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NATIONAL BUREAU OF STANDARDS REPORT

10 185

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OUTDOOR PERFORMANCE OF PLASTICS VI. ELECTRICAL PROPERTIES

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U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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OUTDOOR PERFORMANCE OF PLASTICS VI. ELECTRICAL PROPERTIES

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ABSTRACT

This is the sixth in a series of reports on the outdoor performance of 20 plastics. The results of 3 years of weathering on the dielectric constant and dissipation factor of these materials are discussed.

No significant difference was found between the average dielectric constants of the 3 sites. The average dielectric constant changes little over 3 years and does not seem to be a good index of a material's general performance.

Dissipation factor decreases substantially for the thicker materials but remains fairly stable for the thin ones. It may be useful as an early indicator of deterioration for some materials.

OUTDOOR PERFORMANCE OF PLASTICS

VI. ELECTRICAL PROPERTIES

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13. " " " " - " " -C (10 mil)
14. " " " " - " " -C (60 mil)
15. " " " " - " " -N (60 mil)
16. " " " " - " " -A (4 mil)
17. " " " " - " " -A (10 mil)
18. " " " " - " " -A (60 mil)
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30. " " " " - " " -C (4 mil)
31. " " " " - " " -C (10 mil)
32. " " " " - " " -C (60 mil)
33. " " " " - " " -N (60 mil)
34. " " " " - " " -A (4 mil)
35. " " " " - " " -A (10 mil)
36. " " " " - " " -A (60 mil)
37. " " " " - " " -D (4 mil)
38. " " " " - " " -D (10 mil)
39. " " " " - " " -D (60 mil)
40. " " " " - " " -M (60 mil)

OUTDOOR PERFORMANCE OF PLASTICS
VI. ELECTRICAL PROPERTIES

1. OBJECTIVE

This is the sixth in a series of reports on the effects of weathering on physical properties, appearance properties, and other more fundamental properties of plastics. The goal of this study is to develop rapid and accurate methods for predicting outdoor performance.

NBS Reports previously issued are:

- I. INTRODUCTION & COLOR-CHANGE (#9912)
- II. TENSILE AND FLEXURAL PROPERTIES (#10014)
- III. STATISTICAL MODEL FOR PREDICTING WEATHERABILITY (#10116)
- IV. SIGNIFICANCE OF CLIMATE (#10156)
- V. SURFACE ROUGHNESS (#10179)

This is a report on electrical properties. It presents the results of outdoor exposure for the dielectric constant and dissipation factor of 20 plastics formulated from six base polymers - polyethylene, polymethyl methacrylate, polyethylene terephthalate, polyvinyl fluoride, glass-reinforced polyester, and polyvinyl chloride. These plastics were exposed for up to 36 months in Arizona, Florida, and Washington, D. C. and were tested periodically during this time.

2. INTRODUCTION

2.1 Significance of the Properties

Both dielectric constant and dissipation factor may be affected by a change in the polarization of a material. In the case of a weathered plastic, the conditions to which it is exposed, such as ultraviolet radiation, heat, humidity, and rainfall, could have a significant effect on its polarity. As documented in the preceding report in this series (#10179), the surface of a weathered material can become rough and cracked and may react with water and chemical impurities that are continually deposited on it. Chalking also helps to retain moisture and contamination on the surface^[1]. These surface reactions can increase the polarity of a material and decrease its usefulness as an insulator.

Chain scissions, bond cleavage, and formation of free radicals will add to the number of dipole groups. An increase in the polarity of the polymer molecules can also be expected from oxidation effects such as the formation of carbonyl groups. Dissipation factor has been shown to increase as a result of oxidation reactions in rubber [2].

Such changes in the intrinsic properties of the molecules of the plastic are sometimes detectable by changes in the electrical properties that are measured. Measurements of dielectric constant and dissipation factor could be a way to detect early in the life of a material a fundamental change that it is undergoing. Since molecular changes affect mechanical properties as well as electrical, the detection of a change in electrical properties may indicate a corresponding alteration of physical properties [3]. It may also be a precursor of future improvement or deterioration of flexibility, elongation, tensile strength, etc. For example, increased polarity in polymers can generally be expected to increase rigidity [4]. Some electrical properties may be sensitive measures of weathering in plastics and as such, good predictors of eventual decay.

Some general references on the theory and principles of dielectrics are given at the end of this report [5,6,7,8].

2.2 Dielectric Constant

A system of conductors charged with a quantity of electric charge Q at a potential V has a capacitance $C = Q/V$. By introducing a dielectric material between the conductors, the capacity of the system to store charge can be increased.

The dielectric constant (or permittivity) K' of any homogeneous isotropic material is then defined [9] as "the ratio of the capacitance, C_x , of a given configuration of electrodes with a material as the dielectric, to the capacitance, C_v , of the same electrode configuration with a vacuum as the dielectric":

$$K' = \frac{C_x}{C_v} .$$

K' can be written as ϵ'/ϵ_0 where ϵ' is the dielectric constant of the material and ϵ_0 is the dielectric constant of a vacuum, taken as unity. Thus K' is a dimensionless quantity and is called the relative dielectric constant of the material.

Consider a simple system of conductors - a parallel plate capacitor. The electric field between and perpendicular to the plates is $E = 4\pi s$ where s is the surface charge density. When a dielectric material is inserted between the plates, the electric field decreases to $E = 4\pi s/K'$. Thus, the introduction of a dielectric material between the plates of a capacitor is, in effect, equivalent to a reduction of the surface charge density by an amount $s - s/K' = s(K' - 1)/K'$. The quantity $s(K' - 1)/K'$ is called the polarization P and represents the surface charge induced in the material by the electric field [10].

Since $E = 4\pi s/K'$ and $P = (K'-1)s/K'$, we can obtain the following relationship between K' and P :

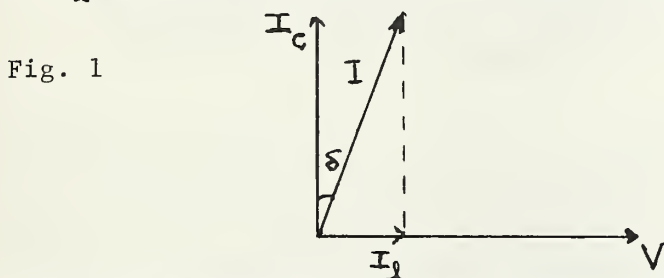
$$K' - 1 = 4\pi P/E .$$

The dielectric constant is indicative of the net polarization of a material. A change in P will be reflected by a change in K' .

2.3 Dissipation Factor

In an ideal capacitor, the current I_c which flows when an alternating potential V is applied is 90° out of phase with the alternating potential. No electrical energy is lost in the material and the total current is equal to the charging current I_c .

In a real capacitor with a dielectric material between the plates, the current has a component I_l in phase with the alternating potential which can be determined by Ohm's law. This Ohmic or loss current is due to the dissipation of part of the electrical energy as heat in the dielectric material. The vector sum of I_c and I_l gives the actual total current I (Fig. 1):



The angle δ between the total current I and the charging current I_c is called the loss angle and the tangent of δ is the loss tangent or dissipation factor D :

$$D = \tan \delta = \frac{\text{loss current } (I_l)}{\text{charging current } (I_c)} = \frac{1}{wRC}$$

where w is 2π times the frequency in cycles per second, R is the resistance of an equivalent parallel circuit, and C is the capacitance. Note that dissipation factor, D , is a dimensionless quantity.

Dissipation factor also can be defined as the ratio of the electrical energy dissipated to the electrical energy stored by the capacitor. An ideal capacitor would have a dissipation factor of 0 since there would be no energy loss.

Since dissipation factor is proportional to the electrical energy lost in the plastic, and the energy stored depends on the plastic's polarity, change in dissipation factor should be a useful index of chemical changes in the plastics.

3. EXPERIMENTAL

A modification of ASTM D150-65T [9] was used by Firestone Plastics to measure dielectric constant and dissipation factor.

Samples were conditioned for 48 hours at 23°C and 50% relative humidity before testing.

Two materials could not be tested because they were too thin: polyvinyl fluoride (one mil) and polyethylene (one mil).

Measurements were made at impressed frequencies of one kilocycle and one megacycle using equal (2 inch) sprayed conductive silver disk electrodes without guard ring. Electrodes were smaller than the specimen size. Sprayed silver electrodes provide greater accuracy than pasted electrodes.

3.1 One Kilocycle

Dielectric constant and dissipation factor were derived from measurements made by a substitution method using a Schering Bridge. Readings are taken with the unknown dielectric both in and out of the circuit. This technique eliminates many of the errors due to the circuit elements.

The following equipment was used:

General Radio Type 716-C Capacitance Bridge
General Radio Type 913-C Beat Frequency Oscillator
General Radio Type 1231-A Amplifier and Null Detector
General Radio Type 722-N 1100 mmfd. Precision Condenser
Dumont Type 224-A Cathode Ray Oscillograph

Formulas used in the calculations were:

$$\text{Dielectric Constant} = \frac{\Delta C - 1.9}{\frac{.705}{t} + 0.3}$$

$$\text{Dissipation Factor (\%)} = \frac{1000 (1) (\Delta D)}{\Delta C}$$

where ΔC = change in capacitance when sample is inserted into circuit

t = thickness of sample (in.)

ΔD = change in dissipation factor when sample is inserted into circuit

3.2 One Megacycle

Measurements were made by a resonance method employing a Boonton Radio Corporation Type 160-A Q- Meter. The higher the value of Q the less energy lost in the dielectric material.

Values were obtained from the following formulas:

$$\text{Dielectric Constant} = \frac{4.45 (C_1 - C_2)t}{S}$$

$$\text{Dissipation Factor (\%)} = \frac{100 C_1 (Q_1 - Q_2)}{(C_1 - C_2) (Q_1 - Q_2)}$$

where t = thickness of sample (in.)
S = area of electrodes (in.²)
C₁ = capacitance when sample is not in circuit
C₂ = capacitance when sample is inserted into circuit
Q₁ = Q-meter reading when sample is not in circuit
Q₂ = Q-meter reading when sample is inserted into circuit

4. RESULTS

Dielectric constant and dissipation factor measurements were made at impressed frequencies of one kilocycle and one megacycle. However, at one megacycle, 11 of the 20 test materials had capacitances too high to be recorded by the testing instrument. Only the 60-mil thick specimens could be measured. The absence of these data made it impossible to adequately judge the usefulness of the one megacycle tests as an index of weathering. Consequently only the one kilocycle data will be discussed in this report.

Eighteen of the plastics could be measured at one kilocycle. (One-mil thicknesses of polyethylene and PVF had capacitances beyond the range of the equipment, even at one kilocycle.) Plots of the dielectric constant and dissipation factor data as functions of exposure time appear at the end of this report as figures 5 through 40.

4.1 Dielectric Constant

Plots of dielectric constant as a function of exposure time (Figs. 5-22) fail to reveal a systematic behavior pattern for the data of any of the plastics. Since the dielectric constant appears to be independent of site, data from the 3 sites may be pooled and a 3 year average dielectric constant calculated for each plastic. These averages are very close to the initial property values, all but three (PMMA, PVC-N, PVC-A4) within 10% of their original values.

Although there is no change in the average value of the property, there may be evidence of a cyclic variation in the data. 60-mil thick materials all show a similar pattern characterized by relatively large fluctuations during the first year which damp out during the next two years. PVC-A (4 mil) also behaves this way. Three 10-mil materials (PVC-C, PVC-A and PVC-D) may have the same pattern with the period of maximum fluctuations shifted to a later time between 12 and 20 months. The remaining plastics have data that either vary randomly or not at all.

In order to determine the general effect of site, type of material, and sample thickness on the dielectric constant, data were grouped into several classes for the purpose of analysis:

- (1) Sites - Arizona, Florida, and Washington, D. C.
- (2) Types - Non-PVC and PVC; white PVC and Clear PVC
- (3) Thicknesses - ≤ 5 mil, 10 mil and 60 mil.

The average dielectric constant was calculated for each of these subclasses at each sampling time. Significance tests were done at the 0.1 level of significance.

No significant difference was found between the average dielectric constants of the 3 sites. A comparison of the variability of data from each site showed no difference between the sites.

There is, however, a very significant difference between the average dielectric constant of PVC's and that of non-PVC's at all 3 locations. The average dielectric constant of the PVC's is significantly higher than that of the non-PVC's (Fig. 2). The glass-reinforced polyester is an exception to this with generally high values. Polyethylene, on the other hand, almost always has the lowest dielectric constant of any of the plastics. At a given site, we also found no significant difference between the variabilities of the PVC's and the non-PVC's.

The effect of pigments in the PVC's can be seen in fig. 3 where average dielectric constant is plotted as a function of exposure time. The white PVC's have a definitely higher average dielectric constant than the clear PVC's. Ranking the average dielectric constants of the 18 plastics also results in a separation of the clear and white PVC's (Table 1).

The interaction of thickness and average dielectric constant may be observed in figure 4. 60 mil materials seem to have lower average dielectric constants than 5 mil and 10 mil materials.

FIGURE 2

AVERAGE DIELECTRIC CONSTANT VS EXPOSURE TIME

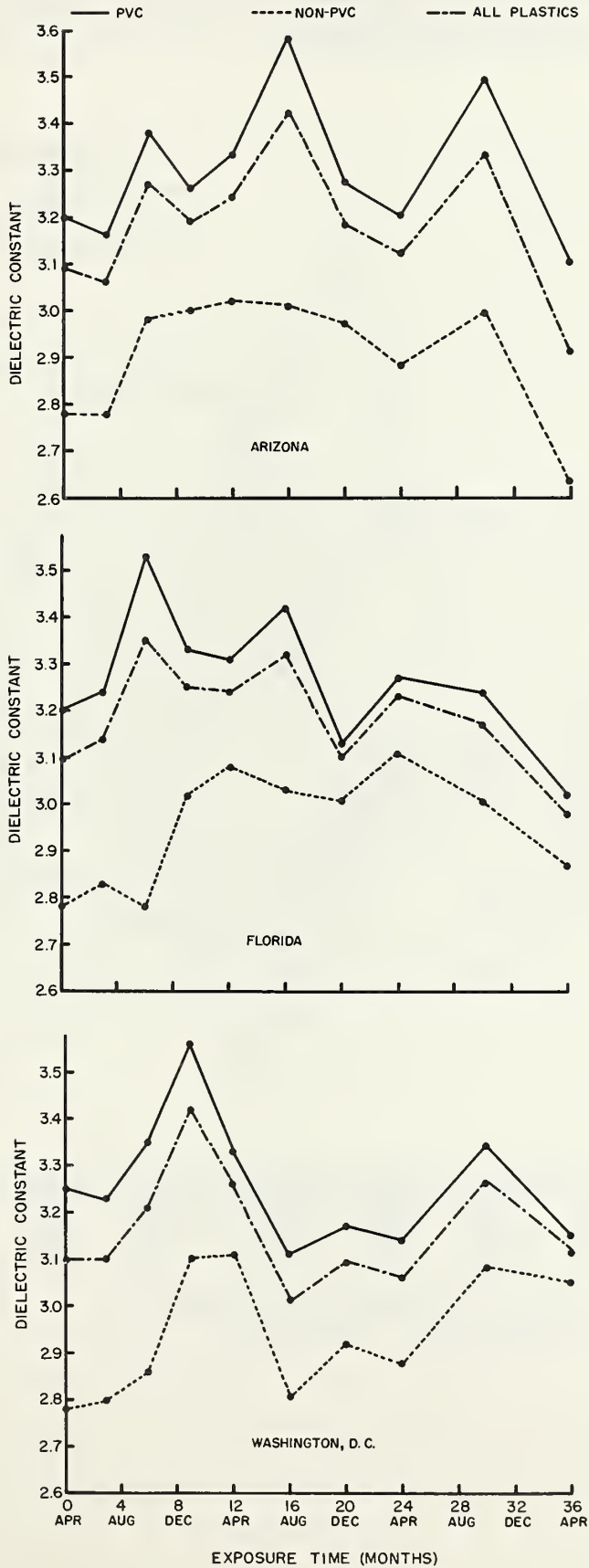


FIGURE 3

AVERAGE DIELECTRIC CONSTANT VS EXPOSURE TIME
FOR CLEAR AND WHITE PVC's

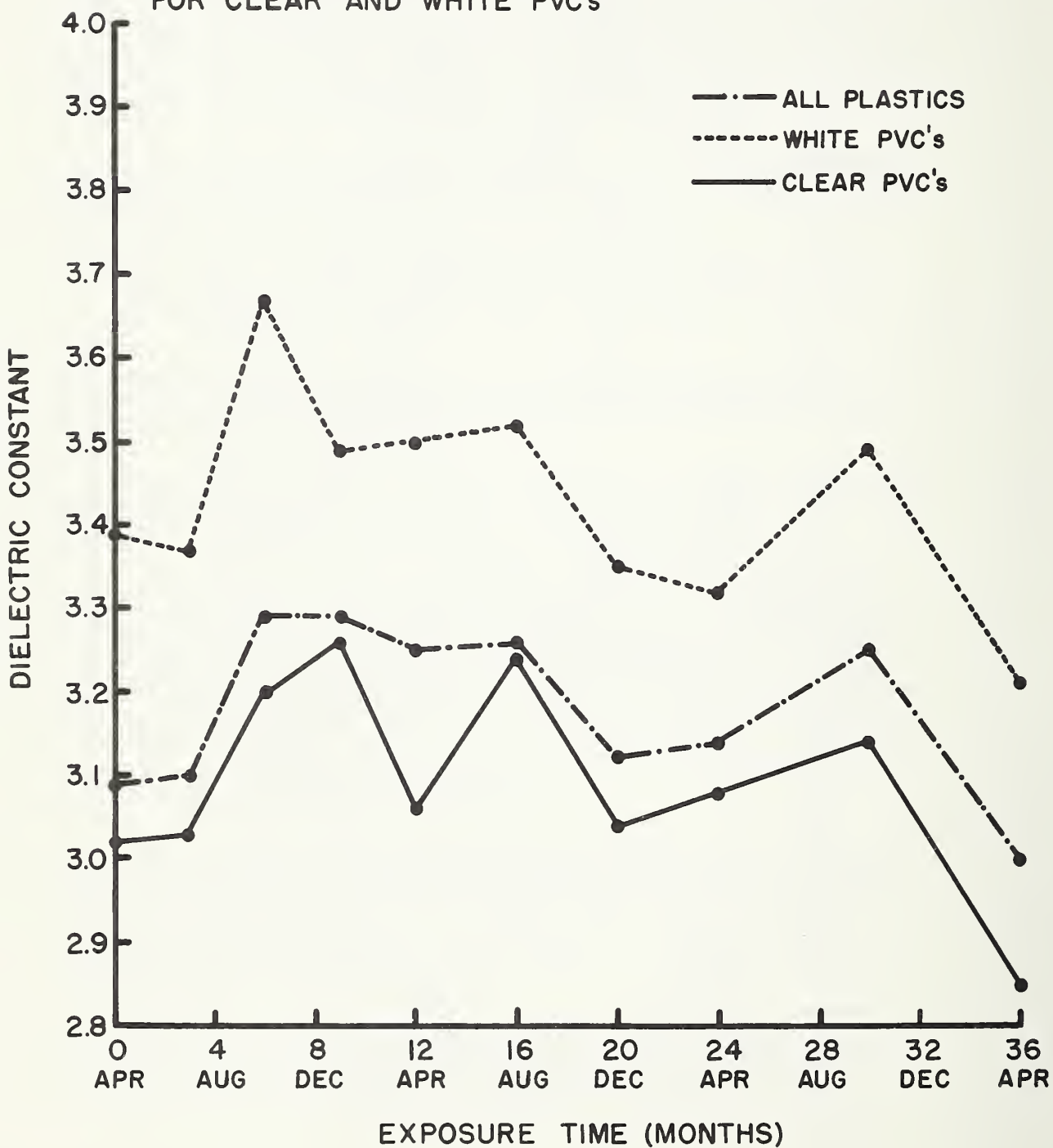
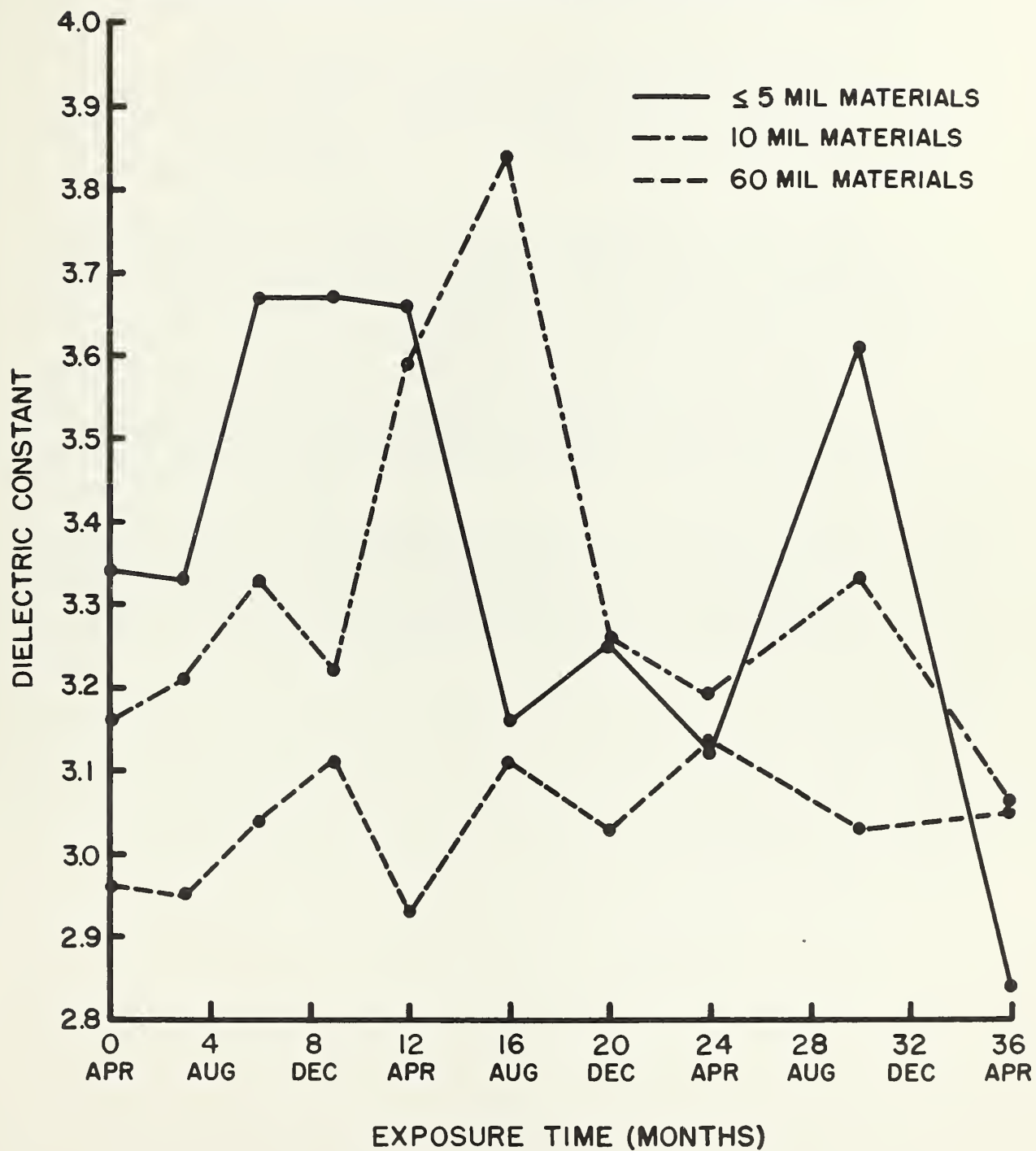


FIGURE 4

AVERAGE DIELECTRIC CONSTANT VS EXPOSURE TIME
FOR PLASTICS OF 3 DIFFERENT THICKNESSES



4.2 Dissipation Factor

Dissipation factor changes very significantly for some materials while for others, it varies little, if at all, from the original values (Figs. 23-40). Values for the unweathered samples ranged between 0 and 5%.

Initial dissipation factor values are related to the thickness of the plastics. When the original property values are ranked in order of increasing magnitude, the 60 mil samples all have higher values than the thinner samples. This is no longer true after the plastics have been exposed outdoors.

A weathered material's retention of its original property value is also dependent on thickness. Except for PMMA, all the 60 mil materials show a substantial decrease in dissipation factor during the 3 years of exposure. Dissipation factors for PE and RP decay to less than 25% of their original values within 12 months. PVC's decrease at a slower rate but lose as much as 50-80% of their initial property values. Note that in RP and all the 60 mil PVC's except PVC-N, there is generally a considerable increase in dissipation factor during the first 3 months. This trend then reverses itself and the property continually deteriorates for the remainder of the 3 years.

A moderate increase in dissipation factor is observed in the Arizona data for PVC-B (10 mil) and PVC-D (4 mil) and for PVC-C (4 mil) in Washington, D. C. Dissipation factors of the other 4, 5 and 10 mil materials vary only slightly or remain constant.

5. CONCLUSIONS AND RECOMMENDATIONS

Dielectric constant seems to be relatively insensitive to the cumulative effect of weathering on plastics. Although the weather is substantially different in Arizona, Florida, and Washington, D. C., the 3 sites cannot be distinguished by their dielectric constant data. Since the average dielectric constant for each plastic is little changed over 3 years while other properties deteriorate significantly, dielectric constant is not a good index of a material's general performance.

Dissipation factor may be a useful measure of early deterioration for some materials. It decreases substantially for the thicker (60 mil) materials while remaining fairly stable for the thinner (4 and 10 mil) ones. The large decrease in dissipation factor for 60 mil materials indicates a decrease in the electrical energy dissipated and/or an increase in the energy stored in the dielectric material.

Generally, as a result of weathering, one would expect an increase in dissipation factor for a pure polymeric material. However, for some of the plastics in this report, dissipation factor decreases. This may be due to the loss of polar additives such as plasticizers which are responsible for some of the energy dissipation in the original unweathered materials. It is not apparent, though, why this decrease should be confined only to 60 mil materials and not to the others.

Relating this property to other more performance-oriented properties might help to predict the ultimate deterioration of a material. Data obtained by Bell Telephone Labs in accelerated aging studies on polyethylene [11], show a correspondence between stress-strain measurements and electrical measurements. Tensile strength and elongation decreased markedly during 155 hours of aging while power factor increased by more than a factor of 10 in the same time period. Power factor is approximately equal to dissipation factor when the loss angle is small. Thus, we might expect changes in dissipation factor to be related to a change in mechanical properties.

TABLE 1

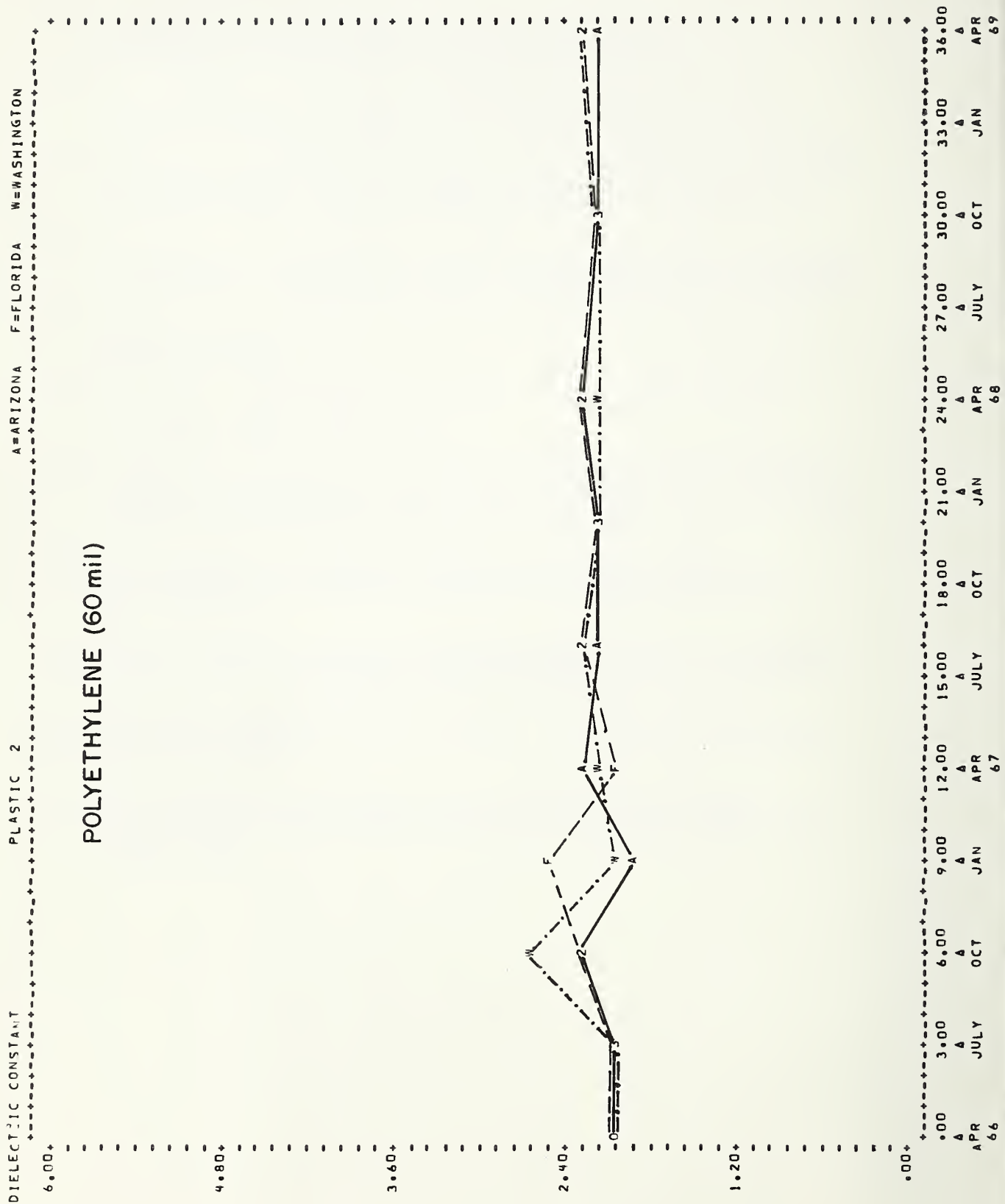
RANKS OF AVERAGE DIELECTRIC CONSTANTS
AVERAGES OVER 36 MONTHS FOR EACH PLASTIC

<u>RANK</u>	<u>PLASTIC</u>	<u>AVERAGE DIELECTRIC CONSTANT</u>
1	PE-60	2.21
2	PVC-C60	2.93
3	PVC-N60	2.95
4	PMMA	2.99
5	PVC-C10	3.09
6	PETP-5	3.16
7	PVC-B60	3.18
8	PVC-B4	3.20
9	PVC-M60	3.22
10	PVC-B10	3.26
11	PVC-C4	3.28
12	PVC-A60	3.30
13	PVC-D60	3.32
14	RP-60	3.40
15	PVC-A10	3.43
16	PVC-D10	3.50
17	PVC-D4	3.61
18	PVC-A4	3.66

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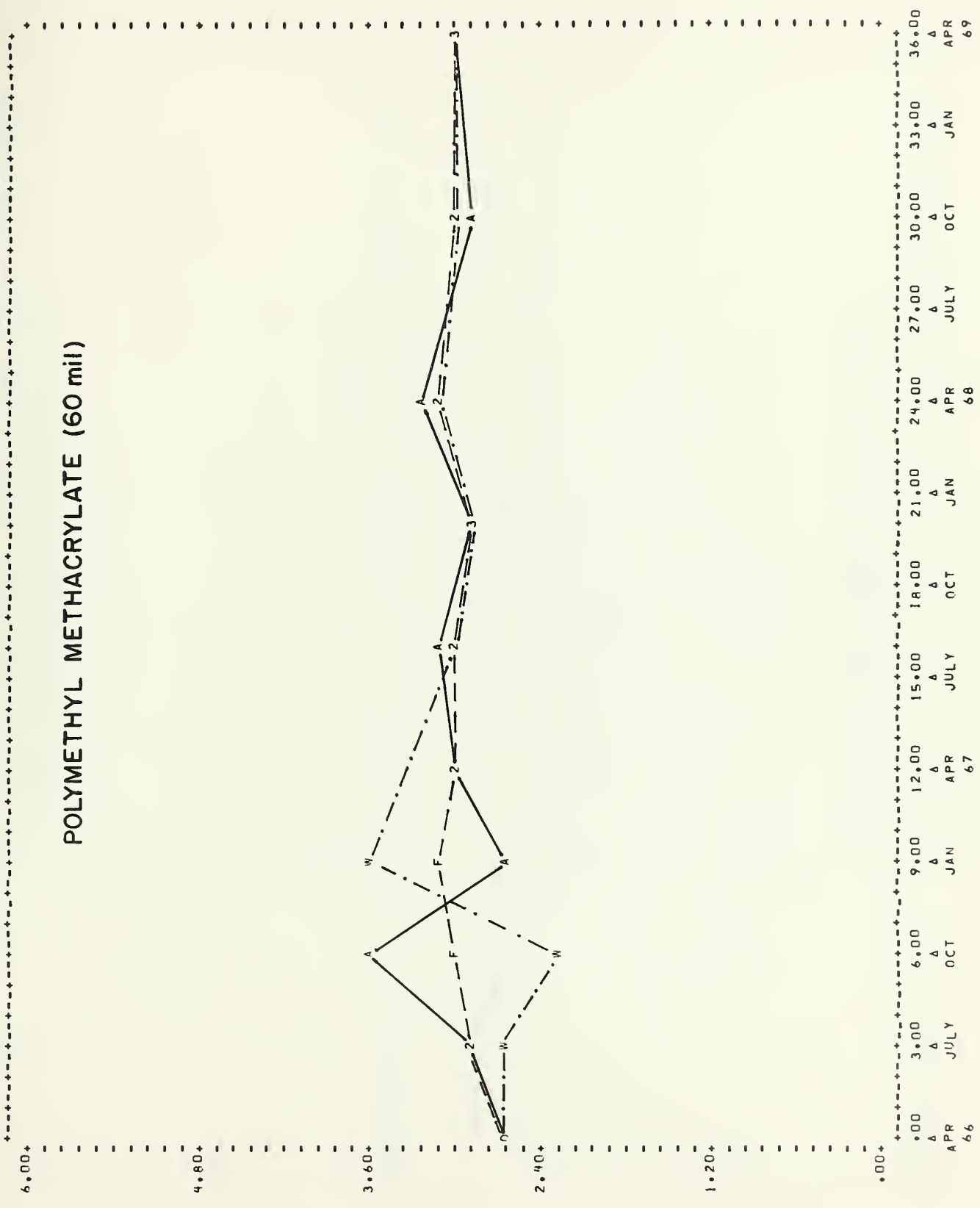
FIGURE 5



DIFLECTRIC CONSTANT PLASTIC 3 A=ARIZONA F=FLORIDA W=WASHINGTON

POLYMETHYL METHACRYLATE (60 mil)

FIGURE 6



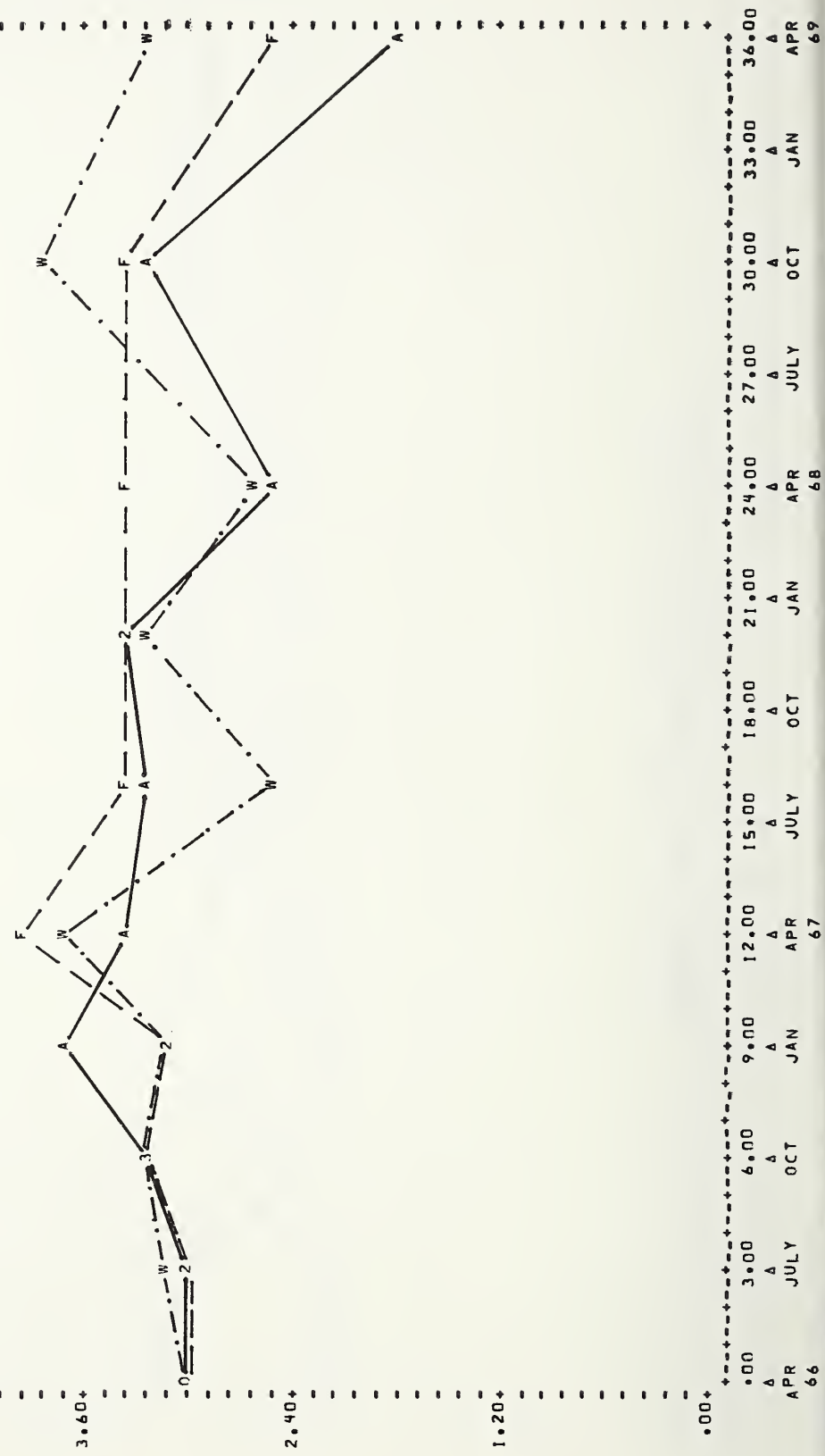
DIELECTRIC CONSTANT

PLASTIC 5

A=ARIZONA F=FLORIDA W=WASHINGTON

POLYETHYLENE TEREPHTHALATE (5 mil)

FIGURE 7



DIELECTRIC CONSTANT PLASTIC 6 A=ARIZONA F=FLORIDA W=WASHINGTON

GLASS - REINFORCED POLYESTER (60 mil)

FIGURE 8

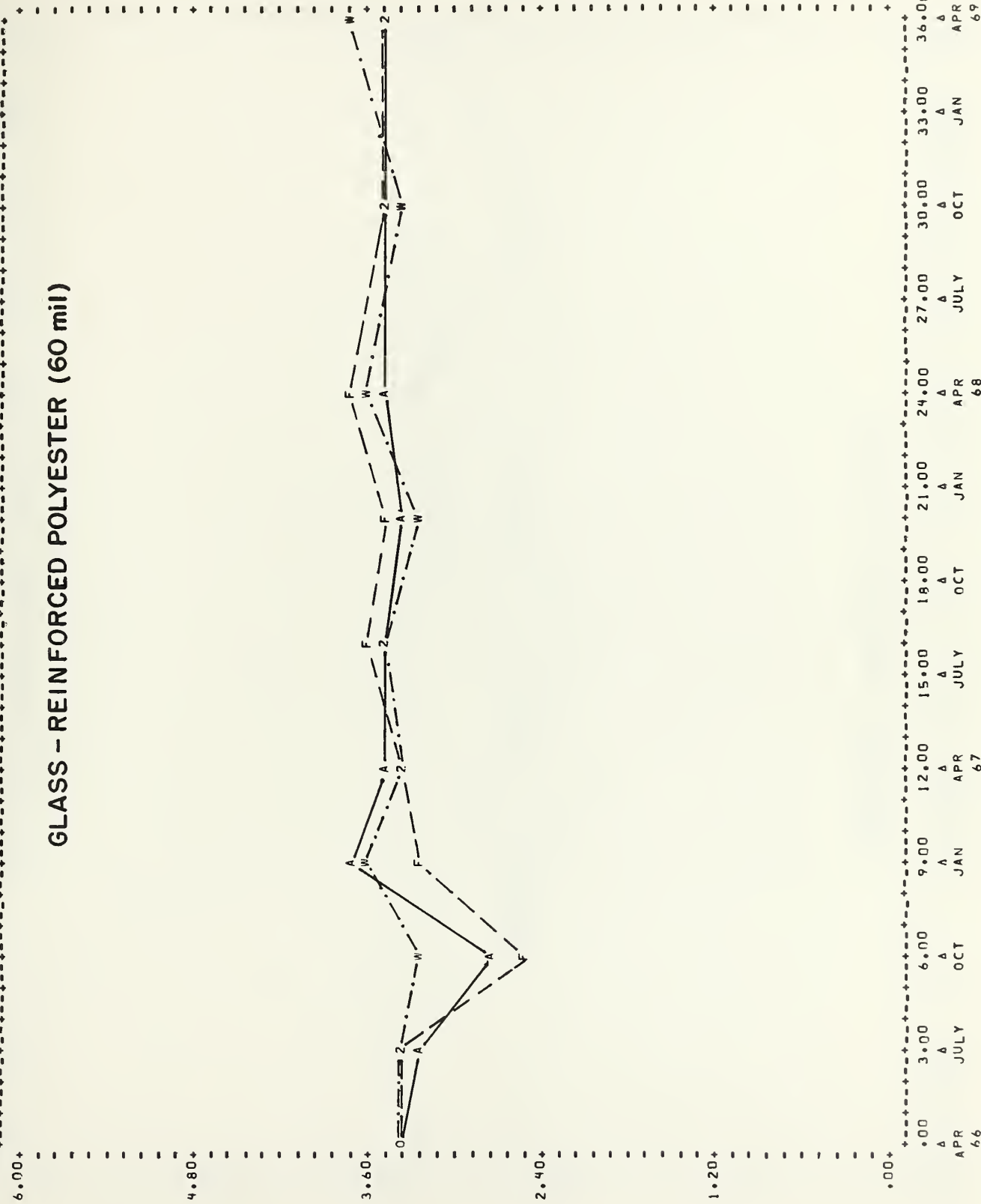


FIGURE 9

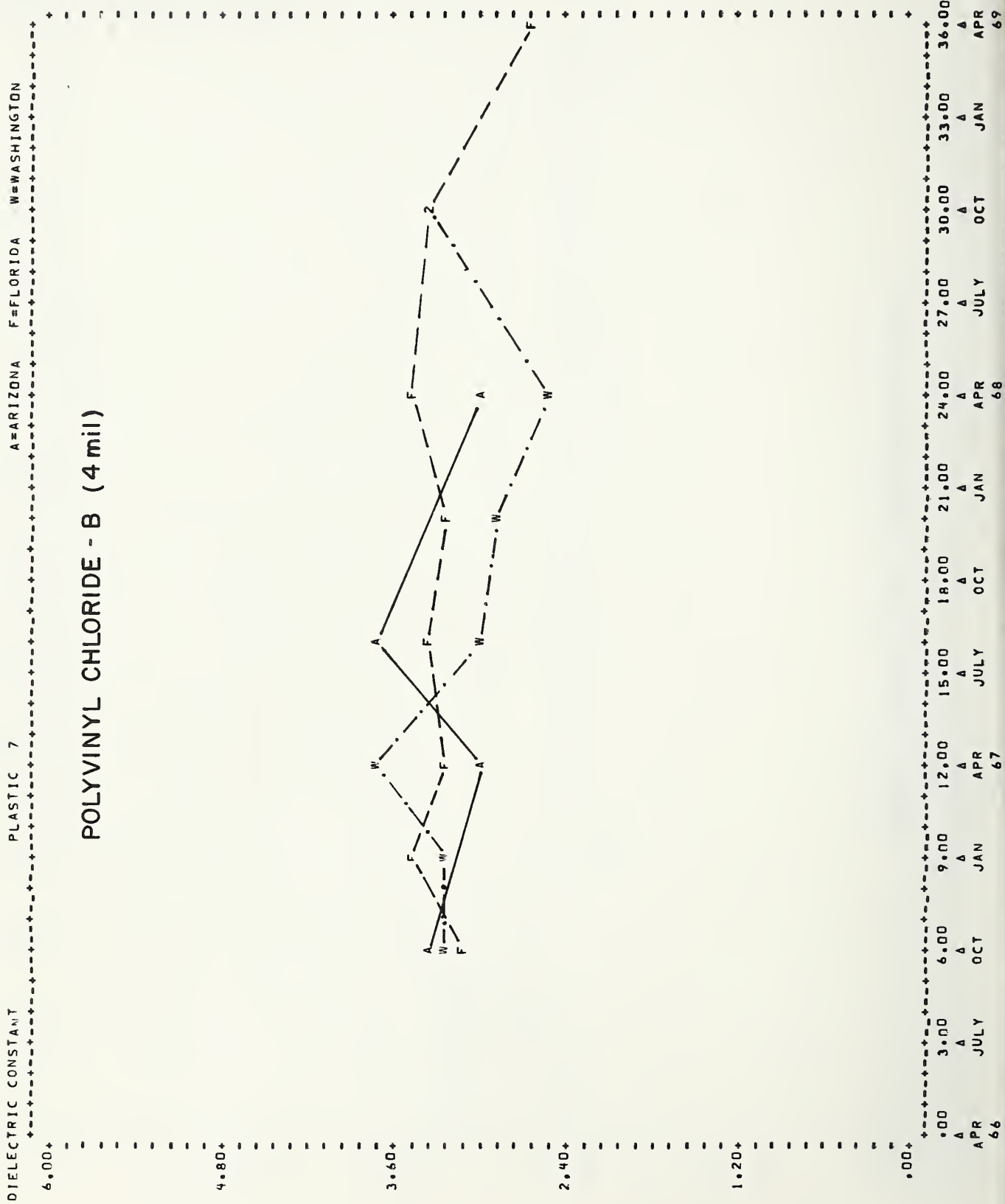


FIGURE 10

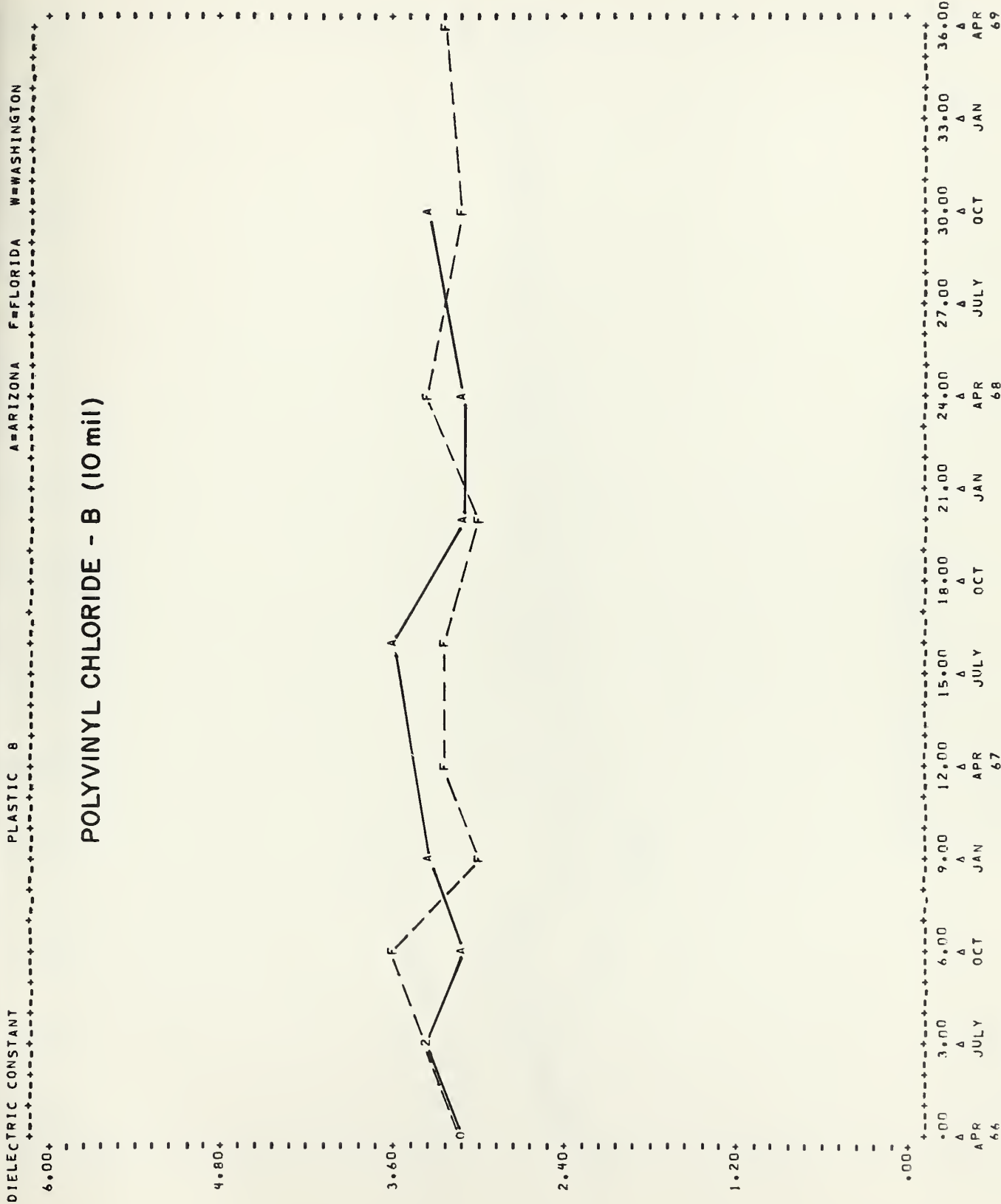


FIGURE II

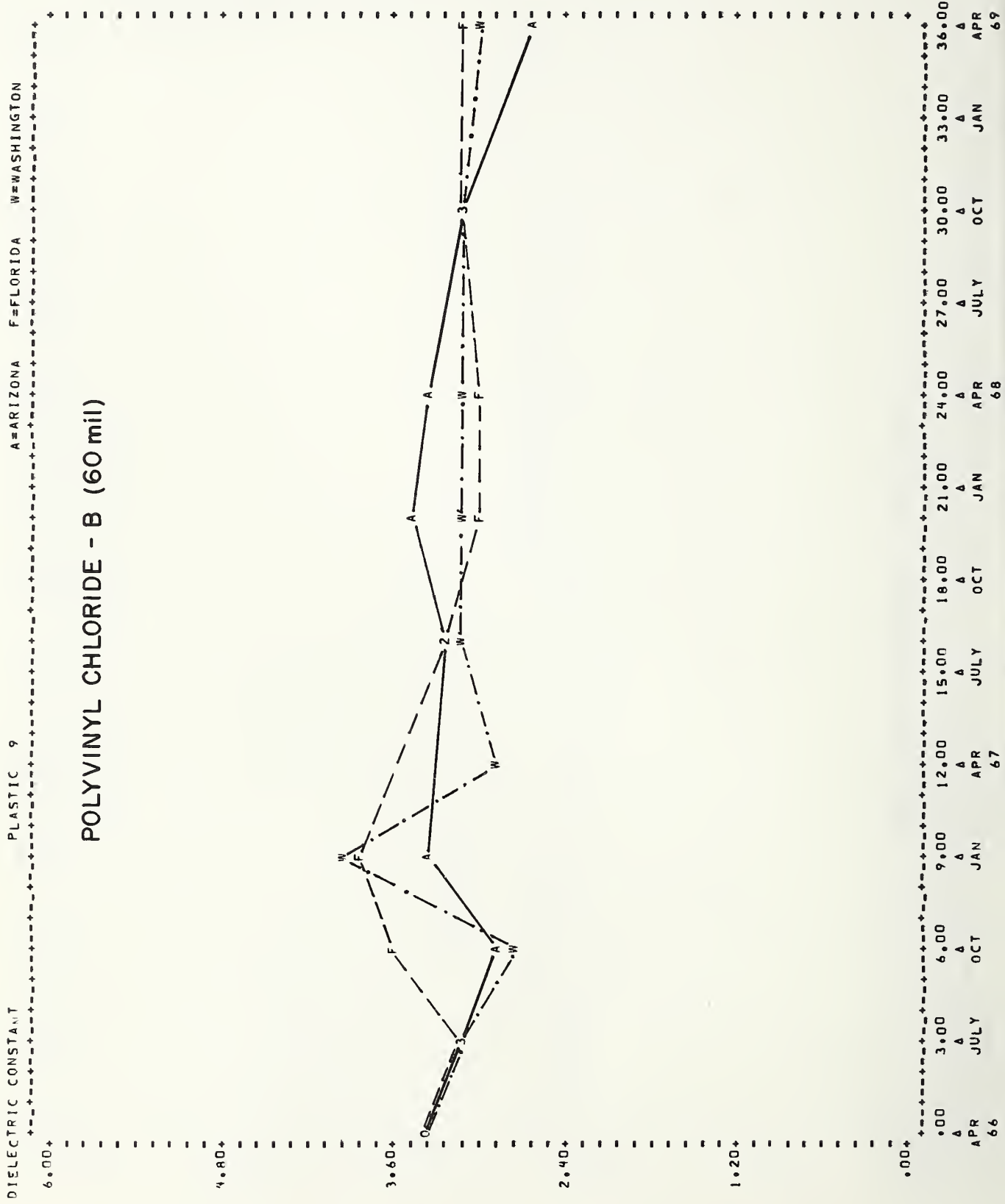


FIGURE 12

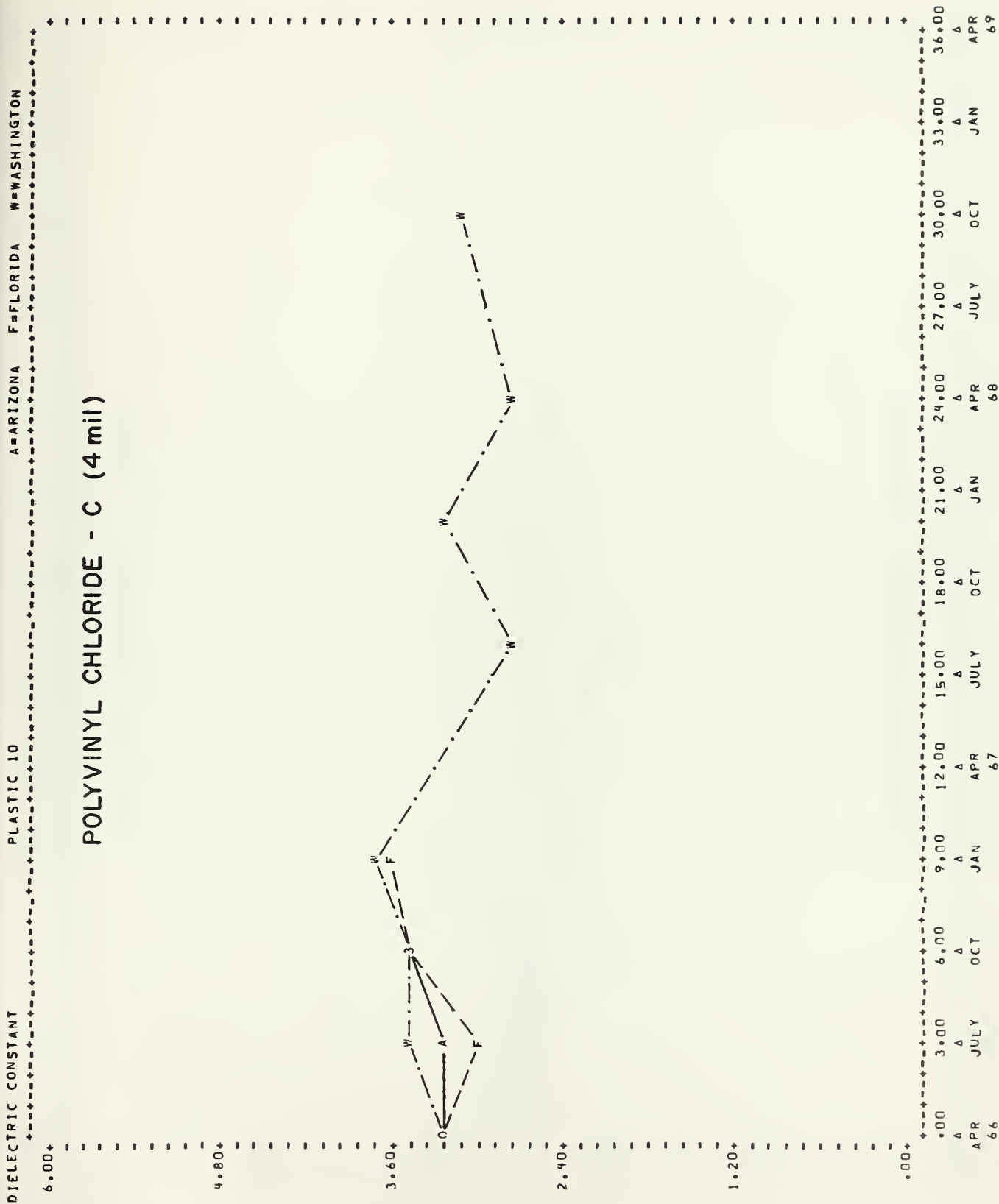
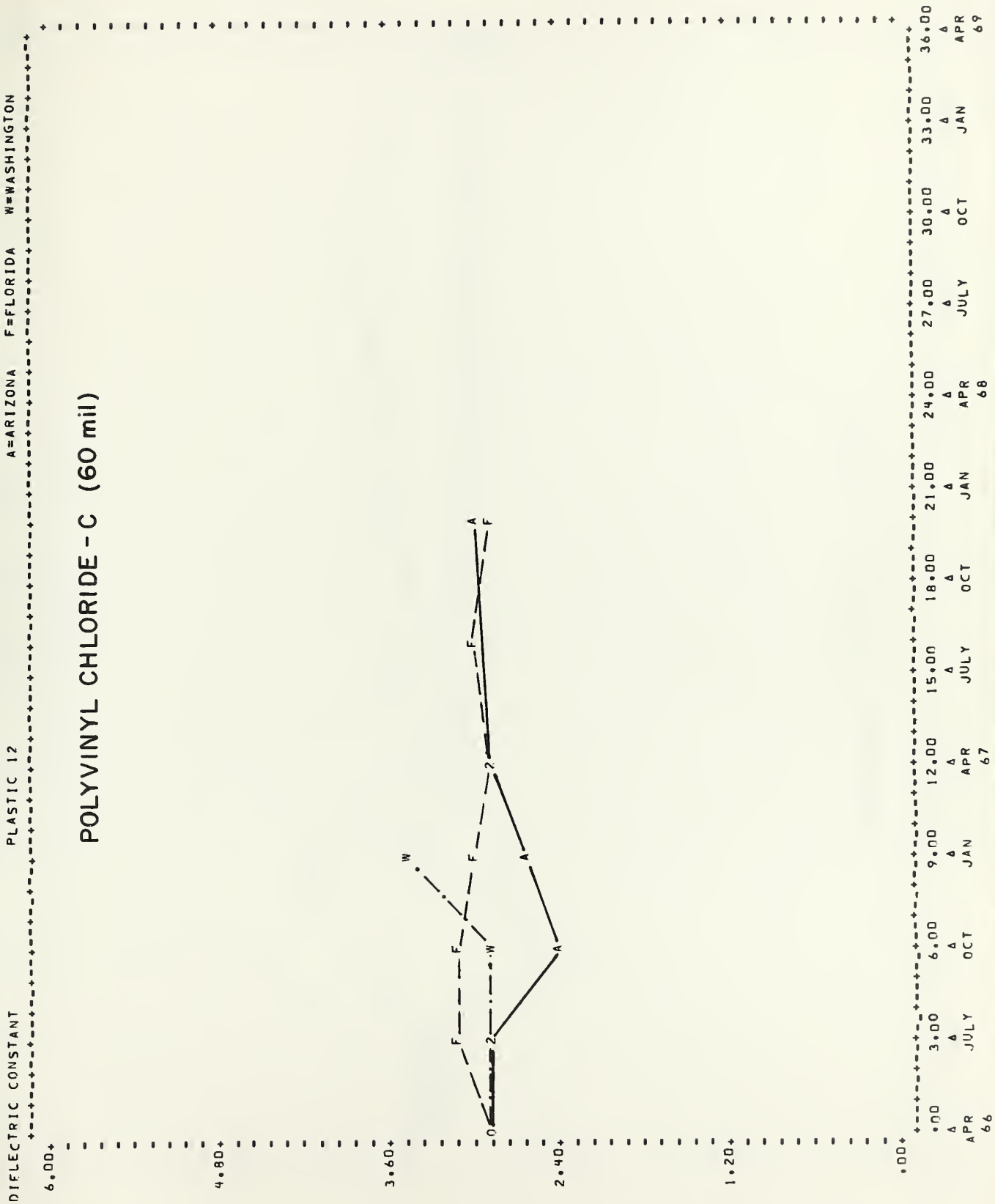


FIGURE 13



A=ARIZONA F=FLORIDA W=WASHINGTON

POLYVINYL CHLORIDE - C (60 mil)



DIELECTRIC CONSTANT

PLASTIC 13

A=ARIZONA F=FLORIDA W=WASHINGTON

W=WASHINGTON

POLYVINYL CHLORIDE - N (60 mil)

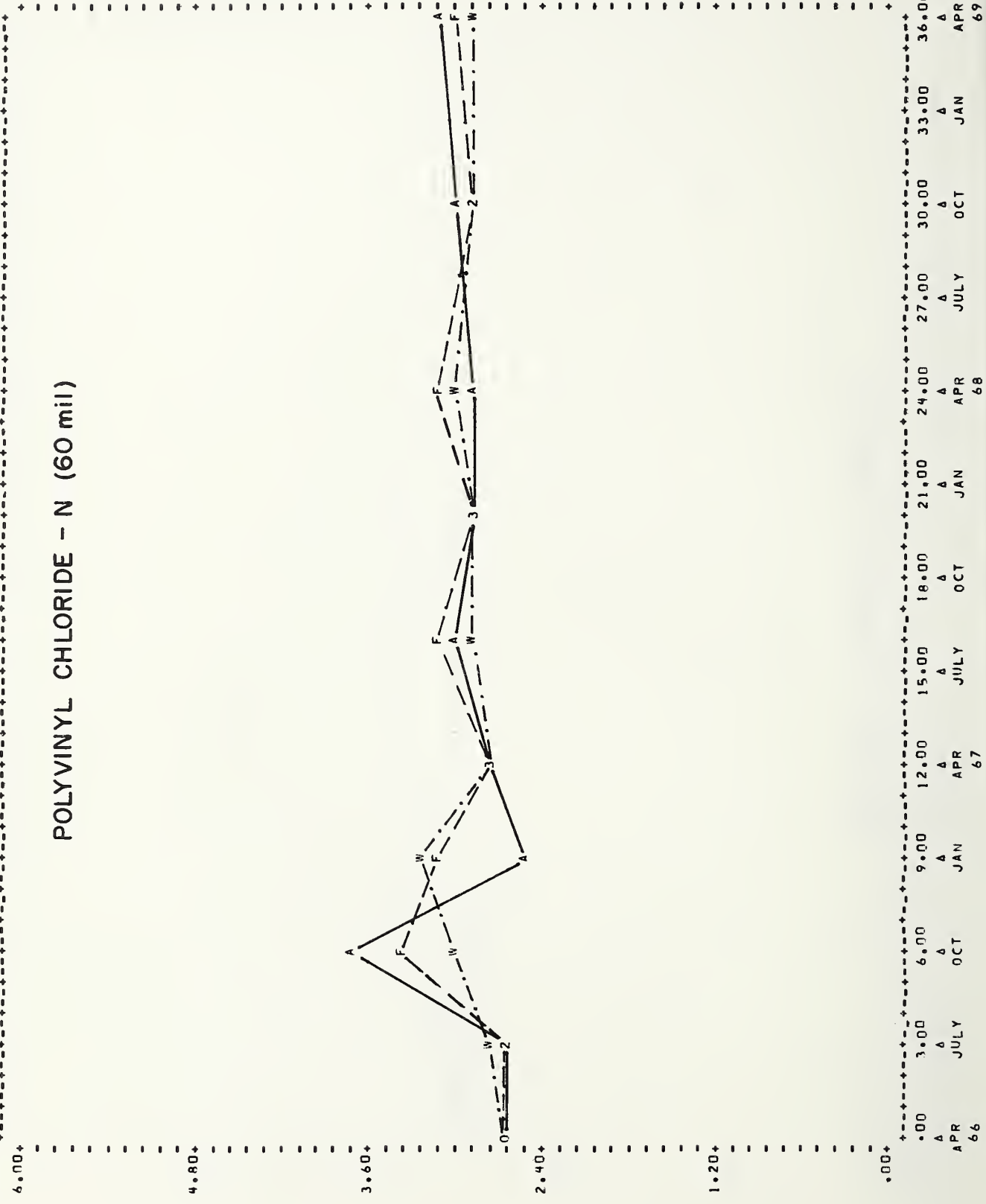


FIGURE 15

FIGURE 16

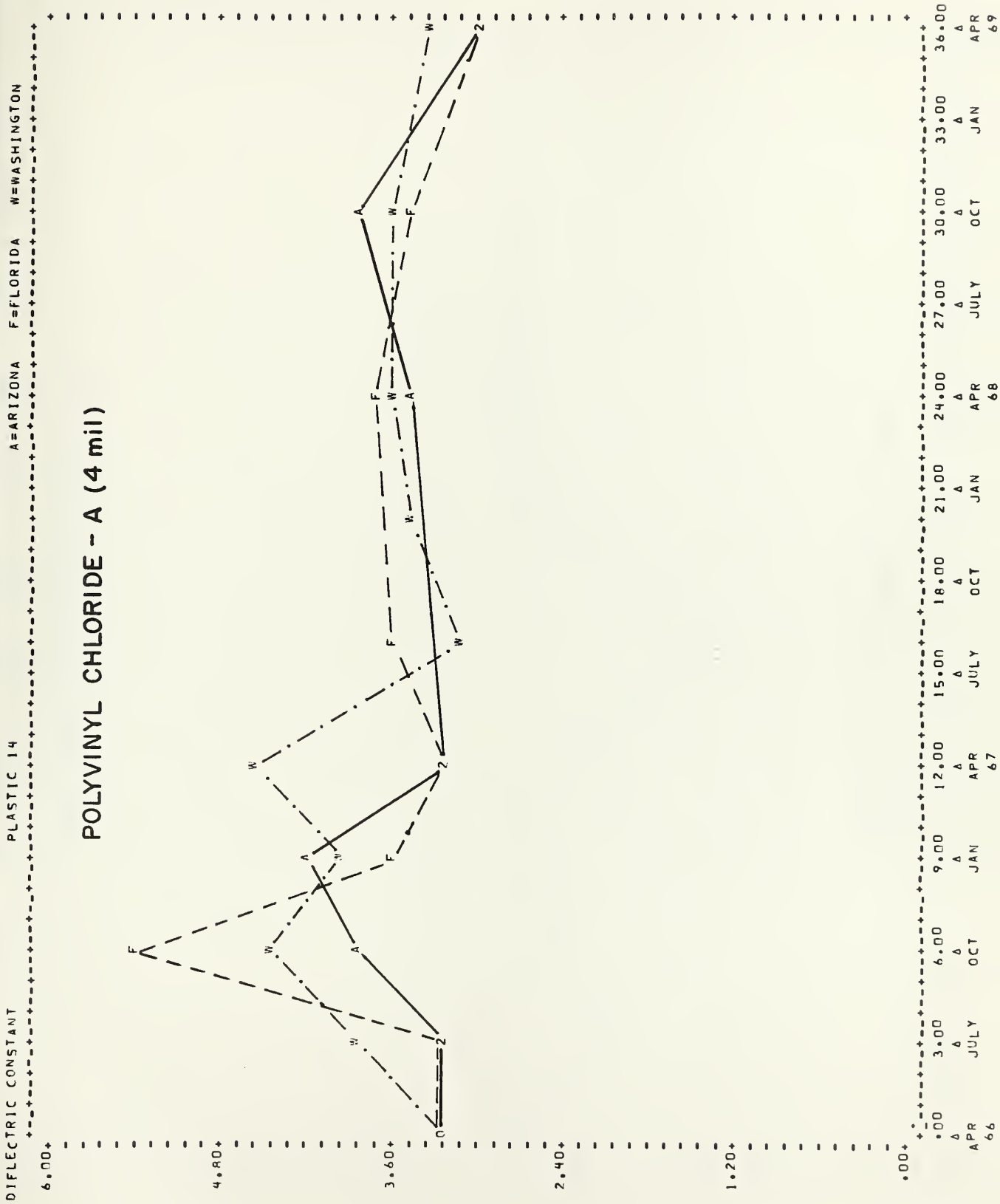


FIGURE 17

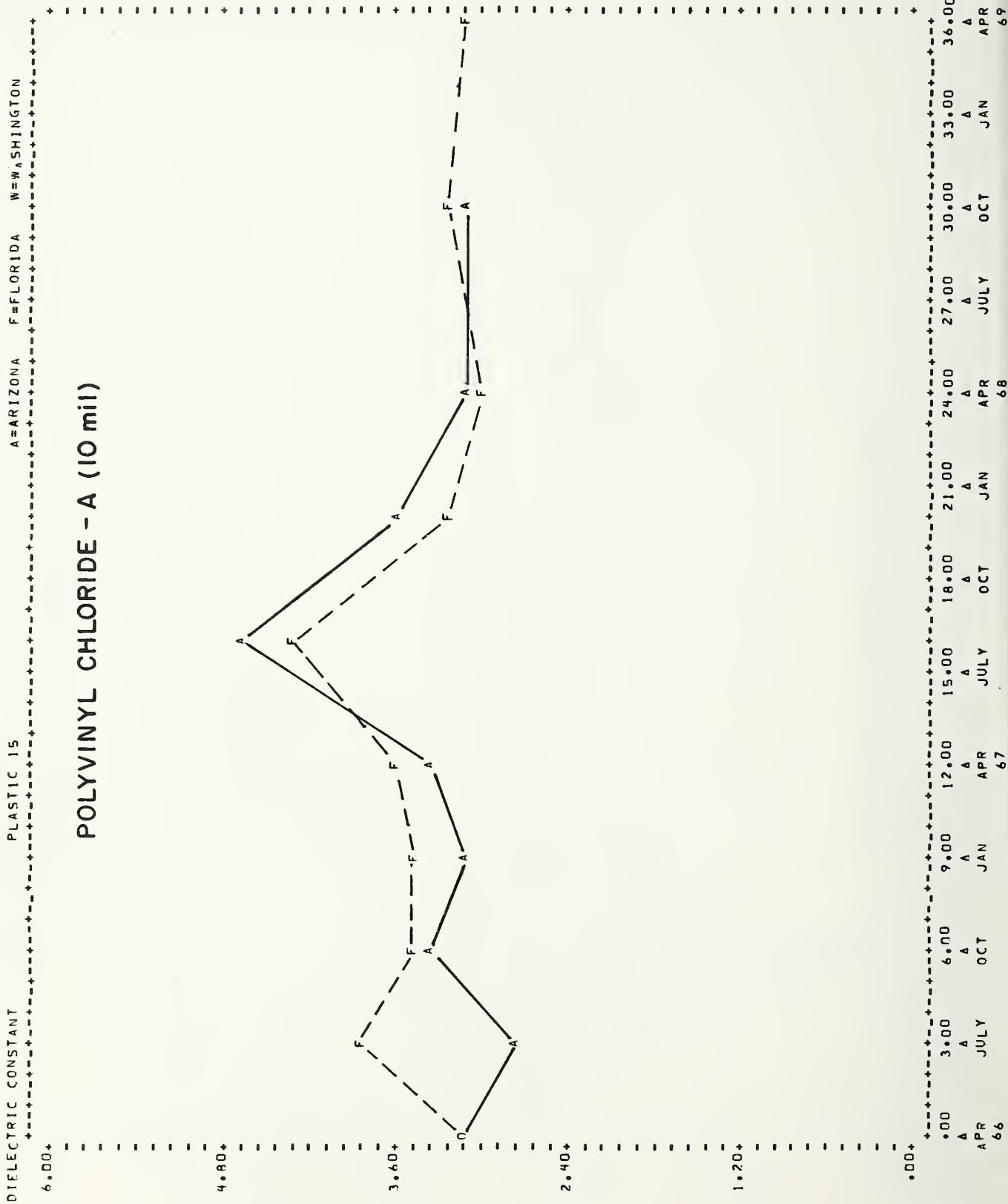


FIGURE 18

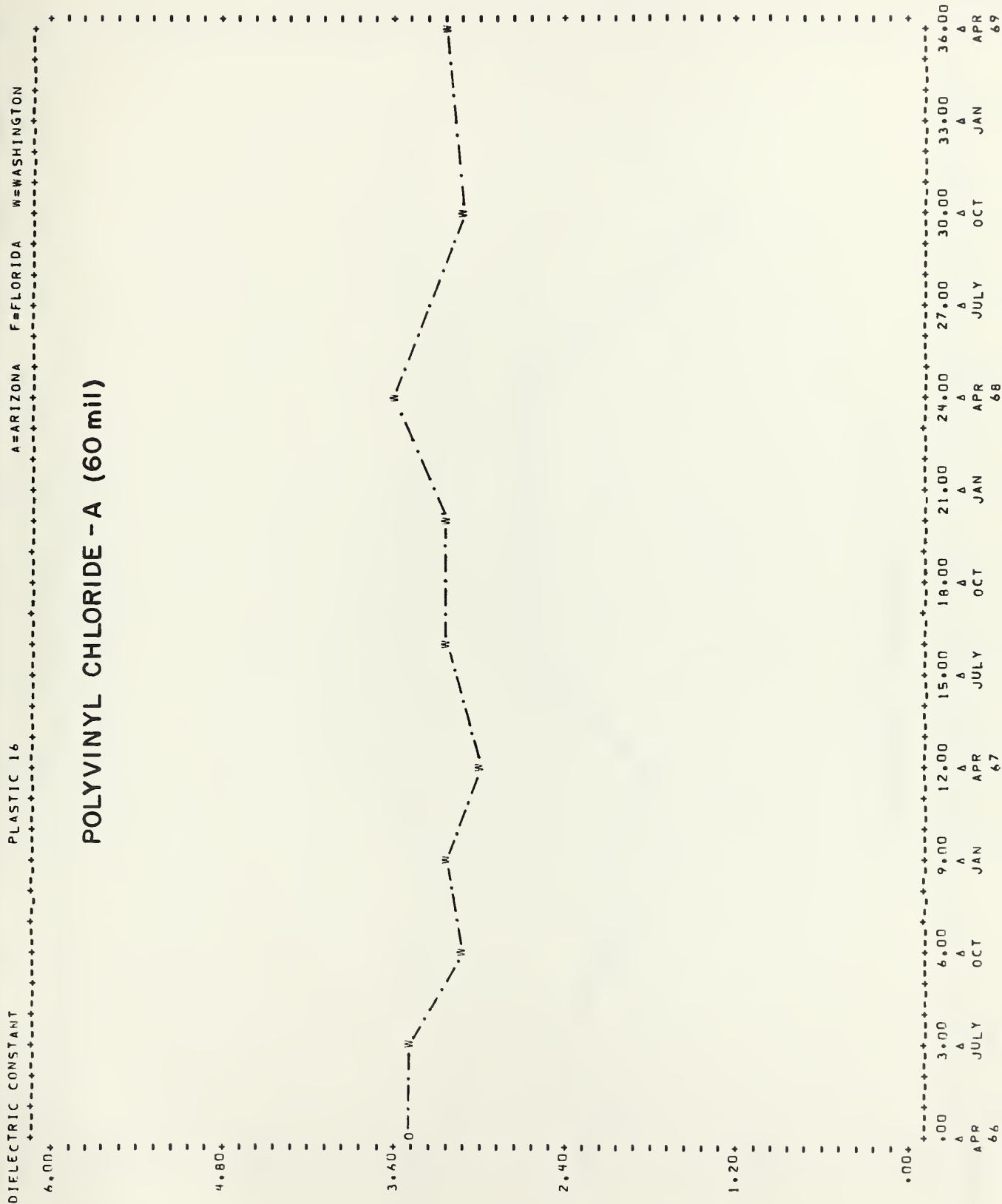


FIGURE 19



FIGURE 20

DIELECTRIC CONSTANT PLASTIC 18 A=ARIZONA F=FLORIDA W=WASHINGTON

POLYVINYL CHLORIDE -D (10 mil)

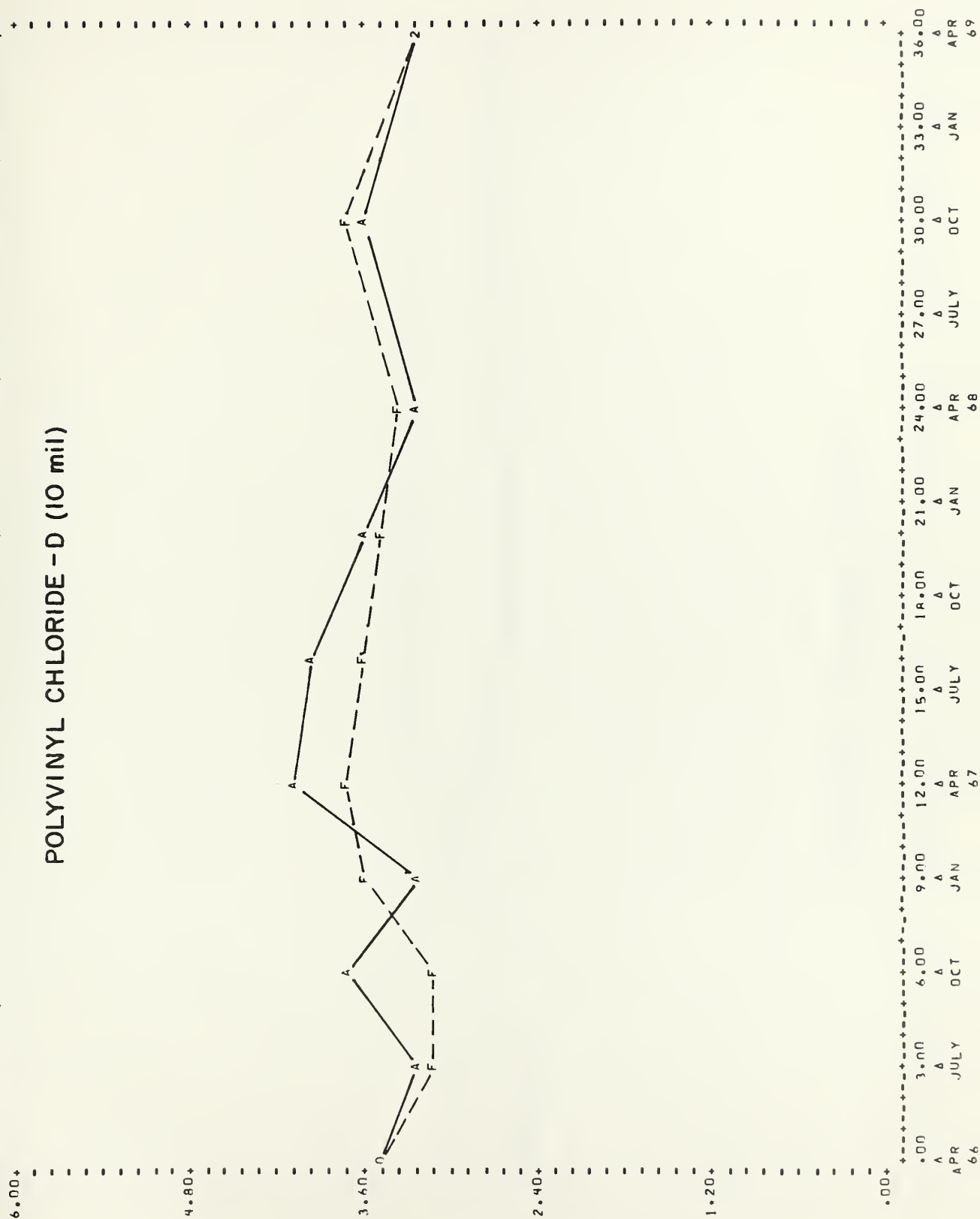


FIGURE 21

DIELECTRIC CONSTANT PLASTIC 19 A=ARIZONA F=FLORIDA W=WASHINGTON

POLYVINYL CHLORIDE - D (60 mil)



0.00 3.00 6.00 9.00 12.00 15.00 18.00 21.00 24.00 27.00 30.00 33.00 36.00
APR JULY OCT JAN APR JULY OCT JAN APR JULY OCT JAN APR
66 67 68 69

FIGURE 22

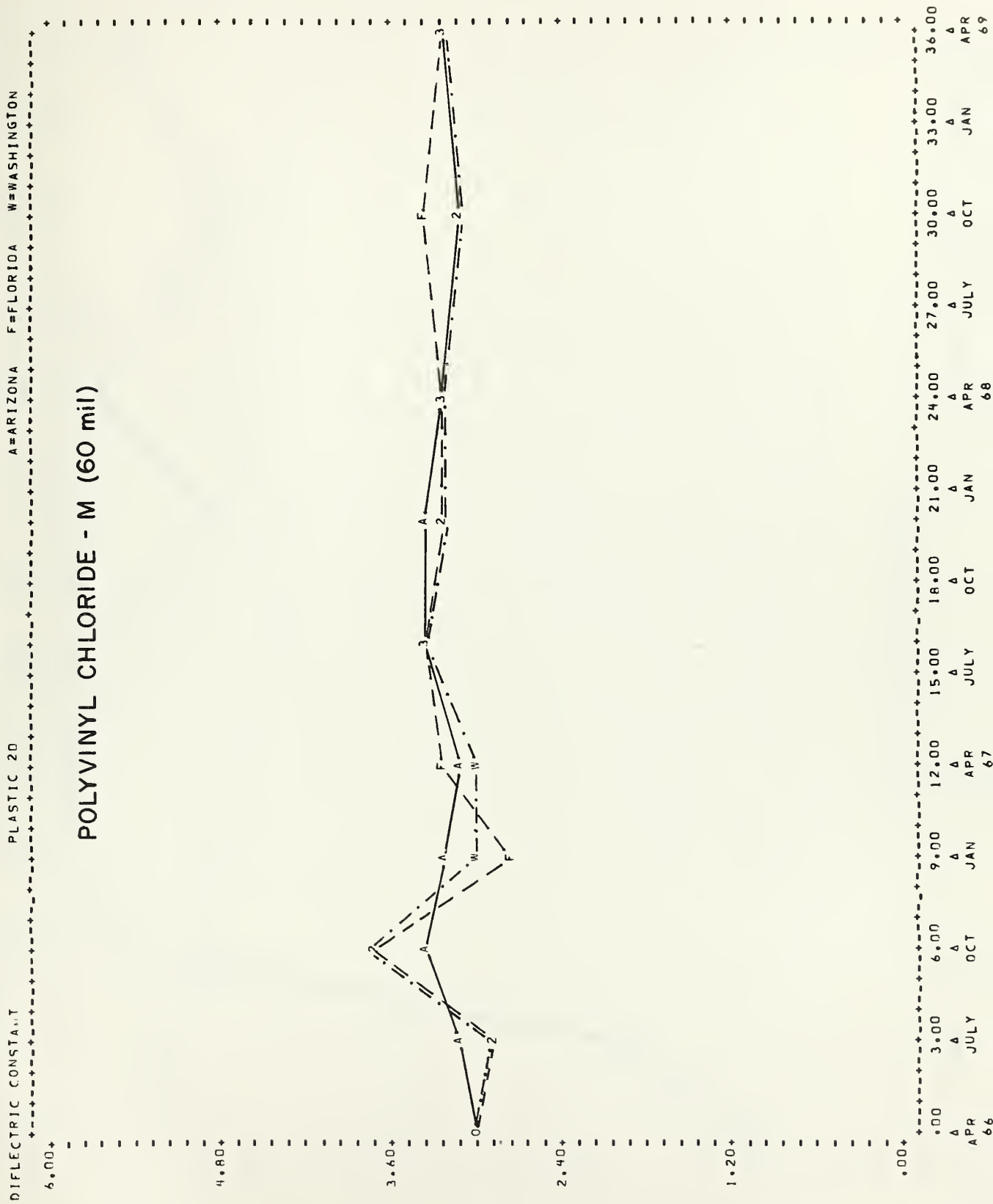


FIGURE 23



FIGURE 24

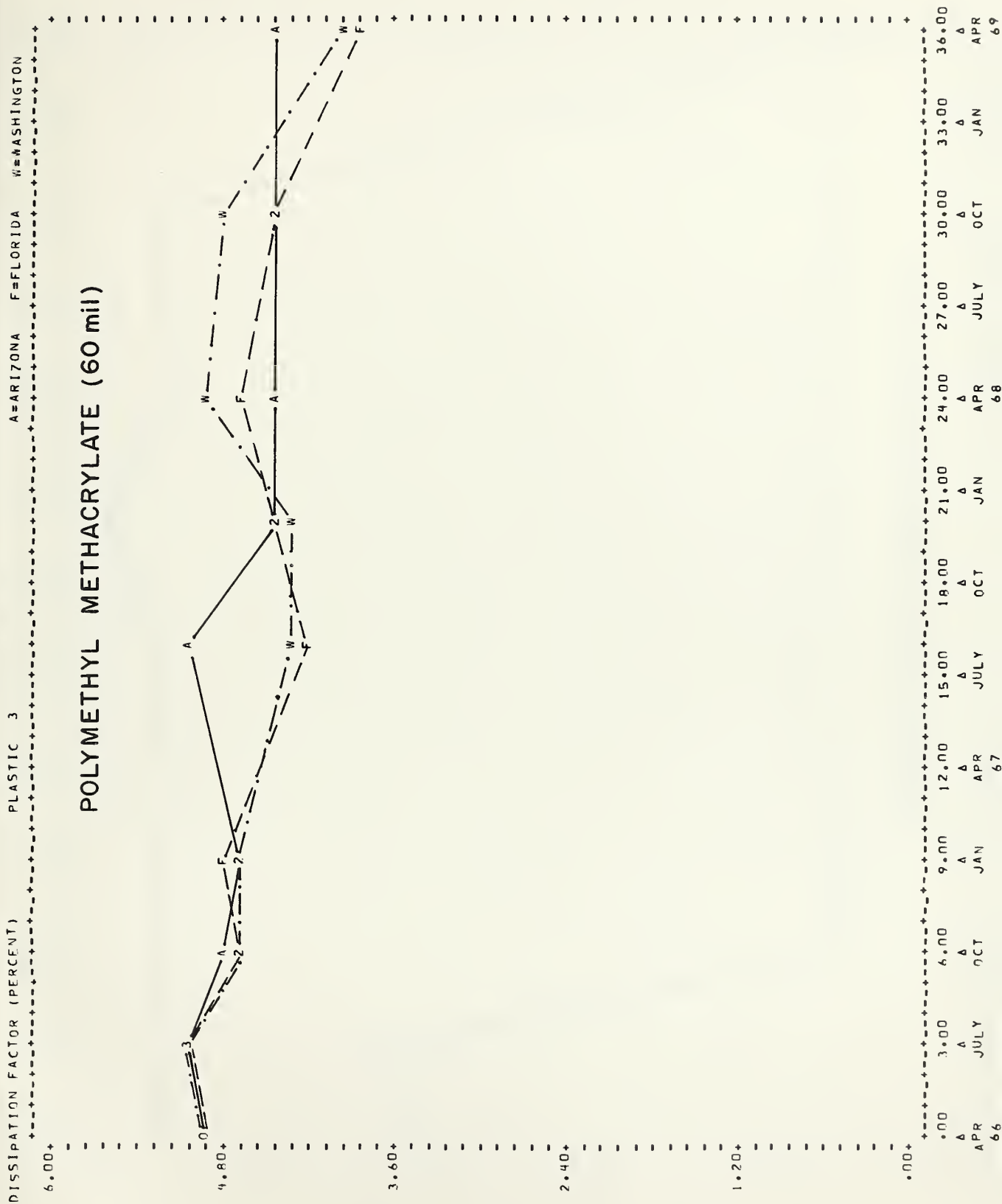


FIGURE 25

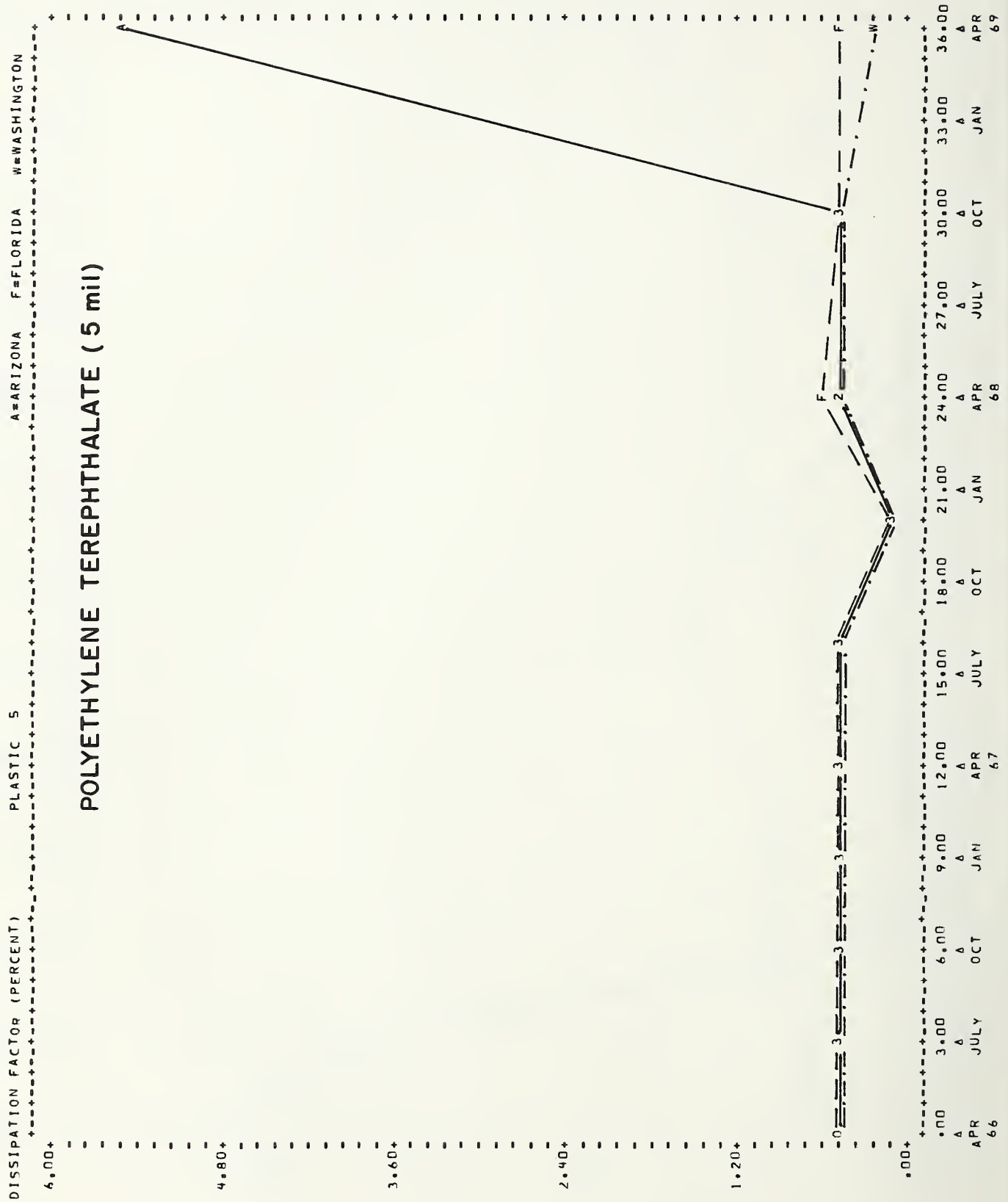


FIGURE 26

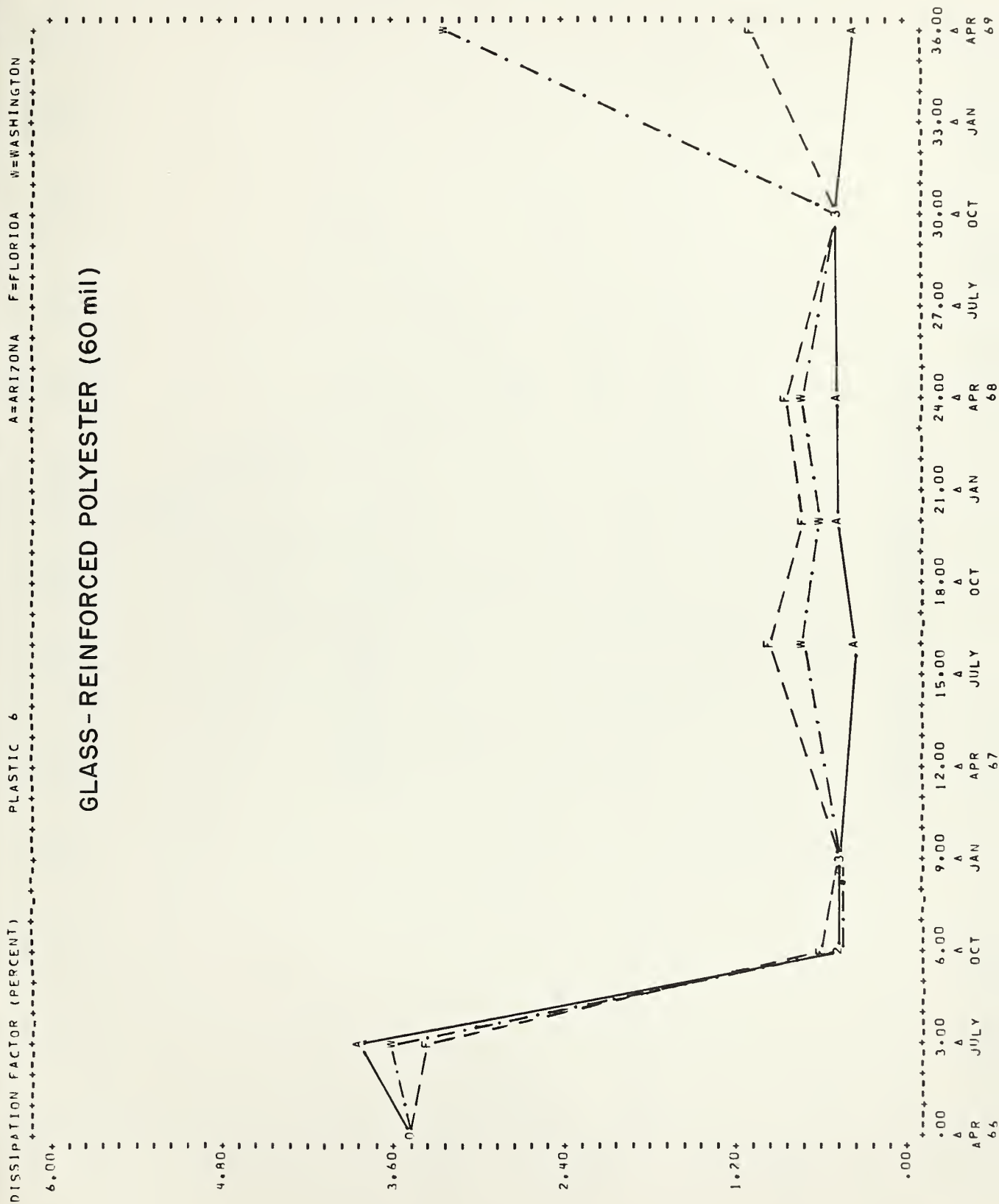


FIGURE 27

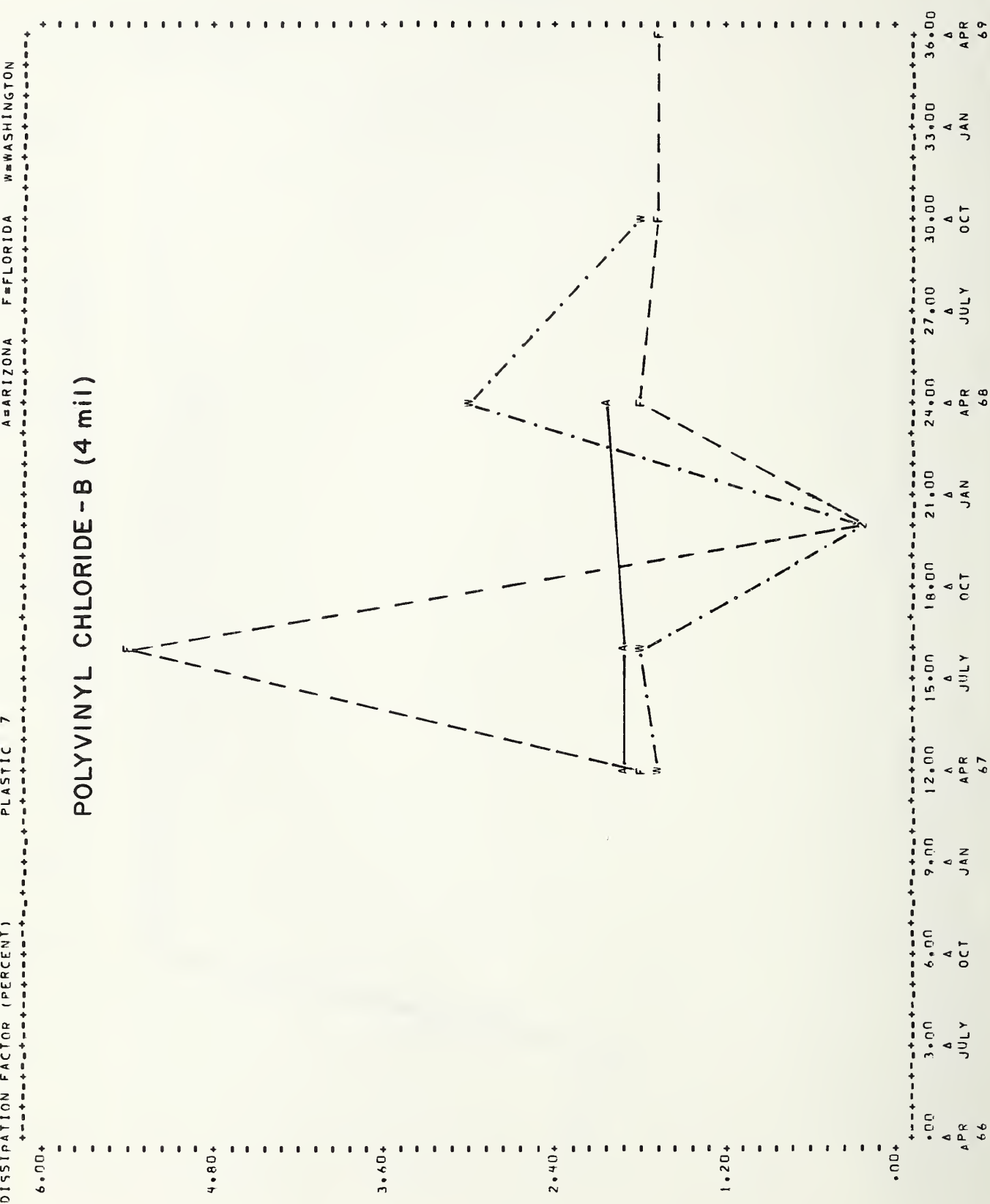


FIGURE 28

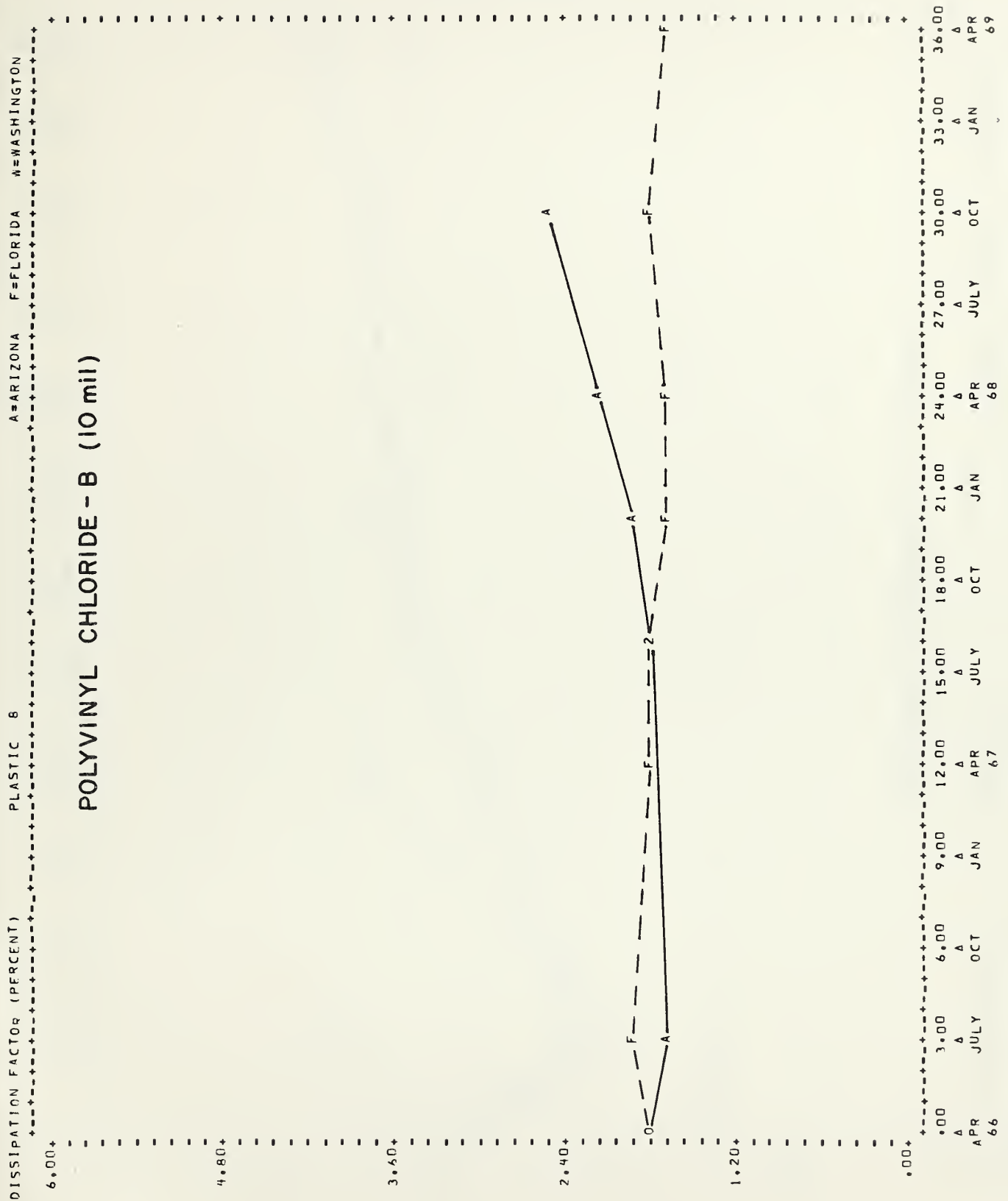


FIGURE 29

POLYVINYL CHLORIDE - B (60 mil)

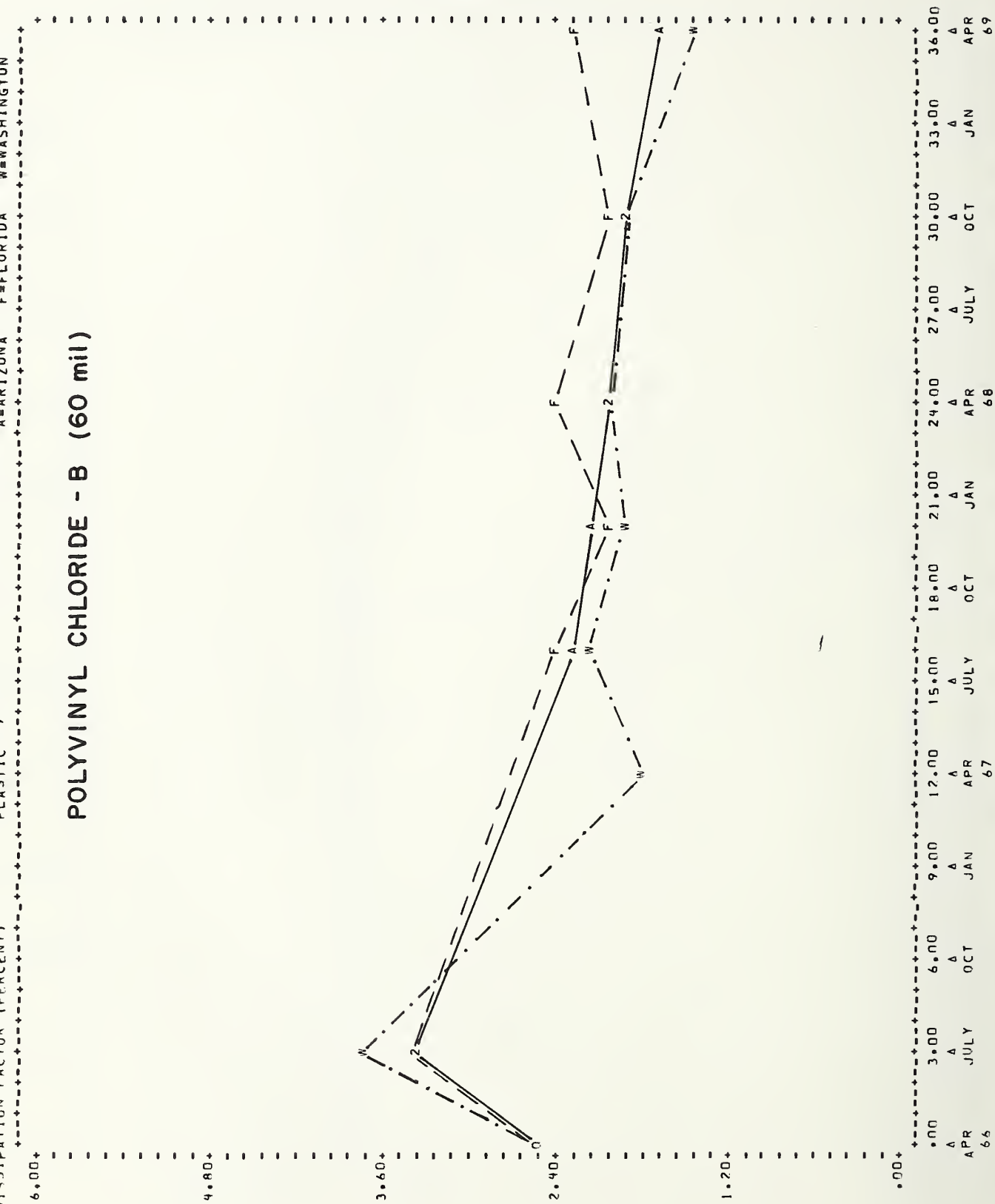


FIGURE 30

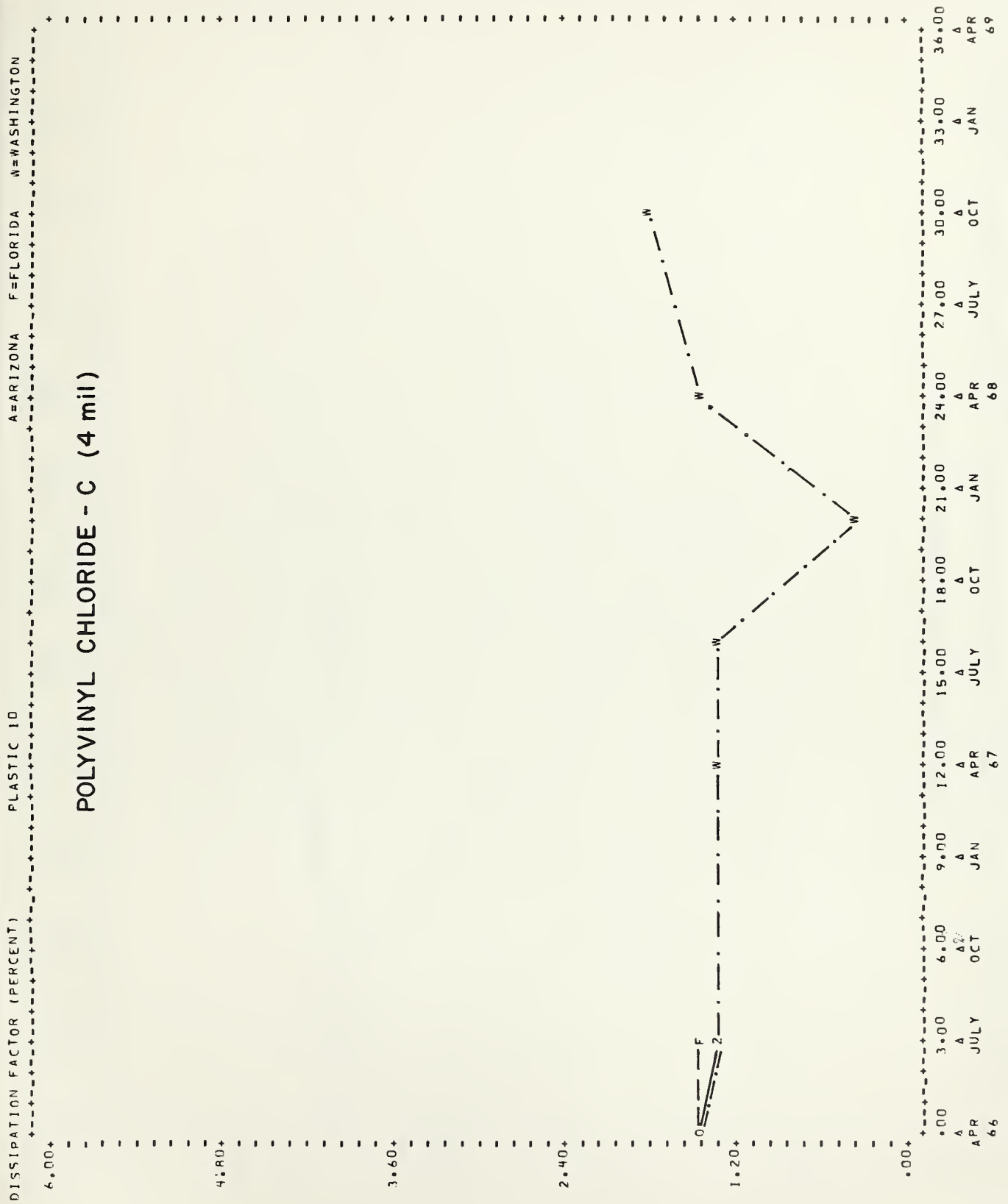


FIGURE 31

POLYVINYL CHLORIDE - C (10 mil)



FIGURE 32

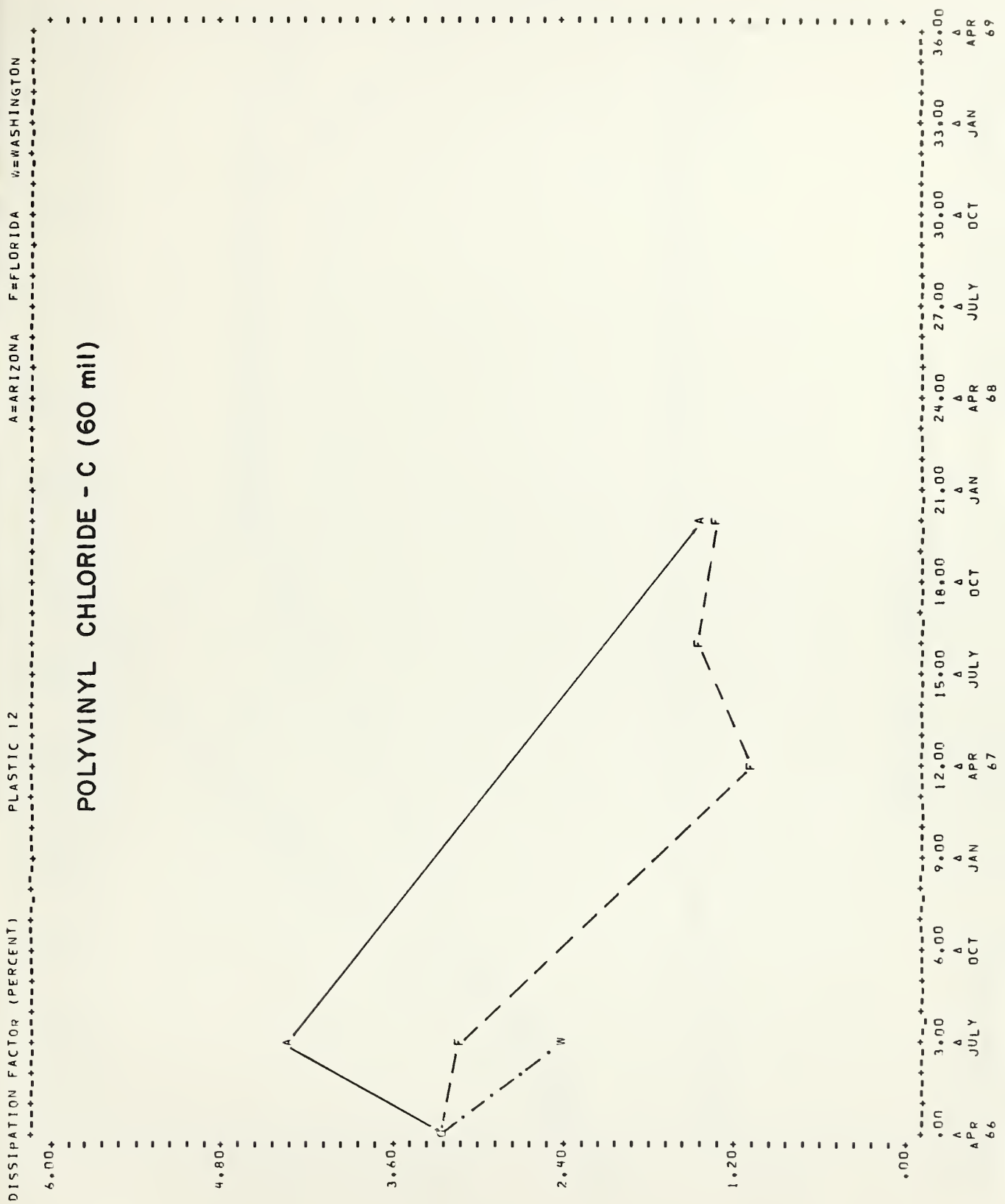


FIGURE 33

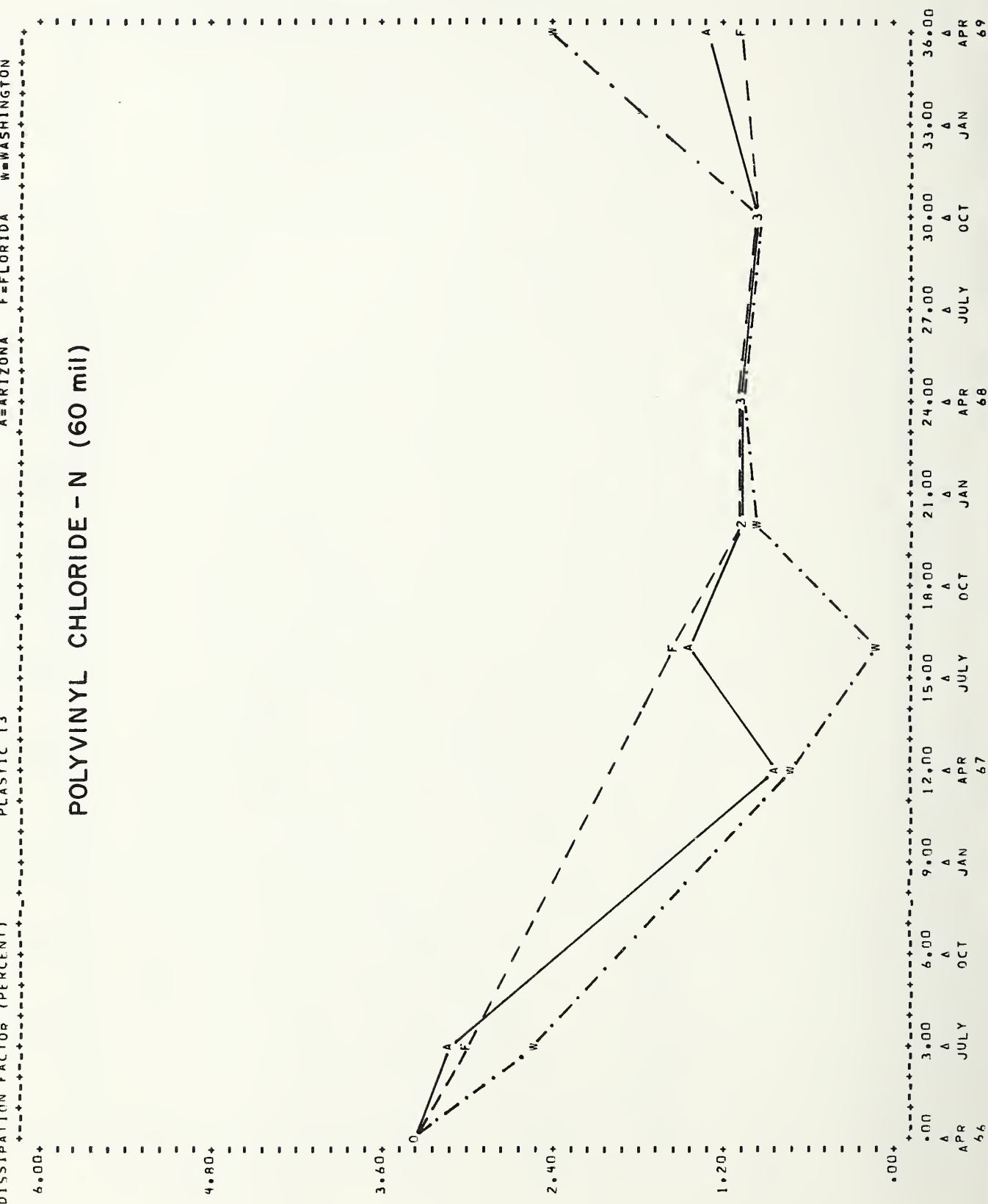


FIGURE 34

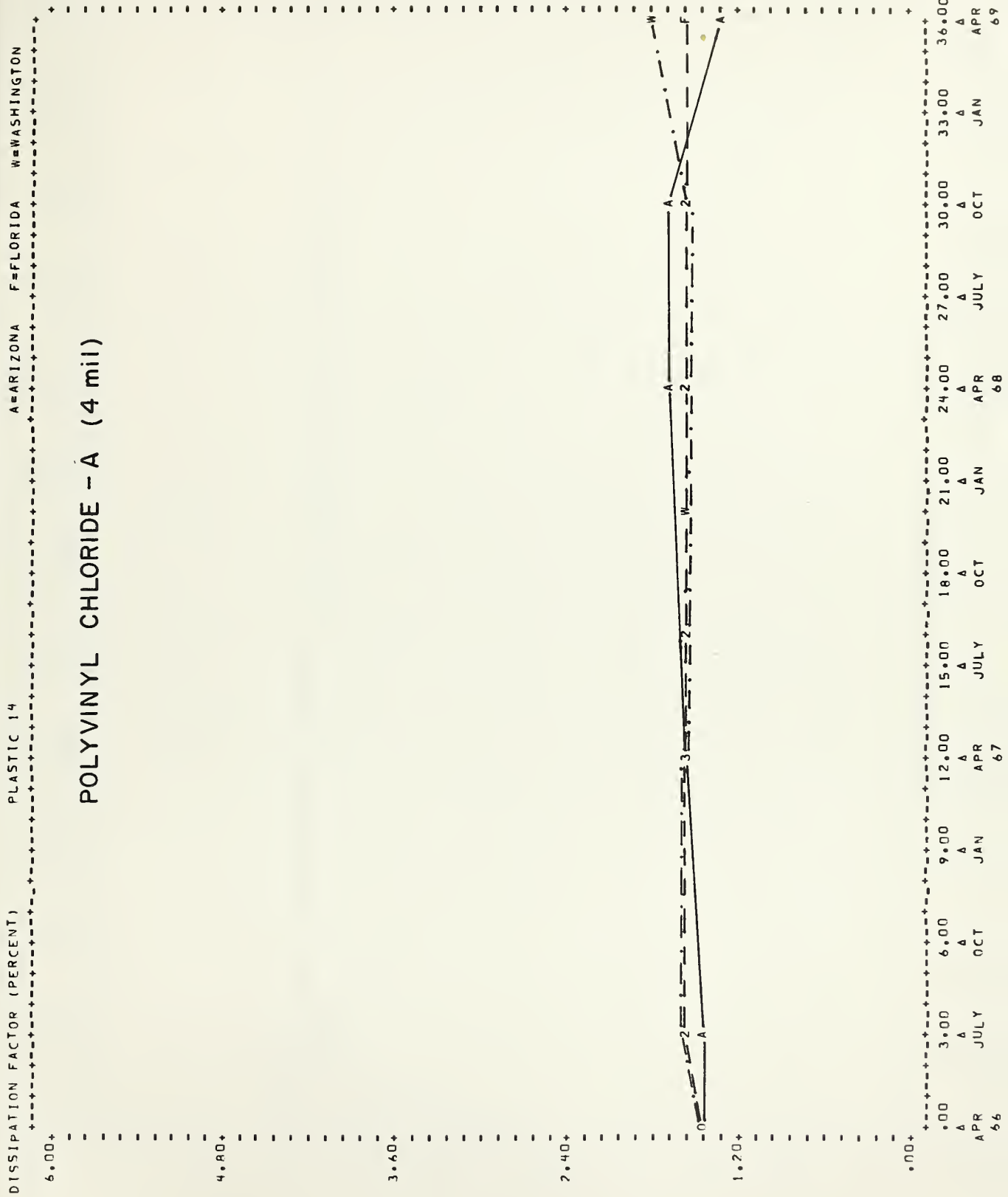


FIGURE 35

POLYVINYL CHLORIDE - A (10 mil)

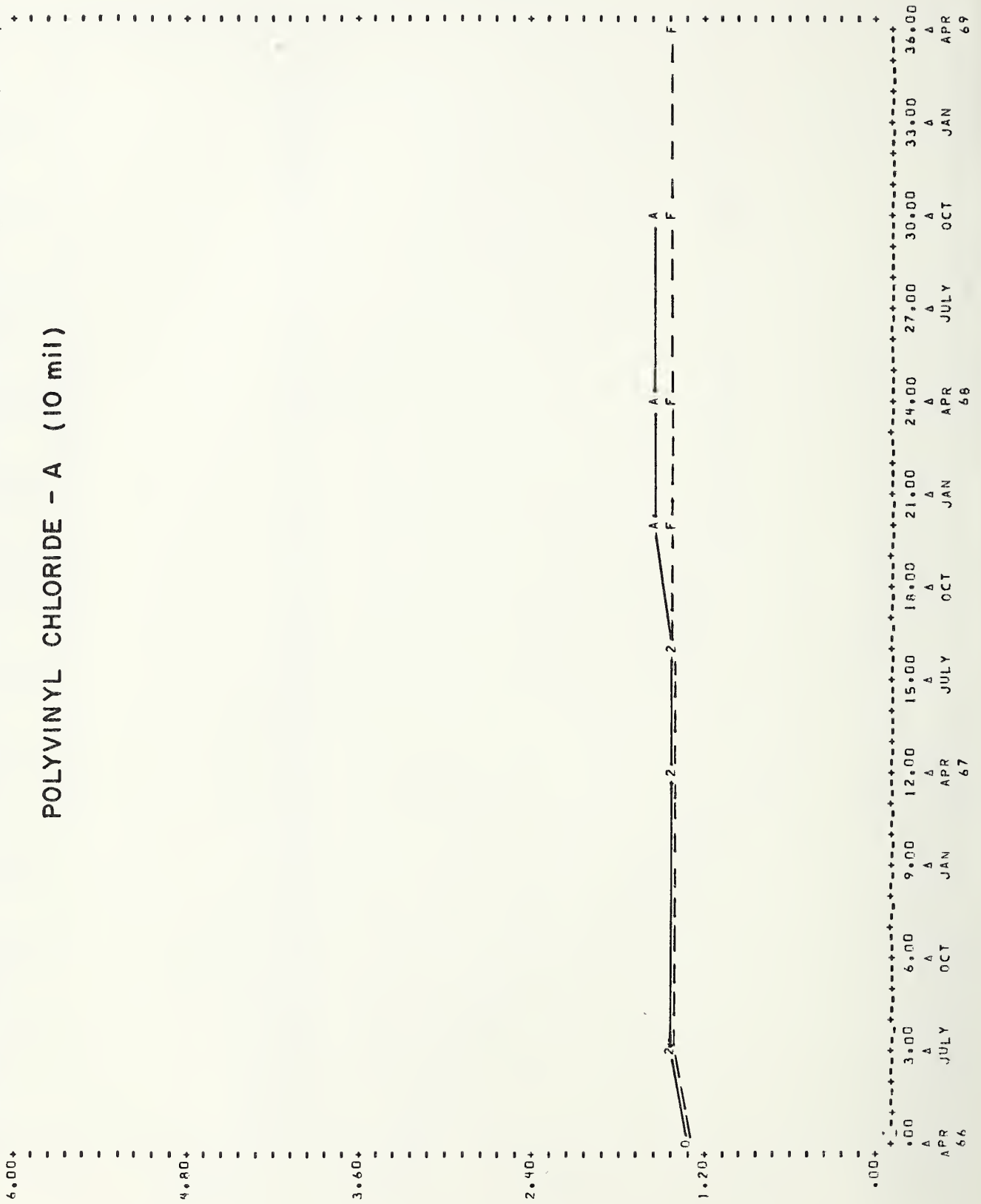


FIGURE 36

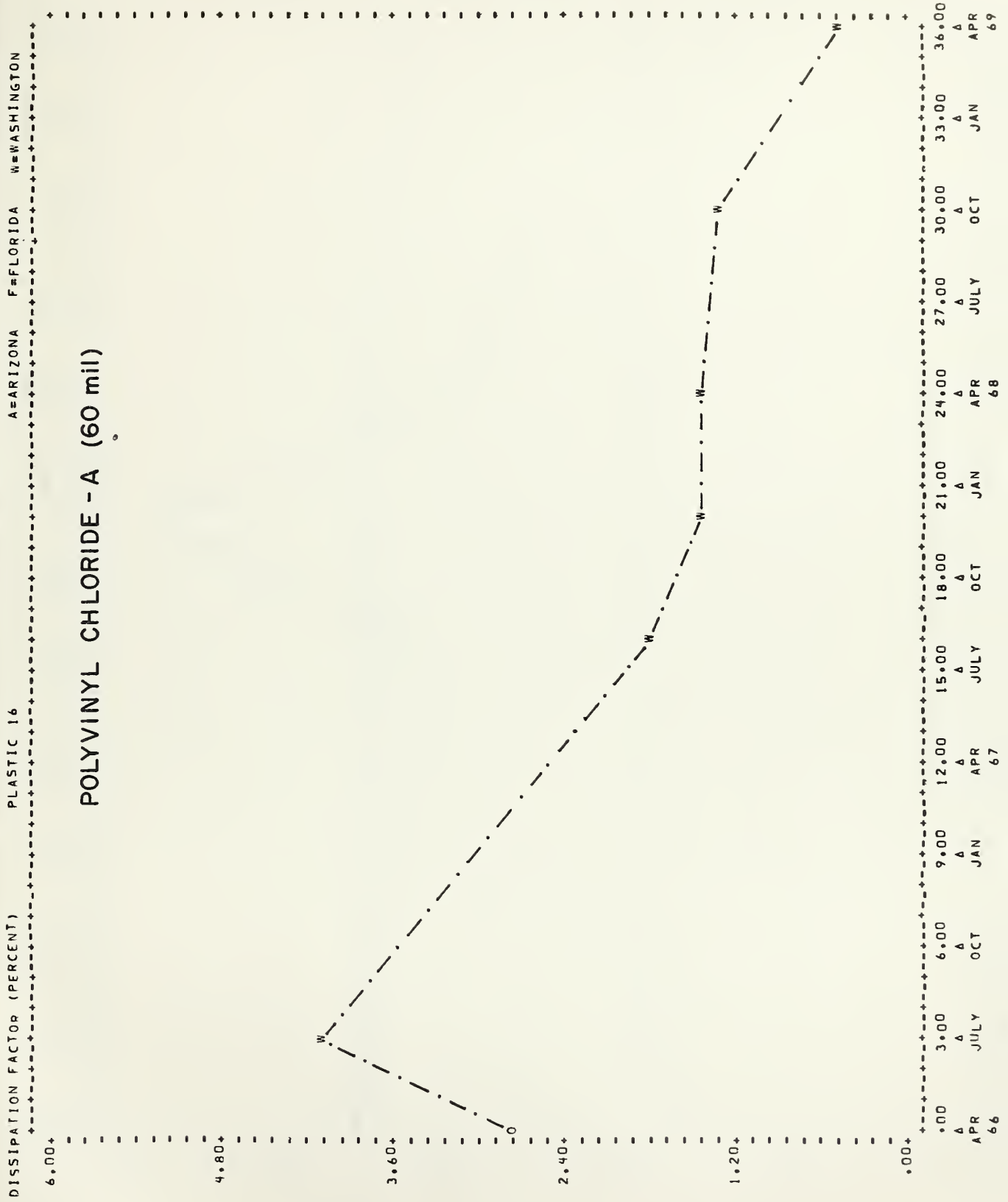


FIGURE 37

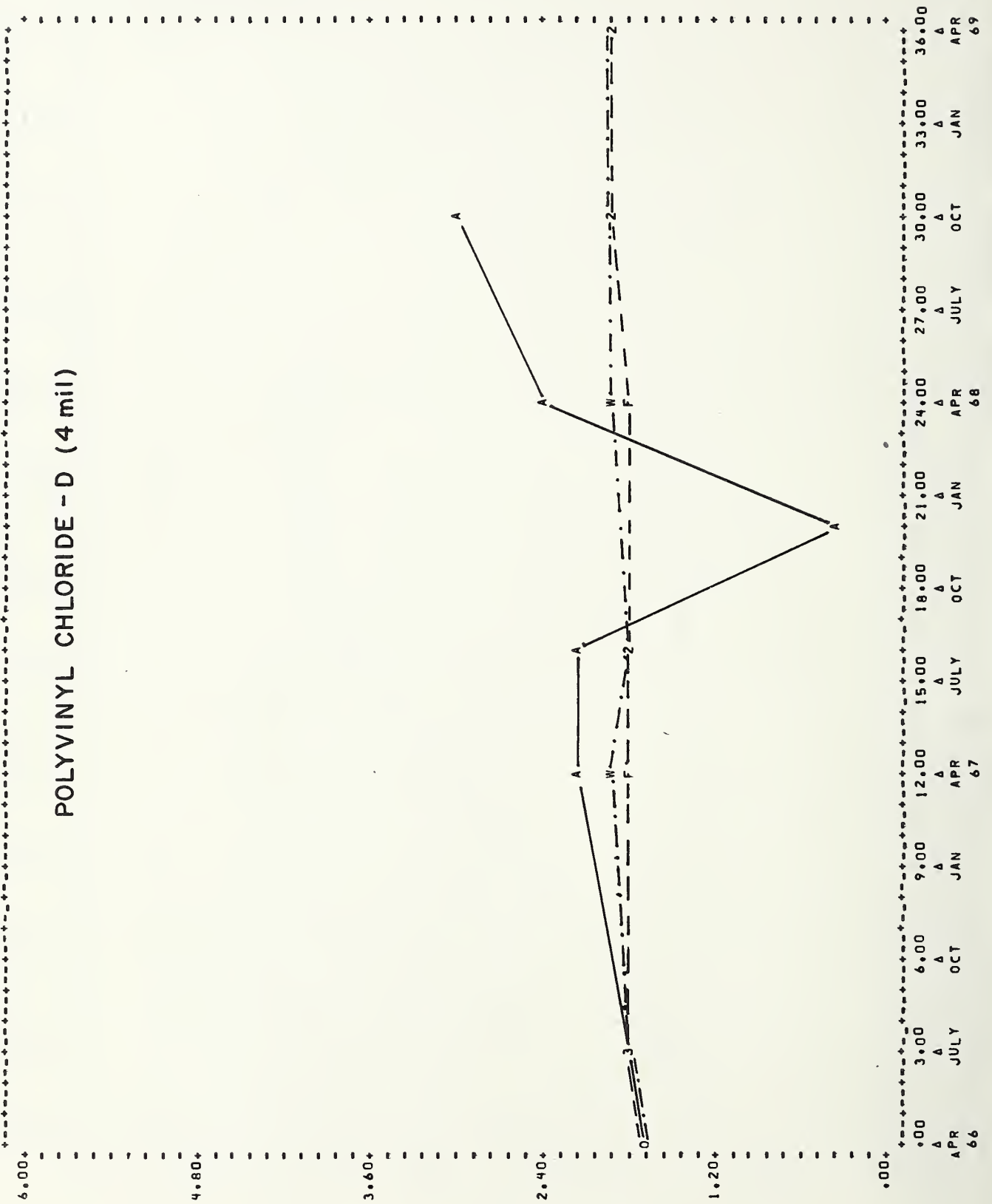


FIGURE 38

DISSIPATION FACTOR (PERCENT)

PLASTIC 18

A=ARIZONA F=FLORIDA W=WASHINGTON

POLYVINYL CHLORIDE - D (10 mil)

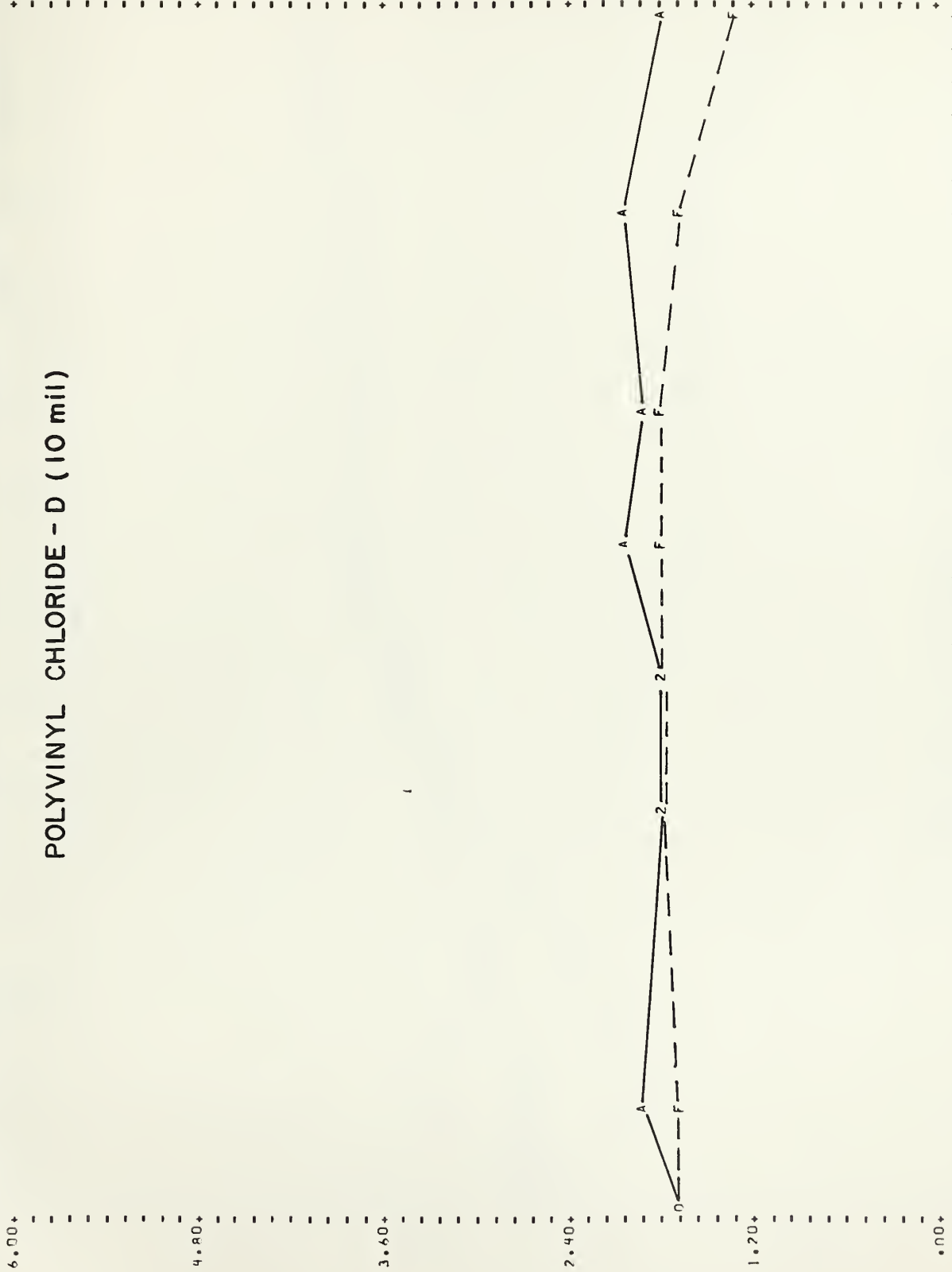


FIGURE 39

POLYVINYL CHLORIDE - D (60 mil)

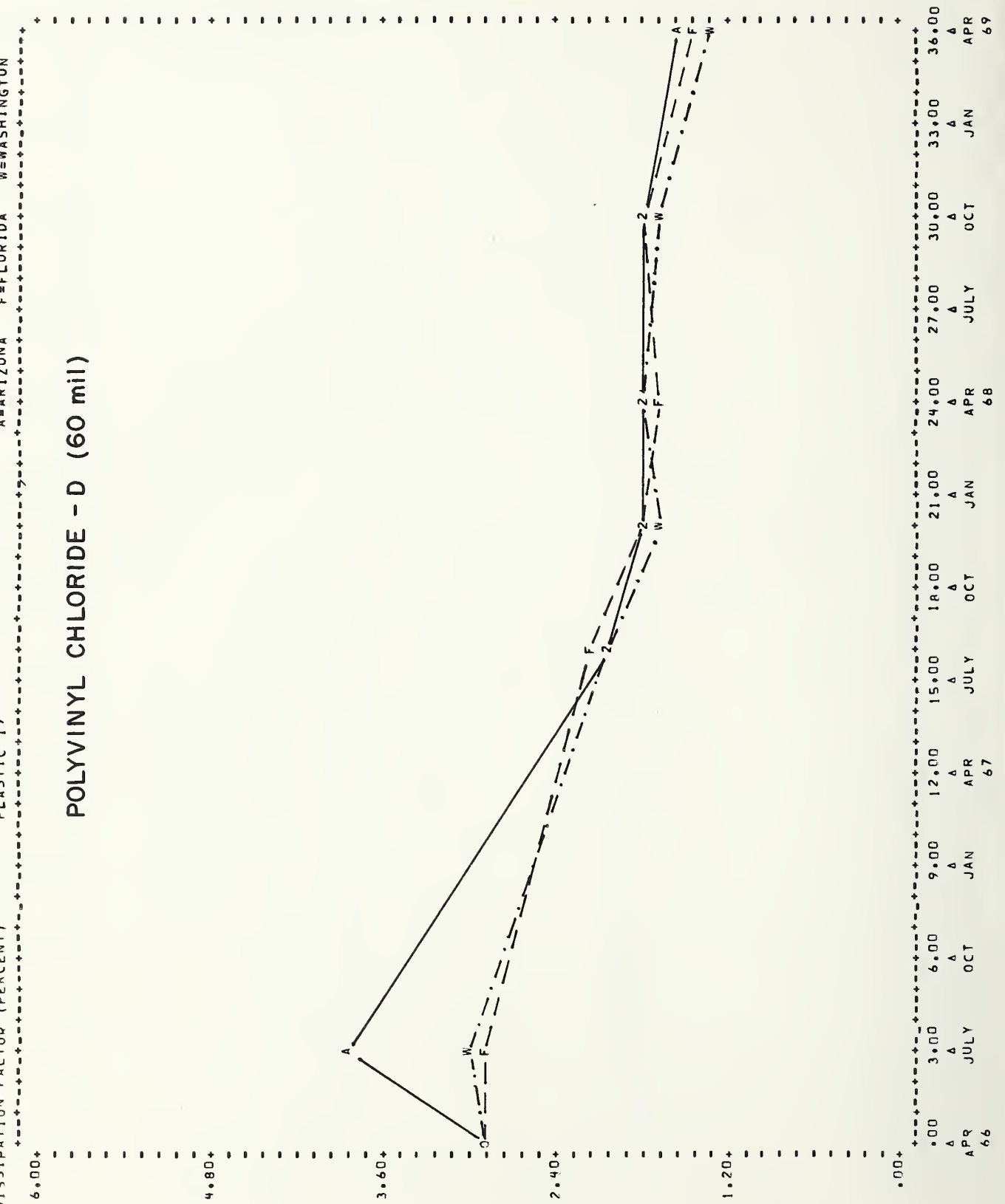


FIGURE 40

