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MAXIMUM QUENCH CURRENT OF ENERGY DOUBLER MAGNETS I

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The data on the maximum quench current values for horizontal dewar test at Magnet Test Facility (MTF test) are summarized and compared with those with the vertical dewar test (VD test). In this report, the data from Magnet No. 53 to 208 are reported. More recent data will be summarized in another report. The shape patterns of the ramp rate dependence of the maximum quench current values for MTF are categorized, and their characteristics are related to the kind and quality of superconducting wire and other magnet characteristics. The maximum current data for the MTF and the VD tests are compared, and the correlation between them is shown. The correlation is clearly seen especially when the maximum current values are in a wider range. The correlation between short sample data and the maximum quench current of MTF test is discussed.

1. Introduction

Up to Magnet No. 208, about 130 completed magnets have been tested by early June 1979 at Magnet Test Facility (MTF).[1] Here a completed magnet has its coil installed inside its own horizontal cryostat and iron yoke. The temperature of the single phase helium at MTF test usually varied from 4.7 to 4.8° K, depending on the operation of the liquid helium refrigeration and distribution system.

The temperature of the outside two phase helium was usually lower by about 0.05° K than that of the single phase helium, being higher than the designed value of 4.5° K. The designed operation temperature of the single phase helium for Energy Doubler magnets in the tunnel is 4.5 to 4.6° K. The difference of 0.2° K downward should increase 4 percent in maximum quench current, if it is limited by short sample data.

Some of the coils were tested in a vertical dewar at Lab 5 before insertion into its own horizontal dewar.[2)] This test is called VD test. This is done in pool boiling liquid helium without an iron yoke, and the temperature of the liquid helium is 4.2° K. The data are taken usually after a couple of training quenches, and most of them were taken at the ramp rate of 47 A/sec, which corresponds roughly to 0.38 kG/sec at the center field.

Through this series of magnets, a lot of developments and modifications on coils and conductors were incorporated. From Magnet 14 to Magnet 96, Type 4 collars were used to clamp coils in position, except Magnet 93. Magnet 93 and all magnets after 97 used Type 5 collars.[3)]

Several different kinds of conductor wire were developed and used. Up to Magnet 103, Stay-Brite wire was used except Magnets 64, 68, 76, and 80. Magnets 64 and 76 used Ebonol wire, and Magnets 68 and 80 used Bismuth wire. From Magnets 104 to 112, some newly developed wires were used, including Zebra wire, Zebra wire with a center Kapton sheet, and Ebonol with a center Kapton sheet. Again, Stay-Brite wire was used from Magnet 110 to 125. Magnets 126, 128, and 129 used Zebra wire for inner coils and Stay-Brite wire for outer coils. From Magnet 163 and on, Zebra wire was used.[3)] Zebra wire is made of 12 Ebonol strands and 11 Stay-Brite strands.

During the initial operation of the Magnet Test Facility, some magnets were not cooled efficiently, because there was no subcooler in operation. Although the maximum quench current values for Magnets 53 to 63 seems reliable, their ramp rate dependence is greatly affected by the insufficient cooling, as described later.

2. Maximum Quench Current Data in MTF and Short Sample Test Data

The maximum quench current data in the MTF test of the completed magnets are shown in Figs. 1a, 1b, and 1c. The transfer function is about 9.98 G/A, thus 4.5 kA corresponds to about 4.5 kG. They are shown in the order of the serial number of the magnets. They are almost in the chronological order of production of coils, but there are many short-term permutation between their serial number and chronological production order.

In Fig. 1, also the short sample data for magnets are shown with square markers. These data for 23 strand cable are taken at 5 Tesla at 4.2 K.[4) There are usually four short sample data for each magnet, corresponding to inner and outer coils and up and down coils. The data used here correspond to the lower value for the two inner coils.

Two different types of maximum quench current for MTF test are shown in Fig. 1. The points shown with circles corresponds to the extrapolated maximum current at $\dot{B}$ = 0 kG/sec, and the point with triangles are data at about 2 kG/sec, corresponding to 200 A/sec. Some of the magnets were measured at such rates, and their observed data are marked with dots at the centers of the marks. The data which were extrapolated are shown with crosses at the centers. The extrapolation was done by eyes, taking into account of data of other similar magnets, which were more thoroughly measured, thus avoiding computer's bias.

We can see the effect of insufficient cooling at the beginning of test series up to Magnet 65. The Test Facility was still in tuning mode, and we observe large ramp-rate dependence. But the maximum quench current values seems reasonable during that period.

The average value of short sample data from Magnets 127 to 160 is low and is about 5.2 kA, which are all inner Ebonol magnets. While the remaining magnets have the average short sample data around 5.55 kA, their difference is about 0.35 kA. The magnets from 127 to 160 seem to have the average maximum current at about 4.3 kA, with three magnets below 4.0 kA. The remaining magnets, except ones 200 and up, seem to have the average maximum current at about 4.45 kA. The difference between the group are 0.15 kA, corresponding to 1.5 kG, which is about half the amount we can expect from the difference in short sample data. This may be caused by a limiting boundary line at 4.6 kG, explained in Section 5. The average maximum current from Magnet 200 to 208 went down to 4.3 kA.

3. Ramp Rate Dependence of Maximum Quench Current in MTF Test

The ramp rate dependence of maximum quench current in MTF test showed several different characteristic shapes. They can be grouped into six major categories and summarized in Table I. The magnets up to 206 are categorized into these groups with respect to their type of conductors and listed in Table II. Their typical data are shown in Figs. 2 to 7. The first three types are commonly observed normal types for Energy Doubler magnets, and the remaining three modes are more or less defective modes. Quench points are shown with stars, and the double triangle marks indicate the short sample limit of the current at 4.2 K. Asterisks are used to show the short sample limit at 4.7 K.

The Type D is observed when there is unsufficient cooling, which happened during early testing period with Magnets 53 to 65. The increase in ac loss in conductor with fast ramp rate drastically reduce the maximum quench current.

Recently a magnet was cooled down and tested with opposite flow of liquid helium, which means the single phase helium in the two phase space, and the result was similar to this D-Type dependence.

The Type E is observed only occasionally with magnets with Ebonol conductor. There seems some defect at the joints between Ebonol conductors, and some strands may have higher resistance at the joints than others. At slow ramp rate, current can be shared between all strands, but when the ramp rate goes up, some strands will not carry current due to resistivity at joints. The flat current at fast ramp rate may be determined by the total number of the available and good strands.

The Type F is observed when there is fairly big defect at the joints between cables and at the joints at power leads. The resistive part generates enough heat to start a lower quench value when excited slowly, while at fast ramp rate the total Joule loss at the joints may not be enough, and thus quenching at higher constant current value.

The Droop Type C is the most normal pattern with Stay-Brite magnets. The maximum quench current decreases by about 1.5 to 3.0 kG when the ramp rate is increased from 0 to 2 kG/A. The more the Stay-Brite conductor is compacted, the more the coupling between strands and the more ac loss, thus increasing the ramp-rate dependence.

The magnets with all Ebonol conductor and ones with inner Ebonol coils have much less coupling between strands. Therefore, these magnets show much less ramp rate dependence, and most of them are in the Flat Type Group A, as shown in Table II. Some magnets show excellent characteristics, but some exhibit unstable conditions. The control of Ebonol thickness may not be easy. When Ebonol coating is too thick, we cannot except current sharing between strands with Ebonol conductor. Consequently, the magnet looses normal stability.

The Zebra conductor is a hybrid between Stay-Brite conductor and Ebonol conductor. Thus, the ac loss and the ramp-rate dependence of a Zebra magnet is somewhere in between the magnets of these two other type conductors. Therefore, we see Types A, B, and C ramp rate dependence for Zebra magnets. There is some freedom for current sharing among Zebra strands.

4. Correlation in Maximum Quench Current Data between VD Test and MTF Test

The correlation between the data of the vertical dewar test and those of the MTF test for same magnets are shown in Fig. 8 and 9, where data points of a magnet are taken as abscissa and ordinate, and the number of the magnet is shown. In Fig. 8, where all Stay-Brite magnets are shown, we cannot see a good correlation between them, but most of them are within 5 percent. It may be partly due to early testing when test procedure at MTF was not established. Be we can see a clear linear correlation between data in Fig. 9, which covers a wider range of data points for Ebonol and Zebra magnets up to Magnet 200.

The maximum field value in a magnet is given by $B^c_{max} = 8.08 \times 1.164 \times I$ for VD test, and $B^c_{max} = 9.98 \times 1.10 \times I$ for MTF test. The same B^c_{max} values for both tests are shown with the B^c_{max} = 100 percent line, and a line with 95 percent for VD test relative to MTF test is also shown. The maximum field values are also indicated. Most of the data are shown to be within a few percent from 100 percent line. The 100 percent line is where the maximum field points in the coil for both cases are same and does not mean for a same B x I line.

Magnets 142 and 158 have rather low quench data for both methods. Their short sample data value for Magnet 142 is low, but one for the other is not low. Therefore, by some reasons, the magnet cannot be excited to full extent, and the reason is the same for both test methods. Magnet 141 has current sharing problems, as discussed before, and was very unstable. That is why this magnet is not on the linear correlation line.

5. Correlation between Short Sample Data and Maximum Quench Current Data of MTF Test

The correlation between the maximum quench current at $\dot{B} = 0$ in MTF test and short sample data are shown in Fig. 10 and 11. In these figures, the short sample current data at 5 Tesla at 4.2 K are taken as abscissa, and the maximum quench current data as ordinates. The 100 percent line corresponds to the expected maximum current of a magnet with that short sample current value at the operating temperature of 4.75 K. The temperature of the single phase helium in the MTF test usually varied from 4.7 to 4.8 K, depending on the operation of the liquid helium refrigeration system. For the calculation of percentage lines, the highest field point at the edge of the inner coil is assumed 1.10 times the central field. The transfer function ratio of field to current is assumed at 9.98 Gauss/Amp. Also the factor of 20 percent decrease/degree in the maximum current is used.

Most of the data points lie between 95 percent line and 105 percent line. The upper boundary limit seems bounded clearly by two straight lines, the one with the 105 percent short sample data and the other horizontal line at 4.6 kA, corresponding to 46 kG. The upper limit at 46 kG may suggest that this series of magnets are quenching due to mechanical deformation of the coil encased in the collar, by magnetic force at 46 kG of the central field. But this field value is well above the designed central field value of 44 kG. According to scissometer test, the inner and outer quadrant coil have shown the compression of about 2.5 mils at the current value of 4.5 kA with VD test.[5)] And the compression value can be expressed in quadrature in the current value.

This may suggest, below 5.2 kA of short sample data, the maximum attainable current is limited by short sample data of the wire, and above it, it is limited by mechanical structure.

A general correlation between short sample data and the maximum quench current in VD test is reported early up to Magnet 159.[6)] A correlation between the poor vertical dewar performance and poor short sample current is observed.

6. Conclusions

A. Correlation between Short Sample Data and MTF Maximum Current

A general linear relation can be seen as shown in Fig. 10 and 11. Most of data are within ±5 percent region from the 100 percent line.

This spread is caused by many other factors affecting maximum quench values. One tenth degree variation in operation temperature causes 2 percent variation. The short sample test data itself may be accurate within 2 percent, but there could be several percent variation within one reel of conductor, which is represented by one short sample datum at one end point. The condition of a warm bore, which is inserted inside the cold bore, affects a few percent downward as shown with Magnet 174 in Fig. 11, when the vacuum inside the warm bore is not good enough. As other reasons of causing quenches, we can think of, mechanical movement including conductor movement inside a collar, collar deformation, and coil movement relative to the core.

B. Upper Limit Boundary of the Above Correlation

The maximum attainable value is limted by short sample data values up to 5.2 kA of short sample data at 5 Tesla. Above that value, the ultimatum value seems limited by the mechanical strength of the collar at 4.6 kA. If this is the case, this type of magnet cannot be excited to substantially higher field by cooling down to 1.8° K. Another possible cause for this limit might be due to the power supply.

C. Short Sample Data

Although there are many other factors affecting the maximum quench values, it is essential to have higher short sample data, at least 5.2 kA at 5 Tesla.

D. The Correlation between MTF Maximum Current and VD Maximum Current

A linear correlation between them can be seen clearly in Fig. 9, where a wider range (15 percent) of magnets are represented. Where many magnets are clustered in a 5 percent range as shown in Fig. 8, the correlation is obscured by the various contributing parameters as described. Also in Fig. 8, there are many early data points which were not measured under established conditions.

E. Ramp Rate Dependence

There are three major patterns for ramp rate dependence of the maximum quench current. The flat type, the flat and bend type, and the droop type. The flat type occurs when there is not much ac loss in the Ebonol conductor, but it may be showing the maximum value is limited by mechanical problem regardless of ramp rate. The droop type is typical for a Stay-Brite magnet, where ac loss may be causing the ramp rate dependence. The intermediate flat and bend type are typical for Zebra magnets.

References

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2. W. B. Fowler et. al., IEEE Trans. Magn., MAG-13, No. 1 (January 1977).

3. W. B. Hanson, Internal Energy Doubler Magnet Weekly Report, April 23, 1979.

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   R. Yamada and M. E. Price, Fermilab Internal Report TM-676 (1976).

5. A. V. Tollestrup et. al., IEEE Trans. Nucl. Sci., NS-24, No. 3 (June 1977).

6. R. H. Flora, Fermilab Internal Report TM-844 (1979).

Table I

Six Different Patterns of Ramp Rate

Dependence of Quench Current

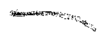
	Shape	Comments
A. Flat type		
B. Flat and bend type		
C. Droop type		
D. Steep droop type		Insufficient cooling
E. Steep and flat type		Current sharing between strands
F. Reverse droop and flat type		Resistive joints, resistive power leads

Table II

Population Distribution of Magnets with Different Type

of Conductors into Six Different Ramp Rate Dependence

Conductor-Type	Ramp-Rate, -Type					
	A	B	C	D	E	F
Stay-Brite (53 ∿ 125)	1		34	4		
Inner Ebonol (126 ∿ 159)	16	1	1		3	
All Ebonol (64, 74, 161, 162)	3		1			
Zebra (104, 105, 163 ∿ 174, 200 ∿ 206)	4	6	5			

Fig. 1a Magnet No. vs. S.S. Data & MTF Test Max. Current

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6/5/79

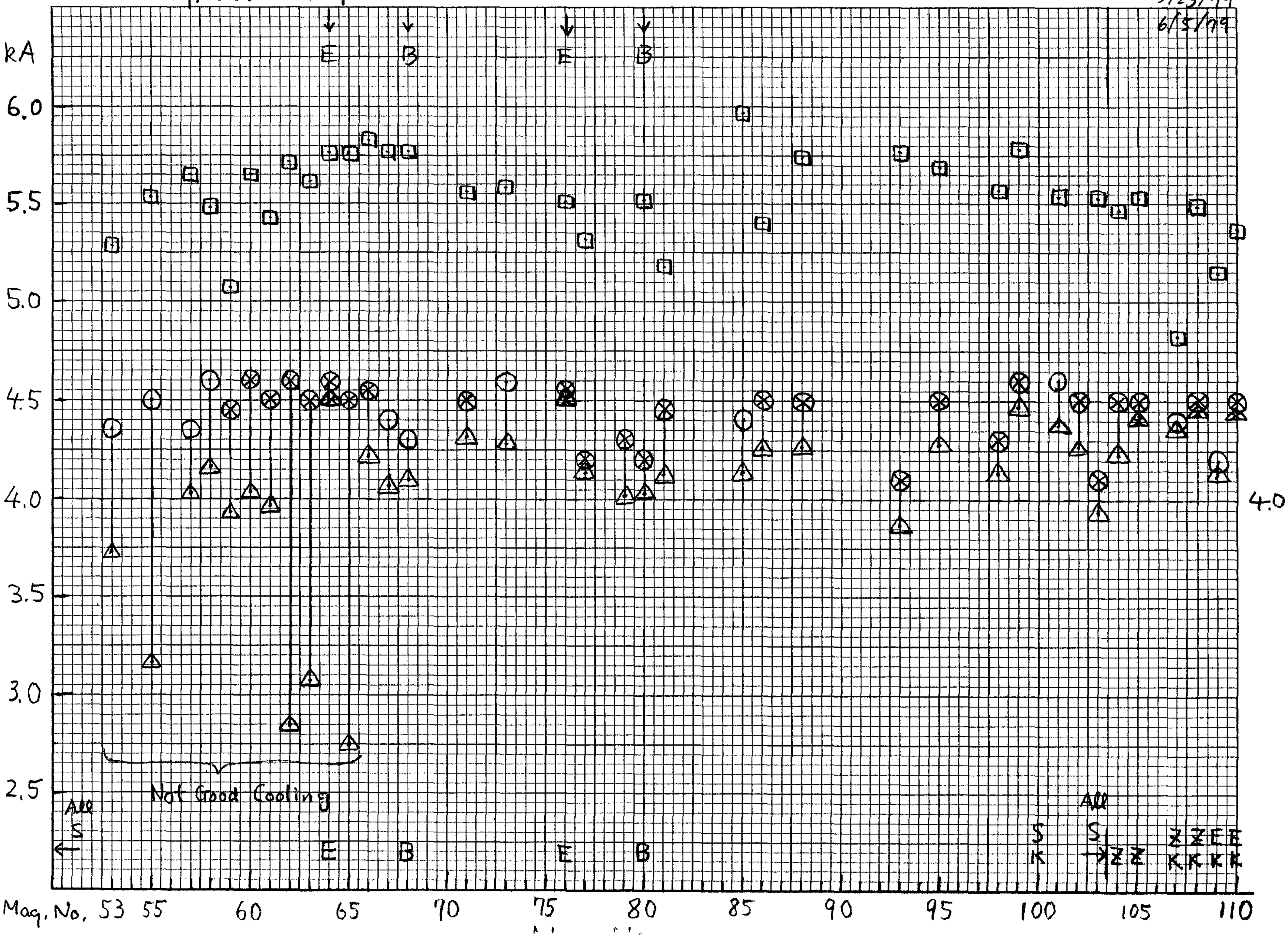


Fig. 1-6 Magnet No. vs. S.S. Data of MTF Test Max Current

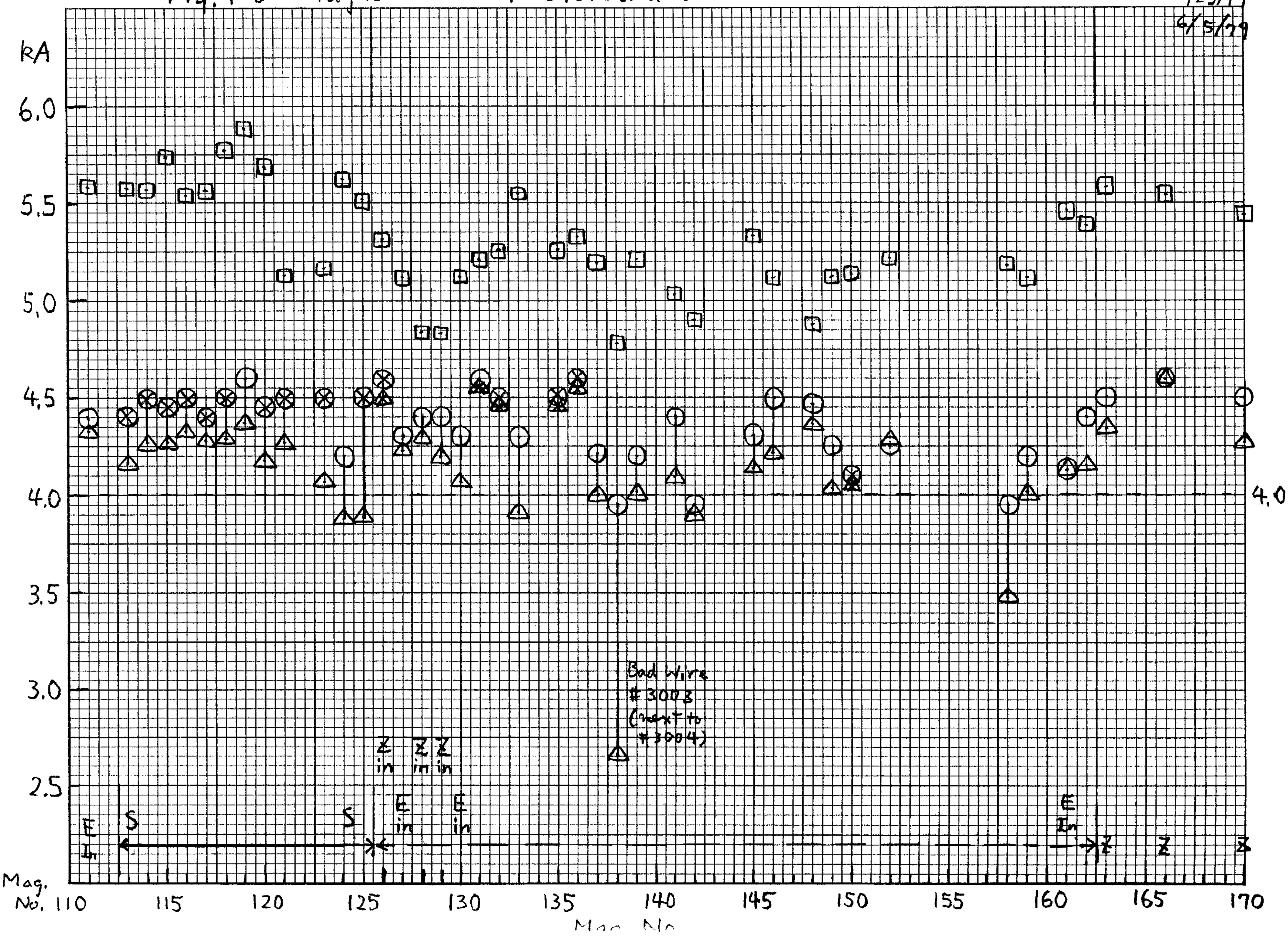


Fig. 1C Magnet No. Vs S.S. Data & MTF Test Max. Current, 5/23/79 6/5/79

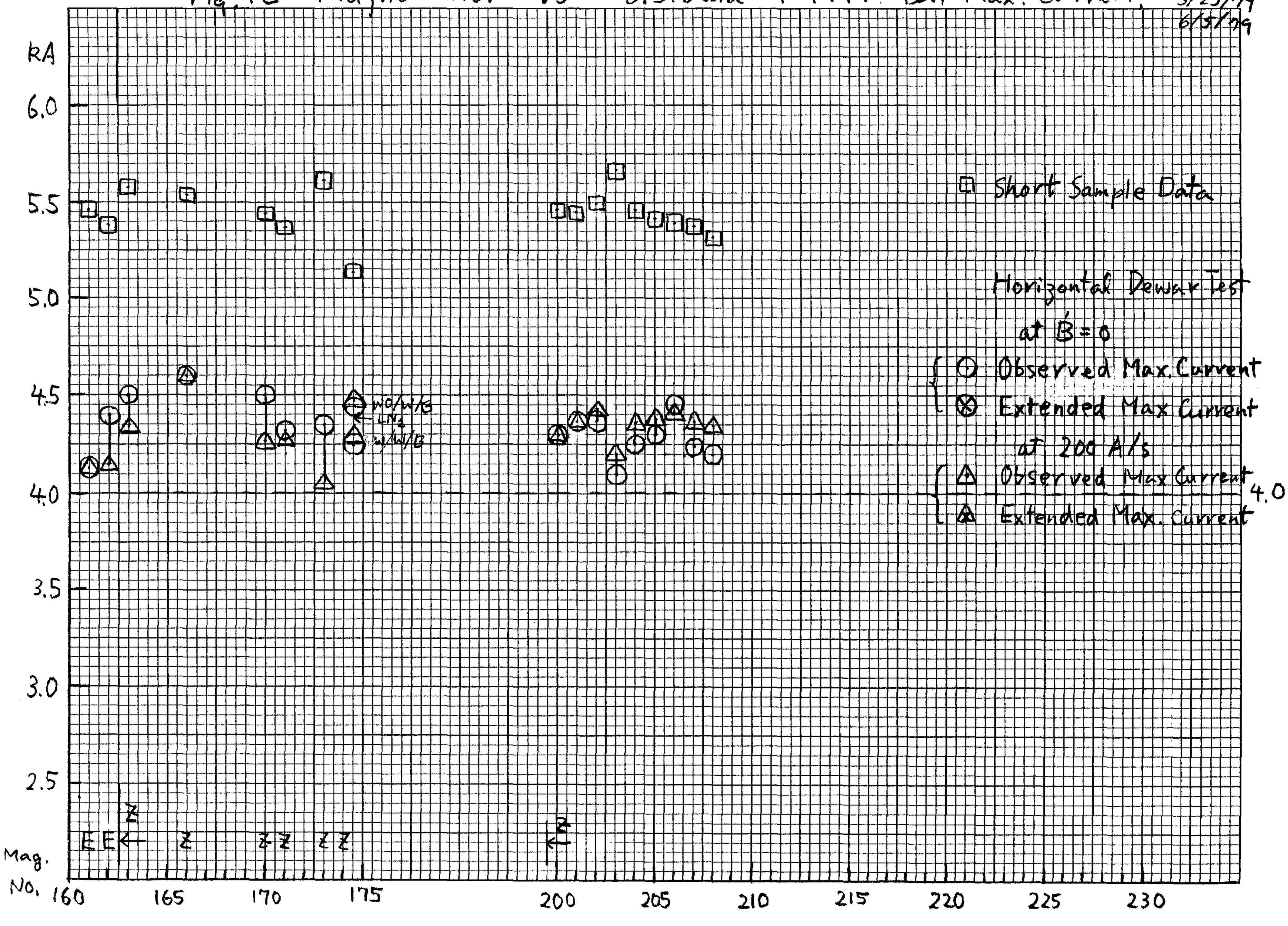


Fig. 2 Flat type Ramp-rate Dependence

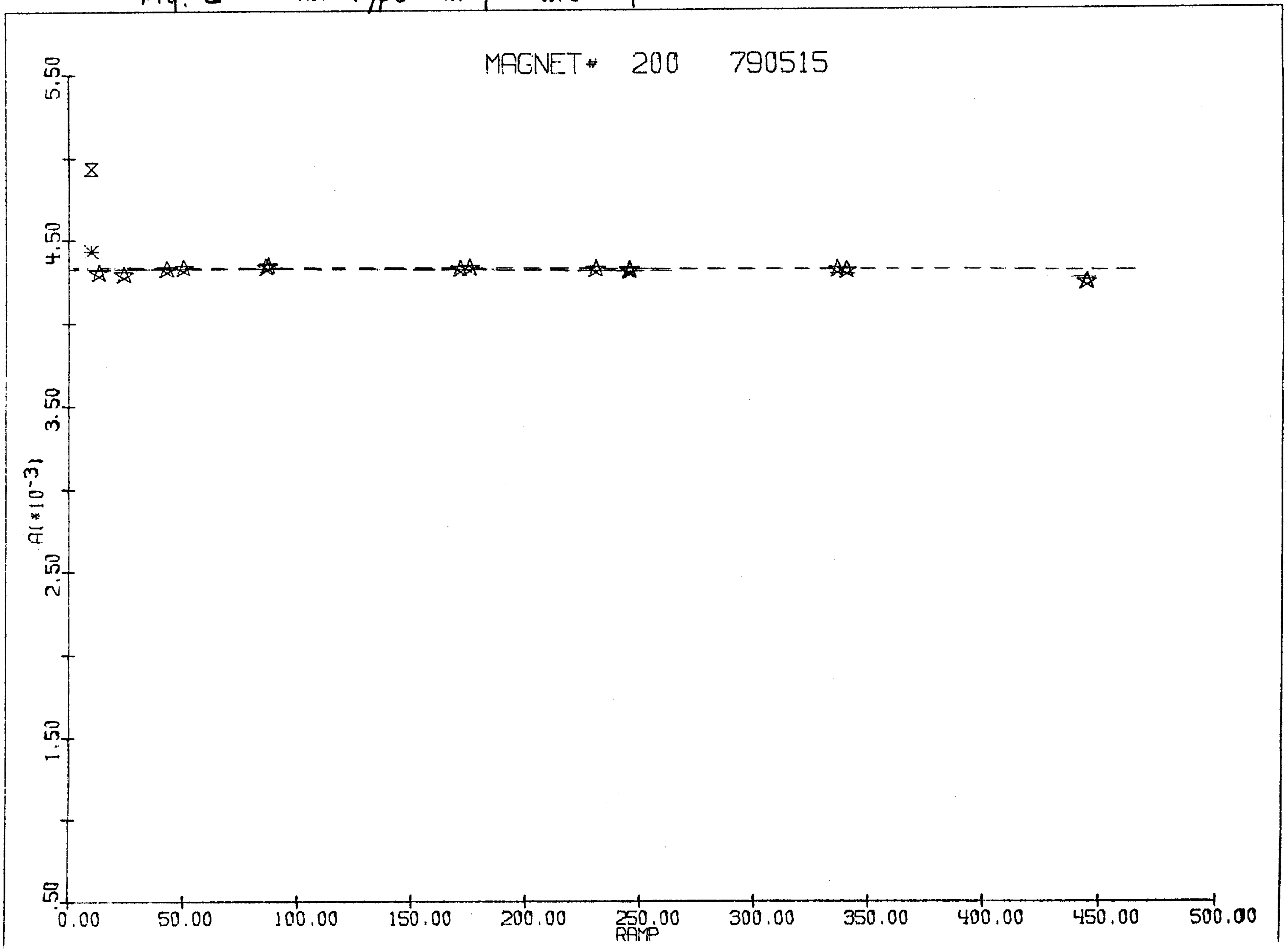


Fig. 3 Flat and Bend type Ramp-rate Dependence

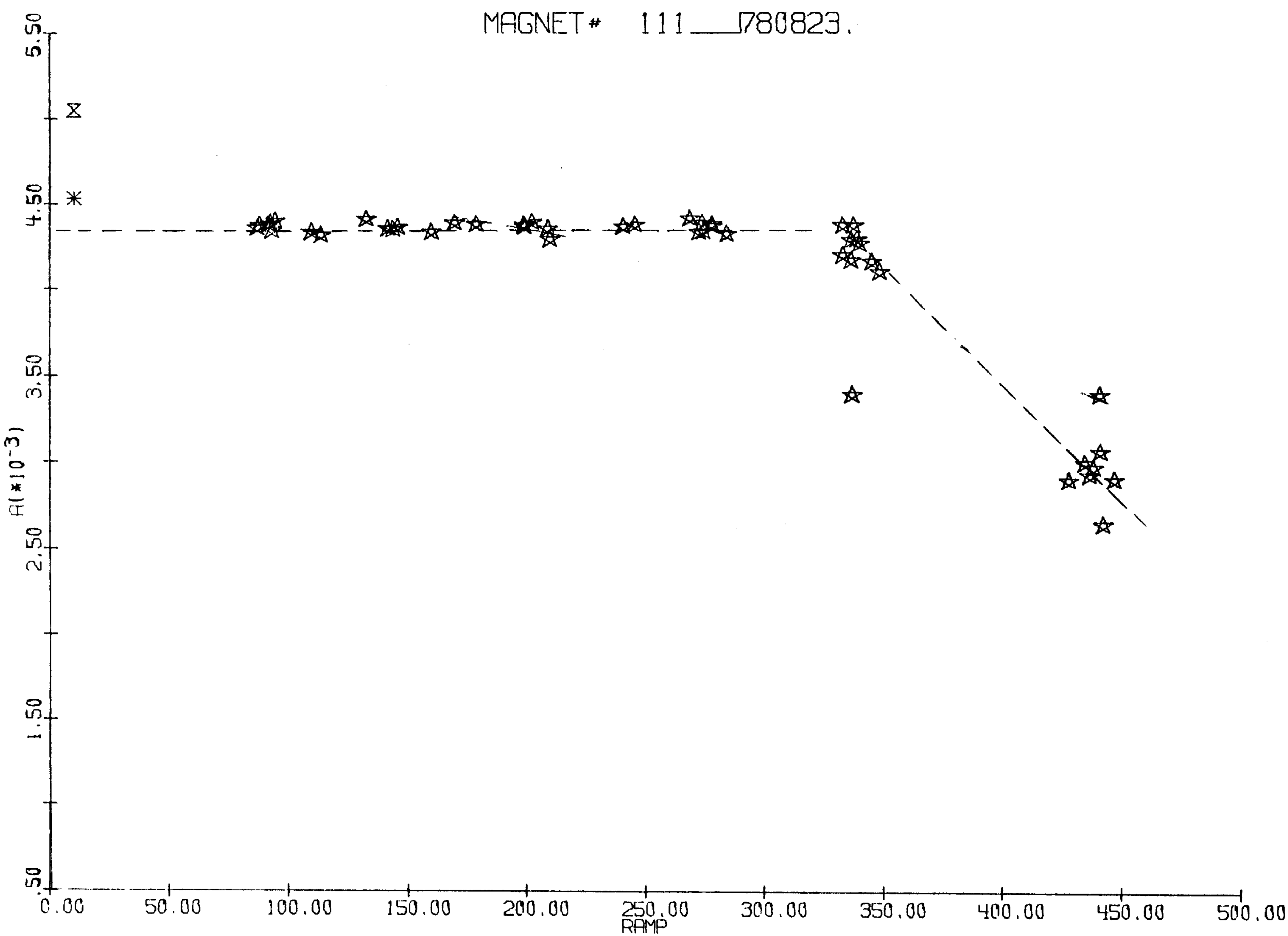
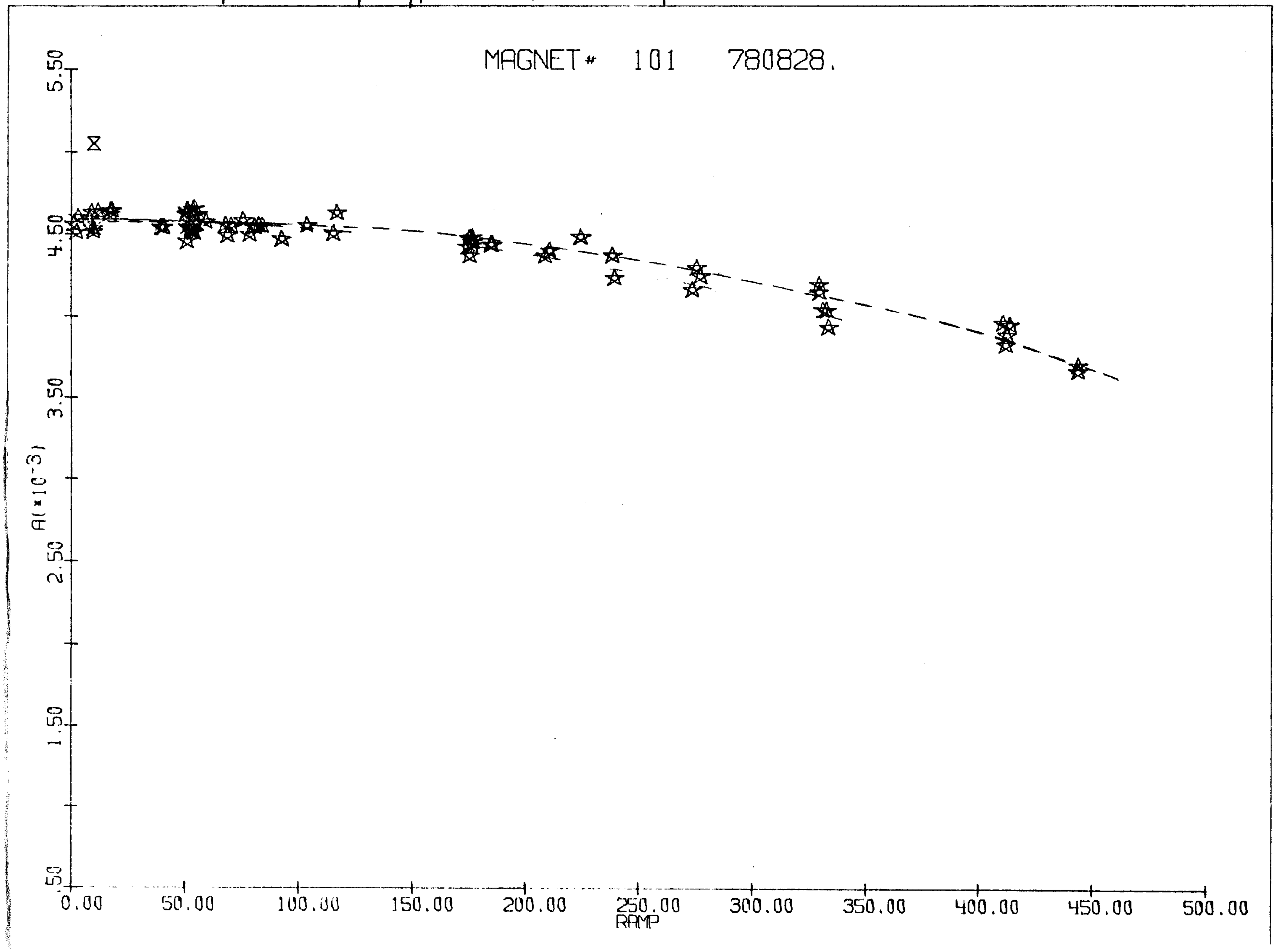


Fig. 4 Droop type Ramp-rate Dependence



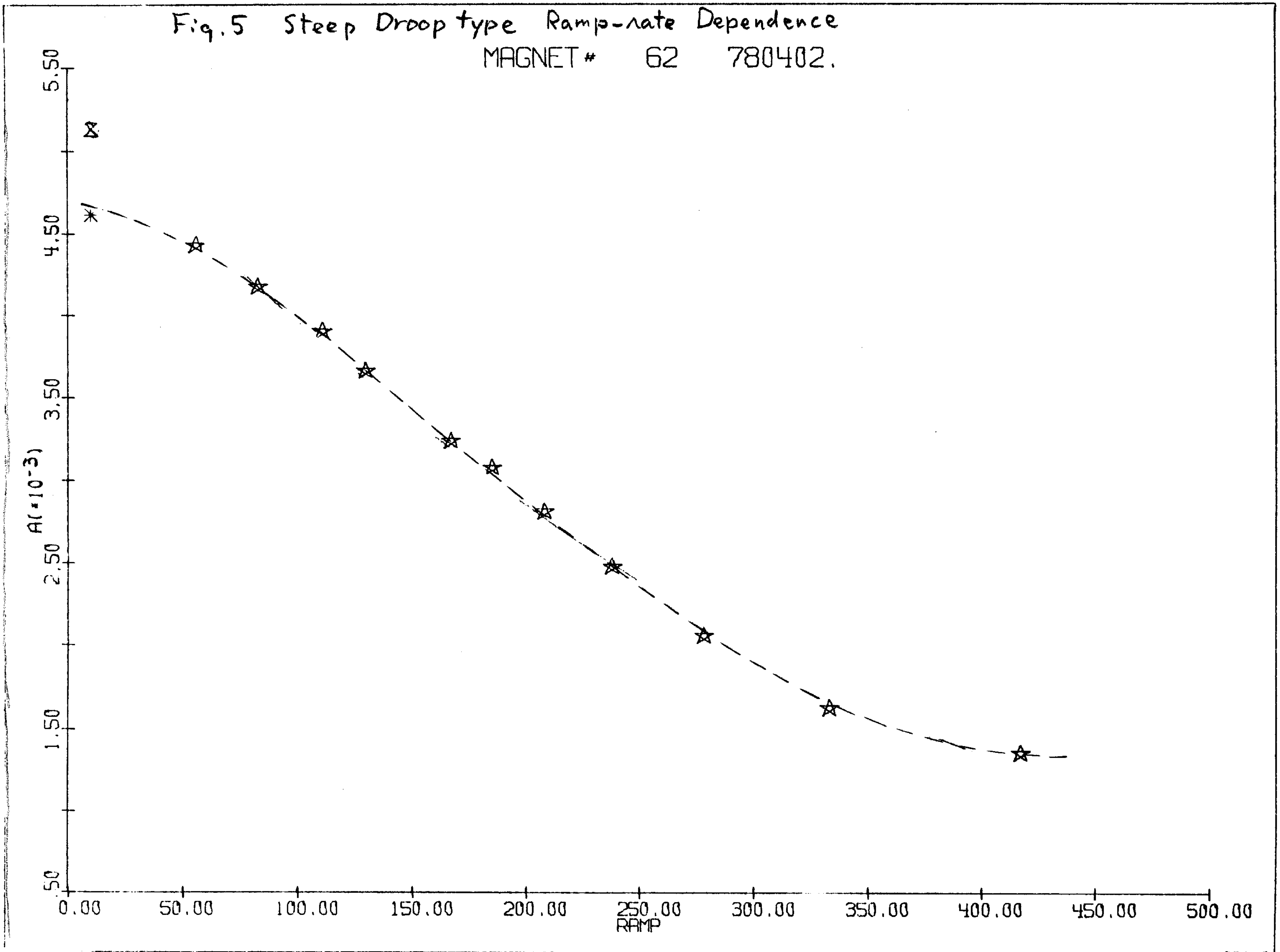


Fig. 5 Steep Droop type Ramp-rate Dependence
MAGNET# 62 780402.
A(*10^-3)
5.50
4.50
3.50
2.50
1.50
.50
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400.00
450.00
500.00
RAMP

Fig. 6 Steep and Flat type Ramp-rate Dependence

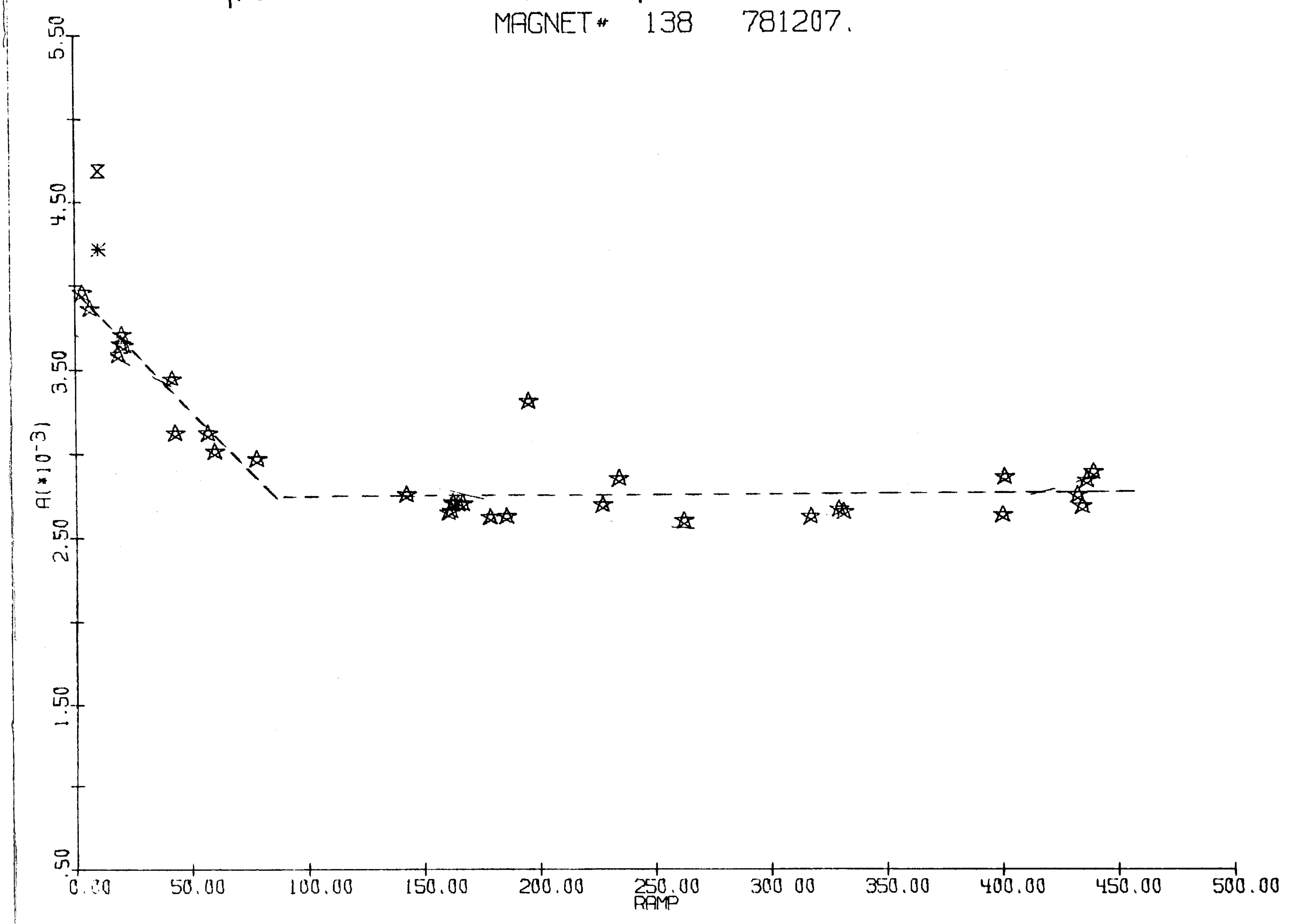


Fig. 7 Reverse Droop and Flat type Ramp-rate Dependence

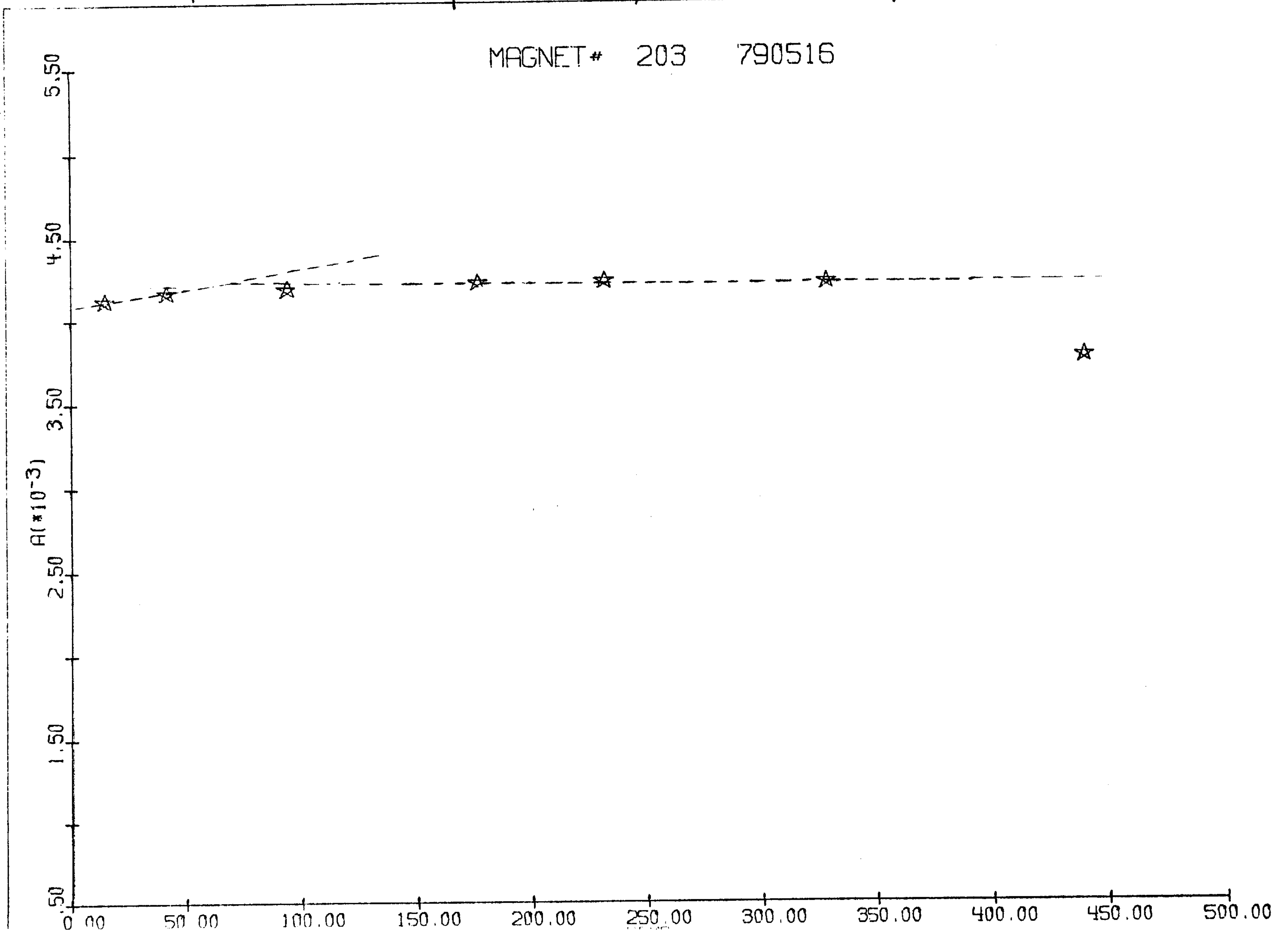


Fig. 8 Max. Current for VD Test & MTF Test

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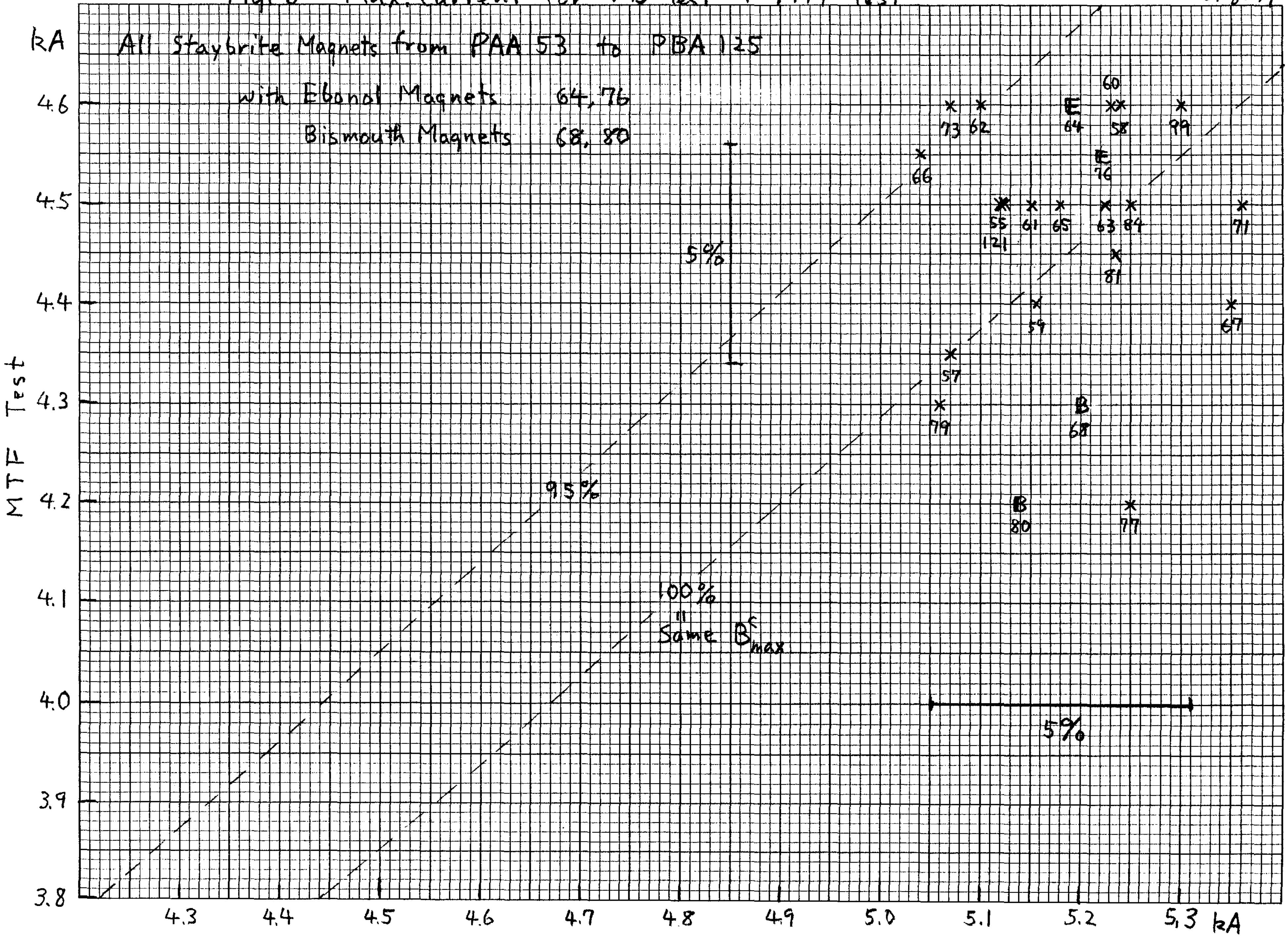

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Fig. 9 Max. Current for V.D. Test & MTF Test

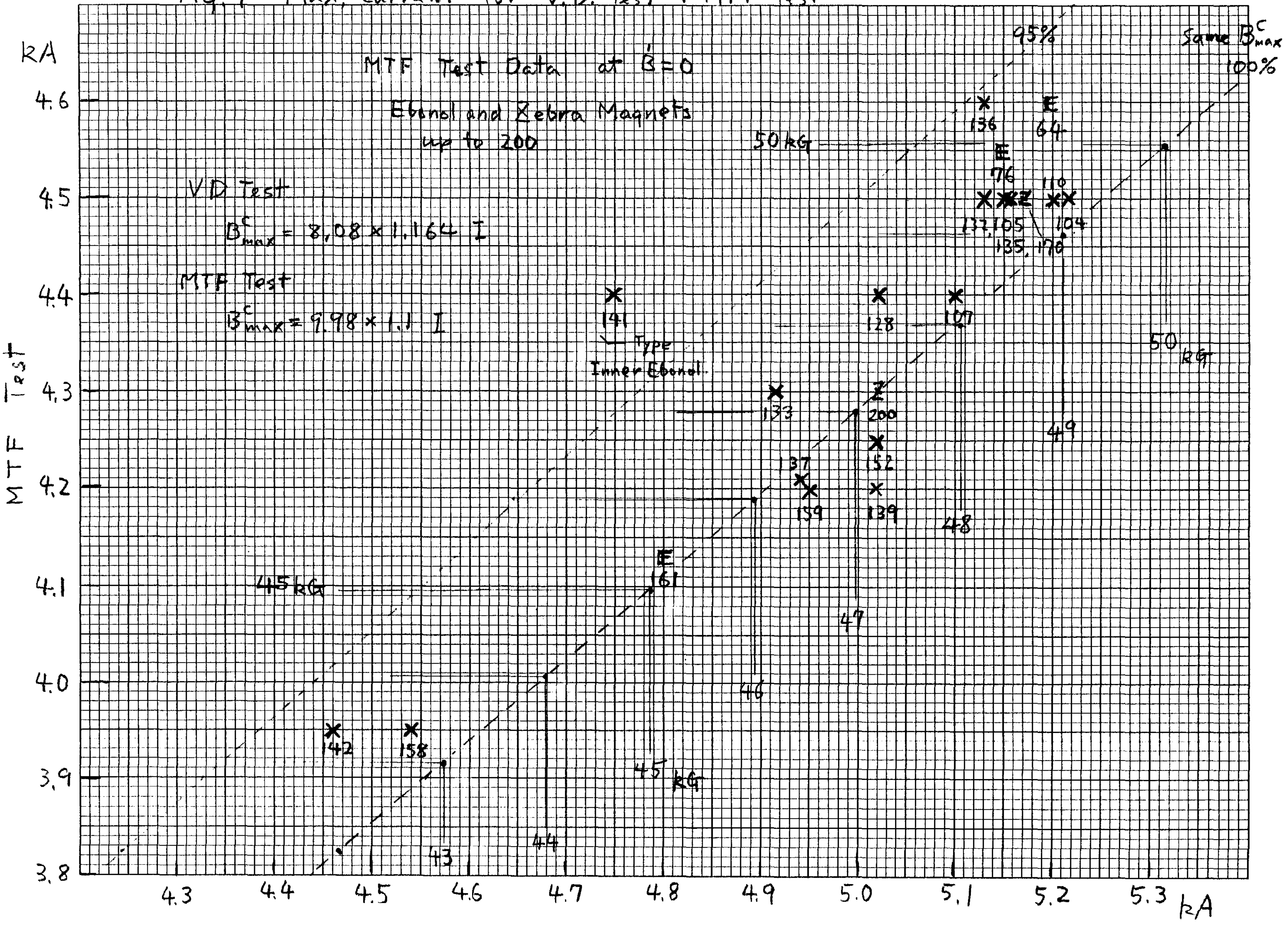

Fig. 10 Short Sample Data vs Estimated Max. Current, for HD Test

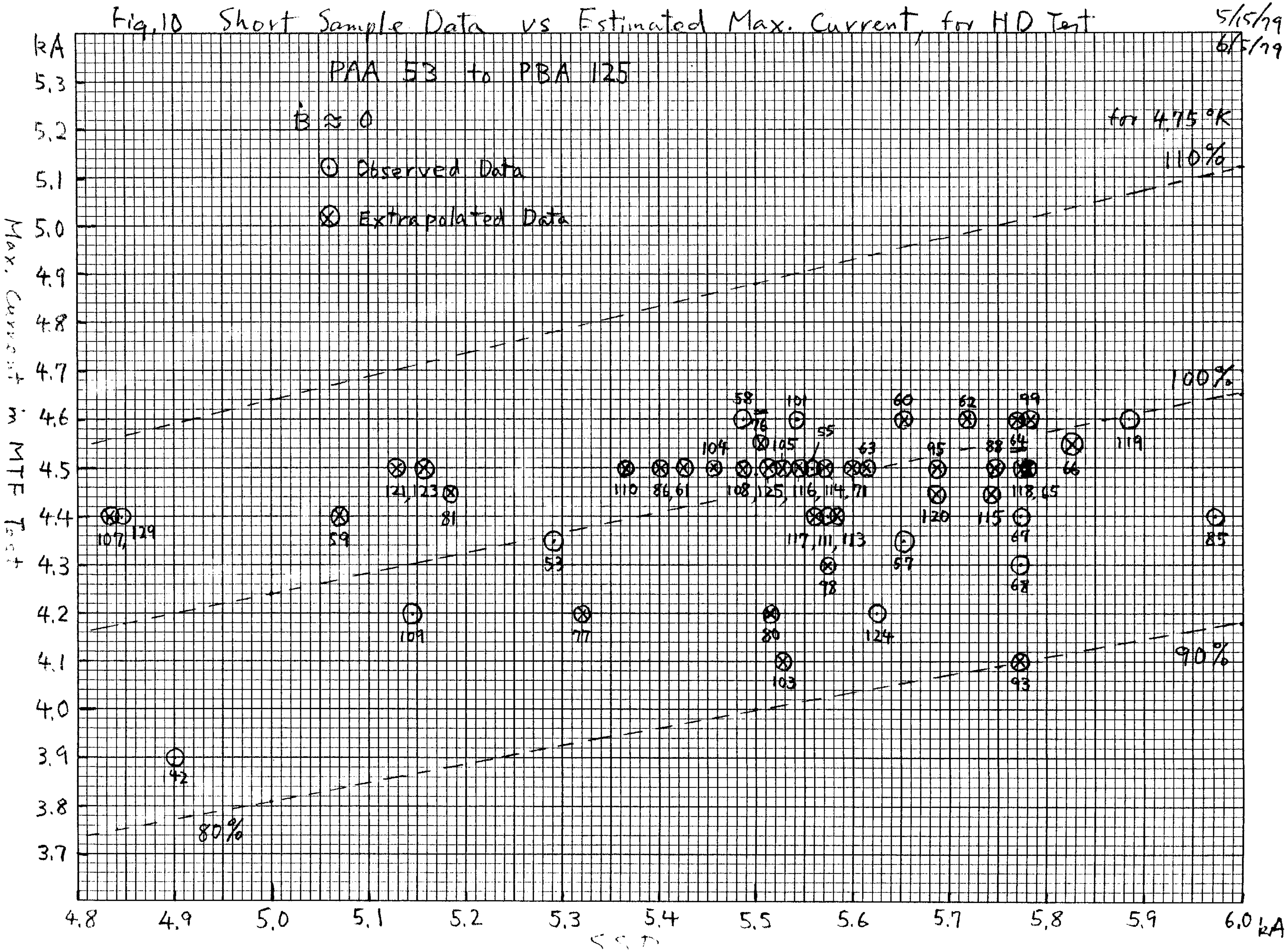

Fig.11 Short Sample Data vs Estimated Max. Current for HD Test

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6/5/79