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O'HARE ASDE-2 RADOME PERFORMANCE IN RAIN; ANALYSIS AND IMPROVEMENT

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16. Abstract

The operational performance of the ASDE-2 radar at O'Hare Airport is severely limited during periods of moderate to heavy rainfall. Using the system performance specifications, an estimate has been made of the ASDE-2's tolerance to power loss and degradation of its circular polarization produced by a radome. Three aspects of the O'Hare radome have been examined as potential sources of excessive loss. These are (a) the metal space frame, (b) the dielectric constant and loss tangent of the membrane material, and (c) the membrane surface properties. It has been concluded that the membrane surface properties permit a water film buildup during rain which will cause severe losses. Hydrophobic coatings were tested in the laboratory before and after exposure to the environment. Two coating materials were found to retain their water shedding properties for several months. One of these coating materials was applied to the O'Hare ASDE-2 radome. Since coating the radome, very substantial improvement in operation has been noted during periods of rainfall.

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PREFACE

The work described in this report was initiated by the Radar Systems Section, Systems Research and Development Service, of the FAA and conducted in the Radar and Navigation Techniques Branch, Electromagnetics Technology Division, of the Transportation Systems Center. The principle objectives were to identify and correct the source of degraded performance of the O'Hare ASDE-2 during rainfall.

The author wishes to acknowledge the efforts and assistance of G. G. Haroules, for helpful discussions and guidance; to J. W. Reardon for fabricating the test rack; and to Messrs. J. T. O'Brien, H. F. Weeks and staff of the Chicago O'Hare Terminal for helpful disscussions and for coating the radome.

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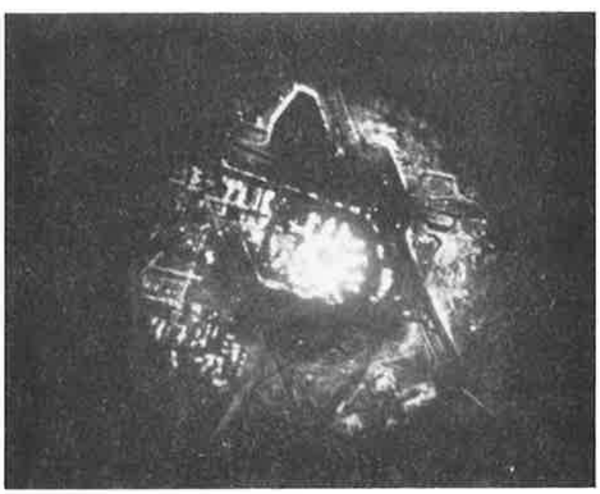
1. INTRODUCTION

The ASDE-2 radar system is used to detect all principal features of an airport surface including aircraft and vehicle movements. These features are displayed on a plan position indicator console. This display is upgraded with new radar returns once per second. This permits ground traffic to be monitored and controlled under conditions which adversely effect visibility such as darkness, rain and fog.

The antenna used in the ASDE-2 system rotates at 60 revolutions per minute. It is housed in a protective radome to prevent wind loading by gusts and to provide protection from adverse weather conditions. The radome used for the ASDE-2 antenna at O'Hare airport is of a novel design. A metal space frame supports optically transparent membrane panels made of polycarbonate sheet. The novel choice of using optically transparent panels was made on aesthetic grounds. It was considered that the public would enjoy the sight of the rotating antenna which is seen from most places in the vicinity of the airport. However, the requirement for an optically transparent membrane material does not permit the use of materials of proven performance in radome applications. When installation of the radome at O'Hare airport was complete, it was found that during periods of moderate to heavy rainfall the radar became virtually inoperative. Figure 1 shows pictures of the radar bright display during a moderate-to-heavy rainfall and after rainfall ceased. The photographs of the display demonstrate the complete inability of the system to operate under conditions of moderate-to-heavy rainfall. ASDE-2 systems deployed at other airports which use air inflated radomes of rubberized canvas, have better performance characteristics during periods of rain. The satisfactory operation at O'Hare at all times other than during a rainfall indicates that the problem is most likely caused by the radome which is the system-to-weather interface.

MODERATE RAINFALL
UNCOATED RADOME



DRY RADOME

Figure 1 ASDE-2 Display during and after a rainfall of moderate intensity

The objective of this study was to locate the source of difficulty at the O'Hare ASDE-2 and determine what measures, if any, can be taken to improve the system operation without destroying the optical transparency of the radome.

2. APPROACH

The radome has been examined as the most probable source of the O'Hare ASDE-2 system's inability to operate satisfactorily in a moderate-to-heavy rainfall. Using the system specifications, the ASDE-2's capacity to operate to the design range of 3 nautical miles under a moderate-to-heavy rainfall rate of 10 mm/hour was evaluated by means of several calculations. The system electrical characteristics of the transmitter, antenna and receiver were derived from the system operating manual and the original design specifications. In these calculations the radome was assumed to contribute zero loss and to cause no degradation of the circular polarization used to suppress rain clutter. Calculation of operational margins, assuming no radome effects, permits an evaluation of the system's tolerance to the introduction of radome losses and circular polarization degradation effects. It was found that the system has little or no margin. All losses are significant if a 3 nautical mile range is to be achieved under a 10mm/hour rainfall rate.

Three aspects of the radome: (a) its metal space frame, (b) its dielectric membrane bulk losses, and (c) its tendency to support a surface water film during rainfall, were examined individually to determine which might result in serious system degradation. Calculations were performed using the exact scattering cross section of the rectangular space frame members to determine the loss and corruption of the circular polarization by the metal space frame. The second item, the losses due to the dielectric membrane, were investigated by means of laboratory measurements. This was necessary since there is no engineering data available concerning the dielectric constant and loss tangent of polycarbonate resin when dry and when saturated with water. The polycarbonate was measured using the short circuited line technique after various periods of submersion in water and exposure to dry and saturated air. The measured values of the dielectric constant and loss tangent were then used to determine the loss resulting from water-saturated polycarbonate resin. Finally, surface water film effects were evaluated by means of calculations. The thickness of a draining water film was calculated for a radome of 18 foot diameter under a 10 mm/hr. rainfall. These calculations assume that the rain drains by the inefficient means of laminar flow. This is the principle drainage mechanism for wetting surfaces such as the polycarbonate used in the O'Hare radome. At 24 GHz the high dielectric constant and loss tangent of water make even a very thin layer of water strongly attenuate microwave energy. The analysis of the three aspects of the radome led to the conclusion that the water film is the most serious cause of the degraded ASDE-2 performance. It is also the only aspect for which there exists a possibility of finding a solution short of replacing the radome.

The water film loss can be greatly reduced by changing the surface characteristics of the polycarbonate. This is accomplished by use of a hydrophobic coating which makes the surface water repellent and causes water to bead and to drain in rivulets. This is a much more efficient drainage mechanism than laminar flow.

A product search was undertaken to find water repellent coatings compatible with the polycarbonate membrane in the O'Hare radome. Several coatings were obtained and were applied to sample panels of polycarbonate. Since there is no engineering data available on the service life of any of the coatings when exposed to a polluted environment it becomes necessary to conduct environmental tests. The coated panels were mounted on a test rack which was placed on the 14 story roof of the TSC Management Building. The panels were removed periodically to measure changes in repellancy. Several suitable tests had to be developed so that relative measurements of repellency could be made. After 3 months of exposure only two of the coatings still provide water shedding properties such as are required for the O'Hare radome. One of the coatings is excluded from use because it leaves the polycarbonate translucent rather than transparent. The desired coating is AFC-HMOD-4 a developmental aircraft windshield water repellent. This coating was applied to the O'Hare ASDE-2 radome. Since coating the radome, very substantial improvement in operation has been noted during periods of rainfall.

3. SYSTEM OPERATION

3.1 SYSTEM SPECIFICATIONS

The ASDE-2 system detects the principal features of the airport surface, including aircraft and vehicle movements, and presents these features on a radar plan position indicator display.[1] The radar must be capable of distinguishing between grass covered areas and runways so that the display shows all runways, taxiways and parking areas in their true relationship to one another. This display allows aircraft controllers to direct the movement of taxiing aircraft and service vehicles. The system permits control to be maintained under conditions of darkness, fog and rain.

The ASDE-2 system achieves high-definition performance by using a very narrow beamwidth and a very short transmission pulse. The radar scans the airport once a second while transmitting 14,400 pulses of RF per second. The azimuth beamwidth of a quarter of a degree results in 10 RF pulses per azimuth resolution cell per scan. The ASDE-2 system operates at 24 GHz where the back scattered energy from rain drops in a moderate to heavy rain can exceed the return from wanted targets when linear polarization is transmitted. To suppress the return from rain, the ASDE-2 employs circular polarization. Circular polarization improves operation in rainfall in the following manner. A right-hand circularly polarized wave incident on symmetrical objects such as perfectly spherical rain drops is reflected as a left-hand circularly polarized wave. If an antenna transmits right-hand circularly polarized radiation it does not receive left hand circularly polarized radiation. Thus a circularly polarized antenna receives no return from symmetrical targets. If the target is a grid of parallel wires or grass area between airport runways one component of the circularly polarized radiation is preferentially reflected. The received power is 6 db below that which would be received using a linearly polarized transmitting and receiving antenna with its electric field aligned for maximum backscattered power. Half of this loss results at the target because of its preferential scattering characteristics and half of this loss results at the circularly polarized antenna when it receives essentially linearly polarized backscattered energy. The loss resulting from more complex targets such as aircraft depends on frequency and orientation and is obtained empirically. The reduction in radar cross section of aircraft due to circular polarization varies from 2 dB to 8 dB.[2]

A measure of the quality and hence effectiveness of a circularly polarized radar is the integrated cancellation ratio, ICR. The ICR is defined as the ratio of signal energy received when circular polarization is transmitted to the signal energy received when linear polarization is transmitted under the conditions that the antenna is surrounded by an infinite number of randomly distributed small spheres. The ICR is the reduction in rain clutter offered by the circular polarized mode of operation.

Table 1 lists the electrical characteristics and also the operational requirements of the ASDE-2 which are used throughout this report.[1]

3.2 CALCULATED SYSTEM PERFORMANCE IN RAIN

In this section the effect of rain on ASDE-2 is evaluated. All radome effects are excluded so that the operational limits exclusive of the radome may be examined. The effect of rain is evaluated in two distinct calculations. The first limiting effect is caused by energy scattered back by rain drops when illuminated by linear or circular polarization. This rain clutter can at times exceed the return from wanted targets such as the grass between taxiways and runways. The second effect of rain drops, atmospheric water vapor and oxygen is attenuation. The atmospheric attenuation limits the maximum range of the ASDE-2 as the returned signal level decreases to the level of the receiver noise.

TABLE 1 ELECTRICAL CHARACTERISTICS AND SYSTEM REQUIREMENTS OF ASDE-2

Component	Characteristics
Transmitter	
Frequency	23,800 to 24,270 Mc
Pulse width	0.02 μsec
PRF	14,400 pps
Peak power	36 to 50 kw
Antenna	
Reflector size	12 by 4 feet
Horizental beamwidth	0.25 degree at 3-db points
Vertical beamwidth	1/2 power beamwidth at -1 degree (shaped cosecant squared from -1 to -5 degrees; linear from -5 to -20 degrees)
Polarization	Linear or circular
Scan rate	60 rpm
Receiver	
Noise figure	19 db (maximum)
Bandwidth	IF 100 Mc; video 50 Mc
AFC	Double band pass, 130-Mc center frequency
Indicator	
Tube	16-inch diameter, flat face aluminized
Definition	1000 lines per diameter (minimum)
Ranges	5600, 6600, 8600, 10,000 and 18,000 feet per radius
Off-centering	Continuously adjustable plus four presettable positions
Systems	
Resolution (at 4000 feet)	20 feet (range), 27 feet (azimuth)
Range	18,000 feet (maximum)
Integrated Cancellation Ratio in CP Mode	11 db (minimum)
Topographic Feature Discrimination	Capable of distinguishing between grass areas vs. runways at maximum range

3.2.1 Rain Clutter and Target Return

The ratio of returned power from a target to the returned power from rain clutter is given by[2]

$$\frac{P_{target}}{P_{rain}} = \frac{K \lambda^4 \sigma_t}{\theta \, \emptyset \, \tau \, Z \, R^2} \qquad (3\text{-}1)$$

where K = constant, for consistent units ≈ 200

λ = wavelength, 1.24cm

σ_t = target cross section, m^2

$\theta, \emptyset$ = one way, half-power antenna beamwidths, 1/4 degree, 1 degree

R = range to clutter cell, 3 nautical miles

τ = pulse length, .02μsec.

z = reflectivity of rain, mm^6/mm^3

The reflectivity of rain is given by[2]

$$z = 200r^{1.3} \qquad (3\text{-}2)$$

where r = rainfall rate in mm/hr. If a moderate to heavy rainfall of 10mm/hr. is assumed, then $z = 4 \times 10^3$

The target of interest in this calculation is grass at the 3 nautical mile range. It will be assumed that the return from runways and taxiways, which have small backscatter coefficients at glancing indidence, are below the level of the rain clutter. However the return from grass around runways and taxiways must be substantially (10dB) above the rain clutter in order for the ASDE-2 to map the airport topography. The target cross section is therefore that for grass at the maximum range.

The area illuminated by a low elevation pulse radar at the maximum range of 3 nautical miles is approximated by the resolution cell which has an area of [2]

$$A_i = \frac{c\,\tau}{2} R \tan\theta = 72 \text{ m}^2 \qquad (3\text{-}3)$$

where c = velocity of light, 3×10^8 meter/sec.

τ = pulse width, $.02 \times 10^{-6}$ sec.

R = maximum range, 5.5×10^3 meters.

θ = azimuth half-power beamwidth, 1/4 degree.

The backscatter coefficients γ for grass-like vegetation at low elevations is taken to be [2,3]

-18dB vertical polarization = .0159

-23dB horizontal polarization = .005

Therefore the target cross section is given by

$$\sigma_t = \gamma_v A_i = 1.15 \text{ m}^2 \qquad (3\text{-}4)$$

for vertical linear polarization. It is now possible to calculate P_{tar}/P_{rain} for the conditions chosen assuming that vertical linear polarization is used.

$$\frac{P_{target}}{P_{rain}} = \frac{2 \times 10^2 \times (1.24)^4 \times 1.15}{0.25 \times 1.0 \times .02 \times 4 \times 10^3 \times 3^2} \qquad (3\text{-}5)$$

$$= 3.1 \text{ or } 4.9 \text{ db}$$

A 4.9dB target to clutter ratio is inadequate for proper system operation. If ASDE-2 had only linear polarization capability it would not be able to operate satisfactorily in a 10mm/hr rainfall. The circular polarization offers a minimum of 11dB of rain clutter suppression. However the return from the target (grass) will also be reduced 6dB as described earlier. A net improvement of 5dB can be expected in using the ASDE-2 circular polarization. Therefore

$$\frac{P_{target}}{P_{rain}} = 9.9 \text{ db} \qquad (3\text{-}6)$$

in 10mm/hr. rain using circular polarization. This level of signal to clutter ratio will permit satisfactory system operation.

Thus the need for circular polarization is demonstrated. Even with its use, 10mm/hr. rainfall rate is the maximum rate under which the system will operate well. It is clear that the radome must not in any significant way reduce the system integrated cancellation ratio.

3.2.2 Atmospheric Attenuation and Maximum Range

The ASDE-2 system losses and the atmospheric losses due to the oxygen line, water vapor line and raindrop scattering all combine to reduce the effective peak transmitted power thereby limiting the maximum system range.

The maximum range of the radar is given by[2]

$$R^4 = \frac{P_T \, A_e^2 \, \sigma_t \, (L_{CP}) \, (L_{WG}) \, (L_{ATMOS})}{4\pi \, \lambda^2 \, k \, T_s \, B_N \, (S/N)} \qquad (3\text{-}7)$$

where

R = maximum range, m

P_T = peak power of transmitter, 50kW

A_e = effective antenna aperture, $2.23m^2$, taken as (.5) of the antenna surface area

σ_t = grass target cross section, $1.15m^2$

Lcp= loss due to use of c_p , - 6db = .25

L_{WGD} = two way loss thru 20 ft. of silver waveguide 4dB = .4

L_{ATMOS} = two way atmospheric attenuation

λ = wavelength of the radiation, .0124m

k = Boltzmann's constant, $1.38 \times 10^{-23} \frac{\text{watt}}{\text{Hz } ^\circ\text{K}}$

T_s = system noise temperature = (F-1) 290°K + T_A = 23,000°K

B_N = noise bandwidth of receiver, 10^8Hz

(S/N) = received signal to receiver noise ratio, 10

The value for the two way atmospheric loss is shown in Figure 2. This figure is taken from reference 2, figure 6-3. The "modified mean attenuation" curve is used. At 24 GHz the two way atmospheric attenuation is taken as 0.7 $\frac{\text{dB}}{\text{nmi}} \frac{\text{hr}}{\text{mm}}$. For the 3 nautical mile range in 10mm/hr. rain the two way attenuation amounts to -21dB or 0.008.

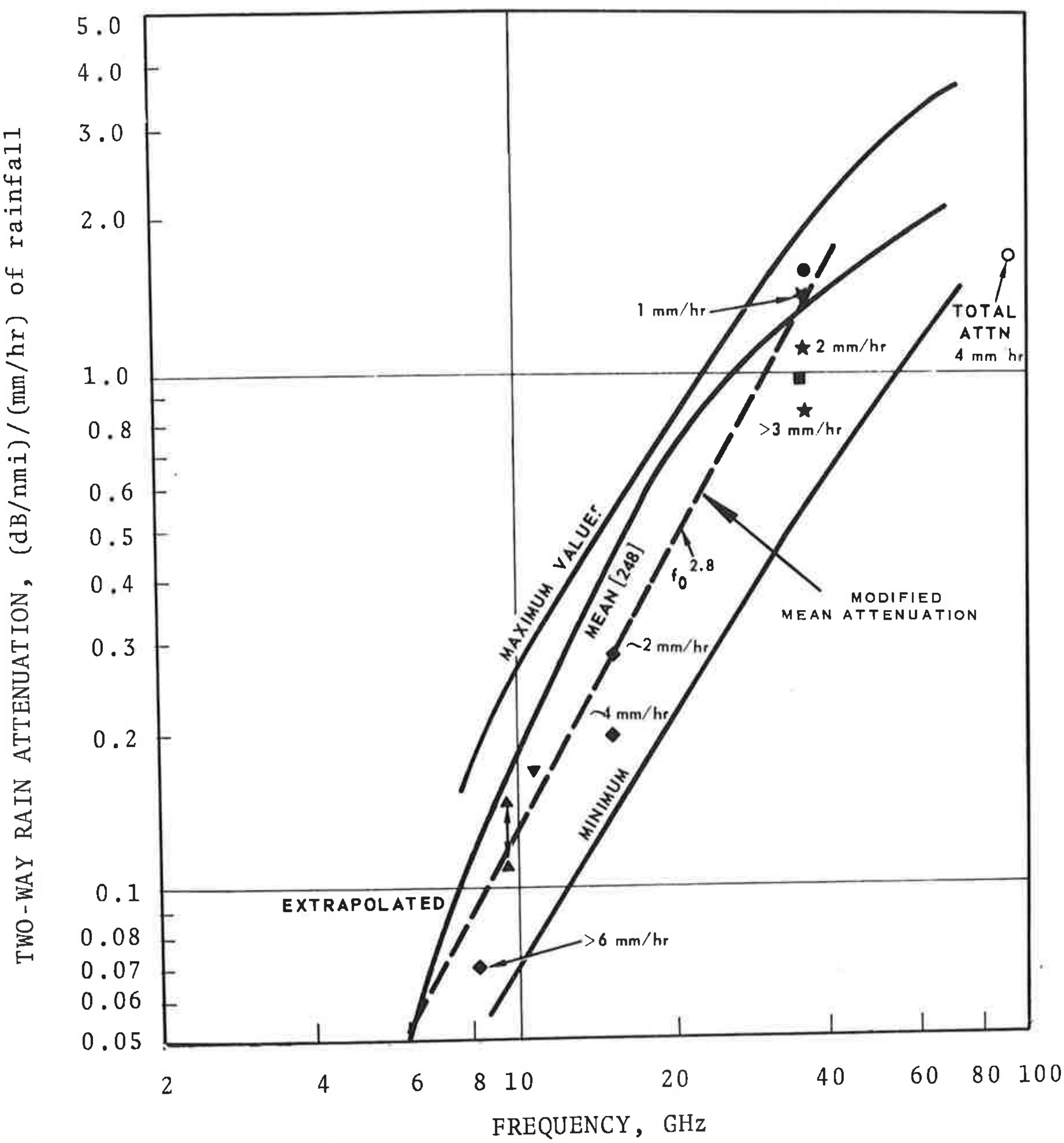


Figure 2 Measured Values of Rain Attenuation -vs.- Frequency (two-way path)

From "Radar Design Principles" by Fred E. Nathanson. Copyright 1969 by McGraw-Hill, Inc. Used with permission of McGraw-Hill Book Company

Substituting the above values into the range equation leads to the result that a S/N of 10 can be expected from grass out to 2.72 nautical miles under a 10mm/hr. rainfall. At the 3nmi range a S/N of 8.2dB is calculated.

The above results which do not include a loss term for the radome indicate that the ASDE-2 is barely capable of meeting its operational requirements under 10mm/hr of rain without any radome losses. Therefore it is imperative that radome losses be kept very small under conditions of rainfall. A two way loss of 12dB thru the radome will reduce the range capability by a factor of 2.

4. RADOME EFFECTS

This section examines the ways in which a metal space frame radome might adversely effect ASDE-2 operation. The areas of interest are the losses and depolarization effects due to the metal space frame, the dielectric loss due to a membrane exposed to water and finally the water film that can accumulate on the surface of a membrane which is not hydrophobic.

4.1 METAL SPACE FRAME

The metal space frame forms a grid in front of the antenna aperture. This grid attenuates the energy radiating from the antenna aperture. This attenuation may be greater for certain polarizations of the radiating energy than for others. This latter effect comes about because the blockage of narrow but deep space frame beams is greater when the incident E-field is parallel to the beam length than when it is orthoginal to the beam length. If the orientation of members is not uniformly distributed there will be a polarization dependent attenuation due to the metal space frame. The effect of this is to degrade the quality of the radar's circular polarization and thereby reduce the rain clutter suppression.

Table 2 lists the characteristics of the radome employed in conjunction with the O'Hare ASDE-2 radar. The analysis of the metal space frame follows that presented in Ref. 4. Considering the radome as a flat sheet the fraction of the area blocked as shown in Figure 3 is

$$\eta = \frac{2\sqrt{3}\ WL}{(L + 2r)^2} + \frac{2\pi}{\sqrt{3}}\left(\frac{r}{L + 2r}\right)^2 = \eta_b + \eta_n \qquad (4\text{-}1)$$

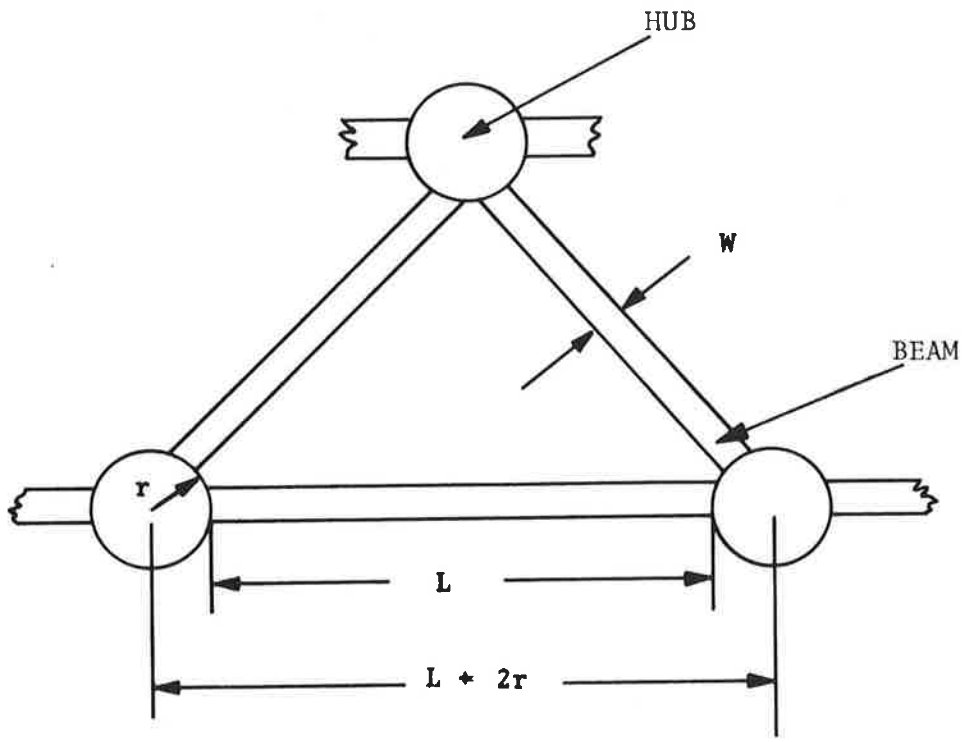
where

w = width of frame beams 5/8"

L = average clear frame beam length between hubs. 35"

TABLE 2 CHARACTERISTICS OF THE O'HARE ASDE-2 RADOME

Characteristic	Dimensions
Diameter	18 feet
Membrane	1/8 inch thick Polycarbonate Sheet,
Beams	5/8" wide, 1 3/4" deep (composite Beam)
Hubs	2" Radius (abstracted from photograph)
Hub to Hub length (average)	39" (abstracted from sample panel), (34" x 37" x 43")



$$\text{BLOCKAGE} = \frac{2\sqrt{3}\,W\,L}{(L+2r)^2} + \frac{2\pi}{\sqrt{3}}\left(\frac{r}{L+2r}\right)^2 = \eta_b + \eta_h \quad (8)$$

Figure 3 Area Blockage By Space Frame

r = radius of hubs 2"

η_b = area blockage due to beams, 0.0498

η_n = area blockage due to hubs, 0.0095

Therefore, if the O'Hare radome is considered as a flat sheet it will block 5.93% of the antenna area. At very high frequencies (optical) the reduction in the axial electric field is

$$\frac{e}{e_o} = 1 - \eta_b - \eta_n \qquad (4\text{-}2)$$

where

e = field strength with radome

e_o = field strength without radome

In order to calculate the loss at 24 GHz the blockage must be modified by using the actual scattering cross section of the beams. This factor, $\sigma_{sc}/2W$, depends on the member cross section, shape and orientation, θ, relative to the incident electric field. The reduction in the axial field then becomes

$$\frac{e}{e_o} = 1 - \eta_b \left[(\sigma_{sc}/2W)_{\parallel} \cos^2 \theta + (\sigma_{sc}/2W)_{\perp} \sin^2\theta\right] - \eta_h \qquad (4\text{-}3)$$

where

$(\sigma_{sc}/2W)_{\perp}$ = scattering cross section of a beam for incident radiation having E field perpendicular to beam length.

$(\sigma_{sc}/2W)_{11}$ = scattering cross section of a beam for incident radiation having E field parallel to beam length.

θ = angle between a member and the electric field;

For the beam cross section of the O'Hare radome the depth to width ratio is 2.8. Figure 4, which is derived from Figures 10 and 22 of Reference 5, presents the scattering cross section of rectangular beams. From the figures it is determined that

$$\left(\frac{\sigma_{sc}}{2W}\right)_{\perp} = 1.06, \text{ and } \left(\frac{\sigma_{sc}}{2W}\right)_{11} = 1.68 \qquad (4\text{-}4)$$

If the beams have a random or equiangular arrangement the average scattering cross section is used resulting in a simplified expression for the axial field reduction

$$\frac{e}{e_o} = 1 - \eta_b \left(\frac{\sigma_{sc}}{2W}\right)_{AVG} - \eta_h \qquad (4\text{-}5)$$

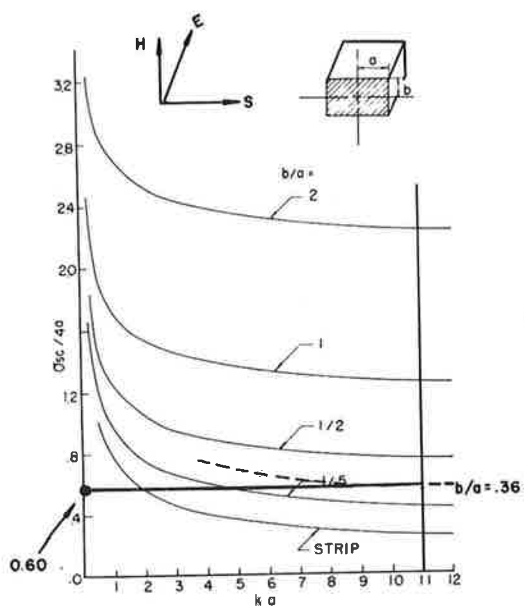
The loss in axial power is then

$$\frac{P}{P_o} = \left| 1 - \eta_b \left(\frac{\sigma_{sc}}{2W}\right)_{AVG} - \eta_h \right|^2 \qquad (4\text{-}6)$$

$$\approx 1 - 2\,\eta_b \left(\frac{\sigma_{sc}}{2W}\right)_{AVG} - 2\,\eta_h \qquad (4\text{-}6)$$

$$\frac{b}{a} = \frac{5/16}{14/16} = .36$$

$$k_a = \frac{2\pi a}{\lambda} = \frac{2\pi}{.49\text{in}} \times 7/8 \text{ in} = 11$$

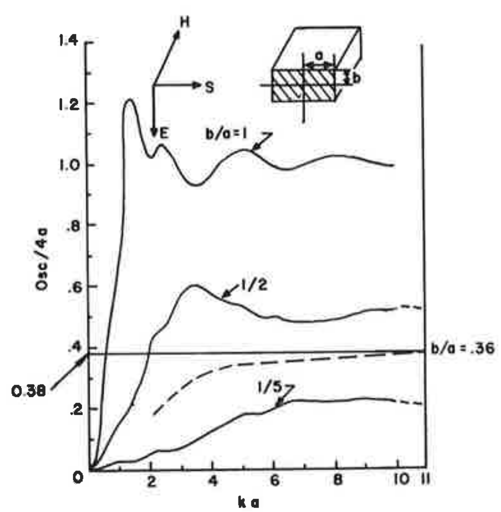


$$\sigma_{sc}/4a_{11} = .6$$

$$\sigma_{sc}/2w = \sigma_{sc}/4b = \sigma_{sc}/4a \times \frac{a}{b}$$

$$\sigma_{sc}/2w_{11} = .6 \times \frac{1}{.36} = 1.68$$

Scattering cross sections for E parallel to beam



$$\sigma_{sc}/4a_{\perp} = .38$$

$$\sigma_{sc}/2w = \sigma_{sc}/4b = \sigma_{sc}/4a \times \frac{a}{b}$$

$$\sigma_{sc}/2w_{\perp} = .38 \times \frac{1}{.36} = 1.06$$

Scattering cross sections for E perpendicular to beam

Figure 4 Scattering Cross Sections of Rectangular Beams

Using $\left(\frac{Q_{sc}}{2W}\right)_{AVG} = 1.37$ the power loss thru a flat sheet radome with beams such as the O'Hare radome employs is 0.74dB.

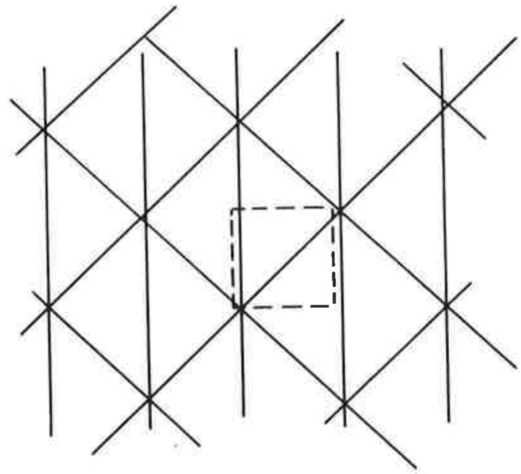
Finally, it is necessary to account for the fact that an actual radome is spherical. In this case the aspect angle of the beams changes away from the axis of the antenna. The illumination taper of the antenna aperture and the radome diameter to antenna diameter effect the blockage by the beams. This factor which increases the apparent blockage of the beams is referred to as the curvature factor, [CF]. Thus the final expression for the loss thru the metal space frame is

$$\frac{P}{P_o} = 1 - 2\eta_b \left(\frac{\sigma_{sc}}{2\ W}\right)_{AVG} \left[CF\right] - 2\eta_h \qquad (4\text{-}7)$$

Assuming a radome to antenna diameter ratio of 1.5, and a 12dB antenna edge taper, the curvature factor is taken as 1.4 from Figure 9 of Reference 4. Based on the above analysis the loss expected due to the metal space frame of the O'Hare radome is 1.03dB. This is the average one way loss due solely to the metal space frame. Space frames with larger beam lengths, L, or smaller beam cross sections would have resulted in a lower loss structure.

The degree of depolarization introduced by the metal space frame can only be calculated if the exact structure of the radome is known. From photographs it appears that the radome panels are of equaliangular arrangement which results in equal effects for all polarization orientation. However the panel received for inspection is somewhat asymmetrical and it is considered advisable to evaluate the depolarization effects of at least one simple grid structure which has unequal attenuation for different polarizations of the incident radiation. The case chosen is a grid consisting of 45^o x 45^o x 90^o triangles as shown in Figure 5. A grid structure which has equal attenuation for all polarizations is also evaluated for purposes of demonstration. This case is a grid of equilateral triangles as shown in Figure 6. For the case of the 45^o x 45^o x 90^o triangle a calculation of the attenuation for radiation with

45° x 45° x 90° PANELS



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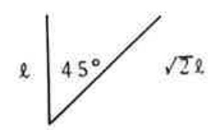


ELECTRIC FIELD VERTICAL

$L = \ell$, $\theta = 0$ $\qquad$ $L = \sqrt{2}\ell$, $\theta = 45$

$$\left(\frac{O_{sc}}{2W}\right)_{\vec{E}_{vert}} = \frac{1}{\ell + \sqrt{2}\,\ell}\left\{\left(\frac{\sigma_{sc}}{2W}\right)_{\parallel}\left[\ell\cos^2 0^\circ + \sqrt{2}\,\ell\cos^2 45\right] + \left(\frac{\sigma_{sc}}{2W}\right)_{\perp}\left[\ell\sin^2 0^\circ + \sqrt{2}\,\ell\sin^2 45^\circ\right]\right\} = 1.50$$

TRANSMISSION LOSS E_{vert} = 1.10db

ELECTRIC FIELD HORIZONTAL

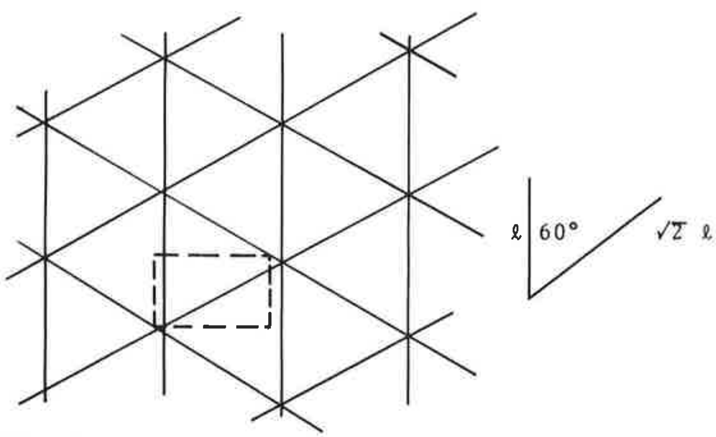
$L = \ell$, $\theta = 90^\circ$ $\qquad$ $L = \sqrt{2}=\ell$

$$\left(\frac{O_{sc}}{2W}\right)_{\vec{E}_{horiz}} = \frac{1}{\ell + \sqrt{2}\,\ell}\left\{\left(\frac{\sigma_{sc}}{2W}\right)_{\parallel}\left[\ell\cos^2 90^\circ + \sqrt{2}\,\ell\cos^2 45\right] + \left(\frac{\sigma_{sc}}{2W}\right)_{\perp}\left[\ell\sin^2 90^\circ + \sqrt{2}\,\ell\sin^2 45^\circ\right]\right\} = 1.24$$

TRANSMISSION LOSS $\vec{E}_{horiz}$ = .91db

Figure 5 Loss Through $45^{o} \cdot 45^{o} \cdot 90^{o}$ Space Frame

60° x 60° x 60° PANELS BASIC UNIT



ELECTRIC FIELD VERTICAL

| L = ℓ, θ = 0

/ L = 2ℓ, θ = 60°

$$\left(\frac{\sigma_{sc}}{2W}\right)_{\vec{E}_{vert}} = \frac{1}{\ell + 2\ell}\left\{\left(\frac{\sigma_{sc}}{2W}\right)_{\parallel}\left[\ell \cos^2 0° + 2\ell \cos^2 60°\right] + \left(\frac{\sigma_{sc}}{2W}\right)_{\perp}\left[\ell \sin^2 0° + 2\ell \sin^2 60°\right]\right\} = 1.37$$

TRANSMISSION LOSS $\vec{E}_{vert}$ = 1.01

ELECTRIC FIELD HORIZONTAL

| L = ℓ, θ = 0

/ L = 2ℓ, θ = 30°

$$\left(\frac{\sigma_{sc}}{2W}\right)_{\vec{E}_{horiz}} = \frac{1}{\ell + 2\ell}\left\{\left(\frac{\sigma_{sc}}{2W}\right)_{\parallel}\left[\ell \cos^2 90° + 2\ell \cos^2 30°\right] + \left(\frac{\sigma_{sc}}{2W}\right)_{\perp}\left[\ell \sin^2 90° + 2\ell \sin^2 30°\right]\right\} = 1.37$$

TRANSMISSION LOSS $\vec{E}_{horiz}$ = 1.01 db

Figure 6 Loss Through $60^{\circ} \cdot 60^{\circ} \cdot 60^{\circ}$ Space Frame

E-field oriented vertically and horizontally will yield the maximum and minimum values of attenuation through the grid. This in turn gives a measure of the degree of ellipticity that the grid causes when circular polarization is transmitted.

Calculation of attenuation for the cases of vertically and horizontally polarized radiation permits the polarization dependent effects of the entire grid to be modeled using a very simple basic unit. The basic units shown in Figures 5 and 6 contain all the necessary information regarding the orientation and lengths of the space frame beams to permit calculation of the attenuations for both horizontally and vertically polarized incident radiation. The effective scattering coefficients $(\sigma sc/2W)_{Effective}$ for a particular orientation of the E-field are the summation of $(\sigma sc/2W)_{\perp}$ and $(\sigma sc/2W)_{11}$ multiplied by the beam lengths and weighted by their angular orientation to the incident polarization. This sum must be normalized to the sum of beam lengths in the basic unit. This normalization is used so that η_b, the area blockage due to the members, remains constant in the two examples.

The summation is given by

$$\left(\frac{\sigma sc}{2W}\right)_{Eff} = \sim \frac{\sum_{n=1}^{m} \left\{ \left(\frac{\sigma sc}{2W}_{11}\right) L_n \operatorname{Cos}^2\theta_n + \left(\frac{\sigma sc}{2W}\right)_{\perp} L_n \sin^2\theta_n \right\}}{\sum_{n=1}^{m} L_n}$$

where

$\left(\frac{\sigma sc}{2W}\right)$ Eff = effective scattering cross section of basic unit for either horizontal or vertical polarizations

L_n = length of η^{th} beam

θ_n = angle between η^{th} beam and the electric field

In Figures 5 and 6 the above equation is used to evaluate the effective scattering coefficients for vertically and horizontally polarized radiation. These coefficients are then used in lieu of $\left(\frac{Q_{sc}}{2W}\right)_{AV}$ in equation 14 to calculate values of radome transmission loss for both vertically and horizontally polarized radiation. It is seen that for equiangular panels there is no difference in the attenuation. For the 45° x 45° x 90° panels the differential attenuation is only 0.19dB. If the radar has a cancellation ratio of 11dB without a radome, a radome with a one way differential attenuation of 0.19 dB may reduce the cancellation ratio to 10.4 dB. This 0.6 dB is not a very serious degradation of the system. The example of the 45° x 45° x 90° triangle is extreme and appears as a very pessimistic model of the actual shapes. The space frame probably does not degrade the cancellation ratio by more than 0.2 dB and consequently this is not a significant problem.

4.2 DIELECTRIC MEMBRANE LOSS

This section presents the results of laboratory measurement carried out to determine the dielectric properties of the radome membrane material. The membrane is made from ultraviolet stabilized polycarbonate resin formed into sheet stock of 1/8 inch thickness. Polycarbonate has the desirable characteristics of high impact strength, dimensional stability, and low water absorption.[6] There is no data available concerning the dielectric constant and loss tangent of polycarbonate in its dry and saturated state at 24 GHz. This data is required so that the loss due to the membrane can be evaluated.

4.2.1 Measurement Technique

The dielectric properties of polycarbonate resin are determined using the short circuited line technique described in reference 7, pp. 625-644. In the short circuited line technique the sample to be measured is machined to fit the waveguide cross section and it is backed immediately by a metal plate which forms a waveguide short circuit. With this arrangement all incident microwave energy is either absorbed by the sample or reflected back toward the generator. The phase and amplitude of the reflected wave, as determined by measuring the VSWR with and without the sample, is required to determine k and tan δ. Figure 7 depicts the change in the standing wave pattern produced by a dielectric. A change in the position of the standing wave minimum, Δ, is indicative of the dielectric constant, k. The difference in the voltage standing wave ratio, VSWR, permits calculation of the loss tangent once k is determined.

The gradual decrease in the amplitude of the standing wave pattern away from the short circuit depicted in figure 7 is due to the effect of waveguide losses in lowering the standing wave ratio. The effects of waveguide loss can be removed from the measurements as described later.

The standing wave pattern is measured using a slotted line. A block diagram of the measurement setup is shown in figure 8. The actual setup used for these measurements is shown in figure 9. For these measurements the short circuited line was implemented by pressing the machined polycarbonate sample into the end of the slotted line. A flat ground silver plate is fastened to the waveguide flange of the slotted line to provide the short circuit. There was no measureable loss associated with this short circuit. The short circuit was polished frequently during the measurements to assure good loss-free contact.

The power and frequency of the generator was constantly monitored during the course of the measurements to insure the accuracy of results. In order to measure distances along the slotted line accurately a dial indicator is used to measure the position of the traveling probe. Readings are possible to 1/10,000 centimeter.

Using the measured data the dielectric constant, k, is derived from the shift in the standing wave pattern by use of the transcendental equation[7]

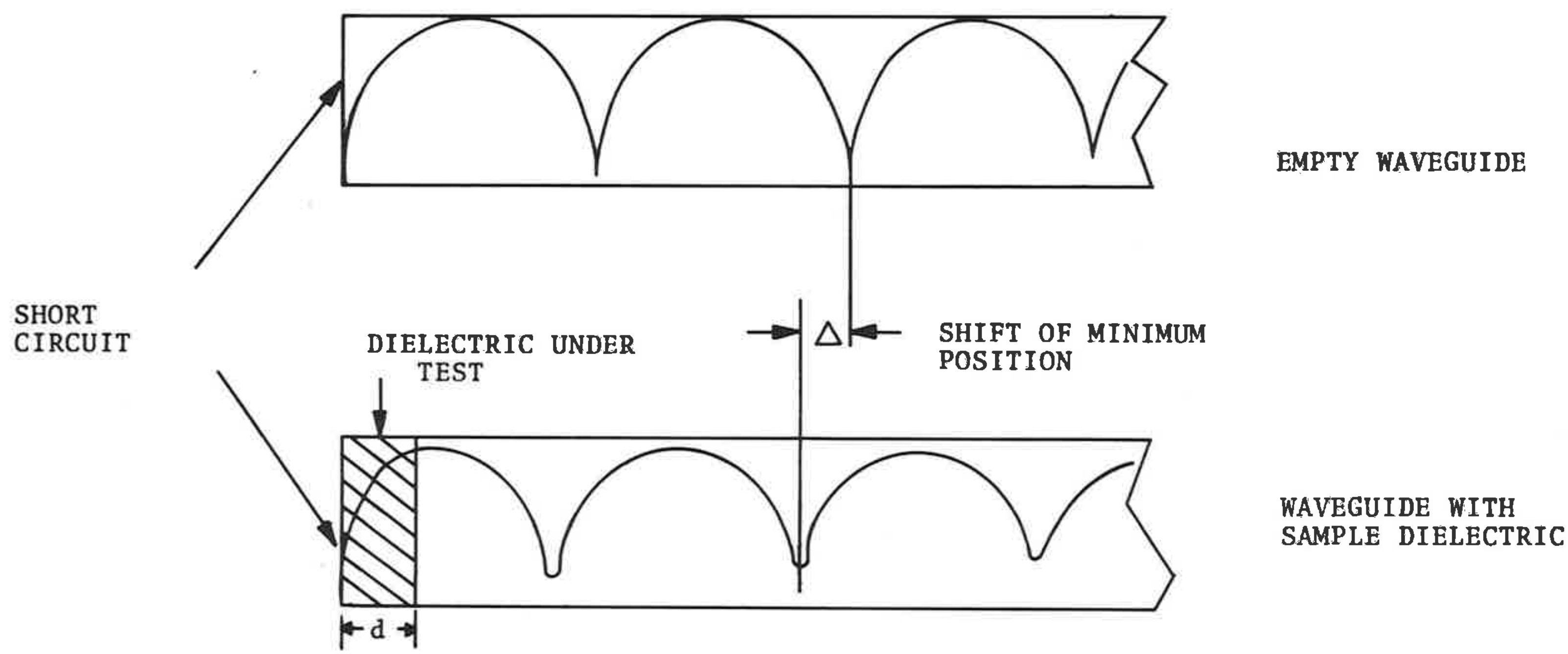


Figure 7 Standing Wave Pattern in Waveguide

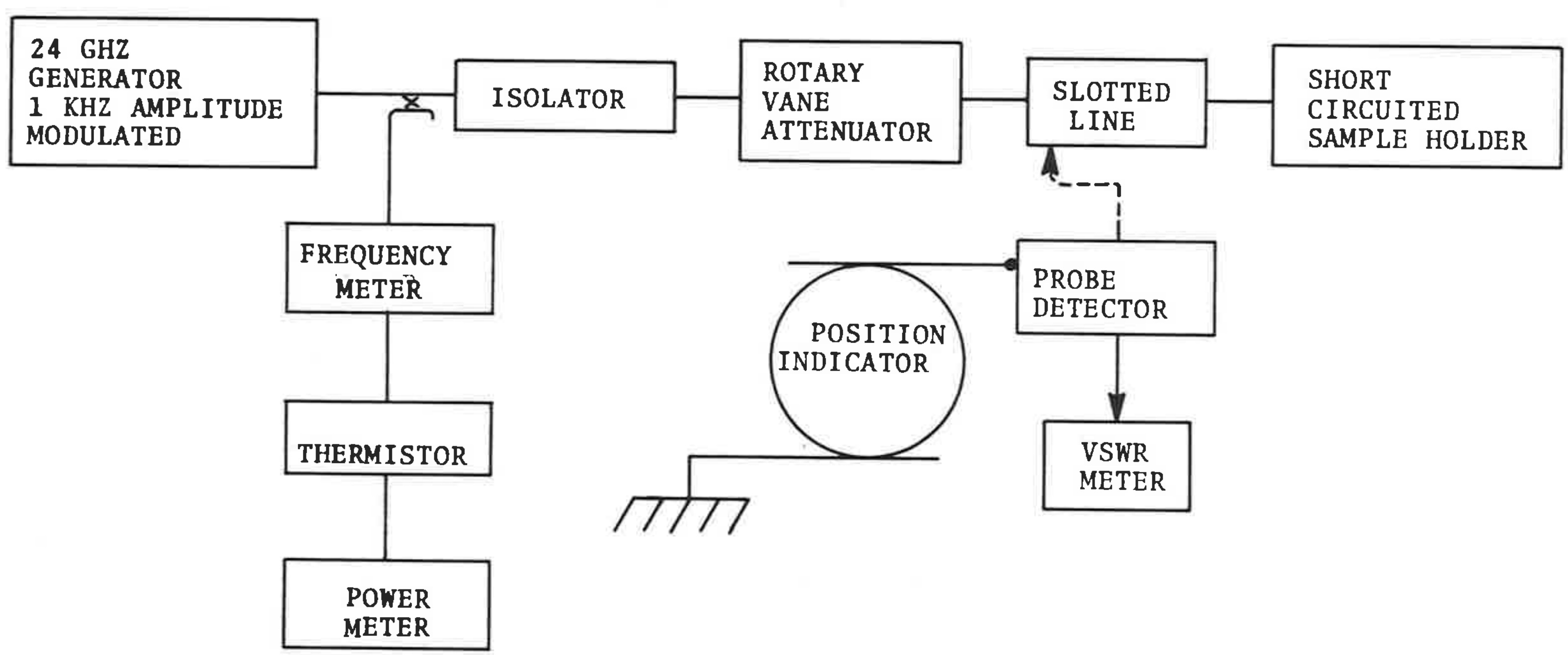
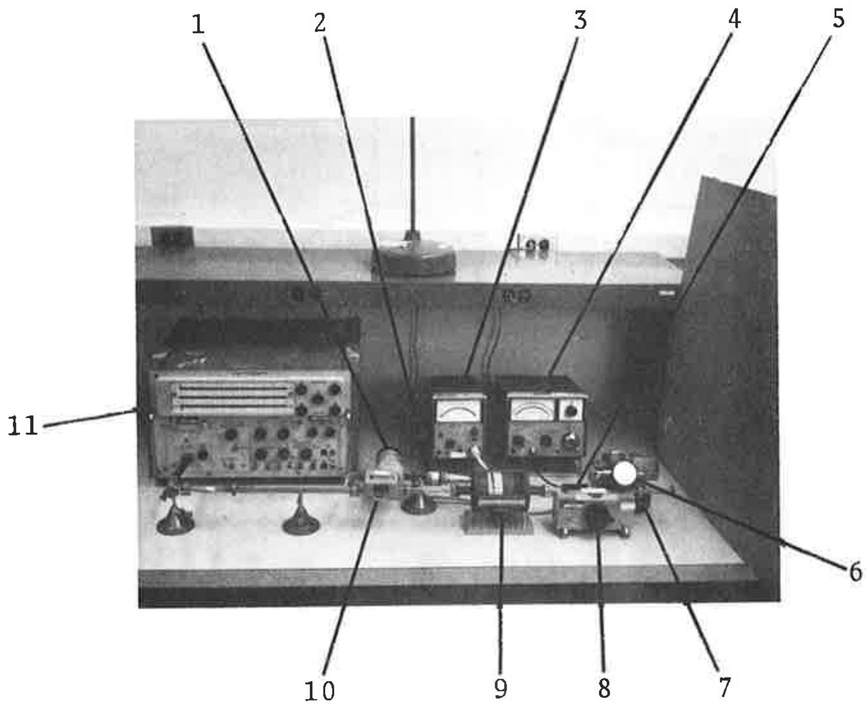


Figure 8 Block Diagram for Dielectric Measurements



1. Frequency Meter
2. Thermistor
3. Power Meter
4. VSWR Meter
5. Probe Detector (Hidden)
6. Position Indicator
7. Short Circuited Sample Holder
8. Slotted Line
9. Rotary Vane Attenuator
10. Isolator
11. 24 GHz Generator 1 KHz Amplitude Modulated

Figure 9 Laboratory Setup for Measuring Dielectric Properties

$$\frac{\tan\ 2\pi V}{V} = \frac{\lambda_g}{d} \tan\ 2\pi U \qquad (4\text{-}9)$$

where

$$V = \frac{d\sqrt{k - p}}{\lambda}$$

$$U = \frac{\Delta + d}{\lambda_g}$$

$$p = 1 - \left(\frac{\lambda}{\lambda_g}\right)^2$$

and d = dielectric sample thickness, cm

λ_g = guide wavelength, cm

λ = free space wavelength, cm

k = dielectric constant

Δ = shift in VSWR minimum position, cm

The method of solution is to evaluate the right hand side of the equation using the measured values of Δ and d and the calculated values of λ_g and p. Having calculated this quantity a plot of $2\pi(\tan x)/x$, where $x = 2\pi V$, is used to find values of V which satisfy the equation. The value of k is then calculated from V. Since multiple values of V satisfy the equation it is usually necessary to measure two samples of different thickness to resolve any ambiguity. Once k is determined the loss tangent is derived from [7]

$$\tan\ \delta = W\left(\frac{k - p}{k}\right) \frac{4\pi \csc 4\pi U}{4\pi V \csc 4\pi V - 1} \qquad (4\text{-}10)$$

where

$$W = \frac{1}{\pi}\ \frac{1}{VSWR}$$

There are several sources of error which must be avoided. Direct measurements of VSWR are very poor for large VSWR's due to deviations of detectors from square law over the large power range to be measured. A far more accurate means of measuring VSWR's is to measure the width of the null at a point 3dB above the minimum. If x and w are the probe positions either side of minimum, 3dB above minimum, the VSWR is calculated using[6]

$$\text{VSWR} \approx \frac{\lambda_g}{\pi(x - w)} \qquad (4\text{-}11)$$

which is accurate to better than 1% for values of VSWR of 13.3 or greater.

The effect of waveguide loss between the sample and probe may be removed from the measurements by measuring the widths of 3dB-above-minimum-points at several positions of the minimum with and without the sample. A plot of the points as shown in Figure 10 results. Extrapolating from the measured points made in the region covered by the slotted line it is possible to remove effects of the waveguide loss.

A list of other requirements for making accurate measurements are[8]

1) filling the narrow dimension of the waveguide completely;

2) assuring that the sample faces are parallel;

3) maintaining the sample against the short circuit.

4.2.2 Test Program Results

The short circuited line technique was used to measure changes in the dielectric constant and loss tangent of polycarbonate due to its absorption of water. Three samples were used in these tests. The surface of one sample was abraded with crocus cloth to increase the surface area and thereby enhance absorption of water. Table 3 presents the results of 48 days of testing of polycarbonate. Sample 1 was first submerged in a beaker of water for 6 days. The following three days sample 2 was also submerged.

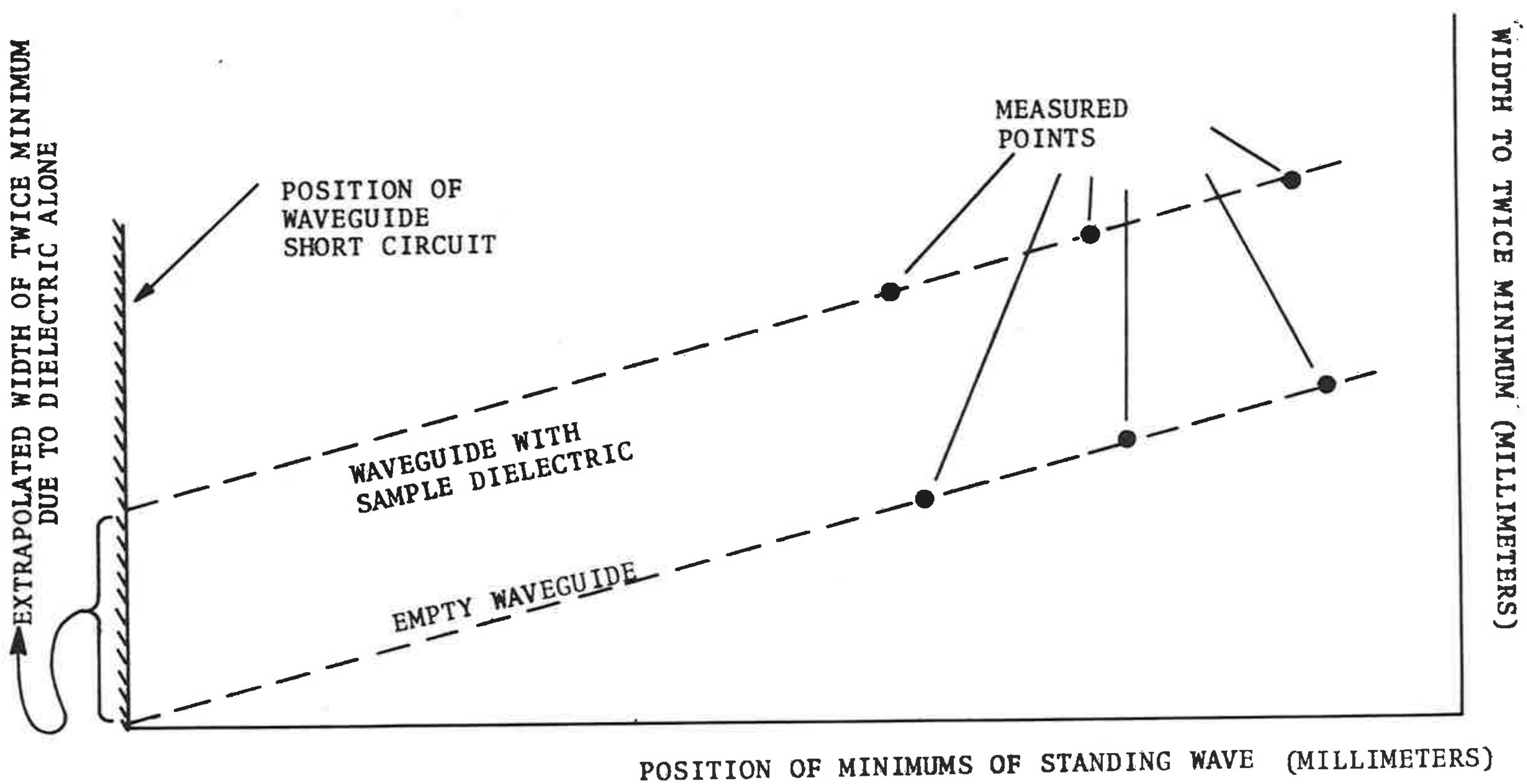


Figure 10 Plot of Measured Data Points

TABLE 3 RESULTS OF WATER ABSORPTION TESTS ON POLYCARBONATE

Duration of Test		Abraded Surface Sample #1	Sample # 2	Sample #3
6 days		Submerged	Lab Environment	Lab Environment
	k	2.76	2.76	2.76
	Tan δ	.0065	.0048	.0048
3 days		Submerged	Submerged	Lab Environment
	k	2.76	2.76	2.76
	Tan δ	.0065	.0065	.0048
1 day		Oven Drying	Oven Drying	Lab Environment
	k	2.70	2.70	2.76
	Tan δ	.0047	.0042	.0048
8 days		Lab Environment	Lab Environment	Lab Environment
	k	2.70	2.72	2.76
	Tan δ	.0050	.0055	.0055
30 days		Saturated Air	Saturated Air	Saturated Air
	k	2.74	2.76	2.79
	Tan δ	.0056	.0064	.0064

It appears that Lexan became saturated with water in less than three days. It is seen that the dielectric constant did not change but the loss tangent increased from tan δ = .0048 to about tan δ = .0065. The samples 1 and 2 were then put into a hot air drying oven at 105°C for 24 hours. The dielectric constant and loss tangent for the dried samples were slightly lower than their initial values.

After 8 days of exposure to laboratory conditions the dielectric properties were similar to their initial properties. The following 30 days the three samples were placed in an air tight container having water in its base. The trapped air becomes saturated with water vapor. The dielectric constants again remained basically unaltered while the loss tangent again increasing slightly to tan δ = .0064.

These tests indicate that polycarbonate absorbs extremely little water. The slightly increased loss tangent does not materially contribute to loss thru the radome. It certainly cannot account for the type of failure occurring at O'Hare Airport.

The one way transmission loss thru an 1/8 inch thick membrane at normal incidence is calculated[9] as 0.32dB for the case of saturated Lexan with a tan ε = .0064.

4.3 SURFACE WATER FILM

During periods of rainfall there is a water film buildup over the upper hemisphere of large spherical radomes. The effect of even a thin water film of several thousands of an inch thickness is to strongly reflect and attenuate high frequency microwave signals. Such an effect in the ASDE-2 can greatly limit the range capability of the radar.

Analytical work has been reported in the literature which predicts the thickness of the water layer to be expected on spherical radomes during a rainfall.[10,11] A model proposed in reference 11 assumes classical laminar flow of water off the randome. The model predicts that the water layer formed on a spherical radome during a rainfall is fairly uniform over the upper hemisphere in the absence of wind.

The water layer thickness produced by various rainfall rates is given by [10]

$$t = \left(\frac{3\mu}{2} \frac{R\ r}{W} \right)^{1/3} \tag{4-12}$$

where

t = water film thickness, inches

μ = viscosity of water

W = weight density of water

r = rainfall rate, mm/hr

R = radius of the radome, feet

the terms

$$\frac{3\mu}{2W} = 8 \times 10^{-10} \frac{in^3 - hr}{ft - mm}$$

In the case of the O'Hare ASDE-2 radome, R, the radius of the radome is 9 feet. Using the model with an assumed 10mm/hr rainfall, the predicted water layer thickness over the radome is $t = 0.0042$ inch. The resultant microwave transmission loss is determined by considering the water layer to lie in free space and calculating the transmission loss thru this layer[10]. This approach is valid in this case since the loss due to the water film is much greater than that due to the radome membrane. Using figure 1 of reference 10, the one way transmission loss thru a water layer of 0.0042 inches at 24 GH is 6dB.

Measured results of radome loss due to water film layers have been reported.[12,13] The results demonstrate the validity of the analytical model. In both reported cases the radome surface was wetting, as is the O'Hare ASDE-2 radome. This permits water films to exist on the surface. On such a wetting surface laminar flow is the principle drainage mechanism. If a radome surface possesses non-wetting properties, water which falls on it will bead and run off in rivulets. This mechanism of water shedding is much more efficient and the losses due to water are significantly reduced. In reference 14 experiments are described which were conducted at 4.2 GHz with a 55 foot diameter radome. The radome is constructed of a laminated membrane using polyvinyl fluoride (PVF) as an outer weather shield. In the manufacturing process some of the silicone mold release adheres to the PVF making recently manufactured material somewhat water repellent so that rain drains in rivulets. The loss measured thru this radome at a simulated 10mm/hr rainfall rate indicates that the equivalent water thickness is approximately 0.4 of that predicted by laminar flow. When this same radome was coated with a liquid wax an even greater repellency occurred. The loss measured indicated that the equivalent water layer thickness was reduced to 1/10 that predicted by laminar flow. It is expected that similar improvement would be noted with smaller diameter radomes.

For the water thickness anticipated with an 18 foot diameter radome the loss in dB is nearly proportional to the water film thickness. If the wetting polycarbonate in the O'Hare radome is coated with a suitable repellent which reduces the water film thickness to 1/10 present thickness the two way loss would be reduced from 12dB to 1.2dB for 10mm/hr rainfall.

Under the present circumstances, taking into account the two way losses ASDE-2 will experience due to the combination of metal space frame, membrane loss and water film loss, the maximum range of ASDE-2 in a 10mm/hr rain is a reduced 1.1 nautical miles. This is the range for maintenance of a S/N of 10 from grass areas.

5. RADOME COATING MATERIALS

This section describes the use of radome coating materials. To start, conventional radome coatings which are found to be unsuitable for use on the O'Hare radome are described. The requirements of a repellent coating for Lexan are discussed. Six coatings which appeared suitable were exposed to the environment to evaluate how well they retain their repellency in a polluted atmosphere. Measurements are made to test water repellency every several weeks. The test results identify the most suitable coating for the O'Hare ASDE-2 radome.

5.1 CONVENTIONAL COATINGS

In the design of metal space frame radomes the membrane material has commonly been a laminate consisting of layers of woven fabric such as fiber-glass or dacron reinforced with vinyl or polyester resins. These fabrics absorb water if unshielded from the weather. Water will spread by capillary action thru the fabric of a panel if even a small hole or crack permits weather exposure. The absorption of water causes the membrane to attenuate incident microwave signals. In order to prevent the absorption of water the membrane is coated with a paint which is impervious to water. This paint is not hydrophobic. Experience has shown that the water impervious coatings such as rubberized paints have a short service life.[15] Laborious procedures of stripping, priming and painting must be carried out every two or three years. In summary, common radome coatings are not suitable for use on polycarbonate for the following reasons:

1. They are not hydrophobic;
2. Application would require etching, priming and painting of the polycarbonate destroying its transparency;
3. Rubber based paints would have a short life expectancy due to airport smog.

5.2 COATING REQUIREMENTS FOR POLYCARBONATE

Laboratory measurements demonstrate that polycarbonate itself is impervious to water, absorbing only a minute amount of water after-weeks of submersion. A polycarbonate surface does not shed water rapidly. Water which falls on the surface spreads in a thin film as is typical of wetting surfaces. The coating for use on polycarbonate should render the surface water repellent or hydrophobic so that water which falls on the surface beads and runs off in rivulets. The characteristics desired in a polycarbonate coating are:

1. Water repellency;
2. Transparency;
3. Non-sticky to flying dust and soot;
4. Retention of repellency for at least one year;
5. Ease of application for periodic replenishment;
6. Thin coating with little or no buildup of material;
7. Compatibility with polycarbonate.

It is expected that any thin water repellent coating will require replenishment periodically. Hopefully an annual coating will suffice. Any coating will deteriorate gradually due to the effects of:

1. Erosion by rain and wind driven dust;
2. Photochemical reaction of the coatings with atmospheric pollutants such as SO_2, NO, O_3 in the presence of sunlight;
3. Accumulation of soot and dust on the coatings which rainfall no longer removes.

5.3 COATING MATERIALS SELECTED FOR TESTING

Polycarbonate resin is a thermoplastic which dissolves in methylene chloride, ethylene chloride and tetrachlorethane.[15] It is crystallized by acetone, ketones and esters. When under stress it may craze in the presence of carbon tetrachloride and aromatic hydrocarbons such as benzene and toluene. It is uneffected by alcohols, freon and neutral detergents. Small amounts of benzene and toluene may be used in a solvent system without crazing. The solvent systems of all coating materials tested were compatible with the requirements of Lexan.

The coating materials selected are listed in table 4. A description of each coating and the method of applying each coating to individual 6" x 12" sample polycarbonate panels is given in the table. In order to remove the silicone mold release from the polycarbonate each panel receives a preliminary washing. A wetting agent and detergent solution is used which leaves no residue when rinsed with water. The panels are then wiped with a cloth soaked in isopropyl alcohol and rinsed again with water. After they are dried the panels are ready to be coated. In addition to the coated panels, an uncoated panel of polycarbonate and a sample of a laminated membrane using PVF outer weather shield were run thru the tests.

It was of interest to evaluate the laminated membrane in these tests since it is a radome membrane material which is representative of a new class of materials being used in radome fabrication. Unlike older radome materials it requires no periodic painting to provide a weather barrier. The weather barrier is a PVF film of 1/1000 inch thickness. This film provides a weather barrier for the service life of the radome.

In addition to testing the repellency characteristics the PVF covered laminate its dielectric properties were measured using the short circuited line technique previously described. The particular samples measured consisted of 3 ply dacron with a bonded PVF film resulting in a total membrane thickness of .035 inch. Measurements were made on samples which were exposed both to dry and saturated air. The measured values of the dielectric constant and loss tangent were then used in computing the single path transmission loss through three ply laminate at normal incidence. The

TABLE 4 COATING MATERIALS APPLIED TO POLYCARBONATE TO IMPROVE WATER REPELLENCY

	MATERIAL	DESCRIPTION	APPLICATION PROCEEDURE
1.	Fumed Silicon Dioxide	A white powder. Spray sample consists of a 1% dispersion of fumed silicone dioxide in a mixture of isopropyl alcohol and propellant with 0.7% resin binder.	Spray onto surface evenly and permit the alcohol to evaporate. The surface has a light frosted appearance. The coating is fragile and cannot withstand handling or any mechanical abrasion.
2.	AFC-HMOD-4 Windshield Water Repellent	Developmental aircraft windshield water repellent. Tested under USAF contract for use on high speed aircraft.	Apply clear liquid to surface with a cloth. Allow 30 minutes for the coating to harden. Wipe off only as much of reside as required.
3.	Paste Wax	Automotive paste wax containing no abrasives.	Spread on surface and allow to dry. Wipe off excess with a damp cloth to polish.
4.	Liquid Wax	A liquid automotive wax with a mild abrasive.	Apply with a damp cloth. After drying remove the excess with a dry cloth.
5.	Plastic Polish	Surface conditioner for glass and plastics. Tested and recommended by USAF for use as an aircraft windshield water repellent.	Apply clear liquid to surface with cloth. After solvent evaporates the residue is wiped away with a cloth.
6.	Silicone Fluid	Asilicone liquid compatable with Lexan. It is used as a base in other silicone products.	Applied with a cloth. The surface has an oily appearance. Remove excess until surface looks and feels dry.

average dielectric properties of the laminate exposed to dry air are: k = 2.75 and tan = 0.012 resulting in a single path transmission loss of 0.57 db. The dielectric properties of the laminate exposed to saturated air was measured as k = 2.80, and tan = 0.021 resulting in a single path transmission loss of 0.60 db. These values of transmission loss are excessive. However the PVF covered laminate is also available in a single ply form. The single ply thickness of .012 inch results in a calculated single path transmission loss of 0.12 db which is much more acceptable.

5.4 WEATHERING ENVIRONMENT

It is desirable to obtain information on how well the coatings will retain their repellent properties after several months of exposure to a polluted atmosphere. Consideration was given to subjecting the coated panels to several environments specified in MIL STD 810B to accelerate the aging process. Environmental testing laboratories have equipment capable of producing the individual environments of dust, rain and sunshine. There are no test chambers capable of producing the mix of conditions as they exist in the natural environment and the individual tests are poorly suited to the present task. As an example: The dust environment would not be useful in checking abrasion effects because the fine dust would cake to the plastic panels in a matter of seconds. It was decided that MIL STD 810B tests would raise more questions than they would answer.

The alternative is real time testing with coated panels exposed to a polluted atmosphere. The test panels were placed side by side on a test rack, figure 11, located on the roof of the TSC Management Building. The roof is the fourteenth story, approximately the height of the ASDE-2 antenna at O'Hare. The panels are located on the south-west corner of the building facing the prevailing spring and summer winds. Fifteen year wind maps show that the wind out of the south-west is between 13 and 24 miles per hour about 7% of the time during the late spring and early summer. The rainfall for the month of June 1972 alone exceeded 6 inches. The presence of oil fired steam electric generators, a rubber processing plant and other commercial smoke stacks in the area contribute

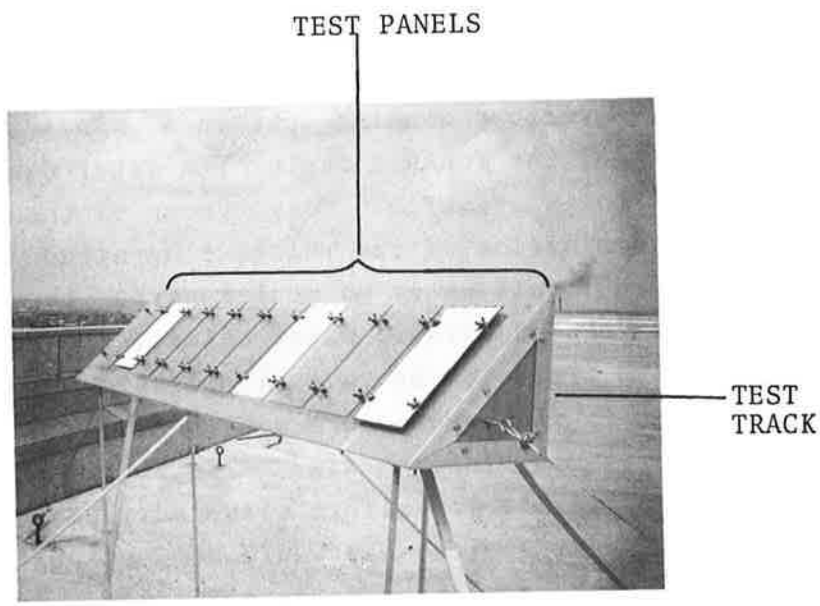


Figure 11 Roof Rack with Weathering Panels

to local soot and pollution. A great amount of wind driven dust has resulted from the demolition of two large buildings within a city block of TSC. Unpaved roads in the immediate vicinity have also contributed to the dust. The dust and soot on the panels after several days is so thick as to prevent measurement of the coatings. It was decided after the first set of measurements to only remove the panels for repellency testing either during or immediately after a rain shower. In this way the natural washing effect of the rain can simultaneously be evaluated.

5.5 TESTING PROCEDURES

Several tests were devised for comparing the relative repellency provided by the various coating solutions. In the most frequently used technique, the contact angle of a water drop with a uniform planar surface is measured. Measurement of the contact angle permits a determination of the relative magnitude of the cohesive forces between liquid water molecules versus the adhesive forces between a surface and liquid water molecules. To perform this measurement with precision an unusual microscope with a horizontal field of view is required. Such equipment was unavailable during the course of these measurements. Also the measurement technique is only applicable to uniform clean surfaces on which point measurements have validity. It would be difficult to extrapolate the data to areas containing surface dust and soot. For these reasons only once were contact angles estimated. This occurred at the end of 11 1/2 weeks of environmental exposure when the panels were unusually free of dust and soot due to a recent heavy rainfall. The measurements were made with the unaided eye observing drops on a panel surface. Contact angles were estimated by use of a protractor. Measurement accuracy is estimated as $\pm$ 10 degrees. Other tests employed survey large surface areas and are less likely to yield erroneous data. The principle tests used are described below.

The principal test employed evaluates repellency by measuring the length of time required for a water drop to travel six inches from a sample panel center to its edge as a function of the tilt angle which the panel makes with the horizontal plane. These tests will be referred to as "tilt angle" tests. Figure 12 shows the jig used to adjust the tilt of the panel for this test. A burette is used to generate constant size water drops at a very slow rate. The water drops fall 1/2 inch to the tilted panel surface. The time required for the water drop to travel from panel center to edge is timed using a stop watch. After one drop traverses the panel the tilt angle is changed and the panel or burette is moved to perform the test in another dry section of the panel. This is necessary since a water trail from previous drops will change the test results. In the near vertical position the drops are shed in a fraction of a second. As the panel is tilted progressively away from the vertical more time is needed for the water to traverse the panel. Eventually an angle is reached at which the water drop stops on the panel after falling from the burette.

This tilting panel technique is a valid test for comparing coatings. It measures directly the rate of water shedding which is the pertinent characteristic desired of the water repellent coatings. The tilting panel technique is easy to execute on newly coated clean panels. As the panels are exposed to the environment and returned for further testing the varying conditions caused by individual pieces of soot require that several measurements be made at each angle over a representative area of the panel.

The results presented in the next section show that the surface may improve from one testing period to a later testing period. This is probably a function of how many heavy cleaning rainfalls were experienced versus how much soot and dust were in the atmosphere in the period immediately preceeding a measurement. The

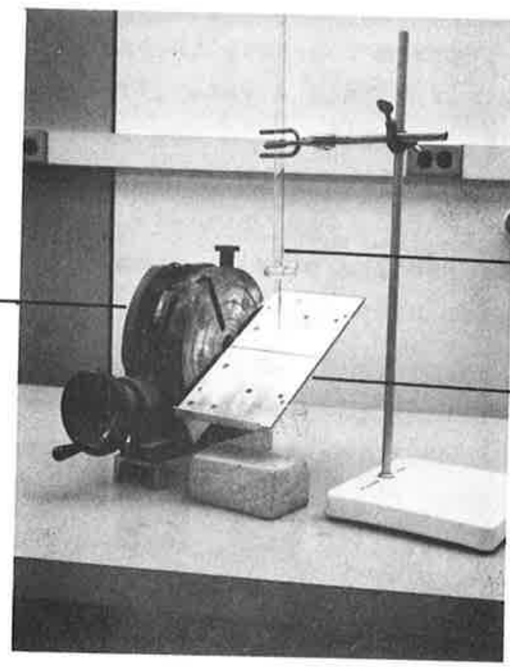


Figure 12 Tilt Angle Measurement Setup

first exposure period was ended with a preceeding period of three days of fog and drizzle. There was such an accumulation of dust and soot that no tests could be performed on the panels. Loose dust and soot were first permitted to flow away under the influence of slowly flowing water in the laboratory. Following this rinsing the panels were tested. Subsequent exposure periods were terminated by removing the panels from the roof rack either during or immediately following a moderate to heavy rainfall. In this way the self cleaning action of the rain is employed to prepare the panels for measurement. The validity of this approach is based on the fact that it is only during a rainfall that repellency is important and consequently only during a rainfall should these measurements be made.

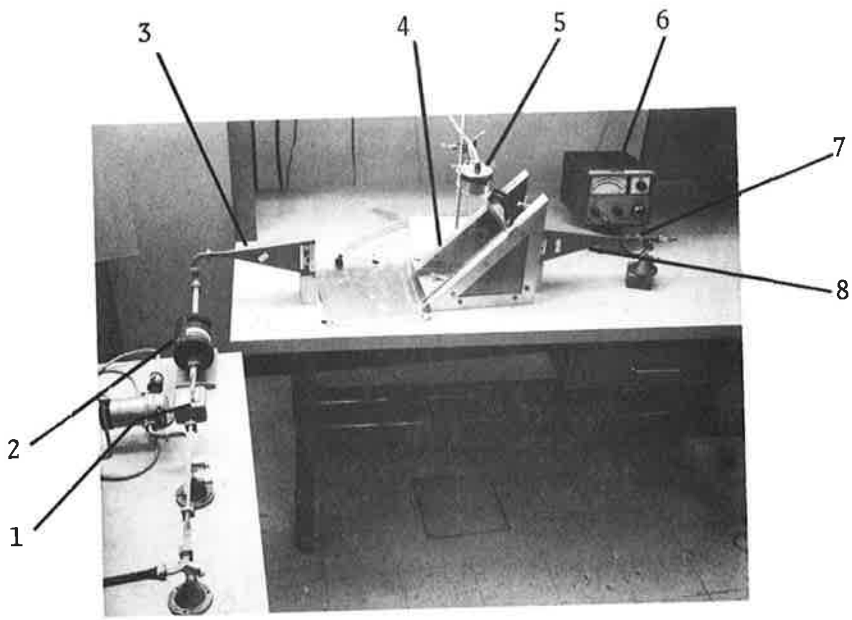
A third test, the "film breakup" test, is used to evaluate the speed with which each of the coatings breaks up a water film and drains a panel surface. This is again directly related to repellency. For this test each panel is submerged in a basin of water. As it is removed, it is tilted at a 45° angle to horizontal. The time required and the extent of the water film breakup are recorded. Any panel which does not break up the water film rapidly has lost the hydrophobic properties which are required.

A fourth test evaluates the tendency of water to spread on a surface. In more repellent panels the contact angle will be steeper and water will spread less. In one version of this test a panel is positioned at 30° to the horizontal plane. A small constant stream of water falls on the panel from a height of one foot. The water striking the panel spreads and drains at the far end of the panel. Measurement of the maximum water spread gives a good indication of a coatings resistance to water film spread. In a second version of this test a fixed amount of water (two drops) is dropped on the panel from a three inch height. The diameter of the water puddle is measured. More repellent coatings will cause the water to accumulate in a smaller puddle.

In a fifth test microwave loss measurements are made thru panels being showered with dripping water. The panel to be tested is positioned at a 45° angle between two microwave horns as shown in figure 13. Water drops fall on the surface of the panel from a cup with many small holes punched in it. The water fall rate is uniform due to the fact that the cup is constantly being filled from a water tap. The water catch under the panel drains into a sink. A block diagram of the setup is shown in figure 14. The measurements made in this experiment provide interesting qualitative results. The measurements made in this experiment will not be quantitative due principally to the small panel size. Due to the small panel size the horns are in close proximity. The horns are within each others near field. If they were spaced further a substantial portion of the radiation would not traverse the test panel. Also the presence of the reflections from the metal frame which supports the panel and the catch basin make quantitative results difficult to obtain. The most useful aspect of this test is the confirmation that the panels which have shown the best repellent properties in the other tests produce the smallest transmission losses.

5.6 RESULTS OF TESTS

The results of the repellency measurements conducted in the laboratory are presented in this section. Eight of the panels were exposed for a total of 11 1/2 weeks. Two panels were added 3 1/2 weeks after the beginning of the tests so that these two have been subjected to 8 weeks of exposure. The eight original panels include an uncoated polycarbonate panel, six polycarbonate panels coated with the six materials described previously in table 4, and a panel of a laminated radome membrane material employing permanent polyvinyl fluoride (PVF) film as a weather protective surface. The two panels added 3 1/2 weeks after the start of testing were a sample of the Laminate coated with fumed silicon dioxide and a second panel of polycarbonate coated with AFC-HMOD-4 aircraft windshield water repellent. In the case of this second panel coated with the



1. Isolator
2. Attenuator
3. Transmitting Antenna
4. Panel Under Test
5. Water Source
6. Meter
7. Crystal Detector
8. Receiving Antenna

Figure 13 Microwave Water Film Loss Measurement Setup

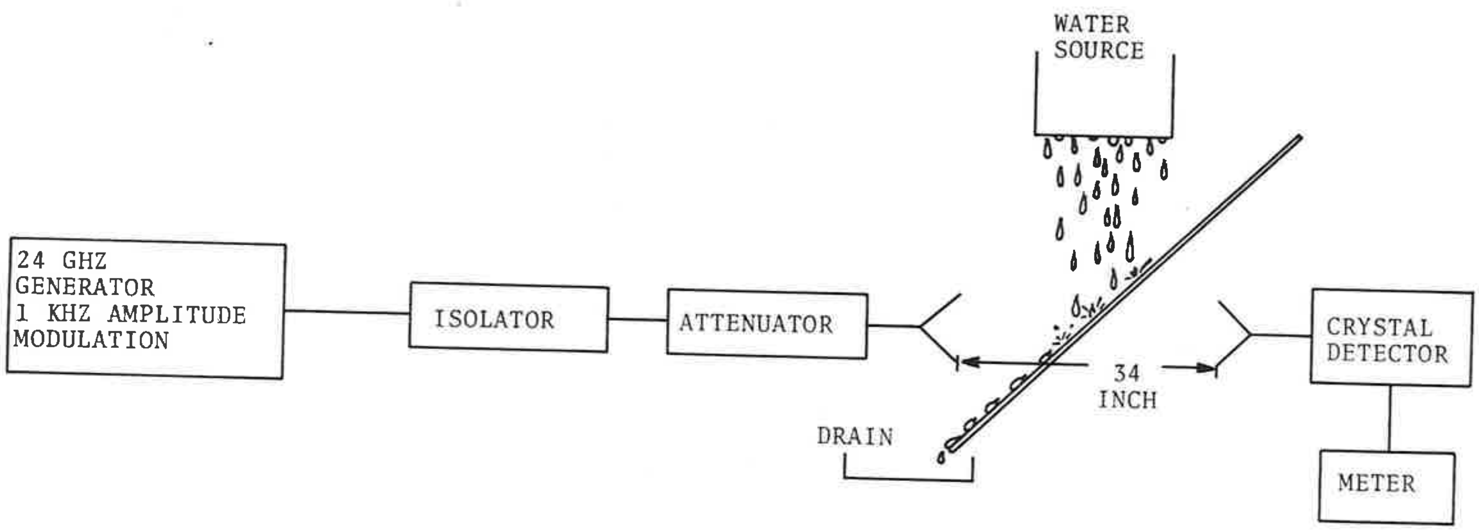


Figure 14 Block Diagram of Microwave Water Film Loss Measurements

water repellent, less of the residue is removed providing a thicker coating which has a slightly greasy appearance.

During the exposure period of 11 1/2 weeks the panels were measured in the laboratory on five occasions. The first tests were conducted on the newly coated panels. The second test was made after 1 week. Subsequent tests were made at increasingly longer intervals. The "tilt angle" test was the first test adopted and was made at the end of each roof exposure period. Other tests were developed to supplement the tilt angle measurements and were only conducted at the end of a few measurement periods. Table 5 presents a calendar showing the testing dates and indicates which tests were performed at the end of each period.

The results of the tilt angle measurements are presented in two sets of figures. The first set shows the relative coating repellency by plotting tilt angle data for all the coatings on one graph for each of the following cases:

a) new panels, figure 15

b) 6 1/2 weeks exposure, figure 16

c) 11 1/2 weeks exposure, figure 17

From this data it is obvious that the fumed silicon dioxide consistently produces results unmatched by any other coating. Also the AFC-HMOD-4 windshield water repellent is considerably better than any of the remaining coatings. The balance of the coatings do little to improve the repellency of polycarbonate after environmental exposure. The coatings may even degrade the repellency of polycarbonate as may be seen from the tests performed after 6 weeks of exposure. The coatings may leave a sticky residue to which dust and soot adhere. A light rain is then unable to wash away the particulate material which adversely effects repellency. The PVF covered laminate on the average is seen to have slightly better repellency than uncoated polycarbonate.

TABLE 5 CALENDAR OF REPELLENCY MEASUREMENTS ON TEST PANELS

DATE	TEST SET#	PERIOD OF EXPOSURE	TESTS PERFORMED
5/12	1	Newly Coated	Tilt Angle
5/19	2	1 Week	Tilt Angle
6/2	3	3 Weeks	Tilt Angle, Film Breakup, Water Spreading
6/6	Two additional	Test Panels Added	1) Heavy Coat of AFC-HMOD-4 on Polycarbonate 2) Fumed silicone dioxide on PVF covered laminate
6/26	4	6 1/2 Weeks	Tilt Angle, Microwave Attenuation
8/2	5	11 1/2 Weeks	Tilt Angle, Film Breakup, Water Spreading Microwave Attenuation, Contact Angle

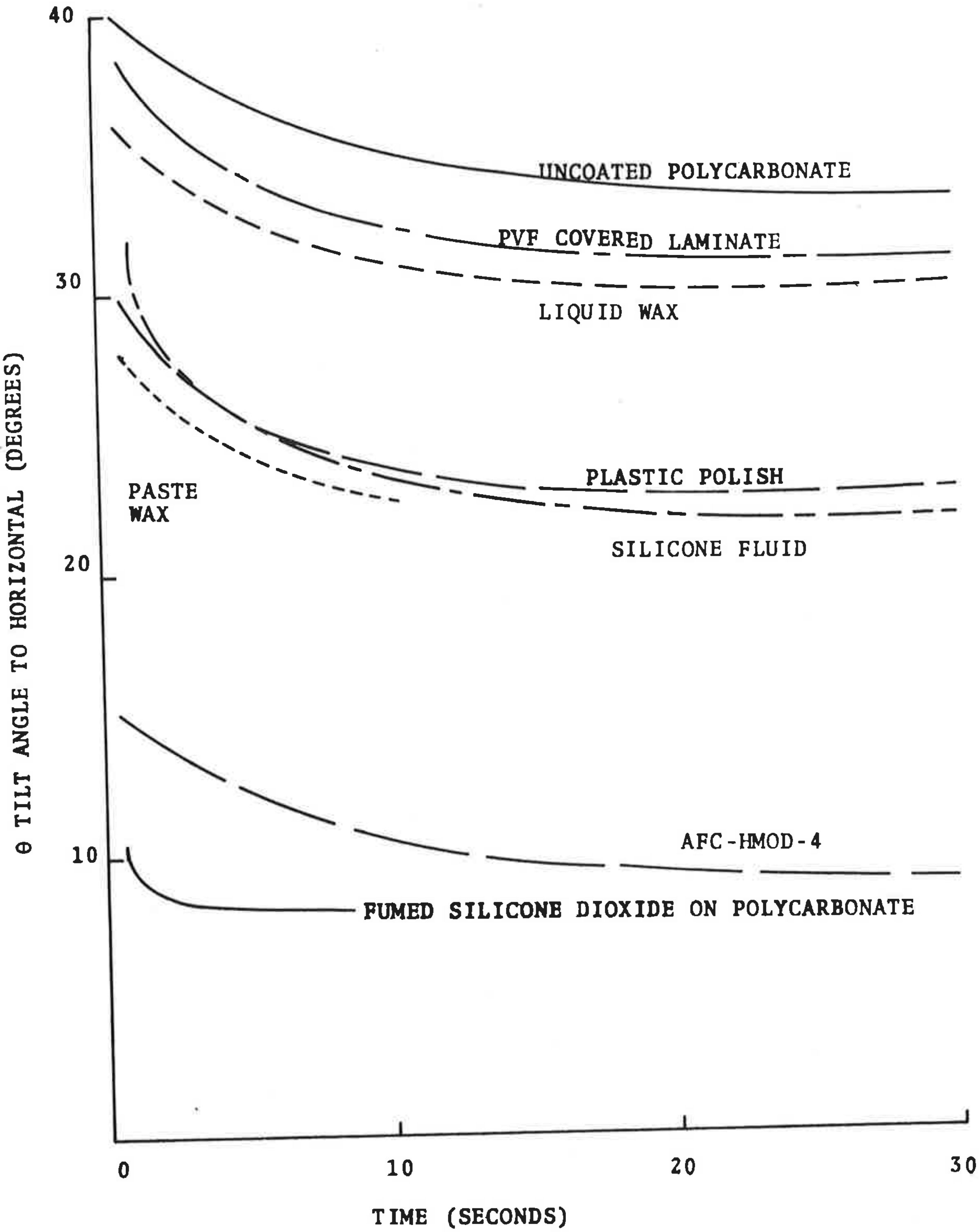


Figure 15 Initial Repellency Test

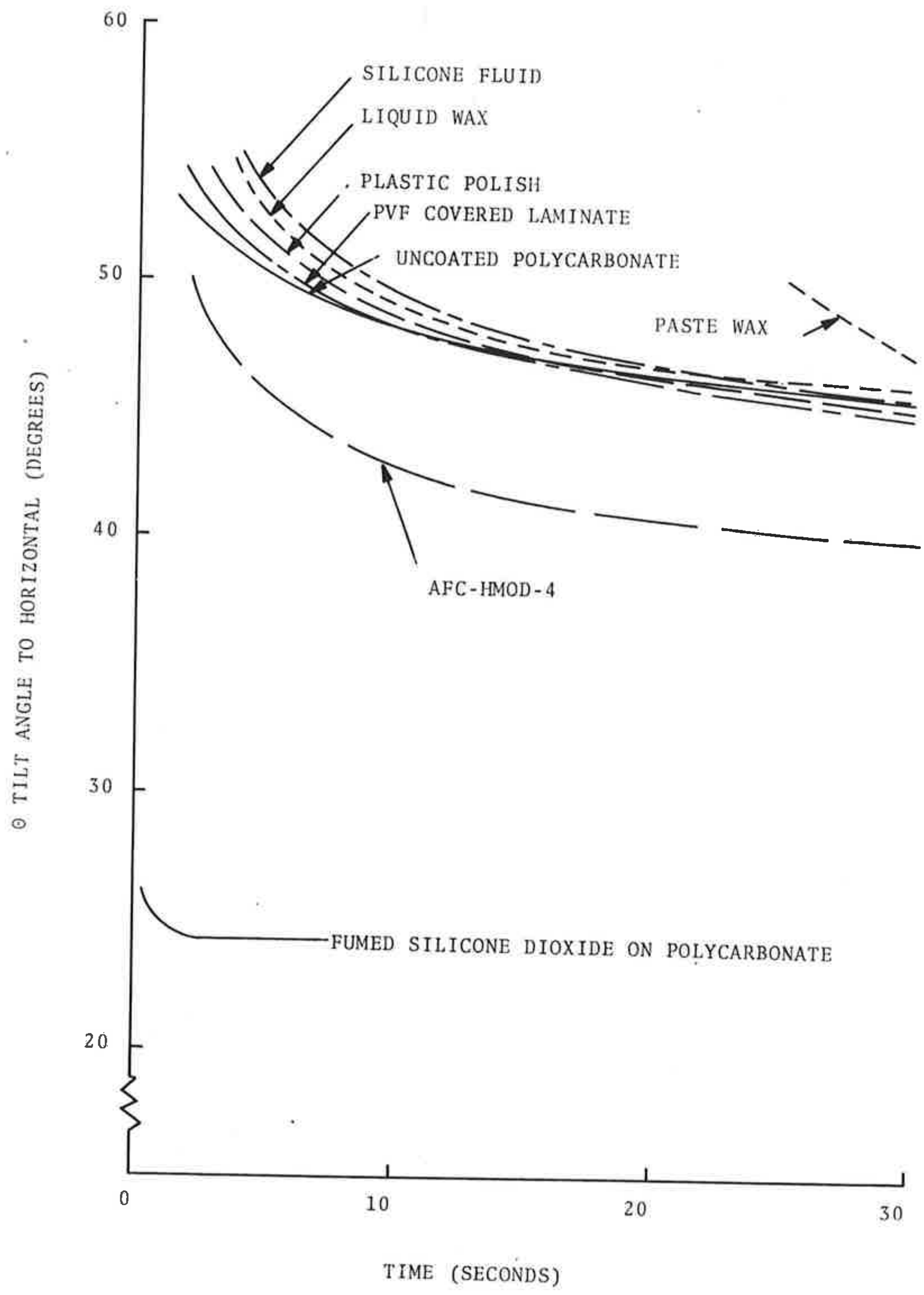


Figure 16 Repellency Tests, 6 1/2 Weeks Weathering

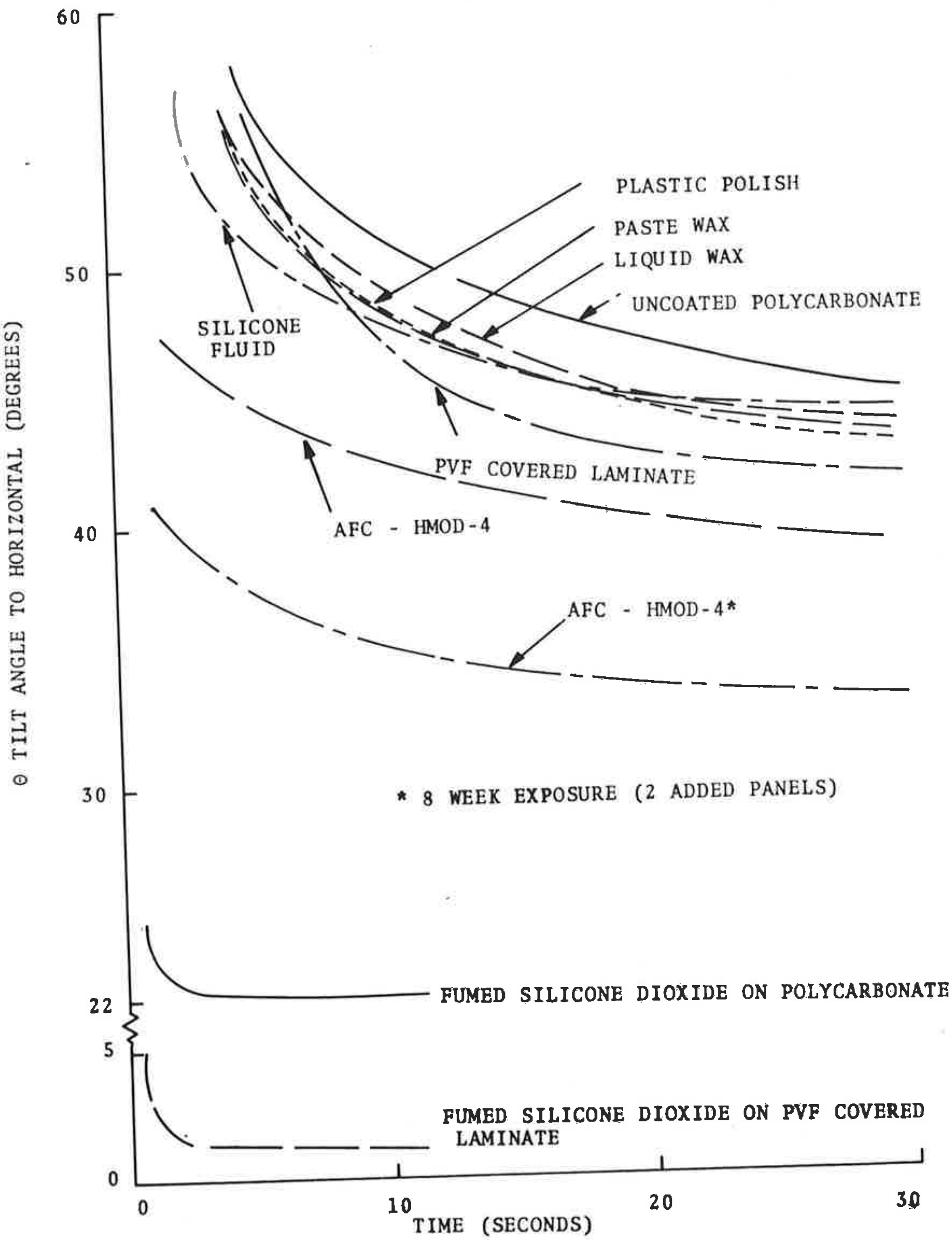


Figure 17 Repellency Tests, 11 1/2 Weeks Weathering

The second set of figures show the changes in repellency with time for several of the more interesting cases. Illustrated are the performance of:

a) uncoated polycarbonate, Figure 18

b) Polycarbonate with AFC-HMOD-4, Figure 19

c) fumed silicone dioxide on polycarbonate, Figure 20

d) PVF covered laminate, Figure 21.

These figures show that AFC-HMOD-4 and fumed silicon dioxide not wearing out rapidly. The largest changes in the data of these coatings is principly due to the particulate material collection and rain washing rates in the period just preceeding measurements. From this data it is inferred that the two coatings probably can be expected to have a useful service life of one year.

The water "film breakup" tests were performed after 3 weeks and after 11 1/2 weeks of exposure. The results are presented in table 6. In the three week tests, films remained on the surface over substantial areas of several of the panels. At 11 1/2 weeks the water film drained from all the panels. Obviously the panels were much cleaner in the latter case. The drainage from fumed silicone dioxide is instantaneous. Surface water drains as fast as the panel is removed from its submerged position. The AFC-HMOD-4 coating also consistently causes rapid drainage.

The results of the two spreading tests are presented in table 7. As previously described the 3-week results measured spreading of a water stream and the 11 1/2 week results measure the puddle size due to two drops of water dropped from a height of 3 inches. Fumed silicone dioxide and AFC-HMOD-4 both show superior repellency characteristics. The balance of the materials offer small improvement over uncoated polycarbonate especially in 11 1/2 week data.

Transmission loss measurements at 24 GHz were made as described previously. These measurements were made at 6 1/2 weeks and 11½ weeks of exposure. The results are given in table 8. The 6½ week data is an average of 4 measurement sets. Two sets were

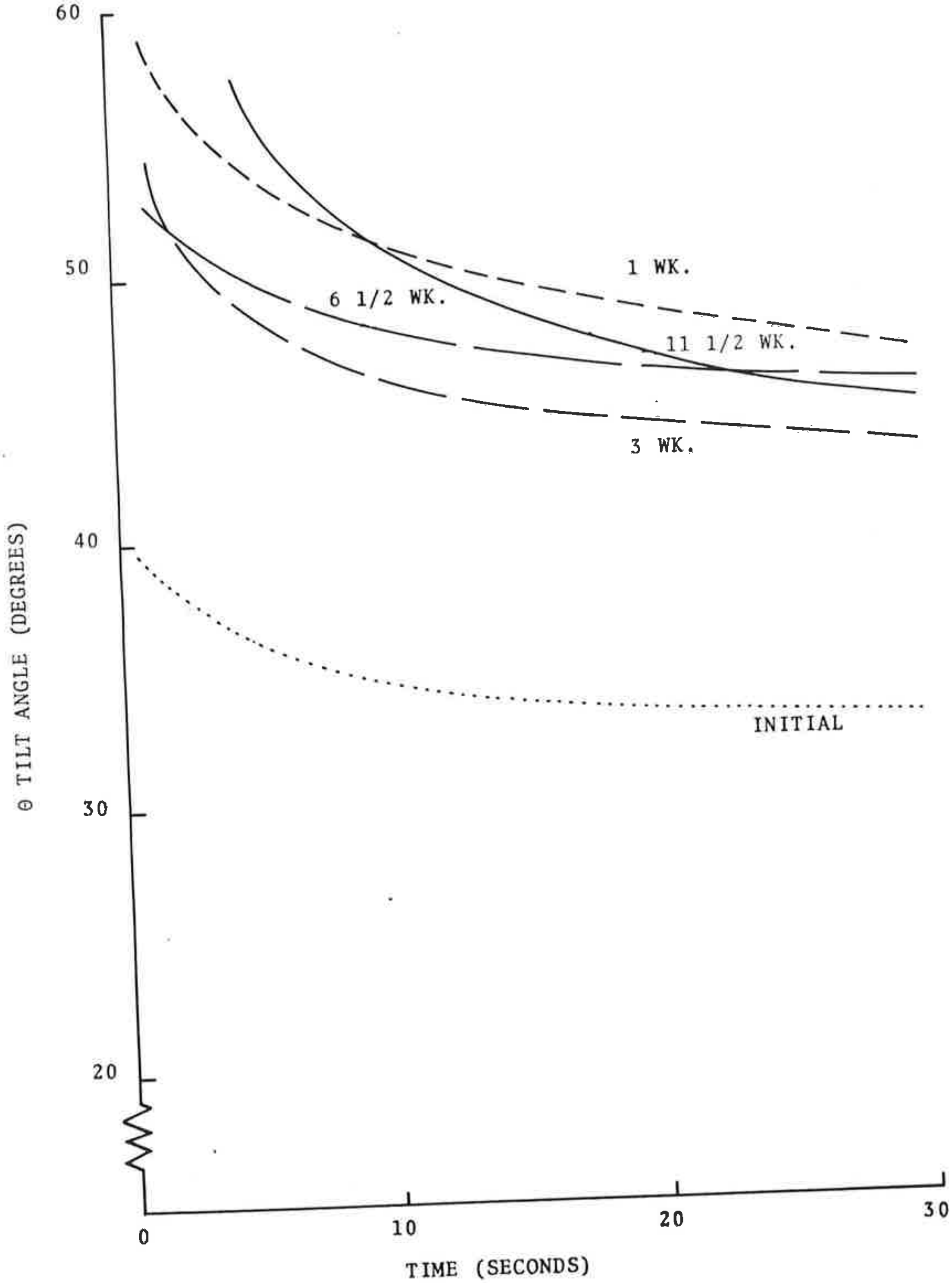


Figure 18 Aging of Polycarbonate (Uncoated)

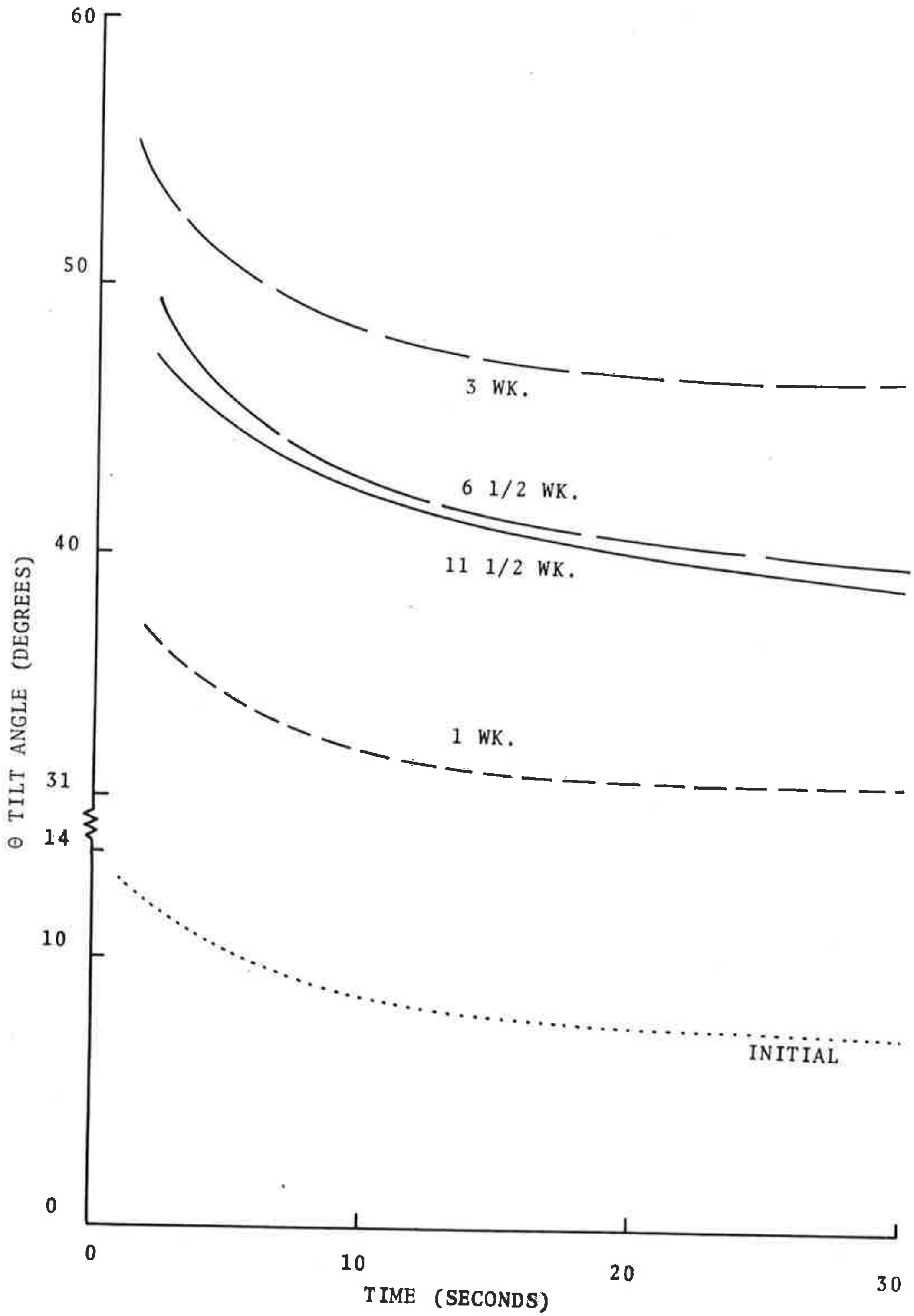


Figure 19 Aging of AFC-HMOD-4

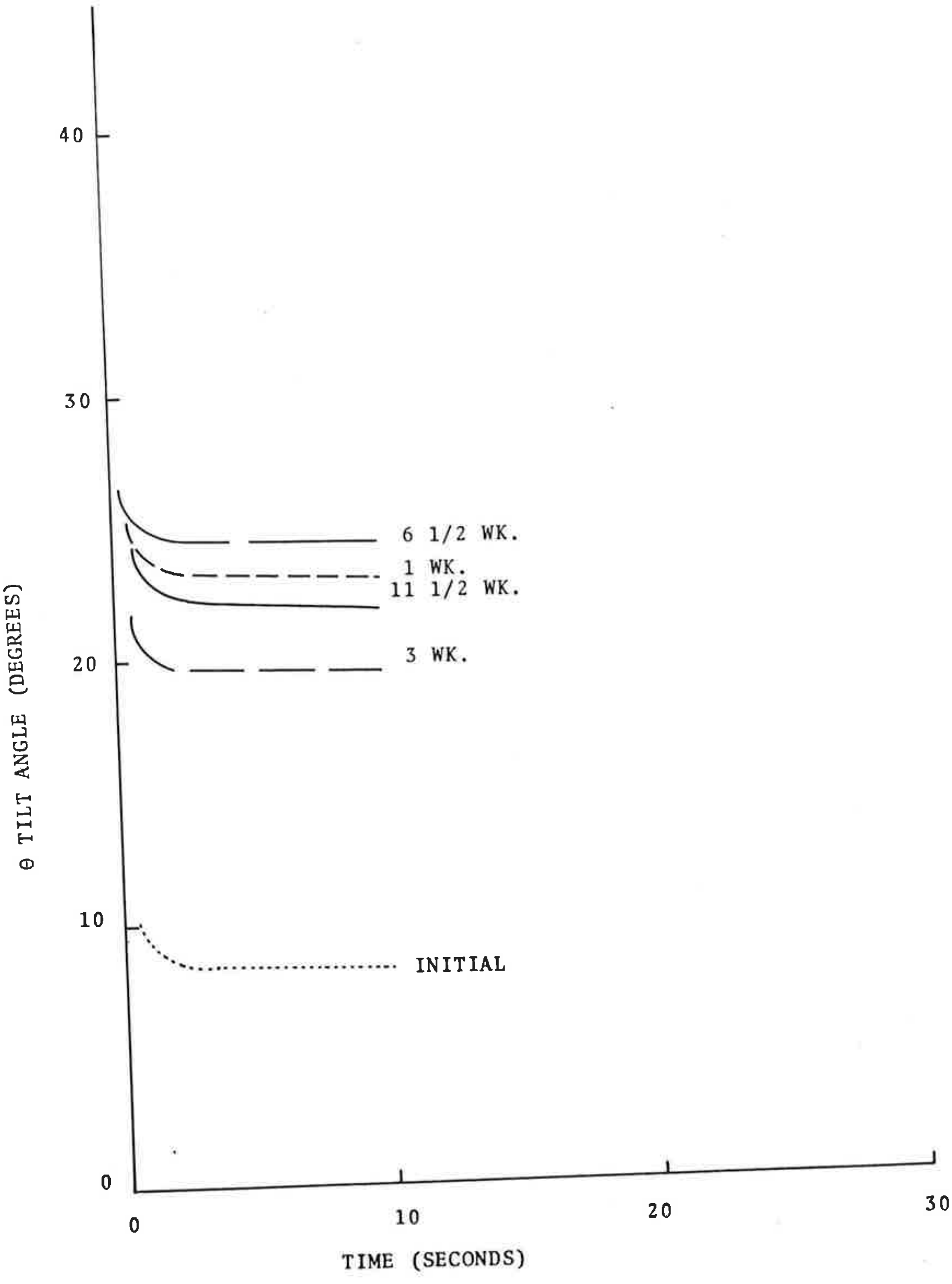


Figure 20 Aging of Fumed Silicone Dioxide on Polycarbonate

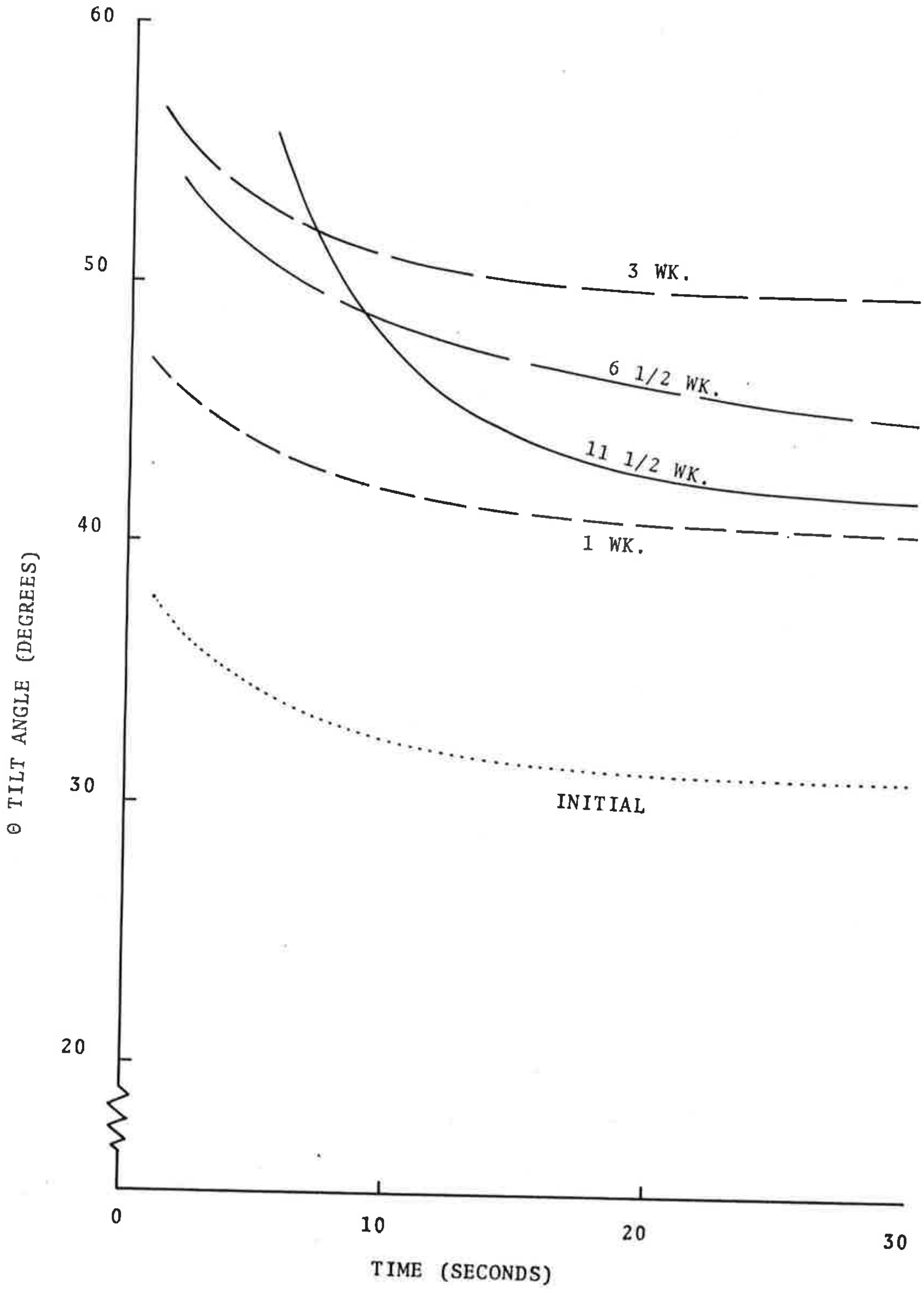


Figure 21 Aging of PVF covered Laminate

TABLE 6 WATER FILM BREAKUP RATES

Material	Rate of Water Film Breakup *
Fumed Silicone Dioxide	Instantaneous
AFC-HMOD-4	Immediate Breakup into Large Drops
PVF Covered Laminate	Rapid Film Breakup
Liquid Wax	30 Seconds for Complete Film Breakup
Paste Wax	10% of Surface Covered by Film after 1 Minute
Uncoated Polycarbonate	50% "
Plastic Polish	80% "
Silicone Fluid	100% "

* 3 Week Results

Material	Rate of Water Film Breakup **
Fumed Silicone Dioxide over PVF covered Laminate***	Instantaneous
Fumed Silicone Dioxide on Polycarbonate	"
AFC-HMOD-4 ***	1 Second
AFC-HMOD-4	2.5 Second
Liquid Wax	5 Second
Plastic Polish	10 Second
Silicone Fluid	10 Second
Paste Wax	20 Second
Uncoated	25 Second (A very thin water film remains)
PVF Covered Laminate	30 Seconds

** 11 1/2 Week Results

*** 8 Week Results

TABLE 7 WATER SPREADING CHARACTERISTICS

Material	Spreading of a Water Stream (Inches)*
Fumed Silicone Dioxide on Polycarbonate	2
AFC-HMOD-4	3 1/2
PVF Covered Laminate	3 1/2
Liquid Wax	4
Paste Wax	4
Uncoated Polycarbonate	5
Plastic Polish	5
Silicone Fluid	5 1/2

* 3 Week Results

Material	Spreading of 2 Drops of Water (Inches)**
Fumed Silicone Dioxide on PVF covered Laminate ***	.3
Fumed Silicone Dioxide on Polycarbonate	.3
AFC-HMOD-4 ***	.4
AFC-HMOD-4	.5
Paste Wax	.8
PVF Covered Laminate	.9
Plastic Polish	.95
Silicone Fluid	.95
Liquid Wax	1.0
Uncoated Polycarbonate	1.0

** 11 1/2 Week Results

*** 8 Week Results

TABLE 8 WATER FILM ATTENUATION MEASUREMENTS AT 24GHz

Material	Water Film Loss (db) *
Fumed Silicone Dioxide on Polycarbonate	0.25
AFC-HMOD-4	0.69
PVF Covered Laminate	1.06
Paste Wax	1.06
Plastic Polish	1.77
Silicone Fluid	1.93
Liquid Wax	2.12
Uncoated Polycarbonate	2.31

* 6 1/2 Week Results

Material	Water Film Loss (db) **
Fumed Silicone Dioxide on PVF covered Laminate ***	0.1
Fumed Silicone Dioxide on Polycarbonate	0.6
AFC-HMOD-4***	1.1
AFC-HMOD-4	1.2
Silicone Fluid	2.3
Plastic Polish	2.3
Paste Wax	2.4
PVF Covered Laminate	2.5
Liquid Wax	3.1
Uncoated Polycarbonate	3.7

** 11 1/2 Week Results

*** 8 Week Results

made with the polarization of the transmitted electric field orientated vertically. The other two sets employed horizontally oriented electric fields. There was no noteable difference between the two data sets. The 11 ½ week data is the average of two data sets both employing radiation with the electric field oriented vertically. The water flow and height of the fall is greater in the 11½ week tests. This results in somewhat larger values of transmission losses in this latter case. The data indicates that use of fumed silicone dioxide should reduce losses by about a factor of 5 while AFC-HMOD-4 should reduce losses by a factor of about 3.

The results of the contact angle measurements are given in table 9. Only fumed silicone dioxide and AFC-HMOD-4 result in large contact angles.

Finally table 10 lists observations concerning the principle drainage mechanism for each of the panels tested. With fumed silicone dioxide droplets appear to roll gaining speed as they roll down an inclined plane. AFC-HMOD-4 and paste wax cause drainage by narrow rivulets. The PVF covered laminate drains by rivulets and wide films. The balance of the materials drain by means of spreading wide films.

TABLE 9 CONTACT ANGLE MEASUREMENTS

Material	Contact Angle *
Fumed Silicone Dioxide on PVF covered Laminate **	140^{o}
Fumed Silicone Dioxide on Polycarbonate	110^{o}
AFC-HMOD-4**	70^{o}
AFC-HMOD-4	50^{o}
Paste Wax	30^{o}
Liquid Wax	25^{o}
PVF Covered Laminate	20^{o}
Plastic Polish	20^{o}
Silicone Fluid	$<10^{o}$
Uncoated Polycarbonate	$<10^{o}$

*11 1/2 Week Results

**8 Week Results

TABLE 10 DRAINAGE MECHANISM

Material	Drainage Mechanism *
Fumed Silicone Dioxide on PVF covered Laminate **	Individual Droplets
Fumed Silicone Dioxide on Polycarbonate	Individual Droplets
AFC-HMOD-4 **	Rivulets
AFC-HMOD-4	Rivulets
Paste Wax	Rivulets
PVF covered Laminate	Mixed Rivulets and Film
Liquid Wax	Film
Plastic Polish	Film
Silicon Fluid	Film
Uncoated	Film

* 11 1/2 Weeks Results

** 8 Weeks Results

6. CONCLUSIONS

The results of the environmental tests lead to the conclusion that soot and dirt collection on panel surfaces is the largest source of degraded repellency. The tests also illustrate that the dust and soot are cleaned from the panel surfaces thru the action of natural rainfall. Thus if one of the better coatings is used on polycarbonate the repellency can be expected to vary with meteorological conditions.

Of the coatings tested fumed silicone dioxide is in a class by itself. After 3 months it shows good adhesion to polycarbonate and the repellency it offers when applied to polycarbonate or PVF covered laminate is outstanding. When sprayed on a transparent surface it leaves a white film resulting in a frosted appearance. On radomes finished with a white film such as PVF, its presence is only noticed as a dulling of finishes that were glossy. This material will undoubtedly find wide use in coating radomes for high frequency applications.

In the case of the O'Hare ASDE-2 radome it is desirable to retain the transparent properties of the radome. The second best coating is AFC-HMOD-4. Two panels were coated with this material. The second panel on which more of the coating residue is allowed to remain appears as an extremely repellent surface. The AFC-HMOD-4 coating is the only material other than fumed silicone dioxide which permits significant improvement over uncoated polycarbonate after 11 1/2 weeks of environmental exposure. It consistently causes water to drain in rivulets and water films break up rapidly.

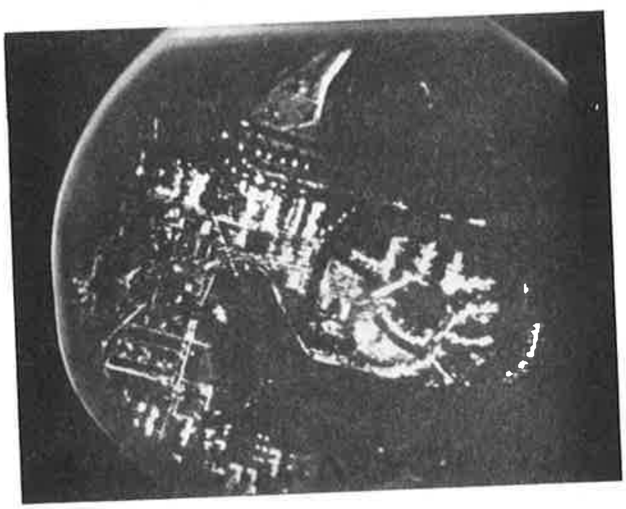
The AFC-HMOD-4 coating was recommended for use on the O'Hare ASDE-2 radome. The quantity of the material which is required for a single coating application is 2 gallons. The cost of the material is $120/gallon. From test data over the last three months it appears that the coating will probably have a useful service life of about one year.

The O'Hare ASDE-2 radome was coated with AFC-HMOD-4 as recommended. The radome was washed with a detergent solution which leaves no residue and rinsed with water. It was then washed down with isopropyl alcohol and rinsed with water again. Finally, the AFC-HMOD-4 coating was applied by cloth and permitted to dry for at least one hour before excess residue was removed. The entire coating process was carried out by the Midwest Field Maintenance Party and required an estimated 60 man-hours to complete. Since coating the radome, very substantial improvement in operation has been noted during periods of rainfall. Figure 22 presents an indication of operational performance in rain before and after the radome was coated. The pictures record the bright display presentation during comparable periods of moderate to heavy rainfall. In the case of the uncoated radome there is severe attenuation through the water layer. After the radome is coated, taxiways and runways with aircraft lined up for takeoff are clearly visible. These results clearly demonstrate that any radome intended for ASDE-2 use must have a water repellent finish.

It is reiterated that tests intended to measure the water repellency of a potential radome material have validity only after the material has been exposed to the environment for an adequate period of time. The time should be sufficient for all traces of the silicone mold releases used in fabrication to be eroded from the material. This will normally require several weeks of environmental exposure.

It is also noted that the PVF covered laminate shows only slightly better repellency characteristics than uncoated Lexan. If a laminated radome material employing a PVF weather barrier were used in ASDE-2, water film loss would most likely continue to be a problem. However coating the PVF with fumed silicone dioxide periodically would eliminate this water film attenuation problem completely if it is proven that it will not be degraded by winter ice and snow.

MODERATE RAINFALL
UNCOATED RADOME



MODERATE RAINFALL
COATED RADOME

Figure 22 ASDE-2 Bright Display During Moderate Rainfall before and after Coating Radome

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