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Dragon Project Report

~~PRELIMINARY REPORT~~

MASTER

RADIOCHEMICAL ANALYSIS OF FISSION PRODUCTS IN THE DRAGON REACTOR

PART I

DESIGN AND OPERATION OF THE SYSTEM

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by

P. ACCIARRI
E. J. MITCHELL

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PART 1

DESIGN AND OPERATION OF THE SYSTEM

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CONTENTS

LIST OF ILLUSTRATIONS

Figure

LIST OF TABLES

RADIOCHEMICAL ANALYSIS OF FISSION PRODUCTS IN THE DRAGON REACTOR

PART 1

DESIGN AND OPERATION OF THE SYSTEM

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1. INTRODUCTION

One of the major objectives of the Dragon Reactor experiment is to study fission product control. This is important because, contrary to most other nuclear reactors, the fuel elements are not contained in a metal cladding. The initial concept of the fuel element was one in which fission products were emitted from the fuel. Their control was effected by passing a fraction of the coolant gas (the "purge stream") over the fuel inserts and into a fission product control system in which fission products would be adsorbed on active charcoal. Because of the very high activities, it was deemed necessary to somewhat delay the fission products within the fuel elements prior to entering the control system. The fuel inserts were therefore enclosed in low permeability graphite fuel boxes and in addition the purge stream was made to pass through an active charcoal bed incorporated into the bottom of each fuel element. By these means it was hoped to produce at least a one hour delay before the fission products entered the fission product control system.

This particular concept has certain inherent disadvantages, and was therefore, superseded - at least for the first Dragon fuel charge - by the introduction of coated particle fuel. The current object is to develop coated particle fuel capable of retaining all but a fraction of the order of 10^{-6} of the gaseous fission products, to the stage where FIFA* burn-ups in excess of 100% can be attained. If this becomes possible, then there might be no need for a purge flow and the associated complex fission product control system in future reactors. However, the only realistic means of developing such fuel involves testing under operational conditions in the Dragon Reactor. To this end a programme to develop and define the limits of such fuels has been laid down. A vital part of this programme is the measurement of fission products released from fuel elements at various locations within the core.

The measurement will be performed by gamma counting and gamma spectrometry of the purge flow. This method was chosen because of its simplicity and adaptability for remote control and because the feasibility of the principles has already been demonstrated in the Pluto Loop. (See Part 2 of this report.) In this report a description of the methods chosen and the equipment used is given. The importance of flexibility has been emphasised, since it is appreciated that certain components cannot be optimised until operational experience has been obtained.

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* FIFA = Fissions per Initial Fissile Atom

It will be shown that the proposed system is capable of recording the activities of certain isotopes of krypton and xenon within the range 10^{-2} to 10^{-6} fractional fission product release with the assumption of no delay in the fuel. With one hour delay in the fuel the system will record in the order of 100% release of these gaseous isotopes.

The system has been designed such as to allow the introduction of new or modified apparatus if this should subsequently be found desirable.

2. SCOPE OF FISSION PRODUCT ANALYSIS SYSTEM

2.1 Types of Fuel Considered

For the purpose of this report two widely differing types of fuel have been considered:-

(a) Coated Particle Fuel with Central Purge Flow

With this fuel element arrangement (see Fig. 1) practically all the gaseous fission products will ideally be retained by the coated particles. Should rupture of the coatings occur, however, gaseous fission products will tend to escape either to the surrounding primary coolant via the graphite fuel element rod or to the central purge flow via the inner graphite sleeve. However, provided the permeability of the inner sleeve is very high in comparison with that of the outer graphite structure, most of the escaping fission products will pass into the purge gas. Probable permeability values for inner and outer graphite respectively are 10^{-5} cm^2/s and 10^{-7} cm^2/s.

Because of the high permeability of the inner graphite, the assumption has been made that the delay of the noble gas fission products through the sleeve is negligible. It has been further assumed that, as a result of ruptured coated particle fuel and/or fissile material contamination of the coated particle surfaces, 10^{-4} of the total fission products will be released into the purge gas, the likely range of such release being 10^{-2} to 10^{-6} approx. The activities listed in Tables 1 to 4 must therefore be appropriately factored if the actual fractional release differs from 10^{-4}.

(b) Uncoated Fuel with Annular Purge Flow

In this case (see Fig. 2) the gaseous fission products will tend to escape via the inner graphite fuel box to the purge gas which flows in the annular space between this box and the outer fuel rod structure. The permeability of the graphite fuel box has been taken as 10^{-6} cm^2/s for which value a delay of 1 hour from the time of fission has been assumed for 100% release of gaseous krypton and xenon from the fuel boxes.

2.2 Fission Products Considered

In both cases (a) and (b) above, no further delay of Xe and Kr has been

Table 1

Activity of Fission Products in the Purge Gas at 50°C and 20 atm Pressure

Coated Particle Fuel 10^{-4} Release. No Decay

Fission Product	Half Life	Y%	Decay Constant λ	Specific Activity 6.76×10^{-3} $Y\lambda$ curies/cc	Activity for 30 cc	Activity for 60 cc
Kr-83m	114m	.48	1.01×10^{-4}	3.2×10^{-7}	9.6×10^{-6}	1.92×10^{-5}
Kr-85m	4.36h	1.5	4.41×10^{-5}	4.36×10^{-7}	1.31×10^{-5}	2.62×10^{-5}
Kr-87	78m	2.7	1.48×10^{-4}	2.62×10^{-6}	7.86×10^{-5}	1.57×10^{-4}
Kr-88	2.7h	3.7	6.95×10^{-5}	1.69×10^{-6}	5.08×10^{-5}	1.02×10^{-4}
Xe-131m	12d	0.03	6.68×10^{-7}	1.32×10^{-10}	3.94×10^{-9}	7.88×10^{-9}
Xe-133m	2.3d	0.16	3.5×10^{-6}	3.68×10^{-9}	1.10×10^{-7}	2.20×10^{-7}
Xe-133	5.27d	6.5	1.5×10^{-6}	6.42×10^{-8}	1.93×10^{-6}	3.86×10^{-6}
Xe-135m	15.6m	1.8	7.4×10^{-4}	8.72×10^{-6}	2.62×10^{-4}	5.24×10^{-4}
Xe-135	9.13h	6.2	2.11×10^{-5}	8.6×10^{-7}	2.58×10^{-5}	5.16×10^{-5}
Xe-138	17m	5.5	6.79×10^{-4}	2.44×10^{-5}	7.32×10^{-4}	1.46×10^{-3}

Table 2

Activity of Fission Products in the Xenon Trap at 50°C and 20 atm Pressure

Coated Particle Fuel. 10^{-4} Release. 3 h Decay

Fission Product	Specific Activity for No Decay	λt	Activity Reduction Factor $e^{-\lambda t}$	Specific Activity (curies/cc)	Activity for 60 cc
Xe-133m	3.68×10^{-9}	0.038	0.962	3.54×10^{-9}	2.08×10^{-7}
Xe-133	6.42×10^{-8}	0.016	0.984	6.32×10^{-8}	3.8×10^{-6}
Xe-135m	8.72×10^{-6}	8.0	3.35×10^{-4}	2.94×10^{-9}	1.76×10^{-7}
Xe-135	8.6×10^{-7}	0.228	0.796	6.84×10^{-7}	4.1×10^{-5}
Xe-138 (Cs-138)	2.44×10^{-5}	7.33	6.55×10^{-4}	1.6×10^{-8}	9.6×10^{-7}

Table 3

Activity of Fission Products in the Xenon Trap at 50°C and 20 atm Pressure

Coated Particle Fuel. 10^{-4} Release. 45 h Decay

Fission Product	Specific Activity for No Decay	λt	Activity Reduction Factor $e^{-\lambda t}$	Specific Activity (curies/cc)	Activity for 60 cc
Xe-133	6.42×10^{-8}	.243	.783	5.02×10^{-8}	3.01×10^{-6}
Xe-135	8.6×10^{-7}	3.42	.033	2.84×10^{-8}	1.7×10^{-6}

Table 4

Activity of Fission Products in the Krypton Trap

at 50°C and 20 atm Pressure

Coated Particle Fuel. 10^{-4} Release

20 h Decay

Fission Product	Specific Activity for No Decay	λt	Activity Reduction Factor $e^{-\lambda t}$	Specific Activity (curies/cc)	Activity for 60 cc
Kr-83m	3.2×10^{-7}	7.26	6.95×10^{-4}	2.22×10^{-10}	3.32×10^{-8}
Kr-85m	4.36×10^{-7}	3.17	4.18×10^{-2}	1.82×10^{-8}	1.09×10^{-6}
Kr-87	2.62×10^{-6}	10.66	2.32×10^{-5}	6.08×10^{-11}	3.65×10^{-9}
Kr-88 (Rb-88)	1.69×10^{-6}	5.0	6.76×10^{-3}	1.14×10^{-8}	6.84×10^{-7}

considered to take place in the small charcoal traps at the lower end of the fuel elements, since at the prevailing temperature of about 350°C the adsorption coefficients for both gases are very low.

Also in both cases, only those fission products which are either gamma emitting or which give rise to gamma emitting daughters have been considered, since the system provides facilities only for gamma measurement and spectrometry. Very short lived, directly produced, fission products, (i.e., $t_{\frac{1}{2}} < 15$ min), have not been considered in activity calculations or gamma spectra.

Metallic and halogenous fission products have also been ignored since these will either be removed by the charcoal traps in the fuel elements or be condensed out on the pipework of the purge gas precooler.

2.3 Range of Experiments

Several experiments both qualitative and quantitative can be carried out and these are listed below:-

(i) In order to obtain the maximum information on the active constituents of the purge flow, the xenon and krypton gases can be separated in charcoal traps as described in Section 3.4.

(ii) After separation, the activity of the xenon and krypton can be independently measured and by gamma spectrometry, the predominant isotopes identified. (See Sections 4 and 5.)

(iii) The gas trapped in the charcoal beds can be allowed to decay for such a period that the short lived isotopes will disappear. The activity of the longer lived isotopes can then be more easily measured. Successive periods of delay will result in the maximum information being obtained.

(iv) A gas sample may be left in a charcoal trap such that a solid daughter product will be formed by decay of the gaseous parent fission product. The gas can then be purged out with clean helium and the activity of the solid daughter measured.

(v) Gamma spectrometry, in addition to total activity measurement, can also be carried out on an unseparated sample. This can be done either with a captive sample or with a continuous flow from the fuel element, in which latter case the contribution from the shorter lived fission products and solid daughter products can be obtained.

3. GENERAL DESCRIPTION OF SYSTEM

The system provides facilities for the following operations to be carried out for any of the 37 individual fuel element assemblies:-

(a) Selective sampling of the purge flow.

(b) Dilution of the purge flow as and when required.

(c) Total activity measurement of the undiluted and/or diluted purge flow.

(d) Gamma spectrometry of the undiluted and/or diluted purge flow.

(e) Separation of the gaseous isotopes of xenon and krypton in the purge flow by means of charcoal traps to permit independent gamma spectrometry of the xenon and krypton.

(f) Separation as above, followed by gamma spectrometry of the solid daughter products of xenon and krypton.

In addition to the above, it will be possible by gamma spectrometry to measure the activity of fission products in the reactor primary coolant when required, the same procedure being adopted as for (c) to (f) above.

The flow diagram (Fig. 3) shows the general principles of the system described below. The diagram has been simplified and includes only those valves, etc., relevant to the scope of this report. The system can be subdivided as follows.

3.1 Purge Gas Sampling and Back-Flushing System

The mounting spikes for the 37-fuel element assemblies incorporate orifices in order to equalise the purge flow should any fuel element become unseated or damaged. From the upstream high pressure side of each orifice, a small bore ($\frac{1}{8}$") capillary pipe passes through the purge gas precooler, and thence to a 37-way selector valve. The selector valve will be fully described in a separate D.P. Report. Each capillary pipe is connected to an individual 3-way, bellows sealed valve in the selector unit and by remotely operating these valves, the purge flow from any particular fuel element may be tapped. The average capillary pipe length from fuel element spike to selector valve is 65 ft 0 in. The purge gas will leave the fuel element at 20 atmospheres (abs.) pressure and 350°C but will have cooled to about 50°C at the selector valve.

In order to reduce the risk of blockage of the capillary pipes by fission product deposition, to approximately equalise the pressure across the valve bellows, to flush the selector valve casing and, of special significance to this report, to prevent cross contamination between different fuel element sampling lines, a back-flushing system is employed.

Clean helium is taken from the return line to the reactor and enters the selector valve casing via isolating valve 41 (normally open). This gas circulates, leaves the casing and is conducted through a fail shut solenoid valve 42 from which it returns to the selector unit via a non-return valve. This valve admits the flushing gas to a manifold which feeds all 37 3-way valves and their associated capillary pipes via the lower valve seats. Since the valves are all normally closed on their upper seats by spring force, continuous back-flushing of the capillary pipes can be achieved. The non-return valve and S.V. 42 are used to prevent the escape of radioactive purge gas into the reactor building should the selector valve casing become ruptured.

When any one valve is operated and depressed onto its lower seat, the flushing gas to that one valve only will be cut off, the remaining 36 valves and capillaries still being back-flushed. By this method, it is considered impossible for leakage of fission products to occur from one fuel element purge line to another.

By operation of a valve, as above, a small flow (approx. 8 cc/s) of purge gas from the related fuel element can be obtained through the upper valve seat, sample gas manifold and isolating valve 43 (normally open) in order to carry out the required activity measurements. The selector valve can be operated either automatically when each purge line will be scanned in sequence, or manually, depending on the nature of the measurements to be performed. Provision has been made for changing the time cycle when operated automatically.

The maximum leak rates specified for the selector valve are .01 cc/min for upper and .02 cc/min for the lower seats of the 3-way valves. The purge flow being sampled could, therefore, possibly be diluted by clean flushing gas as a result of 36 upper seats and one lower seat leaking into the sample manifold, i.e., a flow of .38 cc/min. However, this represents a very small percentage ($<0.1\%$) of the estimated sample gas flow rate of 8 x 60 = 480 cc/min.

3.2 Activity Monitoring System

By opening solenoid valve 48, the purge flow will pass through a pipe coil of known volume in instrument pot I.P. 13 and via isolating valve 50 (normally open) to the main fission product purge line upstream of the delay beds. The total activity in the purge flow can then be measured by means of an activity monitor located concentrically inside the pipe coil. The design of the installation (see Fig. 4) allows for this activity monitor to be either an ion chamber or a scintillation counter, the actual instrument depending on what degree of fission product release is expected for the particular fuel being used. When the scintillation counter is used, gamma spectrometry of the fission products can be carried out.

This monitor is also useful for detection of faulty fuel elements and its use in this respect will be covered in a separate D.P. Report.

When desired, the activity monitor coil can be flushed with clean helium via solenoid valve 49, and by keeping the appropriate valve in the selector unit depressed, the sample gas manifold, 3-way valve and capillary piping can also be back-flushed.

Instrument pot 10 contains an identical pipe coil of equal volume to that in I.P. 13 but for this installation the scintillation counter only is used and gamma spectrometry of the purge flow fission products can be performed. The purge flow through I.P. 10 can either be diluted (see Section 3.3) or undiluted according to the prevailing activity level. Both installations incorporate thermocouples to record the coil temperatures.

3.3 Dilution System

In the case of 100% or substantial fractional fission product release, the activity level of the purge flow will be too high for identifiable gamma spectra to be obtained from the scintillation counter in I.P. 10 or from those in the subsequent charcoal trap system at I.P. 8 and I.P. 9. (See Section 3.4.) The counting rate for 1 hour delay of fission products, assuming 100% gaseous fission product release, is 1.95×10^9 c/s approx. (See Table 5.) If the maximum counting rate that we can measure accurately is 5×10^4 c/s then it is necessary for this purge flow to be diluted by a factor of about 10^5. A dilution system has, therefore, been incorporated and this system will function as follows.

Connected across I.P. 13 and I.P. 10 is a very small bore "standard leak" coil located in instrument pot 14. This coil is .012 in bore and 100 ft long and will provide a known very small flow for a given pressure difference across it. Filters are provided at each end of the coil to prevent possible blockage of the fine bore.

During the total activity measurement at I.P. 13, the solenoid valve 51 will be opened, thus communicating the system to a clean helium supply and this will result in a very small flow of clean helium through the leak coil in I.P. 14, which will dilute the purge gas entering I.P. 13 by a negligible amount. This flow will also serve to prevent any embarrassing fission product leakage into I.P. 14 and I.P. 10.

When an equilibrium activity has been achieved at I.P. 13, solenoid valve 44 is opened to communicate I.P. 10 with low pressure dump tanks via a restriction orifice. The immediate effect is to produce a flow of clean helium via S.V. 51, I.P. 10 and S.V. 44 to the dump tanks, with a large pressure drop at the orifice. Pressure in this part of the system can now be reduced by operating the Control Valve 160. A pressure transducer downstream of S.V. 51 will record the system pressure and by reference to reactor pressure will give an indication of differential pressure across and hence flow through the leak coil as well as the pressure of the sample taken.

Since the dump tank pressure will normally be $1\frac{1}{2}$ to 2 atm (abs.) and the clean helium supply pressure 21 to 23 atm (abs.), a wide range of pressure adjustment is possible. Also the restriction orifice at S.V. 44 can be removed and replaced if necessary.

As soon as this pressure is reduced to less than that at I.P. 13, the flow through the leak coil will reverse and a small flow of radioactive purge gas will mix with the clean helium passing through I.P. 10. Valve 160 will then be further adjusted until the activity recorded at I.P. 10 is in the desired ratio to that previously measured at I.P. 13.

Solenoid valve 44 is then immediately closed and the continued supply of clean, high pressure gas via valves 160 and 51 raises the pressure until clean gas again flows in the reverse direction through the leak coil, thus preventing further supply of radioactive gas to I.P. 10. Solenoid valves 46 and 47 are then opened and the purge sample of known volume and degree of dilution can be driven through the charcoal traps in I.P. 8 and I.P. 9 by means of the carrier flow from S.V. 51.

In the case of coated particle fuel when the fission product release may possibly be down by a factor of 10^6, it will not be necessary to dilute the purge sample. However, collection of the required volume of sample via the leak coil could involve lengthy delay during which many of the shorter lived fission products would have greatly decayed. A by-pass valve, incorporating a removable restriction orifice, is therefore provided across the leak coil so that an undiluted sample can be passed directly through the valve. This valve and orifice combination can also be employed for the lower range of dilution which may be required.

3.4 Xenon and Krypton Separation System

The sample collected in 3.3, whether diluted or not, can undergo a trapping process in order to separate the xenon and krypton gaseous isotopes so that each may be viewed separately by scintillation counters for gamma spectrometry. The separation will be performed by driving the purge sample through traps of activated charcoal located in instrument pots 8 and 9, (see Fig. 5), the gases being trapped by adsorption on the charcoal. The sample will be driven through the traps by means of clean helium at constant flow via S.V. 51, flow control being achieved by means of valve 160 in conjunction with a restriction orifice (removable) at solenoid valve 47. A flowmeter is incorporated downstream of valve 160.

Since the two active gases xenon and krypton exhibit different adsorption coefficients with activated charcoal as the adsorbent, they will progress at different rates through the charcoal traps so that after a certain time, xenon and krypton will be adsorbed in different parts of the system. The two traps have accordingly been arranged so that xenon may be trapped in one and krypton in the other and their activities and gamma spectra independently observed.

The theory of the adsorption process has been dealt with in [1] where the adsorption coefficient of gas on a charcoal bed at a particular temperature has been defined as

$$\phi = \frac{\text{Molecules of gas adsorbed per cc of charcoal bed}}{\text{Molecules of gas per cc of gas phase}} = \text{constant}$$

where the prevailing partial pressure of the gas is well below the saturation pressure of the charcoal.

Fig. 6 shows adsorption coefficient curves [2] for xenon and krypton over a range of temperature for a charcoal bed of 0.49 g/cc density and using 40 mesh charcoal. It can be seen that the ratio of the xenon and krypton coefficients increases with decrease of temperature. Ideally, therefore, a cooling system at, say, sub-zero temperature would be employed. However, because of technical difficulties associated with such a system, it was decided to control the trap temperatures at 50°C, slightly above the predicted ambient, by means of thermostatically controlled heaters.

Reference to Fig. 6 shows that at

40°C $\phi = 14.5$ for krypton and 160 for xenon. Ratio 11

50°C $\phi = 12$ for krypton and 125 for xenon. Ratio 10.5

60°C $\phi = 10$ for krypton and 90 for xenon. Ratio 9.

Hence, if the bed temperature is controlled at 50°C within a few degrees of accuracy, the ratio of the adsorption coefficients for xenon and krypton will not vary appreciably.

The charcoal traps must be large enough to ensure that after a certain time all the xenon and krypton is adsorbed in its respective trap, allowing for "band broadening" of the adsorption and the possibility of some error in the adsorption coefficients. The sharpness of the adsorption bands in the charcoal traps is dependent on the band broadening characteristics of the charcoal bed. The band broadening is given [1] by the formula

$$B = \frac{1}{LS}\sqrt{\frac{D_p G}{\mu}}$$

where S = specific surface of bed (cm^2/cm^3)

L = length of bed (cm)

μ = viscosity of gas (g/cm s)

G = mass flow rate (g/cm^2)

D_p = equivalent diameter of charcoal grains.

It can be seen that the adsorption band is sharper if a fine grain charcoal and a small carrier flow are used. Hence, a bed density of 0.49 g/cc and a carrier flow of only 2 cc/s have been chosen. No experimental data exists at present regarding the length of the adsorption tails but it has been assumed in this case that a sufficiently sharp breakthrough can be achieved. If this is so, and if the volume of the gas sample is 60 cc, the volumes of charcoal containing the adsorbed gases in the respective traps will be:-

(1) For Xenon

$$V = \frac{\text{Gas Volume}}{\text{Adsorption Coefficient}} = \frac{60}{140} = \underline{0.43 \text{ cc}}$$

(2) For Krypton

$$V = \frac{60}{12} = \underline{5 \text{ cc}}$$

The volume of the first trap for xenon has been fixed at 10 cc which should be large enough to ensure adsorption of all the xenon.

The size of the second krypton trap is then determined by the fact that we require the krypton to be adsorbed in its mid-section whilst the xenon is in the middle of the first trap.

The average delay time for a gas having an adsorption coefficient ϕ due to a charcoal bed of volume V and voidage fraction a is given by

$$t = \frac{V(\phi + a)}{F} \quad [1]$$

where F is the carrier gas volume flow rate. Since a is usually negligible compared with ϕ this fraction has been ignored.

$$\therefore t = \frac{V\phi}{F}$$

For the xenon trap, therefore, $t = \frac{10 \times 125}{2} = 625$ s.

In order for coincidence of trapping, the volume of the krypton trap should, therefore, be

$$V = \left(\frac{tF}{\phi_{Kr}}\right) - 10$$

$$V = \left(\frac{625 \times 2}{12}\right) - 10 = \underline{94 \text{ cc}}$$

The size of the krypton trap has, in fact, been made 90 cc. The krypton should then be in the middle third of the 90 cc trap when the xenon reaches the middle of the 10 cc trap. This will occur at about 315 s after the carrier gas has begun to flow, ignoring the free pipe volume between traps.

The volume of the gas sample (60 cc) has been made sufficiently large to ensure that if the activity of the purge gas is down by a factor of 10^6 due to the use of coated particle fuel, it will still be possible to have a fair indication of the fission product activity in the charcoal traps. The choice of sample volume was also influenced by the fact that a "dead leg" will occur in the pipework of the isolated sample and when the carrier gas flows through the system the dead leg may produce "tails" of the active gas. In order to minimise this effect, the sample volume must be relatively large, hence the choice of 60 cc.

3.4.1 Heat Generated in the Charcoal Beds

In order to calculate the heat generated in the traps, the pessimistic assumption has been made that all the xenon and krypton is present contemporarily in the same trap.

The heat generated by 1 cc of sample gas can be obtained from the formula

$$H = EC \; 3.7 \times 10^{10} \text{ MeV/s}$$

$$= EC \; 5.92 \text{ Watts}$$

where E = the sum of the average β-particle energy and the total γ-ray energy for each isotope, and C = the specific activity of the sample (curies) for each isotope. The summation carried out for all isotopes present in the sample indicates that heat generated is of the order of milliwatts and can be ignored for all practical purposes.

3.4.2 Temperature Control and Trap Regeneration

The trap temperature will be regulated at 50°C during activity measurements by means of thermostatically controlled electric heaters. Temperature measurement will be by means of thermocouples buried in the trap body as near to the charcoal as possible.

The heaters will also be capable of raising the trap temperature to 150°C so that by flushing with clean helium, fission products may be driven off to regenerate the traps. During this operation provision has been made for the scintillation counter to be raised clear of the trap by means of a remotely operated electric motor to avoid overheating of and possible damage to the instrument.

A general arrangement of a charcoal trap installation is shown in Fig. 5.

3.5 Installation of Equipment

All the valves and instruments which comprise this system (excepting the γ-spectrometry equipment) will be installed in sealed containment vessels approximately 4 ft 6 in deep and $8\frac{1}{2}$ in minimum inside diameter built into the biological shield floor over the fission product plant room of the reactor building. Biological shield plugs are provided in the mid-section of each vessel, with the valve or instrument assembly below and electric cables, etc., passing through suitable holes in the shield plugs.

Solenoid valves and other electrically actuated equipment will be remotely operated from the main control room.

All the equipment has been designed to permit its being removed and replaced by remote handling equipment during reactor shut down periods. Mechanical seals are made between the valves, etc., and pipe stubs in the containment vessels and the vessels can be monitored by leak detection equipment to locate any possible leakage from the installations.

3.6 Flexibility of System

Because all the valve and instrument assemblies can be removed and replaced by remote handling equipment, various modifications to the system can be made should theoretical premises not be fully borne out in practice. A charcoal trap assembly, for example, can be replaced by one of different volume, geometry, charcoal grain size and charcoal density and a leak coil can be replaced by one of different bore size and/or length. Further, where such items as restriction orifices and filters are fitted, these have been made easily removable so that alternative sizes may be assembled if necessary.

From the operational viewpoint, a wide range of experiments can be performed as described in Section 2. For these experiments, dilution of the purge gas can be varied as can also the carrier flow through the charcoal traps and the trap temperatures.

4. FISSION PRODUCT ANALYSIS - COATED PARTICLE FUEL

The following paragraph outlines the calculation of activities for an assumed fuel condition and fission product release. This is a purely theoretical consideration for purposes of illustration. The actual activity may be somewhat different in practice and indeed one would be very surprised if it were not.

4.1 Calculation of Fission Products Present in the Purge Flow

The activity of the fission products present in the purge gas is calculated for a reactor heat output of 20 MW for which the number of fissions per second is equal to

$$N = 20 \times 3.12 \times 10^{16}$$

$$= 6.24 \times 10^{17} \text{ fissions/s}$$

The rate of production of one fission product

$$= 6.24 \times 10^{15} \, Y \text{ atoms/s}$$

where Y is the yield in %.

Assuming a purge flow of 2.5×10^3 cc/s, (i.e., at 50°C and 20 atm absolute pressure) and a release of gaseous fission products into the purge flow equal to 10^{-4} of the total, then the concentration of a given fission product in the purge gas will be

$$C = \frac{6.24 \times 10^{15} \times Y \times 10^{-4}}{2.5 \times 10^3} \text{ atoms/cc}$$

$$C = 2.50 \times 10^8 \, Y \text{ atoms/cc}$$

The specific activity of the fission product under consideration in the purge gas is equal to

$$\lambda C = \frac{2.50 \times 10^8 \, Y\lambda}{3.7 \times 10^{10}} \text{ curies/cc}$$

$$= 6.76 \times 10^{-3} \, Y\lambda \text{ curies/cc}$$

where λ is the decay constant (s^{-1}).

Table 1 shows the activities of all gamma-emitting fission products in the purge gas plus those which produce gamma-emitting daughters and the corresponding gamma-spectrum is shown at Fig. 7.

The activity of the daughter products in the fixed sample volume can be calculated by the formula

$$A_2 = \lambda_1 C_1 V \left(1 - e^{-\lambda_2 t}\right)$$

$$= A_1 e^{-\lambda_1 t} V \left(1 - e^{-\lambda_2 t}\right)$$

where λ_1 is the decay constant of the parent (s^{-1})

C_1 is the concentration of the parent (atoms/cc)

A_1 is the initial specific activity of the parent (curies/cc)

λ_2 is the decay constant of the daughter (s^{-1})

t is the time during which the sample volume has been allowed to decay (s)

It can be seen (see also Figs. 11 and 14) that there will be a maximum activity from the daughter depending on $\lambda_1 C_1$ and $\lambda_2 t$. For subsequent decay of parent and daughter the activities of each will be very roughly the same. Where there is a continued supply of the parent, (i.e., continuous flow of sample gas) the daughter activity will rise to equal that of the parent according to the formula

$$A_2 = A_1 V \left(1 - e^{-\lambda_2 t}\right)$$

4.2 Fission Product Analysis in the Xenon Trap

It is hoped that by means of gamma spectrometry the following isotopes can be identified:-

Xe-135, Xe-133, and Xe-138: the latter also by means of its solid daughter product Cs-138.

In order to cover this range of identification, 4 separate analyses have to be considered:-

(i) After no decay in the trap it may be possible to identify Xe-138 which has the highest energy peak (see Fig. 8 for γ-spectrum) despite interference from peaks of Xe-135m.

(ii) Since Xe-135m and Xe-138 have short half-lives (15.6 min and 17 min respectively), if the sample is allowed to decay for, say, 3 h, Xe-135 (half-life 9.1 h) can be measured. During this decay time, there will also be a build-up of the solid daughter product Cs-138 owing to decay of Xe-138 according to the formula in Section 4.1. However, Cs-138 has a short half-life (32.2 min) so that after about 1 hour its activity will equal that of the parent whose half-life is only 17 min. Hence, owing to this rapid decay rate no influence will be made on the measurement of Xe-135. The gamma spectrum after 3 h decay is shown at Fig. 9 and the total activities at Table 2.

(iii) If the sample is allowed to decay further for a total of 45 h (see Table 3) the longest lived isotope, Xe-133 (half-life 5.27 days) can then be measured (see Fig. 10 for gamma spectrum).

(iv) As mentioned above, Xe-138 will produce the solid daughter Cs-138 after a short time. It is therefore proposed that, by sweeping out the gaseous fission products with clean helium via Solenoid Valve 51, the activity of the remaining Cs-138 can be measured and hence the activity of the parent calculated. Fig. 11 shows the build-up and decay curve for Cs-138 [3] from which the best soaking time can be established as being about 33 min.

This, of course, must obviously be a separate experiment with another gas sample for the reasons in (ii) above.

4.3 Fission Product Analysis in the Krypton Trap

By means of this second trap gamma spectrometry can be used to determine the presence of Kr-87, Kr-85m and Kr-88 by means of its solid daughter Rb-88.

For identification of these fission products three separate gamma spectra must be considered:-

(i) With no decay in the trap (see Fig. 12) it may be possible to detect only the isotope Kr-87.

(ii) It is doubtful whether Kr-83m can be measured because of the complex low energy spectrum. However, the half-life of Kr-83m is short (114 min) so that decay of the sample will permit the measurement of Kr-85m. In order to also discriminate between Kr-85m and Kr-88 which have half-lives of a similar order (4.3 h and 2.7 h respectively) the delay must be sufficiently long to permit adequate decay of the Kr-88. A delay time of 20 h has therefore been assumed (see Fig. 13 for gamma spectrum and Table 4 for activities).

(iii) As a separate experiment with a second gas sample, advantage can be taken of the decay of Kr-88 to form Rb-88 and the gaseous products flushed from the trap in order to measure the remaining solid daughter. In this case, the flushing direction must be reversed to avoid contamination of the trap with xenon and this can be achieved by flushing via Solenoid Valve 49, I.P. 13 and S.V. 47, valve S.V. 44 being opened to the dump tanks, after first flushing out I.P. 13 down to the main F.P. purge line. From measurement of Rb-88, the activity of the parent Kr-88 can be estimated.

Reference to Fig. 14 will show the build-up and decay of Rb-88 [3] and the best soaking time for this experiment as being 60 min approx.

4.4 Fission Product Analysis of the Unseparated Sample

A further experiment of a less sophisticated nature can also be carried out on the unseparated purge gas. This experiment can be performed in two ways.

(a) The gas sample can be isolated in I.P. 10 as described in Section 3.2, and a total count recorded in addition to gamma spectrometry of the sample. Gamma spectrometry may allow the immediate identification of Xe-138 (see Fig. 7).

The sample can then be allowed to decay and since the Kr isotopes generally have shorter half-lives than those of Xe, decay for several hours will leave only Xe-131m, Xe-133m, Xe-133 and Xe-135. The same considerations of 4.2 will then apply.

Measurement of the solid daughter products Cs-138 and Rb-88 could also be carried out as described in Sections 4.2 and 4.3.

(b) A continuous flow of sample gas can be viewed either at I.P. 13 or I.P. 10 (depending on the order of fission product release) and in this case an equilibrium activity should be reached owing to build-up of the radioactive solid daughters. An advantage of this system is that by means of the continuous flow process the activity of the short-lived fission products will be in equilibrium, decay need only be considered in terms of the effects of sampling line delay and measurement can be more leisurely. Also the solid daughters will build-up to an equilibrium condition and therefore, the subsequent measurement will be simplified. Although by gamma spectrometry it may be possible to identify Xe-138 and Kr-89 peaks, this can be a qualitative analysis only.

Measurement of Cs-138 and Rb-88 can be carried out at a later stage by stopping the purge flow and sweeping the gaseous products away with clean helium.

Taking this experiment further, the gaseous products above could be driven through the charcoal traps and measurements carried out as in Sections 4.2 and 4.3.

It should be noted that for both experiments (a) and (b) above, the volume of purge gas in I.P. 13 or I.P.10 will be only half, (i.e., 30 cc) of that passed through the charcoal traps, the remaining 30 cc being contained in the interconnecting pipework.

5. FISSION PRODUCT ANALYSIS - UNCOATED FUEL

The same remarks apply to the following calculations as for Section 4.

5.1 Calculation of Fission Products Present in the Purge Flow

For a 20 MW output, assuming a purge flow of 2.5×10^3 cc/s (at 50°C and 20 atm absolute pressure), and 100% release of gaseous fission products into the purge flow with no delay, then the concentration of a given fission product will be

$$C_1 = \frac{6.24 \times 10^{15} \times Y}{2.5 \times 10^{3}} \text{ atoms/cc}$$

$$C_1 = 2.5 \times 10^{12} \text{ Y atoms/cc.}$$

The specific activity is equal to

$$\lambda C_1 = \frac{2.5 \times 10^{12} \; Y\lambda}{3.7 \times 10^{10}}$$

$$= 67.6 \; Y\lambda \text{ curies/cc}$$

where λ is the decay constant.

The activities can also be calculated for any assumed value of delay in the fuel element.

The activity of the daughter products can be estimated as in Section 4.1.

Table 5 shows the activities of all the gamma emitting fission products plus those with gamma emitting daughters, assuming 1 hour delay in the fuel element. Fig. 15 shows the gamma spectrum for the unseparated sample and it is apparent that, because of its complexity, it will be very difficult to identify immediately any of the Xe or Kr isotopes. Immediate gamma spectra of the separated Xe and Kr fractions (Figs. 16, 17) are similarly unhelpful. By successive delay in the charcoal traps, however, it will be possible to carry out certain measurements as described below.

5.2 Fission Product Analysis in the Xenon Trap

Measurement of Xe-133, Xe-133m and Xe-135 is expected plus measurement of Xe-138 via its solid daughter product Cs-138. Three analyses are required for this as follows:-

(i) The sample can be allowed to decay for 45 h, after which time activities will be as listed in Table 6 and the gamma spectrum will be as in Fig. 18. The concentration of Xe-133 and Xe-135 can then be measured.

(ii) The sample is allowed to decay further for a total period of 5 days. Measurement of Xe-133m and Xe-133 can then take place. Activities present after this delay period are shown in Table 7 and the gamma spectrum at Fig. 19.

(iii) With a separate gas sample, measurement of the solid daughter product Cs-138 can be performed as previously described in Section 4.2.

Table 5

Activity of Fission Products in the Purge Gas at 50°C and 20 at Pressure

Uncoated Fuel. 100% Release. 1 h Delay in Fuel.

Fission Product	Specific Activity for No Delay = 67.6 $Y\lambda$	λt	Activity Reduction Factor $e^{-\lambda t}$	Specific Activity (curies/cc)	Activity for 30 cc	Activity for 60 cc
Kr-83m	3.2×10^{-3}	0.363	0.696	2.22×10^{-3}	6.66×10^{-2}	1.33×10^{-1}
Kr-85m	4.36×10^{-3}	0.169	0.844	3.68×10^{-3}	1.1×10^{-1}	2.2×10^{-1}
Kr-87	2.62×10^{-2}	0.533	0.587	1.53×10^{-2}	4.59×10^{-1}	9.18×10^{-1}
Kr-88	1.69×10^{-2}	0.25	0.78	1.32×10^{-2}	3.96×10^{-1}	7.92×10^{-1}
Xe-131m	1.32×10^{-6}	2.4×10^{-3}	0.999	1.32×10^{-6}	3.96×10^{-5}	7.92×10^{-5}
Xe-133m	3.68×10^{-5}	1.26×10^{-2}	0.985	3.63×10^{-5}	1.09×10^{-3}	2.18×10^{-3}
Xe-133	6.42×10^{-4}	5.4×10^{-3}	0.995	6.38×10^{-4}	1.91×10^{-2}	3.82×10^{-2}
Xe-135m	8.72×10^{-2}	2.66	0.07	6.1×10^{-3}	1.83×10^{-1}	3.66×10^{-1}
Xe-135	8.6×10^{-3}	7.6×10^{-2}	0.927	7.97×10^{-3}	2.39×10^{-1}	4.78×10^{-1}
Xe-138	2.44×10^{-1}	2.44	0.087	2.12×10^{-2}	6.36×10^{-1}	1.27

Table 6

Activity of Fission Products in the Xenon Trap at 50°C and 20 atm Pressure

Uncoated Fuel. 100% Release. 45 h Decay

Fission Product	Specific Activity for No Decay	λt	Activity Reduction Factor $e^{-\lambda t}$	Specific Activity (curies/cc)	Activity for 60 cc
Xe-131m	1.32×10^{-6}	0.108	0.898	1.19×10^{-6}	7.14×10^{-5}
Xe-133m	3.68×10^{-5}	0.567	0.567	2.09×10^{-5}	1.25×10^{-3}
Xe-133	6.42×10^{-4}	0.243	0.783	5.03×10^{-4}	3.02×10^{-2}
Xe-135	8.6×10^{-3}	3.42	0.033	2.84×10^{-4}	1.70×10^{-2}

Table 7

Activity of Fission Products in the Xenon Trap at 50°C and 20 atm Pressure

Uncoated Fuel. 100% Release. 5 days Decay

Fission Product	Specific Activity for No Decay	λt	Activity Reduction Factor $e^{-\lambda t}$	Specific Activity (curies/cc)	Activity for 60 cc
Xe-131m	1.32×10^{-6}	0.288	0.748	9.88×10^{-7}	5.93×10^{-5}
Xe-133m	3.68×10^{-5}	1.51	0.22	8.1×10^{-6}	4.86×10^{-4}
Xe-133	6.42×10^{-4}	0.648	0.523	3.36×10^{-4}	2.02×10^{-2}
Xe-135	8.6×10^{-3}	9.12	1.09×10^{-4}	9.38×10^{-7}	5.63×10^{-5}

5.3 Fission Product Analysis in the Krypton Trap

In the krypton trap it is hoped to measure the concentration of Kr-85m and Kr-88, the latter by means of its solid daughter Rb-88. Analysis will be by two separate experiments as follows:-

(i) The sample can be allowed to decay for 20 h. (See Table 8 for activity levels and Fig. 20 for gamma spectrum.) Identification and measurement of Kr-85m can then be performed.

(ii) As previously described in Section 4.3, a separate sample can be taken and measurement of Rb-88 carried out by sweeping away the gaseous fission products.

Table 8

Activity of Fission Products in the Krypton Trap
at 50°C and 20 atm Pressure
Uncoated Fuel. 100% Release. 20 h Decay

Fission Product	Specific Activity for No Decay	λt	Activity Reduction Factor $e^{-\lambda t}$	Specific Activity (curies/cc)	Activity for 60 cc
Kr-83m	3.2×10^{-3}	7.27	6.92×10^{-4}	2.22×10^{-6}	1.33×10^{-4}
Kr-85m	4.36×10^{-3}	3.18	7.27×10^{-2}	3.17×10^{-4}	1.9×10^{-2}
Kr-87	2.62×10^{-2}	10.68	2.29×10^{-5}	6×10^{-7}	3.6×10^{-5}
Kr-88 (Rb-88)	1.69×10^{-2}	5	6.75×10^{-3}	1.14×10^{-4}	6.84×10^{-3}

5.4 Fission Product Analysis in the Unseparated Sample

The same considerations will apply here as for the coated fuel case covered in Section 4.4. Because of the assumed 1 h delay in the fuel, however, the contribution from short lived fission products will be much less.

6. ACTIVITY MEASUREMENT OF THE REACTOR PRIMARY COOLANT

Reference to the flowsheet, Fig. 3 will show that a differential pressure transducer is located in instrument pot I.P. 11, one side of which is connected to the dump line from the reactor pressure vessel. This transducer and another (not shown on Fig. 3), form part of the system for faulty fuel element detection (to be described in a separate D.P. Report). A by-pass valve is provided across this pressure transducer so that when desired, a sample of primary coolant gas may be taken through valve S.V. 48 and thence to either I.P. 13 or I.P. 10 so that its activity may be measured and gamma spectra obtained. The same general procedure for activity measurement can be adopted as previously described in Sections 4 and 5, but because of the comparatively low activity level of the primary coolant, some modification of the techniques employed will probably be necessary.

7. DETAILS OF ACTIVITY MEASUREMENTS

7.1 Activity Measurement at I.P. 13

As previously mentioned in Section 3.2, the total activity of the purge flow from any fuel element can be measured at I.P. 13 by either an ion chamber or, for a fission product release of the order of about 10^{-6} or less, a scintillation counter. This measurement can be performed by operating the selector valve manually or automatically.

For automatic scanning of fuel elements the velocity of the scanning system is determined by the time required for the sample gas to flow from the fuel element to the monitor pipe coil plus an allowance for equilibrium conditions to be established. The gas volume in the coil should, therefore, be reasonably small yet high enough to permit activity measurement by an ion chamber during 100% fission product release. The coil volume has, accordingly been made 30 cc and the flow delay time (ignoring possible adsorption of gases on the pipe wall between fuel element and monitor) will be about 35 s, the purge gas having an estimated flow rate of 8 cc/s. Delay times of 50, 70 or 100 s have been provided for on the timing unit of the selector valve control system for automatic activity scanning. These times can be easily supplemented if necessary by fitting different cams to the timer unit.

When the scintillation counter is used, the sensitivity of the system can also be reduced by inserting lead shielding between the counter and the coil. (See Fig. 4.)

7.1.1 Ion Chamber Measurement

The ion chamber being provided is of stainless steel, filled with argon at 6 atm pressure.

The output current of the chamber can be calculated by the approximate formula

$$I = 5.2 \times 10^{6} \frac{C\ V\ E\ S}{D^{2}} \qquad [4]$$

where C is the specific activity of the sample (curies/cc)

V is the volume of the sample gas in the coil (cc)

E is the average γ-energy of the photons (MeV)

S is the sensitivity of the chamber (A/mR/h)

D is the distance between the chamber centre and the source centre (cm).

For the case considered, D = 5.6 cm and V = 30 cc

$$\therefore I = \frac{5.2 \times 10^6 \times 30\ C\ E\ S}{31.4}$$

$$I = 4.98 \times 10^6\ C\ E\ S$$

The computation of ion current for each of the two fuel configurations considered is shown in Tables 9 and 10.

Table 9

Current Output of Total Activity Monitor in the Sample Line at I.P. 13 Using Ion Chamber Coated Fuel. 10^{-4} Release. No Delay Assumed

Fission Product	Specific Activity (curies/cc)	Average γ-Energy (MeV)	Sensitivity S (A/mR/h) x 10^{-12}	Current (amps)
Kr-83m	3.2×10^{-7}	0.0415	6.92	4.59×10^{-13}
Kr-85m	4.36×10^{-7}	0.181	1.33	5.23×10^{-13}
Kr-87	2.62×10^{-6}	0.56	1.0	7.32×10^{-12}
Kr-88	1.69×10^{-6}	2.07	1.0	1.74×10^{-11}
Xe-131m	1.32×10^{-10}	0.163	1.49	1.6×10^{-16}
Xe-133m	3.68×10^{-9}	0.233	1.15	4.91×10^{-15}
Xe-133	6.42×10^{-8}	0.081	3.49	9.04×10^{-14}
Xe-135m	8.72×10^{-6}	0.52	1.0	2.26×10^{-11}
Xe-135	8.6×10^{-7}	0.268	1.13	1.29×10^{-12}
Xe-138	2.44×10^{-5}	0.522*	1.0	6.34×10^{-12}
			Total	5.6×10^{-11}

*Approximate only.

Table 10

Current Output of Total Activity Monitor
in the Sample Line at I.P. 13 Using Ion Chamber
Uncoated Fuel. 100% Release
1 h Delay in Fuel Assumed

Fission Product	Specific Activity C (curies/cc)	Average λ-Energy E (MeV)	Sensitivity S (A/mR/h) x 10^{-12}	Current (Amps)
Kr-83m	2.22×10^{-3}	0.0415	6.92	3.18×10^{-9}
Kr-85m	3.68×10^{-3}	0.181	1.33	4.42×10^{-9}
Kr-87	1.53×10^{-2}	0.56	1.0	4.26×10^{-8}
Kr-88	1.32×10^{-2}	2.07	1.0	1.36×10^{-7}
Xe-131m	1.32×10^{-6}	0.163	1.49	1.6×10^{-12}
Xe-133m	3.63×10^{-5}	0.233	1.15	9.72×10^{-11}
Xe-133	6.38×10^{-4}	0.081	3.49	8.97×10^{-10}
Xe-135m	6.1×10^{-3}	0.52	1.0	1.57×10^{-8}
Xe-135	7.97×10^{-3}	0.268	1.13	1.2×10^{-8}
Xe-138	2.12×10^{-2}	0.522*	1.0	5.52×10^{-8}
			Total Current	2.7×10^{-7}

*Approximate only.

7.1.2 Scintillation Counter Measurement

The scintillation counter being provided will utilise a right cylindrical NaI crystal, 1½" diameter and 1" long.

The counting rate can be calculated by the approximate formula

$$R = 3.7 \times 10^{10} \, C \, V \, \varepsilon$$

where C is the specific activity of the sample (curies/cc)

V is the volume of the sample in the coil (cc)

ε is the intrinsic efficiency of the crystal

(See Section 7.3.1 for details.)

Tables 11 and 12 show the computation of counting rates for coated and uncoated fuel configurations respectively.

Table 11

Counting Rate of the Total Activity Monitor in the Sample Line at I.P. 13 Using Scintillation Counter Coated Particle Fuel. 10^{-4} Release. No Delay Assumed

Fission Product	Average γ-Energy (MeV)	Average Intrinsic Efficiency of the Crystal x 10^{-2}	Specific Activities (curies/cc)	Count Rate for 30 cc c/s
Kr-83m	0.0415	5.75	3.2×10^{-7}	2.04×10^{4}
Kr-85m	0.181	4.50	4.36×10^{-7}	2.18×10^{4}
Kr-87	0.56	2.20	2.62×10^{-6}	6.41×10^{4}
Kr-88	2.07	1.25	1.69×10^{-6}	2.34×10^{4}
Xe-131m	0.163	4.90	1.32×10^{-10}	-
Xe-133m	0.233	4.0	3.68×10^{-9}	1.63×10^{2}
Xe-133	0.081	5.60	6.42×10^{-8}	3.98×10^{3}
Xe-135m	0.52	2.35	8.72×10^{-6}	2.28×10^{5}
Xe-135	0.268	3.60	8.6×10^{-7}	3.44×10^{4}
Xe-138	0.522*	2.35	2.44×10^{-5}	6.37×10^{5}
			Total Count*	1.033×10^{6}

*Approximate only.

7.2 Activity Measurement at I.P. 10

The monitoring system will be identical to that when the scintillation counter is used at I.P. 13 (see Section 7.1.2), the purge sample being either diluted or undiluted as necessary. The count rates shown in Tables 11 and 12 are those which would occur for the undiluted sample for each fuel case.

Table 12

Counting Rate of the Total Activity Monitor in the Sampling Line at I.P. 13 Using Scintillation Counter Uncoated Fuel. 100% Release. 1 h Delay in Fuel Assumed

Fission Product	Average γ-Energy (MeV)	Average Intrinsic Efficiency of the Crystal $\times 10^{-2}$	Specific Activities (curies/cc)	Count Rate for 30 cc C/s
Kr-83m	0.0415	5.75	2.22×10^{-3}	1.42×10^{8}
Kr-85m	0.181	4.50	3.68×10^{-3}	1.84×10^{8}
Kr-87	0.56	2.20	1.53×10^{-2}	3.74×10^{8}
Kr-88	2.07	1.25	1.32×10^{-2}	1.83×10^{8}
Xe-131m	0.163	4.90	1.32×10^{-6}	7.18×10^{4}
Xe-133m	0.233	4.0	3.63×10^{-5}	1.61×10^{6}
Xe-133	0.081	5.60	6.38×10^{-4}	3.96×10^{7}
Xe-135m	0.52	2.35	6.1×10^{-3}	1.59×10^{8}
Xe-135	0.268	3.60	7.97×10^{-3}	3.19×10^{8}
Xe-138	0.522*	2.35	2.12×10^{-2}	5.53×10^{8}
			Total Count	1.95×10^{9}

*Approximate only.

7.3 Activity Measurement in the Charcoal Traps

The same type of scintillation counter will be installed as for I.P. 13 and I.P. 10 and the count rate is given by the approximate formula

$$R = 3.7 \times 10^{10} \, C \, V \, \varepsilon$$

In this case, however, the sample volume passed through the traps will be twice that measured in the coils at I.P. 13 and I.P. 10, as explained in Section 4.4. The crystal efficiency will also be slightly increased since the source is closer to the crystal. Against this, however, the specific activity in each trap will be less owing to the separation of the xenon and krypton, so that the maximum counts recorded and hence the dilution required, will be of the same order.

In order to make quantitative measurements of the concentration of fission products, the intrinsic efficiency of the system must be known. The intrinsic efficiency can be calculated, assuming a point source, by the formula

$$\varepsilon = \frac{\int_0^{\Omega_0} (1 - e^{-\mu x})\, d\Omega}{\Omega_0}$$

where ε is the intrinsic efficiency of crystal

Ω_0 is the solid angle subtended by the crystal measured from the point source

μ is the γ-absorption coefficient for sodium iodide varying with γ-energy

x is the general thickness of the crystal encountered by the γ-radiation

Calculations of peak intrinsic efficiencies for right cylindrical NaI crystals have been made by various groups [5,6,7], and from one such report, [5], efficiencies have been extracted for a 1½ in diameter x 1 in long crystal in order to avoid laborious calculations. It must be noted that the efficiencies calculated in the above report are based on a point source being located on the extended axis of the cylinder whereas in our case the source will be at 90° to this axis. Some margin of error must, therefore, be expected in the efficiencies used.

7.3.1 Measurement at I.P. 9 (Xenon Trap)

The trap will have a bore of 7 mm and will surround the crystal such that the geometric efficiency of the crystal is roughly the same wherever the xenon may be located in the trap.

Tables 13 and 14 show the calculation of count rates for the xenon trap for no decay, 45 hours and 5 days decay for uncoated fuel and no decay, 3 hours and 45 hours decay for coated fuel.

7.3.2 Measurement at I.P. 8 (Krypton Trap)

The same geometry will occur as for the xenon trap above but the trap, being of larger capacity, has a bore of 11 mm. Tables 15 and 16 show the count rates obtained from the krypton trap for no decay and 20 hours decay for both coated and uncoated fuel arrangements.

7.4 Shielding from Background Radiation

The containment vessels which house the instruments are, as stated in Section 3.5, built into the floor above the F.P. plant room and the vessels will protrude below the floor for some 7 in. Background radiation from directly below, attributable to dump tanks and delay beds, etc., is estimated at 10^4 r/h of average energy 1 MeV. Since we would like to

Table 13

Count Rates for Xenon Trap

Coated Particle Fuel. 10^{-4} Release

Fission Product	Intrinsic Efficiency of Crystal $\times 10^{-2}$	Count Rate for no Decay in Trap	Count Rate for 3 h Decay in Trap	Count Rate for 45 h Decay in Trap
Xe-131m	8.30	24.3	-	-
Xe-133m	6.6	5.37×10^{2}	5.18×10^{2}	-
Xe-133	10	1.42×10^{4}	1.4×10^{4}	1.11×10^{4}
Xe-135m	3.9	7.57×10^{5}	2.54×10^{2}	-
Xe-135	6	1.15×10^{5}	9.53×10^{4}	3.78×10^{3}
Xe-138	3.9	2.12×10^{6}	1.6×10^{3}	-
(Cs-138)	2.1	-	7.25×10^{2}	-
	Total Count	3×10^{6}	1.12×10^{5}	1.488×10^{4}

Table 14

Count Rates for the Xenon Trap

Uncoated Fuel. 100% Release

1 h Delay in Fuel Assumed

Fission Product	Intrinsic Efficiency of Crystal $\times 10^{-2}$	Count Rate for no Decay in Trap c/s	Count Rate for 45 h Decay in Trap c/s	Count Rate for 5 days Decay in Trap c/s
Xe-131m	8.3	2.44×10^{5}	2.19×10^{5}	1.83×10^{5}
Xe-133m	6.6	5.31×10^{6}	3.06×10^{6}	1.17×10^{6}
Xe-133	10	1.42×10^{8}	1.11×10^{8}	7.43×10^{7}
Xe-135m	3.9	5.28×10^{8}	-	-
Xe-135	6	1.06×10^{9}	3.5×10^{7}	1.15×10^{5}
Xe-138	3.9	1.82×10^{9}	-	-
	Total Count	3.56×10^{9}	1.49×10^{8}	7.58×10^{7}

Table 15

Count Rates for the Krypton Trap

Coated Particle Fuel. 10^{-4} Release

Fission Product	Intrinsic Efficiency of Crystal x 10^{-2}	Count Rate for No Decay in Trap	Count Rate for 20 h Decay in Trap
Kr-83m	10	7.1×10^{4}	49.4
Kr-85m	7.5	7.26×10^{4}	3.03×10^{3}
Kr-87	3.7	2.15×10^{5}	-
Kr-88	2.0	7.52×10^{4}	5.06×10^{2}
(Rb-88)	4.0	-	1.01×10^{3}
	Total Count	4.31×10^{5}	4.6×10^{3}

Table 16

Count Rates for the Krypton Trap

Uncoated Fuel. 100% Release

1 h Delay in Fuel Assumed

Fission Product	Intrinsic Efficiency of Crystal x 10^{-2}	Count Rate for No Decay in Trap	Count Rate for 20 h Decay in Trap
Kr-83m	10	4.93×10^{8}	4.93×10^{5}
Kr-85m	7.5	6.13×10^{8}	5.28×10^{7}
Kr-87	3.7	1.26×10^{9}	4.93×10^{4}
Kr-88	2.0	5.86×10^{8}	5.06×10^{6}
(Rb-88)	1.7	-	1.01×10^{7}
	Total Count	2.95×10^{9}	6.85×10^{7}

reduce the background count rate below 30 c/s for all the activity measurements, lead shielding has been provided at the lower ends of the appropriate containment vessels. This shielding is 12 in thick at the base of the vessel and has a radial thickness of 4 in around that part of the vessel which projects below floor level. In the two charcoal trap installations, further shielding has been provided inside the containment vessels to reduce any background from pipework, this being particularly important for measurement of Kr-85m where the activity is very low and a background counting rate below 7 c/s is desirable.

7.5 Summary of Counting Rates

Tables 11 to 16 inclusive show the estimated count rates obtained for the unseparated sample and for the separated xenon and krypton fractions for each type of fuel considered.

7.5.1 Coated Fuel. 10^{-4} Release

		Total Count c/s
(a)	Unseparated Sample - no decay	1.033×10^6
(b)	Krypton Trap - no decay	4.31×10^5
(c)	Krypton Trap - 20 h decay	4.6×10^3
(d)	Xenon Trap - no decay	3×10^6
(e)	Xenon Trap - 3 h decay	1.12×10^5
(f)	Xenon Trap - 45 h decay	1.488×10^4

From the above it can be seen that the maximum count rate occurs for case (d) where the count is 3×10^6 c/s. If the maximum count rate for the instrument is 5×10^4 c/s it is apparent that the purge sample must be diluted by a factor of at least

$$\frac{3 \times 10^6}{5 \times 10^4} = 60$$

For this degree of dilution, the minimum count rate recorded will be for case (c) where the count rate, after dilution would be

$$\frac{4.6 \times 10^3}{60} \quad 76 \text{ approx.}$$

For a fission product release of 10^{-6}, no dilution of the purge gas will be required and for a release of 10^{-2} the dilution must be increased to 6×10^3. The count rates obtained will thus be similar to those above and activity measurement of the sample can be achieved over this range of fission product release.

7.5.2 Uncoated Fuel. 100% Release. 1 h Delay in Fuel

		Total Counts c/s
(a)	Unseparated Sample - no decay	1.95×10^9
(b)	Krypton Trap - no decay	2.95×10^9
(c)	Krypton Trap - 20 h decay	6.85×10^7
(d)	Xenon Trap - no decay	3.56×10^9
(e)	Xenon Trap - 45 h decay	1.49×10^8
(f)	Xenon Trap - 5 days decay	7.58×10^7

The maximum count rate occurs for case (d). The dilution required, assuming a maximum count rate of 5×10^4 c/s for the instrument is, therefore,

$$\frac{3.56 \times 10^9}{5 \times 10^4} = 7 \times 10^4 \text{ approx.}$$

For this dilution, the minimum count rate will be for case (c) when the count rate will be reduced to

$$\frac{6.85 \times 10^7}{7 \times 10^4} = 300 \text{ approx.}$$

In the case of the unseparated sample measured at I.P. 13, the sensitivity of the scintillation counter can be reduced by the insertion of lead shielding between the counter and the coil, when an average reduction factor of 0.13 can be obtained in the counting rate. Without lead shielding, it should be possible to measure a maximum concentration of fission products $\frac{1}{7 \times 10^4}$ approx. of that considered in Table 5. With lead shielding, however, this figure can be increased to $\frac{1}{10^4}$ approx. so that there will be an appreciable overlap between the ion chamber system and the scintillation counter system.

8. ACKNOWLEDGMENTS

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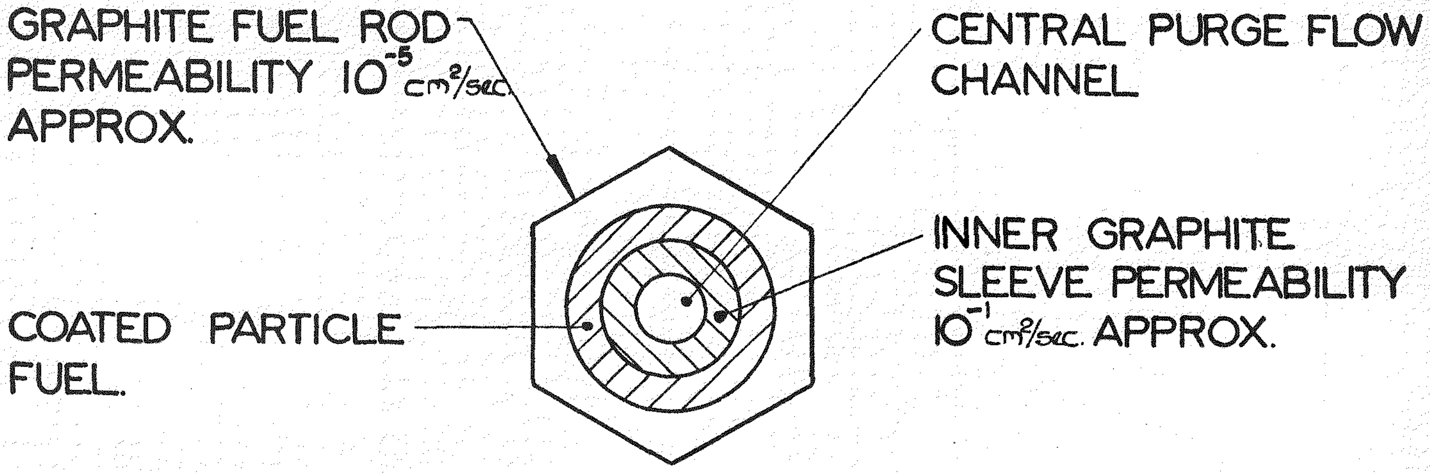


FIG. 1. DIAGRAMMATIC SKETCH OF COATED FUEL ARRANGEMENT.

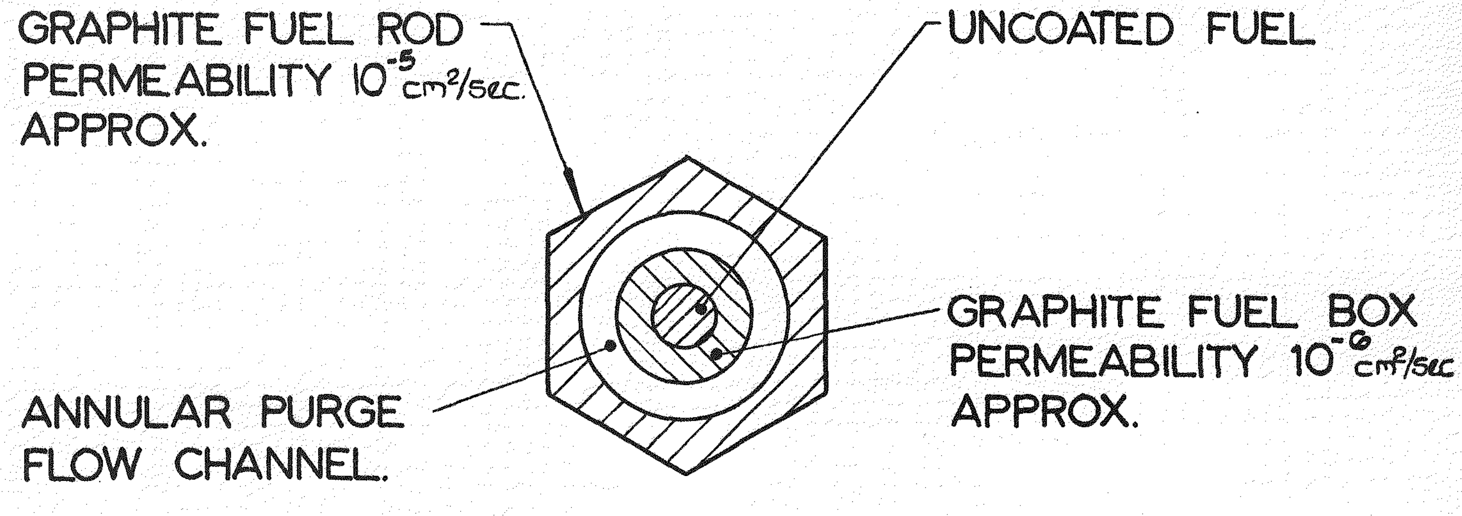


FIG. 2. DIAGRAMMATIC SKETCH OF UNCOATED FUEL ARRANGEMENT.

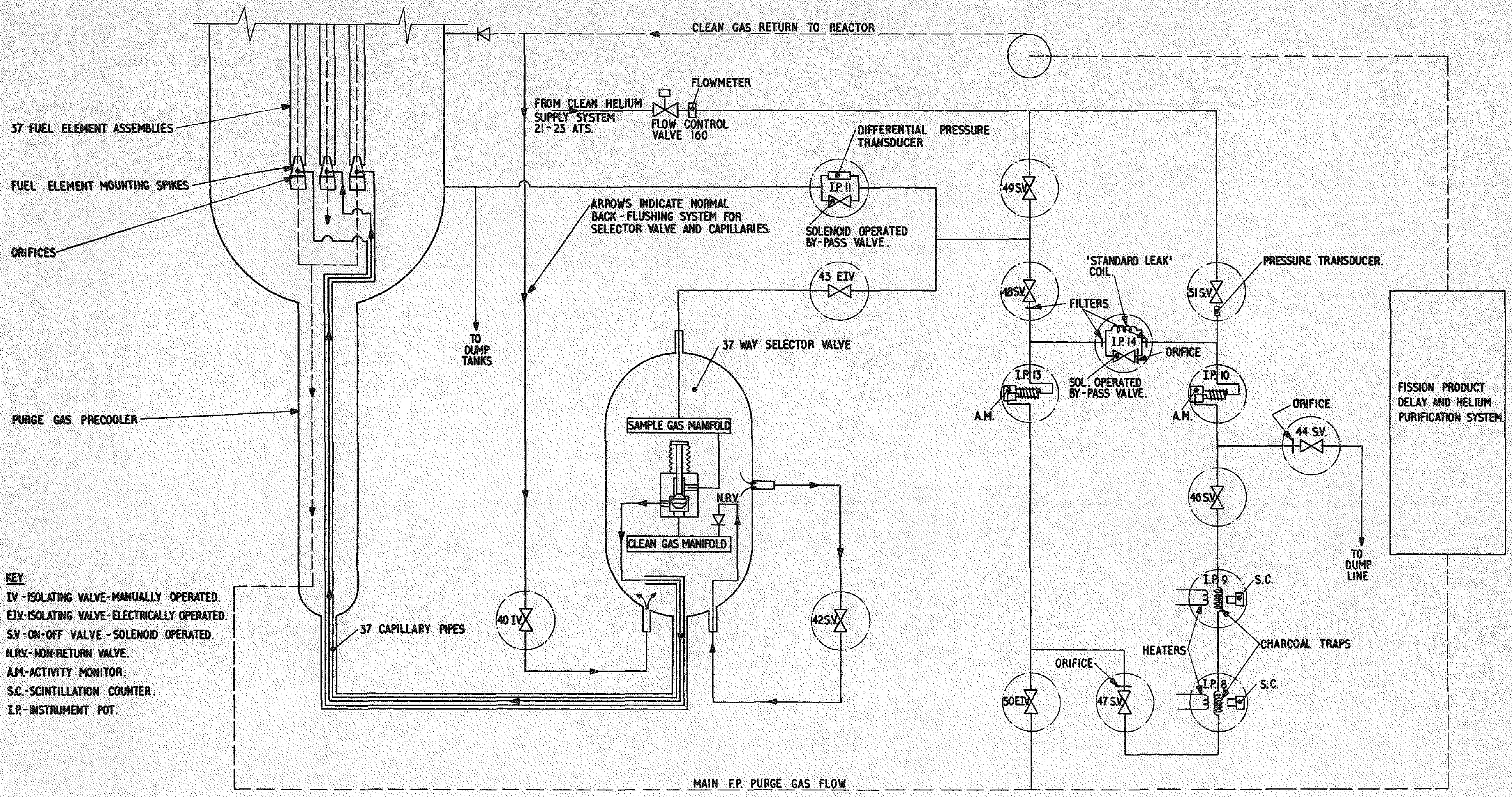


FIG. 3 FLOW DIAGRAM - FUEL ELEMENT PURGE GAS SAMPLING, MONITORING AND RADIOCHEMICAL ANALYSIS SYSTEM.

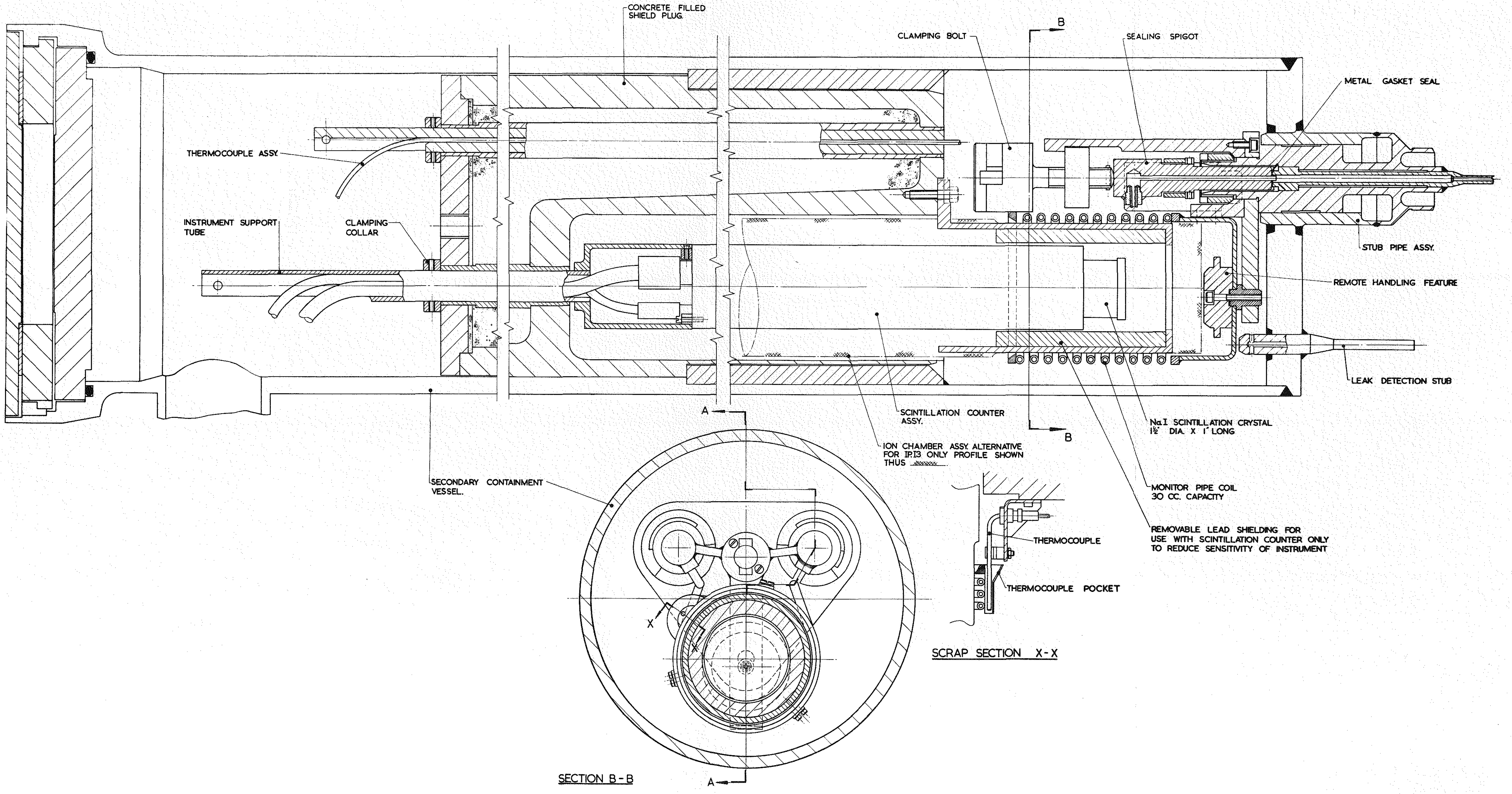
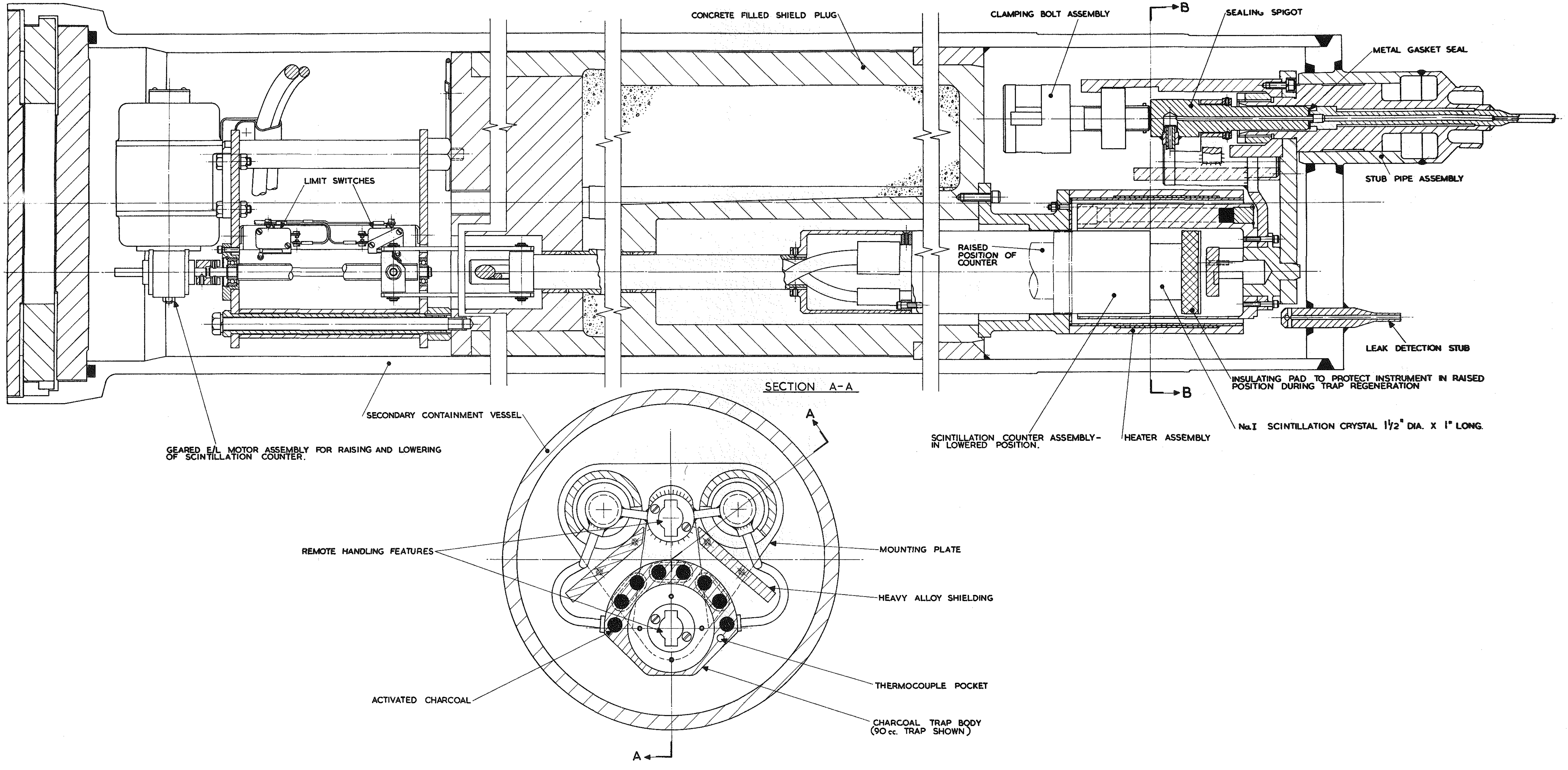


FIG. 4 INSTALLATION OF TOTAL ACTIVITY MONITOR - I.P. 10 AND I.P. 13



SECTION A-A

SECTION B-B
(COUNTER AND HEATER OMITTED.)

FIG. 5 INSTALLATION OF CHARCOAL TRAP AND SCINTILLATION COUNTER, IP.8 AND IP.9

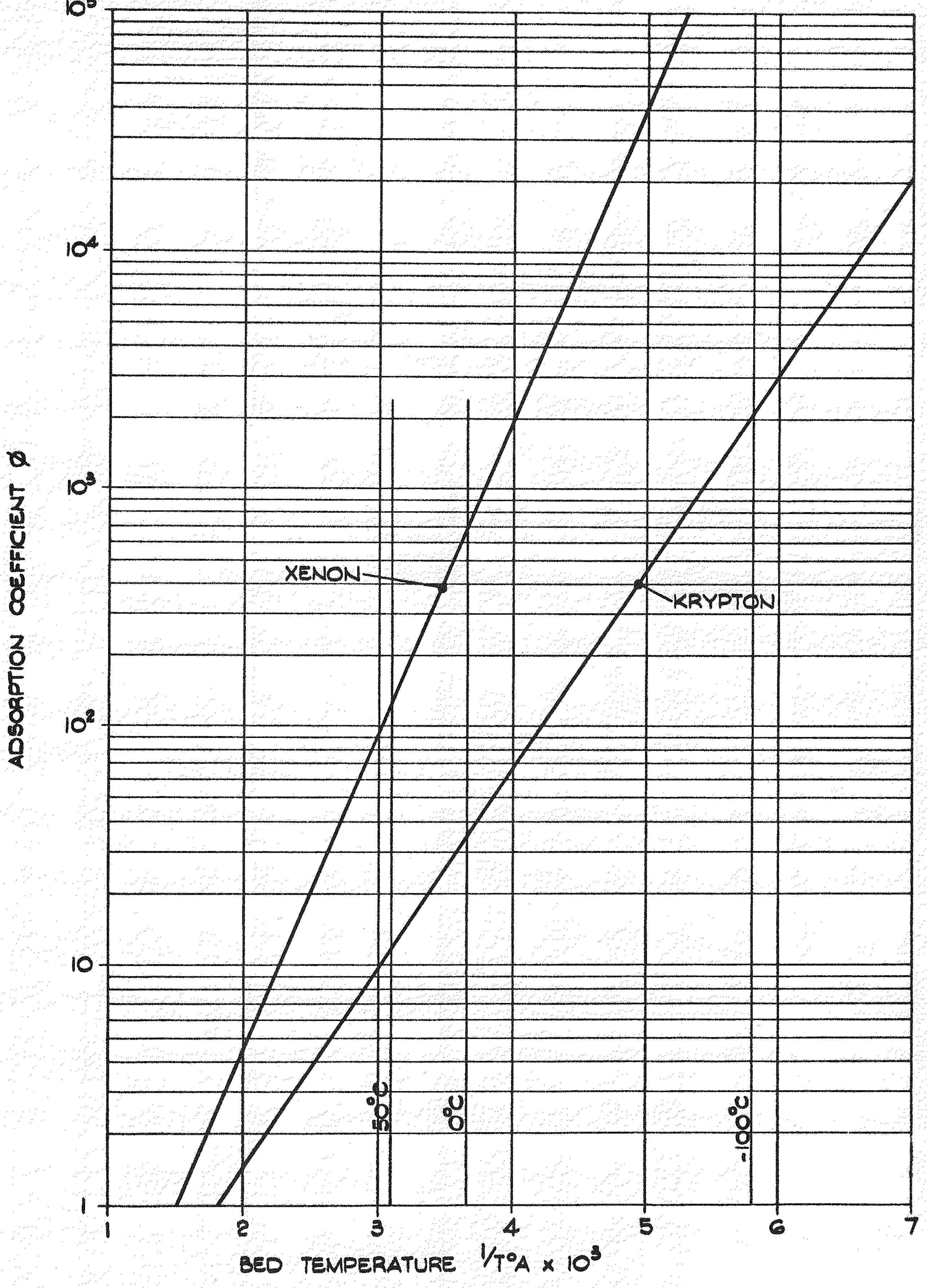


FIG. 6 PLOT OF ADSORPTION COEFFICIENT VS TEMPERATURE FOR Xe AND Kr ON CHARCOAL BED OF DENSITY 0·49 gm/cc & 40 MESH.

FIG. 7 γ SPECTRUM OF UNSEPARATED PURGE SAMPLE ASSUMING NO DECAY.

COATED PARTICLE FUEL 10^{-4} RELEASE

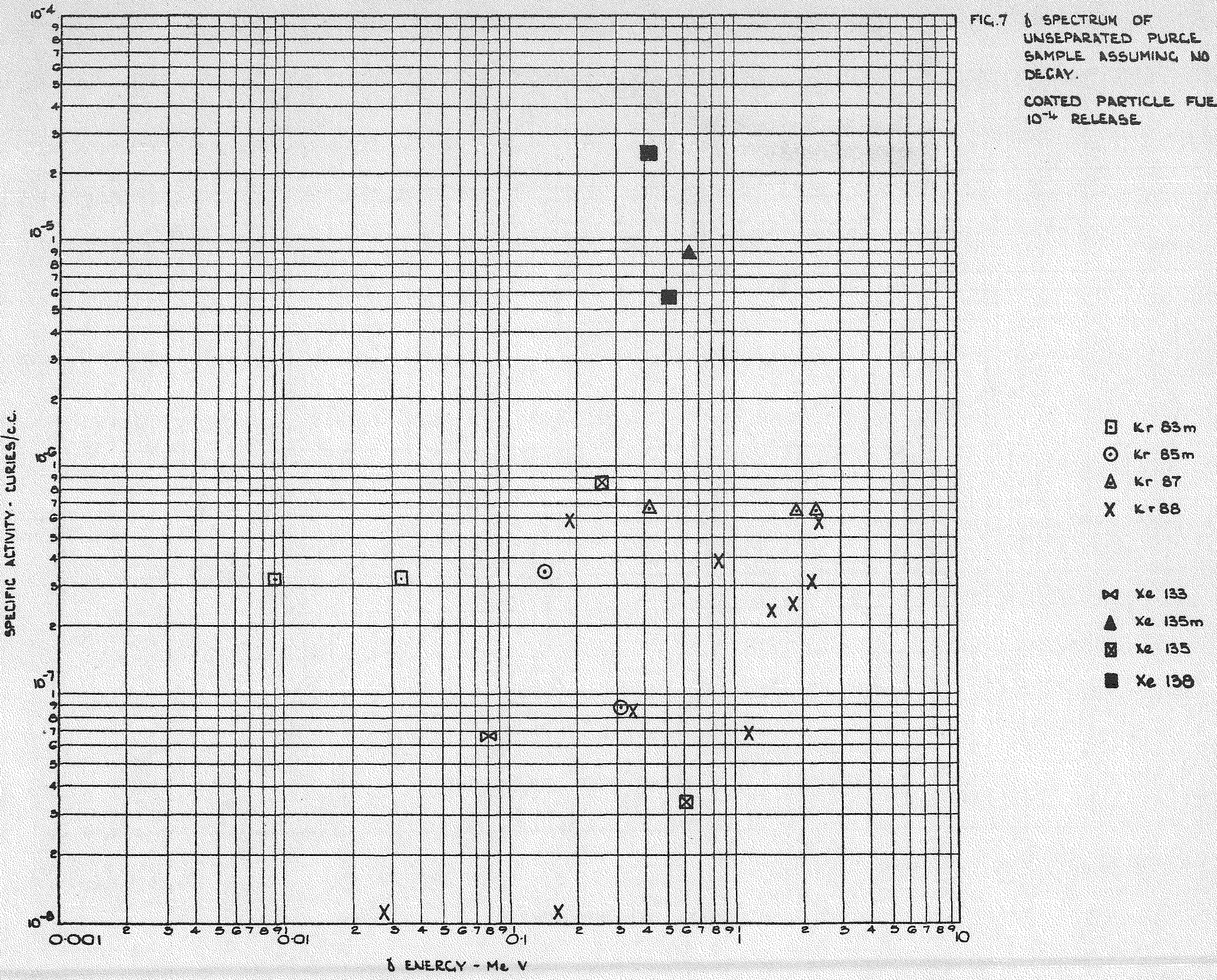
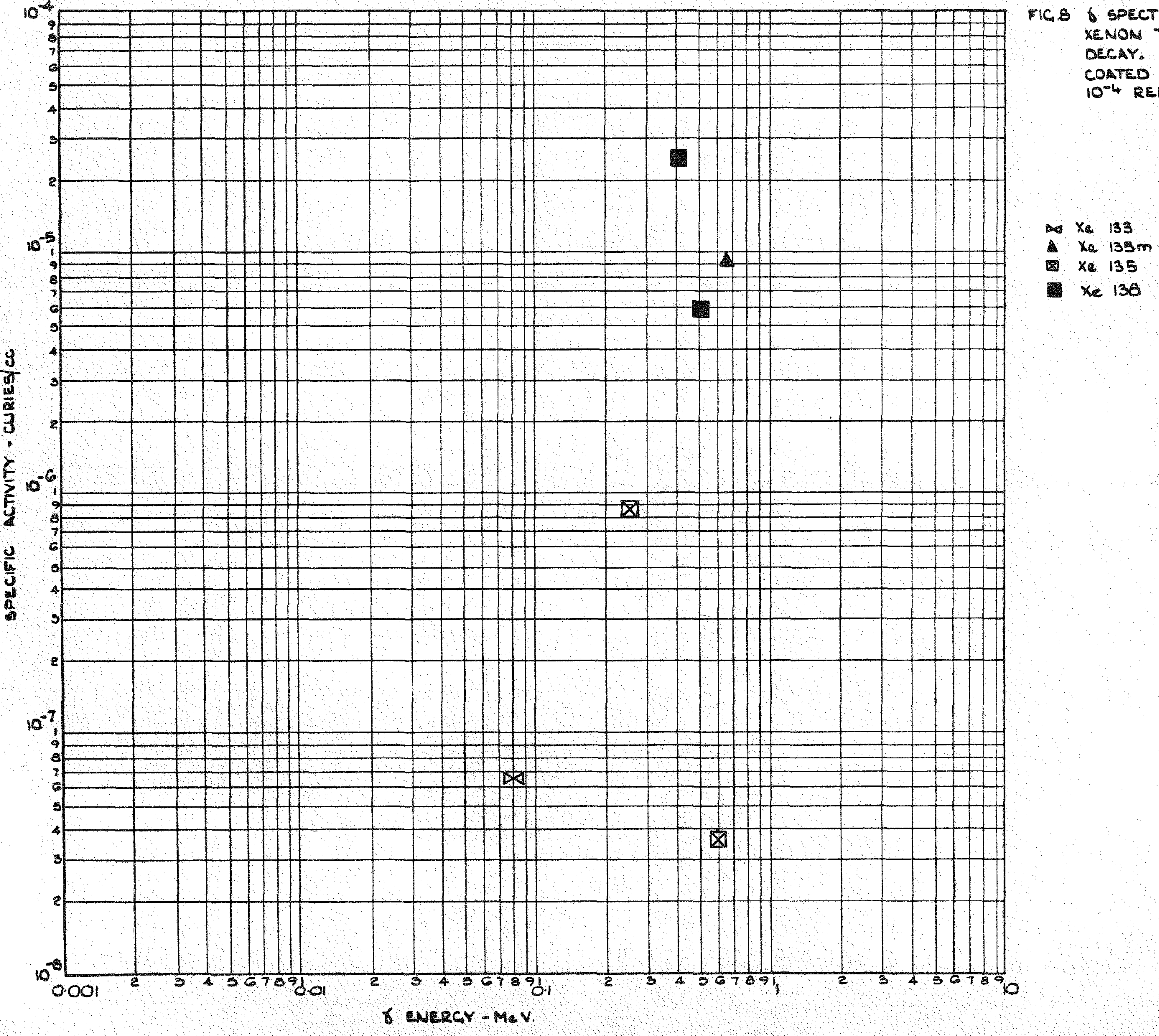


FIG.8 γ SPECTRUM FOR XENON TRAP, - NO DECAY.
COATED PARTICLE FUEL.
10^{-4} RELEASE.



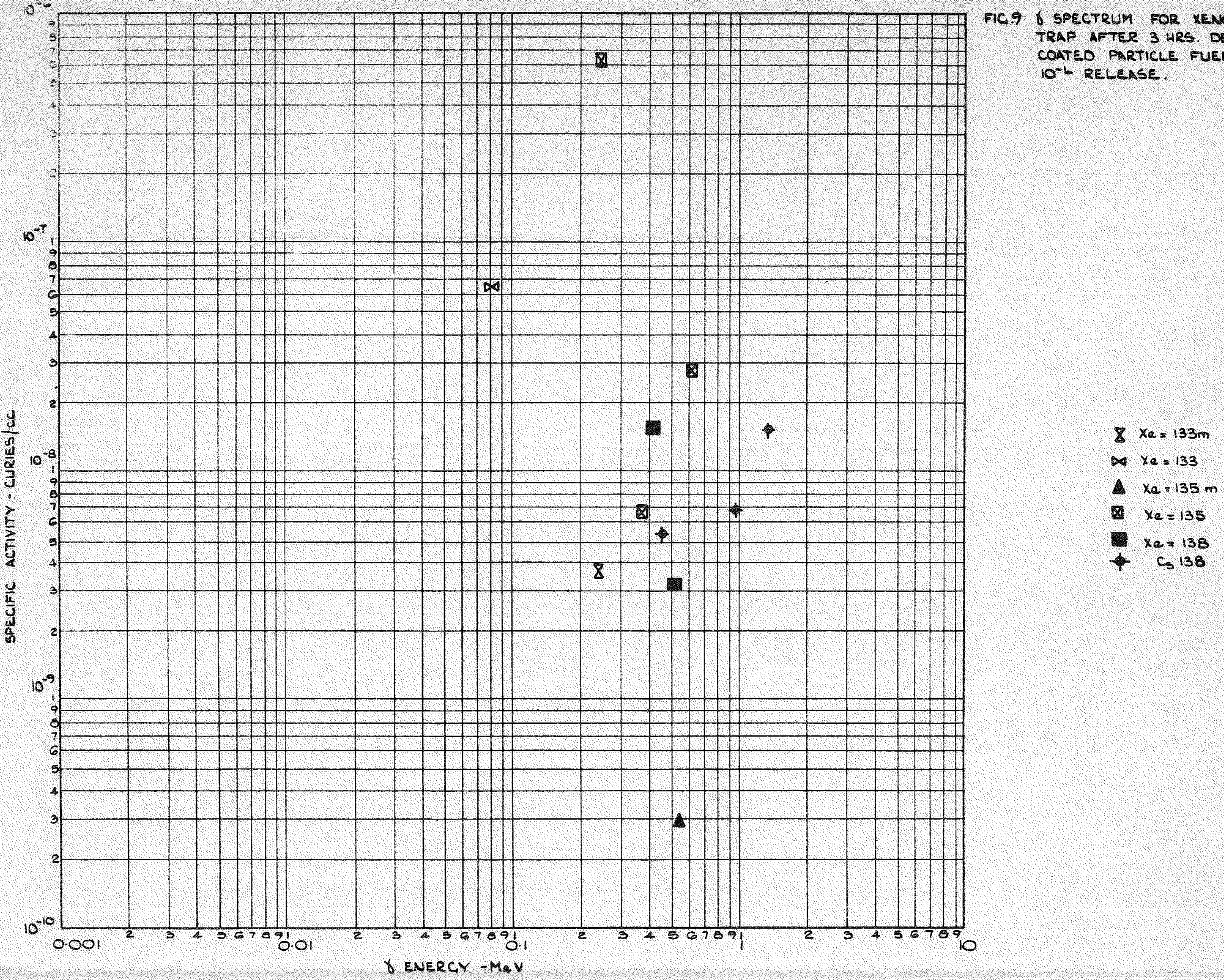


FIG. 9 γ SPECTRUM FOR XENON TRAP AFTER 3 HRS. DECAY. COATED PARTICLE FUEL. 10^{-6} RELEASE.

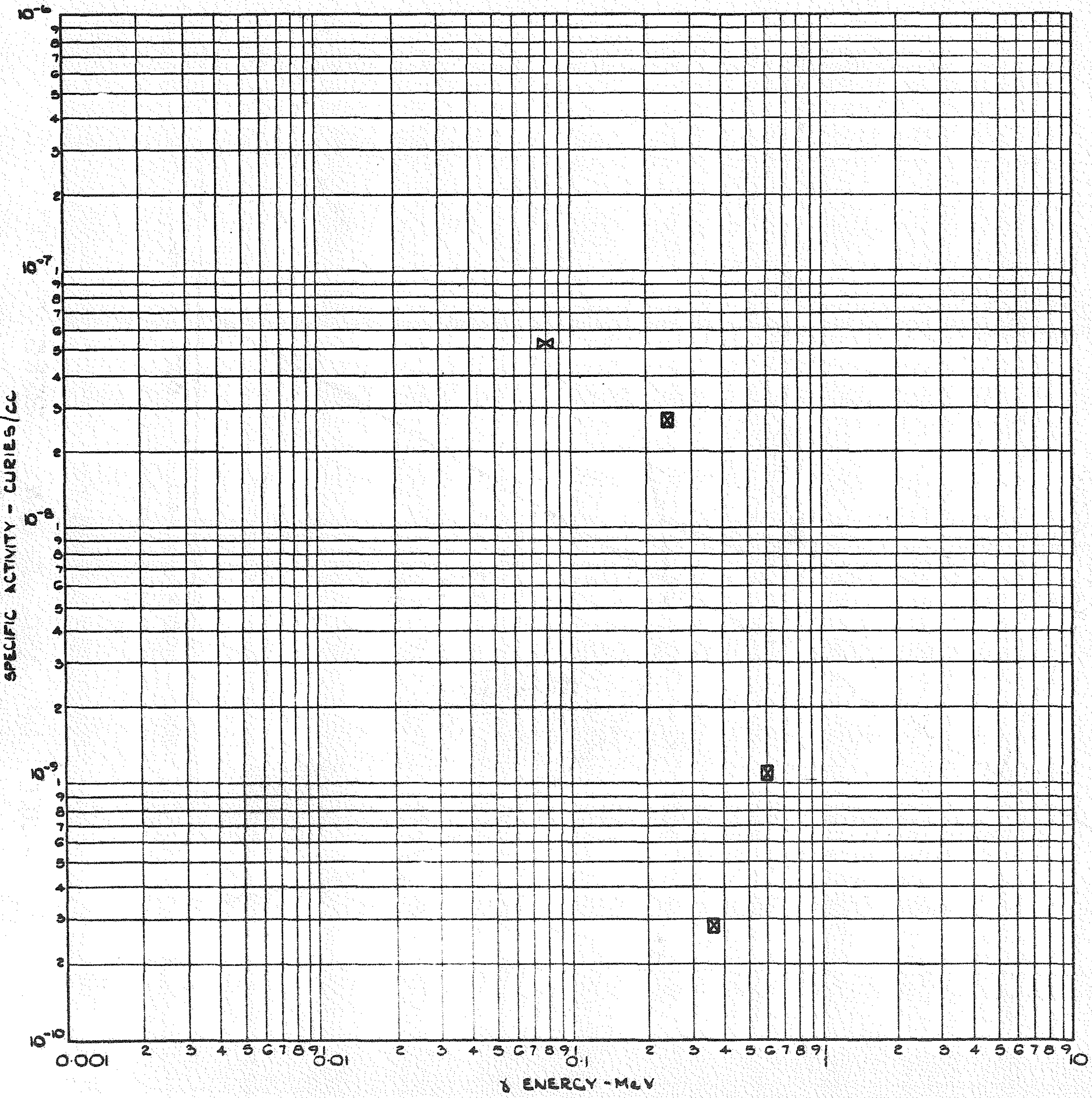


FIG.10 γ SPECTRUM FOR XENON
TRAP AFTER 6.5 HRS. DECAY.
COATED PARTICLE FUEL.
10^{-6} RELEASE.

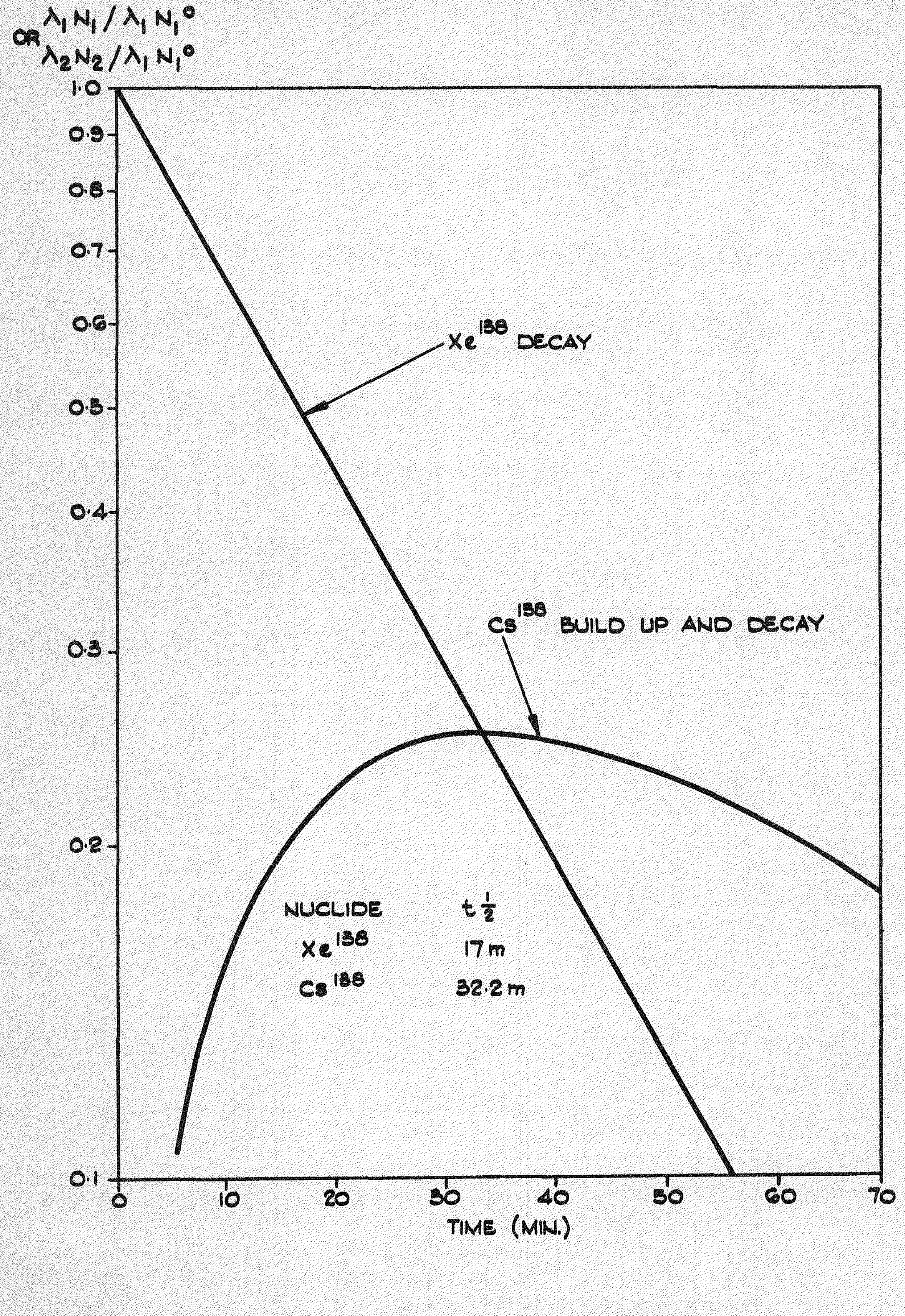
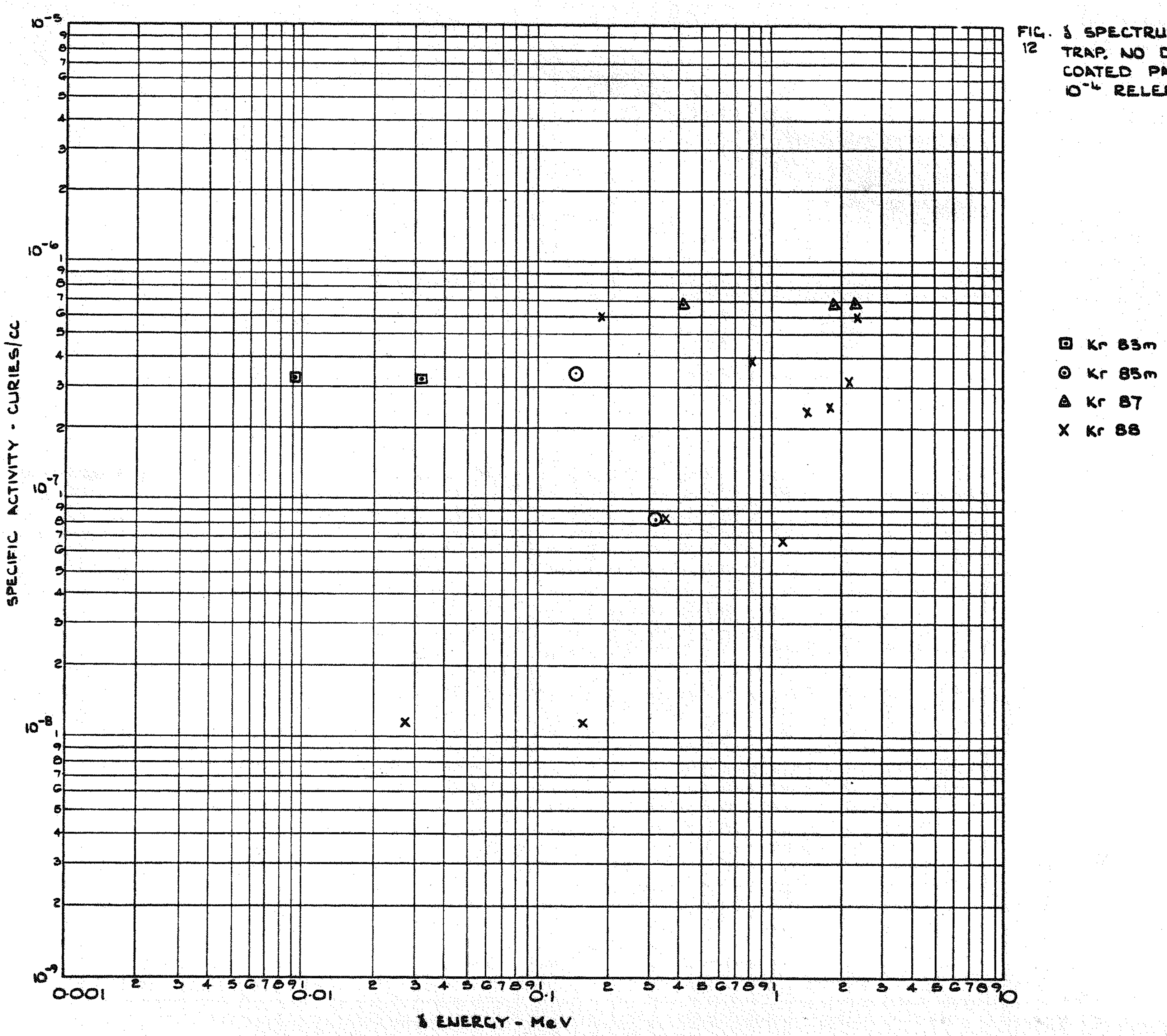


FIG. 11 BUILD UP AND DECAY CURVES

$Xe^{138} \rightarrow Cs^{138} \rightarrow Ba^{138}$

FIG. 12 γ SPECTRUM FOR KRYPTON TRAP, NO DECAY. COATED PARTICLE FUEL. 10^{-4} RELEASE.



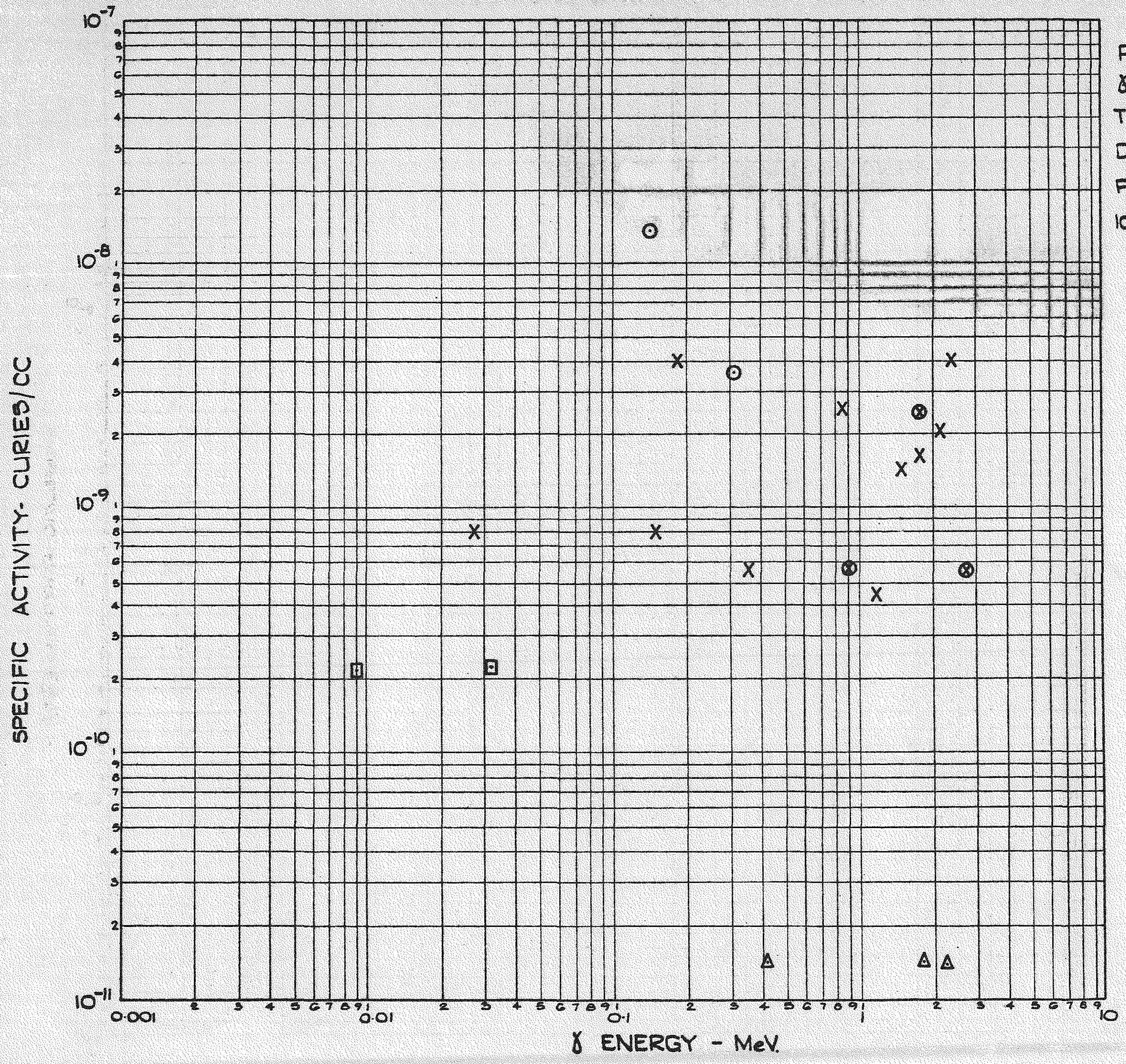


FIG. 13
γ SPECTRUM FOR KRYPTON TRAP AFTER 20 HOURS DECAY. COATED PARTICLE FUEL.
10^{-4} RELEASE.

⊡ Kr 83m
⊙ Kr 85m
△ Kr 87
X Kr 88
⊗ Rb 88

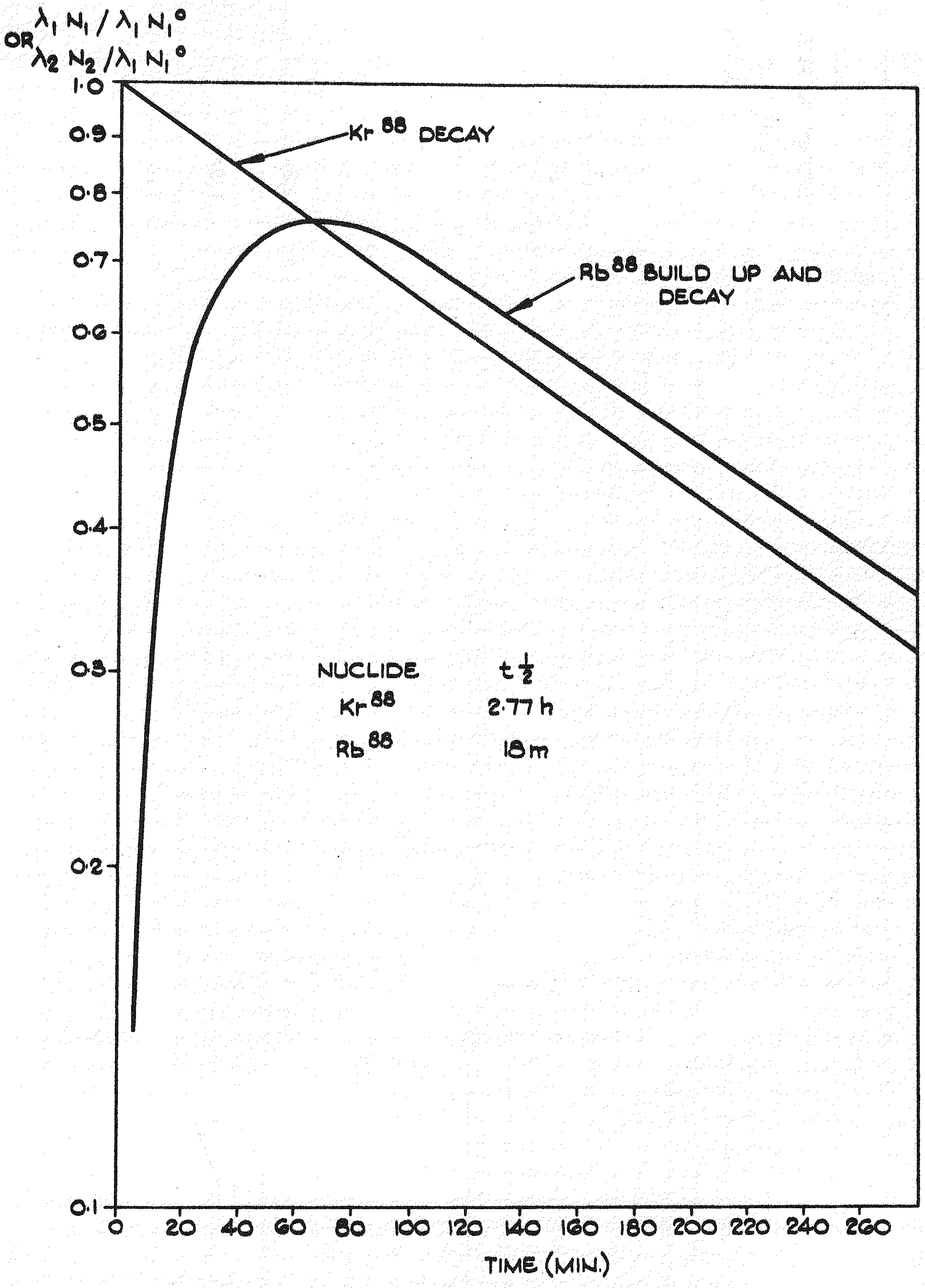


FIG. 14 BUILD UP AND DECAY CURVES

$Kr^{88} \rightarrow Rb^{88} \rightarrow Sr^{88}$

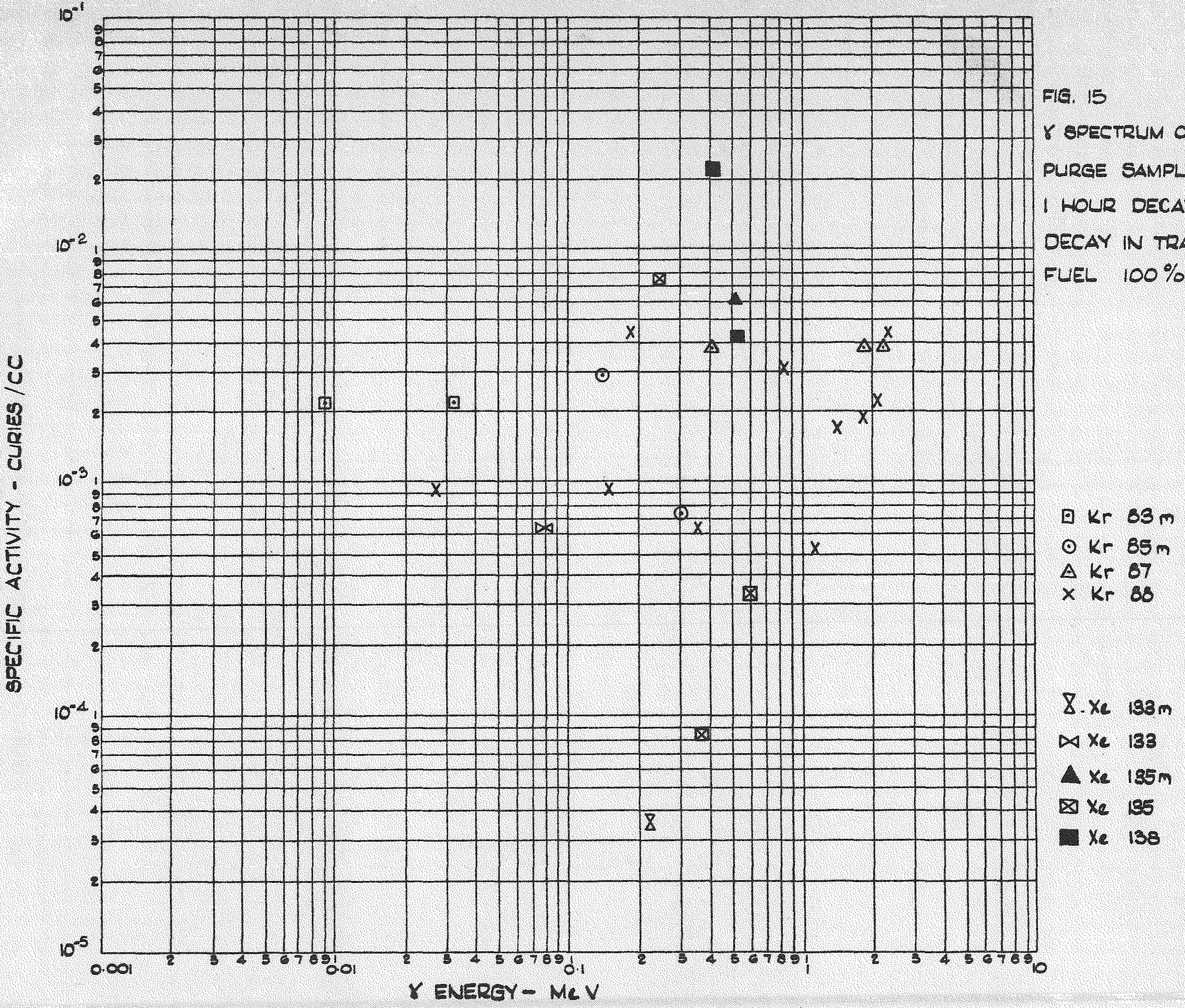


FIG. 15

γ SPECTRUM OF UNSEPARATED PURGE SAMPLE, ASSUMING 1 HOUR DECAY IN FUEL, NO DECAY IN TRAP. UNCOATED FUEL 100 % RELEASE

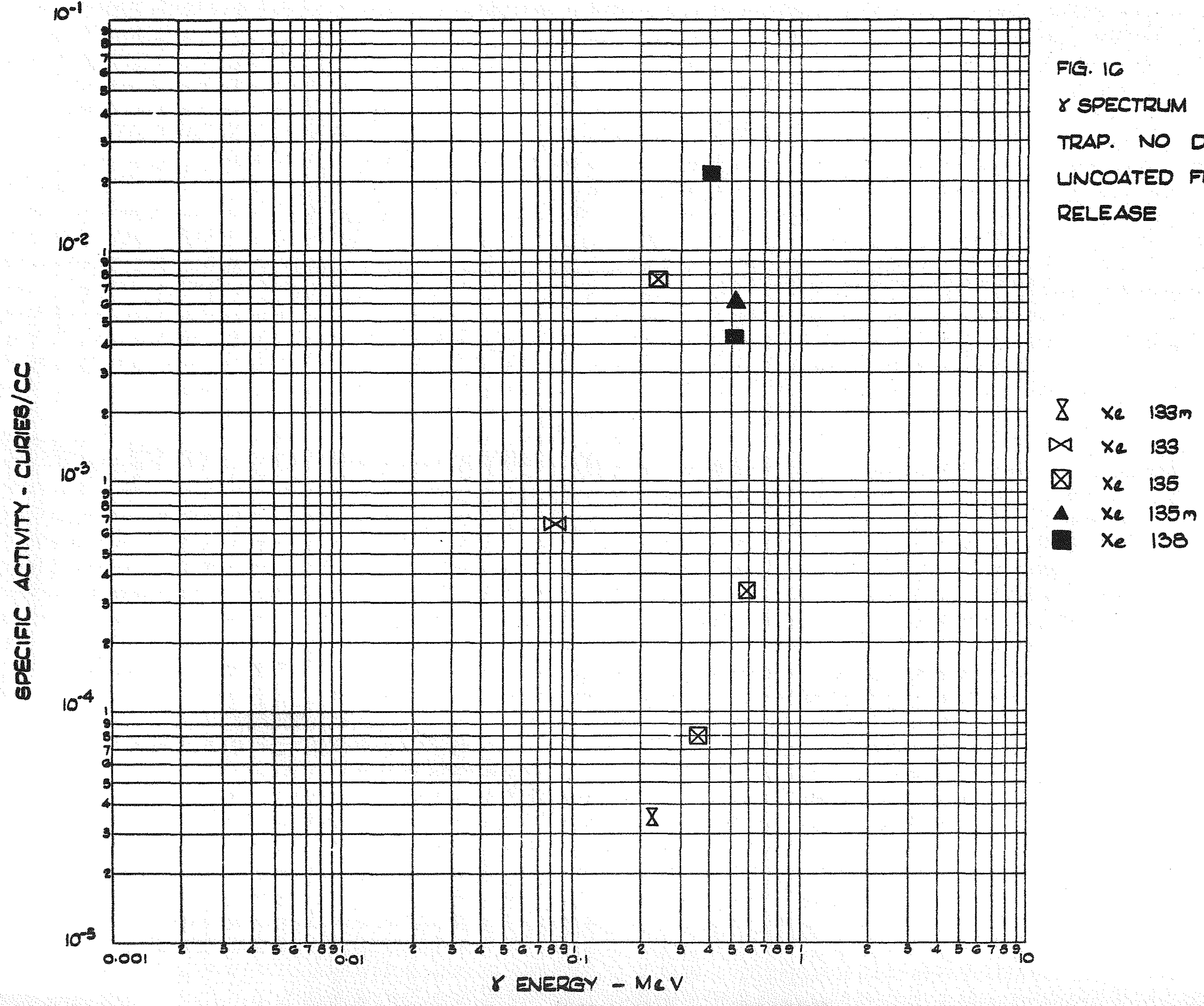


FIG. 16

γ SPECTRUM FOR XENON TRAP. NO DECAY. UNCOATED FUEL. 100% RELEASE

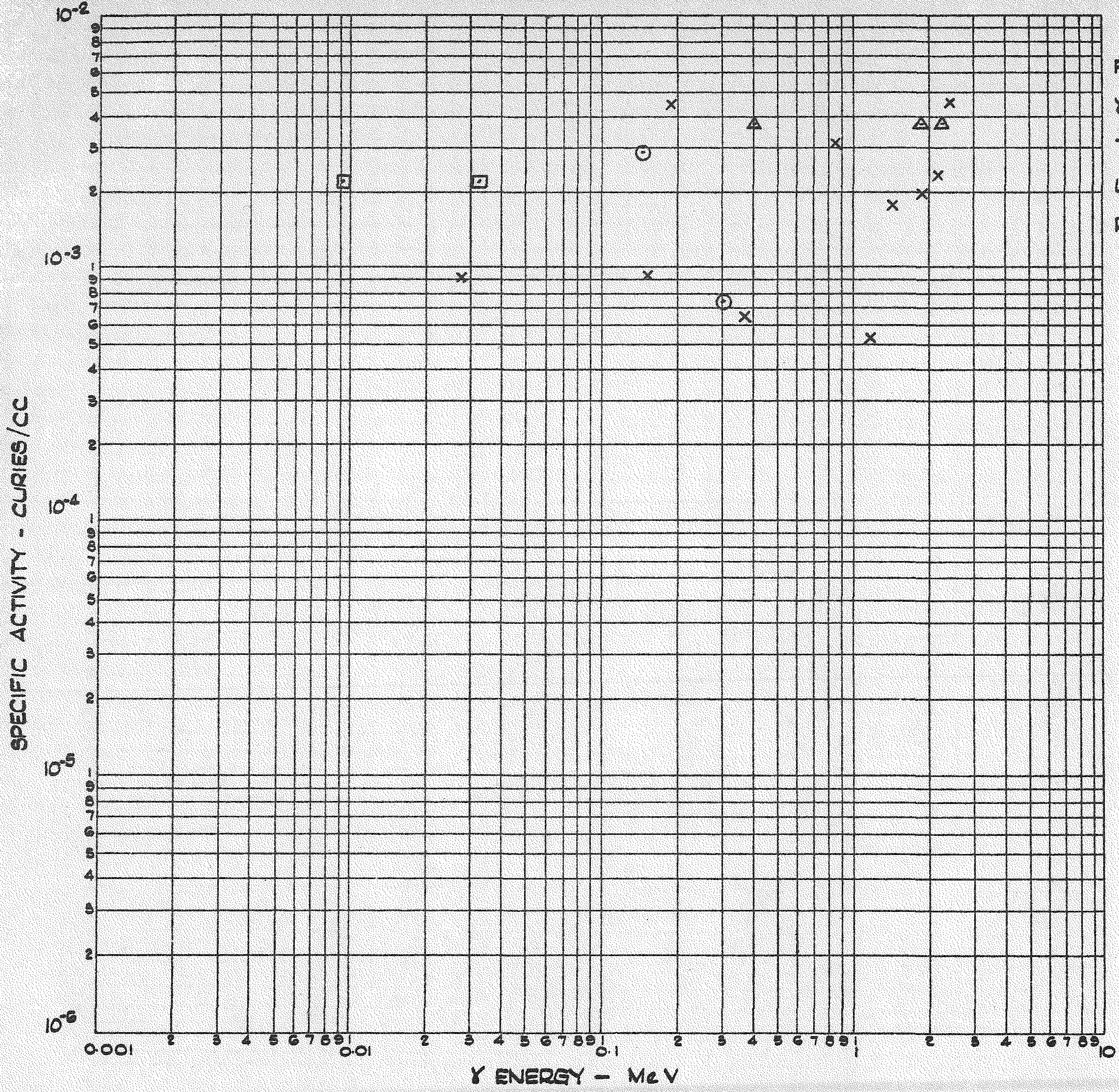
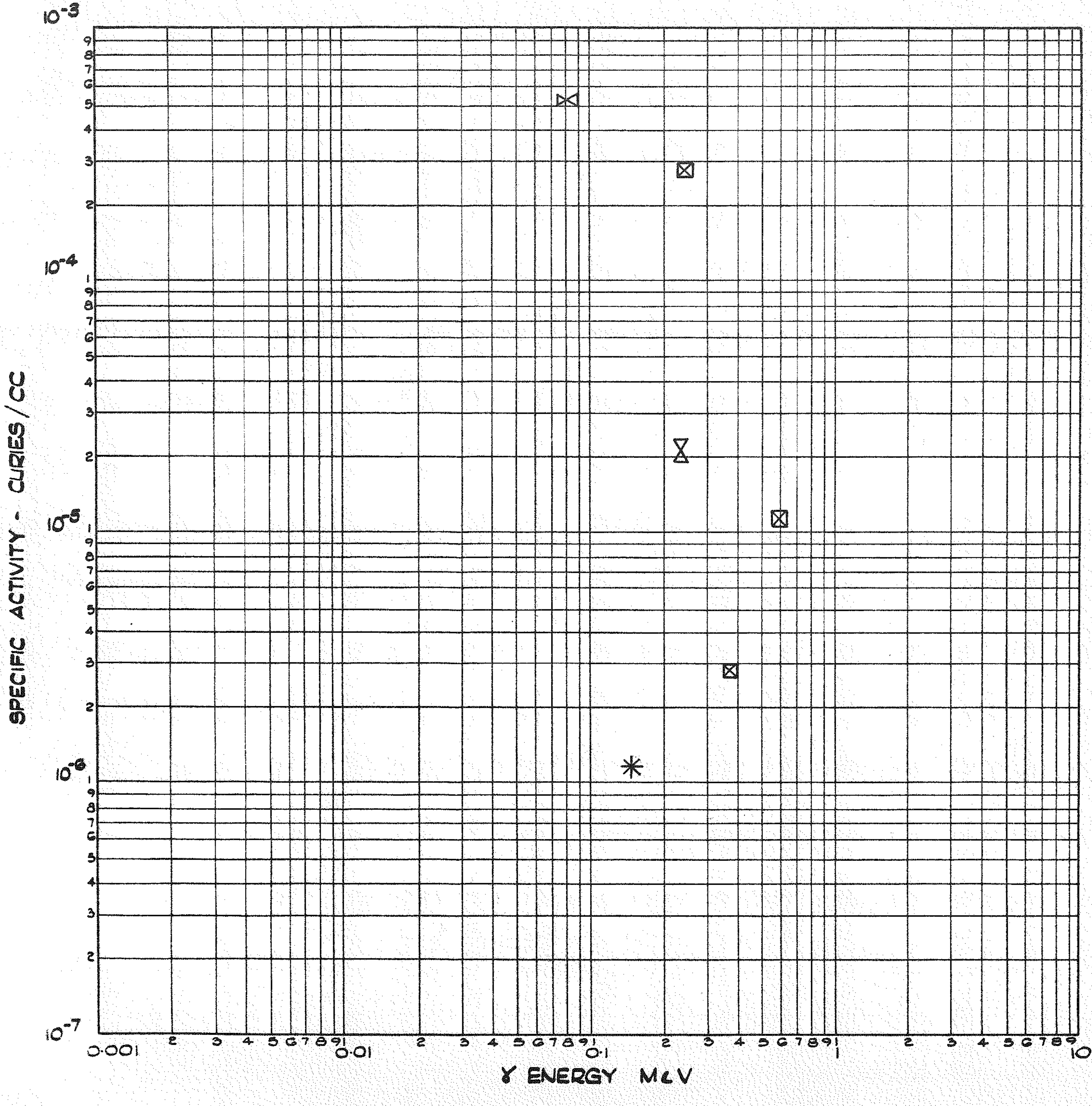


FIG. 17

γ SPECTRUM FOR KRYPTON TRAP, NO DECAY, UNCOATED FUEL. 100% RELEASE

FIG. 18

γ SPECTRUM FOR XENON TRAP AFTER 45 HOURS DECAY. UNCOATED FUEL. 100% RELEASE



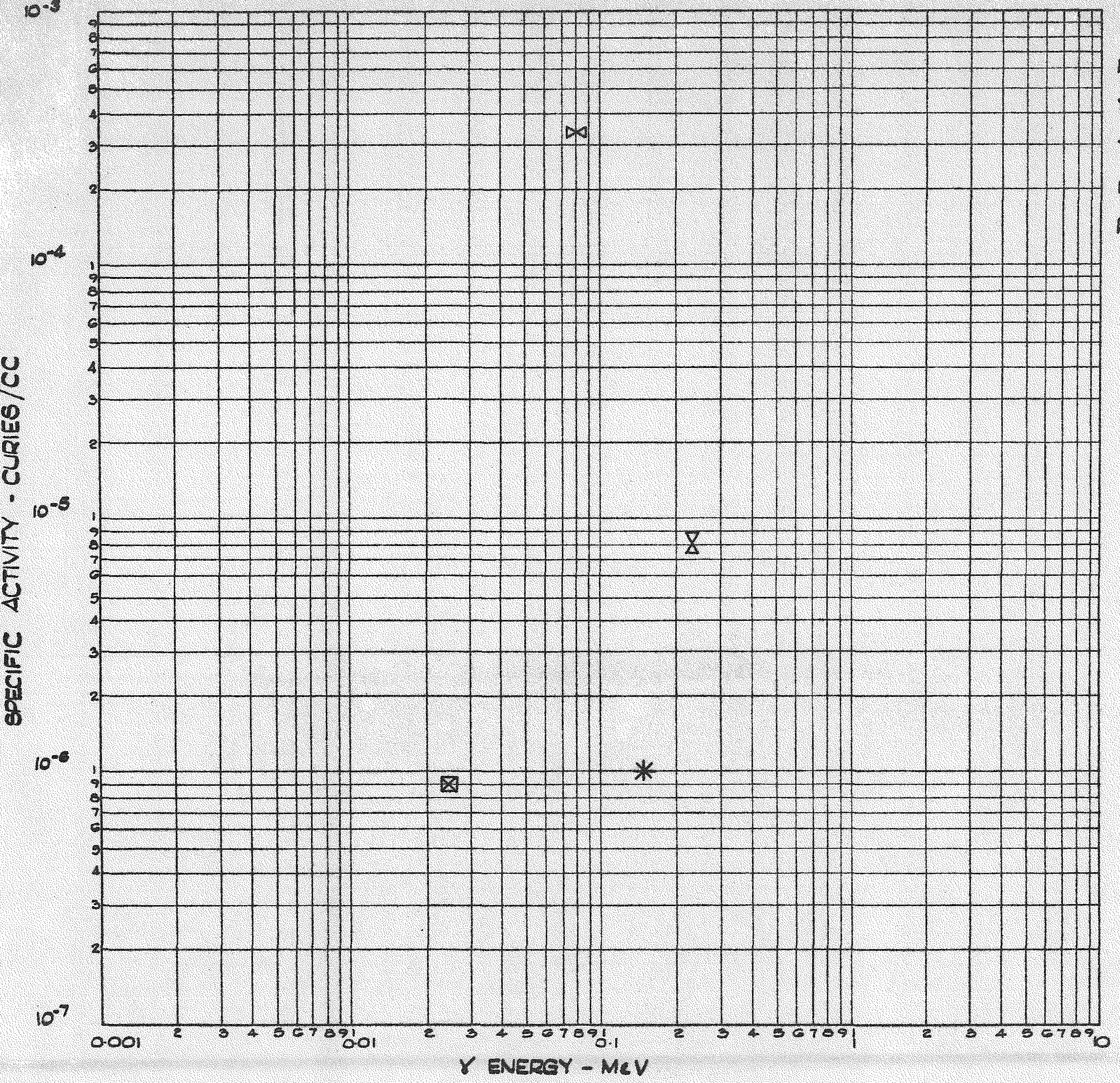


FIG. 19

γ SPECTRUM FOR XENON TRAP AFTER 5 DAYS DECAY. UNCOATED FUEL. 100% RELEASE.

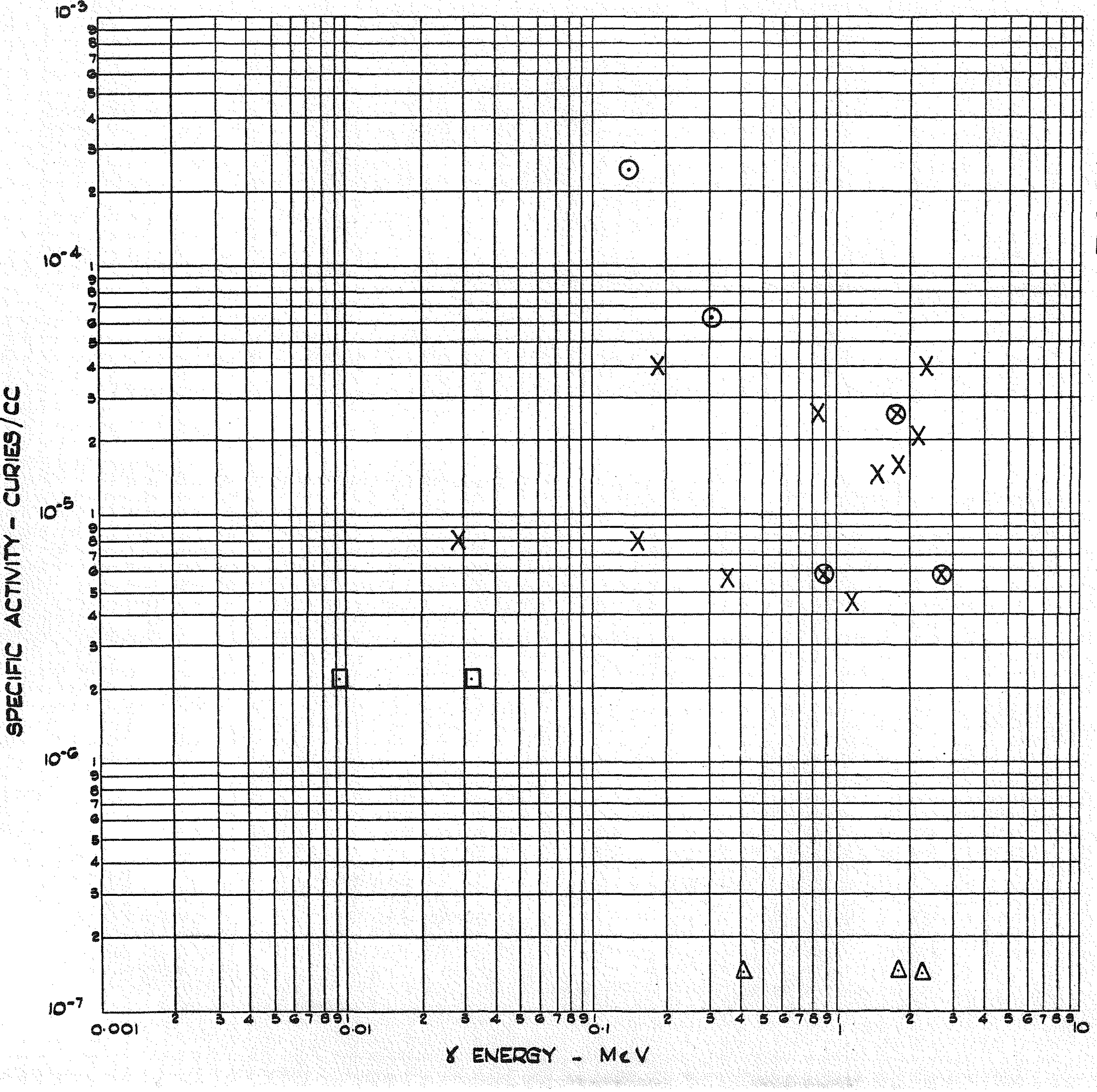


FIG. 20

γ SPECTRUM FOR KRYPTON TRAP AFTER 20 HOURS DECAY. UNCOATED FUEL 100% RELEASE