UNIVERSITY OF MICHIGAN

DEPARTMENT OF MECHANICAL ENGINEERING AND APPLIED MECHANICS
Cavitation and Multiphase Flow Laboratory

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CAVITATION EROSION VIBRATORY TESTS

by

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M.E. 490 - Winter Term

under the supervision of:

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CAVITATION THEORY AND MEASUREMENT OF EROSION

Cavities form when the local pressure of a liquid is reduced below the vapor pressure. These cavities,after growing,collapse by moving to zones of higher pressure or undergoing a local pressure rise. The collapse of the vapor cavities causes waves of very high intensity pressure which can damage structural material by compression fatigue.

The erosion is not uniform microscopically.This is because the damage of individual pressure waves is function of the distance from the collapse point to the surface of the solid.

To measure cavitation damage the specimens were weighed after certain increments of time and the MDPR (Mean Depth of Penetration Rate) was found and plotted as a function of the Total (Cumulative) Time. MDPR is calculated from :

$$MDPR = \frac{W}{\rho A t}$$

Where : W = cumulative weight loss (milligrams)

ρ = density of specimen (gram/cubic ~~inches~~) (g/cc)

t = cumulative time (hr)

A = Area (in^2)

The units of MDPR is (mils/hr).This method has been followed for the Venturi and vibratory systems.

THE VIBRATORY SYSTEM

DESCRIPTION

e system is shown in Fig.1.It consists of an oil bath,a vessel,a Titanium horn,and a power pply.The horn is attached to a crystal,vibrating with a maximun amplitude of 3.0 mils. essure can be applied on the vessel by compressed air.The specimen is applied on top of e horn.

The reduction of pressure,for cavitation ,is obtained by vibrations transmitted the horn by the piezoelectric crystal.The high acceleration obtained produces regions high and low pressure which cause the bubbles,existing in rough surfaces,to grow and llapse in zones of high pressure.The collapse produces very high pressures at the center the bubble which lead to high intensity waves (because of acceleration),that damage e material.

RESULTS AND CONCLUSIONS

total of 18 tests were done on different materials,under different conditions.

CAST IRON	#2 & #5 :	160 F,19.5 PSI, 1.78 mils.
C.S. 1018	#4 & #6 :	200 F,26.2 PSI, 1.38 mils.
	#5 & #9 :	200 F,26.2 PSI, 1.78 mils
	#11 & #14:	80 F, 1.0 ATM, 1.78 mils
S.S. 316	#10 & #15:	200 F,26.2 PSI, 1.78 mils
	#5 & #8 :	160 F,19.5 PSI ,1.78 mils
	#6 & #7 :	160 F,19.5 PSI, 1.38 mils
	#9 & #11:	80 F, 1.0 ATM, 1.78 mils
	#13 & #14:	80 F, 1.0 ATM. 2.00 mils

n the following pages the graphs and calculations (done by Mr.J.He) are included.

onclusions : CAST IRON . Cast Iron shows a rapid increase in the MDPR in the first hour of test.This is observed for both specimens, and it suggests it cannot be a simple error in the experiment .It is probably due to the structure of Cast Iron.

C.S. 1018 . The same sharp and rapid increase in the MDPR is also seen in C.S. 1018.
Comparing the results of specimens #4 & #6 (200 F,26.2 PSI, 1.38 mils with the results of specimens #5 & #9 (200 F, 26.2 PSI, 1.78 mils), is clear that there is a sharp increase in weight loss,and in MDPR (both Max. & Avg.) when the amplitude is raised from 1.38 mils to 1.78 mils. (the increase in MDPR Avg. is +78%).This suggests that the MDPR is a function of the amplitude.

S.S. 316 . Comparing the results of #5 & 8 (160 F, 19.5 PSI, 1.78 mils) and #6 & 7 (160 F, 19.5 PSI, 1.38 mils) we can see,from the graphs that there is a sharp increase in weight loss and MDPR Max. and Avg.,when the amplitude is increased.(the increase in MDPR Avg. is +164.16%).As in case of the C.S. 1018 the MDPR is a function of amplitude as a function of amplitude is also the weight loss. The relation between MDPR and amplitude is :

$$\text{Max.MDPR} \propto A^{x}$$

To calculate x more tests should be done.

The conclusions on the previous specimens also apply in the case of specimens #9 & 11 (80 F, 1 ATM., 1.78 mils) and specimens #13 & 14 (80 F, 1 ATM., 2.0 mils).Both the MDPR and the weight loss increase increasing the amplitude.
Comparing S.S. 316 #5 & 8 (160 F, 19.5 PSI, 1.78 mils) with Cast Iron #2 & 5 (160 F, 19.5 PSI, 1.78 mils) is evident that in S.S. 316 both the MDPR and the weight loss are lower than in Cast Iron, suggesting that Stainless Steel is less subject to cavitation than Cast Iron.
The same is true,and more evident,when S.S. 316 #10 & 15 (200 F, 26.2 PSI, 1.78 mils) is compared to C.S. 1018 #5 & 9 (200 F, 26.2 PSI, 1.78 mils).

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From all the plot and date regarding MDPR vs. time,it appears that the rate is low in the first part of the test,probably because the surface of the sample is smooth; after a certain amount of time (and damage has occured) the rate is high because of the rough surface and the large number of bubble growth centers present.After a long time the rate decreases because more damage does not change the roughness of the surface. This is probably due to the fact that for the formation of a bubble, is required a nucleus,and nuclei are available in small numbers at the beginning of the test,and at the end the number of nucleation points remains constant.

MATERIAL DAMAGE SHEET · Messerschmitt Belt

RN: Ti

PLITUDE: 1.38 mils

TER:

MPERATURE: 200°F

ESSURE: 26.2 PSIa

RQUE:

E-RUN:

MATERIAL: CS 1010

NUMBER: #4

APPROX. DATE: 5/64

DENSITY:

AREA:

M. D. P. FACTOR: C=0.033085 mil/mg

MMENTS:

+12% difference of MDPR across the W.L.

$MDPR_{MAX} = 0.382$ mil/hr
9.706 μm/hr

$MDPR_{AVG} = 0.250$ mil/hr.
6.350 μm/hr

$I_P = 3.5$ mins

Operator: MrHSu

DATA

E ERVAL	CUMULATIVE TIME	WEIGHT LOSS	CUM. WT. LOSS	M. D. P. μm/hr	M. D. P. R. mil/hr
7	0	0	0		
5	15	1.05	1.05		0.1390
5	40	2.65	3.70		0.2104
0	60	2.65	6.35		0.2670
0	80	3.85	10.20	9.706	0.3821
0	100	3.35	13.55		0.3325
0	120	2.50	16.05		0.2481
0	140	2.45	18.50		0.2432
0	160	1.65	20.15		0.1638
				AVG:	..
				6.350	0.2500

MATERIAL DAMAGE SHEET

RN: Ti

MATERIAL: CS 1018

IPLITUDE: 1.38 mils

NUMBER: #6

TER:

APPROX. DATE: 6/20/80

MPERATURE: >200°F

DENSITY:

ESSURE: >6.2 psia

AREA:

RQUE:

M. D. P. FACTOR: C = 0.033085 mil/mg

E-RUN:

MMENTS:

$MDPR_{max} = 0.331$ mil/hr

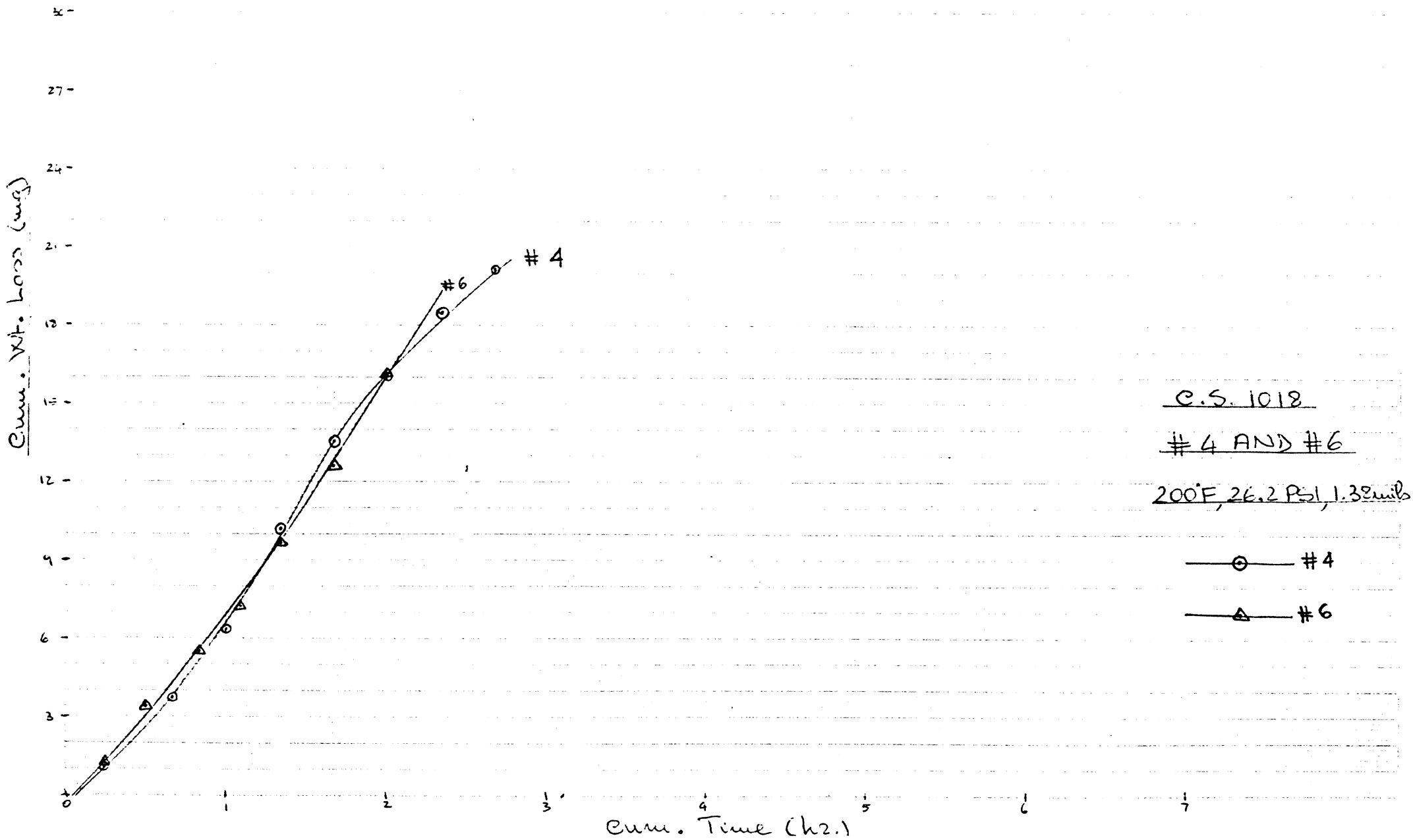
$MDPR_{AVG} = 0.2666$

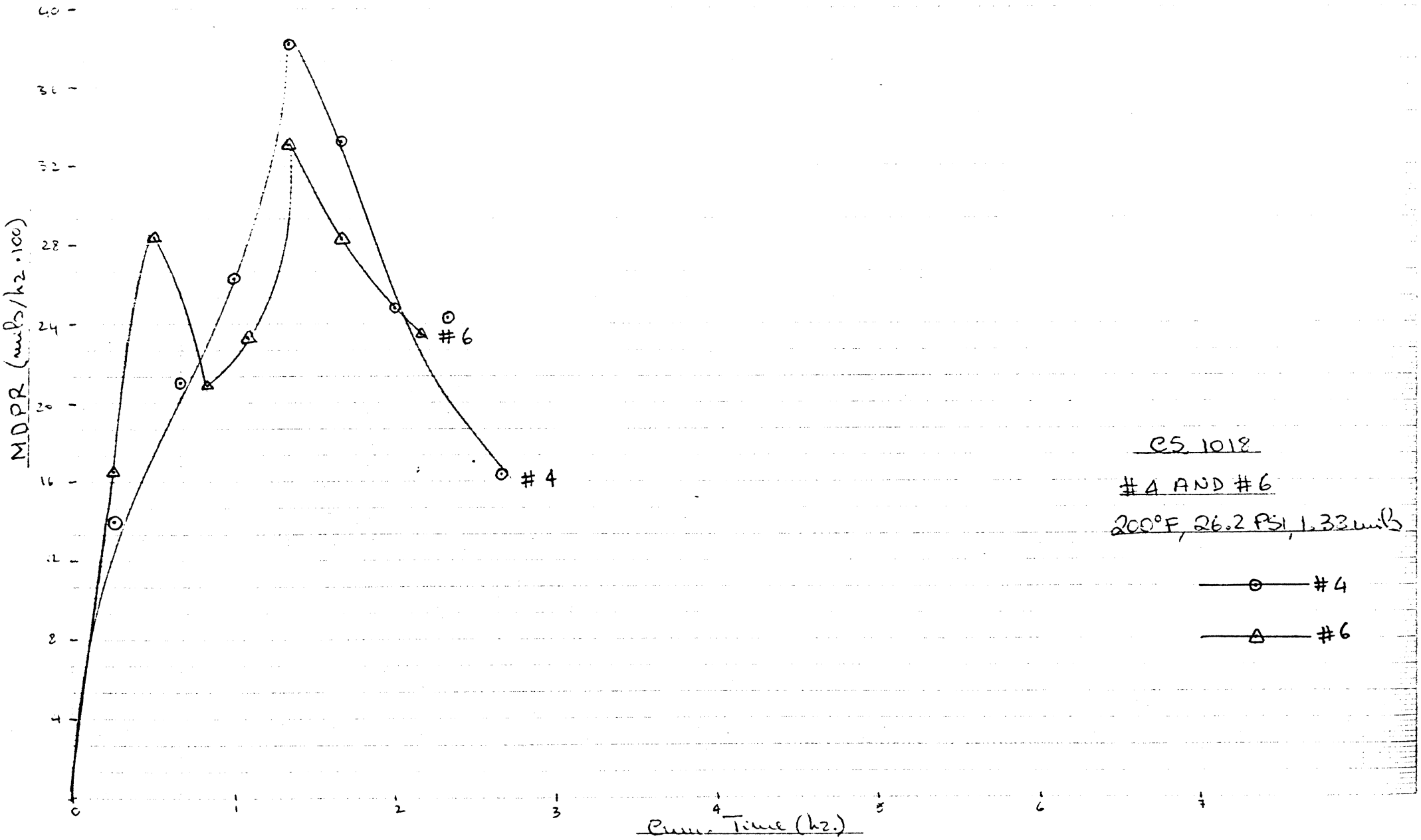
Operator: Mr. HSu

$IP_{0.1mil} = 35$

DATA

ME ERVAL	CUMULATIVE TIME	WEIGHT LOSS	CUM. WT. LOSS	M. D. P. μm/hr	M. D. P. R. mil/hr
0	0	0	0		
5	15	1.75	1.75		0.1654
5	30	2.15	3.90		0.2545
0	50	2.10	5.50		0.2084
5	65	1.75	7.25		0.2316
5	80	2.50	9.75	8.404	0.3309
0	100	2.85	12.60		0.2829
0	130	3.55	16.15		0.2350
				AVG	
				6.264	0.2466


Cum. Wt. Loss (mg)
Cum. Time (hrs.)
#4
#6
C.S. 1018
#4 AND #6
200°F, 26.2 PSI, 1.38 mils
#4
#6


MDPR (mils/hr · 100)
Cum. Time (hr.)
#6
#4
CS 1018
#4 AND #6
200°F, 26.2 PSI, 1.33 mils
#4
#6

MATERIAL DAMAGE SHEET

RN: Ti
MATERIAL: CS 1018
PLITUDE: 1.78 mil
NUMBER: # 5
TER:
APPROX. DATE: 6/12 /'20
MPERATURE: 200°F
DENSITY:
ESSURE: 26.2 PSIa
AREA:
RQUE:
M. D. P. FACTOR: C = 0.033065 mil/mg
E-RUN:

MMENTS:

$MDPR_{MAX} = 0.625$ mil/hr $= 15.883$ μm/hr

$MDPR_{AVG} = 0.433$ mil/hr $= 11.09$ μm/hr

$IP_{0.1\,mil} = .21$ mins

Operator Mr. Hsu

DATA

ME ERVAL	CUMULATIVE TIME	WEIGHT LOSS	CUM. WT. LOSS	M. D. P. μm/hr	M. D. P. R. mil/hr
0	0	0	0		
0	10	1.50	1.50		0.2978
0	30	3.25	4.75		0.3226
0	60	5.75	10.50		0.3505
0	80	5.00	15.50		0.4963
0	90	3.15	18.65	15.883	0.6253
0	100	2.90	21.55		0.5757
0	120	5.85	27.20		0.5608
0	140	5.55	32.75		0.3672
				AVG:	
				11.209	0.4232

MATERIAL DAMAGE SHEET

V

)RN: Ti

MATERIAL: CS1018

MPLITUDE: 1.78 mils

NUMBER: #9

ATER:

APPROX. DATE: 6/16/80

MPERATURE: >200°F

DENSITY:

ESSURE: 262 psia

AREA:

)RQUE:

M.D.P. FACTOR: C=0.033085 mil/mg

.E-RUN:

)MMENTS:

$MDPR_{max} = 0.635$ mil/hr

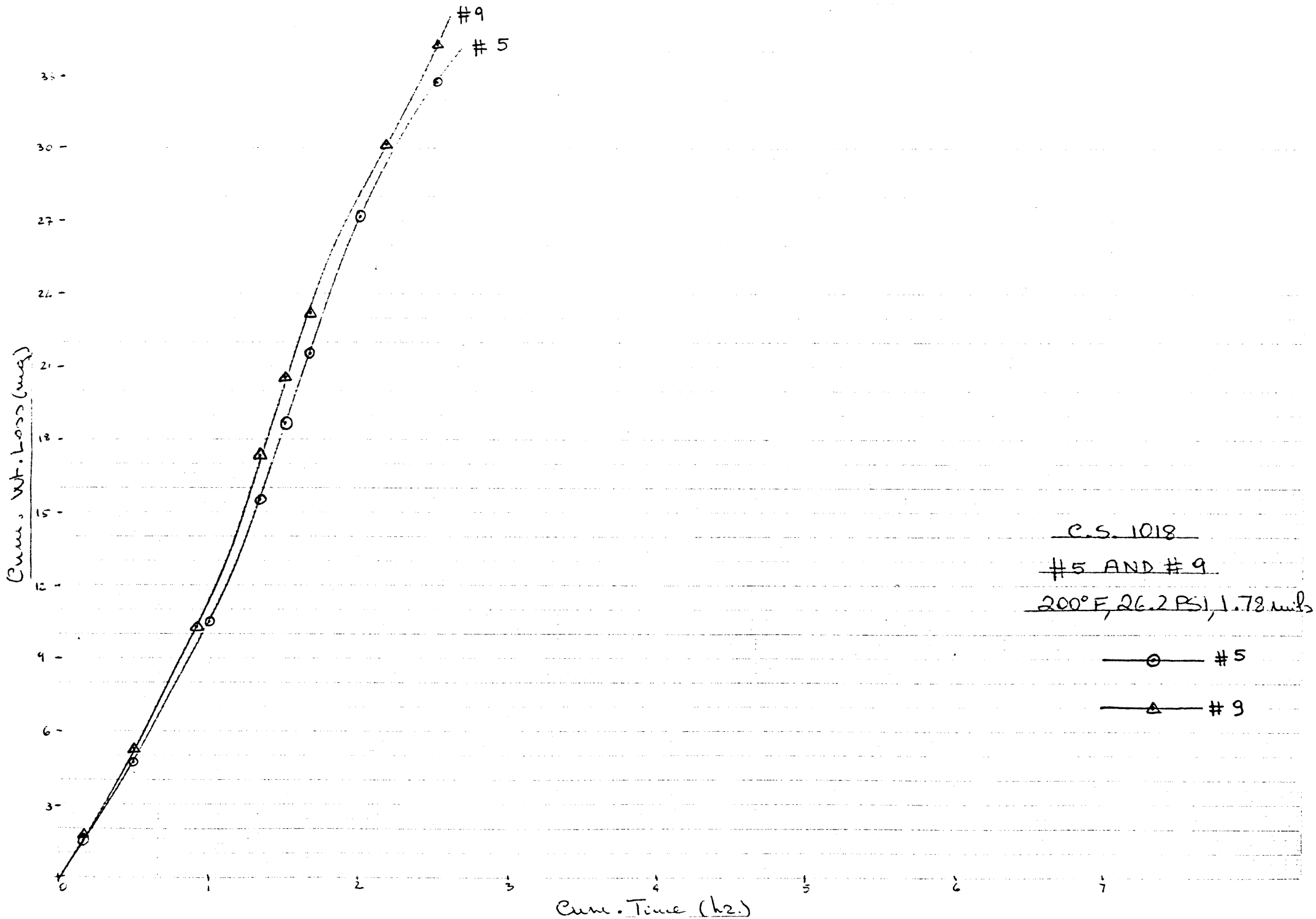
$MDPR_{AVG} = 0.453$

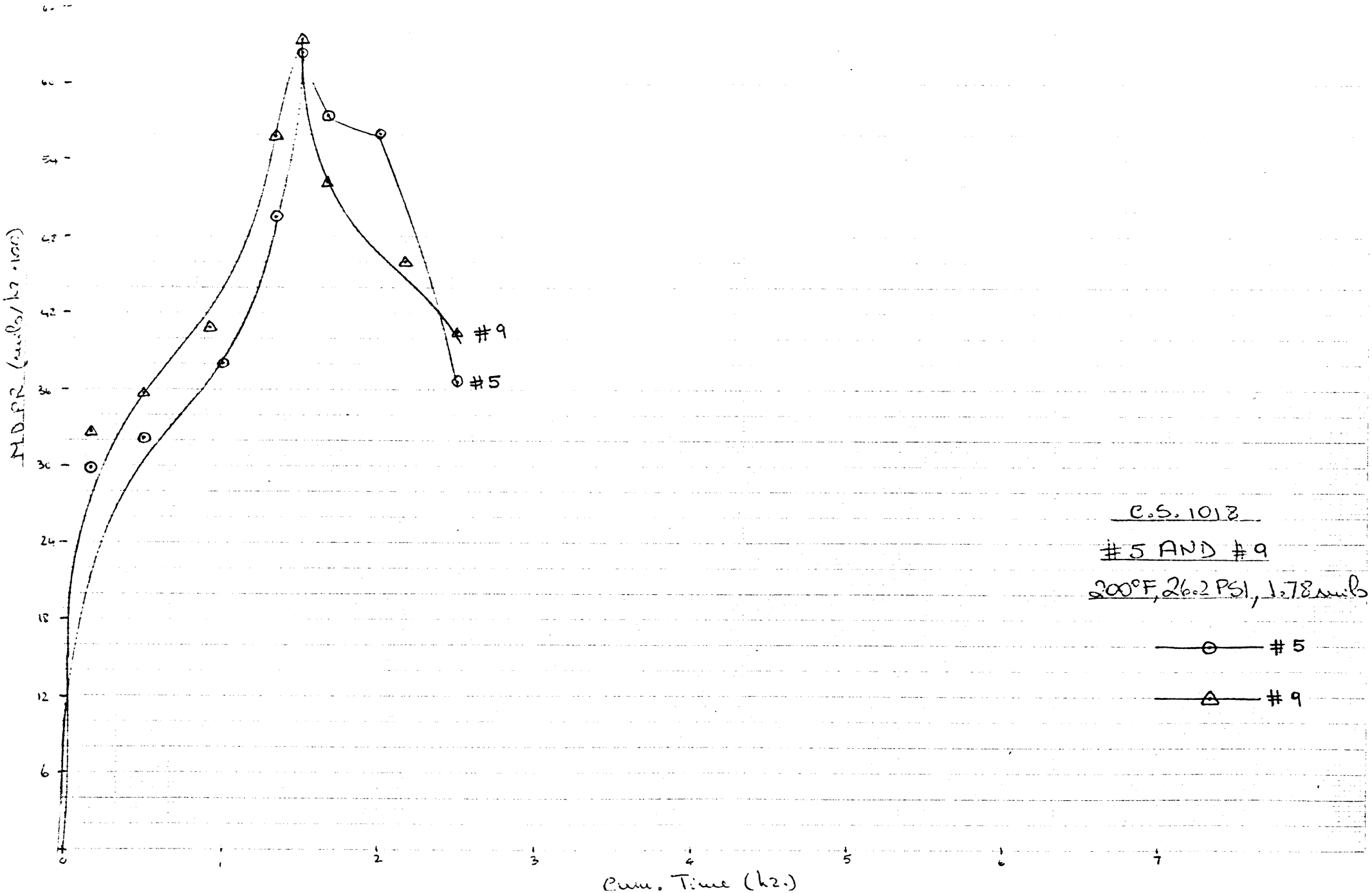
$T.P._{0.1\,mil} = 20$ min

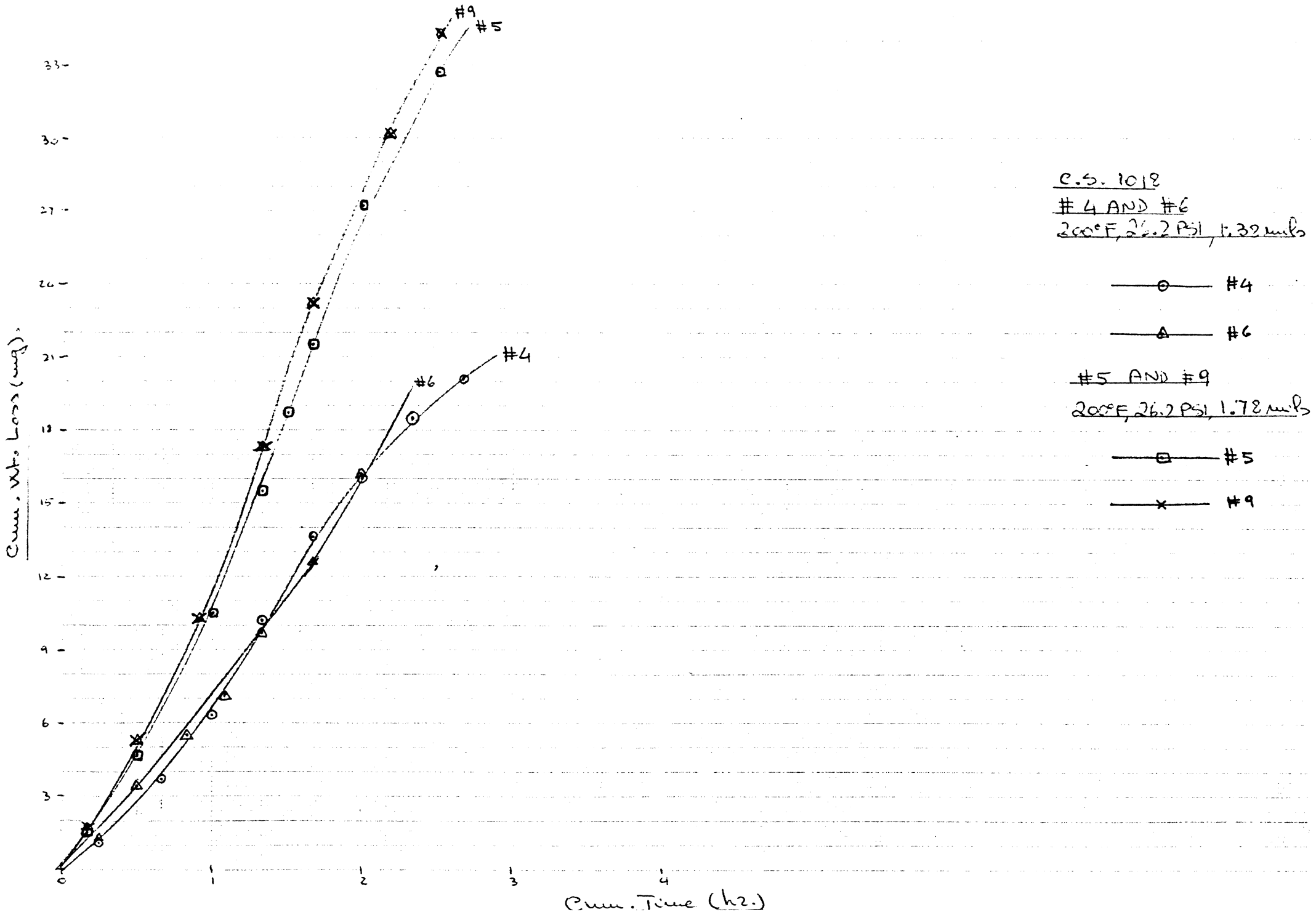
Operator: Mr. Hsu

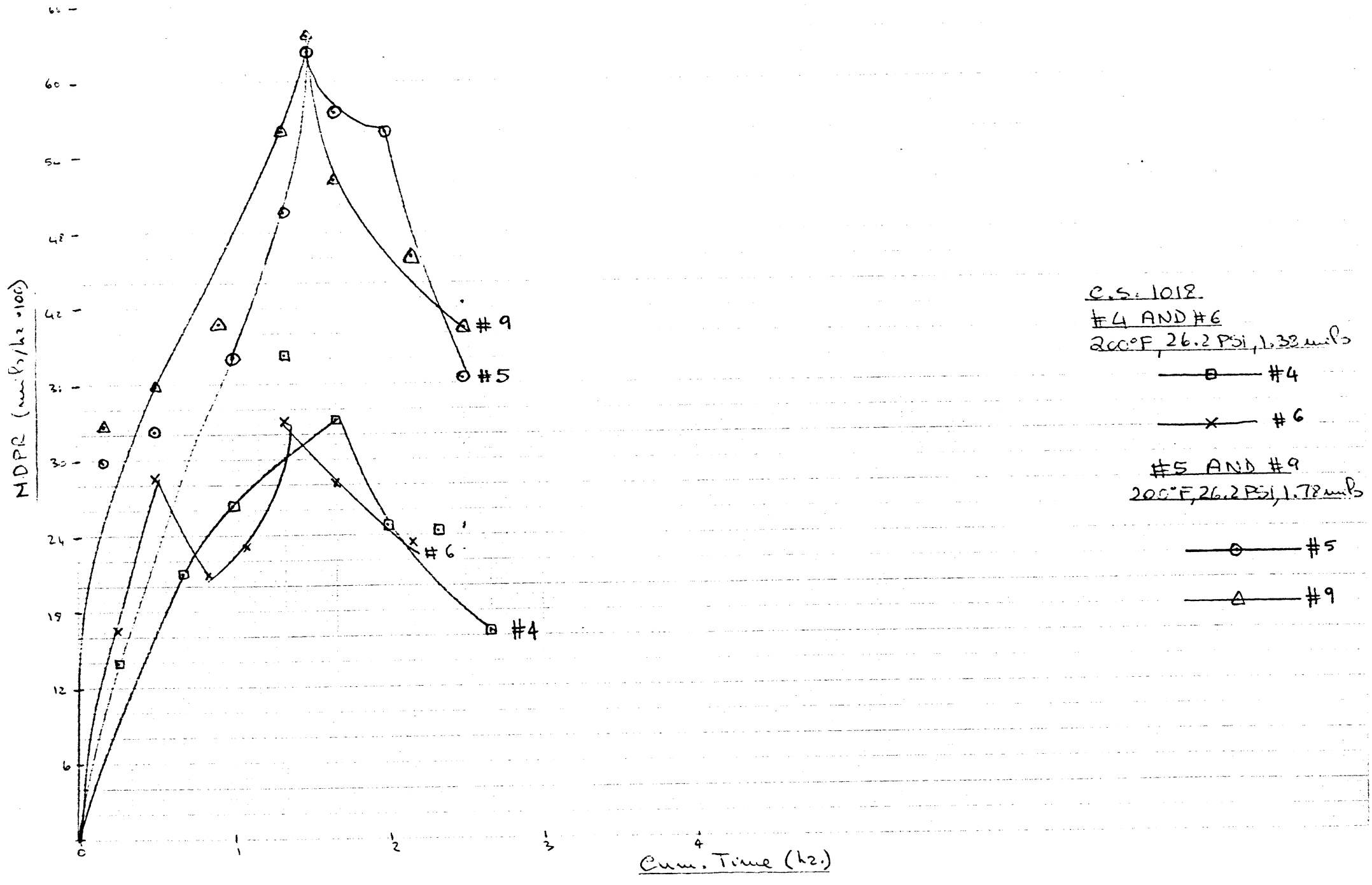
DATA

ME TERVAL min	CUMULATIVE TIME min	WEIGHT LOSS	CUM. WT. LOSS	M.D.P. μm/hr	M.D.P.R. mil/hr
0	0	0	0		
10	10	1.65	1.65		0.3275
20	30	3.60	5.25		0.3573
35	65	5.05	10.30		0.4090
25	80	7.05	17.35	14.219	0.5598
10	90	3.20	20.55	16.135	0.6352
10	100	2.65	23.20		0.5261
30	130	6.95	30.15		0.4549
20	150.	4.10	34.25		0.4070
				AVG.	
				11.513	0.4533


#9
#5
Cum. Wt. Loss (mg)
Cum. Time (hr.)
C.S. 1018
#5 AND #9
200°F, 26.2 PSI, 1.78 mils
#5
#9


MDPR (mils/hr ·100)
Cum. Time (hr.)
#9
#5
C.S. 1018
#5 AND #9
200°F, 26.2 PSI, 1.78 mils
#5
#9


#9
#5
#4
#6
33
30
27
24
21
18
15
12
9
6
3
0
1/1
1/2
1/3
1/4
Cum. Wt. Loss (mg).
Cum. Time (hr.)
C.S. 1018
#4 AND #6
200°F, 26.2 PSI, 1.32 m/s
#4
#6
#5 AND #9
200°F, 26.2 PSI, 1.78 m/s
#5
#9


MDPR (mils/hr ×100)
60
50
48
42
36
30
24
19
12
6
0
1/1
1/2
1/3
1/4
Cum. Time (hr.)
#9
#5
#6
#4
C.S. 1018.
#4 AND #6
200°F, 26.2 PSI, 1.38 mpy
#4
#6
#5 AND #9
200°F, 26.2 PSI, 1.78 mpy
#5
#9

MATERIAL DAMAGE SHEET

S: TL

LITUDE: (DIAL SETTING = 15) 45 mm / 1.75 mil

ER: FRESH

PERATURE: 80 °F

SURE: 1 atm

UE:

RUN:

MATERIAL: 1018 C.S.

NUMBER: #11

APPROX. DATE: JUNE 1980

DENSITY: 7.85 g/cc

AREA: 0.235 in^3

M.D.P. FACTOR: $C = 1/\rho A = 0.033085$

MENTS:

$MDPR_{max} = 0.433$ mil/hr $= 11.009$ μm/hr

$MDPR_{AVG} = 0.320$ mil/hr $= 8.135$ μm/hr

$I.P._{0.1\,mil} = 51$

operator: Brian Sloat

DATA

VAL	CUMULATIVE TIME (min)	WEIGHT LOSS (grams)	CUM. WT. LOSS (grams)	M.D.P. μm/hr	M.D.P.R. (mils/hr)
	0	0.0	0.0		0.0
	15	0.0005	0.0005		0.0667
	30	0.00095	0.00145		0.0959 0.126
	60	0.0029	0.00435		0.144 0.192
	90 ✓	0.00595	0.0103	10.000	0.221 0.394
	120	0.0053	0.0156		0.258 0.351
	180	0.0122	0.0278		0.307 0.404
	240	0.011	0.0388		0.321 0.364
	270	0.00595	0.04475		0.329 0.396
	300 ✓	0.00655	0.0513	11.009	0.339 0.433
	360	0.0068	0.0581	8.135	0.3204 0.225

MATERIAL DAMAGE SHEET

RN: Tl

PLITUDE: Dial Setting = 15 45.2 μm 1.78 mil

TER: Fresh

MPERATURE: 80°F

ESSURE: 1 atm.

RQUE:

E-RUN:

MATERIAL: 1018 C.S. V

NUMBER: #14

APPROX. DATE: June 1980

DENSITY: 7.85 g/cc.

AREA: 0.235 in²

M.D.P. FACTOR: $C = \frac{1}{\rho A} = 0.033085$

MMENTS:

$MDPR_{max} = 0.407$ mil/hr $= 10.336$ μm/hr

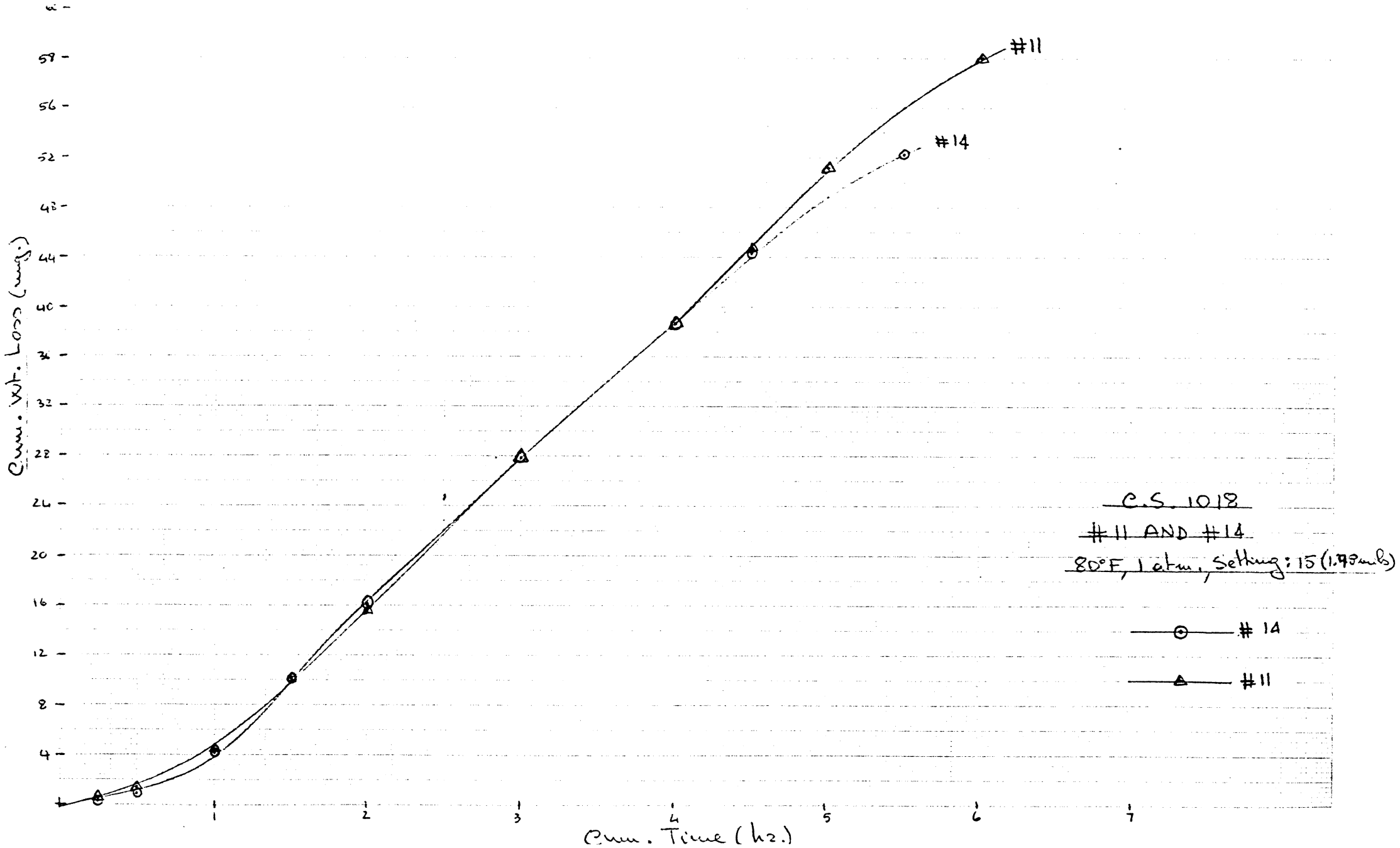
$MDPR_{AVG} = 0.314$ mil/hr $= 7.983$ μm/hr

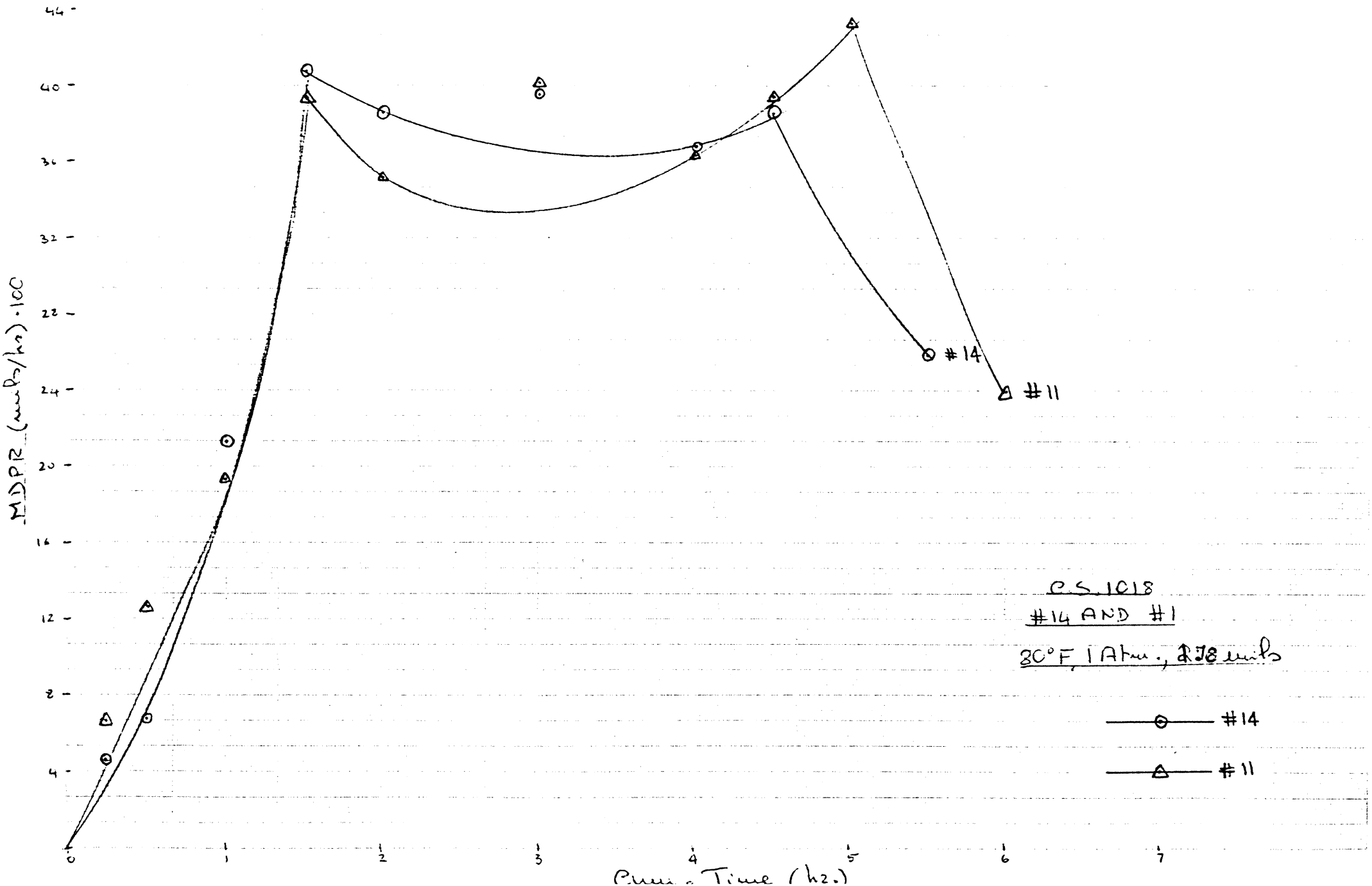
$IP_{.1mil} = 55$ min

Operator: Brian Seal

DATA

E ERVAL (s)	CUMULATIVE TIME (mins)	WEIGHT LOSS (grams)	CUM. WT. LOSS (grams)	M.D.P. μm/hr	M.D.P.R. (mils/hr)
	0.0	0.0	0.0		0.0
	15	0.00035	0.00035		0.046
	30	0.0005	0.00085		~~0.056~~ 0.066
	60	0.0032	0.00405		~~0.134~~ 0.212
	90	0.00615	0.0102	10.336	~~0.225~~ 0.4070
	120	0.0058	0.016		~~0.266~~ 0.384
	180	0.01193	0.02793		~~0.308~~ 0.3950
	240	0.01072	0.03865		~~0.320~~ 0.355
	270	0.0058	0.04445		~~0.327~~ 0.334
	33.0	0.0078	0.05225	7.983	~~0.314~~ 0.258


Cum. Wt. Loss (mg.)
Cum. Time (hr.)
#11
#14
C.S. 1018
#11 AND #14
80°F, 1 atm., Setting: 15 (1.95 mb)
14
#11


MDPR (mils/hr) · 100
Run Time (hrs.)
#14
#11
P.S. 1018
#14 AND #1
30°F, 1 Atm., 238 mils
#14
#11

MATERIAL DAMAGE S. ET

HORN: Ti

AMPLITUDE: (DIAL SETTING = 15) 45.2 μm (1.78 mil)

WATER: Fresh

TEMPERATURE: 160°F

PRESSURE: 19.5 psia

TORQUE:

PRE-RUN:

MATERIAL: Cast Iron

NUMBER: #2

APPROX. DATE: June 1980

DENSITY: 7.29 g/cc

AREA: 0.236 in²

M.D.P. FACTOR: $C = \frac{1}{\rho A} = 0.03548$

COMMENTS:

×412.5 μ

$MDPR_{max} = 1.228$ mil/h

$MDPR_{AVG} = 31.18$ μm/h

$= 0.656$ mil/h

$= 16.66$ μm/h

$I_{P_a/mil} =$

Operator

Brian Seal

DATA

TIME INTERVAL (min)	CUMULATIVE TIME (min)	WEIGHT LOSS (grams)	CUM. WT. LOSS (grams)	M.D.P.	M.D.P.R. (mils/hr.)
0	0	0.0	0.0		0.0
30	30	0.00825	0.00825		0.585
30	60	0.0173	0.02555		~~0.907~~ 1.228
30	90	0.0082	0.03375		0.798 0.582
60	150	0.01785	0.0516		0.732 0.633
60	210	0.0131	0.0647		0.656 0.465

MATERIAL DAMAGE SHEET

ORN: Ti

MATERIAL: Cast Iron

MPLITUDE: (DIAL SETTING = 15) 95.2 μm (+3.8 mil)

NUMBER: # 5

'ATER: Fresh

APPROX. DATE: June 1980

EMPERATURE: 160 °F

DENSITY: 7.29 g/cc

RESSURE: 14.5 psia

AREA: 0.236 in²

ORQUE:

M.D.P. FACTOR: $C = \frac{1}{EA} = 0.03548$

RE-RUN:

OMMENTS:

$MDPR_{max} = 1.047$ mil/hr = 26.585 μm/hr

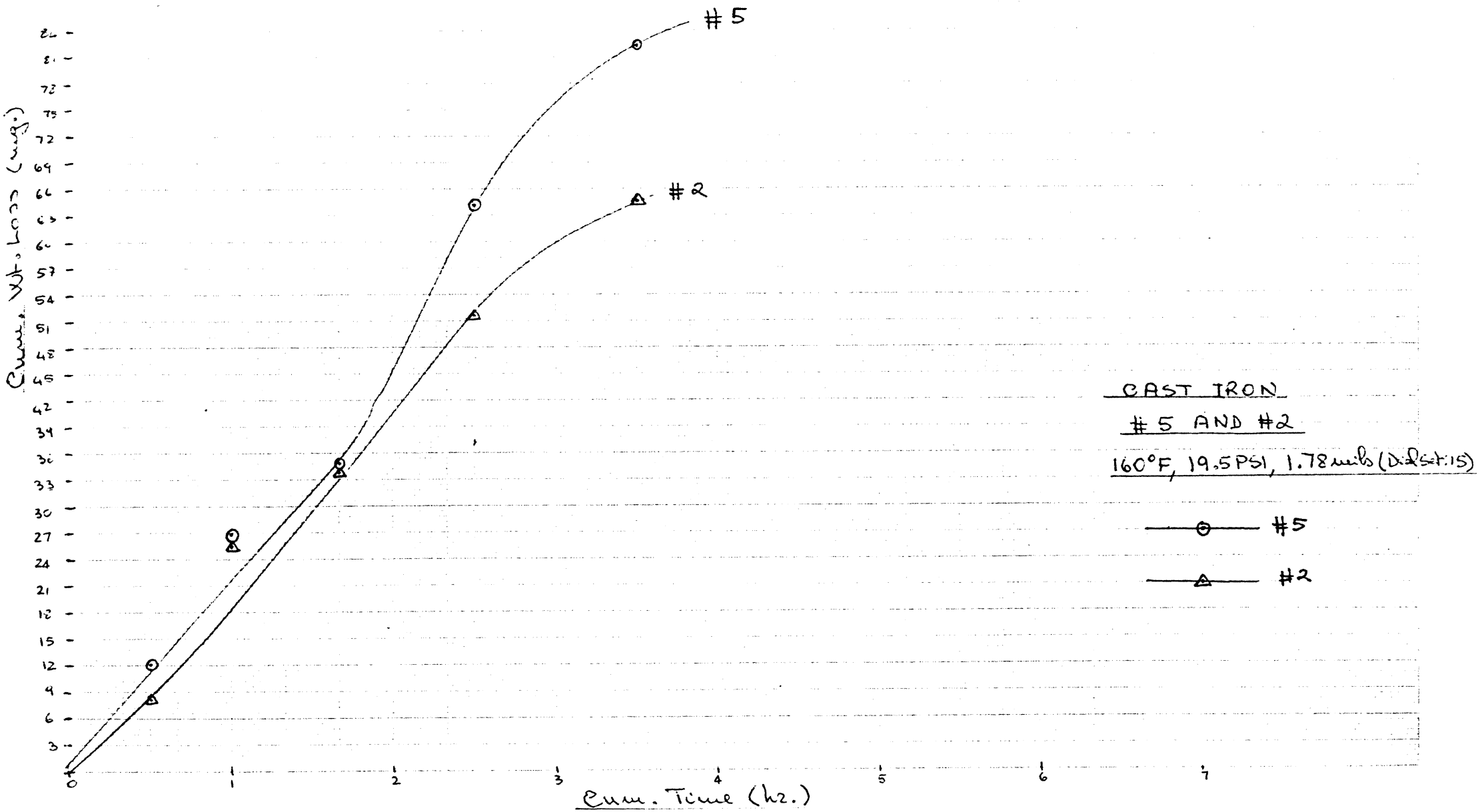
$MDPR_{AVG} = 0.836$ " = 21.242 μm/hr

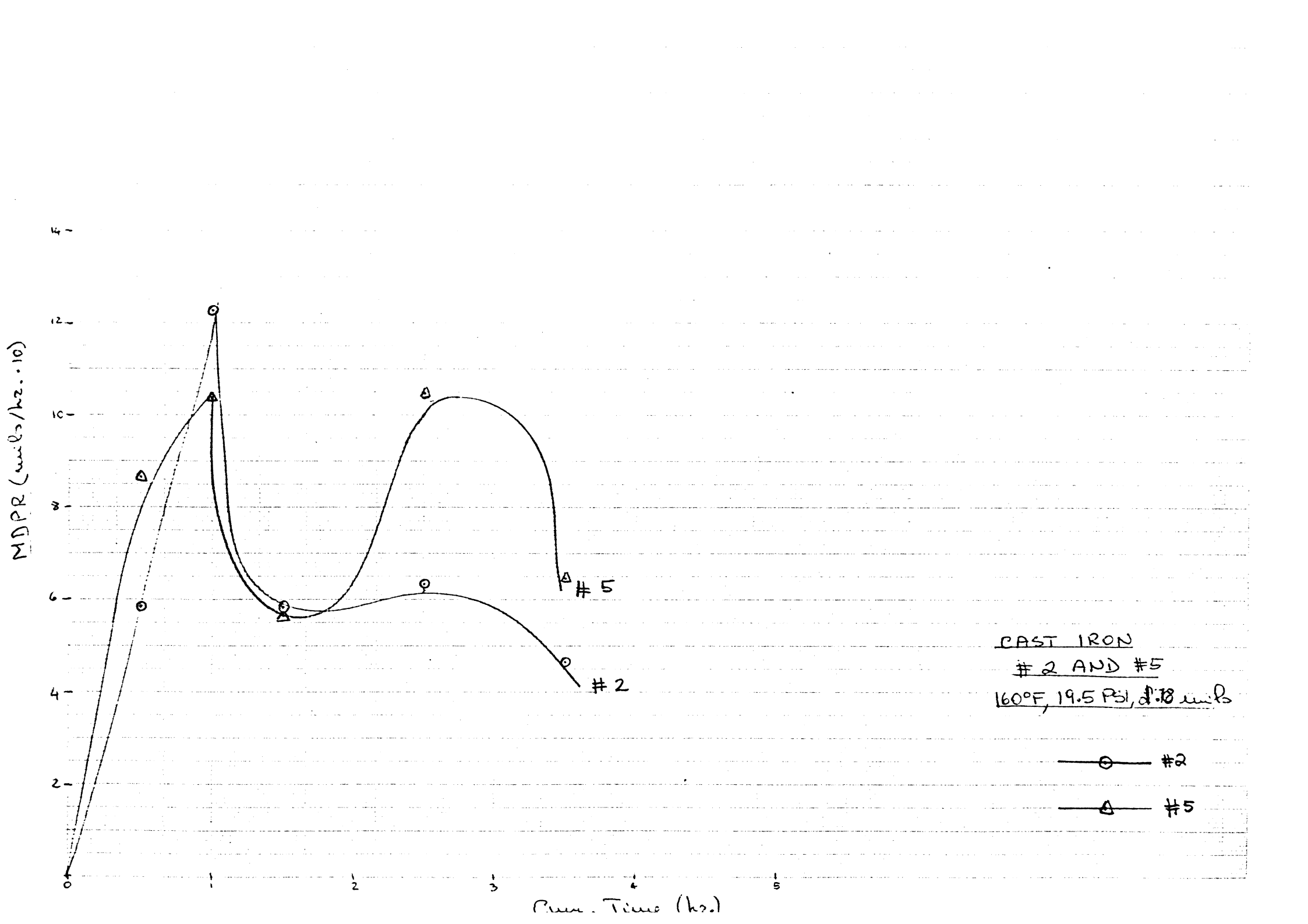
$IP_{.1mil} =$

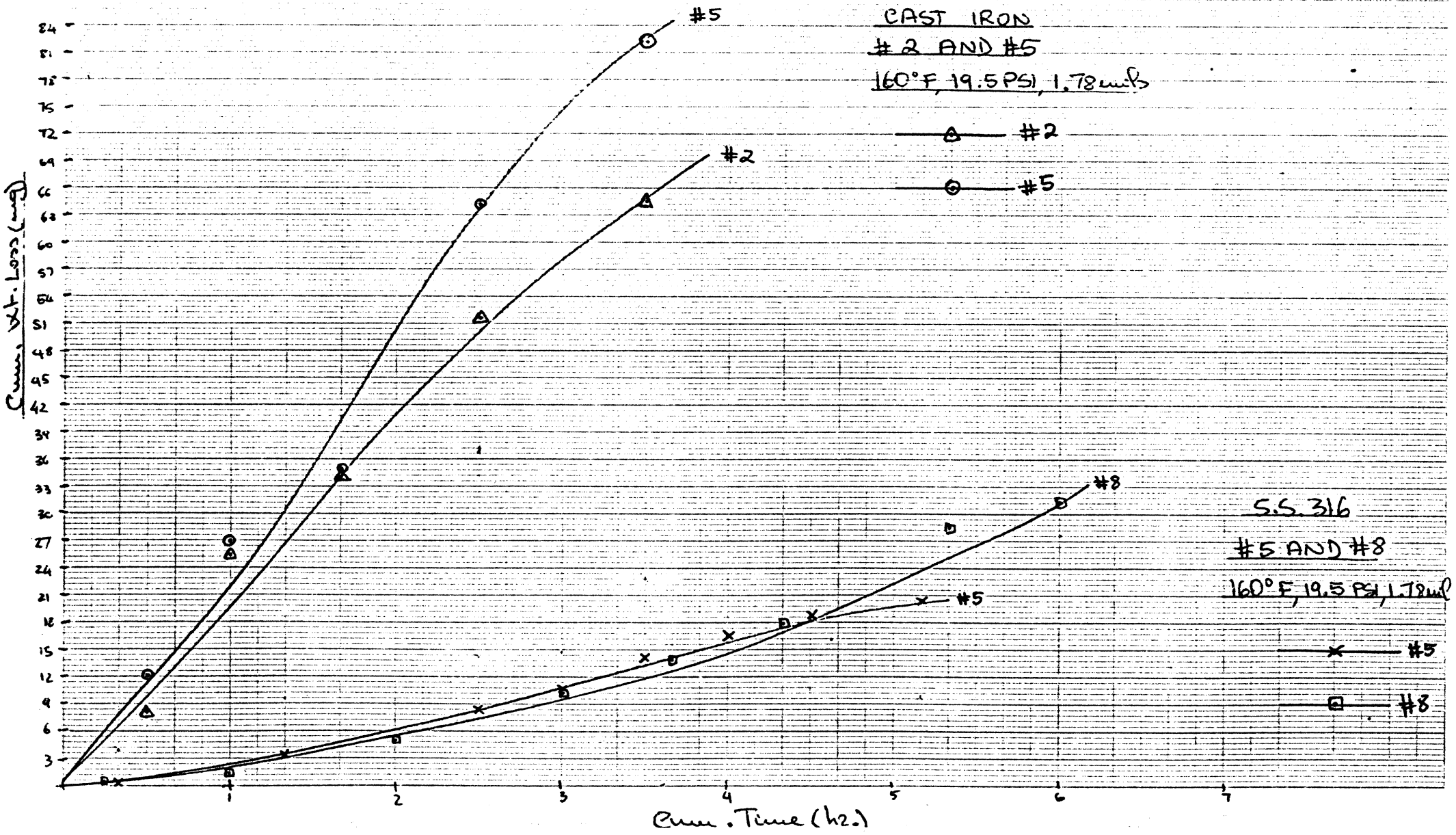
Operator
Brian Seal

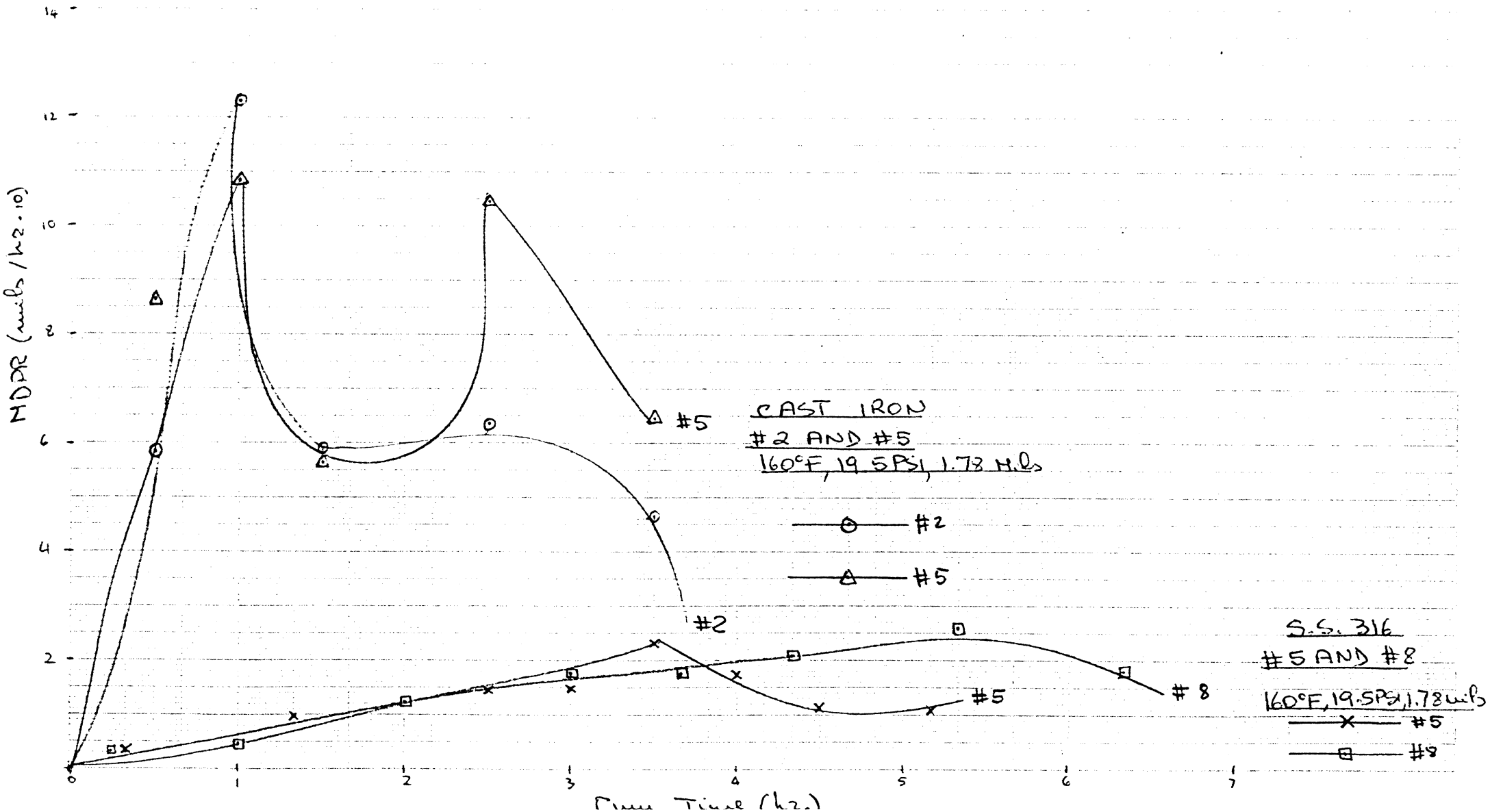
DATA

ME TERVAL (min)	CUMULATIVE TIME (min)	WEIGHT LOSS (grams)	CUM. WT. LOSS (grams)	M.D.P. μm/hr	M.D.P.R. (mils/hr)
)	0	0.0	0.0		0.0
)	30	0.0122	0.0122		0.866
)	60	0.0146	0.0268	26.315	~~0.951~~ 1.036
)	90	0.008	0.0348		~~0.823~~ 0.568
)	150	0.0295	0.0643		~~0.913~~ 1.047
)	210	0.0182	0.0825	26.585	~~0.836~~ 1.047 0.646
					21.242


#5
#2
Cum. Wt. Loss (mg.)
Cum. Time (hr.)
CAST IRON
#5 AND #2
160°F, 19.5 PSI, 1.78 mils (D-2Sat.15)
#5
#2


MDPR (mils/hr. · 10)
Cum. Time (hr.)
0
1
2
3
4
5
2
4
6
8
10
12
#5
#2
CAST IRON
#2 AND #5
160°F, 19.5 PSI, d.18 mils
#2
#5


CAST IRON
#2 AND #5
160°F, 19.5 PSI, 1.78 ml/s
#2
#5
#5
#2
S.S. 316
#5 AND #8
160°F, 19.5 PSI, 1.78 ml
#5
#8
#8
#5
Cum. Wt. Loss (mg)
Cum. Time (hr.)


MDPR (mils/hr.10)
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
Time Time (hr.)
#5
#2
#5
#8
CAST IRON
#2 AND #5
160°F, 19.5PSI, 1.78 M.Ls
#2
#5
S.S. 316
#5 AND #8
160°F, 19.5PSI, 1.78 mils
#5
#8

MATERIAL DAMAGE SHEET

RN: Ta

PLITUDE: 1.78 mil

TER:

MPERATURE: 160°F

ESSURE: 19.5 psi

RQUE:

E-RUN:

MATERIAL: SS316

NUMBER: #5

APPROX. DATE: 4/15

DENSITY:

AREA:

M.D.P. FACTOR: $C = 0.03283 \frac{mil^2}{mg}$

MMENTS:

+164.16 MDPR

$MDPR_{max} = 0.2208$

$MDPR_{AVG} = 0.1296$

$IR_{0.1\,mil} =$

operator:
M. Hsu

DATA

E ERVAL um	CUMULATIVE TIME min	WEIGHT LOSS mg	CUM. WT. LOSS mg	M.D.P. $\frac{\mu m}{hr}$	M.D.P.R. $\frac{mil}{hr}$
0	0	0	0		
0	20	0.40	0.40		0.0396
0	80	2.90	3.30		0.0952
0	150	5.05	8.35		0.1621
0	180	2.25	10.60		0.1677
0	210	3.50	14.10	5.837	0.2298
0	240	2.55	16.65		0.1674
0	270	1.70	18.35		0.1116
0	310	2.05	20.40		0.1095
				AVG	
				3.293	0.1296

MATERIAL DAMAGE SHEET

RN: Ti
PLITUDE: 1.78 mil
TER:
MPERATURE: 160°F
ESSURE: 19.5 psi
RQUE:
E-RUN:

MATERIAL: SS 316
NUMBER: # 8
APPROX. DATE: 4/17/80
DENSITY:
AREA:
M.D.P. FACTOR: C = 0.03283 mil/mg

MMENTS:

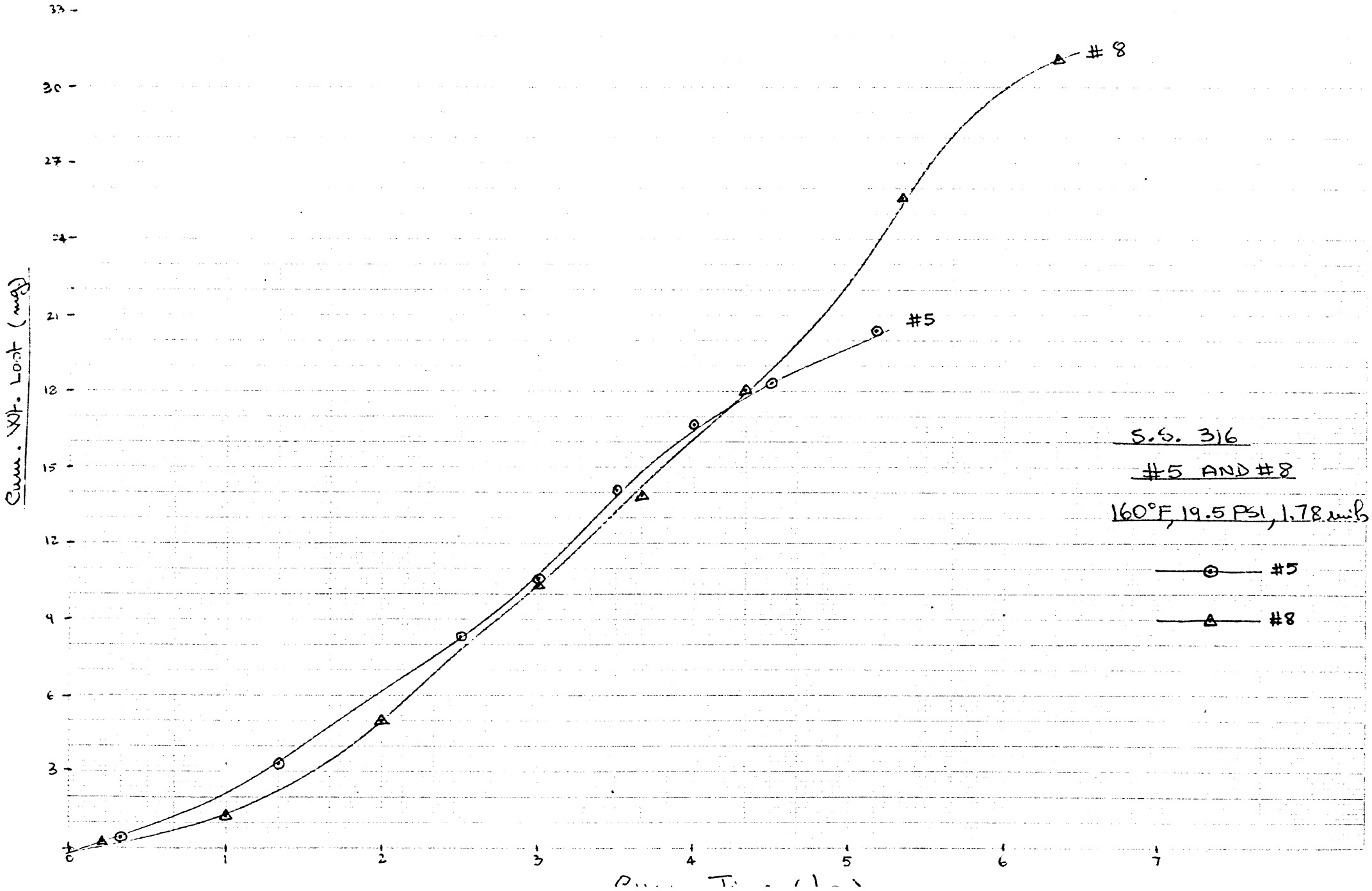
$MDPR_{max}$ = 0.2511 mil/hr
$MDPR_{AVG}$ = 0.1615 "

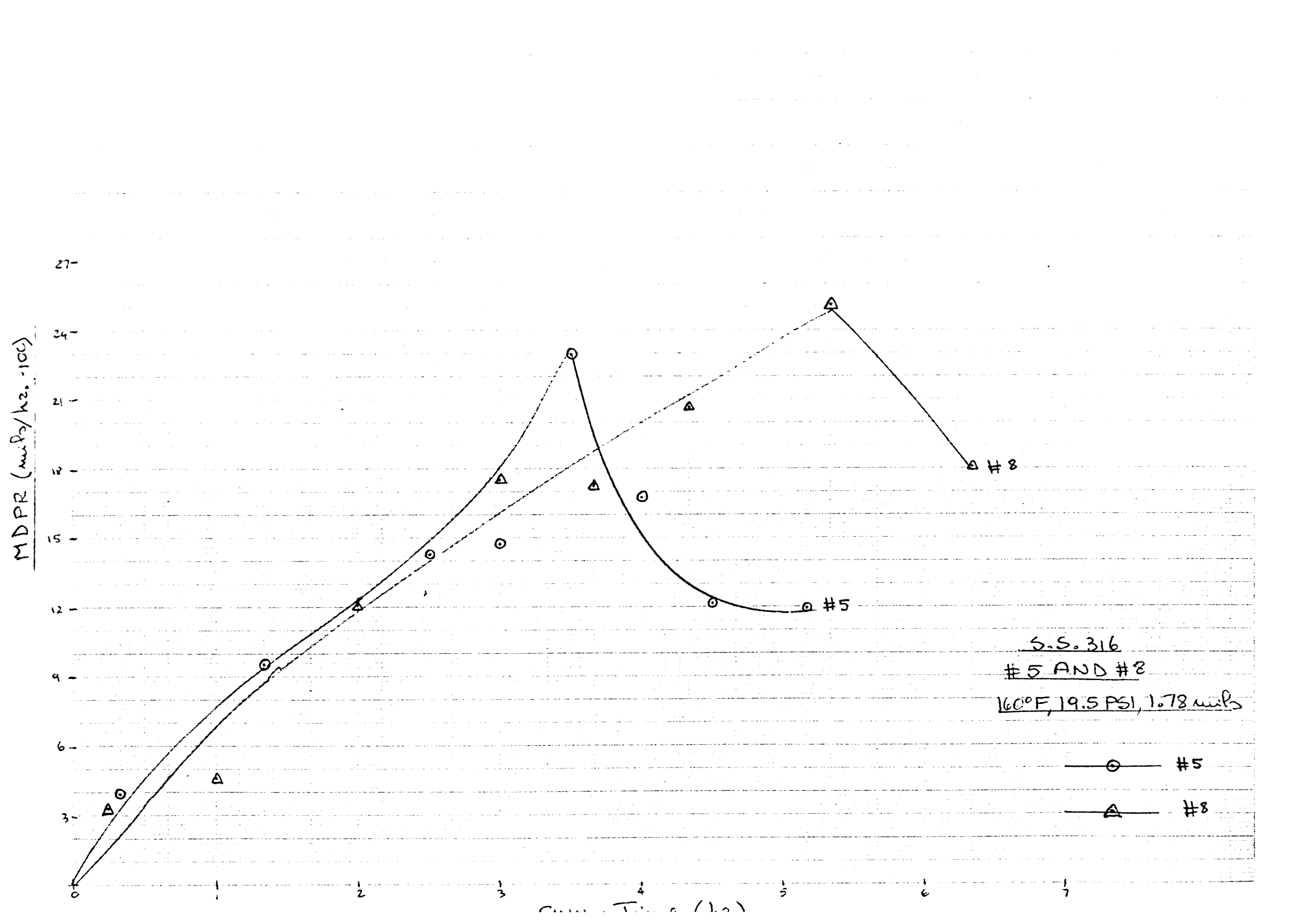
$IP_{0.1\ mil}$ =

Operator:
Mr Hsu

DATA

E ERVAL min	CUMULATIVE TIME min	WEIGHT LOSS mg	CUM. WT. LOSS mg	M.D.P. μm/hr	M.D.P.R. mil/hr
0	0	0	0		
5	15	0.25	0.25		0.0325
5	60	1.05	1.30		0.0460
0	120	3.70	5.00		0.1215
0	180	5.35	10.35	4.461	0.1756
0	220	3.50	13.85		0.1724
0	260	4.20	18.05	5.253	0.2068
0	320	7.60	25.65	6.379	0.2511
0	380	5.50	31.15		0.1806
				AVG	
				4.101	0.1615


Cum. Wt. Lost (mg)
33
30
27
24
21
18
15
12
9
6
3
0
1
2
3
4
5
6
7
#8
#5
S.S. 316
#5 AND #8
160°F, 19.5 PSI, 1.78 m/s
#5
#8


MDPR (mils/hr. -10C)
27
24
21
18
15
12
9
6
3
0
1
2
3
4
5
6
7
#8
#5
S.S. 316
#5 AND #8
160°F, 19.5 PSI, 1.78 mils
#5
#8

MATERIAL DAMAGE SHEET

N: Ti MATERIAL: SS 316

PLITUDE: 1.38 mil (dial set 8) NUMBER: #6

ER: Tap water APPROX. DATE: 5/19/80

PERATURE: 160°F (19.5 psia) DENSITY: ρ =

SSURE: 19.5 psia. AREA: A =

QUE: M. D. P. FACTOR: C = 0.03283 mil/mg

-RUN:

MENTS:

$MDPR_{max} = 0.0788$ mil/hr

$MDPR_{AVG} = 0.0479$

$IP_{0.1mil} =$

perator:
Mr. HSu

DATA

RVAL (min)	CUMULATIVE TIME (min)	WEIGHT LOSS (mg.)	CUM. WT. LOSS (mg)	M. D. P. μmg/Hr	M. D. P. R. mil/Hr
0	0	0	0		
5	15	0.05	0.05		0.0066
0	45	0.10	0.15		0.0066
0	105	0.25	0.40		0.00657
0	165	1.60	2.00		0.05253
0	225	1.40	3.40		0.04596
0	285	2.40	5.80	2.002 ✓	0.0788
0	345	2.15	7.95		0.0706
0	375	1.00	8.95		0.0657
0	405	0.90	9.85		0.0591
				AVG =	0.0479
				1.219	

MATERIAL DAMAGE SHEET

N: Ti

MATERIAL: SS 316

PLITUDE: 1.38 mil (dial set 8)

NUMBER: # 7

ER:

APPROX. DATE: 5/19/80

IPERATURE: 1600 F.

DENSITY: ρ =

SSURE: 19.5 psia.

AREA: A =

QUE:

M. D. P. FACTOR: C = 003283 mil/mg

-RUN:

IMENTS:

$MDPR_{max} = 0.1181$ mil/hr

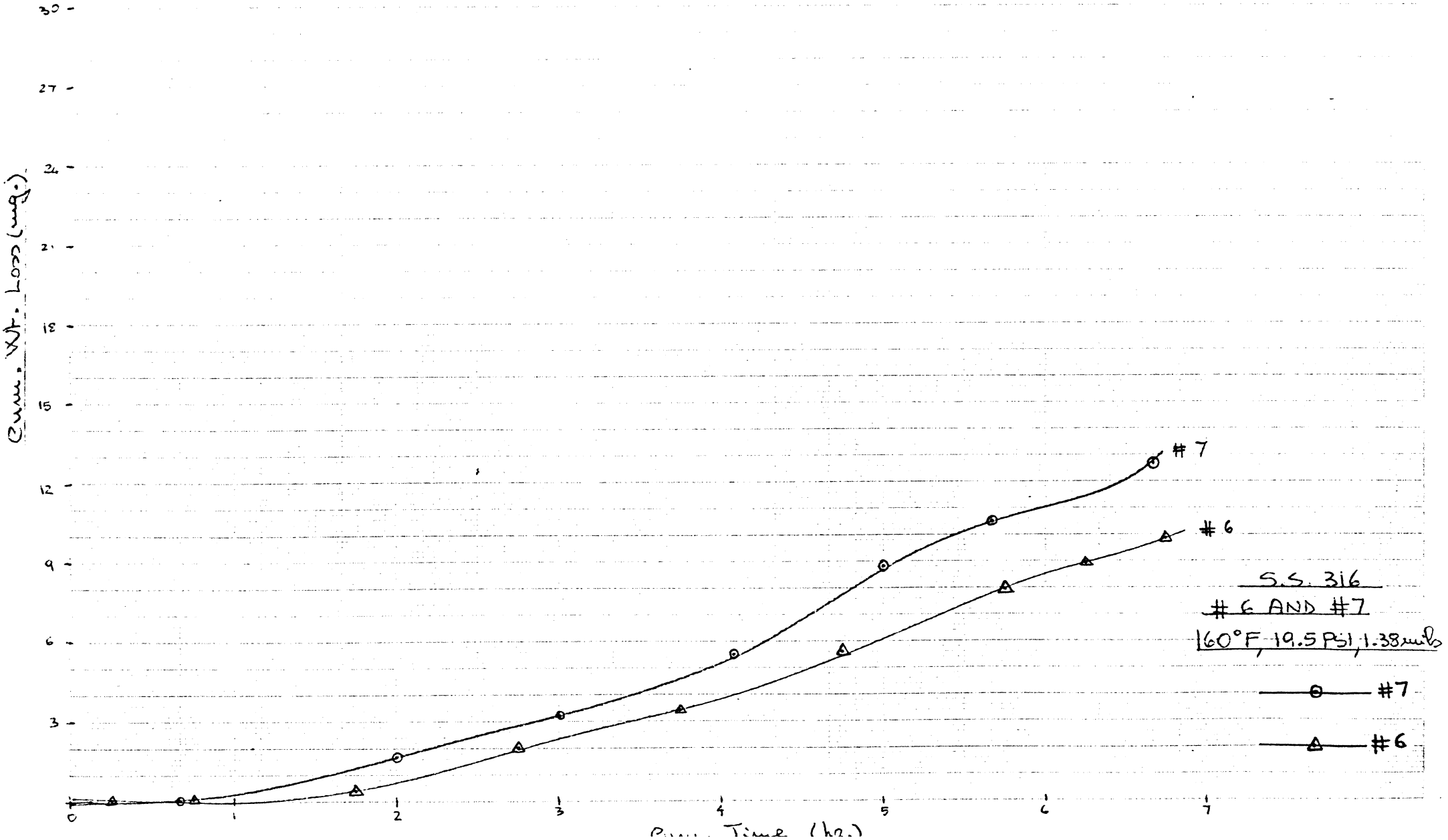
$MDPR_{AVG} = 0.0623$

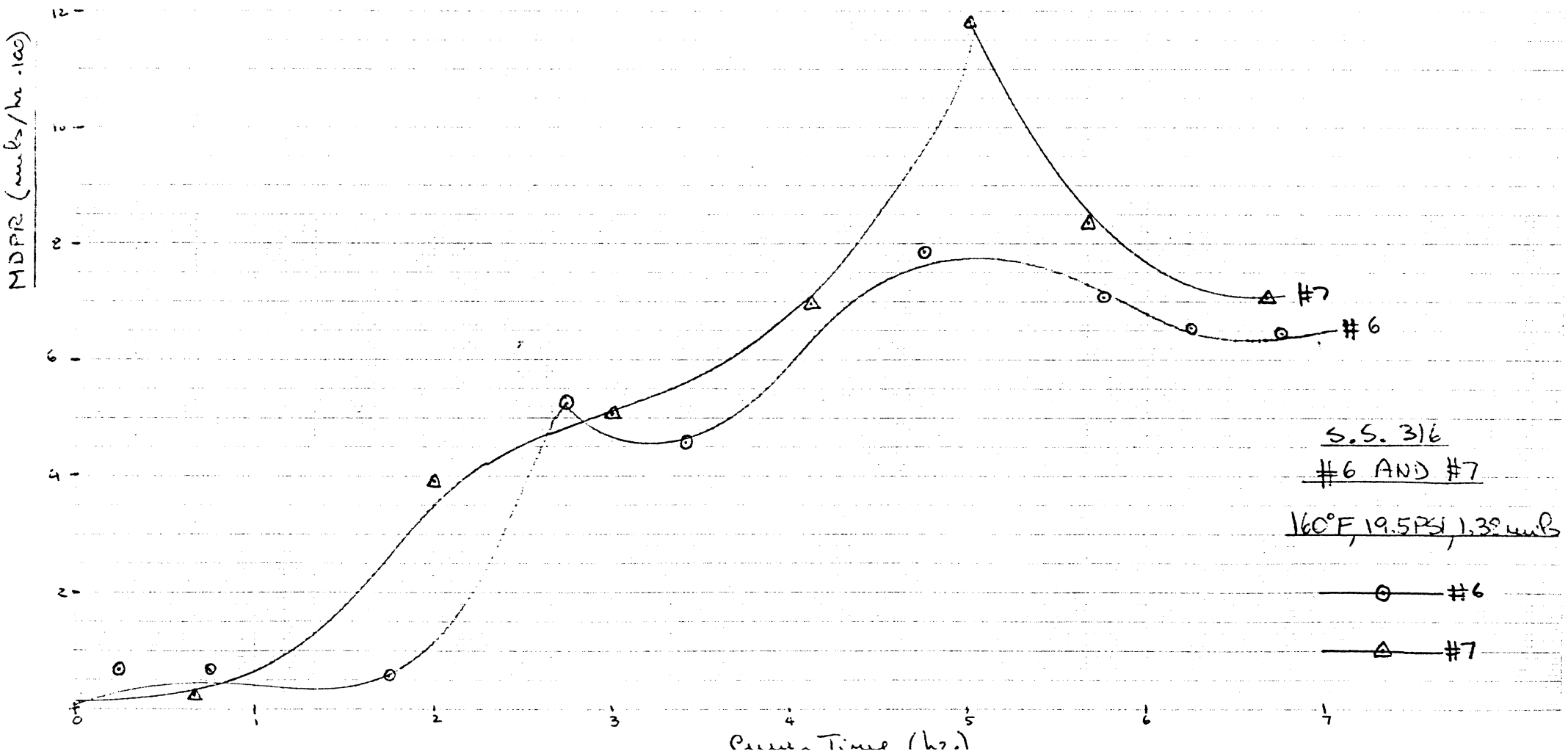
$IP_{.1\,mil} =$

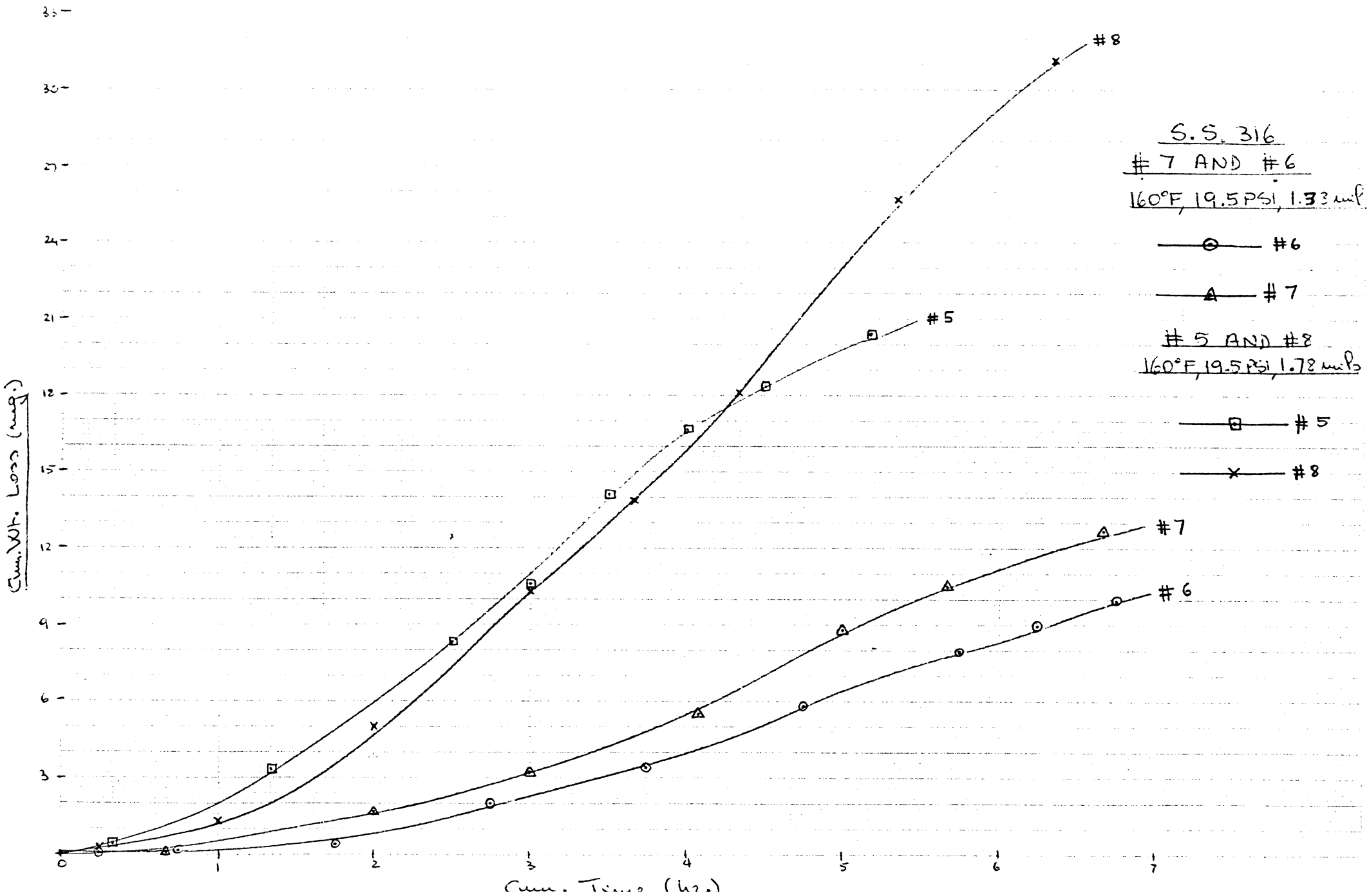
erator:
Mr. Hsin

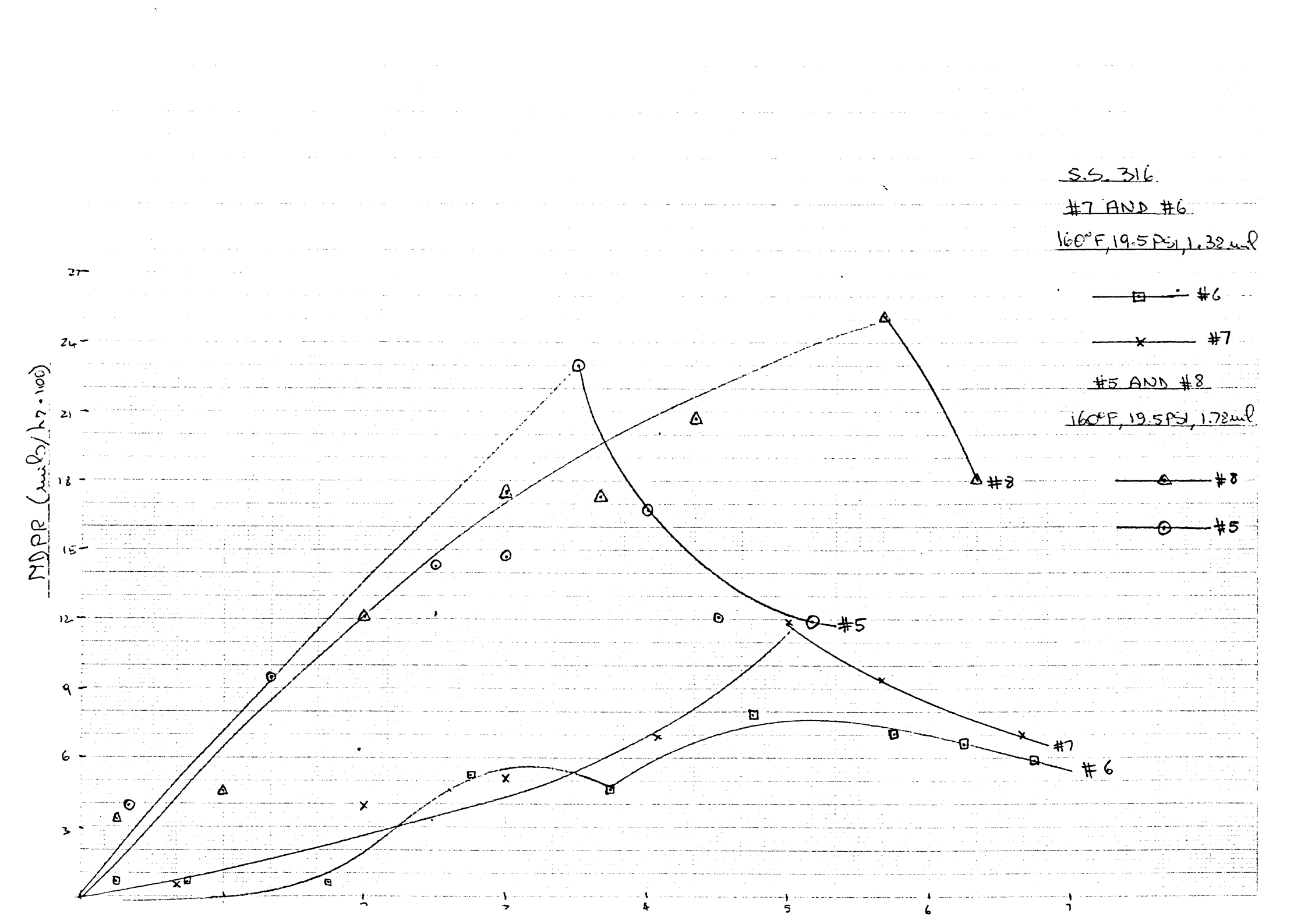
DATA

E ERVAL (min)	CUMULATIVE TIME (min)	WEIGHT LOSS (mg)	CUM. WT. LOSS (mg)	M. D. P. μm/hr	M. D. P. R. mil/hr
0	0	0	0		
0	40	0.05	0.05		0.00246
0	120	1.60	1.65		0.0394
0	180	1.55	3.20		0.0509
5	245	2.30	5.50		0.0697
5	300	3.30	8.80	3.002	0.1181
0	340	1.70	10.50		0.0837
0	400	2.15	12.65		0.0706
				AVG =	
				1.582	0.0623


Cum. Wt. Loss (mg.)
30
27
24
21
18
15
12
9
6
3
0
1
2
3
4
5
6
7
Cum. Time (hr.)
#7
#6
S.S. 316
#6 AND #7
160°F, 19.5 PSI, 1.38 m/s
#7
#6


MDPR (mols/hr · 100)
12
10
8
6
4
2
0
1
2
3
4
5
6
7
Process Time (hrs.)
#7
#6
S.S. 316
#6 AND #7
160°F, 19.5 PSI, 1.3% mols
#6
#7


S.S. 316
#7 AND #6
160°F, 19.5 PSI, 1.33 mils
#6
#7
#5 AND #8
160°F, 19.5 PSI, 1.78 mils
#5
#8
#8
#5
#7
#6
Cum. Wt. Loss (mg.)
Cum. Time (hr.)
0
1
2
3
4
5
6
7
3
6
9
12
15
21
24
30
33


S.S. 316
#7 AND #6
160°F, 19.5 PSI, 1.32 mil
#6
#7
#5 AND #8
160°F, 19.5 PSI, 1.72 mil
#8
#5
MDPR (mils/hr · 100)
27
24
21
18
15
12
9
6
3
#8
#5
#7
#6

MATERIAL DAMAGE SHEET

HORN: Ti

MATERIAL: SS-316

AMPLITUDE: 1.78 mils Set-15 (45.2 μm / 1.78 mil)

NUMBER: #11

WATER: Fresh water.

APPROX. DATE: 6/2 to 6/9

TEMPERATURE: 70°F

DENSITY: 7.91 g/cm³

PRESSURE: 1 bar - Open vessell

AREA: 0.235 in²

TORQUE:

M.D.P. FACTOR: c = 0.03283

PRE-RUN:

COMMENTS:

+39.42% MDPR

$$c = \frac{1}{\rho \cdot A} \qquad MDPR = \frac{c \cdot WL\ (g)}{T\ (hr)}$$

I.P. = 1.85 hours

$MDPR_{MAX}$ = 0.280 mils/hr

$MDPR_{AVG.}$ = 0.131 mils/hr

Operator

Mr. Nicoseri

DATA

TIME INTERVAL Mins.	CUMULATIVE TIME Mins.	WEIGHT LOSS g	CUM. WT. LOSS g.	M.D.P.	M.D.P.R. mils/hr
0	0	0	0		0
30	30	0.00026	0.00026		0.017
30	60	0.00046	0.00082		0.030
60	120	0.00285	0.00367		0.093
60	180	0.00456	0.00823		0.149
60	240	0.00524	0.01347		0.172
60	300	0.00353	0.01700		0.230
60	360	0.00177	0.01877		0.053
60	420	0.00410	0.02287		0.134

MATERIAL DAMAGE SHEET

HORN: Ti

MATERIAL: SS-316

AMPLITUDE: Set=15 or 1.78 mils (45.2 mm 1.78 mil)

NUMBER: #9

WATER: Fresh water

APPROX. DATE: 6/9 to 6/16

TEMPERATURE: 80° F

DENSITY: $\rho = 7.91$ g/cu³

PRESSURE: Open vessel 1 bar

AREA: 0.235 in²

TORQUE:

M. D. P. FACTOR: $C = 0.03283$ mils/

PRE-RUN:

COMMENTS:

$MDPR_{MAX} = 0.156$ mils/hr

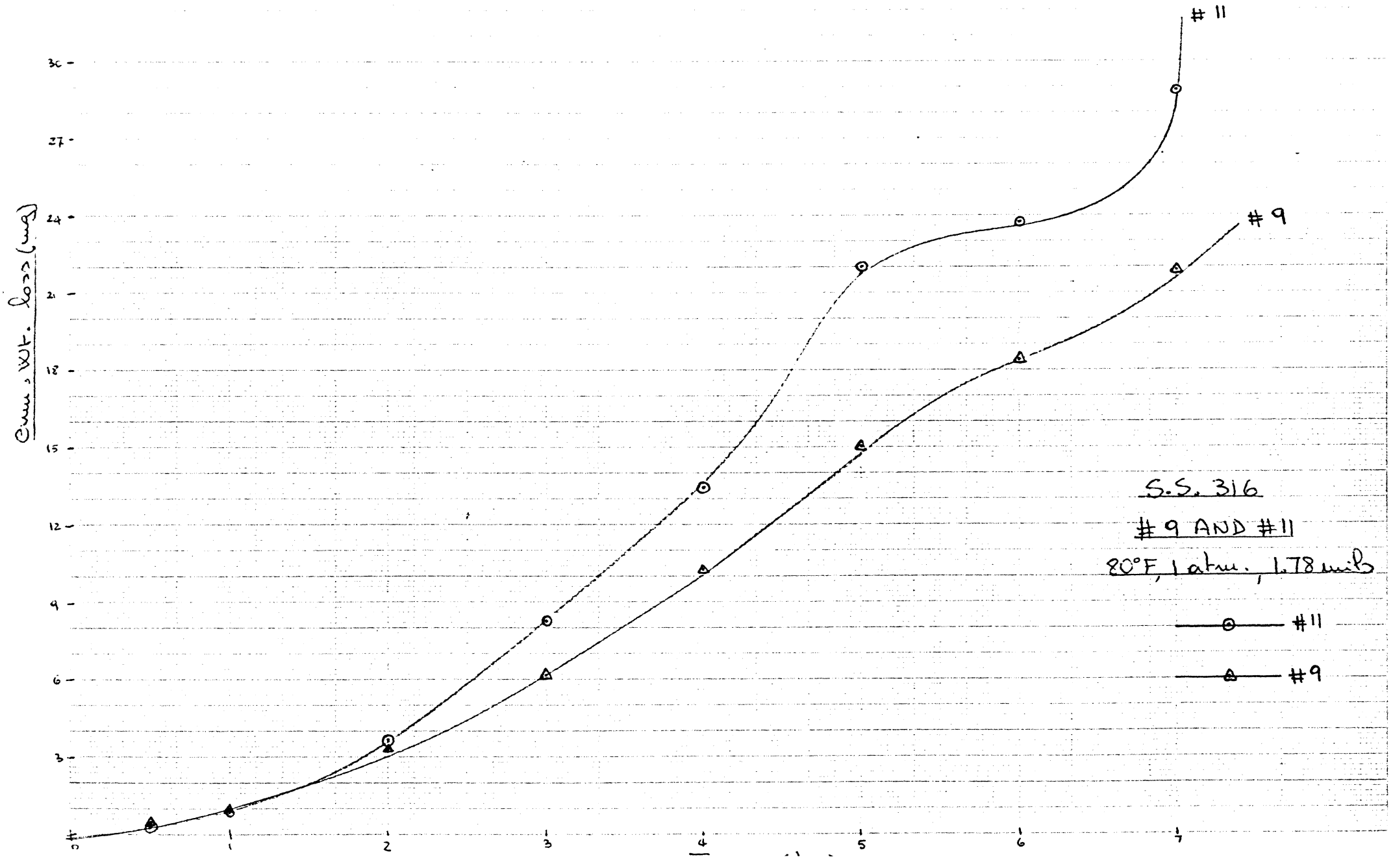
$MDPR_{AVG} = 0.0978$ mils/hr

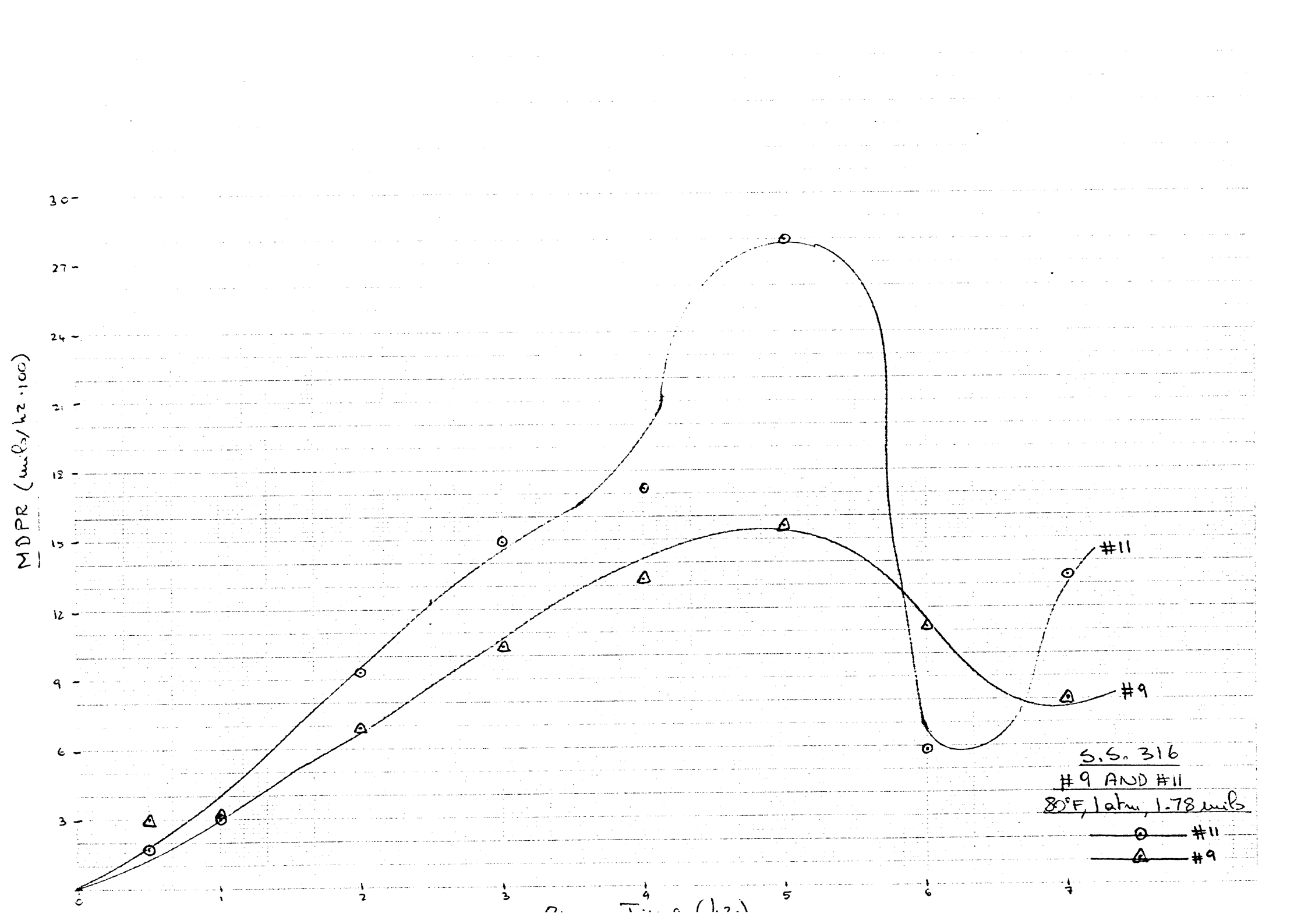
I.P. = 1.95 min hours

Operator
Mr. Nosseri

DATA

TIME INTERVAL min.	CUMULATIVE TIME min.	WEIGHT LOSS g.	CUM. WT. LOSS g.	M. D. P.	M. D. P. R. mils/hr
0	0	0	0		0
	30	0.00045	0.00045		0.030
	60	0.00049	0.00094		0.032
60	120	0.00209	0.00303		0.069
60	120	0.00316	0.00619		0.104
60	240	0.00406	0.01025		0.133
60	300	0.00475	0.01500		0.156
60	360	0.00340	0.01840		0.112
60	420	0.00245	0.02085		0.080


#11
#9
S.S. 316
#9 AND #11
80°F, 1 atm., 1.78 mils
#11
#9
cum. wt. loss (mg)
30
27
24
21
18
15
12
9
6
3
0
1
2
3
4
5
6
7


MDPR (mils/hr·100)
30
27
24
21
18
15
12
9
6
3
0
1
2
3
4
5
6
7
#11
#9
S.S. 316
#9 AND #11
80°F, 1 atm, 1.78 mils
#11
#9

MATERIAL DAMAGE SHEET

ORN: Ti

MATERIAL: SS-316

MPLITUDE: Set=19.5 oz) 2.0 mils

NUMBER: #13

ATER: Fresh water.

APPROX. DATE: 6/17 to 6/20

CMPERATURE: 80°F

DENSITY: $\rho = 7.91\ g/cm^3$

RESSURE: Open vessell, 1 Bar

AREA: 0.235 in^2

ORQUE:

M. D. P. FACTOR: $e = 0.03283$ mils/mg

RE-RUN:

OMMENTS:

$MDPR_{MAX.} = 0.197$ mils/hz

$MDPR_{AVG.} = 0.144$ mils/hz

I. P. = 1.5 hz

DATA

ME TERVAL min.	CUMULATIVE TIME min.	WEIGHT LOSS g.	CUM. WT. LOSS g.	M. D. P.	M. D. P. R. mils/hz.
0	0	0	0		0
30	30	0.00006	0.00006		0.004
30	60	0.00089	0.00095		0.058
60	120	0.00556	0.00651		0.133
00	180	0.00463	0.01114		0.152
60	240	0.00391	0.01505		0.128
20	300	0.00420	0.01925		0.138
00	360	0.00535	0.02460		0.176
60	420	0.00600	0.03060		0.197

MATERIAL DAMAGE SHEET

ORN: Ti

MPLITUDE: 2.0 mils (Set 19.5)

ATER: Fresh water.

EMPERATURE: 30°F

RESSURE: 1 bar, open vessel

ORQUE:

RE-RUN:

MATERIAL: SS.-316

NUMBER: #14

APPROX. DATE: 6/23

DENSITY: 7.91 g/cm³

AREA: 0.235 in²

M. D. P. FACTOR: C = 0.03233

OMMENTS:

I.P. = 1.4 hz.

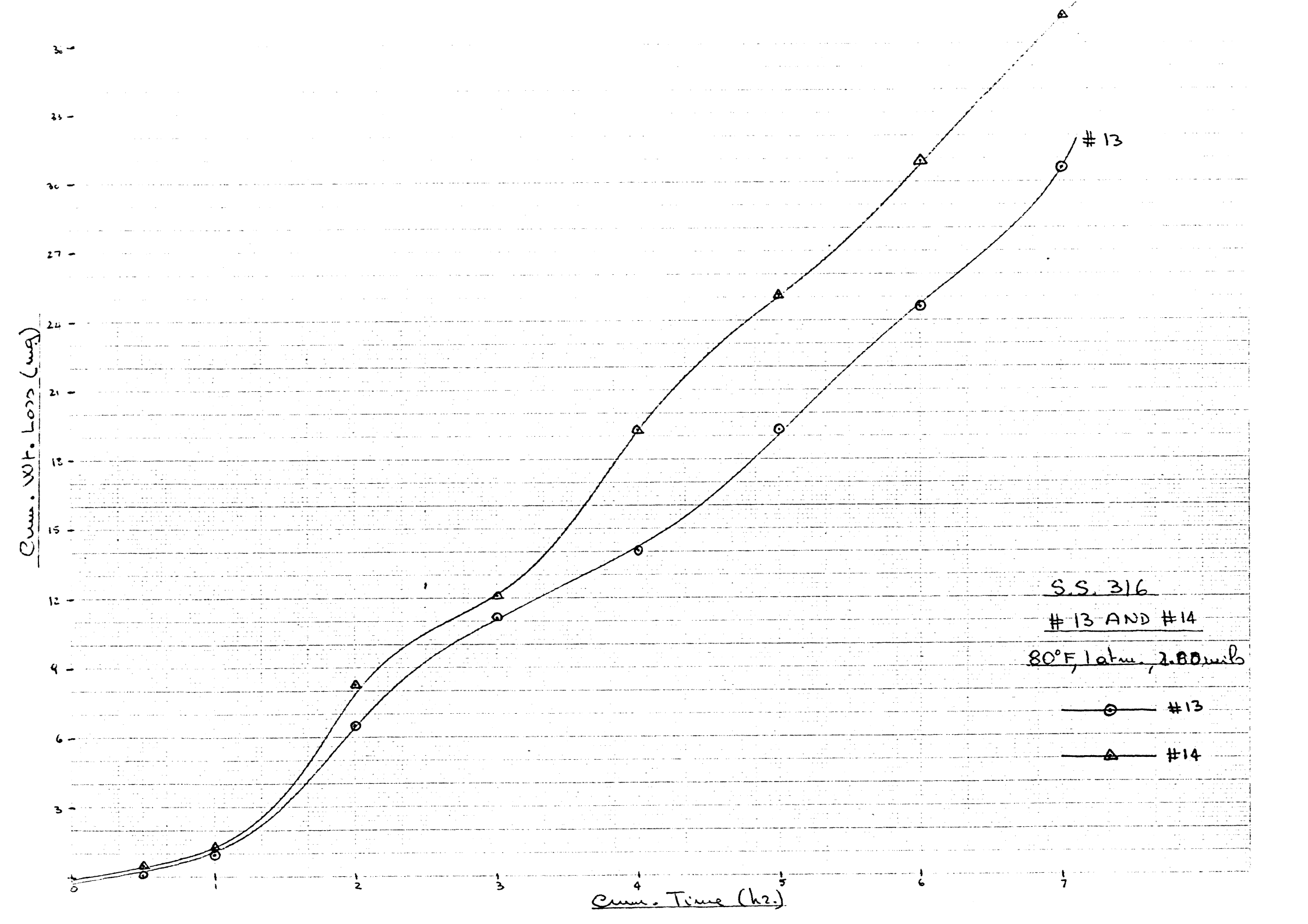
$MDPR_{MAX}$ = 0.235 mils/hz

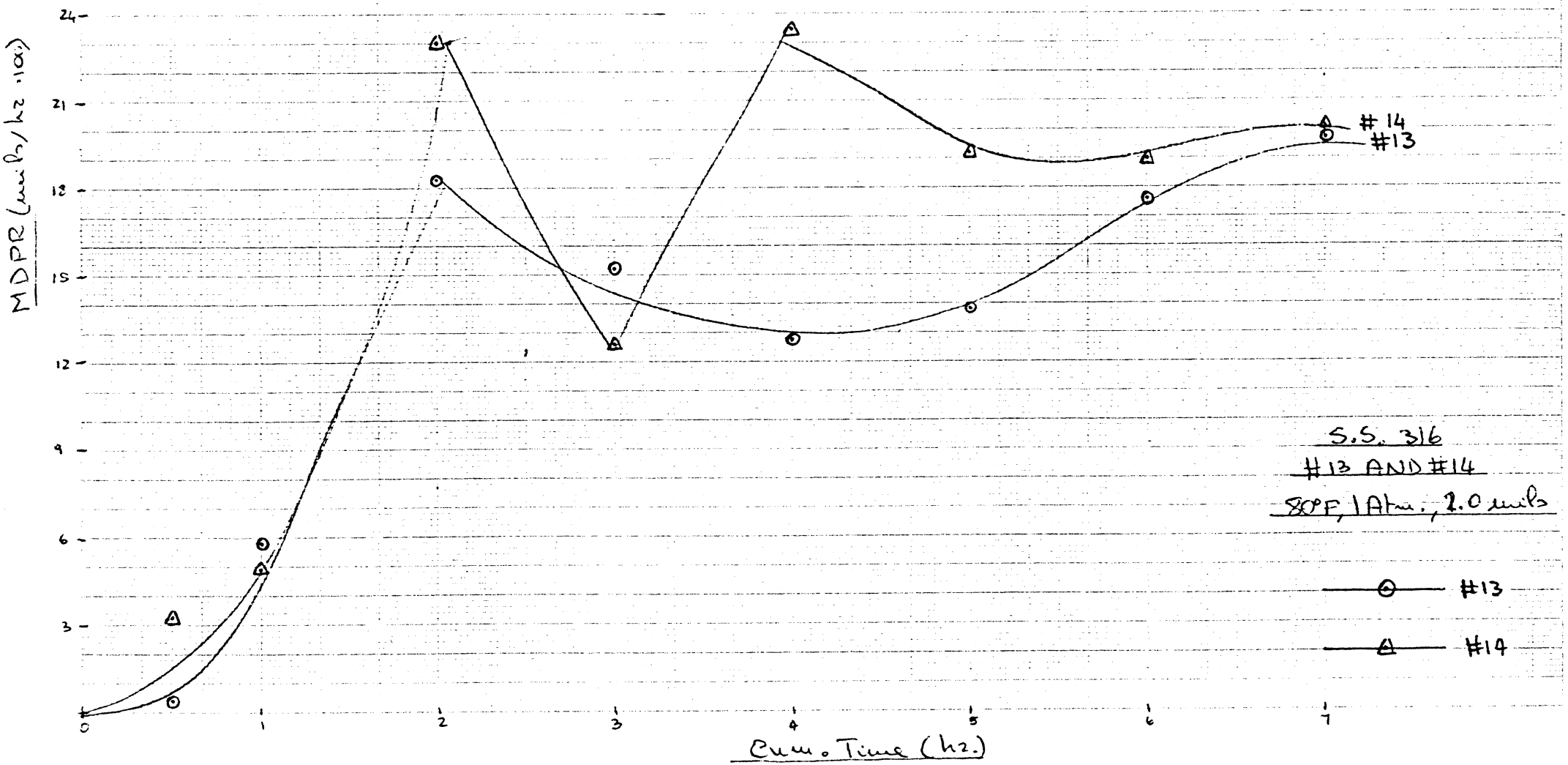
$MDPR_{AVG}$ = 0.175 mils/hz

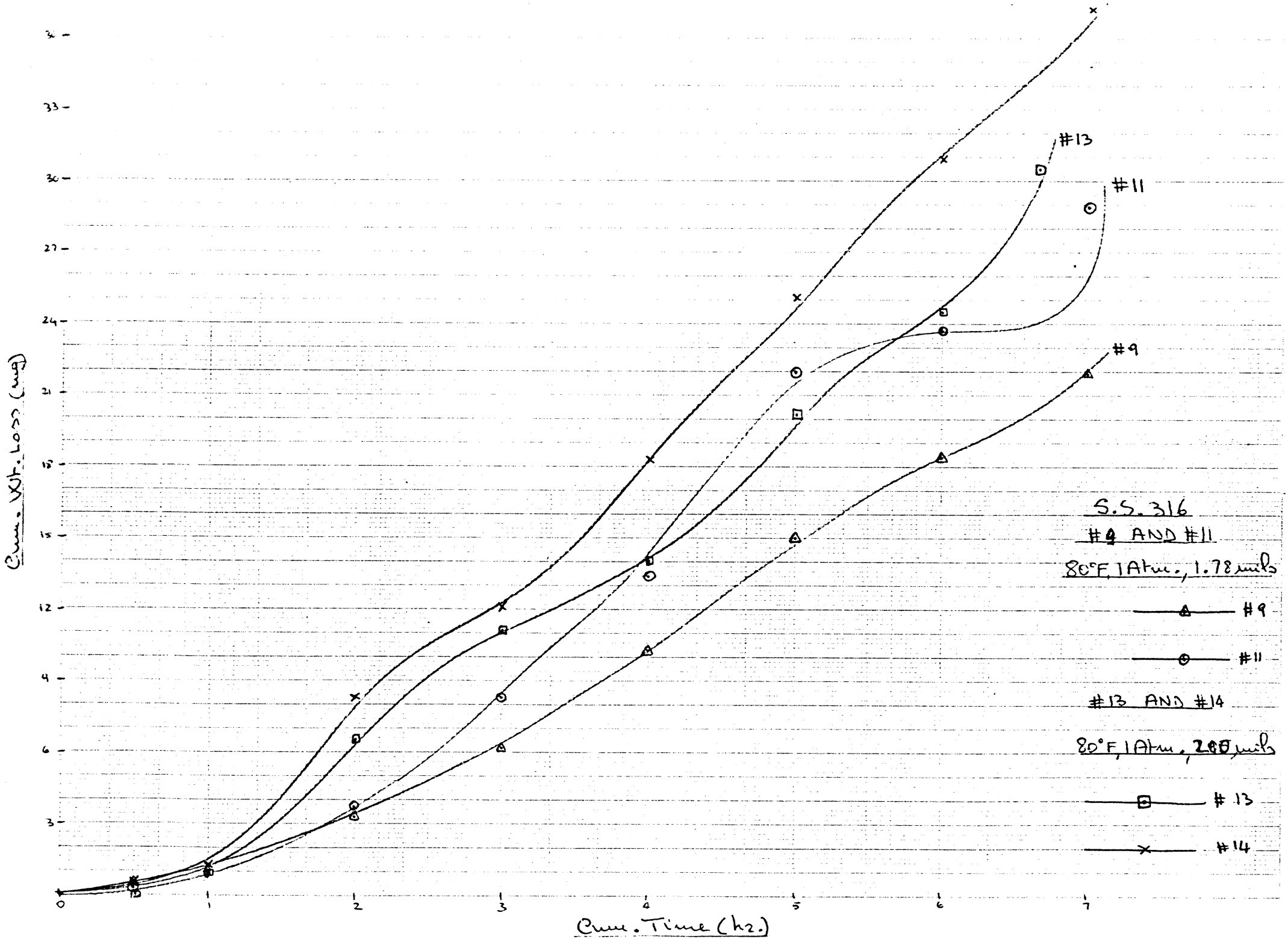
Operator
Mr. Messori

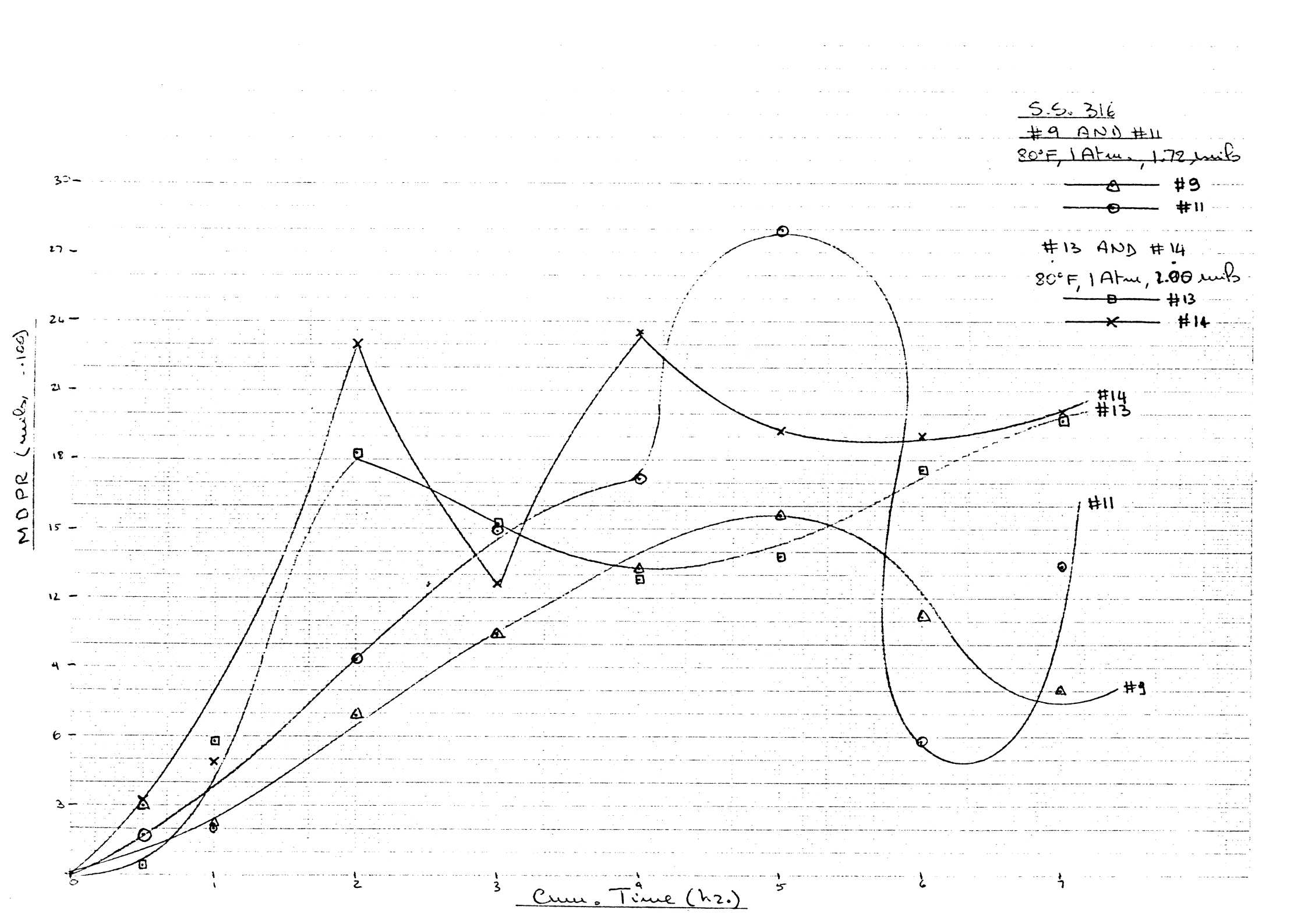
DATA

ME TERVAL Min.	CUMULATIVE TIME Min.	WEIGHT LOSS g.	CUM. WT. LOSS g.	M. D. P.	M. D. P. R. mils/hz
0	0	0	0		0
30	30	0.00050	0.00050		0.033
30	60	0.00075	0.00125		0.049
60	120	0.00700	0.00825		0.230
60	180	0.00384	0.01209		0.126
60	240	0.00716	0.01925		0.235
60	300	0.00585	0.02510		0.192
60	360	0.00580	0.03090		0.190
60	420	0.00636	0.03726		0.209


Cum. Wt. Loss (mg)
Cum. Time (hr.)
S.S. 316
#13 AND #14
80°F, 1 atm., 2.80 mils
#13
#14
#13


MDPR (mils/hr)
24
21
18
15
12
9
6
3
0
1
2
3
4
5
6
7
Cum. Time (hr.)
#14
#13
S.S. 316
#13 AND #14
800F, 1 Atm., 2.0 mils
#13
#14


Cum. Wt. Loss (mg)
Cum. Time (hr.)
0
1
2
3
4
5
6
7
3
4
6
9
12
15
18
21
24
27
30
33
#13
#11
#9
S.S. 316
#9 AND #11
80°F, 1 Atm., 1.78 mils
#9
#11
#13 AND #14
80°F, 1 Atm., 200 mils
13
#14


S.S. 316
#9 AND #11
80°F, 1 Atm., 1.72 mils
#9
#11
#13 AND #14
80°F, 1 Atm, 2.00 mils
#13
#14
MDPR (mils/.100)
30
27
24
21
18
15
12
9
6
3
0
1
2
3
4
5
6
7
Cum. Time (hrs.)
#14
#13
#11
#9

MATERIAL DAMAGE SHEET

RN: Ti
PLITUDE: 1.78 mils
TER:
MPERATURE: >200°F
ESSURE: >6.2 psia
ROQUE:
E-RUN:

MATERIAL: SS 316
NUMBER: #10
APPROX. DATE: 6/2 /80
DENSITY:
AREA:
M.D.P. FACTOR: C = 0.03283 mil/mil

MMENTS:

$MDPR_{max} = 0.158$ mil/hr

$MDPR_{Avg} = 0.112$ mil/hr

$IP_{0.1\,mil} =$

perator:
Mr. Hsu

DATA

E ERVAL	CUMULATIVE TIME	WEIGHT LOSS	CUM. WT. LOSS	M.D.P. μm/hr	M.D.P.R. mil/hr
0	0	0.00	0.00		
0	30	0.75	0.75		0.0492
.0	60	1.50	2.25		0.0985
0	120	3.35	5.60	2.204	0.110
0	180	3.05	8.65		0.100
0	210	2.10	10.75	2.502	0.1379
0	240	2.35	13.10	3.919	0.1543
0	270	2.40	15.50	4.003	0.1576
0	330	3.20	18.70		0.1051
				AVG	~~0.1116~~
				2.875	0.1116

MATERIAL DAMAGE SHEET

RN: Ti

PLITUDE: 1.78 mil

TER:

MPERATURE: >600°F

CSSURE: >6.2 psia

RQUE:

C-RUN:

MATERIAL: SS 316

NUMBER: #15

APPROX. DATE: 6/9/80

DENSITY:

AREA:

M.D.P. FACTOR: $C = 0.03283 \frac{mil}{\mu m/hr}$

Hsu

MMENTS:

$MDPR_{max} = 0.1541 \frac{mil}{hr}$

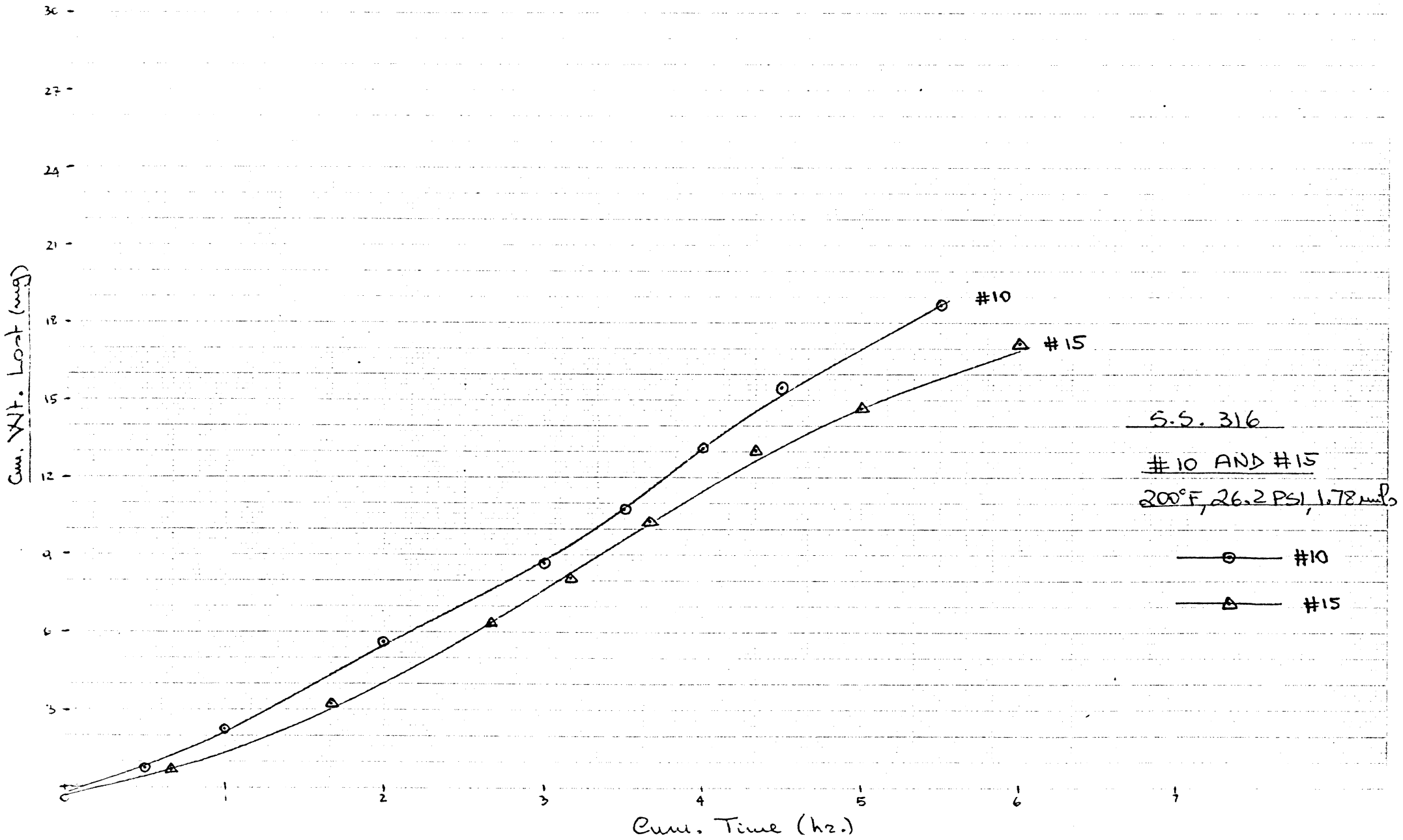
$MDPR_{AVG} = 0.0941 \frac{mil}{hr}$

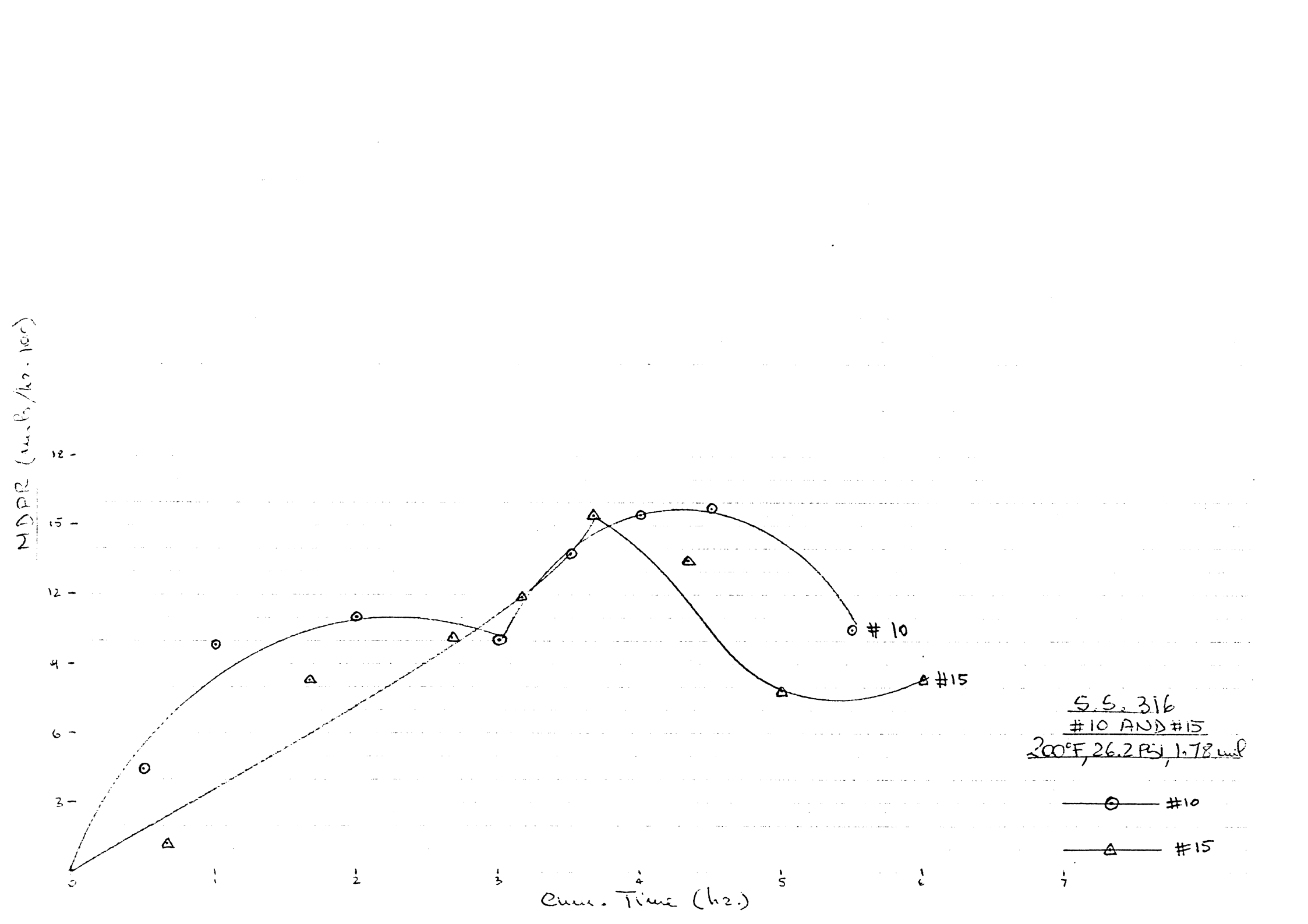
Operator: Mr. Hsu

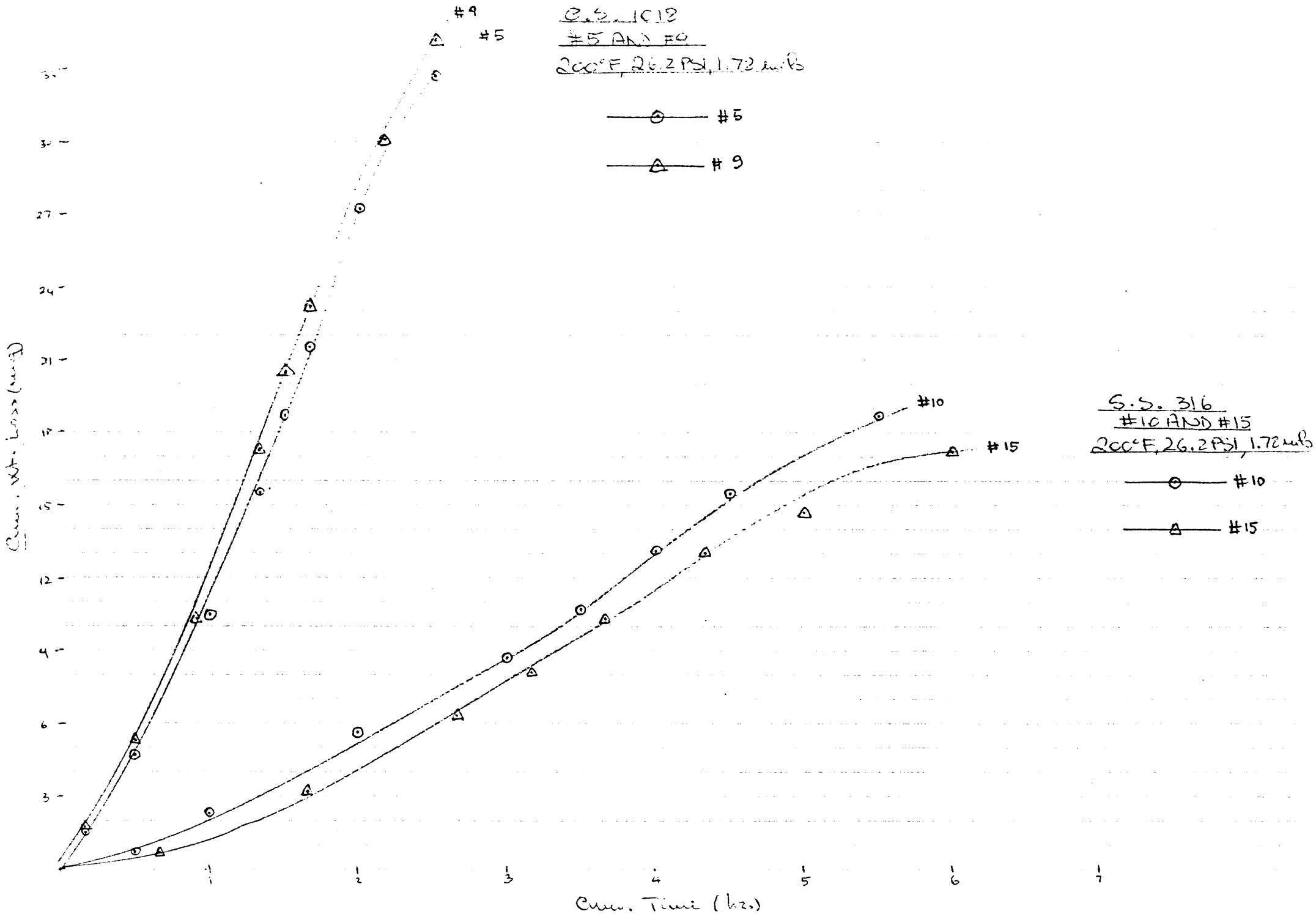
$I \cdot P_{0.1mil} =$

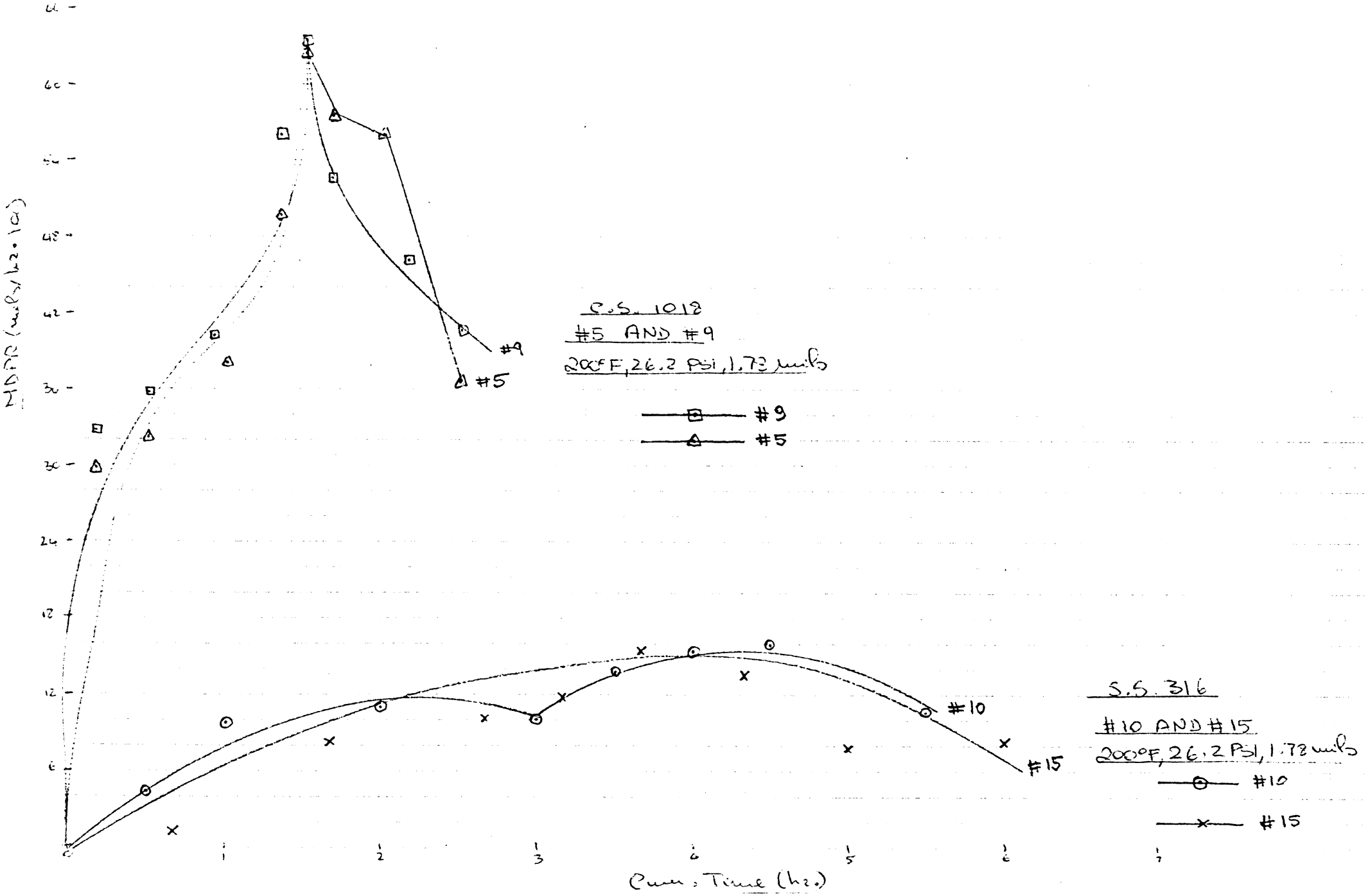
DATA

E ERVAL	CUMULATIVE TIME	WEIGHT LOSS	CUM. WT. LOSS	M.D.P. $\mu m/hr$	M.D.P.R. mil/hr
2	0	0.00	0.00		
0	40	0.70	0.70		0.0123
2	100	2.55	3.25		0.0837
0	160	3.10	6.35		0.1018
0	190	1.80	8.15		0.1182
0	220	2.15	10.30	3.011	0.1541
0	260	2.75	13.05		0.1354
2	300	1.60	14.75 14.65		0.0788
0	360	2.55	17.20		0.0837
				AVG	
				2.391	0.0941


Cum. Wt. Lost (mg)
30
27
24
21
18
15
12
9
6
3
0
1
2
3
4
5
6
7
Cum. Time (hr.)
#10
#15
S.S. 316
#10 AND #15
200°F, 26.2 PSI, 1.78 mils
#10
#15

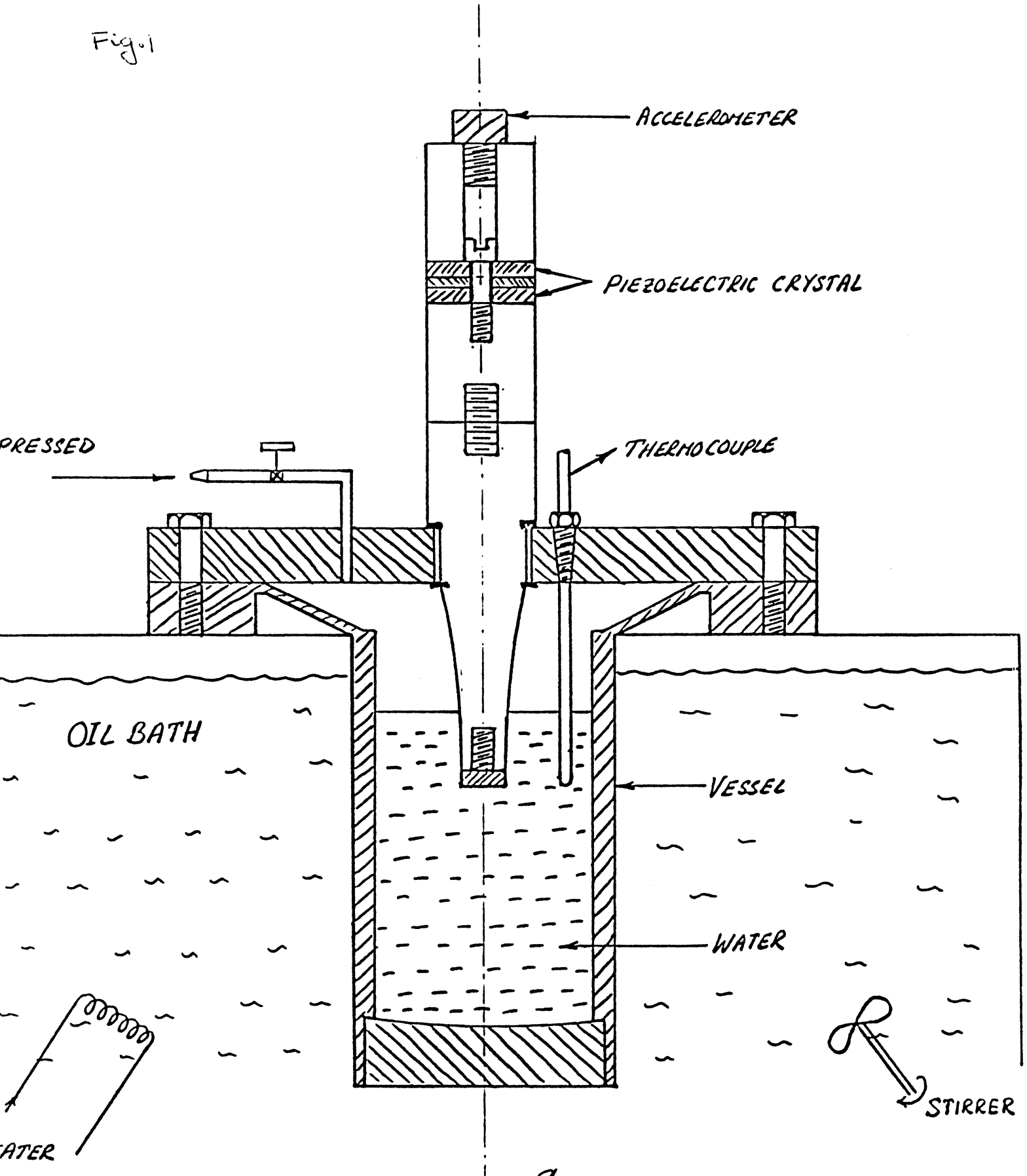

MDPR (mils/hr. tor)
12
15
12
9
6
3
0
1
2
3
4
5
6
7
Cum. Time (hr.)
10
#15
S.S. 316
#10 AND #15
200°F, 26.2 PSI, 1.78 mil
#10
#15


#9
#5
C.S. 1018
#5 AND #9
200°F, 26.2 PSI, 1.72 mils
#5
#9
#10
#15
S.S. 316
#10 AND #15
200°F, 26.2 PSI, 1.72 mils
#10
#15
Cum. Wt. Loss (mg)
Cum. Time (hrs)


MDR (mils/hr • in)
Cum. Time (hrs)
#9
#5
#10
#15
S.S. 1018
#5 AND #9
200°F, 26.2 PSI, 1.73 mils
#9
#5
S.S. 316
#10 AND #15
200°F, 26.2 PSI, 1.73 mils
#10
#15

'B'

Fig.1



THE VIBRATORY SYSTEM

Table 1

Material Mechanical Properties and Erosion Data

Alloy	U.T.S. psi x 10^{-6}	E psi x 10^{-6}	ρ g/cc	UR psi	BHN	MDPR μm/hr	Normalized MDPR
Aluminum 1100-0	11	10	2.71	6.1	41	6.48	36.6
Aluminum 2024-T-4	60	10.6	2.77	180	78	2.56	14.0
Cast Iron (3% C)	32.5	15.5	7.29	34.1	184	0.688	3.76
Carbon Steel -1018	70	30.0	7.85	81.8			
Stainless Steel-316	81.25	29.0	7.91	114	134	0.181	1.0

Notes

U.T.S. = Ultimate tensile strength

E = Elastic modulus

ρ = density

UR = Ultimate Resilience = $(UTS)^2/2E$

BHN = Brinell hardness

Aluminum properties from Alcoa Structural Handbook, 1960

Cast iron and carbon steel Properties from Kent's Mechanical Engr's Handbook, 12th ed., Design and Production, 1952.

Stainless Steel-316 - properties measured for ASTM G-2 Cavitation Round Robin, Materials Research and Standards, Oct. 1970, p. 19, F. G. Hammitt, et al, ASTM.