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F5 SEPTUM FAILURE ANALYSIS

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AGS DIVISION TECHNICAL NOTE

No. 152

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Many different F5 septum magnets have been designed and some of these have been tested and used in the AGS. This analysis will be confined to those designs using the flattened tube as a flexible electrical and cooling water connecting element.

Stress Analysis

The dimension of this flexible element is shown in Figure 1. The material stress is calculated under several assumed conditions and the result shown in Table I.

Condition 1 -- d.c. operation, septum expands 0.03 in. and is clamped in middle (i.e. both ends move 0.015 in.).

Condition 2 -- d.c. operation, septum expands 0.03 in. but is free so that end spring forces balance.

Condition 3 -- pulsed operation, septum expands 0.02, clamped as in Condition 1.

Condition 4 -- pulsed operation, septum expands 0.02 free as in Condition 2

Table I

	D.C.		Pulsed	
Copper Stress	Condition 1 Clamped	Condition 2 Free	Condition 3 Clamped	Condition 4 Free
Upstream	68.9 Kps*	5.73	45.9	3.82
Downstream	10.6	12.3	7.1	8.2

*Kps = 1000 lbs/sq. in.

The cyclic stress limits for non-ferrous metal have not been established but 6 Kps is believed to be a satisfactory design level. We are above this level in most cases and therefore long life is not to be expected. In this case, long life implies 10^7 to 10^8 cycles. Assuming 100 hours of operation per week, we accumulated 1.3×10^5 pulses per week. Thus fatigue failure should occur in 77 weeks or about 2 years, which has not been the case.

The upstream end under Condition 1 (clamped) could not exist otherwise immediate failure would occur. The septum must slide to release this high stress condition. In the best condition with septum completely free, the largest stress is on the long "downstream" piece where failure has been observed.

Visual Observations

I made a visual inspection of all previously failed F5 septums on March 7, 1979 and found no evidence of stress failure. Instead, I found melted and sprayed and missing solder in two cases. Evidence of evaporated water on soft soldered joints was observed in all cases.

The F5 septum, removed March 8th, also had melted and sprayed solder but in this case it came from an electrical joint and may have indicated electrical failures. A water leak near this joint may exist, but this has not been confirmed due to the high radiation exposure entailed.

I was given permission to autopsy an F5 septum. During this autopsy, I found bright melted solder inside the water passage. From this observation, I can determine that the solder melted after water was removed. Thus we must conclude that the solder melting is occurring after power and water flow are removed. There is also no evidence of electrical arcing at the melted joints.

The only element of the F5 magnet large enough to have the necessary thermal mass to do this "after the fact" melting is the core iron.

This core could have been beam heated. When the water flow is removed, the copper septum will find the mean core temperature, and if this is above the solder melting temperature, a melt will occur.

Magnet Core Beam Heating

To examine this possibility, Alan Stevens was kind enough to examine the run on his beam code and examine the energy reposition in the F5 core. Attached is his report as Appendix A.

From the results of this work it was determined that typical operation deposits about 200 watts in the F5 core. A majority of this energy is deposited in a line along the outer core tip adjacent to the septum copper (region 2, Appendix A, Figure 1).

Calculate Thermal Distribution

In order to make temperature estimates, a simple model approximating of Alan Stevens' results was devised. This model assumed that all the energy was supplied by two line heaters in the outer pole tips (region 2, Appendix A, Figure 1) each delivering 100 watts.

The magnet is cooled by three mechanisms:

1. Radiation.
2. Conduction out to the supports.
3. Conduction to the water cooled passages.

The simplified model ignores radiation loss and thermal conduction to the water cooled septum.

Conduction of the 100 watts from the upper pole tip to the base required a temperature difference of $11^{o}C$. The temperature drop on the stainless steel base is about $1^{o}C$. But conduction along the support to the mounting ends required a temperature drop of $97^{o}C$. Thus the core center can get very hot, $138^{o}C$, while the ends remain cool ,$41^{o}C$, assuming a $30^{o}C$ ambient. Thermocouples mounted on the core ends read $47^{o}C$ with beam on. This is a reasonable performance confirmation of this very simple model.

One hundred thirty-eight degrees centigrade will not melt solder, 170 C is needed but it is close.

A independent check of this thermal model is accomplished by measuring the thermal time constant and computing the mean thermal condution coefficient from the following:

$$K = M/\lambda \qquad \text{and} \qquad \Delta T = P/K$$

where

K = thermal loss coefficient from all causes

λ = measured time constant

P = beam heating from beam code.

Results are:

$\lambda = 2.8$ sec

$P = 202$ watts

$M = (\text{iron only}) = 1.78 \times 10^{4}\ J/^{o}C$

$K = 1.77\ \text{watt}/^{o}C$

$\Delta T = 114^{o}C$ rise $+ 26^{o}C$ ambient $= 140^{o}C$.

In this case the temperature is the mean value not the hottest point.

An improved thermal model would include the energy deposition as indicated in Alan Steven's work, Appendix A, Figure 2.

Making this change increases the average temperature of the F5 core because energy is more densely deposited in regions with the poorest cooling (near the middle). Figure 2 illustrates this computed temperature rise. Using this model and normal AGS operating conditions the same 200 watts of beam heating produces an average core heating temperature of 180°C sufficient to melt solder.

Thermocouple Measurements

Thermocouples were placed on the ends of the F5 iron. This location is unfortunately near the heat sink and the temperature changes are small at this point. Nevertheless, these thermocouples can be used to monitor abnormal beam loss on F5. Temperature above 42.5°C indicate abnormal beam heating and average temperature above solder melting temperature. Operations above this temperature should be avoided.

Distr: Department Admin.
AGS Division S&P
A. Stevens

OLD DESIGN

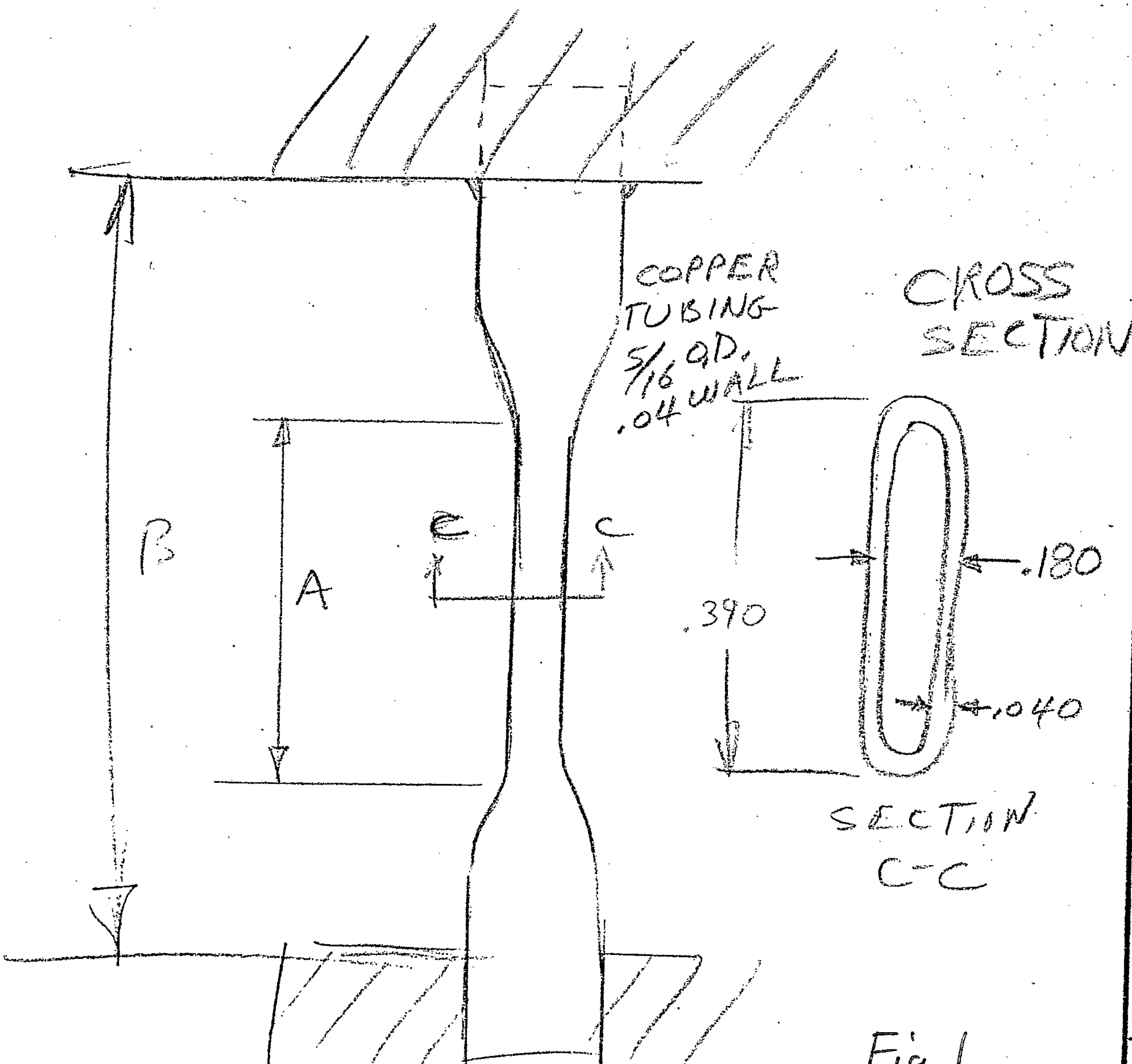


Fig 1

	A	B
UPSTREAM	1"	2"
DOWNSTREAM	3 3/8	4 [illegible]

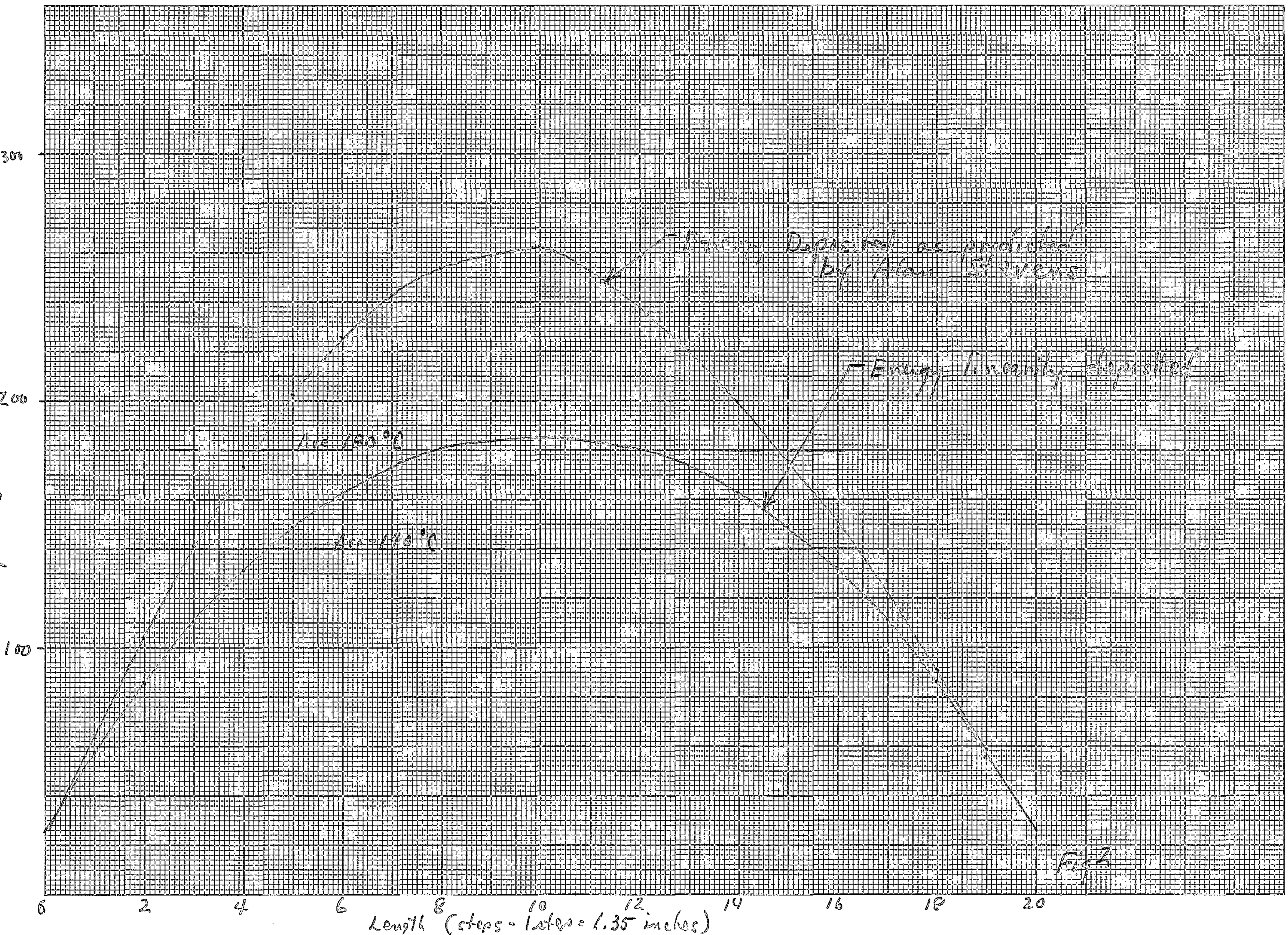

Energy Deposited as predicted by Alan Stevens
Energy linearly deposited
Ave 180°C
Ave 140°C
300
200
100
0
2
4
6
8
10
12
14
16
18
20
Length (steps - 1 step = 1.35 inches)

Fig 2

APPENDIX A

Energy Deposition in F5

Figure 1 shows the approximation of the F5 septum magnet. 30 GeV/c protons are incident on the septum, uniformly distributed over an area .076 cm (septum width = .030 in.) x 1.2 cm. The septum (.076 x 1.8 cm) is copper, with the remainder of the material taken as iron. A magnetic field of B = 2.5 kg is assumed in the gap, but ignored (B = 0) in the yoke, coil region, etc. Previous experience has shown this to be a good approximation. The effects of multiple scattering and diffractive elastic scattering are included everywhere.

Energy densities are calculated in five regions. Region 1 is the septum area intercepting the beam (.076 x 1.2 cm). The remaining regions are .6 x .6 cm areas as shown. Note up-down symmetry is assumed.

The densities in GeV/cm^{3*} per inident proton are shown below as a function of length z (bins in Z = Z = 1.32 cm).

Other relevant numbers are that 78% of the incident energy escapes, and that a total of 2.8 GeV per proton is deposited in septum and iron. (Deposited energy plus escaped energy never equals incident energy because of binding energy subtractions.)

Note that in the mid plane, energy deposition peaks at the end of the magnet.

An extensive map of the energy deposition can be made if required.

*1 GeV = 1.6 x 10^{-10} Joules

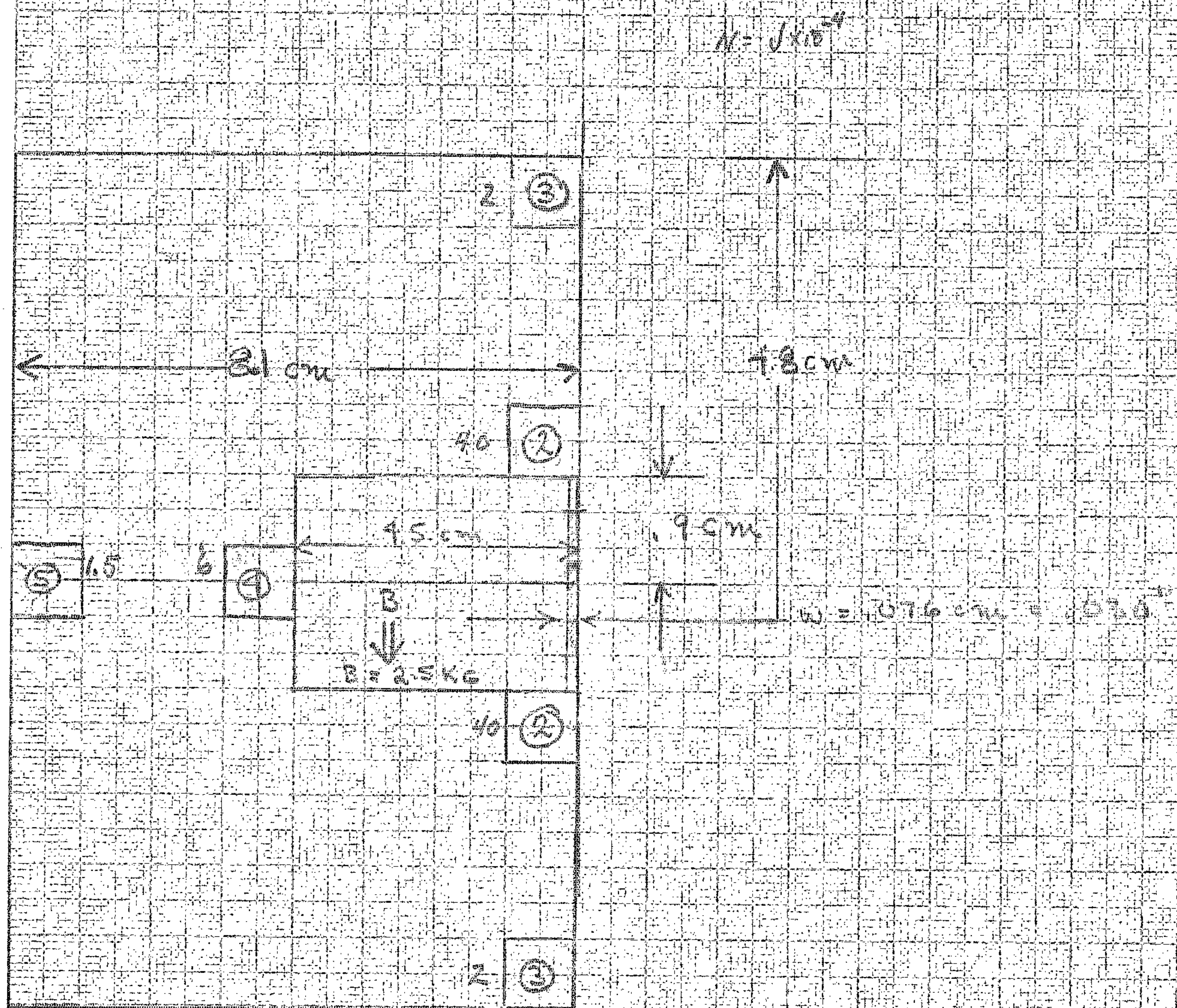


Fig 1
FS Representation
(not to scale)

16

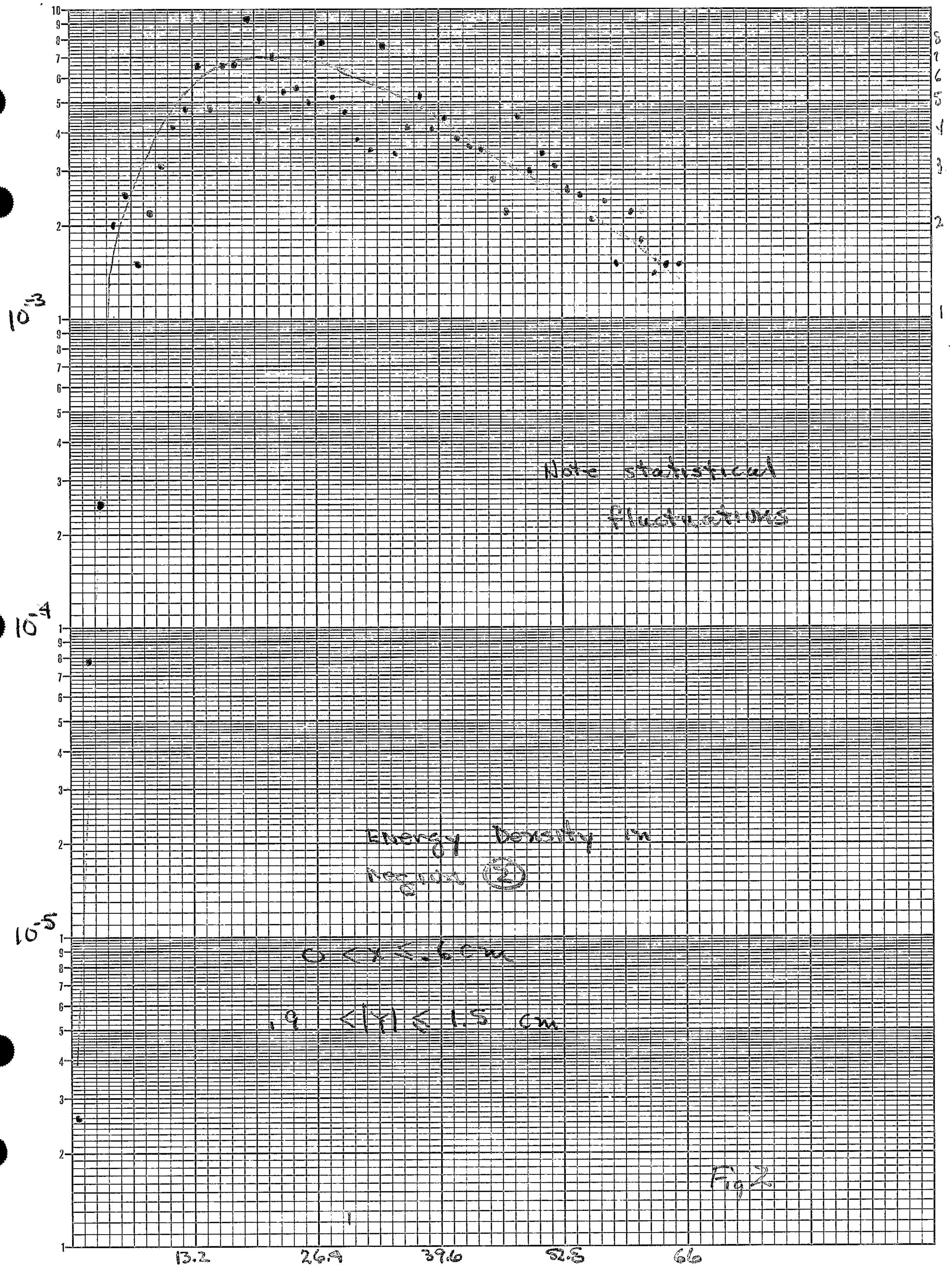
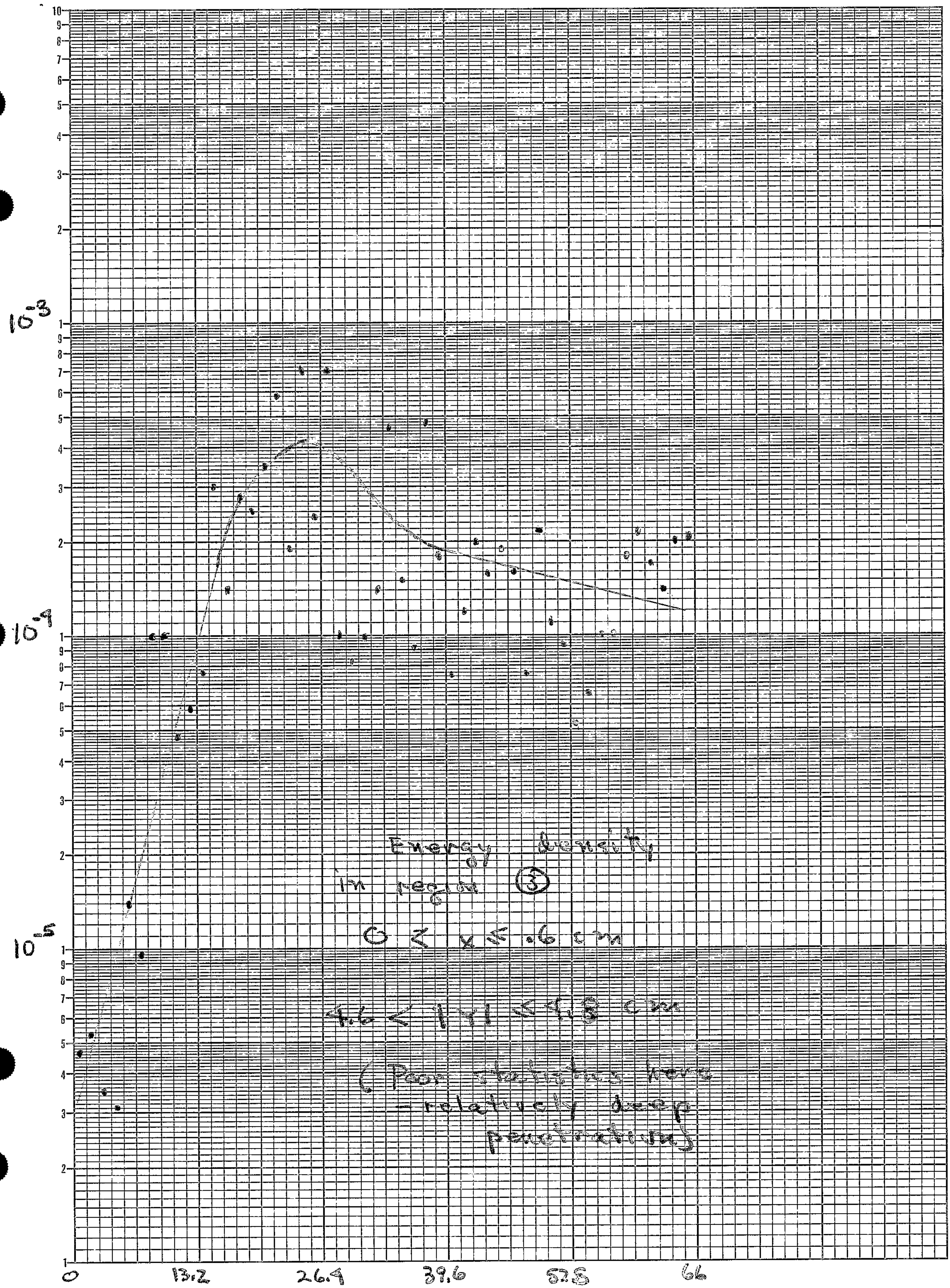
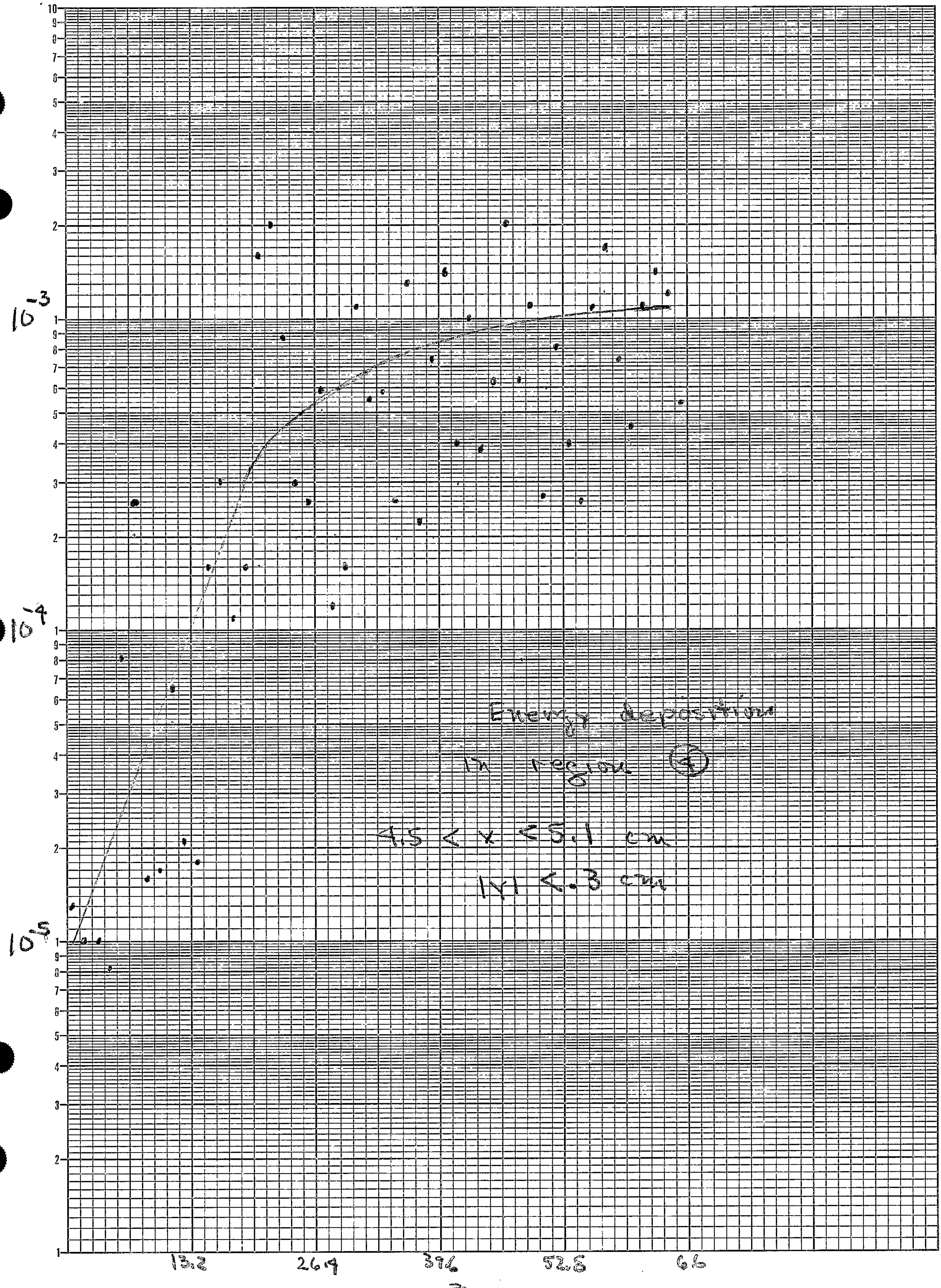

Note statistical fluctuations
Energy Density in Region ②
0 < x ≤ .6 cm
.9 < |Y| ≤ 1.5 cm
10^{-3}
10^{-4}
10^{-5}
13.2
26.4
39.6
52.8
66

Fig 2


10-3
10-4
10-5
Energy density
in region 3
0 < x ≤ .6 cm
4.6 < |y| ≤ 4.8 cm
(Poor statistics here
- relatively deep
penetrations)
0
13.2
26.4
39.6
52.8
66



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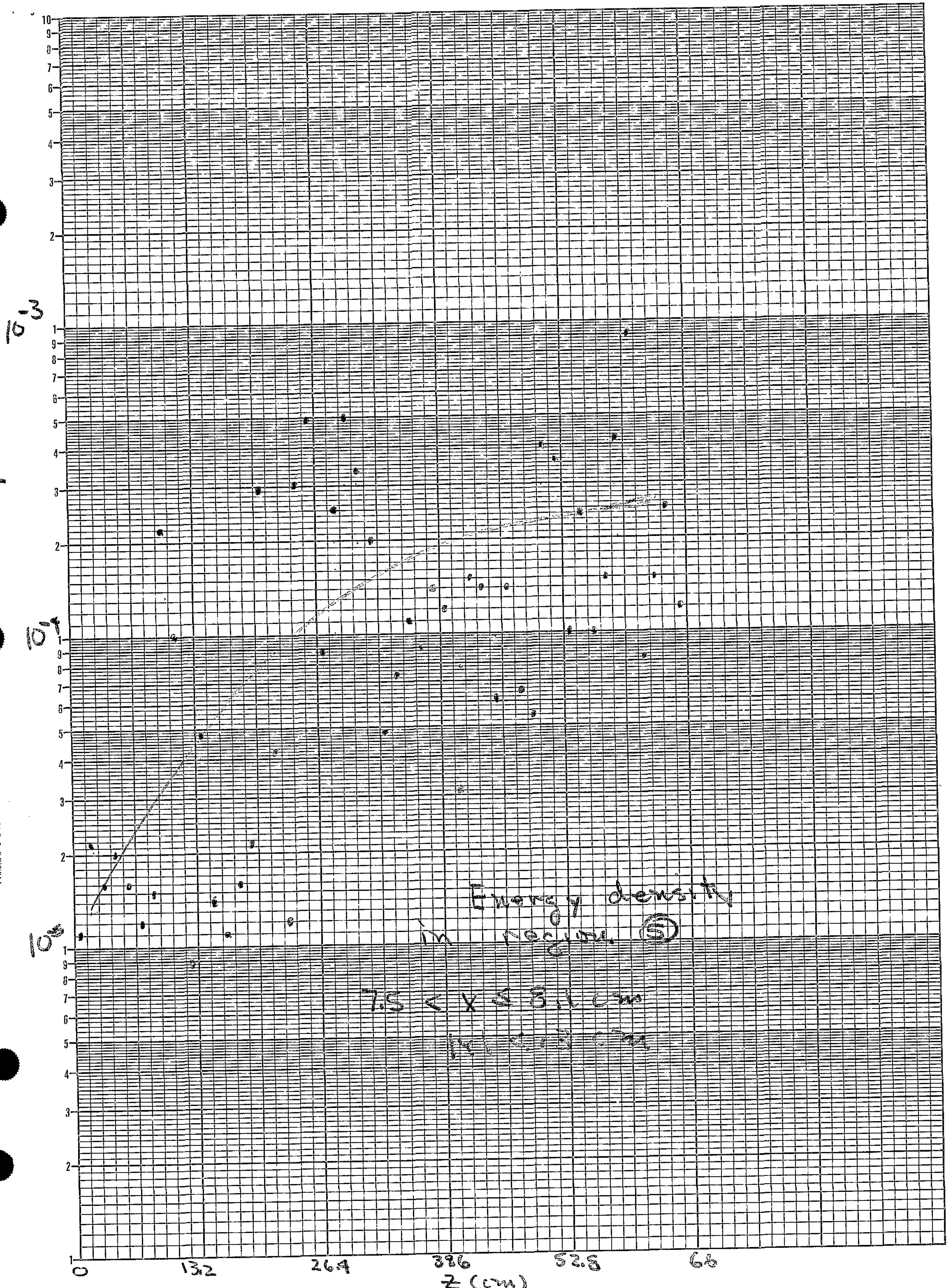
GeV/cm³ p
10⁻³
10⁻⁴
10⁻⁵
Energy density
in region 5
0
13.2
26.4
39.6
52.8
66
z (cm)