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NEUTRON METROLOGY IN LAMPF, USA

EXPERIMENTS CODED # 986 AND # 987

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SUMMARY

The characterization of appropriate materials for fusion reactors requires a high intensity neutron source which simulates the neutron spectrum and the radiation conditions at the positions of interest in a fusion reactor (first wall).
A neutron spectrum of interest is found in the Clinton P. Anderson Los Alamos Meson Physics Facility (LAMPF).
Various ceramic materials and some polycrystalline graphites were irradiated in this facility during two intervals of time in 1986 and 1987.
The specimens were accompanied by several sets with activation detectors.
This report presents the saturation activities per atom obtained from these sets.

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1. INTRODUCTION

Radiation damage in candidate first-wall materials by fast neutrons (14 MeV) is expected to be a severe problem in future fusion reactors.
To achieve a simulation of the neutron spectrum and radiation conditions valid for fusion reactors, a fast neutron field could be of interest.
For these purposes traditionally neutrons in a fission-reactor represent the best environment available as an approximation of fusion circumstances.
One of the problems in using fission reactor irradiations to simulate fusion first-wall radiation damage is the low fluence rate of neutrons at energies above about 5 MeV.
High-energy spallation neutron sources, based on the spallation process of high-energy protons (600-800 MeV) with high-Z (Uranium, Lead) or low-Z (Copper) materials seem very useful to solve this problem.
Therefore a radiation damage experiment was carried out in the rebuilt beam-stop area (Target Station A-6) of the Clinton P. Anderson Los Alamos Meson Physics Facility (LAMPF) with a spallation spectrum considerably harder than a fission neutron spectrum.
Ceramic materials as well as some polycrystalline graphites supplied by several institutes and accompanied by activation detector sets were irradiated during two intervals of time in 1986 and 1987.
Saturation activities per atom for the reactions of interest based on the measured activity and the actual irradiation history are presented in this report.

2. EXPERIMENTAL DATA

2.1. Description of the irradiation facility

The Clinton P. Anderson Los Alamos Meson Physics Facility (LAMPF) is a proton linear accelerator with an average beam current of about 0.75 mA. The facility produces a beam of protons with an energy of about 750 MeV and with a diameter of 50 mm.
Irradiations at LAMPF are possible in the direct primary proton beam as well as in a spallation neutron fluence rate that results from the interaction of the primary beam with a number of targets in the beam-stop area at its downstream extremity.
This irradiation was carried out in one of the eight neutron irradiation inserts of the Target Station A-6, in particular in the high neutron fluence rate position insert number 3 (see figure 1).

2.2. Actual loading of the experiment

The lower part of the insert number 3 is a water cooled canister which provides a volume with dimensions of 508x254x127 mm^3 for irradiation purposes. Within this volume seven capsules with test specimens were arranged. Among the other capsules four of them contained:
- structural ceramics such as SiC, AlN, BN, Si_3N_4 and Al_2O_3 in the form of bending test, thermal shock test and thermal conductivity test specimens;
- insulator ceramics which included mainly Al_2O_5 or $MgAl_2O_3$;
- a broad variety of fine grained, highly isotropic graphites.

At the top of the stainless steel capsules a helium gas inlet and a gas outlet are located together with six thermocouple throughputs and a central 300 W heating element.
A more detailed description about the specific loading scheme of the specimens and the design of the capsules coded 1 to 4 is given in a Technical Note which deals with the loading of this LAMPF irradiation [1].

2.3. Neutron metrology instrumentation

For the purpose of neutron metrology each capsule was instrumented with two fluence detector set packages, one at the front side and one at the

back side with respect to the proton beam (see figure 2).
Based on earlier experiments in the irradiation environment at the LAMPF target station A-6 a package was chosen consisting of Fe, Cu, Ni, and Co as foil materials.
The diameter of all foils is approximately 2 mm, while the thickness measures about 0.13 mm for the first two foils (Fe and Cu) and 0.08 mm for the remaining foils.
Each foil package was enclosed in a recess of a special tube made of stainless steel with an outer diameter of 3.1 mm (see figure 3). Tubes with two different lengths, viz. 19 and 25 mm, were available for respectively the front side and back side positions on each capsule.
The foils were separated by Ni rings and locked by crossed Ni wire retainers in each tube.
The foil sequence for each package is also indicated in figure 3.
The position of the detector set packages are identified by two numbers for instance 1.3 or 3.6.
The first number of these codes presents the capsule number and the second number the nearest tube with specimens in the capsule.
The codes and mass values found for the foils are given in table 6.
The mass values of the foils have been determined with an uncertainty of about 1 per cent.

2.4. Detection reactions

Product nuclei of several reactions were detected with a Ge(Li) gamma spectrometer.
Taking into account the time interval between the last date of the irradiation (end of 1987) and the time period of the measurements (1989) in combination with the half lives valid for the products, the reactions listed on the next page remain:

Target Material	Reaction Type	Product Nuclide	Half Life	Remark
Fe	(n,x)	^{46}Sc	83.79 d	*
Fe	(n,p)	^{54}Mn	312.14 d	
Fe	(n,x)	^{54}Mn	312.14 d	
Fe	(n,x)	^{56}Co	77.9 d	
Fe	(n,x)	^{57}Co	271.7 d	
Fe	(n,x)	^{60}Co	5.271 a	*
Cu	(n,x)	^{46}Sc	83.79 d	*
Cu	(n,x)	^{54}Mn	312.14 d	
Cu	(n,x)	^{56}Co	77.9 d	
Cu	(n,x)	^{57}Co	271.7 d	
Cu	(n,x)	^{58}Co	70.82 d	
Cu	(n,x)	^{60}Co	5.271 a	
Cu	(n,x)	^{65}Zn	243.9 d	
Ni	(n,x)	^{46}Sc	83.79 d	*
Ni	(n,x)	^{54}Mn	312.14 d	
Ni	(n,x)	^{56}Co	77.9 d	
Ni	(n,x)	^{57}Co	271.7 d	
Ni	(n,x)	^{58}Co	70.82 d	
Ni	(n,x)	^{60}Co	5.271 a	
Co	(n,x)	^{54}Mn	312.14 d	
Co	(n,x)	^{57}Co	271.7 d	
Co	(n,γ)	^{60}Co	5.271 a	

* too low activity

The figures 4 to 7 are enclosed in order to give an indication of the gamma spectra found for each type of foil (Fe, Cu, Ni, and Co respectivily).
It was impossible to measure more product nuclei such as ^{58}Co in the Co foil due to the high activity of ^{60}Co.

2.5. Irradiation history

The first part of the irradiation took place during the second half of 1986 (coded experiment # 986) while the second part was performed during a similar period in 1987 (coded experiment # 987).
The temperature of the capsules was about 673 K.
This second irradiation interval up to the end of 1987 was necessary to reach the target value of 1 dpa in specimen materials such as graphite and SiC.
The irradiation history was received in the form of a plot with the integrated beam current versus a time axis.
The averaging was performed over periods of 8 hours. So, the total irradiation history involved about 700 points. These were read from the plot and converted to a computer file (see figure 8). This file was used as part of the input for a code that calculated the specific saturation activity values and a number of parameters characterizing the irradiation history. The results of some primary calculations indicated that it was allowed to perform the further calculations with an irradiation history composed in the following way.
The total irradiation time corresponds with an uninterrupted irradiation interval of 188.5 d at an average beam current of 0.75 mA, divided in 72.64 d for the first part and 115.9 s for the second one.
The start of the first part was on 860909 1600 h and ended on 861215 1600 h while the second part lasted from 870617 0800 h up to 871201 0000 h.

2.6. Fluence detector sets

Although seven capsules were irradiated, the appointment was made that the Netherlands Energy Research Foundation ECN would measure the foils originating from four capsules only.
Afterwards it turned out that the second fluence detector set from capsule 4 was not available.

2.7. Counting procedure

The foils which were not etched were counted with a high purity calibrated Ge detector (relative efficiency 22.1 per cent ; FWHM 1.95 keV at 1.33 MeV) and the etched foils were counted with a calibrated Ge(Li) detector (rela-

tive efficiency 18.6 per cent ; FWHM 1.75 keV at 1.33 MeV). Distances of 100 and 200 mm from the detector surfaces were applied.
Only the cobalt foils were counted at a distance of 1600 mm.
The detectors were coupled to a multichannel analyser.
The counting times for several foils were rather long, i.e. 30 h was used for the majority of the foils. Even these long counting times did not give in all cases the required accuracy of the counting results. Especially the activity determinations for the nuclides near the detection limit were for some countings questionable.
The most uncertain activity values were derived for the nuclides:
- ^{46}Sc, ^{56}Co (from the etched foils) and ^{60}Co from the iron foils,
- ^{46}Sc and ^{65}Zn from the copper foils,
- ^{46}Sc from the nickel foils.

2.8. Calculation procedures

The counting information for all foils originating from the Ge(Li) spectrometer chain was transmitted to a CDC CYBER 185 main computer. Afterwards the further analysis was performed by a computer code called NDDT. A brief survey of these calculations is given in the following part :

- Peak area determination.
  If a peak is detected at a certain channel position, the peak area is calculated. For this determination about 2 x FWHM channels on each side of the centre of the peak (FWHM means full width at half maximum) are applied. Through the channel contents the best Gaussian on a linear background is calculated with a non-linear least squares method.

The analytical function describing the peak region is :

$$y(x) = A_1 \exp\left[-\frac{(x-A_2)^2}{2A_3^2}\right] + A_4 + A_5(x-A_2)$$

where x = channel number ;
y(x) = channel contents in channel x ;
A1 = maximum of the Gaussian distribution ;
A2 = location of this maximum ;
A3 = width of the Gaussian distribution (FWHM = $2\sqrt{2\ln 2} \times A3$) ;
A4 = height of the linear background at A2 ;
A5 = slope of the background .

- Identification.
- The energy which accompanies the calculated peak position is obtained by multiplying the channel number of the peak with the channel width. The channel width is available. The identification is obtained by comparing the obtained energy values with the energies from a library.

- Peak efficiency.
The countings for the peak efficiency calibration procedure with calibrated reference sources were applied before this series of countings and are treated in the same way as other countings.
A simple identification procedure yields the radionuclide. The activity data of the reference sources are available in a special library. From these data the peak efficiencies were calculated. For various peak energies the efficiencies were available, so a smooth curve could be calculated.
The mathematical function which was applied for this purpose has the following form :

$$E_p(E) = \exp\left[\sum_{i=1}^{n} b_i (\ln E)^{n-i}\right] ,$$

where

$E_p(E)$ = the peak efficiency at energy E (in keV) ;
b_i = the parameters giving the best fit ;
n = the number of parameters (5) applied in the calculation .

- Activity calculation.
With aid of the identification procedure and a nuclear data library the decay constant for an identified nuclide can be obtained. By means of this constant and other data the activity is calculated.

The following relation is applied :

$$A(t_r) = \frac{C_A \times C_{SA} \times N}{p_\gamma \times E_p} \times \frac{\lambda}{1-e^{-\lambda t_m}} \times \frac{e^{\lambda(t_b-t_m)}-1}{\lambda(t_b-t_m)} \times e^{\lambda t_w} ,$$

where

$A(t_r)$ = activity at the reference time ;
C_A and C_{SA} = corrections for source selfshielding and encapsulation shielding ;

N = peak area ;

P_γ = gamma ray emission probability ;

E_p = peak efficiency ;

λ = decay constant ;

t_m = preset counting time ;

t_b = real counting time (t_m + correction for insensitive time) ;

t_w = waiting time between reference time t_r and begin of counting.

The activity is calculated for each identified nuclide, taking into account all detected photopeaks of the radionuclide.
The total counting rates in this series of countings were very low, a correction for the dead time effect was not necessary.

- Saturation activity.
A computer code called VILLA calculated the specific saturation activity values for the nuclides of interest by means of the irradiation history and activity values at reference time with the relation :

$$a = \frac{A_{t_r}}{N \sum_{i=1}^{n} (1-e^{-\lambda t_i})} ,$$

where a = specific saturation activity ;

A_{t_r} = activity at reference time;

N = number of atoms in target material ;

λ = decay constant ;

t_i = irradiation time.

2.9. Chemical treatment of foils

To investigate the possibility of a cross-contamination effect from other foils or the Ni-wire rings on each foil separately, the surface of several foils was treated with hydrochloric acid (HCL) during about 2 minutes.
Only the Co foils were not involved in this procedure because the activity of these foils was and is still too high for easy handling.
In view of a determination of the total helium content at Rockwell International Corporation, USA all the Fe foils were treated this way.
The removal of the surface material from Fe is also necessary to avoid material which could have been contaminated by helium during the irradiation.
The specific saturation activity values found after this etching treatment are calculated also.

3. RESULTS

The specific saturation activity and total uncertainties found for each reaction at an average beam current of 0.75 mA, derived from the different types of foil material are presented in the tables 1 to 4. These tables contain data before and after etching of the foils.
The conversion factors which give the relation between the activity at the end of the irradiation and the specific saturation activity values are shown in table 5.
The mass values of the foils before and after etching are given in table 6.
To simplify the interpretation some extra information based on the data from the tables 1 to 4 are added in to the tables 7 and 8.
In a number of cases there is a remarkable difference in the specific saturation activity before and after etching. The counting of the foils gave for some reactions difficulties due to the relative low activities and the background counting rate of the gamma spectrometer. The reactions which are pertubed by one of these effects are given in the following list:

-Iron foil

reaction $Fe(n,x)^{46}Sc$	For two foils a reduction of the specific saturation activity due to etching of more than 20 % was found. The differences for the other foils are less than 10 %. The reason is probably the counting method and the low activity.
reaction $Fe(n,x)^{56}Co$	Became unmeasurable for 6 of the 7 foils, the specific activity in the remaining foil was changed less than 30 % by etching. Can partly be explained by decay.
reaction $Fe(n,x)^{57}Co$	For all the foils the specific saturation activity was reduced by etching with a factor of about 2.
reaction $Fe(n,x)^{60}Co$	The results for this reaction show a large spread before and after etching. The reason is probably the counting method and the low activity for this reaction product.

-Copper foil

Only one of the copper foils was etched.

reaction $Cu(n,x)^{46}Sc$ Too much spread in the results (background) effect.

reaction $Cu(n,x)^{56}Co$ A slight reduction of specific saturation activity seems to be present.

-Nickel foil

Only one of the nickel foils was etched.

reaction $Ni(n,x)^{46}Sc$ Too much spread in the results (background effect).

reaction $Ni(n,x)^{56}Co$ A reduction of specific saturation activity is present.

-Cobalt foil

The relatively high ^{60}Co activity was the reason that the etch procedure was not executed.

In table 7 the specific saturation activities normalized in respect to the foil position 3.6 are presented.
The specific saturation activities relative to the reaction $Fe(n,x)^{54}Mn$ are given in table 8.
In these tables the original activity values are applied because etching results are not available for all foils.
The impact of the etching is so important that it is tried to give a final set of specific saturation activities in which for the iron foils the activities after etching are given and for the other foils the original values. For the specific saturation activities of these foils which were affected by the etching procedure and which were not all etched and recounted, a remark is given in table 9, which contains the relevant data.
In table 9 also the total uncertainty data are given for the various specific saturation activities.
These uncertainties are based on the counting uncertainties and estimated uncertainties for a number of effects.

The effects taken into consideration are:

- The uncertainty in the mass determination estimated as 1% ;
- Changes in the neutron irradiation field during the irradiation. No information is available on the actual value and for that reason an uncertainty of 3% is adopted. In the case that better information is obtained this value has to be corrected ;
- A neutron fluence gradient will be present over the foil package. Also for this effect no reliable data are available at the moment and for that reason a cursory estimate is made of 2.5%.
- The total uncertainy in the activity determination of the various radio nuclides is 2.5%. This information is derived from a quality control procedure which is executed in our laboratory [2].

From the results of table 9 it can be seen that capsule 3 was probably mounted in a 180 degree turned position. Of course, also an interchange of detector sets might be the reason. This conclusion is based on the higher activity detected for the detectors of set 3.6 in respect to the ones of set 3.1 and the data for the other capsules.
The nuclear data which were needed in the calculations were taken from [3].

4. DISCUSSION

From the data given in table 9 it can be concluded that 17 reactions can be applied for each position in the further characterization of the neutron spectrum during the irradiation. At this moment we can conclude that a somewhat modified set would have been more suitable, i.e. the mass of the cobalt foil was relatively large and the other foils could have been heavier.
Another effect which has influenced the number of reactions which could be determined from the activated foils was the waiting time between the end of the irradiation and the start of the countings. It would have been advantageous if this waiting time had been 1 year instead of 2 years. A much shorter waiting time had not been useful due to the interrupted irradiation period. The interruption of the irradiation with a time span of about 0.5 year made the application of reaction products with relative short half-lifes not useful for fluence determinations. This report supplies the specific saturation activities for the foils which could be counted by gamma-spectrometry. For a good characterization of the neutron spectrum the Helium contribution in the iron foils is also valuable but has still to be determined. Information on the proton fluence can probably be obtained from the countings of aluminium containing samples. The latter has still to be started.

5. CONCLUSIONS

The counting procedure has been completed successfully and the results for the specific saturation activities are listed in table 9. In order to obtain the characterization of the neutron field a neutron spectrum adjustment procedure has to be executed on the data of table 9.
During the evaluation of the counting results it turned out that the foils were contaminated with radionuclides not originating from the target material. An etching procedure was used to reduce the perturbation. Additional information especially for the high-energy region can be obtained by a helium determination of the iron foils. A procedure to obtain these values is started.

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Table 1. Specific saturation activities α (per atom, per s, per 0.75 mA) and uncertainties deriv
Fe foils before and after etching.
(NE indicates the not etched foils and E the etched foils)

Pos. codes :	1.1		1.3		2.1		2.6		3.1		3.6		4.1	
	NE	E	NE	E	NE	E	NE	E	NE	E	NE	E	NE	E
Reaction														
$Fe(n,x)^{46}Sc$														
α (* 10^{-16})	8.30	6.74	4.34	4.09	6.44	3.98**	4.35	4.32	11.1	10.6	26.5	26.6	8.12	8.18
unc. (in %)	5.0	7.4	5.0	7.3	5.0	4.9	5.0	5.7	4.9	5.7	4.9	4.9	5.0	5.6
$^{54}Fe(n,p)^{54}Mn$														
α (* 10^{-13})	5.78	5.80	3.58	3.57	4.63	4.58	3.39	3.37	6.78	6.75	11.9	11.8	5.80	5.77
unc. (in %)	5.1	4.8	5.1	4.8	4.9	4.8	5.1	4.8	5.1	4.8	5.0	4.8	5.1	4.8
$Fe(n,x)^{54}Mn$														
α (* 10^{-14})	3.35	3.37	2.07	2.07	2.69	2.66	1.97	1.95	3.93	3.92	6.88	6.87	3.37	3.35
unc. (in %)	5.1	4.8	5.1	4.8	4.9	4.8	5.1	4.8	5.1	4.8	5.0	4.8	5.1	4.8
$Fe(n,x)^{56}Co$														
α (* 10^{-16})	4.73	*	1.98	*	3.55	*	2.32	*	6.69	*	15.8	12.2	4.79	*
unc. (in %)	5.0	*	5.4	*	5.2	*	5.4	*	5.0	*	5.0	5.5	5.0	*
$Fe(n,x)^{57}Co$														
α (* 10^{-17})	11.0	4.20	5.82	2.18	6.35	3.32	4.75	2.07	12.7	6.17	27.1	14.7	11.1	4.26
unc. (in %)	4.9	7.5	5.1	6.7	5.0	5.3	5.1	6.6	4.9	5.4	4.9	5.2	4.9	6.5
$Fe(n,x)^{60}Co$														
α (* 10^{-17})	7.13	9.80	6.47	5.28	2.90	3.21	2.34	2.05	9.06	3.27	3.99	4.54	2.46	2.41
unc. (in %)	5.2	5.3	5.0	5.0	5.2	5.5	5.9	5.8	5.1	5.1	6.0	5.1	5.5	5.5

* not detected
** based on one peak (1120 keV)

Table 2. Specific saturation activities a (per atom, per s, per 0.75 mA) and uncertainties derived from the Cu foils before and after etching. (NE indicates the not etched foils and E the etched foil of pos.3.6)

Pos. codes :	1.1 NE	1.3 NE	2.1 NE	2.6 NE	3.1 NE	3.6 NE	3.6 E	4.1 NE
Reaction								
$Cu(n,x)^{46}Sc$								
a ($* 10^{-17}$)	13.0	7.37	11.0	7.69*	18.9	54.9	52.5**	11.7
unc. (in %)	6.6	9.2	9.6	10.	6.4	5.5	13.	6.9
$Cu(n,x)^{54}Mn$								
a ($* 10^{-15}$)	2.74	1.34	2.00	1.37	3.57	8.44	8.30	2.72
unc. (in %)	4.9	4.9	4.8	4.9	4.9	4.9	4.8	4.9
$Cu(n,x)^{56}Co$								
a ($* 10^{-16}$)	14.1	7.10	12.8	7.25	18.2	42.2	37.9	13.9
unc. (in %)	4.8	4.9	5.1	4.9	4.8	4.8	4.9	4.8
$Cu(n,x)^{57}Co$								
a ($* 10^{-15}$)	6.59	3.41	4.83	3.25	8.30	17.7	17.4	6.48
unc. (in %)	5.1	5.0	5.5	5.4	5.1	5.1	5.1	5.1
$Cu(n,x)^{58}Co$								
a ($* 10^{-15}$)	10.5	5.79	7.98	5.65	12.7	25.2	25.2	10.3
unc. (in %)	4.9	4.9	4.9	4.9	4.8	4.9	4.8	4.9
$Cu(n,x)^{60}Co$								
a ($* 10^{-15}$)	7.17	4.34	5.62	4.00	8.41	15.0	15.1	7.16
unc. (in %)	5.0	5.0	4.9	4.9	4.9	4.9	5.2	4.9
$Cu(n,x)^{65}Zn$								
a ($* 10^{-17}$)	24.0	8.72	17.1	9.59	28.5	76.2	77.8	20.8
unc. (in %)	6.0	6.6	6.5	6.3	5.5	5.7	6.3	5.3

* based on one peak (1120 keV)

** based on one peak (889 keV)

Table 3. Specific saturation activities α (per atom, per s, per 0.75 mA) and uncertainties derived from the Ni foils before and after etching. (NE indicates the not etched foils and E the etched foil of pos.3.6)

Pos. codes :	1.1 NE	1.3 NE	2.1 NE	2.6 NE	3.1 NE	3.6 NE	3.6 E	4.1 NE
Reaction								
$Ni(n,x)^{46}Sc$								
α (* 10^{-16})	2.90	1.54	2.04	1.49*	3.81	11.7	9.93	2.09
unc. (in %)	6.6	8.5	6.6	5.5	6.5	6.3	7.1	6.6
$Ni(n,x)^{54}Mn$								
α (* 10^{-15})	7.45	4.41	5.91	4.27	9.02	16.6	16.7	6.69
unc. (in %)	4.9	4.9	4.9	4.9	4.9	4.9	4.8	5.0
$Ni(n,x)^{56}Co$								
α (* 10^{-15})	16.9	9.81	13.0	9.61	20.1	38.3	32.7	15.2
unc. (in %)	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
$Ni(n,x)^{57}Co$								
α (* 10^{-14})	6.72	4.12	5.25	3.88	7.73	13.5	13.7	6.02
unc. (in %)	5.2	5.1	5.2	5.1	5.2	5.2	5.2	5.2
$Ni(n,x)^{58}Co$								
α (* 10^{-14})	9.82	6.17	7.46	5.65	11.0	17.5	17.7	8.50
unc. (in %)	5.0	5.0	5.0	5.0	5.0	5.0	4.8	5.0
$Ni(n,x)^{60}Co$								
α (* 10^{-15})	4.59	2.89	3.65	2.61	5.24	8.79	9.05	4.10
unc. (in %)	4.8	4.9	4.9	4.9	4.9	4.9	4.8	4.8

* based on one peak (1120 keV)

Table 4. Specific saturation activities α (per atom, per s, per 0.75 mA) and uncertainties derived from the Co foils.

Pos. codes :	1.1 NE	1.3 NE	2.1 NE	2.6 NE	3.1 NE	3.6 NE	4.1 NE
Reaction							
$Co(n,x)^{54}Mn$							
α (* 10^{-15})	10.4	10.5	11.6	5.33	12.1	26.6	10.9
unc. (in %)	8.9	7.5	9.3	9.6	4.5	5.4	7.3
$Co(n,x)^{57}Co$							
α (* 10^{-14})	2.34	1.46	1.92	1.50	2.93	5.13	2.52
unc. (in %)	5.0	5.5	5.1	5.3	5.3	5.1	5.2
$^{59}Co(n,\gamma)^{60}Co$							
α (* 10^{-12})	6.89	6.19	6.36	6.15	7.36	8.58	6.69
unc. (in %)	4.9	4.9	4.9	4.9	4.9	4.9	4.9

Table 5. Conversion factors between the specific activity values (Bq.kg-1) at the end of the irradiation and the specific saturation activity values as presented in the tables 1 to 4 (expressed in 10^{+24}).

Foil :	Fe		Cu		Ni		Co	
	Reaction	factor	Reaction	factor	Reaction	factor	Reaction	factor
	$Fe(n,x)^{46}Sc$	5.85	$Cu(n,x)^{46}Sc$	5.14	$Ni(n,x)^{46}Sc$	5.57	$Co(n,x)^{54}Mn$	2.88
	$^{54}Fe(n,p)^{54}Mn$	0.176	$Cu(n,x)^{54}Mn$	2.67	$Ni(n,x)^{54}Mn$	2.89	$Co(n,x)^{57}Co$	3.15
	$Fe(n,x)^{54}Mn$	3.03	$Cu(n,x)^{56}Co$	5.29	$Ni(n,x)^{56}Co$	5.73	$^{59}Co(n,\gamma)^{60}Co$	0.645
	$Fe(n,x)^{56}Co$	6.02	$Cu(n,x)^{57}Co$	2.92	$Ni(n,x)^{57}Co$	3.16		
	$Fe(n,x)^{57}Co$	3.32	$Cu(n,x)^{58}Co$	5.44	$Ni(n,x)^{58}Co$	5.89		
	$Fe(n,x)^{60}Co$	0.681	$Cu(n,x)^{60}Co$	0.598	$Ni(n,x)^{60}Co$	0.648		
			$Cu(n,x)^{65}Zn$	3.11				

Table 6. Mass values (in mg) of the foils.
(NE indicates the not etched foils and E the etched foils)

Code	Fe NE	Fe E	Cu NE	Cu E	Ni NE	Ni E	Co NE
1.1	2.350	0.5196	4.665	-	2.675	-	1.647
1.3	2.467	1.898	4.654	-	2.703	-	1.627
2.1	2.204	2.088	4.547	-	2.700	-	1.674
2.6	2.628	2.265	4.640	-	2.404	-	1.652
3.1	2.480	2.113	4.744	-	2.290	-	1.574
3.6	2.605	2.099	4.667	4.426	2.707	2.343	1.621
4.1	2.664	2.315	4.710	-	2.895	-	1.654

Table 7. Normalized specific saturation activity values for the various reactions in each foil (not etched) with respect to the data valid for position 3.6.

Pos. codes:	1.1	1.3	2.1	2.6	3.1	3.6	4.1
Reaction							
Fe foil							
$Fe(n,x)^{46}Sc$	0.31	0.16	0.24	0.16	0.42	1.00	0.31
$^{54}Mn(n,p)^{54}Mn$	0.49	0.30	0.39	0.28	0.57	1.00	0.49
$Fe(n,x)^{54}Mn$	0.49	0.30	0.39	0.29	0.57	1.00	0.49
$Fe(n,x)^{56}Co$	0.30	0.13	0.23	0.15	0.42	1.00	0.30
$Fe(n,x)^{57}Co$	0.40	0.21	0.23	0.17	0.46	1.00	0.41
$Fe(n,x)^{60}Co$	1.79	1.62	0.73	0.59	2.27	1.00	0.62
Cu foil							
$Cu(n,x)^{46}Sc$	0.24	0.13	0.20	0.14	0.34	1.00	0.21
$Cu(n,x)^{54}Mn$	0.33	0.16	0.24	0.16	0.42	1.00	0.32
$Cu(n,x)^{56}Co$	0.33	0.17	0.30	0.17	0.43	1.00	0.33
$Cu(n,x)^{57}Co$	0.37	0.19	0.27	0.18	0.47	1.00	0.37
$Cu(n,x)^{58}Co$	0.42	0.23	0.32	0.22	0.50	1.00	0.41
$Cu(n,x)^{60}Co$	0.46	0.29	0.37	0.27	0.56	1.00	0.48
$Cu(n,x)^{65}Zn$	0.32	0.11	0.22	0.13	0.37	1.00	0.27
Ni foil							
$Ni(n,x)^{46}Sc$	0.25	0.13	0.17	0.13	0.33	1.00	0.18
$Ni(n,x)^{54}Mn$	0.45	0.27	0.36	0.26	0.54	1.00	0.40
$Ni(n,x)^{56}Co$	0.44	0.26	0.34	0.25	0.53	1.00	0.40
$Ni(n,x)^{57}Co$	0.50	0.31	0.39	0.29	0.57	1.00	0.45
$Ni(n,x)^{58}Co$	0.56	0.35	0.43	0.32	0.63	1.00	0.49
$Ni(n,x)^{60}Co$	0.52	0.33	0.42	0.30	0.60	1.00	0.47
Co foil							
$Co(n,x)^{54}Mn$	0.39	0.39	0.44	0.20	0.45	1.00	0.41
$Co(n,x)^{57}Co$	0.46	0.28	0.37	0.29	0.57	1.00	0.49
$^{59}Co(n,\gamma)^{60}Co$	0.80	0.72	0.74	0.72	0.86	1.00	0.78

Table 8. Normalized specific saturation activity values for the various reactions in each foil (not etched) with respect to the data valid for the reaction $Fe(n,x)^{54}Mn$.

Pos. codes : Reaction	1.1	1.3	2.1	2.6	3.1	3.6	4.1
$Fe(n,x)^{46}Sc$	0.025	0.021	0.024	0.022	0.028	0.039	0.024
$^{54}Fe(n,p)^{54}Mn$	17.2	17.2	17.2	17.2	17.2	17.2	17.2
$Fe(n,x)^{54}Mn$	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$Fe(n,x)^{56}Co$	0.014	0.0096	0.013	0.012	0.017	0.023	0.014
$Fe(n,x)^{57}Co$	0.0033	0.0028	0.0024	0.0024	0.0032	0.0039	0.0033
$Fe(n,x)^{60}Co$	0.0021	0.0031	0.0011	0.0012	0.0023	0.0006	0.0007
$Cu(n,x)^{46}Sc$	0.0039	0.0036	0.0041	0.0039	0.0048	0.0080	0.0035
$Cu(n,x)^{54}Mn$	0.082	0.065	0.074	0.070	0.091	0.12	0.081
$Cu(n,x)^{56}Co$	0.042	0.034	0.048	0.037	0.046	0.061	0.041
$Cu(n,x)^{57}Co$	0.20	0.16	0.18	0.16	0.21	0.26	0.19
$Cu(n,x)^{58}Co$	0.31	0.28	0.30	0.29	0.32	0.37	0.31
$Cu(n,x)^{60}Co$	0.21	0.21	0.21	0.20	0.21	0.22	0.21
$Cu(n,x)^{65}Zn$	0.0072	0.0042	0.0064	0.0049	0.0073	0.011	0.0062
$Ni(n,x)^{46}Sc$	0.0087	0.0074	0.0076	0.0076	0.0097	0.017	0.0062
$Ni(n,x)^{54}Mn$	0.22	0.21	0.22	0.22	0.23	0.24	0.20
$Ni(n,x)^{56}Co$	0.50	0.47	0.48	0.49	0.51	0.56	0.45
$Ni(n,x)^{57}Co$	2.01	1.99	1.95	1.97	1.97	1.96	1.79
$Ni(n,x)^{58}Co$	2.93	2.98	2.77	2.87	2.80	2.54	2.52
$Ni(n,x)^{60}Co$	0.14	0.14	0.14	0.13	0.13	0.13	0.12
$Co(n,x)^{54}Mn$	0.31	0.51	0.43	0.27	0.31	0.39	0.32
$Co(n,x)^{57}Co$	0.70	0.71	0.71	0.76	0.75	0.75	0.75
$^{59}Co(n,\gamma)^{60}Co$	205.7	299.0	236.4	312.2	187.3	124.7	198.5

Table 9. Final set of specific saturation activities a
(per atom, per s, per 0.75 mA)
The uncertainty is given for a confidence level of 67 per cent

Pos. codes : Reaction	1.1	1.3	2.1	2.6	3.1	3.6	4.1	Uncertainties in %	
$^{54}Fe(n,p)^{54}Mn$ ($*10^{-13}$)	5.80	3.57	4.58	3.37	6.75	11.8	5.77	5.	
$Fe(n,x)^{54}Mn$ ($*10^{-14}$)	3.37	2.07	2.66	1.95	3.92	6.87	3.35	5.	
$Fe(n,x)^{57}Co$ ($*10^{-17}$)	4.20	2.18	3.32	2.07	6.17	14.7	4.26	5 to 7.	#
$Cu(n,x)^{54}Mn$ ($*10^{-15}$)	2.74	1.34	2.00	1.37	3.57	8.30	2.72	5.	
$Cu(n,x)^{56}Co$ ($*10^{-16}$)	12.7*	6.38*	11.5*	6.51*	16.3*	37.9	12.5*	5.	##
$Cu(n,x)^{57}Co$ ($*10^{-15}$)	6.59	3.41	4.83	3.25	8.30	17.4	6.48	5.	
$Cu(n,x)^{58}Co$ ($*10^{-15}$)	10.5	5.79	7.98	5.65	12.7	25.2	10.3	5.	
$Cu(n,x)^{60}Co$ ($*10^{-15}$)	7.17	4.34	5.62	4.00	8.41	15.1	7.16	5.	
$Cu(n,x)^{65}Zn$ ($*10^{-17}$)	24.0	8.72	17.1	9.59	28.5	77.8	20.8	5 to 7.	#
$Ni(n,x)^{54}Mn$ ($*10^{-15}$)	7.45	4.41	5.91	4.27	9.02	16.7	6.69	5.	
$Ni(n,x)^{56}Co$ ($*10^{-15}$)	14.4*	8.38*	11.1*	8.20*	17.2*	32.7	13.0*	5.	##
$Ni(n,x)^{57}Co$ ($*10^{-14}$)	6.72	4.12	5.25	3.88	7.73	13.7	6.02	5.	
$Ni(n,x)^{58}Co$ ($*10^{-14}$)	9.82	6.17	7.46	5.65	11.0	17.7	8.50	5.	
$Ni(n,x)^{60}Co$ ($*10^{-15}$)	4.59	2.89	3.65	2.61	5.24	9.05	4.10	5.	
$Co(n,x)^{54}Mn$ ($*10^{-15}$)	10.4	10.5	11.6	5.33	12.1	26.6	10.9	5 to 9.	#
$Co(n,x)^{57}Co$ ($*10^{-14}$)	2.34	1.46	1.92	1.50	2.93	5.13	2.52	5.	
$^{59}Co(n,\gamma)^{60}Co$ ($*10^{-12}$)	6.89	6.19	6.36	6.15	7.36	8.58	6.69	5.	

* the specific saturation activities are corrected for the contamination with help of the information derived from the etched foil of position 3.6

\# the actual values of the uncertainties can be found in table 1 to 4

\## the uncertainty of the for etching corrected foils should be increased with 4 per cent.

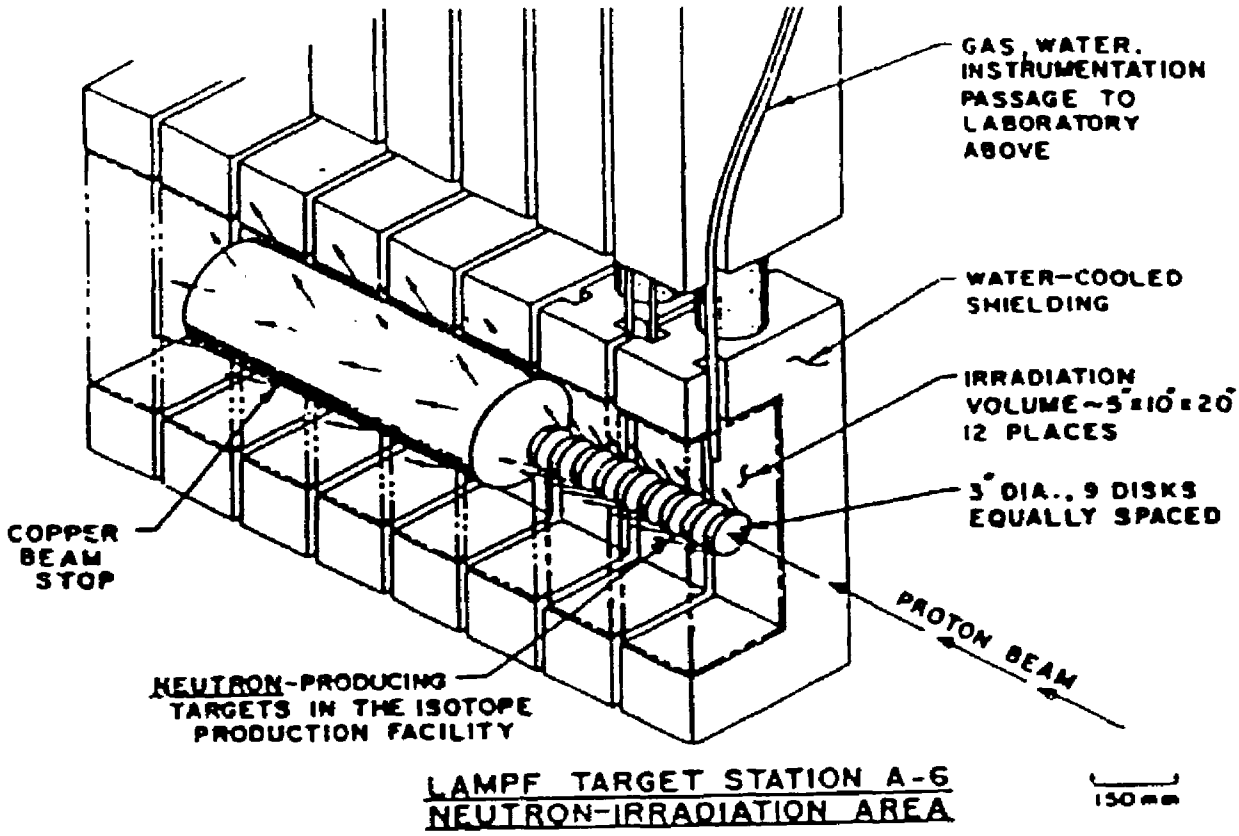


Fig. 1a: Schematic of the relation of the neutron-irradiation inserts, #1-8, to the neutron-producing targets in Target Station A-6

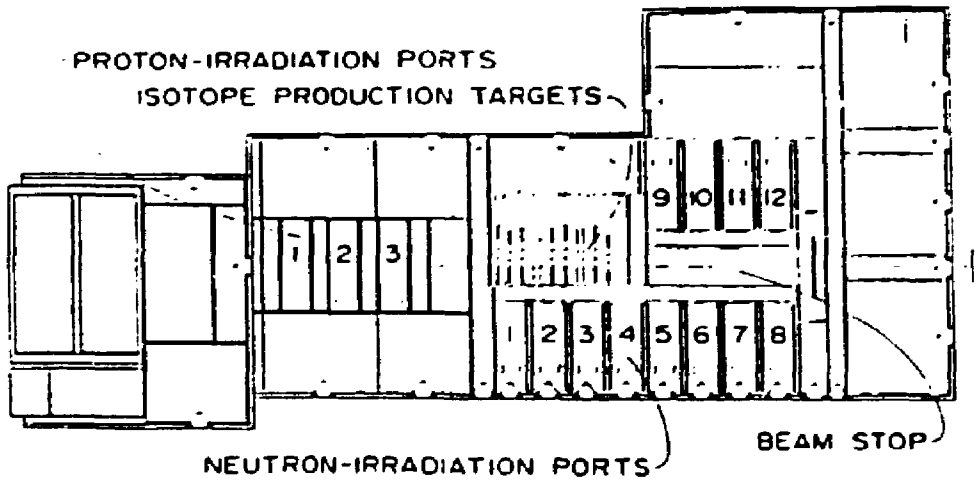


Fig. 1b: Neutron-irradiation insert locations relative to other components in Target Station A-6. This is a top view.

Fig. 2: Picture of capsule 4

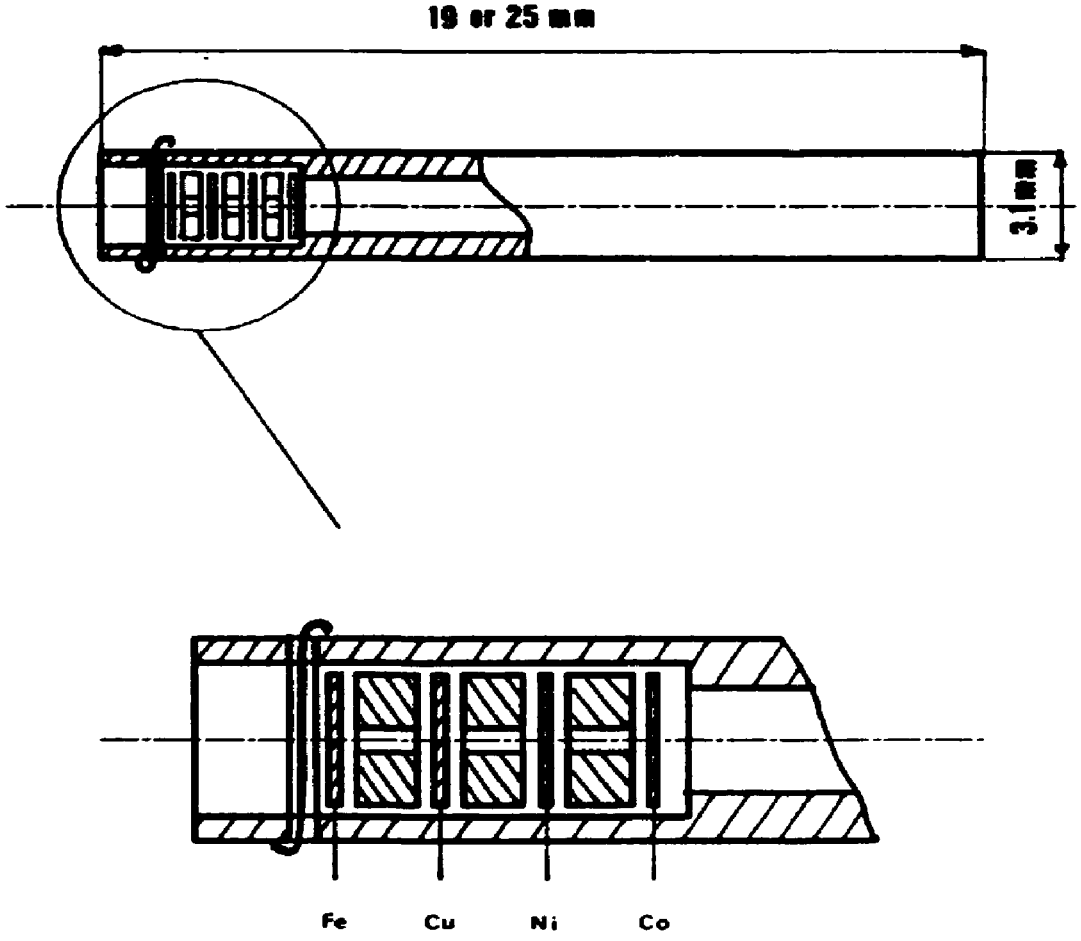


Fig. 3. Foil package.

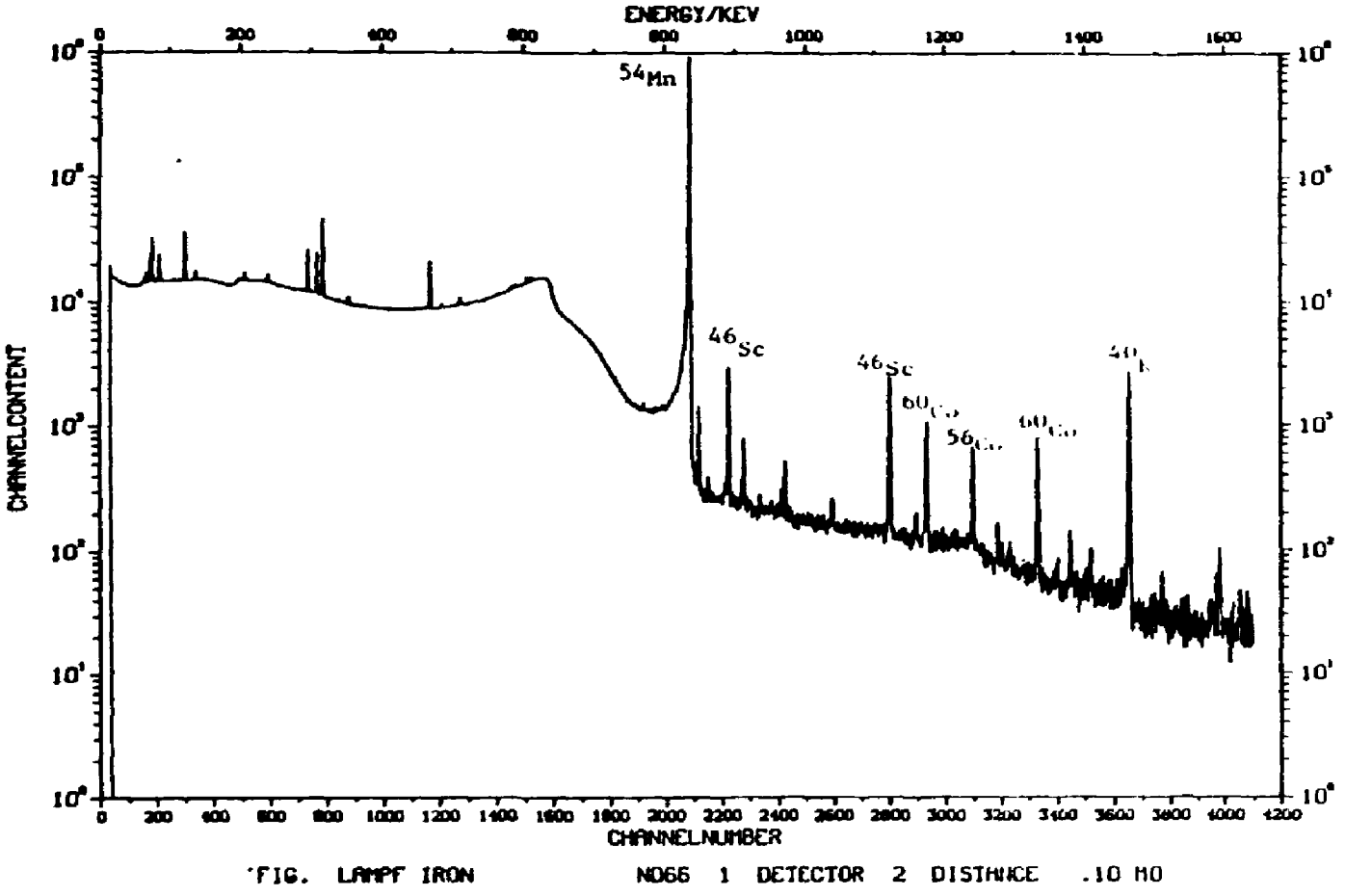


Fig. 4. Gamma spectrum of Fe foil.

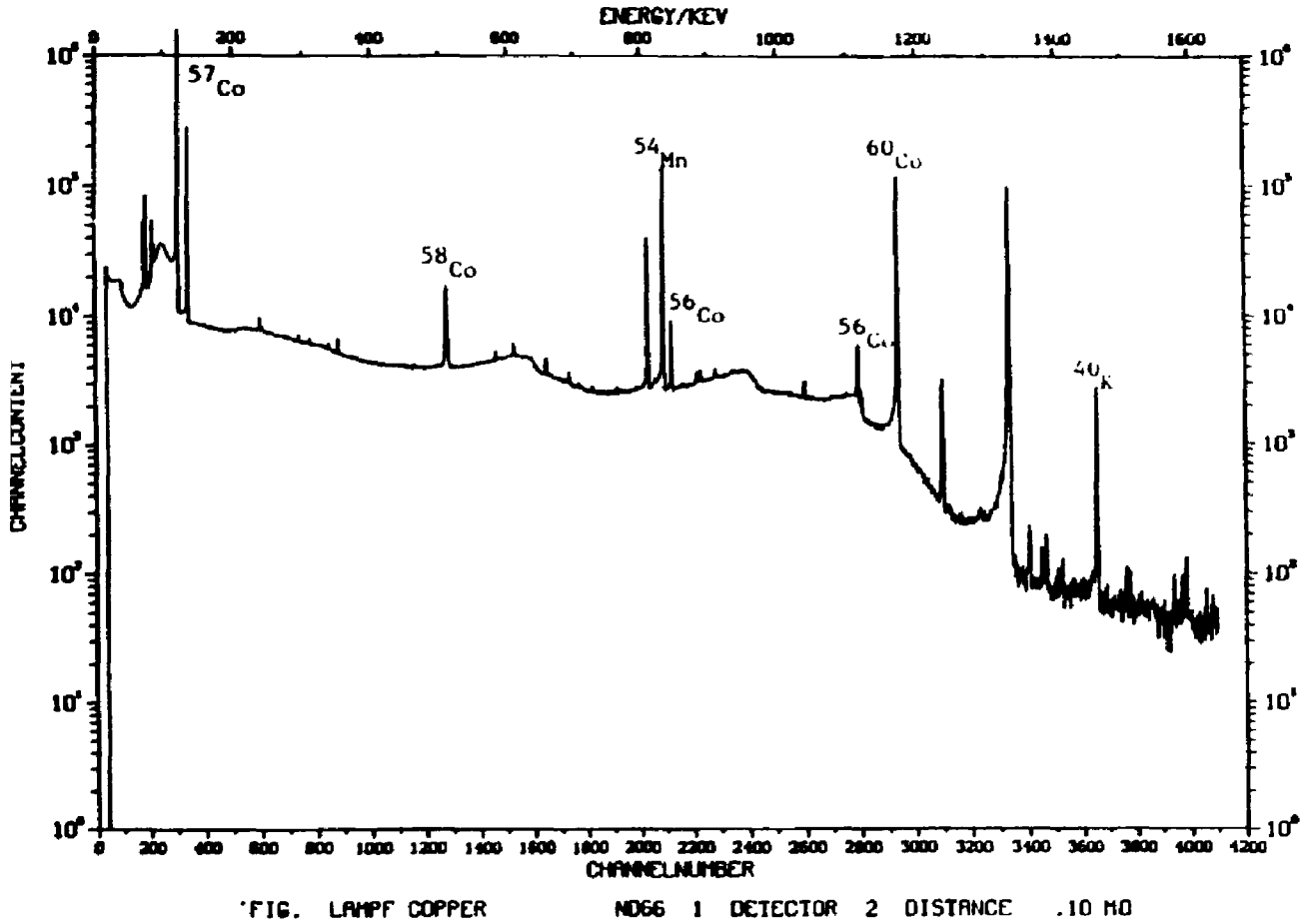


Fig. 5. Gamma spectrum of Cu foil.

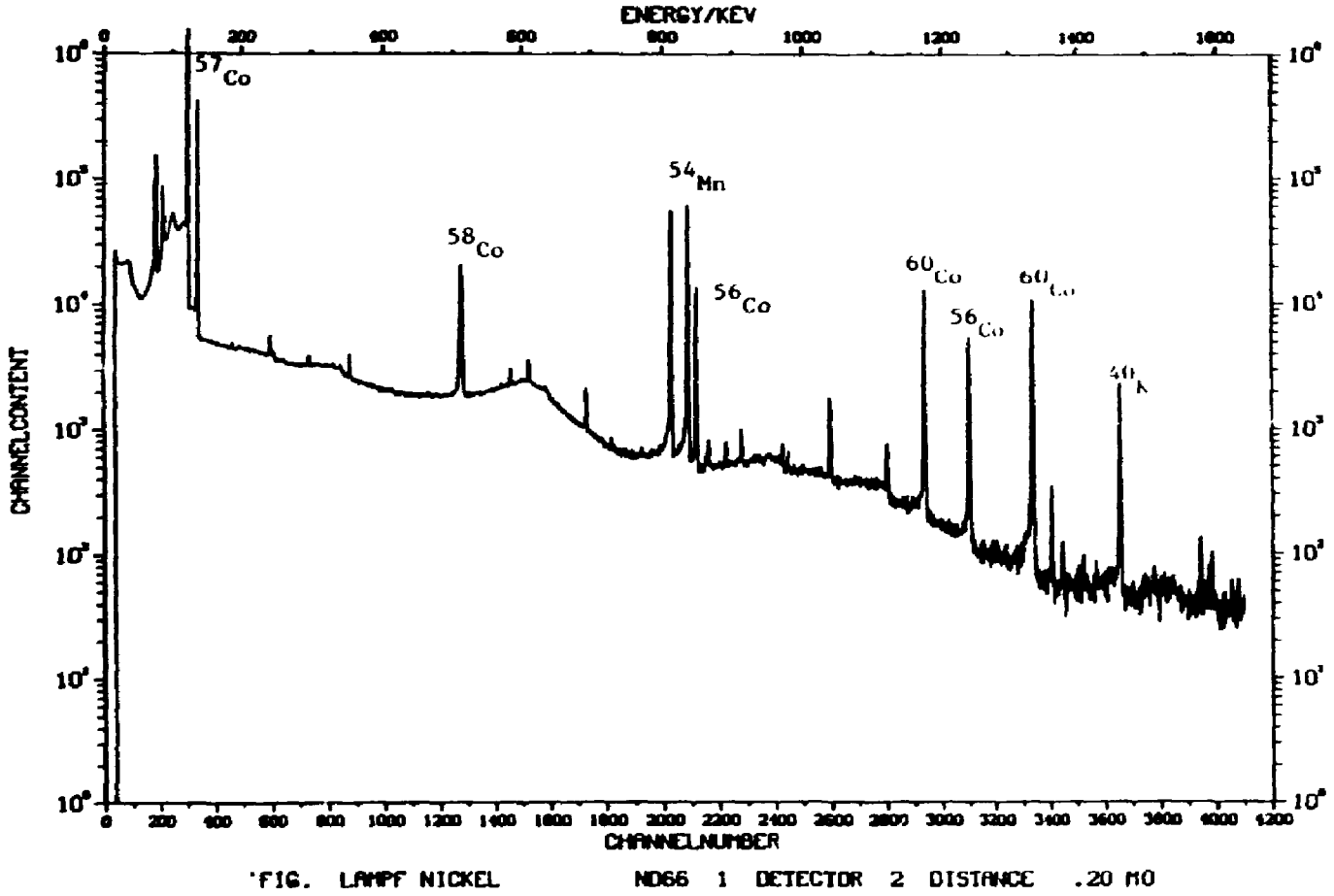


Fig. 6. Gamma spectrum of Ni foil.

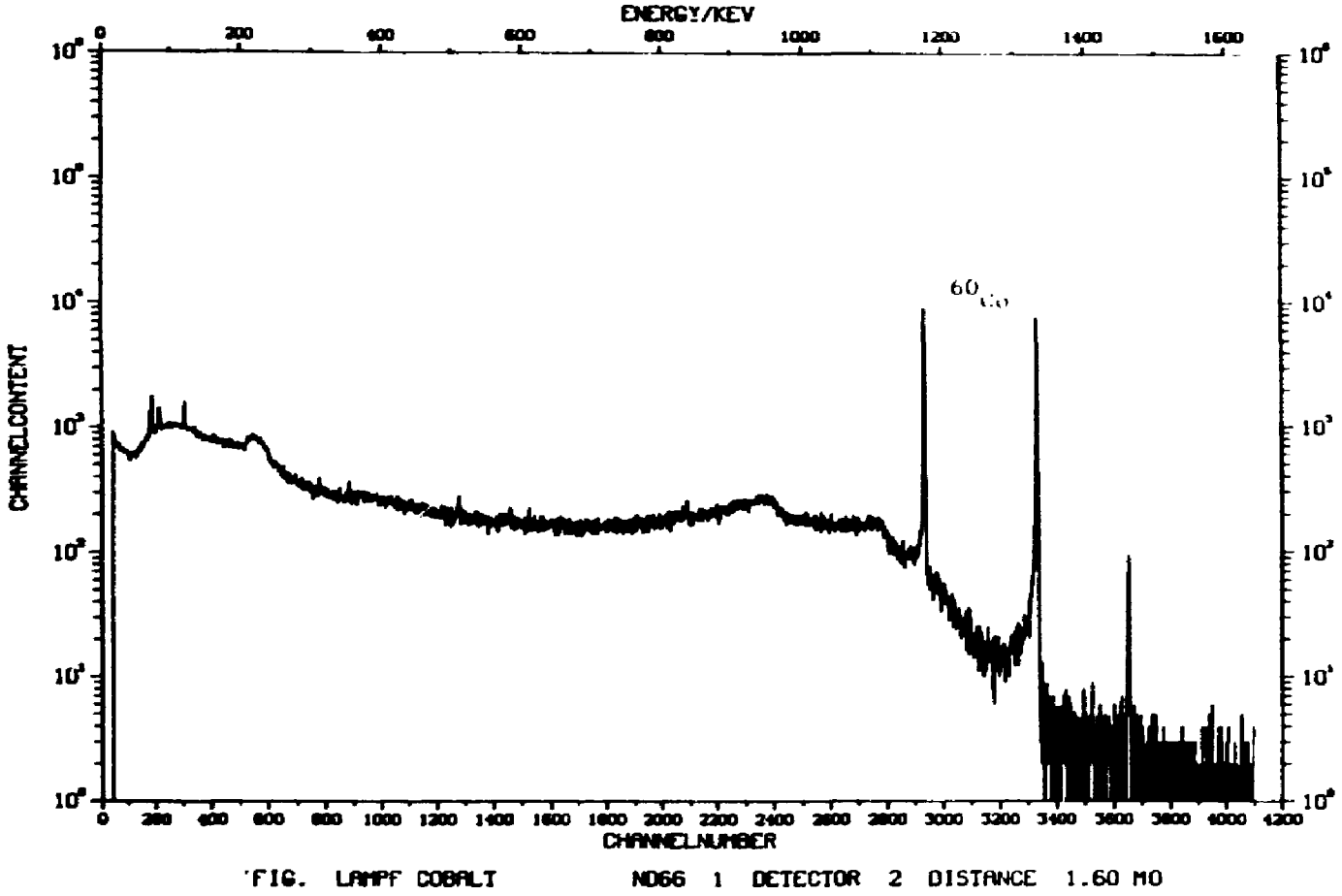
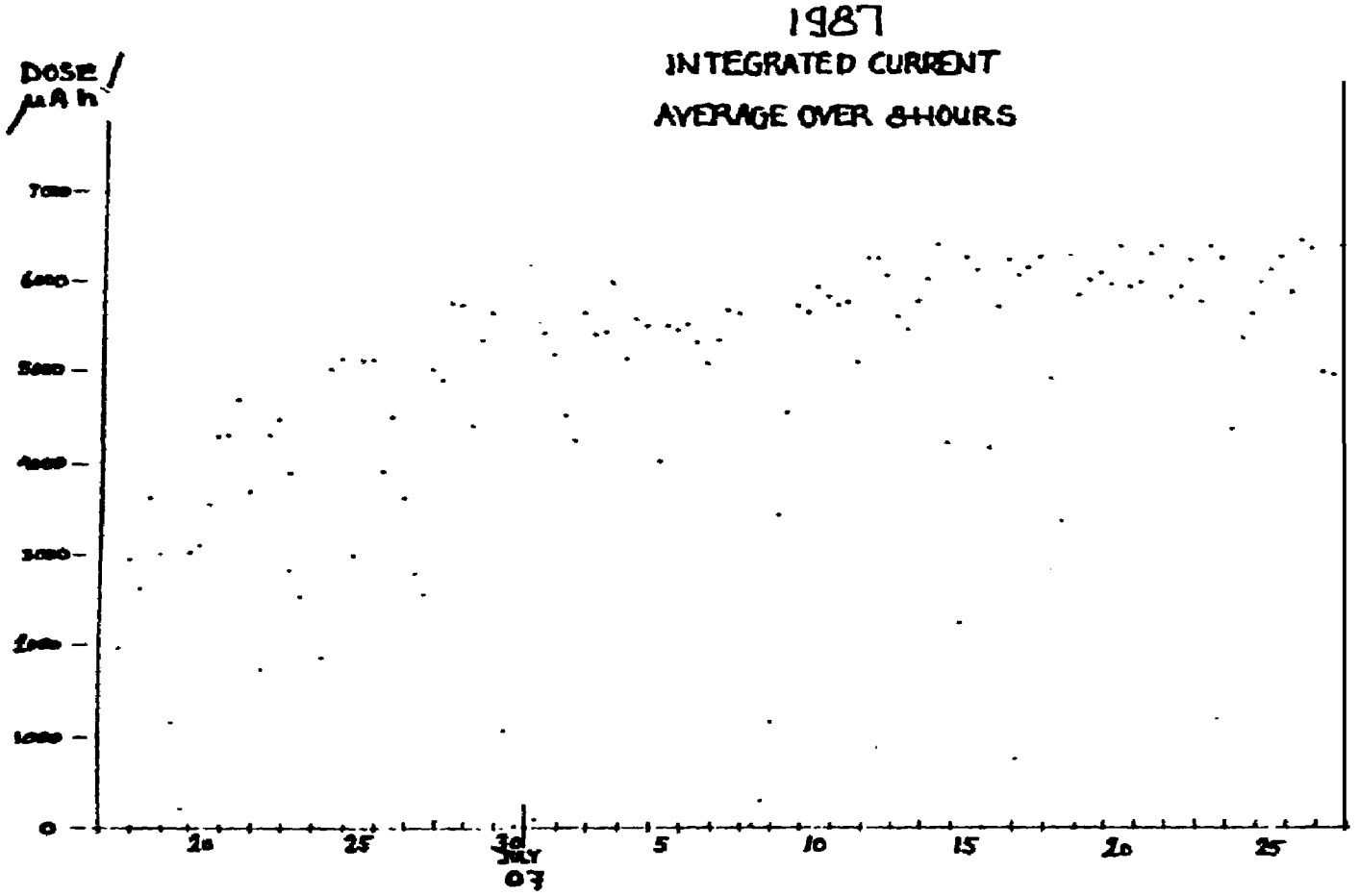


Fig. 7. Gamma spectrum of Co foil.



DATE	CLOCK TIME	mH
870617	800	0.245
870617	1600	0.367
870617	2400	0.327
870618	800	0.453
870618	1600	0.375
870618	2400	0.144
870619	800	0.0269
870619	1600	0.376
870619	2400	0.387
870620	800	0.443
870620	1600	0.538
870620	2400	0.538
870621	800	0.587
870621	1600	0.462
870621	2400	0.213
870622	800	0.538
870622	1600	0.559
870622	2400	0.485
870623	800	0.315
870623	1600	0.000
870623	2400	0.231
870624	800	0.626
870624	1600	0.642

DATE	CLOCK TIME	mH
870625	800	0.638
870625	1600	0.637
870625	2400	0.488
870626	800	0.562
870626	1600	0.452
870626	2400	0.346
870627	800	0.317
870627	1600	0.525
870627	2400	0.612
870628	800	0.719
870628	1600	0.713
870628	2400	0.548
870629	800	0.618
870629	1600	0.704
870629	2400	0.133
870630	800	0.000
870630	2400	0.00865
870701	800	0.676
870701	1600	0.646
870701	2400	0.563
870702	800	0.530
870702	1600	0.704
870702	2400	0.677

Fig. 8. Indication of irradiation history.