BURN-UP DETERMINATIONS and DIMENSIONAL MEASUREMENTS of TRIGA-HEU FUEL ELEMENTS FROM THE 14 MW STEADY STATE CORE

C.Toma, Al.Alexa, T.Crăciunescu, M.Pîrvan,
R.Dobrin

ABSTRACT

In this paper are presented the results of nondestructive examination in Post Irradiation Examination Laboratory for twenty five fuel rods selected from 14 MW steady state core. Gamma scanning and dimensional measurements were carried out in order to determine burn-up and diametral deflection of the fuel rods.

Also, some comparisons with SSR Safety Report estimations for the maximum burn-up pin were made.

INTRODUCTION

After a SSR operating time interval coresponding to about 122oo MWD energy releasing a number of 25 fuel rod some of them having the highest burn-up were selected for nondestructiv examination in Post Irradiation Examination Laboratory (PIEL).

Two kinds of measurements were made :

- burn-up determination and its axial distribution using high precision gamma scanning.
- dimensional measurements for diametral profile determination.

A computer controlled element positioning stage existing in PIEL was used for both types of measurements.

GAMMA SPECTROMETRY INSTALLATION

The gamma spectrometry installation in hot laboratory is shown schematically in figure 1. This includes four main sections, the scanning system, the collimator, the detector, and the data acquisition and processing system.

The main features for these sections are the following :

The element positioning stage has four degrees of motion

X - left and right motion past the collimator
Y - inward and outward motion with respect to the
   collimator slit
Z - upward and downward movement past the collimator slit
Ø - rotation of the fuel rod around its vertical axis

The motions are powered by stepping motors and the positions are recorded by digital encoders Accuracy in movement is ±o.o25 mm.

The collimator is of sintered tungsten with three slits parallelipiped in shape with width of o.1 mm, o.25 mm and o.5 mm depending on the definition and the counting rate.

The detector is Ge intrinsic featuring high resolution (1,81 KeV for E_γ = 1.33 MeV).

AXIAL AND RADIAL GAMMA DISTRIBUTIONS IN SSR-14 MW FUEL PINS

Fuel pins for 14 MW steady state reactor consist of U-ZrH with Erbium as consumable poison. The initial uranium-235 mass is about 41 g. Fuel column length is 55.88 cm and the pellet diameter is 12.7o mm.

Axial distribution for a number of gamma radioactive fission products is especially interesting to determine burn-up. This serve to make intercomparison of the fuel pins from different positions in the reactor core, to arrange fuel pin in fuel clusters on burn-up criterion, to assure a correct fuel management and to compare with the burn-up values obtained from burn-up computer codes.

Fuel pins are examined individually and are rotated during the measurements to even the effects of non-uniform gamma source density and pin bowing. Gamma spectra are accumulated for a given period of time (typically 1o-15 minutes) to obtain relativ concentration of the different fission products: Zr-95, Cs-137, Ce-144, La-14o.

During irradiation some measured fuel pins ocupied positions in the core near the maximum neutron flux.

For axial distribution of the fission products of interest ten fuel rods were measured using a collimator slit of o.5 mm in 1.5 mm increments, a number of 5 fuel rods were measured using a different step of 2.o mm. For other ten fuel rods we used different steps or collimator slit.

Radial measurements were taken on some pins (3o3, 583, 5o7, 667) using a o.25 mm vertical slit in o.25 mm increments. These type of measurements were carried out for a number of five angular orientation.

Examples of axial profiles for different isotopes are shown in the fig. 2, 3, 4, 5, 6. They belong to fuel pin # 581. Cs-137 axial profile provides data to determine number of fissions from the volume limited by collimator slit. Examples of diametral profiles for Cs-137 (fuel pin # 3o3) are shown in the fig. 7. Diametral profile provides data to determine gamma self absorbtion in fuel pellets.

BURN-UP DETERMINATION

Based on the date obtained from axial gamma scanning burn-up determination is possible using the relation :

$$B.U. = N_f \cdot \overline{E}/V \ (MWD/cm^3)$$

where :

N_f = number of fission from the volum V

$\overline{E}$ = average energy in a fission act

V = sample volume determined by slit collimator

N_f is given by :

$$N_f = A \cdot f_1 \cdot f_2/(\lambda \cdot Y \cdot \varepsilon \cdot S \cdot S_1 \cdot S_2)$$

where :

A = photopeak area of the fission product monitor

$f_1 = e^{\lambda t_1}$ = correction factor for the disintegration of the burn-up monitor after irradiation termination ,

t_1 = cooling time

$f_2 = \lambda t_2/(1 - e^{-\lambda t_2})$ = correction factor for disintegration of the burn-up monitor during irradiation

λ = disintegration constant

t_2 = irradiation time

Y = fission yield of the burn-up monitor

ε = detection efficiency

S = emission probability of the gamma photon

S_1, S_2 = correction factors for gamma attenuation in fuel and clad.

For complicated irradiation history the correction factor f_2 is rather determined using a computer code.

Based on data obtained from diametral gamma scanning and using a computer code for tomographycal reconstruction was possible to get isotope distribution in a fuel pin cross section In this method the input data were diametral profile of the isotope.

For image reconstitution from an insufficient number of projections, maximum entropy method is used considering experimental data as restrictions.

In this way from five diametral profile specific to on isotope we got (see fig. 7):

- a threedimensional view of the activity distribution reproduced in the left corner in fig. 7.
- a(x, y) cross section of the above distribution in the middle (a higher density of points represents a higher activity)
- a vertical cross section in the direction indicated by arrow where diametral profile is more clear.

COMMENTS ON GAMMA SCANNING AND BURN-UP RESULTS

At the measurement time about 12.2oo MWD energy releasing were recorded for the SSR core while in SSR Safety Report 7ooo MWD had been established as fuel fifetime objective.

Therefore the decision was taken to study by nondestructive method fuel behaviour.

The fuel pins to be investigated were selected to cover a broad spectrum of burn-up values.

In Table 1 are given the burn-up values for the measured pins in MWh/cm^3 and also in MWD/pin.

Are specified also reactor core position of the pin during irradiation pin serial number and metal atom percent burn-up defined as :

$$b = \frac{N_o^U - N_t^U}{N_o}$$

where :

N_o^U = atom density of uranium (U-235 + U-238) at begining of life

N_t^U = atom density of uranium (U-235 + U-238) at burn-up time, t

N_o = metal atom density at begining of life

$(N_o^U + N_o^{Er} + N_o^{Zr})$

Δm in the last column represent U-235 burned mass.

The measured worths for burn-up is in the interval 7.75 - 18.35 MWD/pin.

U-235 burned mass for the greatest burn-up is 2o.13 g representing 49% from the initial U-235 loading. In SSR Safety Report 62% from the initial U-235 mass is presumed to be burned in the case of maximum-power pin after 6oo full power days. Therefore the burn-up values demonstrates our measured pins did not attain the maximum-power pin burn-up value. The same conclusion is drawn analysing metal atom percent burn-up "b".

All of the uranium in a fuel pin represent 4.2% of the metal atoms by the definition of "b".

The data in Safety Report shown that the maximum burn-up pin has a metal atom percent burn-up of 2.5% after 6oo days operation at 14 MW. The values in Table 1 for the measured pin show a maximum b = 1.83%.

Axial gamma profiles presents particularities depending on burn-up, cooling time, care fuel pin position during irradiation, increment used during spectra acquisition.

Cs-137 axial gamma profile is important because it is a good burn-up monitor its profile being fissions profile in fuel pin. Its half life is long compared with irradiation time, it has a high fission yield, a gamma energy suitable and a small neutron absorbtion cross section.

Diametral profiles obtained after mathematical treatment of the diametral scanning spectra show two maximums in isotope activity at the edge of the fuel pellet, because of the gamma ray absorbtion in the fuel.

The presence of the three minimums in axial gamma profile shows integrity of the fuel pellets during irradiation even when high burn-up is attained.

From Cs-137 axial gamma profile the ratio between maximum burn-up in a fuel pin and burn-up at the top or bottom of the same fuel pin is available. These ratios show a more uniform burn-up for the bottom half of the core in comparison with top half of the reactor core.

DIMENSIONAL MEASUREMENTS

The same computer controlled element positioning stage existing in PIEL was used for dimensional measurements.

Two displacement inductive transducers method with differential transformer and movable core is used.

Fuel pin is vertical moving step by step between the two indicators being supported for a good stability during measurements in a fuel pin holder.

Besides the step by step vertical motion is possible the rotation movements with o.o9 degrees increment.

The transducer having a measurement range of ± 2.5 mm is messuring the distance between a refference surface and fuel pin surface.

Transducer calibration is done using a standard cylinder whose diameter was 13.o8 mm and whose lateral surface was the refference surface.

The transducers indication when the indicators are in close contact with the refference surface is zero.

The values of the unknown diameter is the sum of the refference diameter (13.o8) and algebric sum of the transducers worths.

The transducer sensitivity is given by :

$$S = \frac{U_e/U_i}{d} \quad \frac{mV/V}{mm}$$

where :

U_e = transducer output voltage

U_i = transducer input voltage

d = core displacement

Output voltage amplitude U_e is proportional with the core displacement, therefore with diameter variation, and the phase is indicating variation sign.

MEASUREMENTS RESULTS

Twenty HEU fuel rods were measured recording for every one the following :

- longitudinal diametral profile
- bending profile

These profiles were recorded for three fuel orientation separated by 12o degrees.

Figures 8, 9, 1o, 14, 15, 16 presents longitudinal diametral profiles for pins # 583 and # 836 at three orientation while figures 11, 12, 13, 17, 18, 19 presents bending profiles for the same pins at three orientation.

In accordance with diameter measurements resulted smaller diameters at the pellets interfaces in comparison with adjacent zones.

From the longitudinal diametral profile one can sees an increasing diameter in the proximity of the middle of the fuel pin and the existence of three minimums at the pellets interfaces positions.

The comparison of axial diametral profile with axial gamma profile indicates the coincidence of the minimums for the two profiles.

The explanation of smaller diameters in linked with the lack of the material at the pellet interface combined with fuel swelling. In this region diametral increasing due to fuel swelling is smaller than in the region far from pellet interface. Here the fuel swelling is greater determining on increased diameter.

The maximum diameter worth for measured pins is in the interval 14.o94-14.449 mm resulting a maximum diameter increasing of o.695 mm considering the initial diameter of 13.754.

SSR Safety Report estimate for the maxim burn-up pin (b = 2.5%) a diameter increasing of o.46 mm.

Bow measurement indicated for 17 fuel pin values smaller than 2 mm while for the rest of 3 fuel pins values greater than 2 mm.

The explanation is based on the presence of the intermediate spacers inside the fuel clusters and periodically rotation of the fuel pin.

In Table 2 are given the values for average diametral, deflection - Δ

Average diametral deflection is defined by :

$$\Delta = \frac{D - D_i}{D} \%$$

where :

D_i = initial diameter = 13.754 mm

D = postirradiation diameter

For 15 fuel pins from 2o the average diametral deflections were greater than 2.5%, the maximum value being 3.47%.

Fig. 19 presents the bending profile for fuel rod 836 where bow value is 1.386 mm.

Table 1

Nr. crt.	Pin serial number	Burnup			Irov (%)	Δm (Gram)	Diametral deflection Δ %
		MW/cm³	MWD/pin	b (%)			
1	303	2,63	7,75	0,77	10	8,50	2,14
2	0.35	3,60	10,60	1,06	10	11,63	2,94
3	507	3,62	10,66	1,06	10	11,70	
4	456	3,67	10,81	1,08	10	11,86	
5	667	3,80	11,19	1,11	10	12,28	
6	517	3,83	11,28	1,12	10	12,38	2,46
7	365	3,88	11,43	1,14	15	12,54	1,74
8	162	4,17	12,28	1,22	10	13,48	
9	265	4,17	12,28	1,22	10	13,48	2,60
10	579	4,39	12,93	1,29	10	14,19	
11	364	4,72	13,90	1,39	15	15,25	2,28
12	206	4,92	14,49	1,44	15	15,90	2,94
13	680	4,95	14,58	1,46	15	16,00	2,34
14	005	5,01	14,75	1,47	15	16,19	3,00
15	583	5,04	14,84	1,48	10	16,29	3,19
16	368	5,28	15,55	1,55	15	17,06	3,03
17	840	5,36	15,78	1,57	15	17,32	3,3
18	015	5,41	15,93	1,59	15	17,48	3,37
19	581	5,46	16,08	1,60	15	17,64	3,41
20	741	5,47	16,14	1,61	15	17,68	3,17
21	836	5,52	16,26	1,62	10	17,84	3,47
22	188	5,64	16,61	1,66	15	18,22	3,33
23	426	5,81	17,11	1,71	15	18,78	3,32
24	848	5,95	17,52	1,75	15	19,23	3,26
25	670	6,23	18,35	1,83	15	20,13	3,34

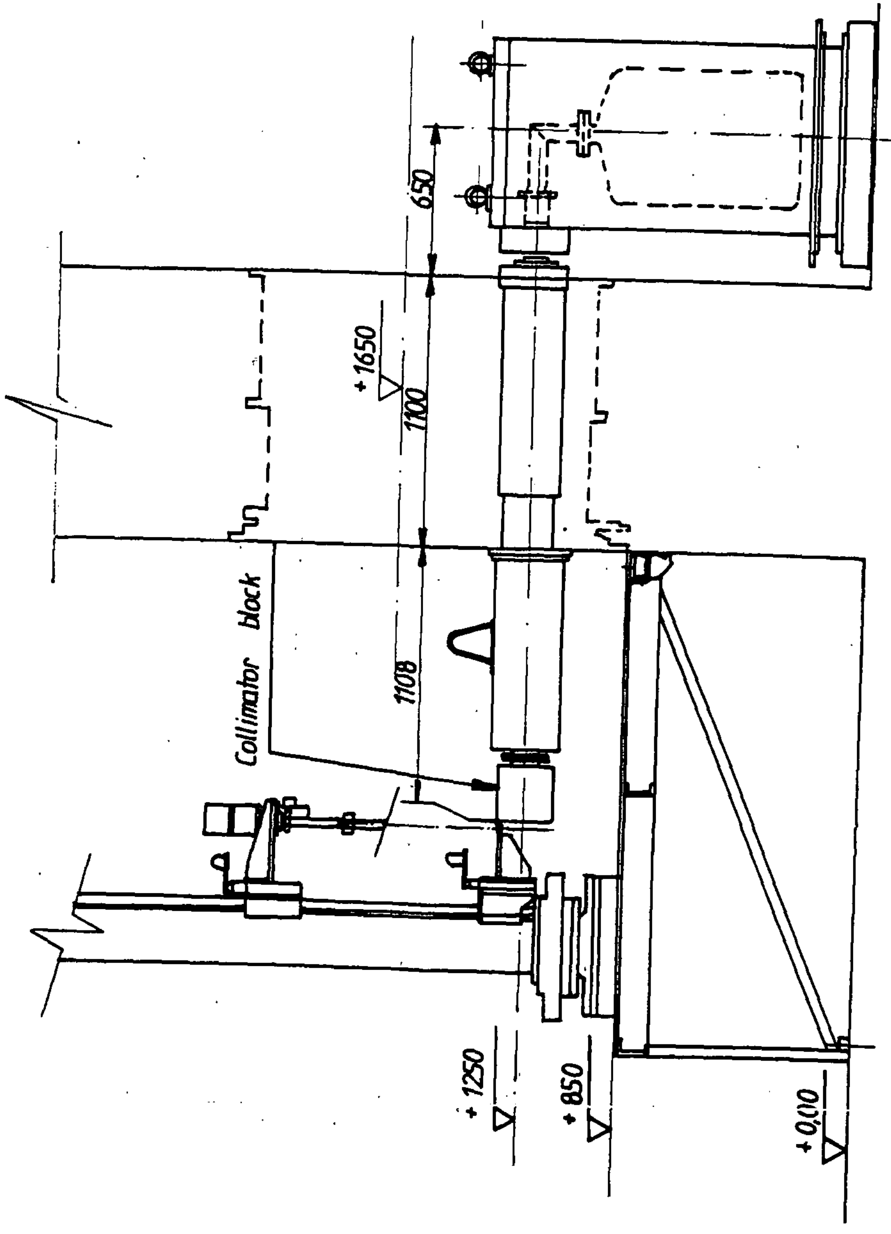


Fig.1 HOT CELL GAMMA SCANNING FACILLITY

* TRIGA 0581 * PROFIL AXIAL TOTAL *

TOTAL GAMMA AXIAL PROFIL

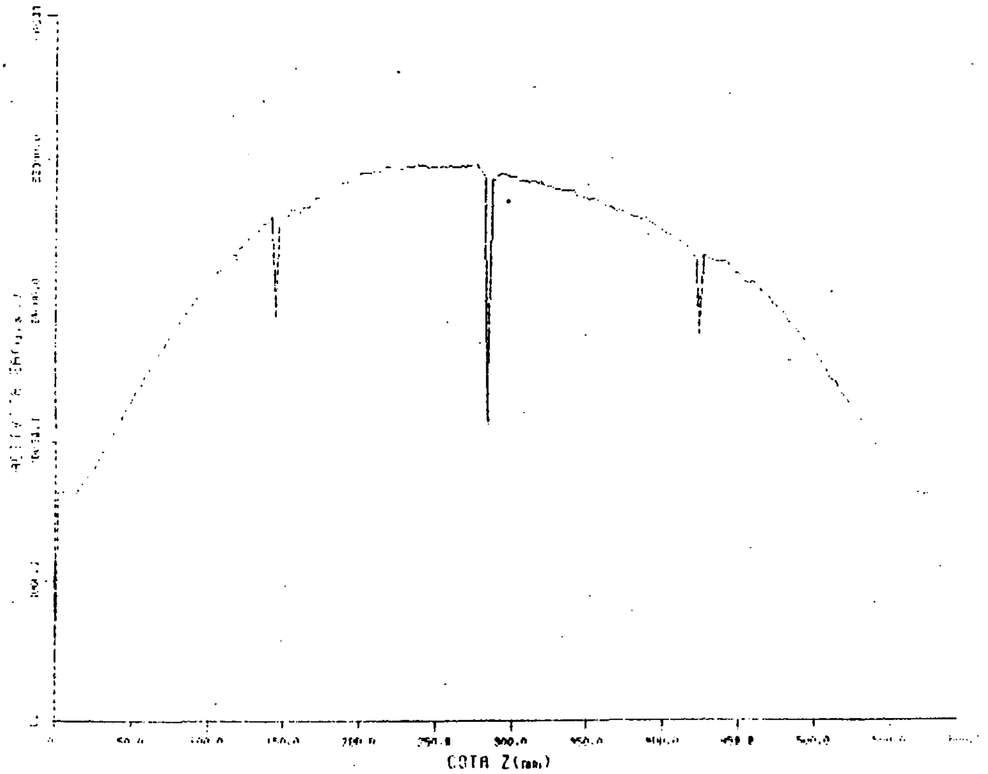


Fig.

* TRIGA 0581 * PROFIL AXIAL CS-134 (604.6 KeV) *

AXIAL PROFIL

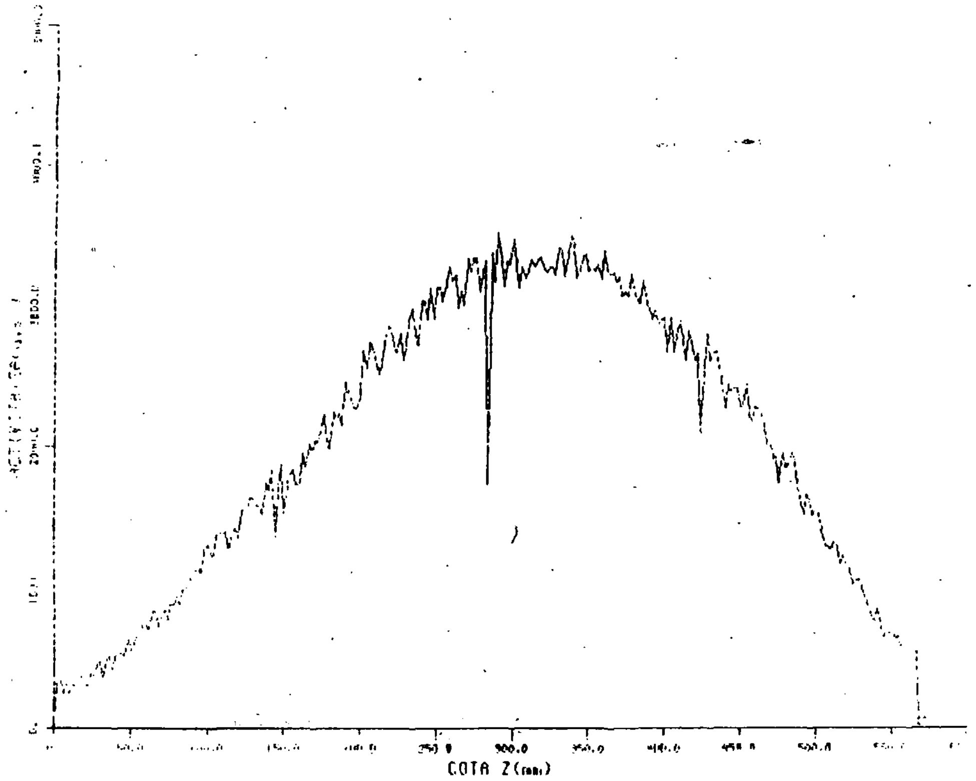


Fig.3

* TRIGA 0581 * PROFIL AXIAL CS-137 (661.643 KeV) *

AXIAL PROFIL

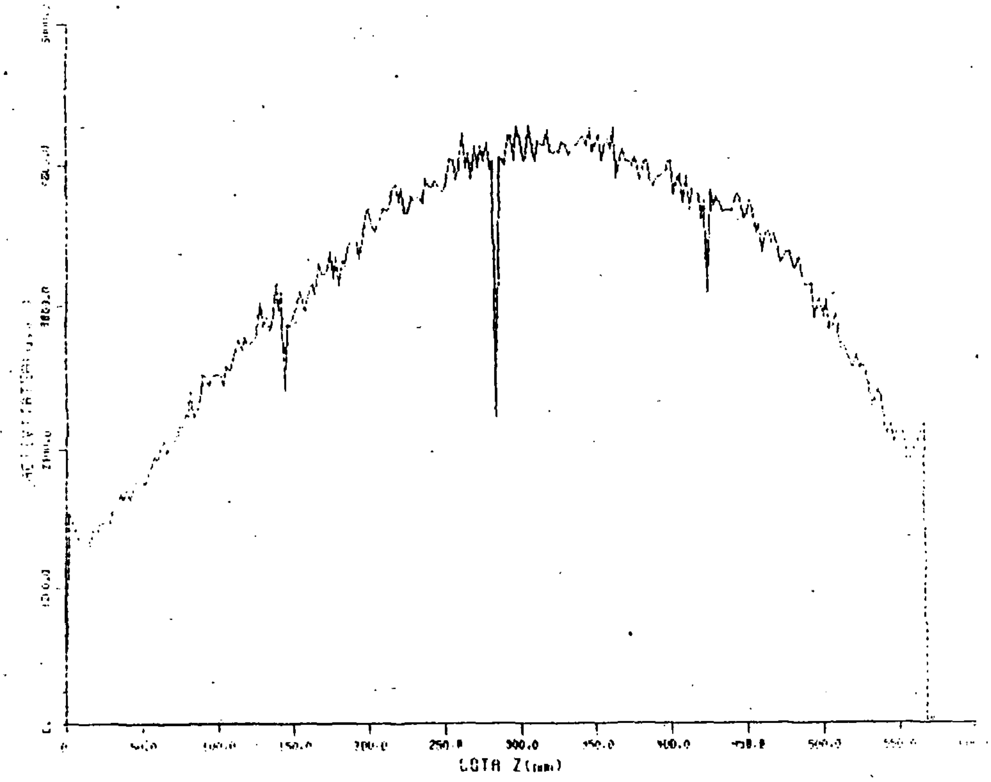


Fig. 4

* TRIGA 0581 * PROFIL AXIAL ZR-95 (724.23 KeV) *

AXIAL PROFIL

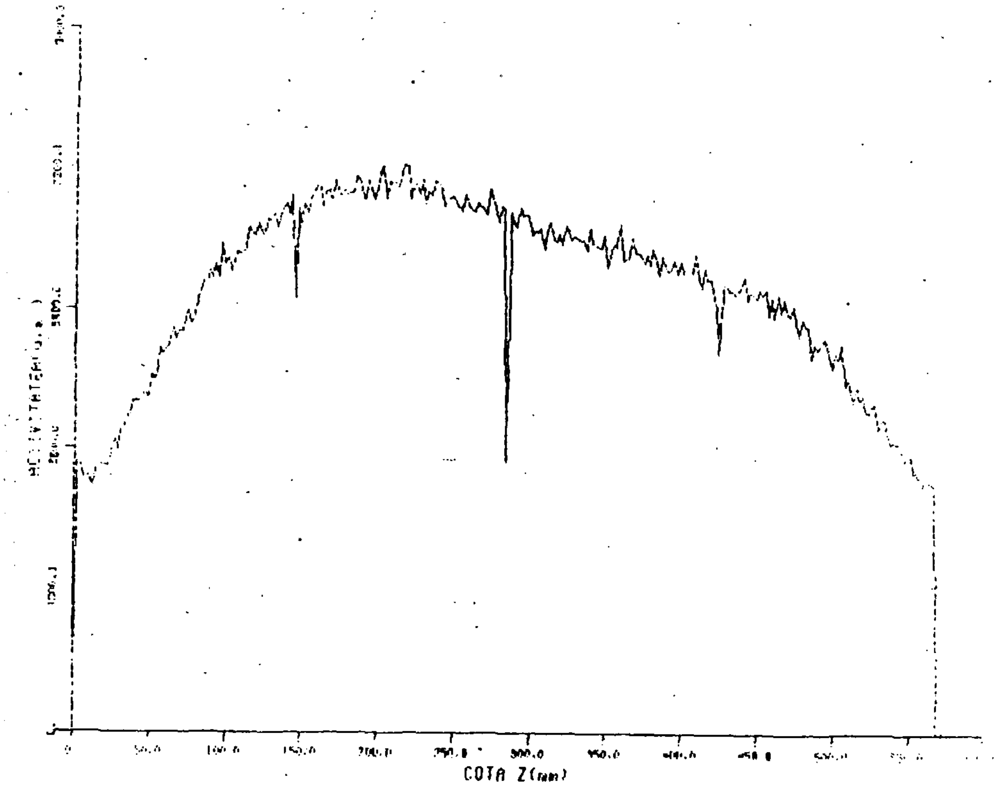


Fig. 5

AXIAL PROFIL

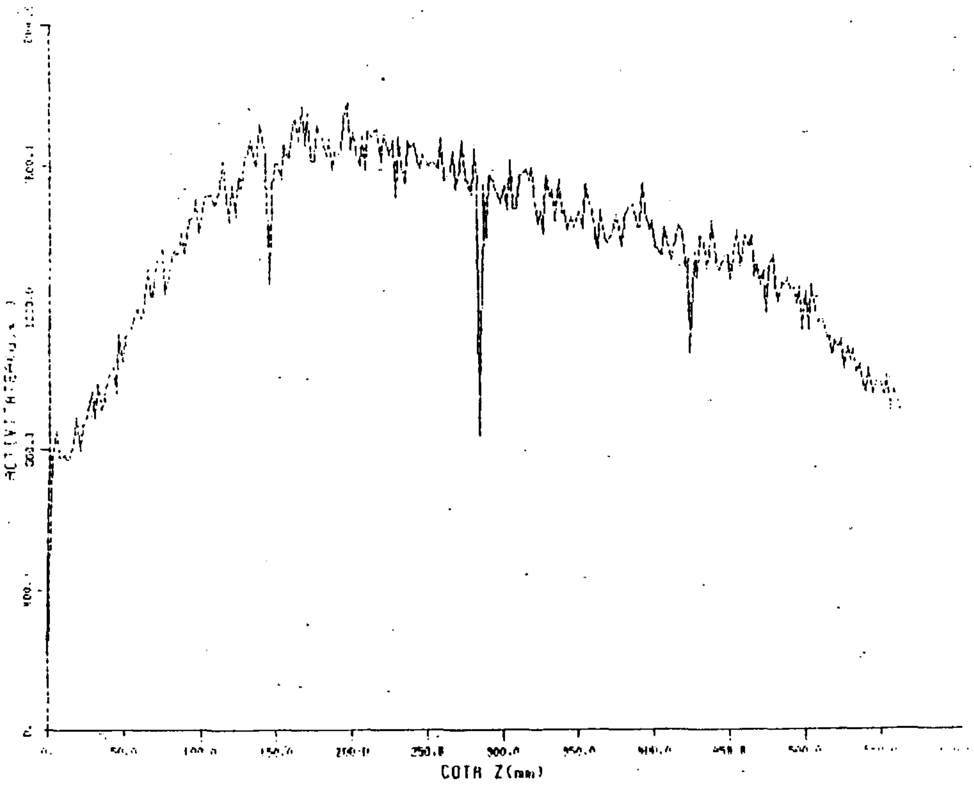


Fig. 6

CROSS SECTION DISTRIBUTIONS

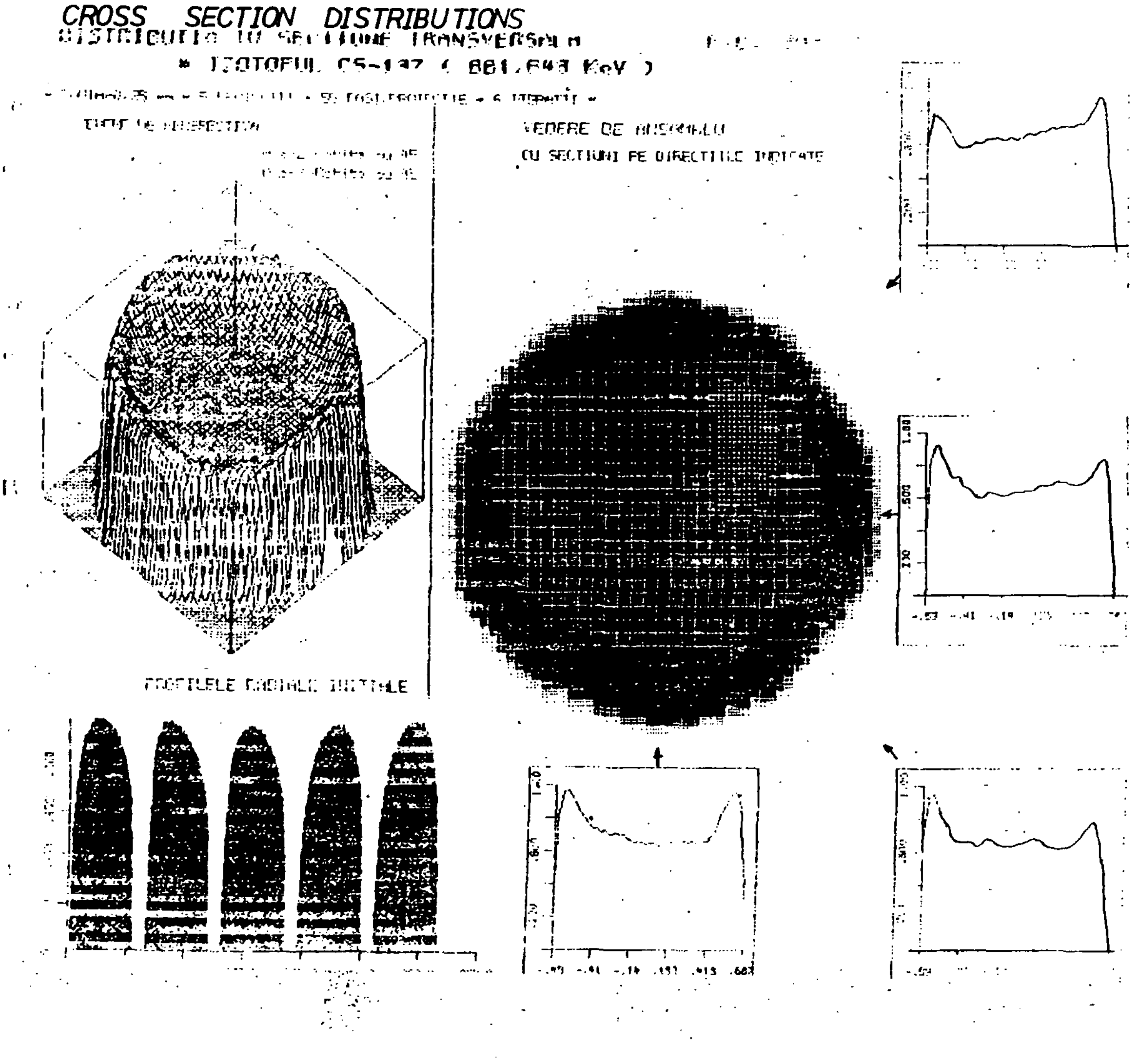
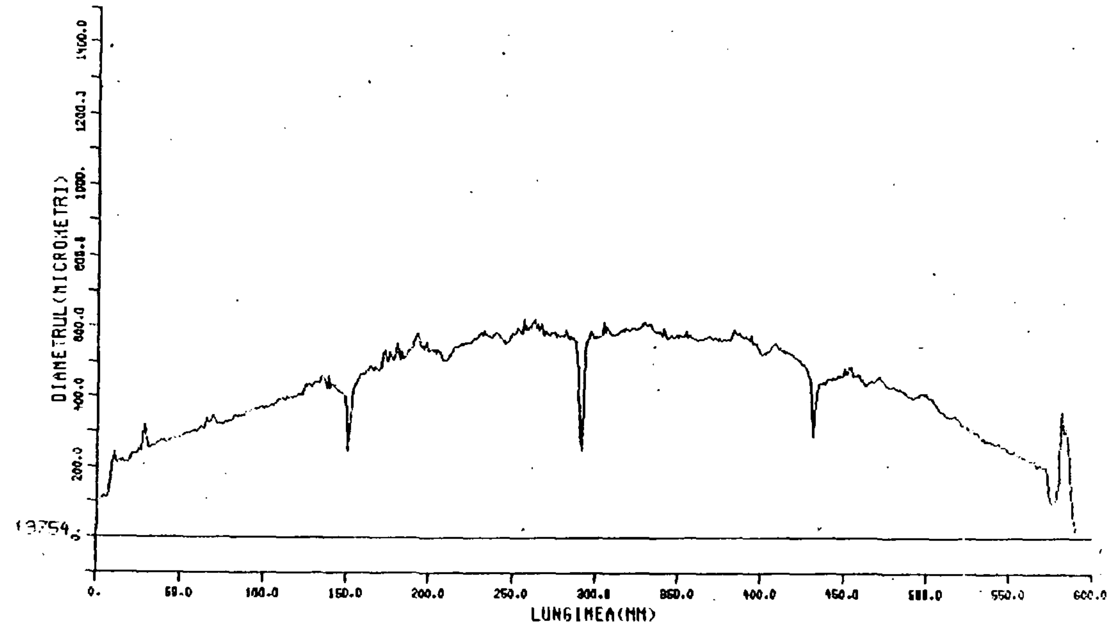


Fig.7

EC TRIGA 583 PROFIL DIAMETRAL LONGITUDINAL * R= 0 (GRADE)

LONGITUDINAL DIAMETRAL PROFIL



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        DUPA IRADIERE                    583IDD1

 DIAMETRUL MEDIU          14192    MICROMETRI
 ABATEREA STANDARD        5.6      MICROMETRI
 DIAMETRUL MAXIM          14377    MICROMETRI* LA COTA 256
 DIAMETRUL MINIM          13775    MICROMETRI* LA COTA 590
   DEFORMATIA DIAMETRALA SPECIFICA MEDIE 3.19
   UMFLAREA SPECIFICA MAXIMA       4.53     PROCENTE  * LA COTA   256
   UMFLAREA SPECIFICA MINIMA       .153     PROCENTE  * LA COTA   590
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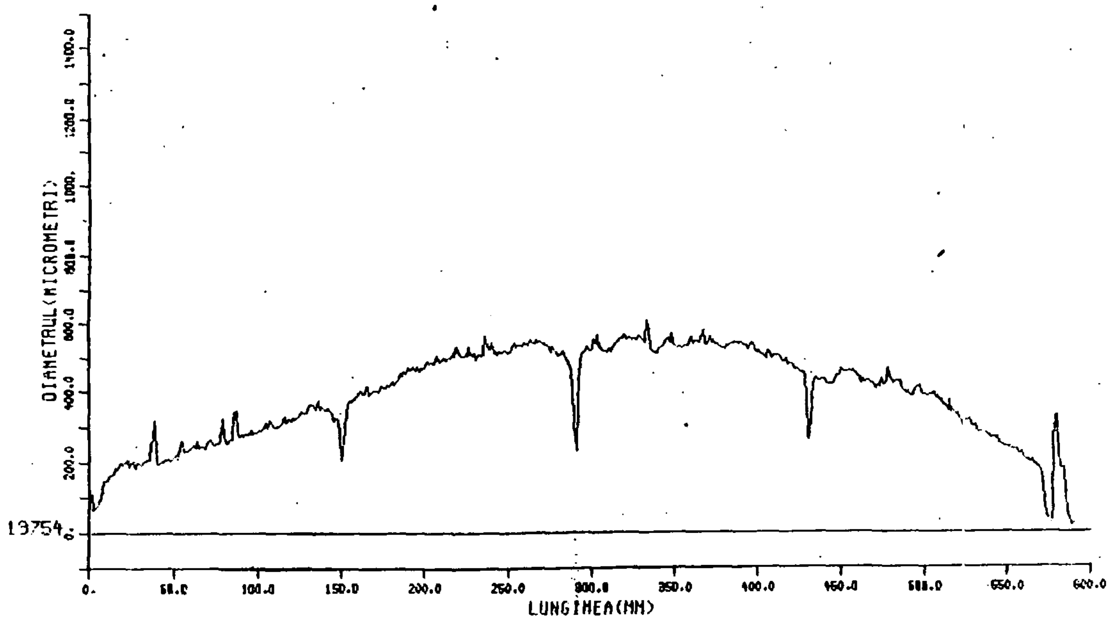
Fig. 8

EC TRIGA 583 PROFIL DIAMETRAL LONGITUDINAL * R= 120 (GRADE)

LONGITUDINAL DIAMETRAL PROFIL



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        DUPA IRADIERE                    583IDD2

 DIAMETRUL MEDIU          14145    MICROMETRI
 ABATEREA STANDARD        5.5      MICROMETRI
 DIAMETRUL MAXIM          14361    MICROMETRI* LA COTA 334
 DIAMETRUL MINIM          13771    MICROMETRI* LA COTA 589
   DEFORMATIA DIAMETRALA SPECIFICA MEDIE 2.84
   UMFLAREA SPECIFICA MAXIMA       4.41     PROCENTE  * LA COTA   334
   UMFLAREA SPECIFICA MINIMA       .129     PROCENTE  * LA COTA   589
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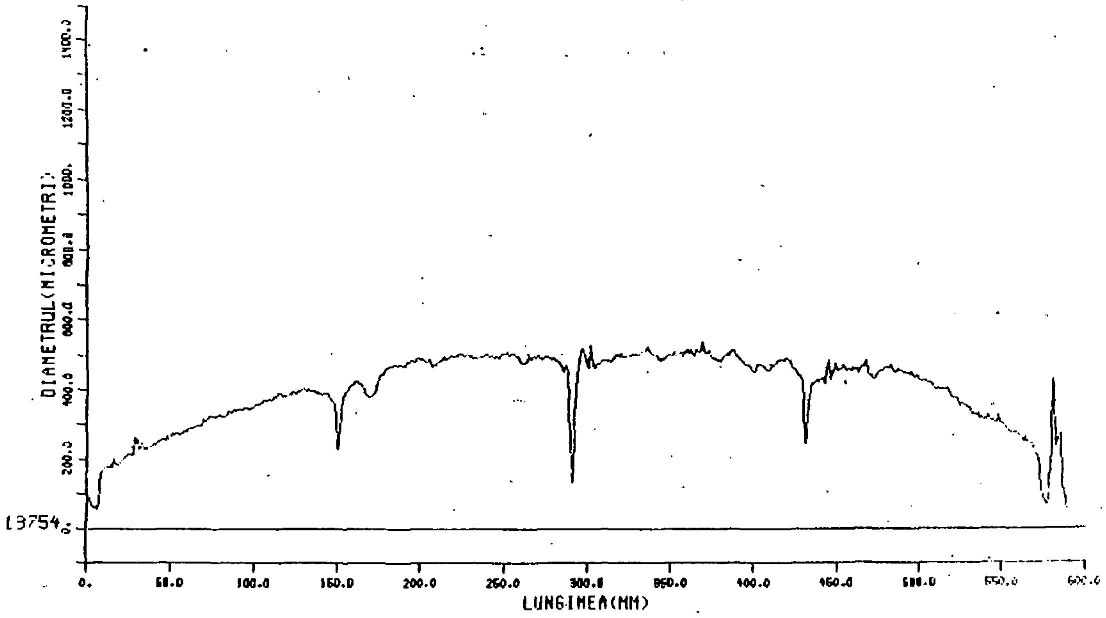
Fig.9

EC TRIGA 583 PROFIL DIAMETRAL LONGITUDINAL * R= 240 (GRADE)
LONGITUDINAL DIAMETRAL PROFIL



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      DUPA IRADIERE             5831DD3

DIAMETRUL MEDIU         14153   MICROMETRI
ABATEREA STANDARD       4.4     MICROMETRI
DIAMETRUL MAXIM         14288   MICROMETRI* LA COTA 369
DIAMETRUL MINIM         13804   MICROMETRI* LA COTA 590
  DEFORMATIA DIAMETRALA SPECIFICA MEDIE 2.90
  UMFLAREA SPECIFICA MAXIMA   .  3.88    PROCENTE  * LA COTA   369
  UMFLAREA SPECIFICA MINIMA      .364    PROCENTE  * LA COTA   590
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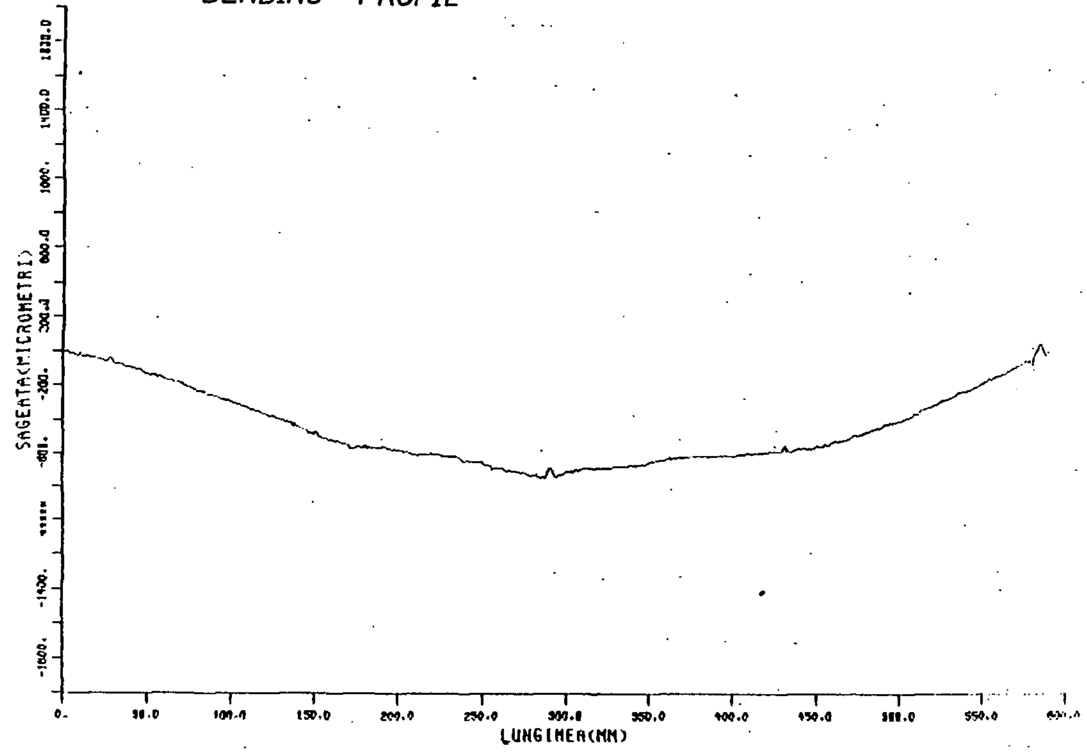
Fig. 10

EC TRIGA 583 PROFILUL INCOVOIERII * R= 0 (grade)
BENDING PROFIL



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      DUPA IRADIERE             5831D11
SAGEATA                 751   MICROMETRI
  * LA COTA             287
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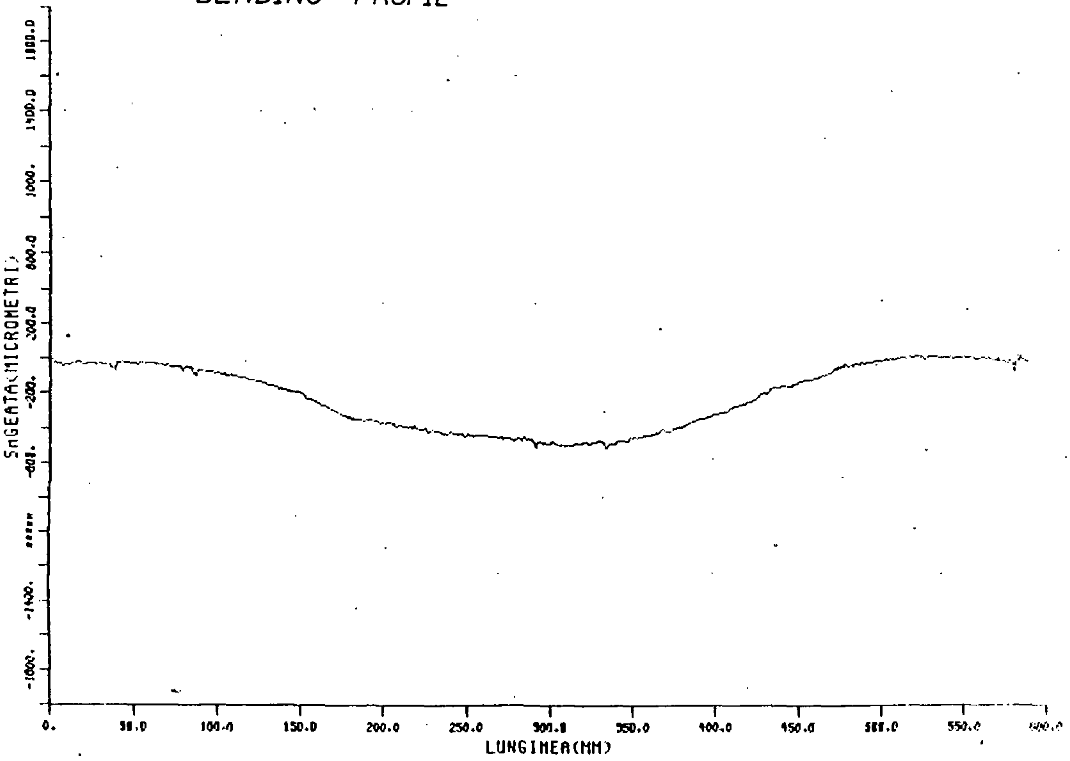
Fig. 11

EC TRIGA 583 PROFILUL INCOVOIERII * R= 120(grade)
BENDING PROFIL

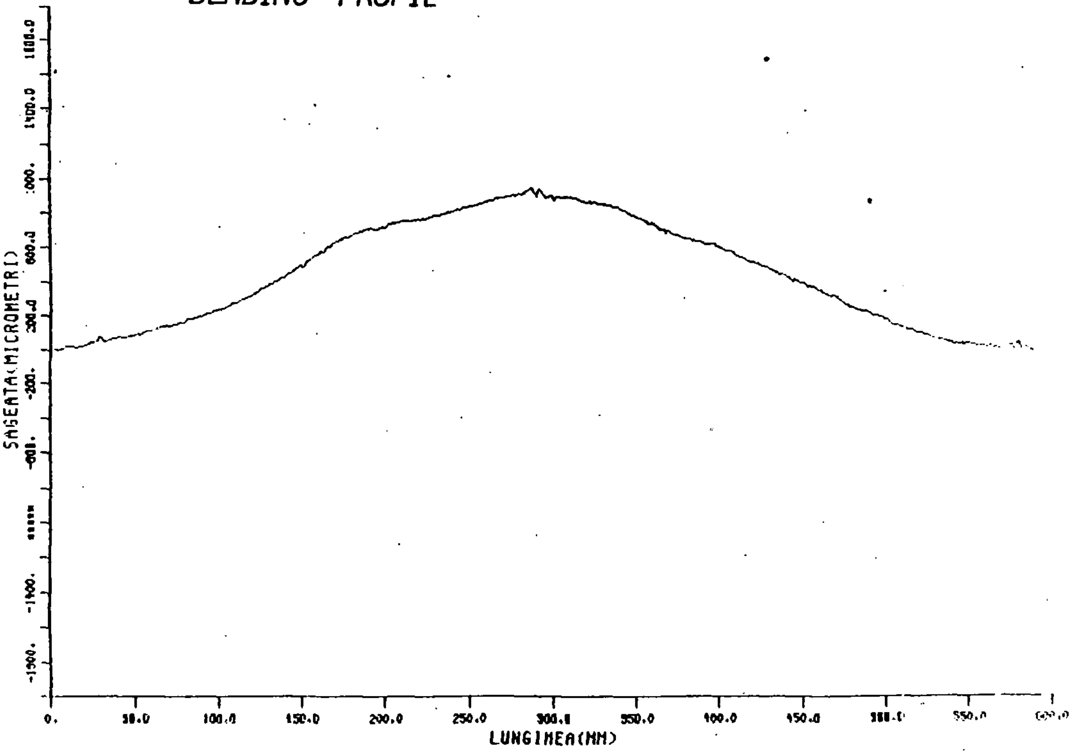


DUPA IRADIERE **5831012**

SAGEATA 504 MICROMETRI
* LA COTA 334

Fig. 12

EC TRIGA 583 PROFILUL INCOVOIERII * R= 240(grade)
BENDING PROFIL



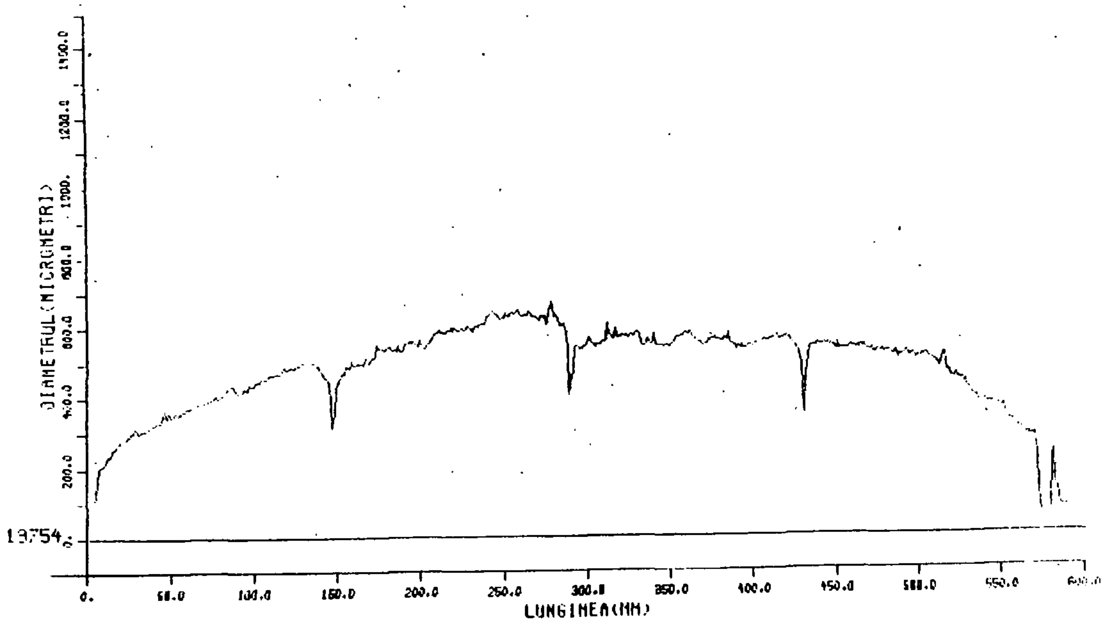
DUPA IRADIERE **5831013**

SAGEATA 957 MICROMETRI
* LA COTA 288

Fig. 13

EC TRIGA 836 PROFIL DIAMETRAL LONGITUDINAL * R= 0 (GRADE)

LONGITUDINAL DIAMETRAL PROFIL



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DUPA IRADIERE                 8361DD1

DIAMETRUL MEDIU         14231   MICROMETRI
ABATEREA STANDARD       5.1     MICROMETRI
DIAMETRUL MAXIM         14425   MICROMETRI* LA COTA 278
DIAMETRUL MINIM         13806   MICROMETRI* LA COTA 576
  DEFORMATIA DIAMETRALA SPECIFICA MEDIE 3.47
  UMFLAREA SPECIFICA MAXIMA      4.88     PROCENTE  * LA COTA   278
  UMFLAREA SPECIFICA MINIMA      .378     PROCENTE  * LA COTA   576
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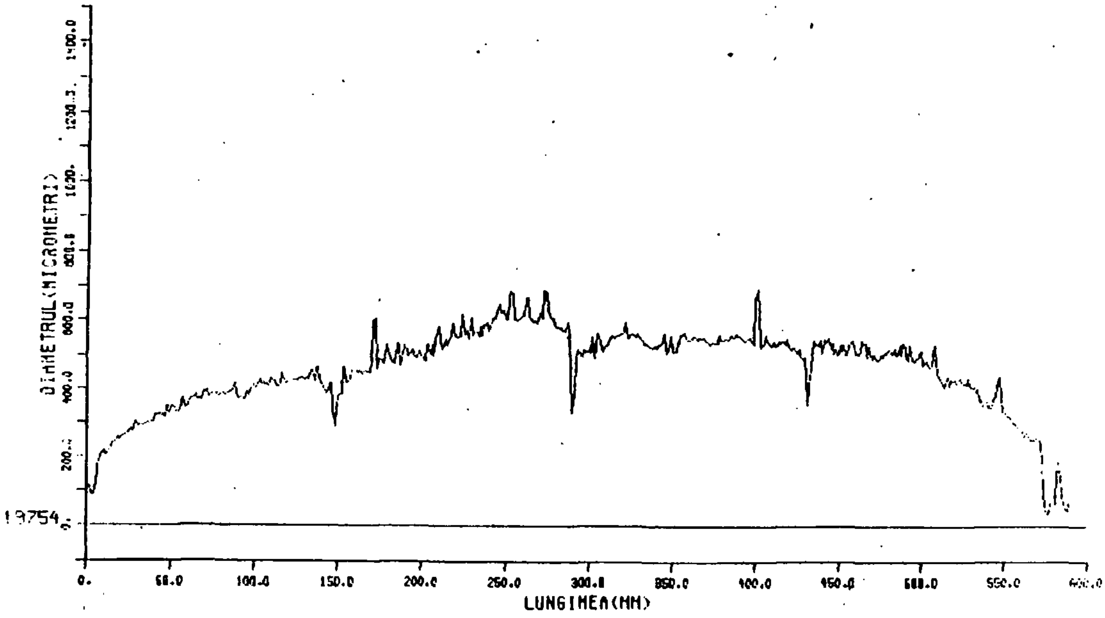
Fig. 14

EC TRIGA 836 PROFIL DIAMETRAL LONGITUDINAL * R= 135 (GRADE)

LONGITUDINAL DIAMETRAL PROFIL



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DUPA IRADIERE                 8361DD2

DIAMETRUL MEDIU         14211   MICROMETRI
ABATEREA STANDARD       5.2     MICROMETRI
DIAMETRUL MAXIM         14449   MICROMETRI* LA COTA 401
DIAMETRUL MINIM         13789   MICROMETRI* LA COTA 576
  DEFORMATIA DIAMETRALA SPECIFICA MEDIE 3.32
  UMFLAREA SPECIFICA MAXIMA      5.05     PROCENTE  * LA COTA   401
  UMFLAREA SPECIFICA MINIMA      .254     PROCENTE  * LA COTA   576
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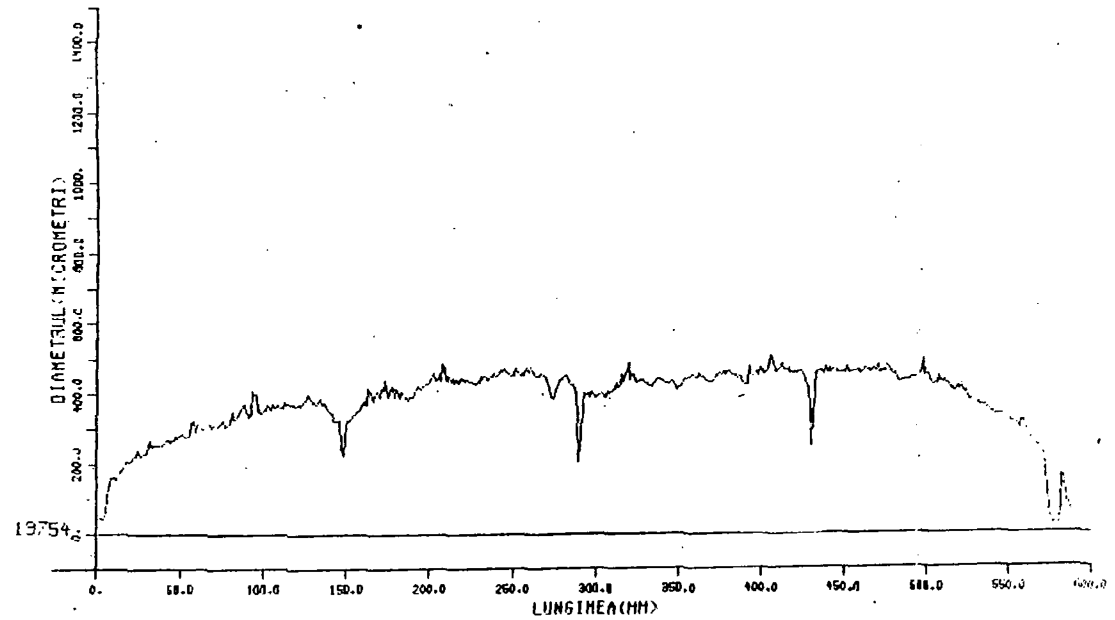
Fig. 15

EC TRIGA 836 PROFIL DIAMETRAL LONGITUDINAL * R= 225 (GRADE)
LONGITUDINAL DIAMETRAL PROFIL



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      DUPA IRADIERE                 8361003

DIAMETRUL MEDIU          14136   MICROMETRI
ABATEREA STANDARD        4.0     MICROMETRI
DIAMETRUL MAXIM          14267   MICROMETRI* LA COTA 406
DIAMETRUL MINIM          13726   MICROMETRI* LA COTA 580
  DEFORMATIA DIAMETRALA SPECIFICA MEDIE 2.78
  UMFLAREA SPECIFICA MAXIMA      3.73    PROCENTE  * LA COTA   406
  UMFLAREA SPECIFICA MINIMA      .100    PROCENTE  * LA COTA   500
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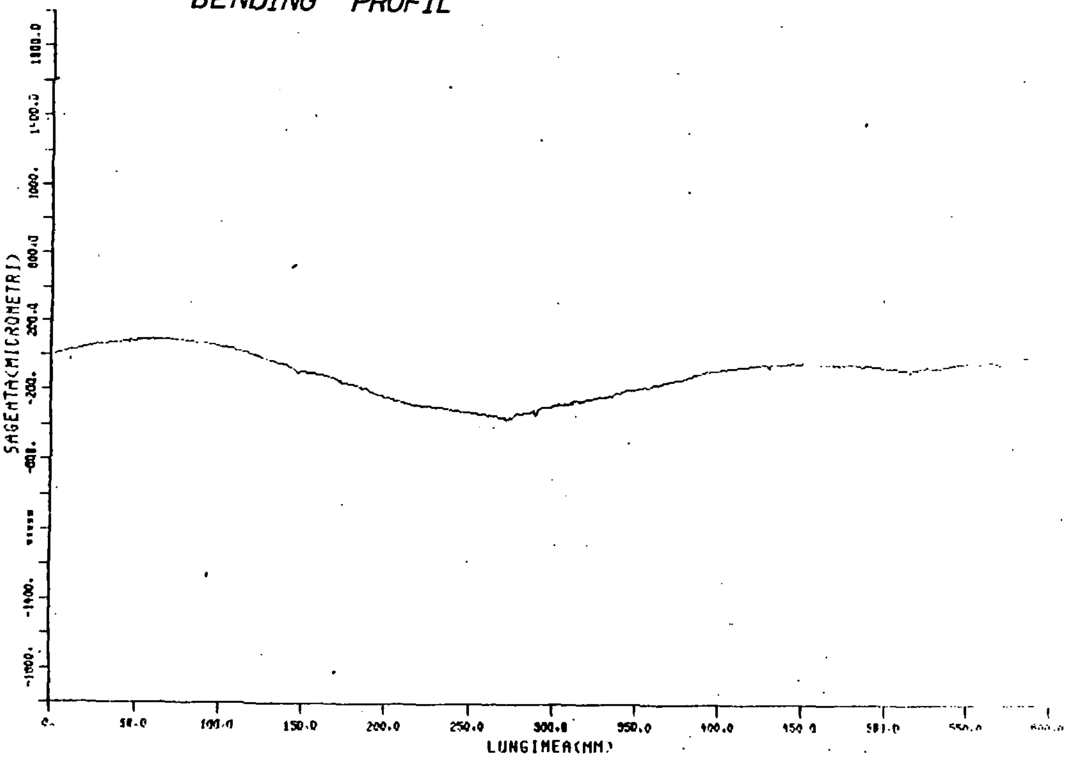
Fig.16

EC TRIGA 836 PROFILUL INCOVOIERII * R= 0 (grade)
BENDING PROFIL



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      DUPA IRADIERE                 8361011
SAGEATA                  302   MICROMETRI
  * LA COTA             272
SAGEATA                   96   MICROMETRI
  * LA COTA              92
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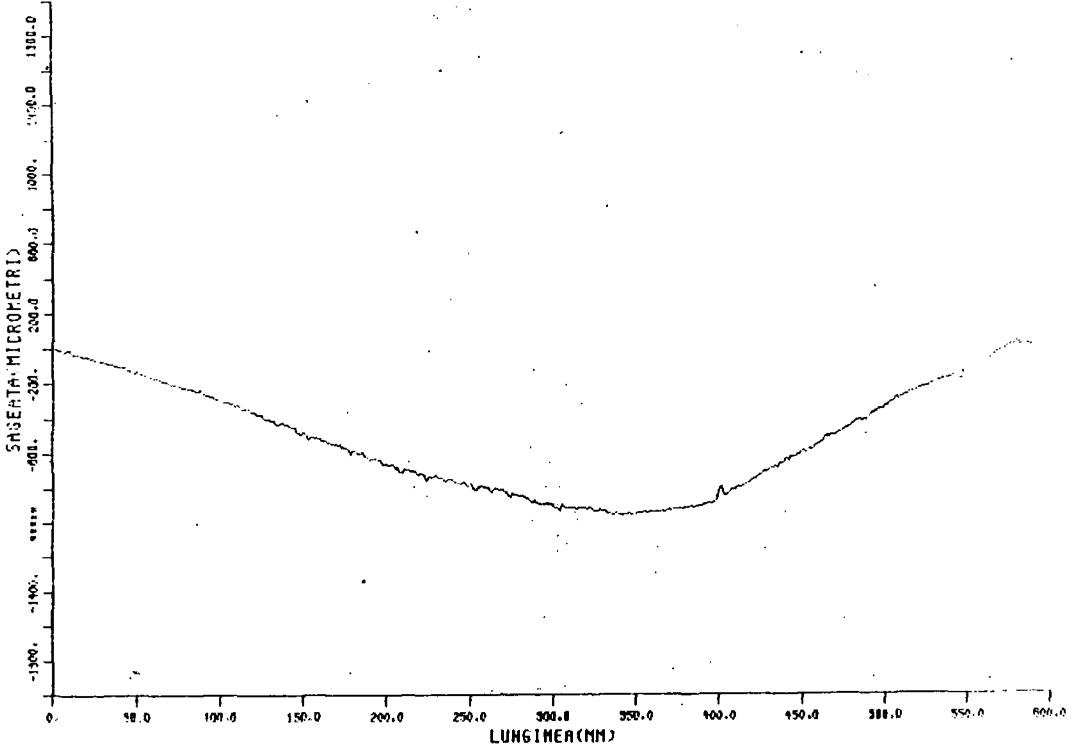
Fig.17

EC TRIGA 836 PROFILUL INCOVOIERII * R= 135(grade)

BENDING PROFIL



DUPA IRADIERE **8361D12**

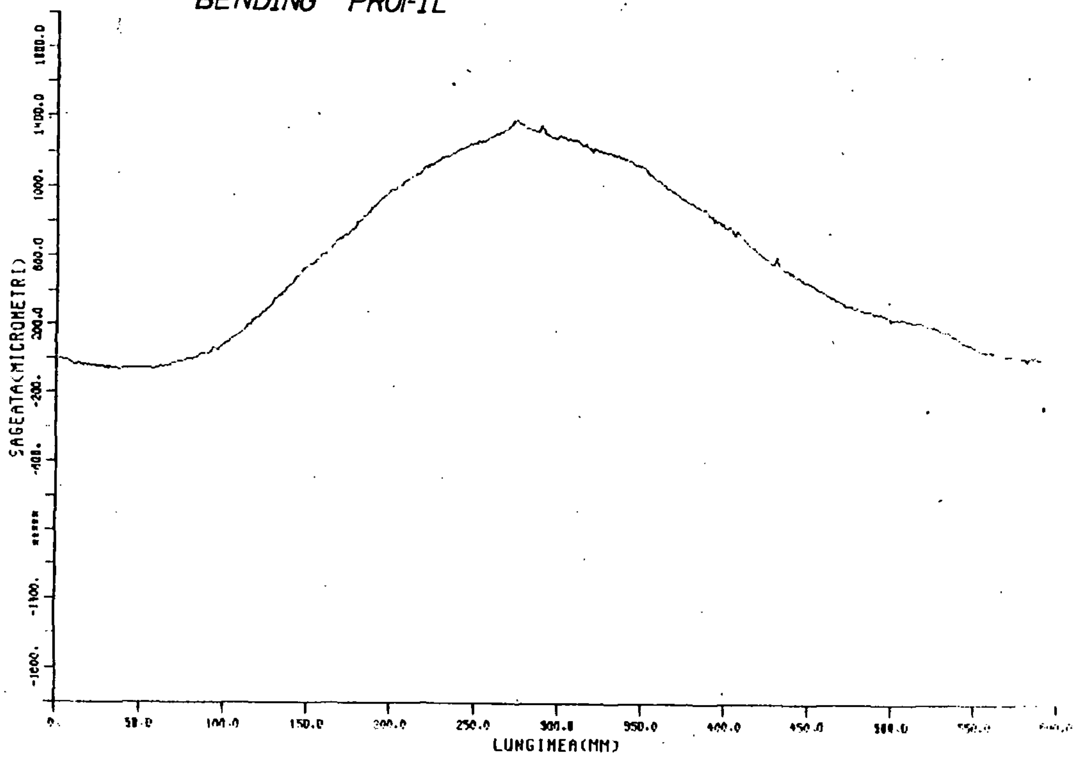
SAGEATA 951 MICROMETRI

* LA COTA 312

Fig. 18

EC TRIGA 836 PROFILUL INCOVOIERII * R= 225(grade)

BENDING PROFIL



DUPA IRADIERE **836ID13**

SAGEATA 1366 MICROMETRI

* LA COTA [illegible]

Fig. 19