T H E   U N I V E R S I T Y   O F   M I C H I G A N

College of Engineering

Department of Nuclear Engineering

Laboratory for Fluid Flow and Heat Transport Phenomena

Report No. MMPP-344-1-T
01357-3-T

PRELIMINARY RESULTS:

ASTM ROUND-ROBIN TEST

WITH VIBRATORY CAVITATION AND LIQUID IMPACT FACILITIES

(6061-T 6511 ALUMINUM ALLOY, 316 STAINLESS STEEL, COMMERCIALLY PURE NICKEL)

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Abstract

A "round robin" test program using three materials of widely varying mechanical properties is being conducted under the auspices of the ASTM Committee G-2 on Erosion by Cavitation or Impingement. The purpose of this test program is to study the variation in results produced by several laboratories ostensibly operating under the same conditions. Of the twelve laboratories taking part in this program, eight have reported results using vibratory cavitation damage facilities; and one has reported results using an impingement damage facility.

The data from these labs are represented on various damage or damage rate vs. time curves. These results show that all labs rank the materials in the same order; however, when data on one material from different laboratories are plotted on the same graph, a very substantial spread is found.

Acknowledgments

The authors would like to acknowledge especially the assistance of Dr. Robert Cheesewright of the Mechanical Engineering Department, Queen Mary College, University of London, London, England (formerly visiting Assistant Professor, Nuclear Engineering Department, University of Michigan) in the planning of this report and in helpful criticisms during its preparation. We would also like to acknowledge the assistance and helpful criticisms of Prof. C. A. Siebert of the Chemical and Metallurgical Engineering Department of this University. In addition Messrs. D. J. Kemppainen and E. E. Timm, research assistants of this laboratory are largely responsible for the planning and conducting of our portion of the test work.

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I. INTRODUCTION

One objective of ASTM Committee G-2 on Erosion by Cavitation or Impingement has been to establish a standard vibratory test for cavitation damage. In order to investigate more realistically than has hitherto been possible the effect on the results from such a test of the different parameters which characterize the various test facilities, a "round robin" test program has been initiated with three standard materials covering a wide range of mechanical properties. The materials used by each laboratory are identical, coming from the same heat and in many cases the same piece of bar stock. As far as seemed reasonably practicable the test conditions to be used in the various laboratories have been specified (see Appendix); however, a complete identity of test conditions is not possible because of the inherent differences in the various laboratory facilities. It is thus part of the objective of the "round robin" test to determine the importance of these various parameters, as well as the effect of the minor variations between facilities ostensibly operating at the same conditions.

To investigate the general applicability of the results to other cavitation and/or impingement erosion processes, it is desirable that the same three standard materials be evaluated in other forms of test apparata. For this reason tests in liquid-impact facilities have been projected in addition to the vibratory cavitation tests.

The laboratories which have agreed to participate in the "round robin" project are:

1. National Engineering Laboratory (NEL), East Kilbride, Glasgow, Scotland

2. NASA Lewis Center, Cleveland, Ohio
3. University of Minnesota, Minneapolis, Minnesota
4. Monsanto Chemical Company, St. Louis, Missouri
5. California Institute of Technology (CIT), Pasadena, California
6. Naval Applied Science Laboratory (NASL), Brooklyn, New York
7. Hydronautics Inc., Laurel, Maryland
8. Westinghouse Electric Corp., Lester, Pennsylvania
9. General Motors Corp. (GM), Warren, Michigan
10. University of Michigan, Ann Arbor, Michigan
11. Electricité de France (Jet Impingement test only), Chatou, S. & O., France
12. English Electric Corp. (Jet Impingement test only), Leicester, Whetstone, England

All the laboratories so far reporting, except Electricité de France, employed the vibratory type cavitation erosion apparatus. Therefore the results of Electricité de France, the only laboratory so far reporting which used the impact test, are separately presented, while those of the other laboratories are grouped together for comparison.

The three standard materials are:

1. 316 Stainless Steel, supplied by the Jones & Laughlin Steel Corp.
2. 270 commercially pure nickel, supplied by the International Nickel Co.
3. 6061-T6511 aluminum alloy, supplied by the Aluminum Company of America.

All of the samples from each of the three materials come from the same heat, have received the same processing and heat treating (and mostly have come from the same piece of bar stock). Therefore, the uniformity of the material itself is very good.

In this report, the properties of the materials tested, the testing conditions at individual laboratories, and the test results are presented, as well as the wave forms from the transducers used by the different facilities. Photographs of the specimens at various stages of the tests are available but have been omitted from this preliminary report due to lack of time. They will be included in a final version.

So far, only three materials have been included in the program, although it is hoped that the project will eventually be expanded to cover additional materials.

II. MATERIAL PROPERTIES

The properties of the materials tested were determined by the following laboratories:

1. Worthington corp., Harrison, N. J., supplied the tensile test data.
2. NASA Lewis Center supplied the metallographic tests and the hardness test data. In addition they measured the chemical compositions which agree closely with information supplied by

the vendors. Both are listed in Table 1.

3. Oak Ridge National Laboratory supplied the Charpy Impact test data.

4. The University of Michigan supplied the density data. It also conducted hardness tests which agreed closely with those supplied by NASA. Table 1 lists all these material properties.

5. Although at one point it had been thought desirable to have each laboratory heat treat the specimens after fabrication to remove cold work, it was later decided that this was impractical (see Appendix). However, Electricité de France did anneal the nickel and stainless steel specimens after fabrication and tested both annealed and unannealed specimens. As shown in Figs. 20, 21 and 22, there was considerable difference in damage results.

III. TESTING CONDITIONS AT INDIVIDUAL LABORATORIES

The pertinent test parameters include frequency, amplitude, and wave form of the transducer; roughness and diameter of specimen surface; pH value of water, air content and temperature of water; and barometric pressure. All the laboratories used the conventional flat buttons except CIT which used rimmed specimens. These data are collected and shown in Table 2. The wave forms available are reproduced as shown in Figs. 1-3 (Monsanto's wave form, as stated in their report, "appears sinusoidal to eyes through microscope"). The following laboratories have so far reported results:

1. National Engineering Laboratory, East Kilbride, Glasgow, Scotland
2. NASA Lewis Center, Cleveland, Ohio
3. University of Minnesota, Minneapolis, Minnesota
4. Monsanto Chemical Company, St. Louis, Missouri
5. California Institute of Technology, Pasadena, California
6. Naval Applied Science Laboratory, Brooklyn, New York

7. Hydronautics Inc., Laurel, Maryland

8. University of Michigan, Ann Arbor, Michigan

9. Électricité de France, Chatou, S. & O., France

TABLE 1 Material Properties

	316 SS	2% Ni	6061-T6511 Al Alloy
Chemical Composition (%) Provided by Supplier	C 0.05 Mn 1.62 Ni 13.03 Cr 17.45 Mo 2.72 Co 0.11 Cu 0.21 S 0.027 P 0.024 Si 0.66	Ni 99.9 Min.	Mg 0.8-1.2 Si 0.4-0.8 Cr 0.15-0.35 Cu 0.15-0.40 Al Bal. Nominal composition range.
Chemical Composition (%) Quoted by NASA	Cr 18 Ni 13 Mo 2.5 Mn 1.6 Fe Bal.	Ni 99.98	Mg 1.0 Si 0.6 Cu 0.25 Cr 0.25 Al Bal.
Tensile (psi) Strength (Newton/m2)	81,250 560×10^6	48,750 336×10^6	47,260 328×10^6
0.2% Yield (psi) Strength (Newton/m2)	31,310 216×10^6	8,000 55.2×10^6	40,680 281×10^6
Elongation (%)	69.0	61.0	21.5
Reduction of Area (%)	76.9	91.5	44.0
Hardness (Rockwell-B)	74.8	24.9	60.1
Charpy Impact (Ft-Lb) Strength (Joules)	136.0 184.1	91.0 123.5	5.5 7.47
Density (Gm/cm3)	7.91	8.94	2.71

Metallographic data are shown on separate pages as Figs. 23, 24, & 25.

TABLE 2-A Testing Conditions for Vibratory Facilities

Condition \ LAB	NEL	MINN	NASA	MONSANTO	CIT	NASL	U of M	Hydronautics
Frequency (kc/s)	20.0	6.0	25.5	20.0	15.0	13.0	20.0	14.2
Amplitude (mil)	2.0	4.0	1.75	2.0	2.0	1.85	2.0	1.6
(m)	5.08×10^{-5}	10.16×10^{-5}	4.445×10^{-5}	5.08×10^{-5}	5.08×10^{-5}	4.7×10^{-5}	5.08×10^{-5}	1.588×10^{-5}
Specimen (in)	.625	.625	.563	.500	.625	.625	.547	.625
Diameter (m)	1.588×10^{-2}	1.588×10^{-2}	1.435×10^{-2}	1.27×10^{-2}	1.588×10^{-2}	1.588×10^{-2}	1.389×10^{-2}	1.588×10^{-2}
Temp. of (^{o}F)	75 ± 1	75 ± 1	75 ± 1	75 ± 1	75 ± 1	75 ± 1	75 ± 1	75 ± 1
Water (^{o}C)	$23.9\pm.556$	$23.9\pm.556$	$23.9\pm.556$	$23.9\pm.556$	$23.9\pm.556$	$23.9\pm.566$	$23.9\pm.556$	$23.9\pm.556$
Pressure (in. Hg)	29.06	29.27	29.17	30.07	29.25		29.25	29.87
Above Water Surface (Newton/m^2)	98.4×10^3	99.05×10^3	98.7×10^3	101.75×10^3	98.98×10^3		98.98×10^3	101.08×10^3
pH Value of water	4.2/5.6	6.9/7.5	5.5	8.4	6.25	6.8	7.18	7.2
Air content (Ml/l)	11.9/13.3		16.85	4/16	9.03/9.73		12.8	
of Water % (saturation)	68.5/76.5		97*	23/92	52/56		73.7	
Specimen Surface Roughness (μ)	23-30	3-4	0	Al 12 Ni 4 SS 6	8	32	Al 27 Ni 15 SS 18	32

*Initial Value

TABLE 2-B Testing Conditions for Impingement Facilities

Condition / LAB	Electricité de France	English Electric
Jet Diameter (m)	.005	
RPM	2900	
Diameter Disk (m)	0.6	
Specimen Height (m)	1.5×10^{-2}	
Specimen Diameter (m)	1.8×10^{-2}	
Linear Velocity of Target at Diameter Corresponding to Jet Axis (m/s)	94	
Jet Velocity (m/s)	14	
Resultant Velocity (m/s) $(V_j^2 + V_{target}^2)^{\frac{1}{2}}$	95	
Temp. (°C.)	15.5	
Pressure Surrounding Jet		
pH value		
Air Content		
Specimen Surface Roughness		

Details of their tests, which have not been possible to include here, are given in their individual reports (1-9).

IV. CAVITATION DAMAGE COMPARISONS

1. The raw data from the vibrating cavitation erosion tests on an accumulative weight loss and accumulative volume loss basis are grouped in Figs. 4-9 (Average values of 2 or 3 samples were used in those cases where an individual laboratory tested more than one sample of each material).

2. The accumulative mean depth of penetration (MDP) is calculated using the weight loss data and the equation:

$$MDP = C \cdot W \text{ mils},$$

where W=the weight loss in milligrams
C=a material constant given by

$$C = \frac{1000}{25.4} \cdot \frac{1}{PA}$$

where P=density in mg/mm^3 (=g/cm^3)
A=specimen area in mm^2

The "C" values are listed in Table 3.

3. Mean Depth of Penetration Rate (MDPR)

These values are derived by multiplying the weight loss rate by "C", and they are shown in Figs. 13-15.

"Smoothed" versions of these curves have been constructed from the accumulated MDP curves, Fig. 10-12. These were constructed by simply taking the best straight line approximation to the data after the incubation period to display clearly the different rates involved on this basis. Hence, no fine detail of the rate curves is given by these figures (except in a few cases where the deviatio s from a straight line was very substantial). These "smoothed"

TABLE 3

Specimen Diameter (in)	Material	Density (g/cm^3)	"C"
0.625	S.S.	7.91	.0252
	Ni	8.94	.0223
	Al	2.71	.0737
0.563	S.S.	7.91	.0310
	Ni	8.94	.0274
	Al	2.71	.0907
0.547	S.S.	7.91	.0330
	Ni	8.94	.0288
	Al	2.71	.0935
0.500	S.S.	7.91	.0393
	Ni	8.94	.0348
	Al	2.71	.115

The accumulated MDP plots are shown in Figs. 10-12.

plots of MDPR are shown in Figs. 13a-15a.

4. Plots of accumulated Mean Depth of Penetration which convert all data to estimated data if the amplitude were 2 mils, so that these results can be approximately campared on the basis of the same amplitude, are shown in Figs. 16-18. This was accomplished by assuming that MDP $\approx A^n$, and taking a mean value for n of 1.7. This mean value represents a rough average of the available data, since Hobbs asserted that the weight loss varied with the amplitude to the 1.5 power,[10] while Thiruvengadam indicated that it varied with the amplitude squared.[11]

The amplitude conversion factors for the data from the four laboratories which used amplitudes other than 2 mils are shown below;

Lab.	Amplitude (mils)	Conversion Factor
Minn.	4.0	0.308
NASL.	1.85	1.143
NASA	1.75	1.255
Hydronautics	1.6	1.462

5. Comparison of frequency and MDPR peaks.

By taking peak values of the MDPR curves and plotting these against frequency, the approximate effect of frequency can be shown (Fig. 19). By plotting the peak values from the smoothed MDPR plots against frequency, the three curves shown in Fig. 19a result.

6. The results of the impingement erosion damage from Electricité de France are shown in Figs. 20-22 on an accumulative weight loss basis. Their testing conditions are shown in Table 2-B.

For comparison, the damage curves of the three materials have been plotted together (Fig. 22a).

V. DISCUSSION OF RESULTS

From the results supplied by the laboratories reporting to date, there has been the expected broad agreement between the overall rankings of the three different materials, i.e., all the laboratories ranked stainless steel, nickel, and aluminum alloy in order of decreasing damage resistance. The jet impingement apparatus of Electricité de France showed the same result.

When the test data for one material from different laboratories are plotted on the same graph, a very substantial spread is found. This is presumably due to the minor differences in testing equipment and parameters. In terms of smoothed rates, without any correction for amplitude (Fig. 13a, 14a, and 15a), the maximum difference for each material is approximately a factor of three.

If the amplitude correction is made the overall spread in average damage rates is even greater, primarily because the high amplitude Minnesota data is dropped well below the others when its 4 mil amplitude is corrected to 2 mils while previously it had been intermediate in the group (i.e., the amplitude correction is apparently too great in this case). However, the amplitude correction reduces the factor between the other facilities to a factor of about two if the aluminum from the high frequency (25.5 kc) NASA unit (discussed later) is also ignored for the moment. Note that this overall grouping includes the rimmed CIT specimens whereas all others are the standard flat design.

On the basis of the same frequency and same amplitude of units, NEL, Monsanto, and U of M data should be comparable, but to the contrary, the damage rates of all three materials produced by NEL were the highest obtained (except for Al); those of Monsanto were always (without exception) the lowest; while those of U of M were midway in between the two extremes.

However, from the information available, there are some differences in the test apparatus and water used by these laboratories. NEL used a magnetostrictive transducer and a stepped horn. While Monsanto and U of M used piezoelectric transducers and catenoidal horns. The air contents and the pH values of the water also showed some variation.

Figs. 19 & 19a attempt to indicate very roughly the influence of frequency. The peak MDPR values from Figs. 13-15 are plotted against frequency for each material from the actual MDPR as well as from the smoothed MDPR plots. From these curves it appears that there is little effect of frequency between 15 and 25 kc, except for aluminum, where the damage is almost doubled going from 20 to 25 kc. Hence, it is conceivable that such an effect may be real as a result of the following argument*. For higher frequencies there are presumably more bubbles collapsing on the surface, but these will tend to be bubbles of smaller maximum diameter, at least as the frequency becomes quite large. Thus for higher frequency there may be more blows but their average intensity may be lower. Such an attack may be relatively ineffective against a material of high fatigue strength, perhaps greater than the stress induced by most of the bubbles, but highly effective against weaker materials.

*First suggested to the authors by R. Cheesewright, Queen Mary College, University of London.

Thus the relative position of different materials on a scale of cavitation resistence may depend upon the intensity of the blows. This appears to be illustrated by the present tests in that the damage factor between aluminum and nickel is about 4.3 at 20 kc and 6.8 at 25 kc (Fig. 19).

It may also be concluded from the present results that no simple relation will predict the effect of frequency on damage.

Figs. 20-22a show the impact test results from Electricité de France. It is interesting to note that their further annealing of the stainless steel and nickel specimens after fabrication has increased the slope of the weight loss vs. time curve by a factor of about 2 for the stainless steel, but not affected the incubation period; for the nickel the effect upon the slope is much less, but the incubation period is reduced by annealing by a factor of more than 2.

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Address reply to →

This is to invite your laboratory to participate in a round-robin cavitation damage test program using vibratory cavitation test facilities. While it is expected that eventually various metallic and non-metallic materials will be included, it is planned to start with only three:

a. Aluminum type 6061-T-58 (Alcoa designation)

b. Stainless Steel Type 316 (annealed)

c. Pure Nickel, Type 270, annealed (International Nickel Company)

It is presently planned that your laboratory will be supplied at least 4-inch lengths bar stock, with a diameter of at least 5/8 inch, of these materials, from which you will fabricate at least two of your own standard specimens, so that two tests can be run on each material by each laboratory. The specimen surface to be cavitated should be a ground finish (32 micro inch rms). For each material room temperature stress-strain curve and hardness will be measured and will be available to all participants. The residue of bar stock of each material will be maintained in a "materials bank" in the writer's laboratory to be available for later checks if desired. Each participating laboratory should anneal the stainless steel and nickel materials after specimen fabrication (but not the aluminum alloy) to be sure that no non-uniform cold work is induced in the specimen by the fabrication process. Standard annealing specifications for these materials will be furnished to the participating laboratories.*

While it is planned that each participating laboratory should conduct the tests in a manner which they consider suitable, the following standard test specifications must be followed to eliminate the effect of unnecessary variables.

a. Test Fluid-Distilled (or deionized) water at 75°F ± 2°F, atmospheric

* It was later decided (meeting of May 11, 1967) that this step would be omitted, and it is so recorded in the minutes of that meeting.

pressure (which should be measured).

b. At least 5 weight loss vs. duration points for each test. The spacing of these points is to be as considered appropriate by the participating laboratory.

c. If at all possible, two specimens per material should be tested.

We hope that this first series of tests can be completed and reported within six months of receipt of materials. All results obtained from the round-robin program will be made available to all participating laboratories. Each participating laboratory must furnish the following information, in addition to the weight loss vs. duration points.

a. Brief description, identification or illustration of apparatus (transducer, horn, generator, specimen design).

b. Frequency (kcps).

c. Double amplitude (inches).

We welcome your comments on the suitablity of these specifications. We are also enclosing a copy of a brief report prepared by A. Thiruvengadam of Hydronautics, Inc., which describes presently available information on the performance of the high frequency (20kc/s) devices in common use today. I would also like to call to your attention "Accelerated-Cavitation Research" by W. J. Rheingans, Trans. ASME, July 1950, pp. 705-724, which presents similar information for the 6500 cps "standard ASME" magnetostriction device.

May we please hear from you in regard to your participation in the proposed "round-robin" test program?

Sincerely yours,

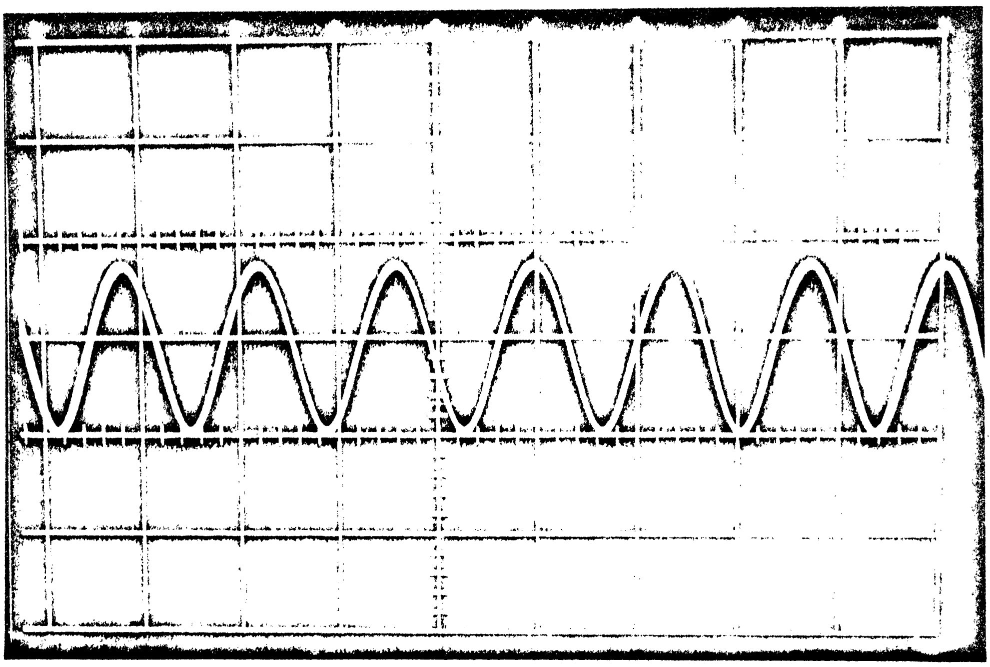
Frederick G. Hammitt
Professor
Chairman Sub-Committee I

FGH:sc

Enclosure

Fig 1.

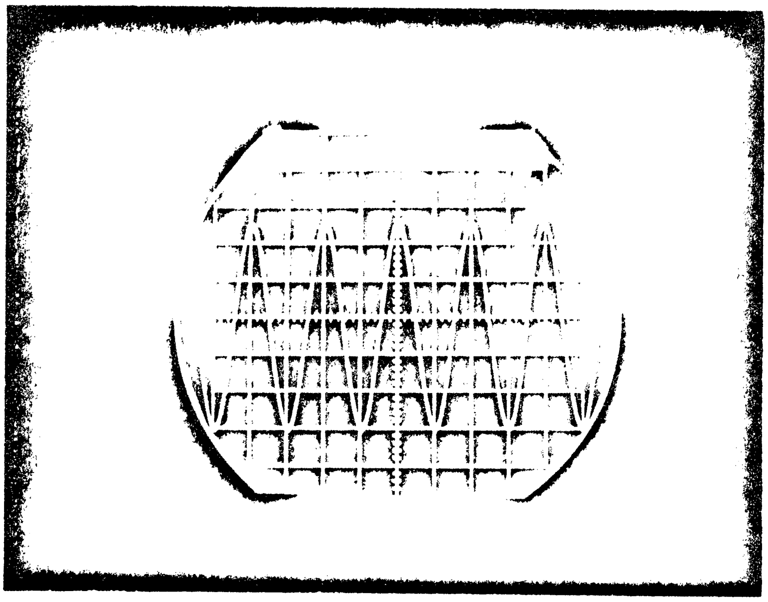
Wave form "California Institute of Technology"



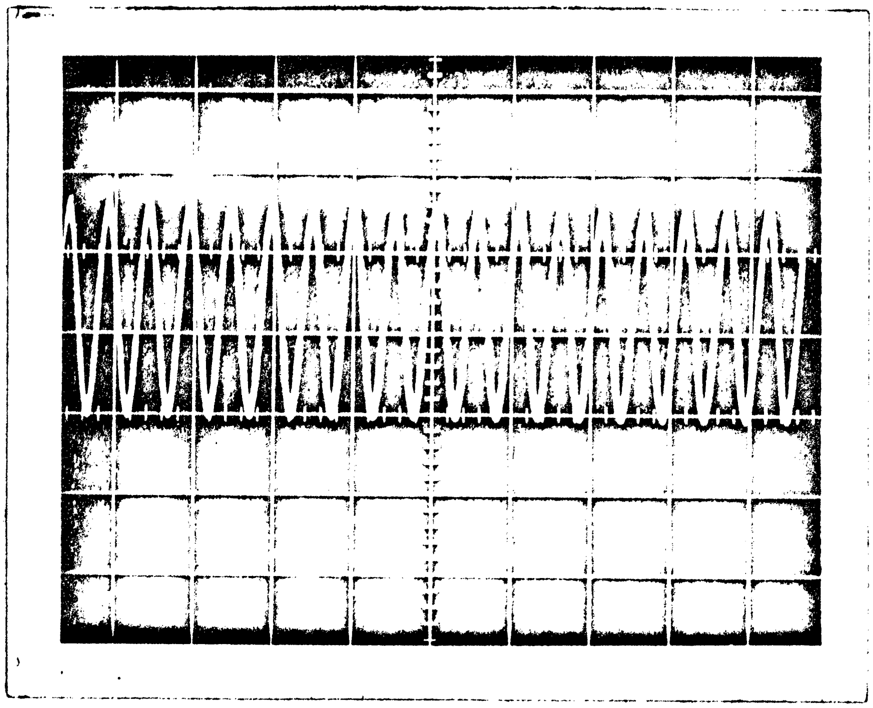
Oscillogram of specimen wave form. Taken from amplitude monitoring "feeler coil" positioned near tip of horn.

Fig. 2

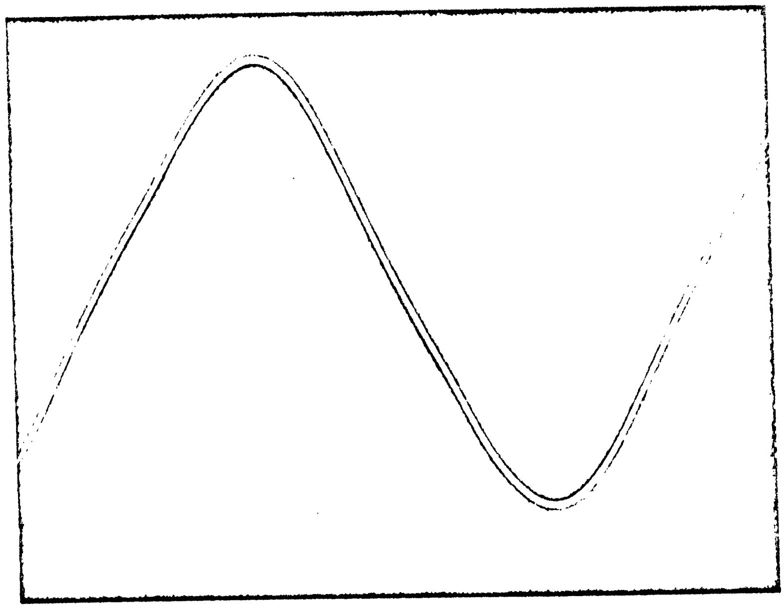
Wave Form "NASA Lewis Center"



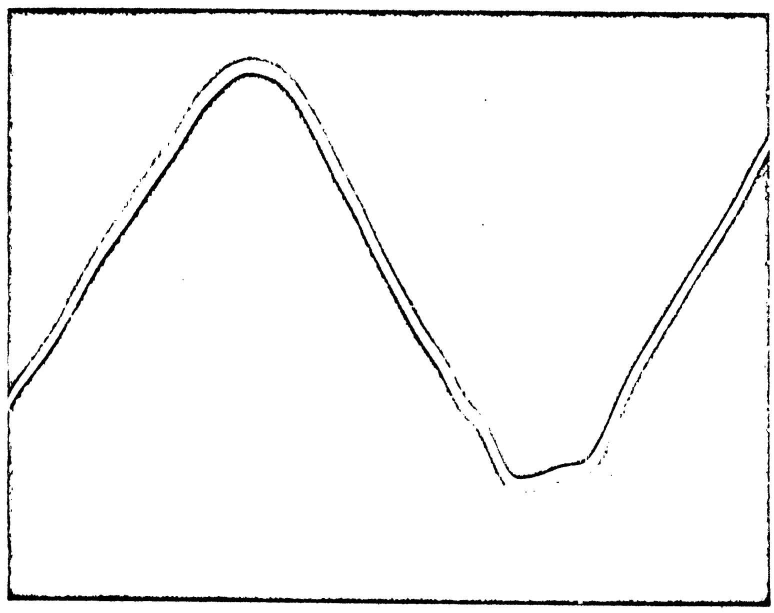
Wave Form "University of Michigan"



Wave Form "University of Minnesota"



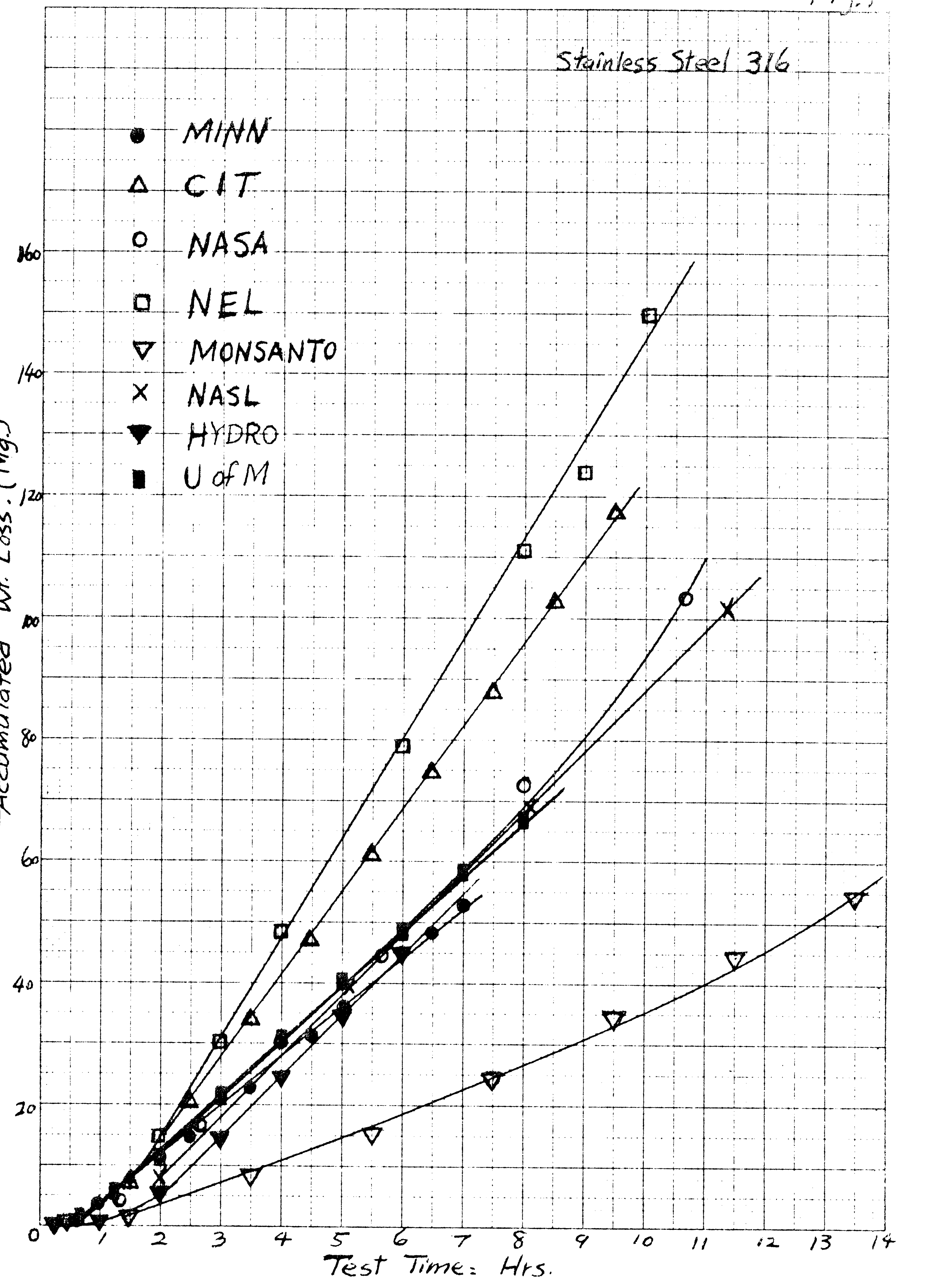
(a) Operating in Air



(b) Operating submerged in water 1/8 inch

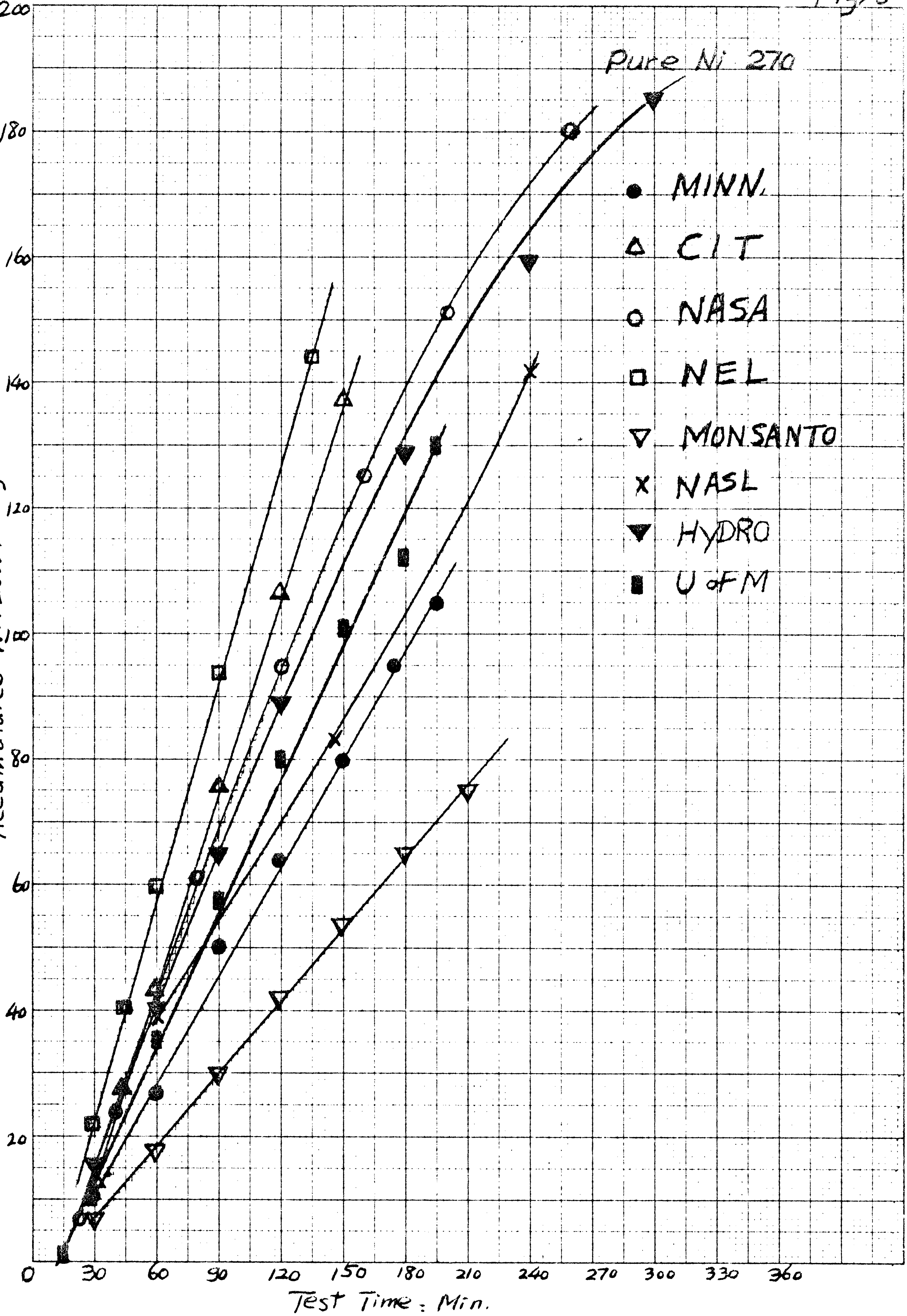
~~Fig. 2~~ Typical Oscilloscope Records of the Horn Oscillation

Fig. 4



Stainless Steel 316
MINN
CIT
NASA
NEL
MONSANTO
NASL
HYDRO
U of M
Accumulated Wt. Loss. (Mg.)
160
140
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Test Time: Hrs.

Fig. 5



Pure Ni 270
MINN.
CIT
NASA
NEL
MONSANTO
NASL
HYDRO
U of M
200
180
160
140
120
100
80
60
40
20
0
30
60
90
120
150
180
210
240
270
300
330
360
Test Time: Min.

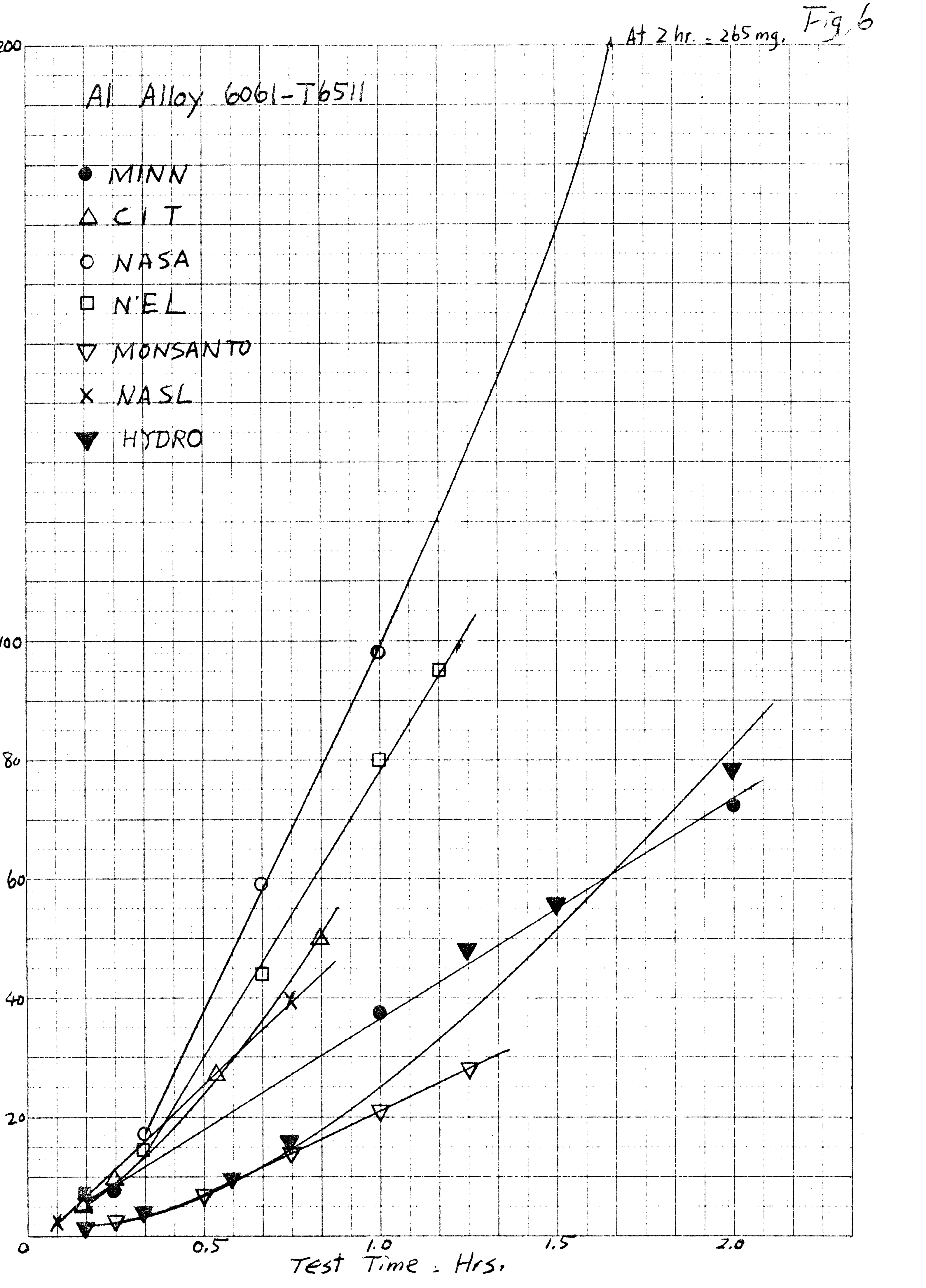
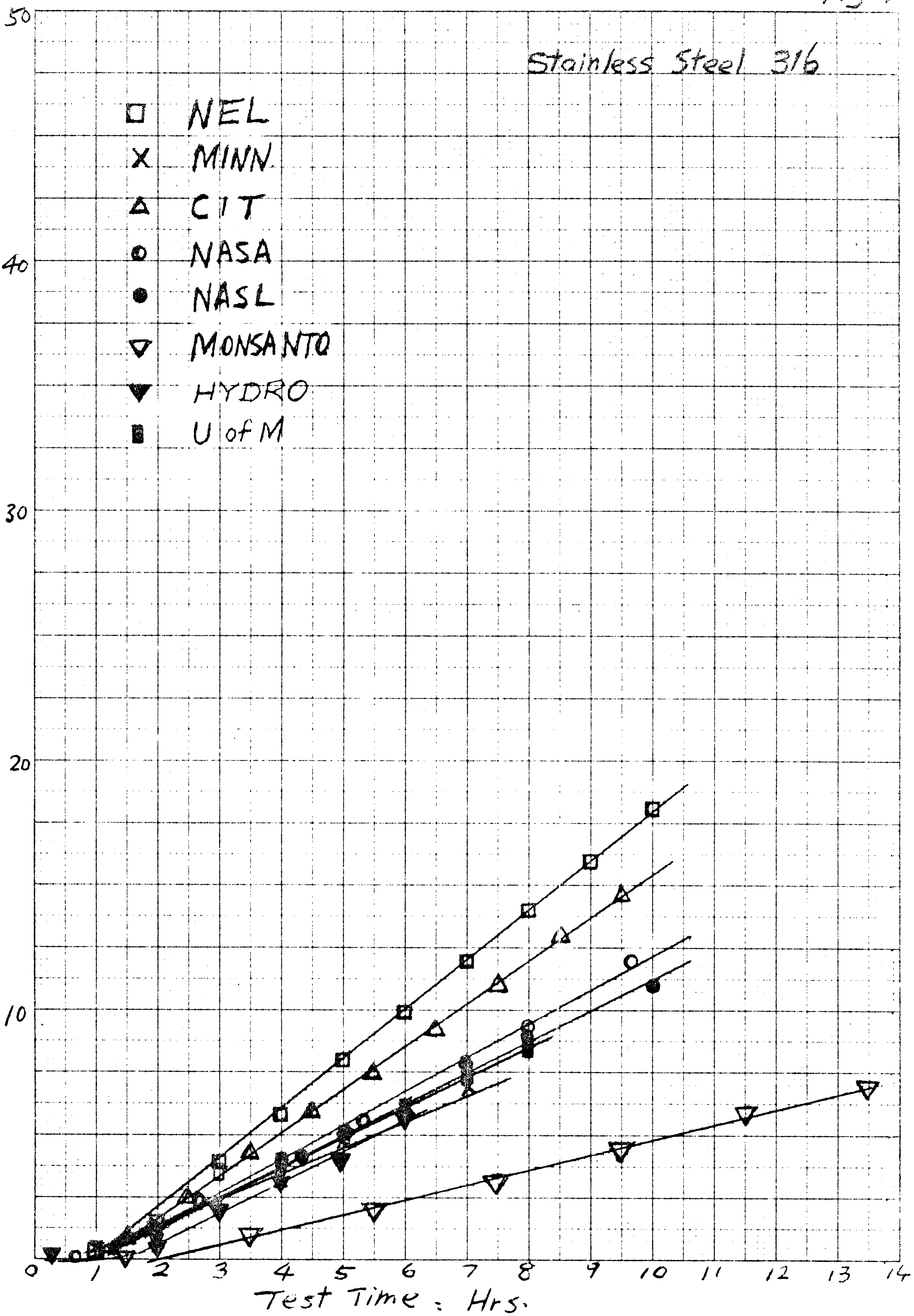


Fig. 6
At 2 hr. = 265 mg.
Al Alloy 6061-T6511
● MINN
△ CIT
○ NASA
□ NEL
▽ MONSANTO
× NASL
▼ HYDRO
200
100
80
60
40
20
0
0.5
1.0
1.5
2.0
Test Time : Hrs.

Fig 7



Stainless Steel 316
NEL
MINN
CIT
NASA
NASL
MONSANTO
HYDRO
U of M
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Test Time : Hrs.

Fig 8

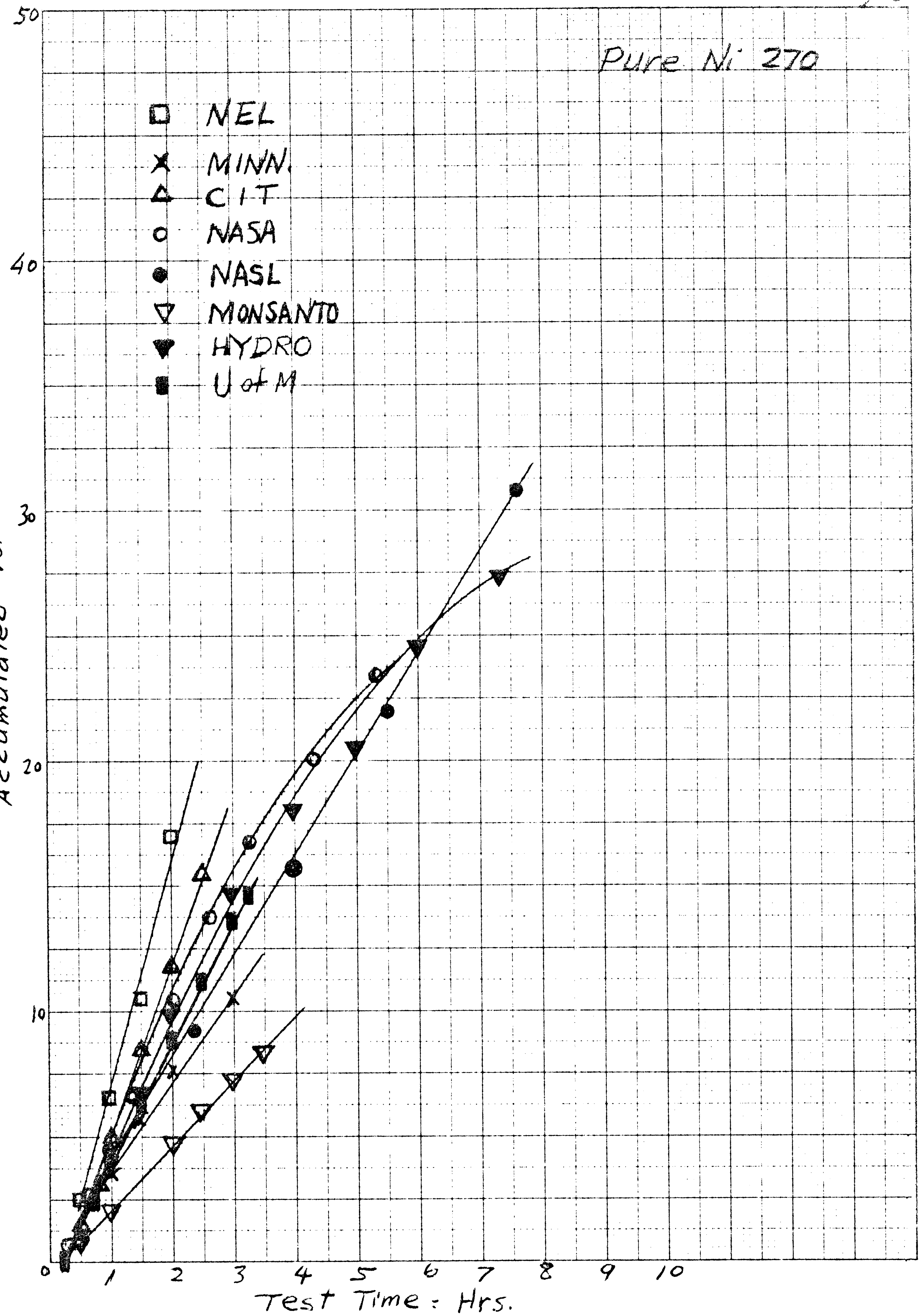

Pure Ni 270
NEL
MINN.
CIT
NASA
NASL
MONSANTO
HYDRO
U of M
Accumulated
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9
10
Test Time: Hrs.

Fig. 9

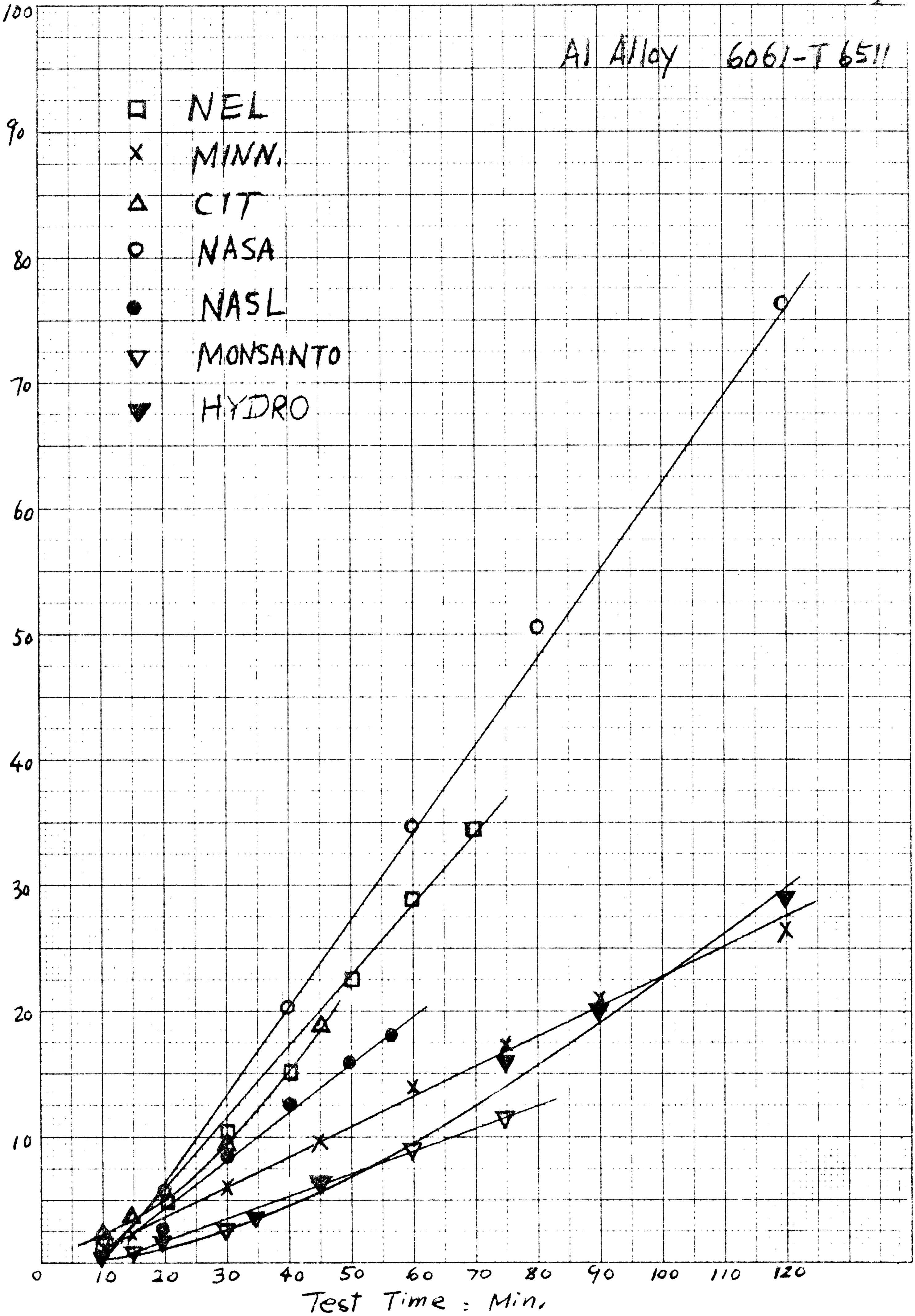

Al Alloy 6061-T6511
NEL
MINN.
CIT
NASA
NASL
MONSANTO
HYDRO
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
110
120
Test Time : Min.

Fig. 10

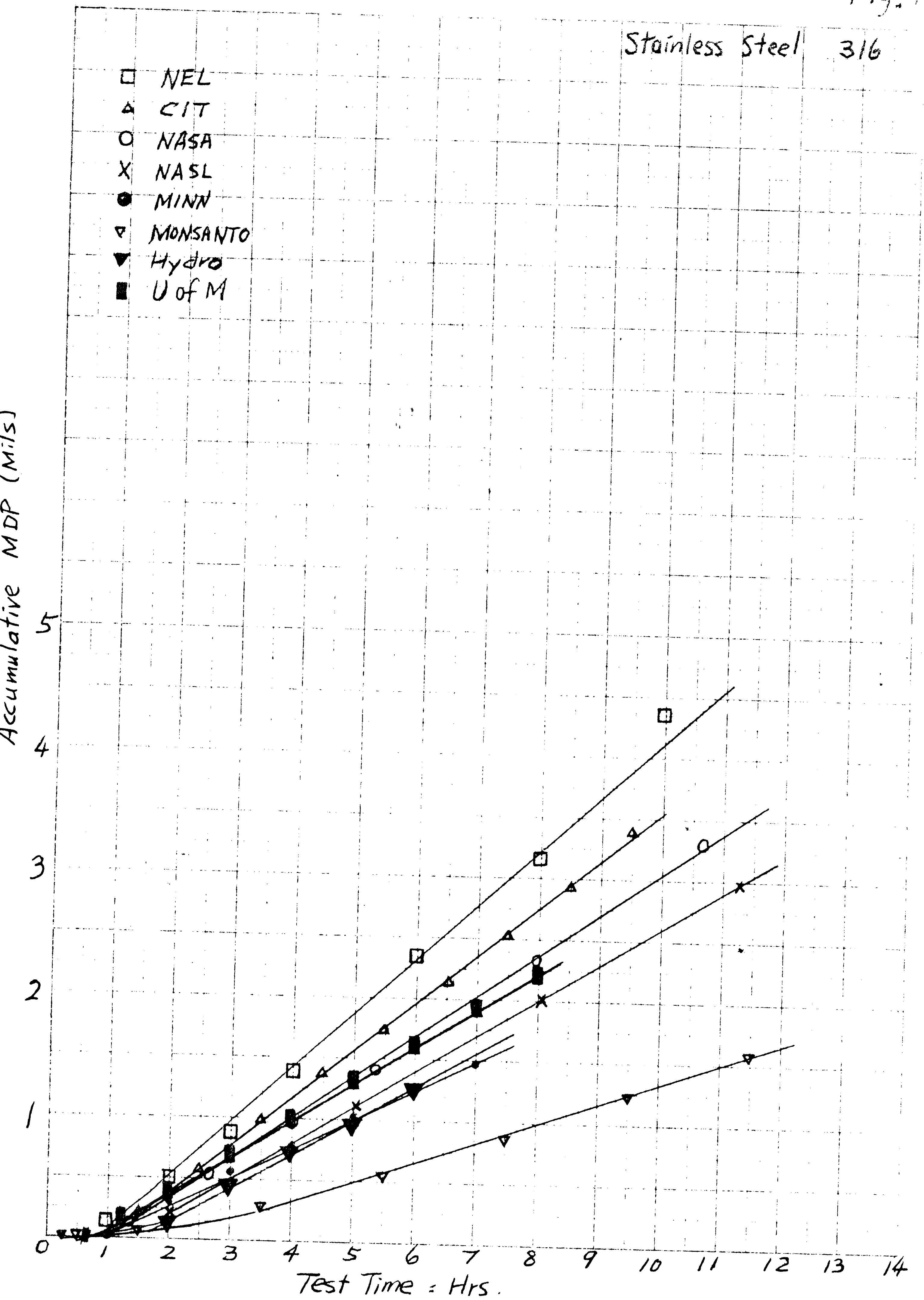

Stainless Steel 316
NEL
CIT
NASA
NASL
MINN
MONSANTO
Hydro
U of M
Accumulative MDP (Mils)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Test Time : Hrs.

Fig. 11

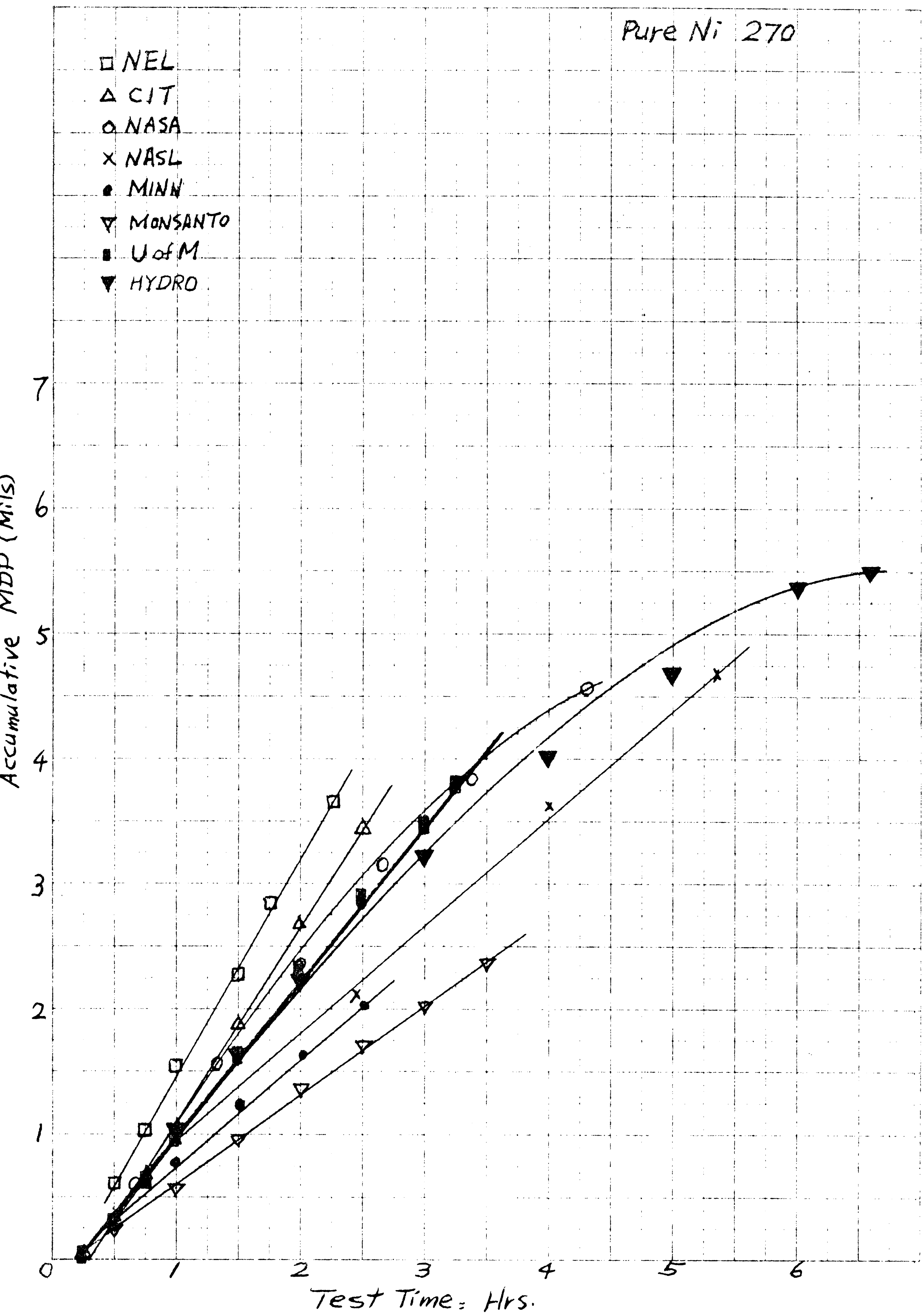
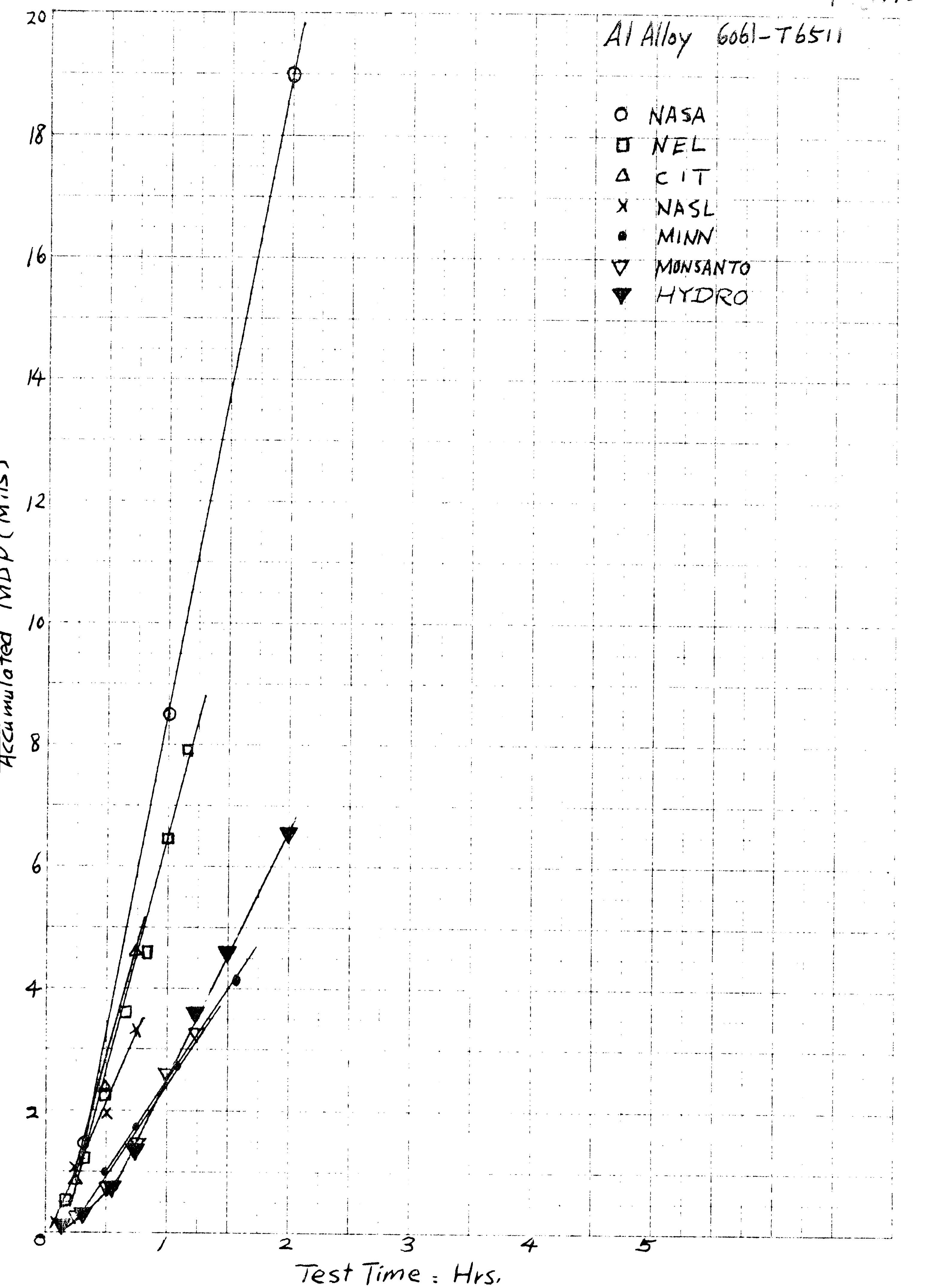
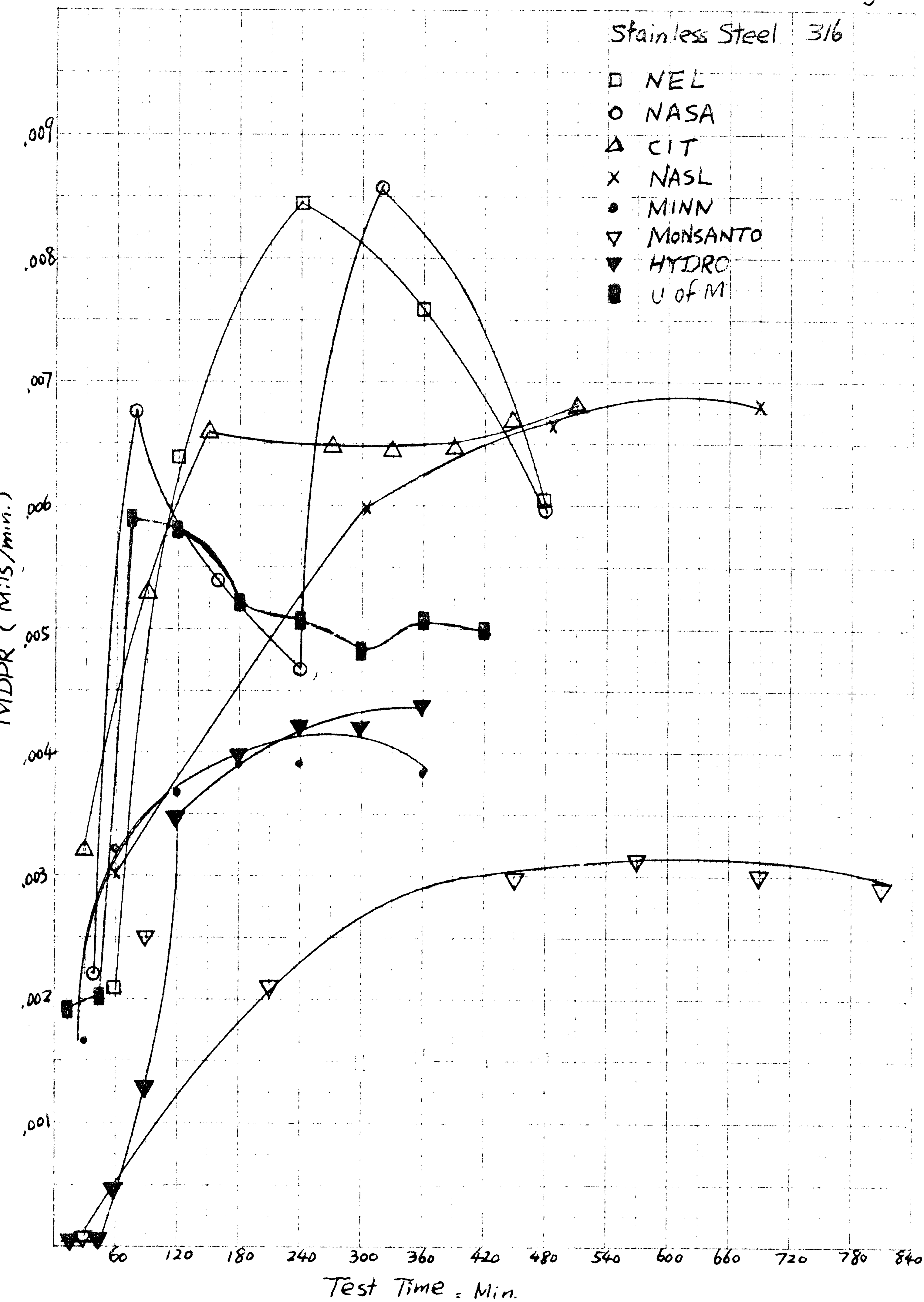

Pure Ni 270
NEL
CIT
NASA
NASL
MINN
MONSANTO
U of M
HYDRO
Accumulative MDP (Mils)
Test Time: Hrs.
0
1
2
3
4
5
6
7

Fig. 12



Al Alloy 6061-T6511
O NASA
□ NEL
Δ CIT
X NASL
● MINN
▽ MONSANTO
▼ HYDRO
Accumulated MDP (Mils)
Test Time : Hrs.
0
2
4
6
8
10
12
14
16
18
20
1
2
3
4
5

Fig. 13



Stainless Steel 316
NEL
NASA
CIT
NASL
MINN
MONSANTO
HYDRO
U of M
.009
.008
.007
.006
.005
.004
.003
.002
.001
MDPR (Mils/min.)
60
120
180
240
300
360
420
480
540
600
660
720
780
840
Test Time = Min.

Fig. 13a

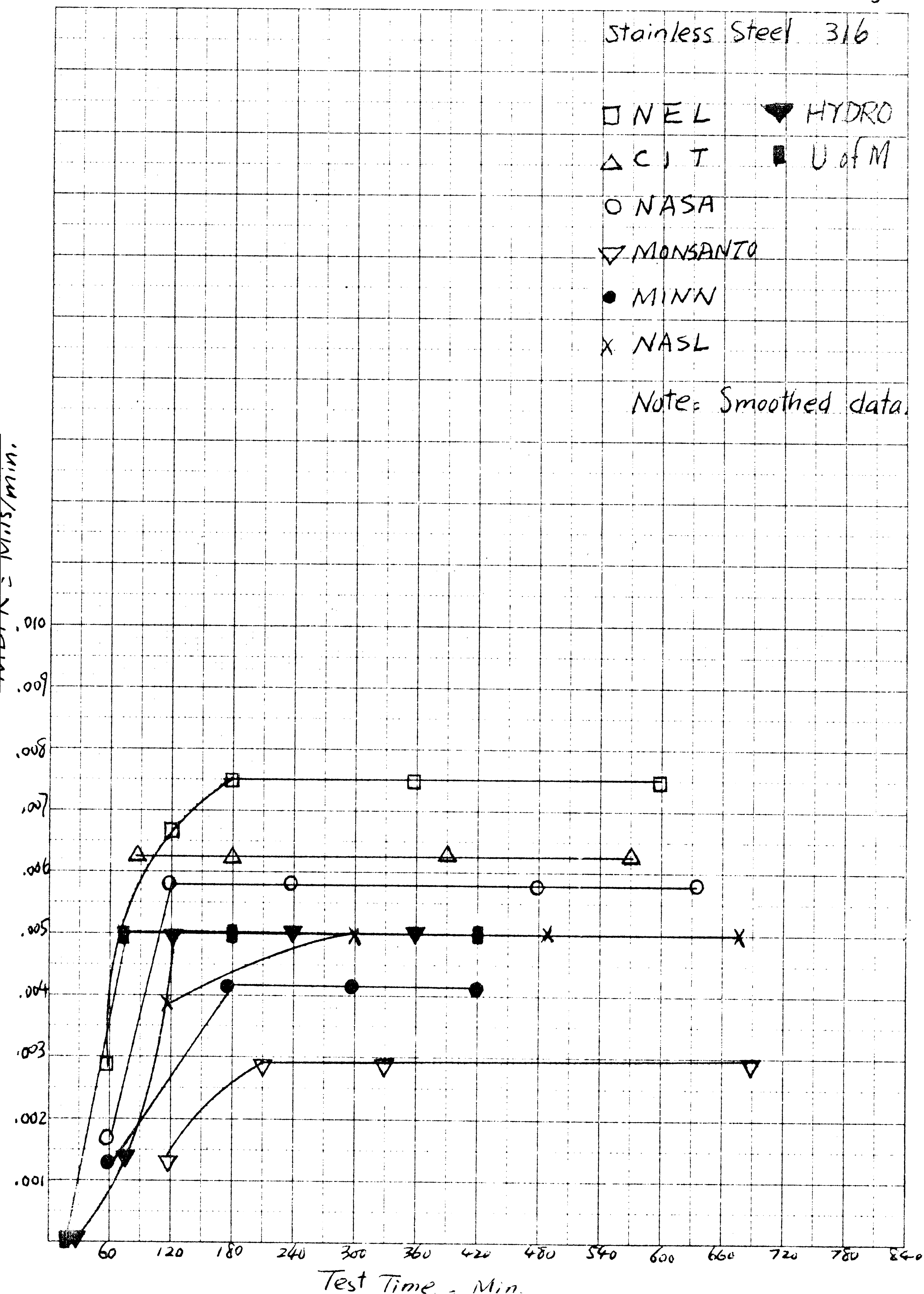
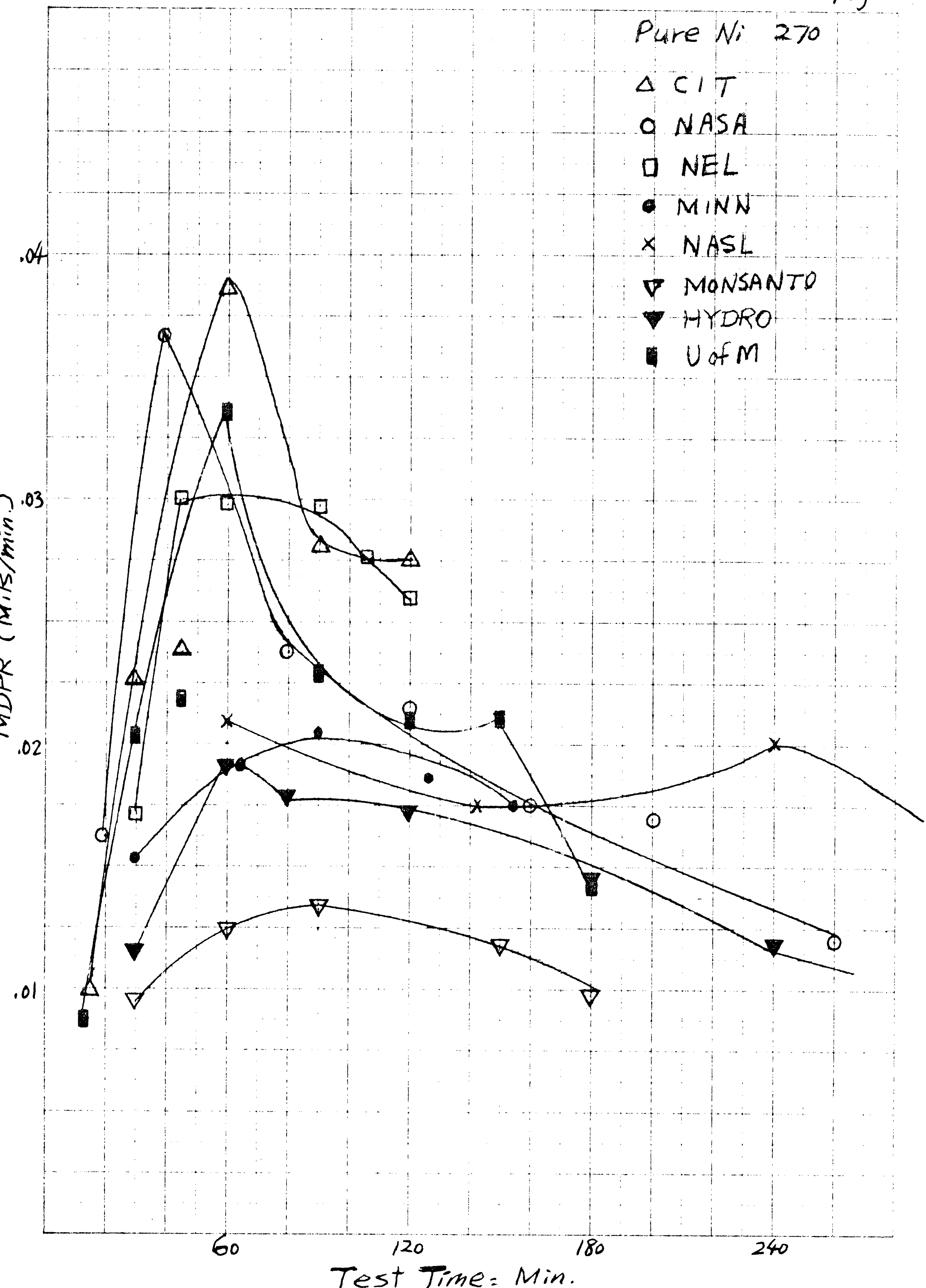
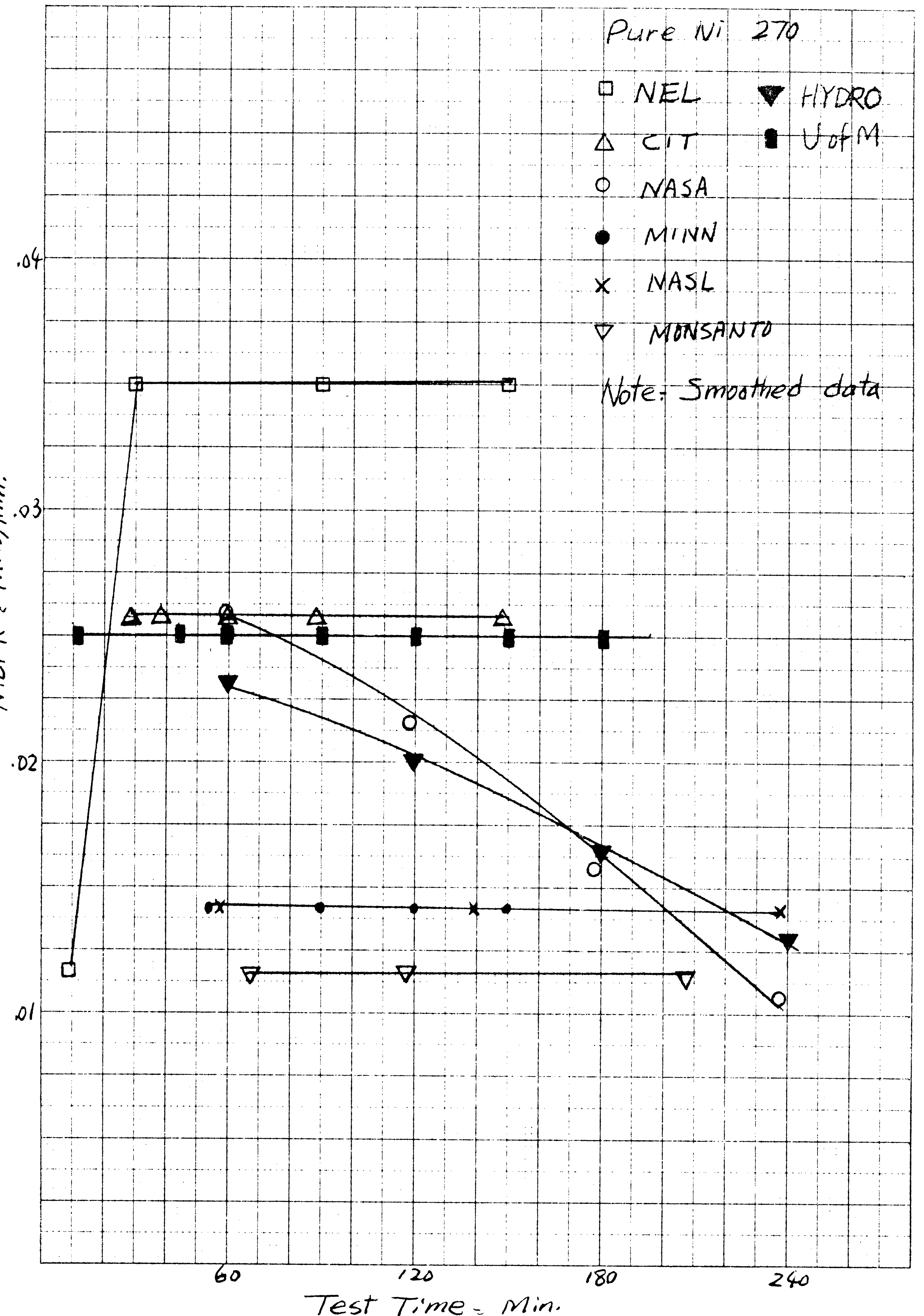

Stainless Steel 316
NEL
CIT
NASA
MONSANTO
MINN
NASL
HYDRO
U of M
Note: Smoothed data.
.010
.009
.008
.007
.006
.005
.004
.003
.002
.001
60
120
180
240
300
360
420
480
540
600
660
720
780
840
Test Time - Min.
Mils/min.

Fig. 14


Pure Ni 270
CIT
NASA
NEL
MINN
NASL
MONSANTO
HYDRO
U of M
.04
.03
.02
.01
MDPR (Mils/min.)
60
120
180
240
Test Time: Min.



Pure Ni 270
NEL
CIT
NASA
MINN
NASL
MONSANTO
HYDRO
U of M
Note: Smoothed data
.04
.03
.02
.01
60
120
180
240
Test Time - Min.

Fig. 14a

Fig. 15

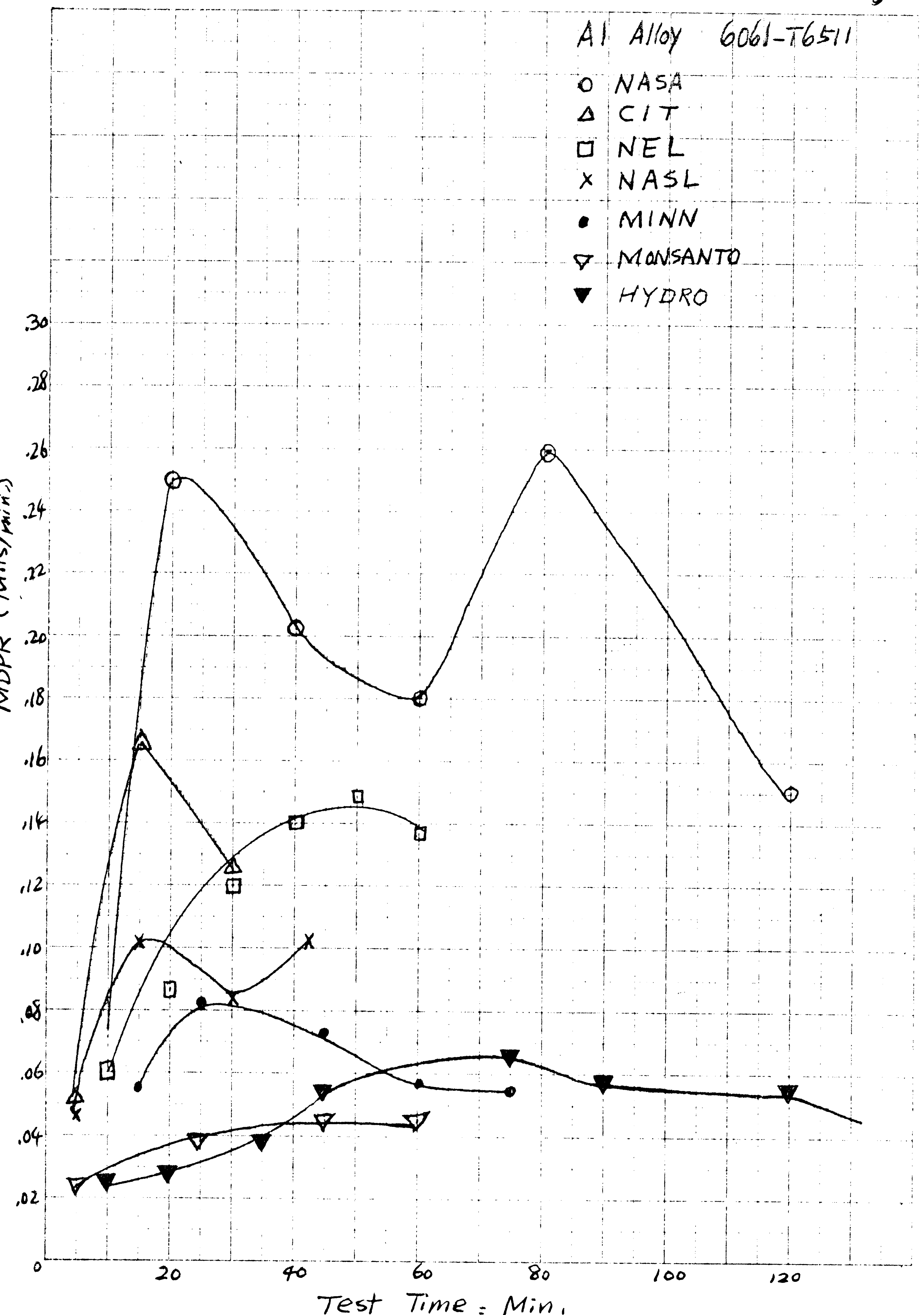

Al Alloy 6061-T6511
NASA
CIT
NEL
NASL
MINN
MONSANTO
HYDRO
.30
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
20
40
60
80
100
120
Test Time - Min.

Fig. 15a

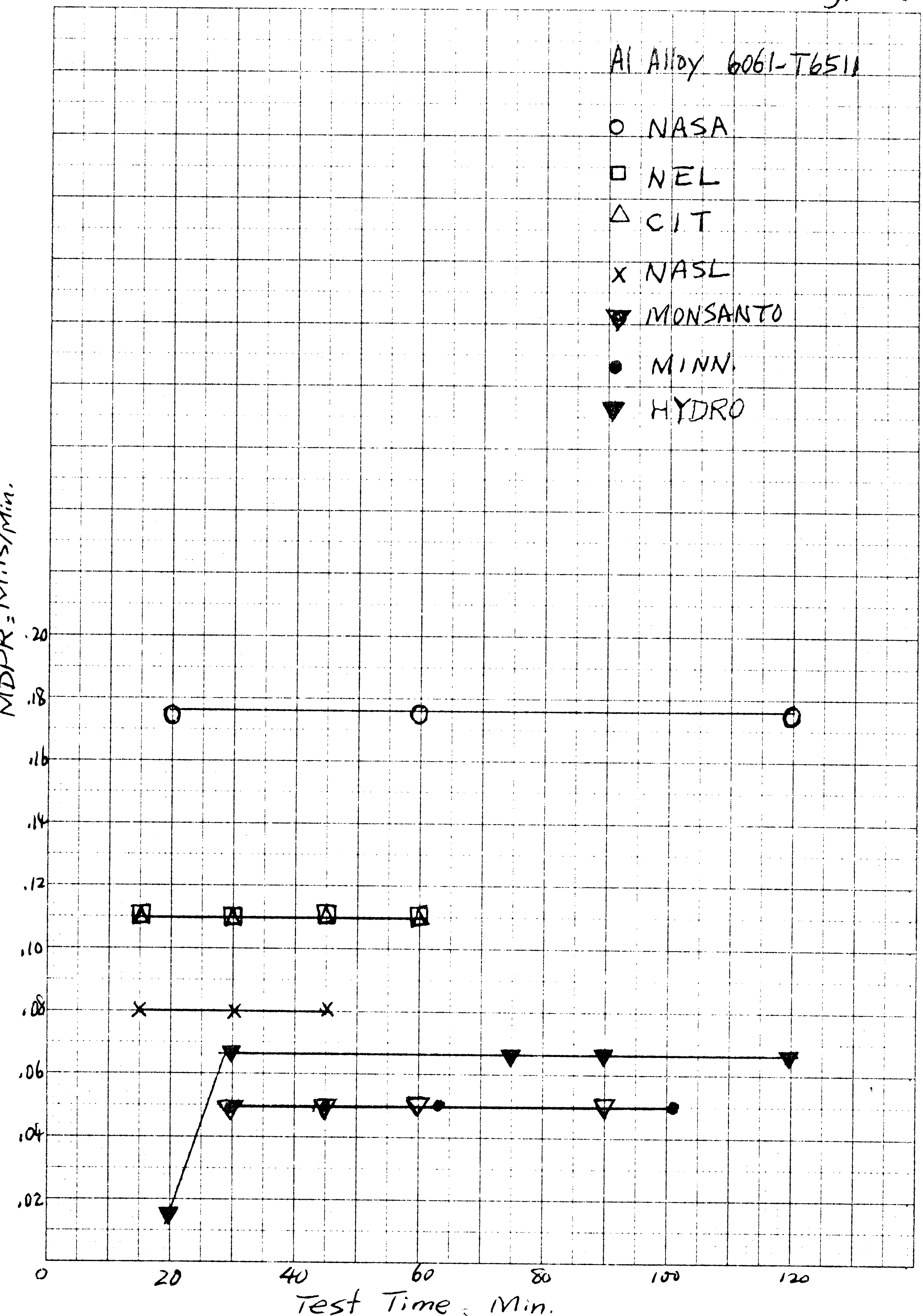
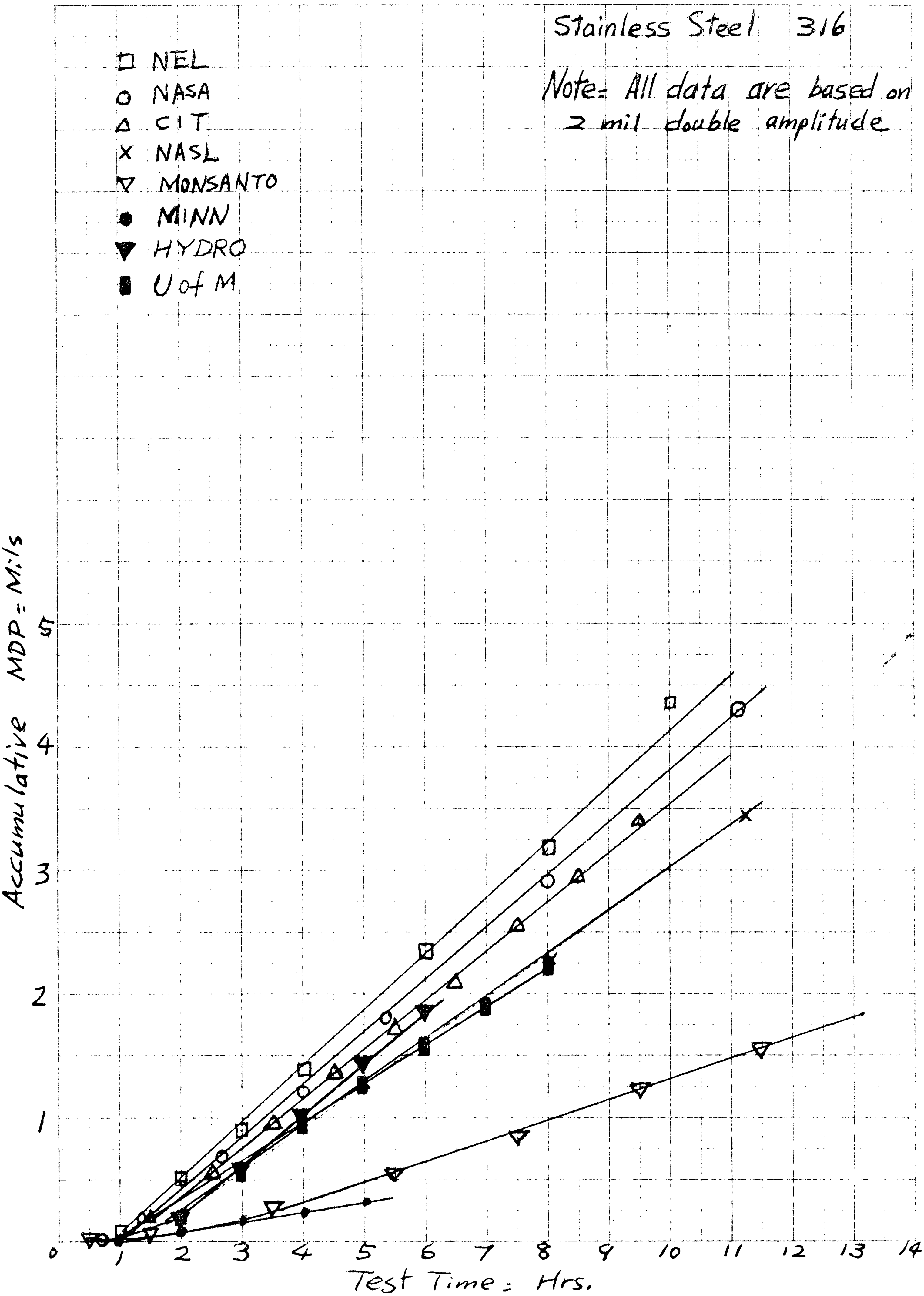

Al Alloy 6061-T651
O NASA
□ NEL
△ CIT
x NASL
MONSANTO
MINN.
HYDRO
MDPR, Mils/Min.
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
20
40
60
80
100
120
Test Time, Min.

Fig. 16



Stainless Steel 316
Note: All data are based on 2 mil double amplitude
□ NEL
○ NASA
△ CIT
× NASL
▽ MONSANTO
● MINN
▼ HYDRO
■ U of M
Accumulative MDP = Mils
Test Time = Hrs.
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

Fig. 17

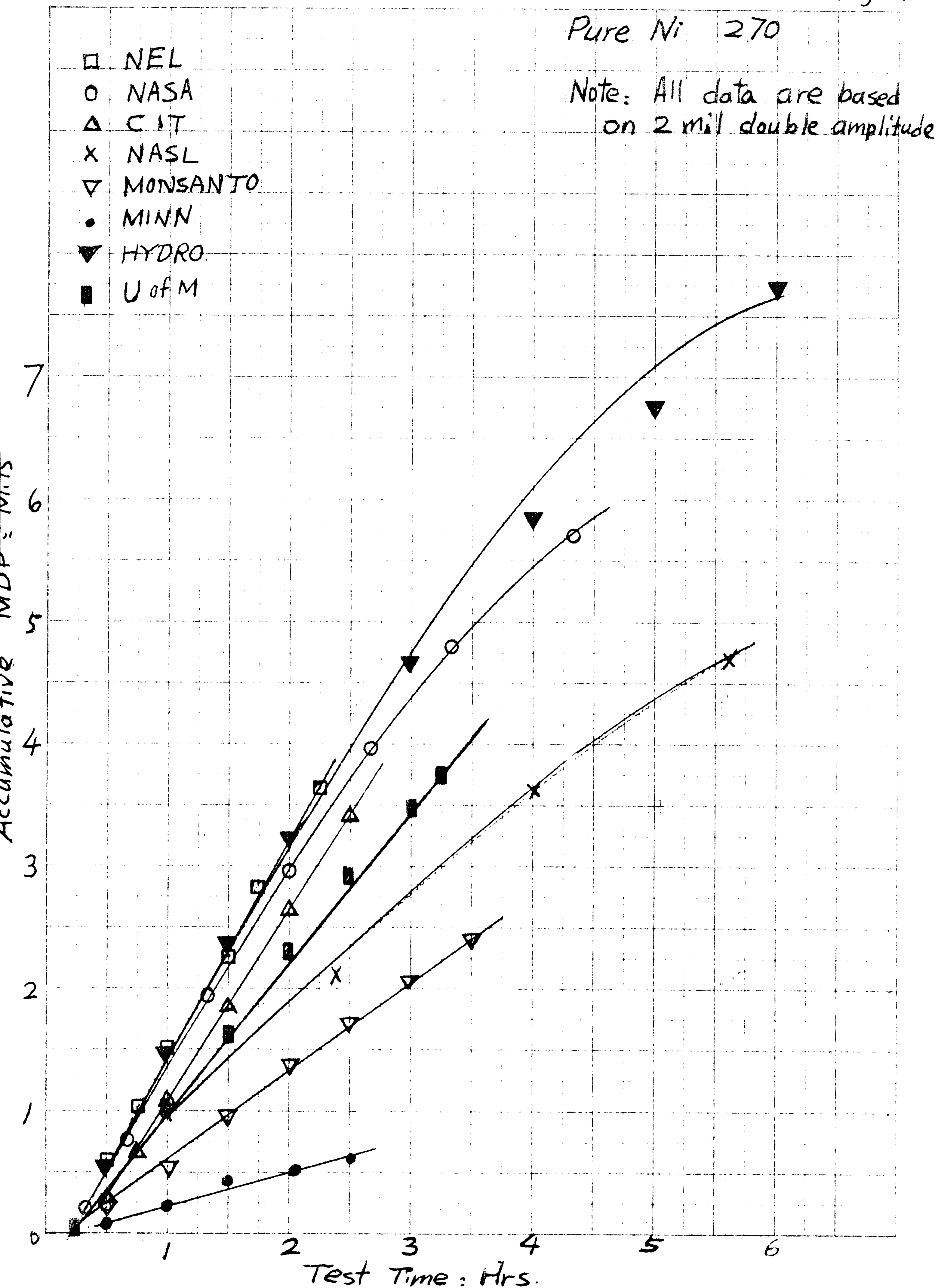
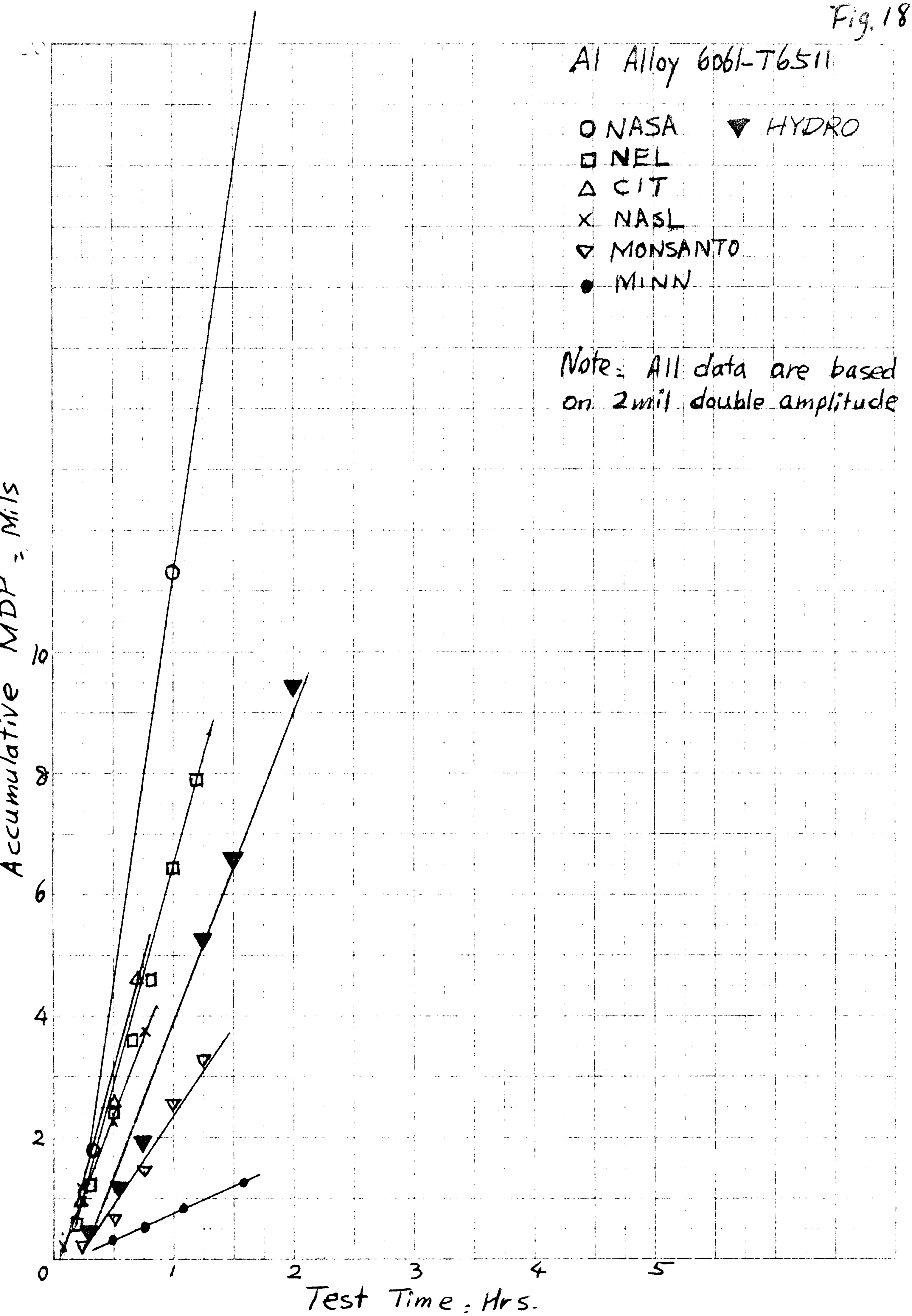
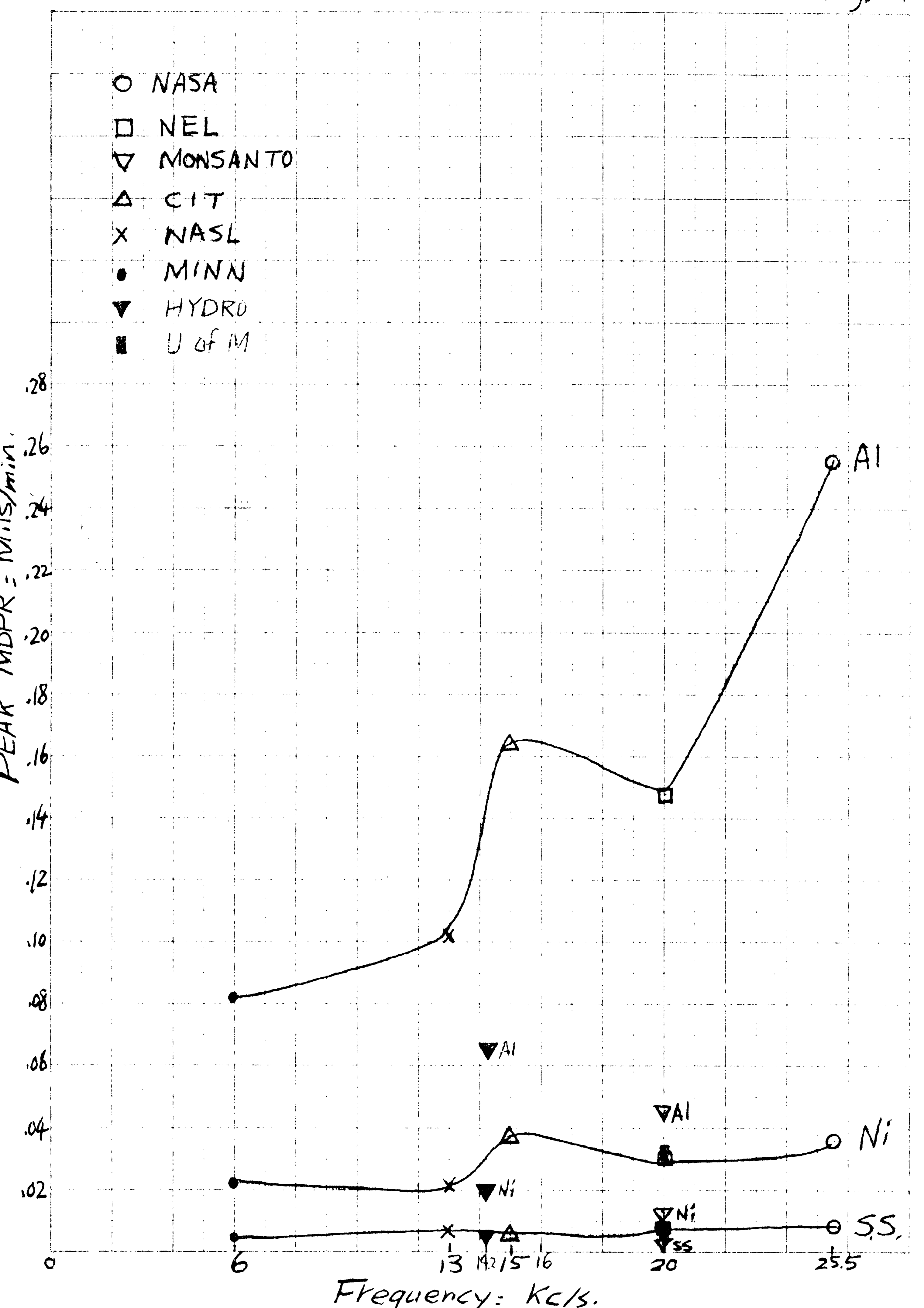

Pure Ni 270
□ NEL
○ NASA
△ CIT
× NASL
▽ MONSANTO
• MINN
▼ HYDRO
■ U of M
Note: All data are based on 2 mil double amplitude
Accumulative MDP : Mils
Test Time : Hrs.
0
1
2
3
4
5
6
7

Fig. 18



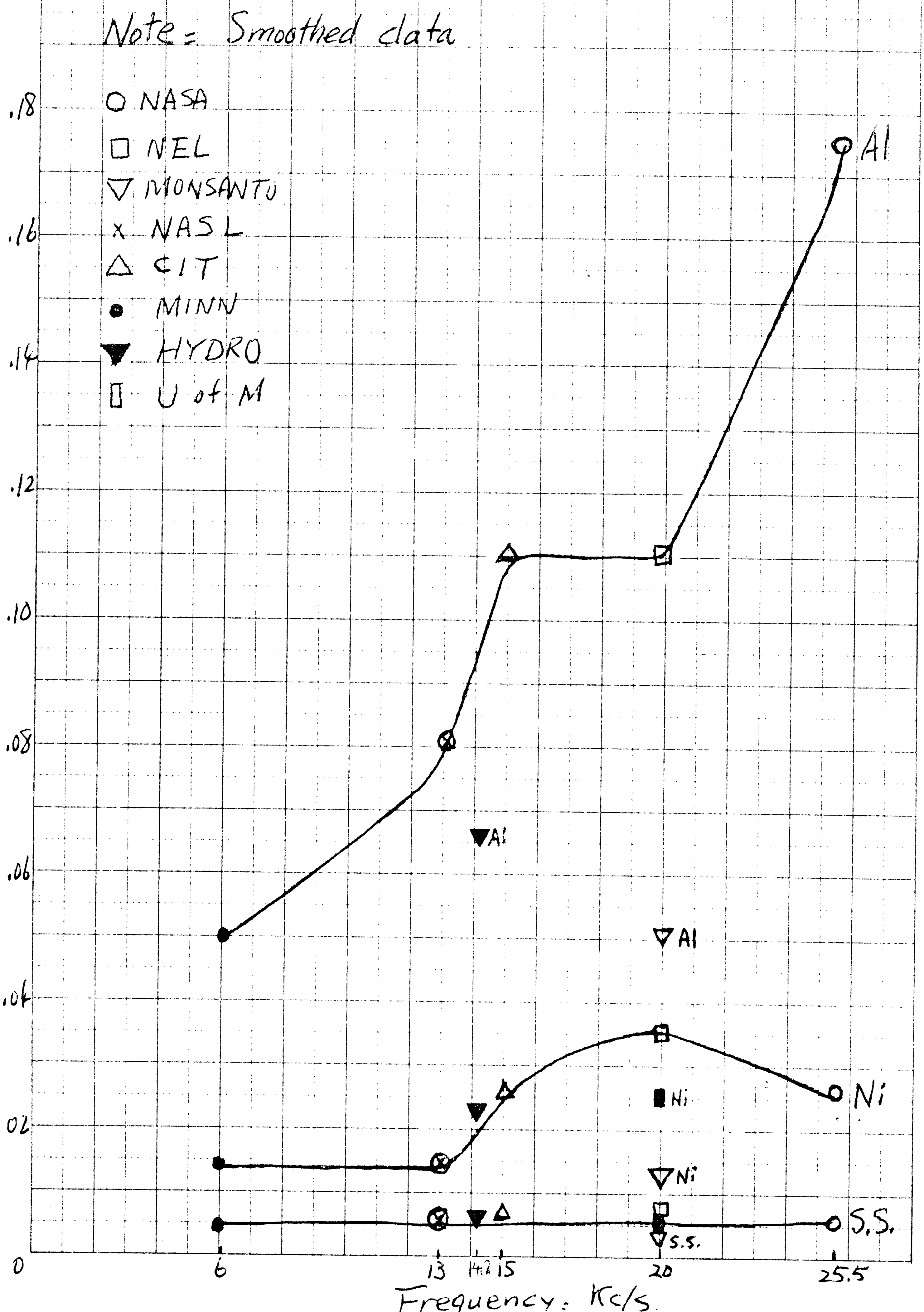
Al Alloy 6061-T6511
NASA
HYDRO
NEL
CIT
NASL
MONSANTO
MINN
Note: All data are based on 2mil double amplitude
Accumulative MDP : Mils
Test Time : Hrs.
0
1
2
3
4
5
2
4
6
8
10

Fig. 19



O NASA
□ NEL
▽ MONSANTO
△ CIT
X NASL
● MINN
▼ HYDRO
■ U of M
PEAK MDPR: Mils/min.
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
6
13
14.2
15
16
20
25.5
Al
Ni
S.S.
SS
Frequency: Kc/s.

Fig. 19a



Note = Smoothed data
O NASA
□ NEL
▽ MONSANTO
x NASL
△ CIT
● MINN
▼ HYDRO
▯ U of M
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
Al
Ni
S.S.
▼Al
▽Al
Ni
▽Ni
S.S.
6
13
14.2
15
20
25.5
Frequency: Kc/s.

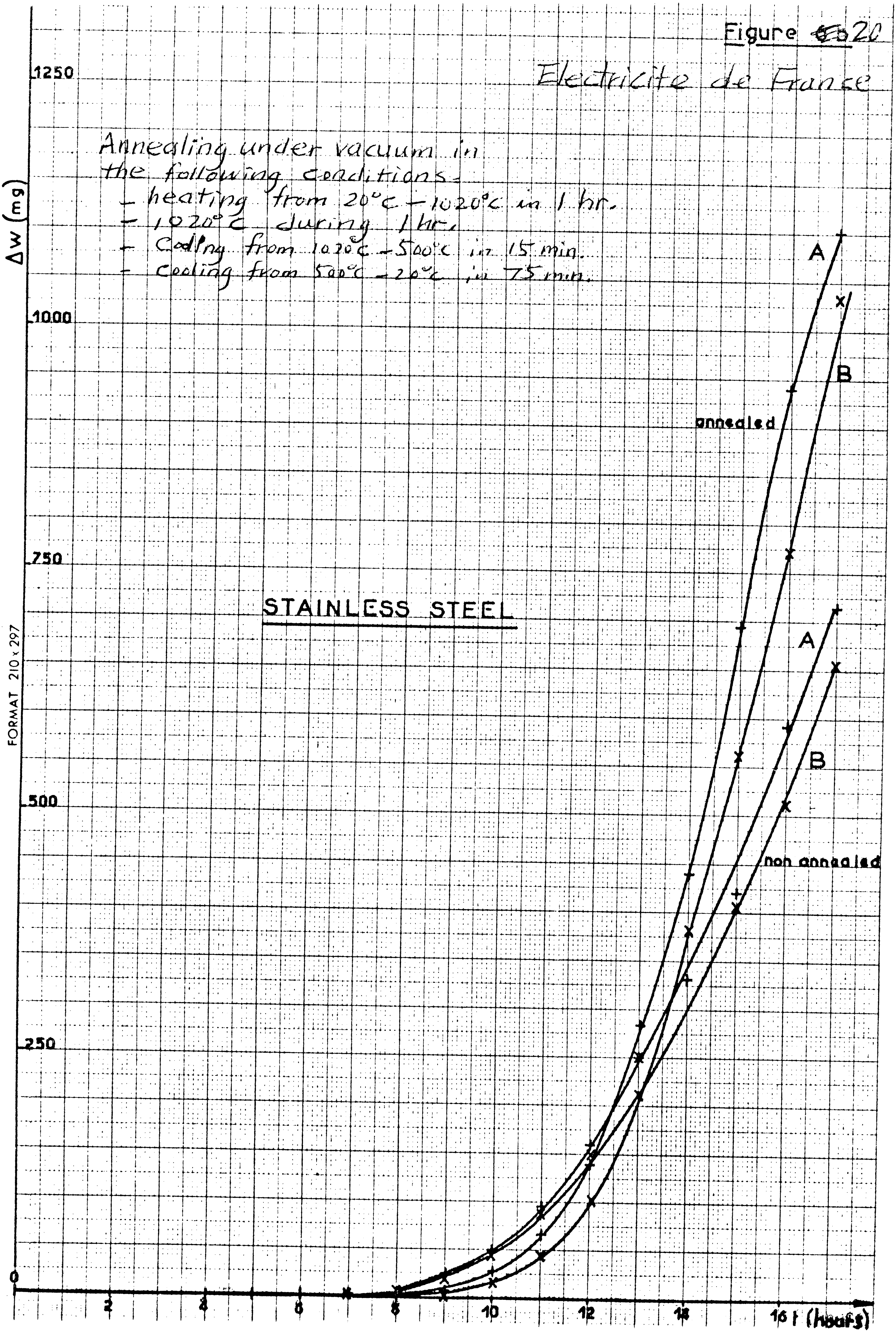

Electricite de France
Annealing under vacuum in the following conditions:
- heating from 20°c - 1020°c in 1 hr.
- 1020°c during 1 hr.
- Cooling from 1020°c - 500°c in 15 min.
- cooling from 500°c - 20°c in 75 min.
STAINLESS STEEL
ΔW (mg)
1250
1000
750
500
250
0
2
4
6
8
10
12
14
16
t (hours)
A
B
annealed
A
B
non annealed
FORMAT 210 x 297

Figure 20

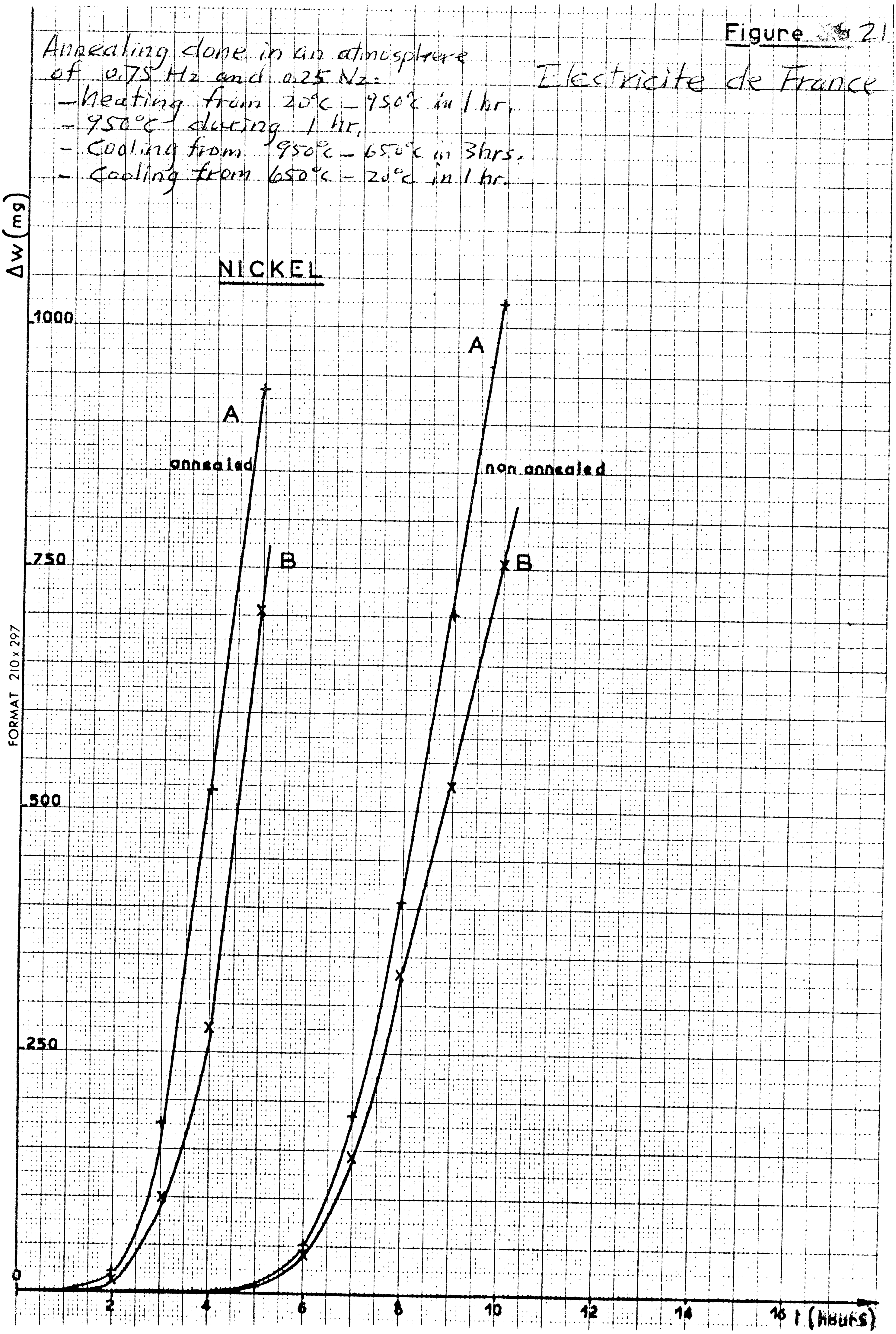


Figure 21
Electricite de France
Annealing done in an atmosphere of 0.75 H2 and 0.25 N2:
- heating from 20°c – 950°c in 1 hr.
- 950°c during 1 hr.
- Cooling from 950°c – 650°c in 3hrs.
- Cooling from 650°c – 20°c in 1 hr.
Δw (mg)
NICKEL
1000
750
500
250
0
A
B
annealed
non annealed
2
4
6
8
10
12
14
16
t (hours)
FORMAT 210 x 297

Figure 22

Electricite de France

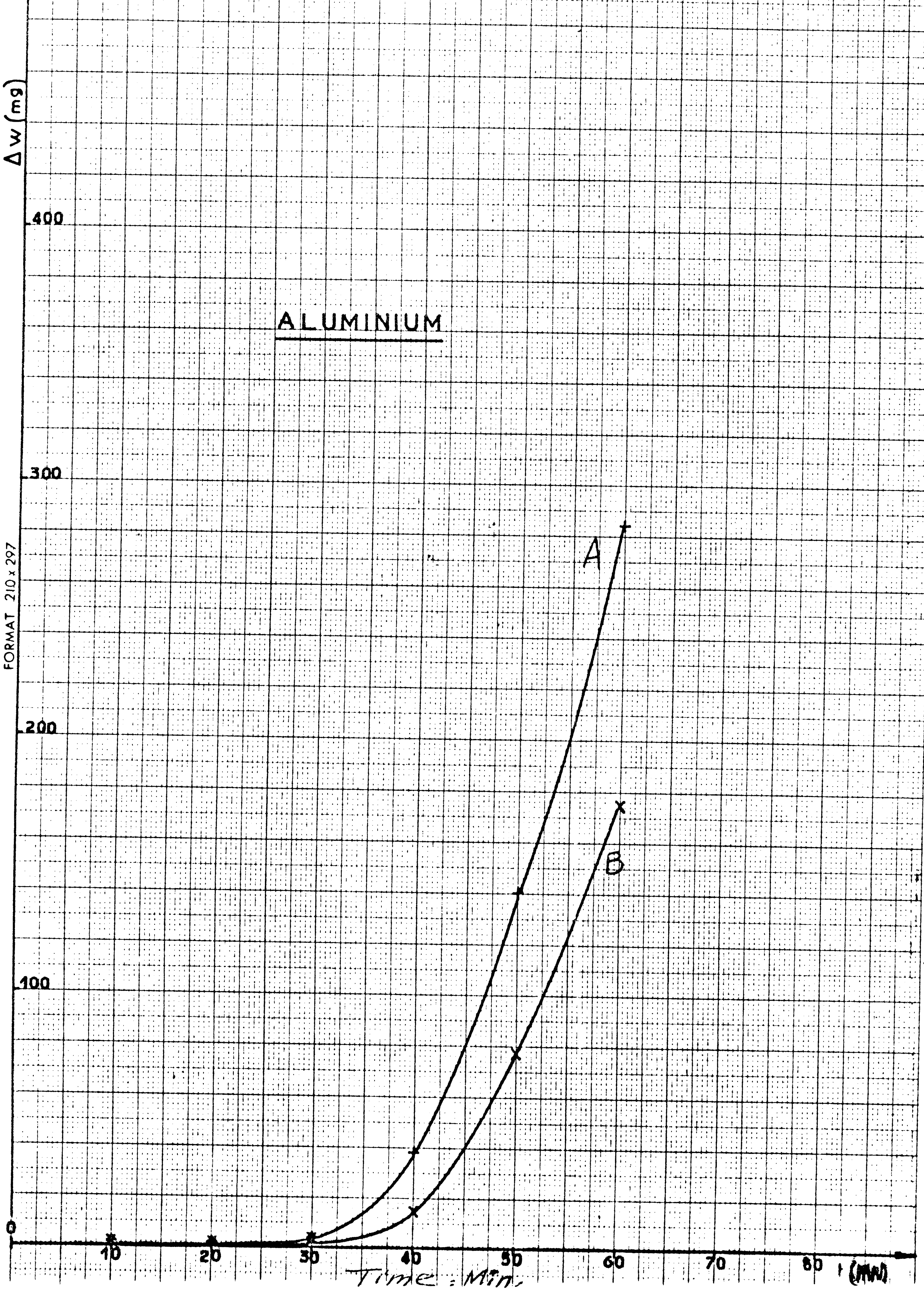


Fig. 22a

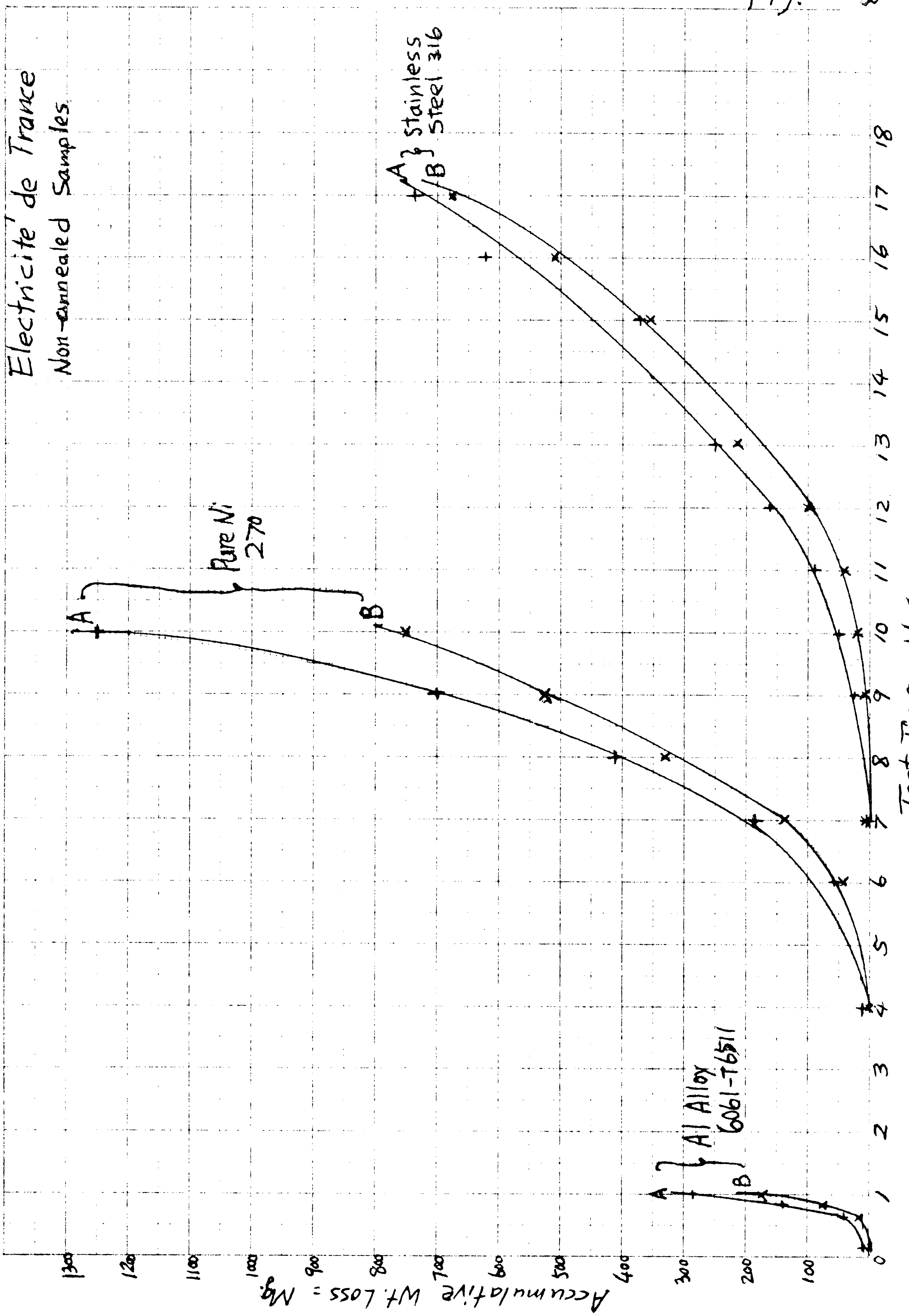
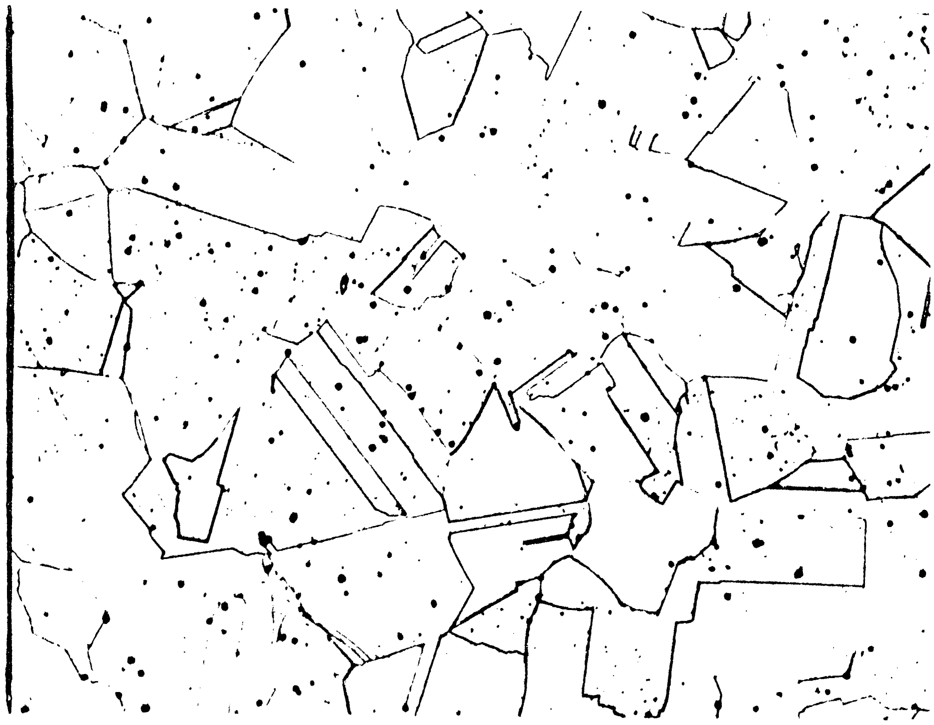

Electricite' de France
Non-annealed Samples
Pure Ni 270
A
B
Stainless Steel 316
A
B
Al Alloy 6061-T6511
A
B
Test Time: Hrs.
Accumulative Wt. Loss = Mg.
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300

Fig. 23

316 Stainless Steel (18 Cr, 13 Ni, 2.5 Mo, 1.6 Mn, Bal. Fe)



250X

Etchant: 30 ml HCl, 30 ml Glycerine
10 ml HNO_3 + Electrolytic

Grain Size: No. 4*
(8 grains/square inch at 100X)

Fig. 24

Ni-270 (99.98% Ni)

(250 X)

Etchant: 92% HCL, 5% H_2SO_4, 3 HNO_3

Grain Size: Two different grain sizes:
Approx. 60% Grain size 0*
(1/2 grain/square inch at 100X)

Approx. 40% Grain size 2*
(2 grains/square inch at 100X)

*ASTM Austenite Grain Size Standard
Measured by use of Grain size measuring eyepiece, and comparison of 100X photomicrograph with ASTM standard grain size charts.

Fig 25

6061-T6511 Aluminum
(1.0% Mg, 0.6% Si, 0.25% Cu, 0.25% Cr, Bal Al)

250X

Etchant: 30 ml Glycerine, 20 ml HNO_3
10 ml HF

No grain boundaries visible.