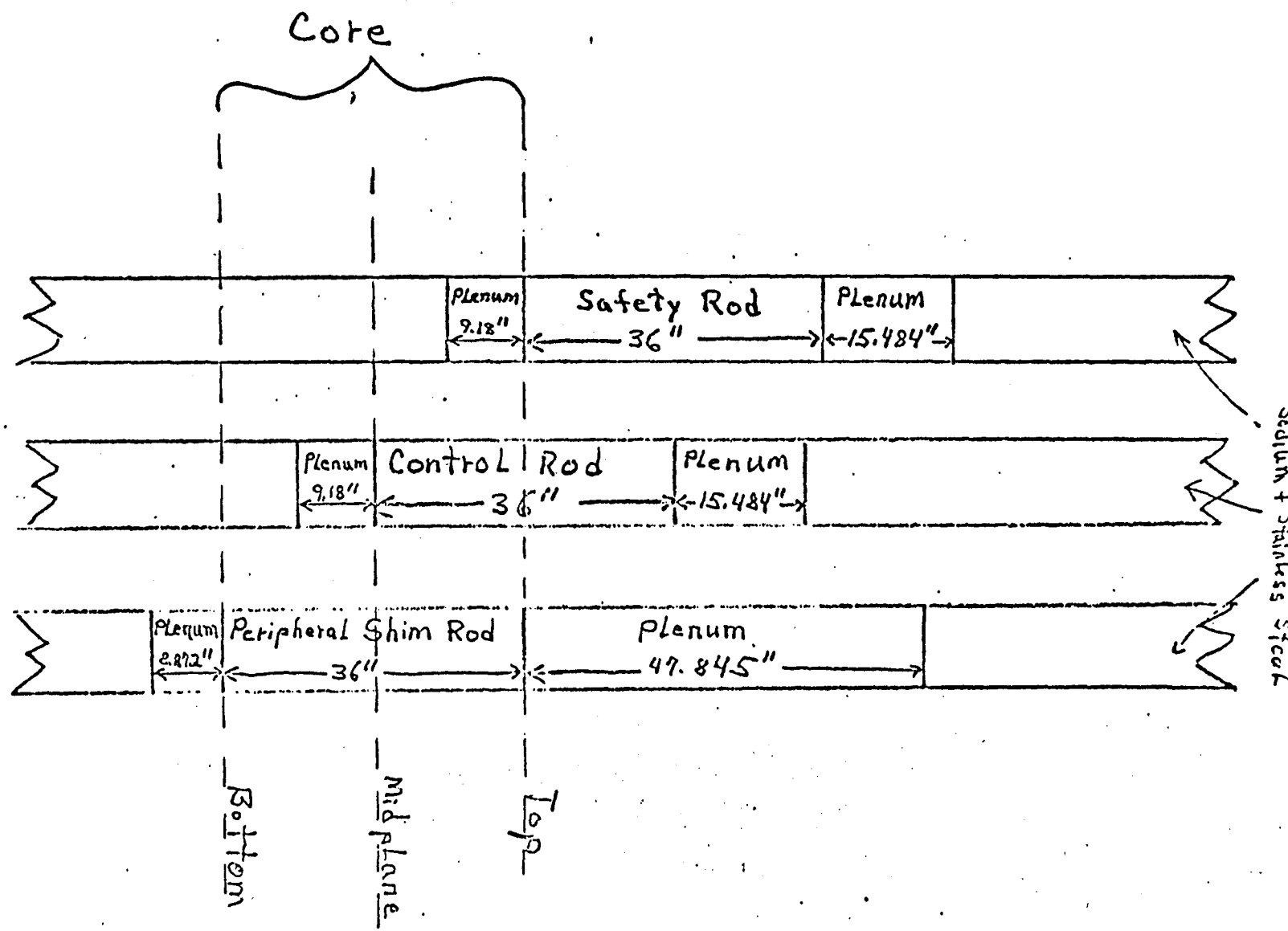
$R(t)$ = Ratio of the number of x-atoms to the number of y-atoms, at time t

R_0 = initial ratio (set equal to 1 for this study)

$U_R^{\pm}$ = upper(+) and lower(−) 1σ uncertainties in the ratio at time t

$U_x^{\pm}$, $U_y^{\pm}$ = 1σ uncertainties in the reaction rate for isotopes x and y

$(\phi\sigma)_x$, $(\phi\sigma)_y$ = atom reaction rates for isotopes x and y



FTR Control Rod Plena

LASL-AEC-OFFICIAL

SPACING FORMULA

$$\text{Spacing} = \frac{\text{MAX}(R_o,\ 1.005R + 3U_R^+)}{\text{MIN}(R_o,\ 0.995R - 3U_R^-)}$$

Where:

R_o = initial ratio

R = final ratio

$U_R^{\pm}$ = upper (+) and lower (−) 1σ uncertainties in the ratio R

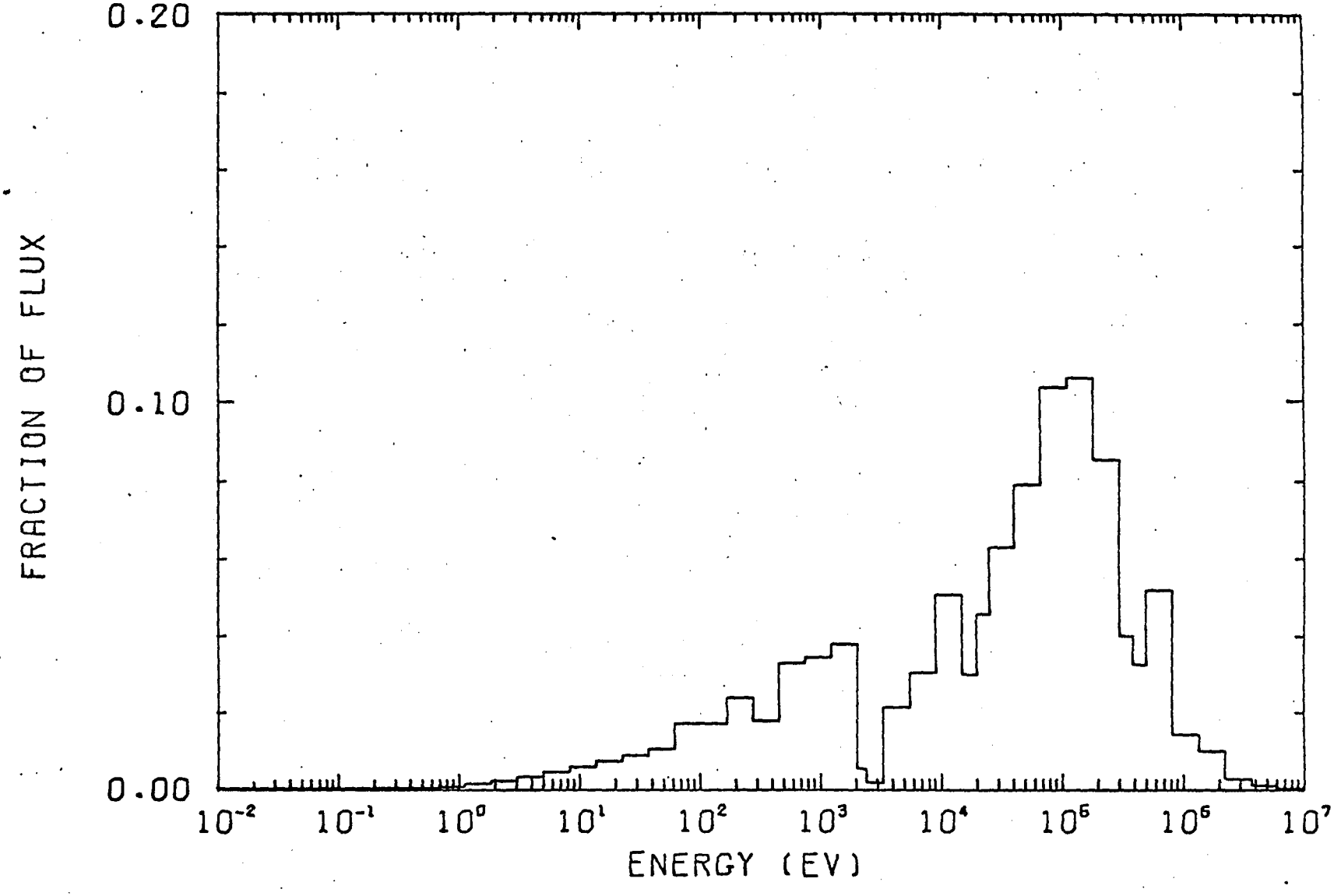
(2 slides)

FTR TAG BURNUP AND SPACINGS

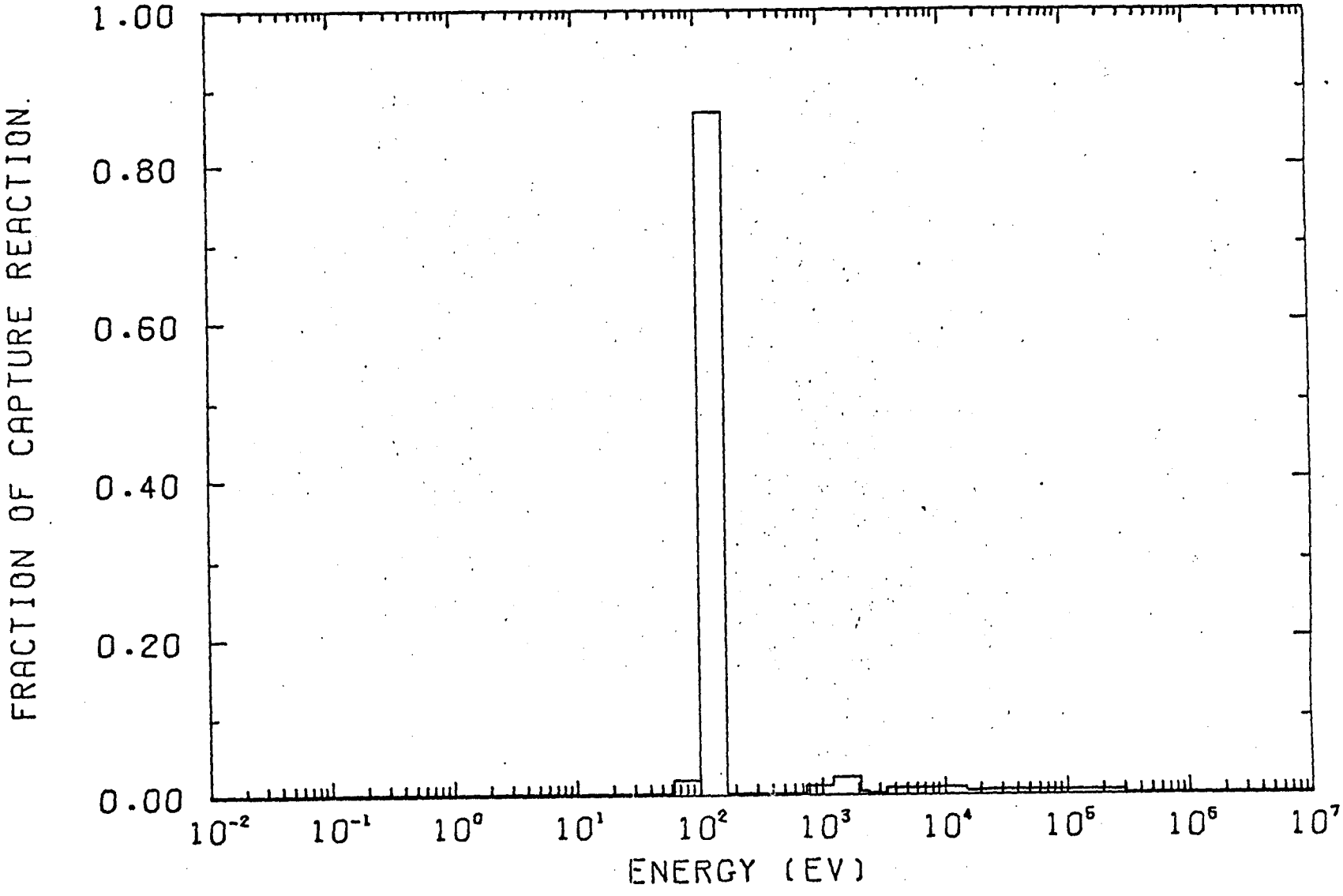
Tag	Subassembly with max tag changes	Final ratio* at max exposure (1σ uncertainty)	Minimum spacing
Fuel Subassemblies			
Kr-78/Kr-80	Central subassembly	$1.010^{+.004}_{-.004}$	1.032
Xe-126/Xe-129	Row 5 No. 49	$1.026^{+.013}_{-.010}$	1.080
Kr-82/Kr-80	Row 5 No. 73	$.985^{+.008}_{-.009}$	1.064
Absorber Subassemblies Assuming Connected Plena**			
Kr-78/Kr-80	Row 5 control rod CR-7	$1.001^{+.010}_{-.012}$	1.079
Xe-126/Xe-129	Row 7 shim rod PSR-3	$1.067^{+.033}_{-.025}$	1.189
Kr-82/Kr-80	Row 7 shim rod PSR-3	$.964^{+.018}_{-.020}$	1.134
Absorber Subassemblies Assuming Disconnected Plena			
Kr-78/Kr-80	Lower plenum of CR-7	$.991^{+.024}_{-.027}$	1.183
Xe-126/Xe-129	Lower plenum of PSR-3	$1.181^{+.097}_{-.071}$	1.537
Kr-82/Kr-80	Lower plenum of PSR-3	$.908^{+.045}_{-.051}$	1.395

* All initial ratios were taken to be 1. Maximum exposure times are as follows: fuel rod = 300 days; row 3 safety rod = 300 days; row 5 control rod = 400 days; row 7 shim rod = 600 days.

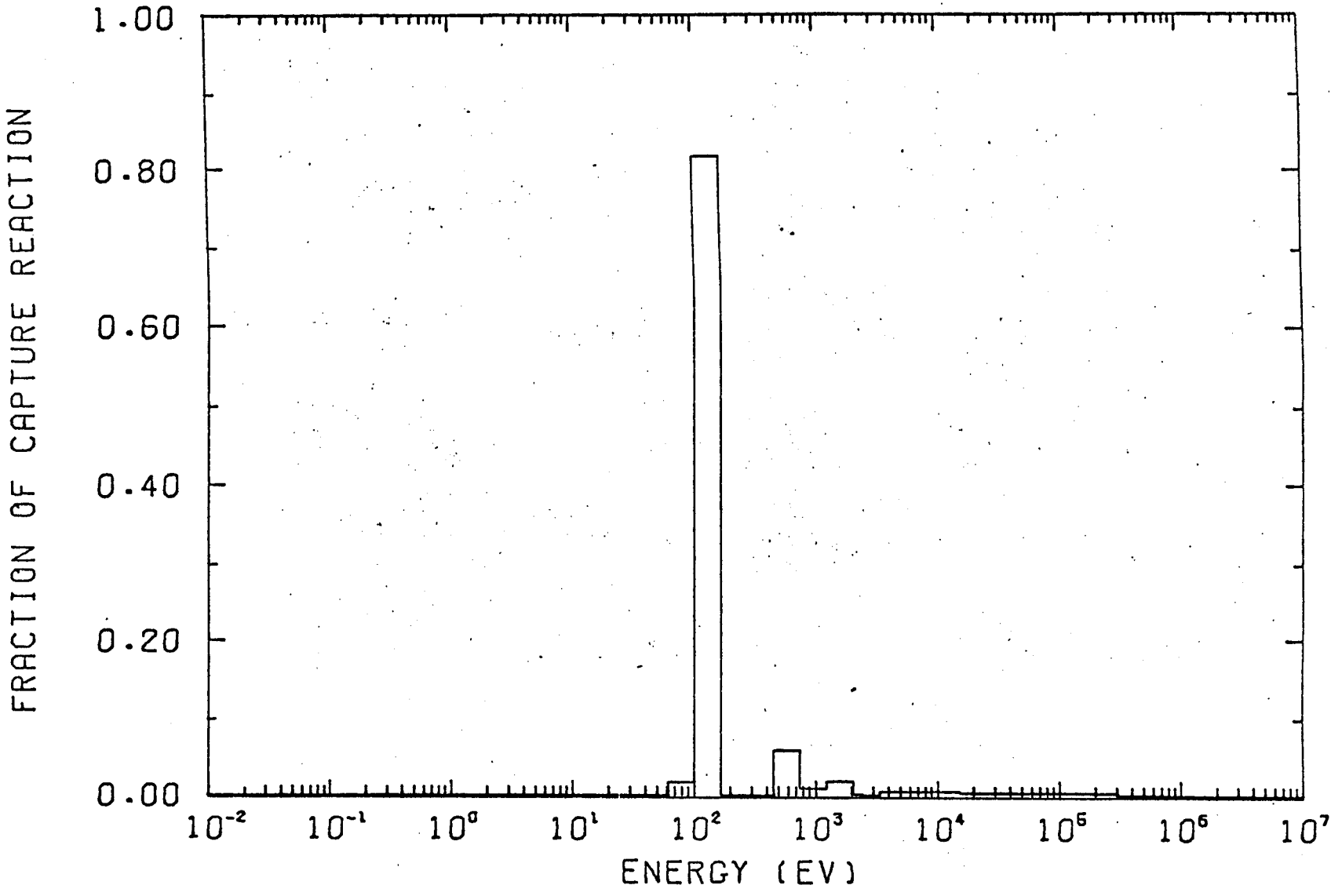
** Gases can move between the upper and lower plena of an absorber subassembly.



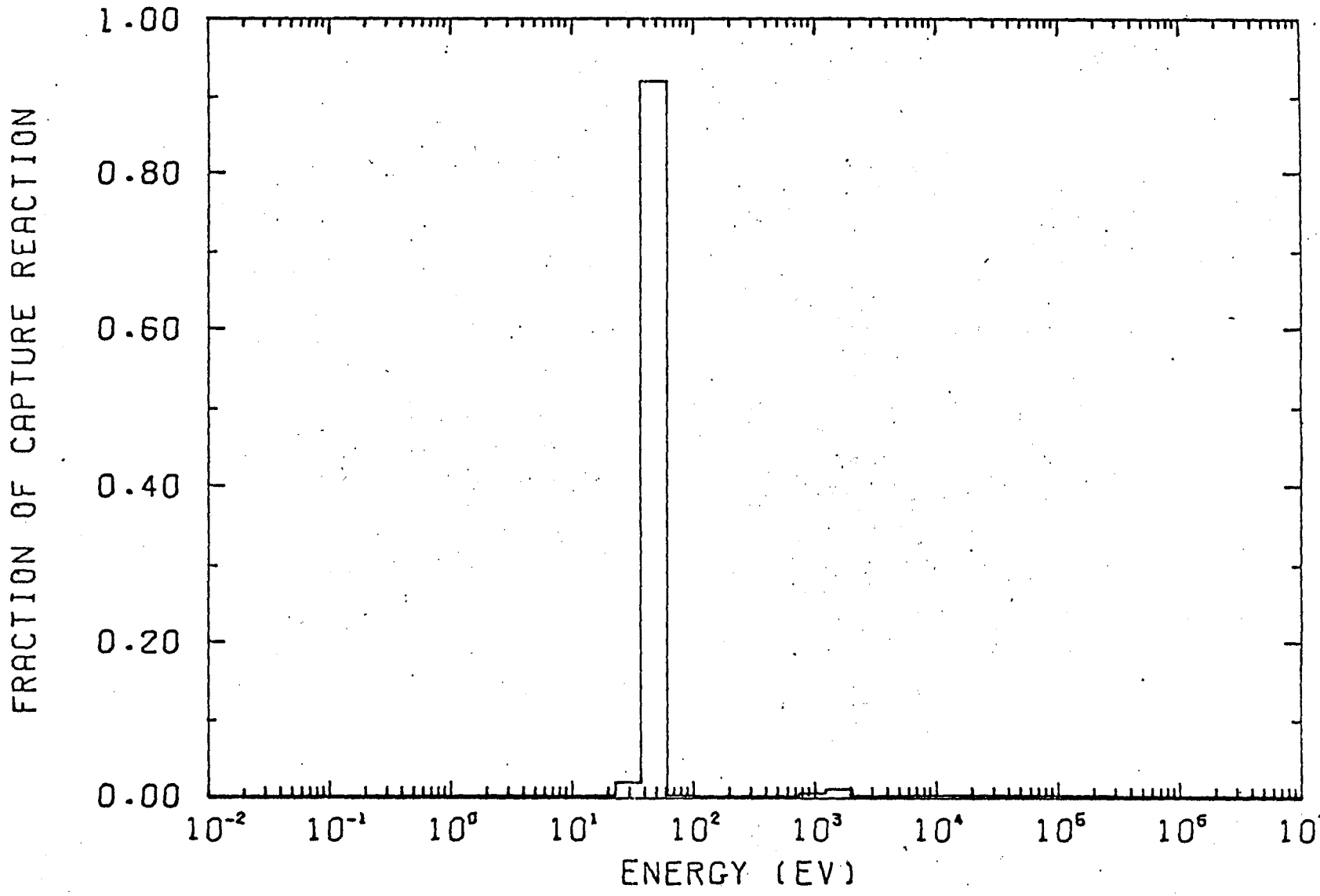
FTR FLUX BREAKDOWN



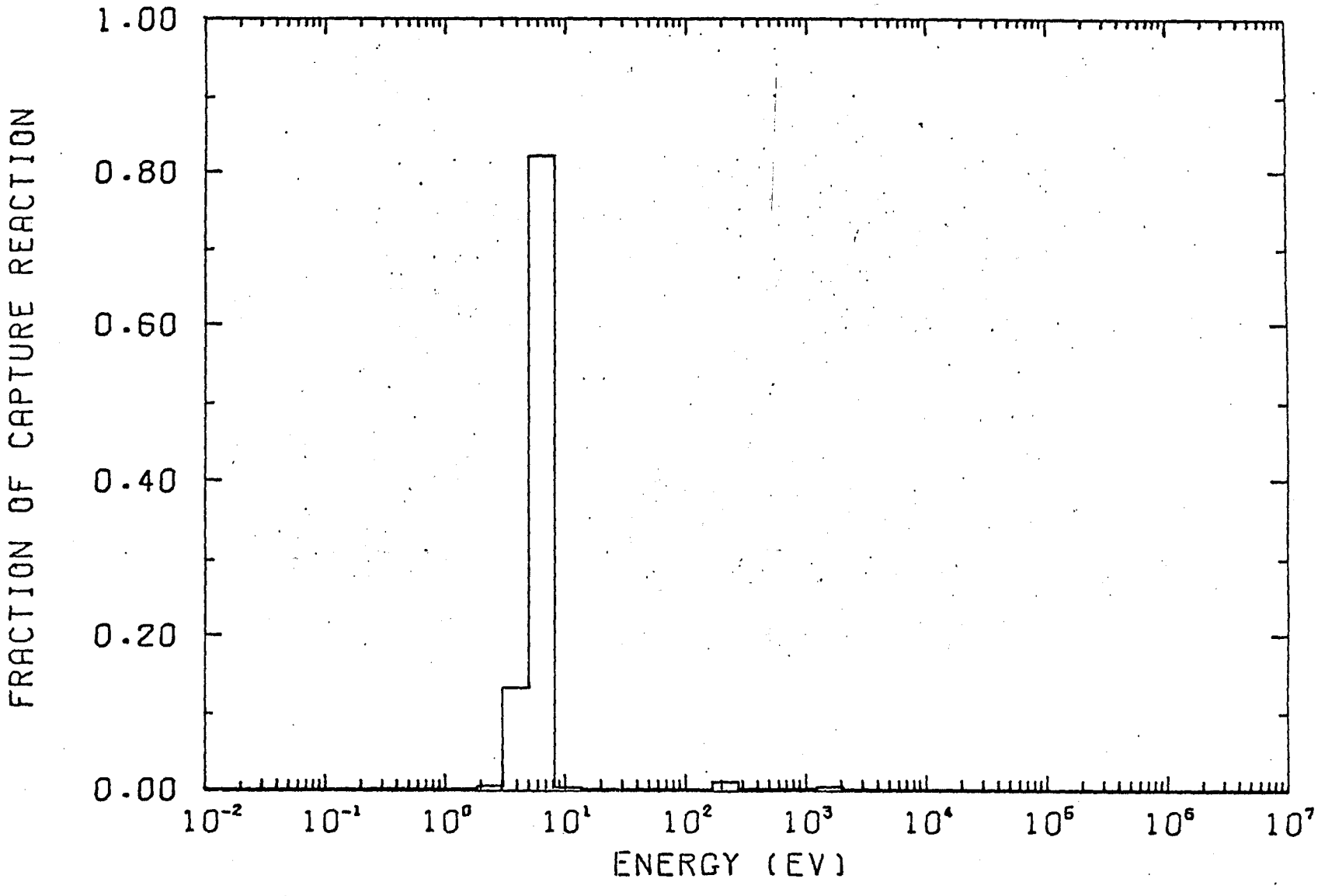
KR-78 CAPTURE REACTION BREAKDOWN



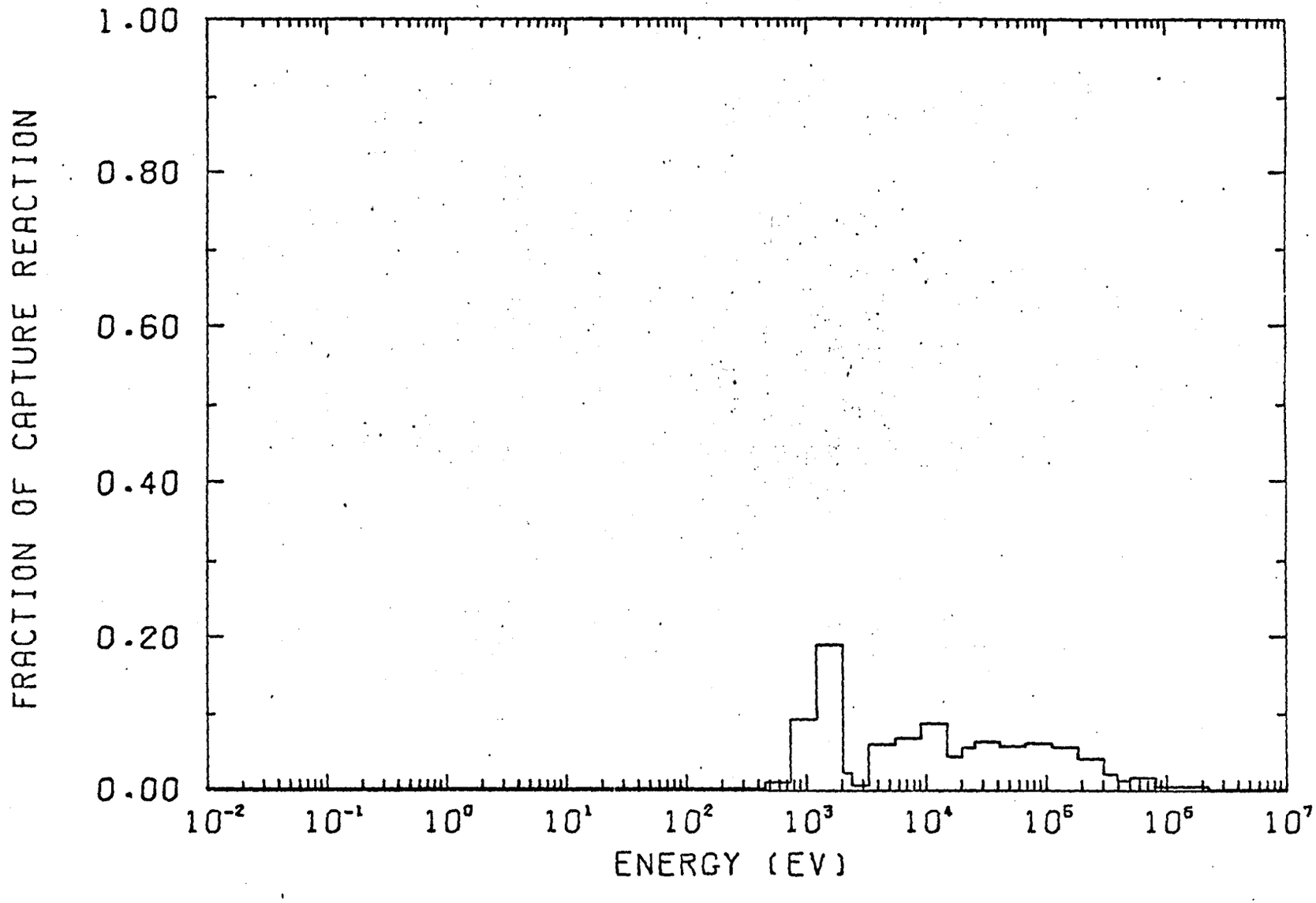
KR-80 CAPTURE REACTION BREAKDOWN



KR-82 CAPTURE REACTION BREAKDOWN



XE-124 CAPTURE REACTION BREAKDOWN



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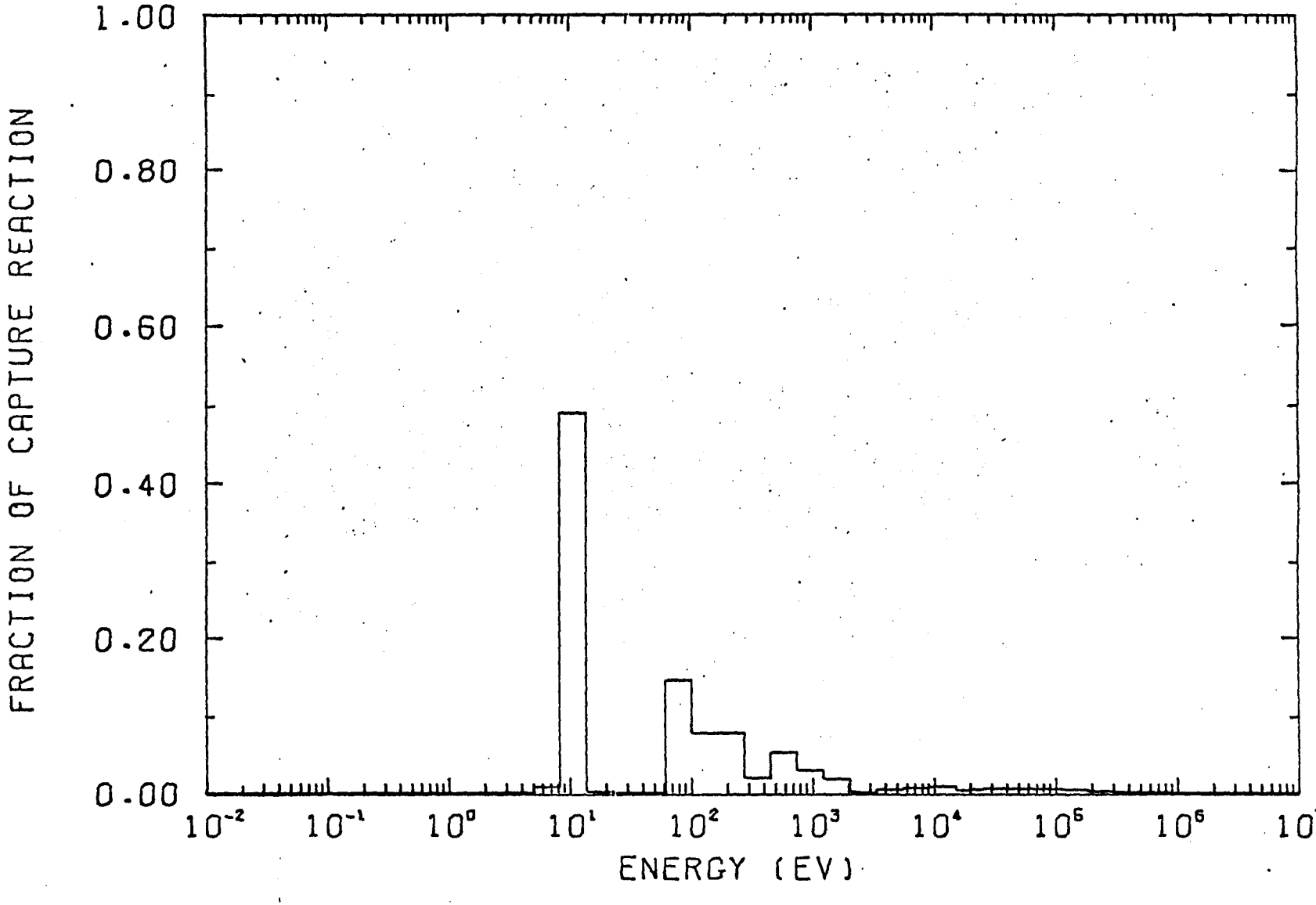

XE-129 CAPTURE REACTION BREAKDOWN