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SEMI-ANNUAL REPORT

FACTORS AFFECTING THE STICKING OF INSECTS ON MODIFIED AIRCRAFT WINGS

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O. YI, R. CHAN, N. S. EISS, U. PINGALI AND J. P. WIGHTMAN

VIRGINIA POLYTECHNIC INSTITUTE
AND STATE UNIVERSITY

216 NORRIS HALL
BLACKSBURG, VIRGINIA 24061

Telephone: (703) 961-6824
TLX: EZLINK 9103331861
VPI-BKS
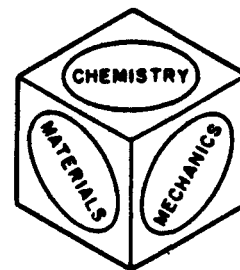
CHEMISTRY
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PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

from

Chemistry Department and Mechanical Engineering Department

Virginia Polytechnic Institute and State University

Blacksburg, VA 24061

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I. Introduction

Insects have been collected by road tests in past studies and a large experimental error was introduced during the road tests caused by a variable insect flux. The presence of such errors has been detected by studying the insect distribution across a half-cylinder mounted on the top of a car using aluminum strips only. After a nonuniform insect distribution (insect flux) was found from three road tests, a new arrangement of samples was developed. The feasibility of coating aircraft wing surfaces with polymers to reduce the number of insects sticking onto the surfaces was studied with fluorocarbon elastomers, styrene butadiene rubbers, and Teflon.

II. Background

Wetting is defined as the displacement from a surface of one fluid by another, and there are three recognized types, namely, spreading, adhesional and immersional wetting (1). Usually wetting means that the contact angle between a liquid and a solid surface is zero or close to zero such that the liquid easily spreads over the solid. Non-wetting means that the contact angle is greater than 90° so the liquid tends to ball up and run off the surface easily (2). Since only two types of wetting (spreading and adhesional) are relevant to the present study, these are discussed below.

In spreading wetting, a liquid which is already in contact with the solid surface spreads, so that the solid/liquid and liquid/gas interfacial areas are increased but the solid/gas interfacial area is decreased. The spreading coefficient (S) is defined (2) as

$$S = -\Delta G_s/A = \gamma_{sg} - (\gamma_{sl} + \gamma_{lg}) \qquad [1]$$

where ΔG_s is the free energy due to spreading, γ_{sg} is the surface energy of the solid in equilibrium with the liquid vapor, γ_{lg} is the liquid surface

tension, γ_{sl} is the solid/liquid interfacial tension and A is the wetting area. γ_{sg} is usually equal to γ_s which is the surface tension of the solid against its own vapor. If S is positive or zero, the liquid will spread spontaneously over the solid surface. If S is negative, the liquid will remain as a drop with a finite contact angle on the solid surface. Spreading of a particular liquid on a given solid mainly depends on the surface energy of the solid.

The equilibrium contact angle (θ) is determined by a minimum in the total surface free energy, that is, the quantity $[-\gamma_{sg}A_{sg} + \gamma_{sl}A_{sl} + \gamma_{lg}A_{lg}]$ is a minimum, where A is interfacial area. The change in the free energy of the system by spreading to cover an extra area as shown in Figure 1 (1) is given by

$$dG = \gamma_{sl}\ dA + \gamma_{lg}\ dA\ \cos\theta - \gamma_{sg}\ dA \qquad [2]$$

At equilibrium, dG = 0 so

$$\gamma_{sl} + \gamma_{lg}\ \cos\theta - \gamma_{sg} = 0 \qquad [3]$$

or

$$\cos\theta = (\gamma_{sg} - \gamma_{sl})/\gamma_{lg} \qquad [4]$$

For a given liquid, if the system is at equilibrium, the contact angle is a function only of $(\gamma_{sg}-\gamma_{sl})$, the surface energy of the solid and the interfacial surface energy.

Adhesional wetting occurs when a liquid which is not originally in contact with the solid surface contacts and adheres to the solid surface. In adhesional wetting, the liquid/gas interfacial area is decreased. The work of adhesion (W_a) is defined (1) as

$$W_a = -\Delta G_a/A = \gamma_{sg} + \gamma_{lg} + \gamma_{sl} \qquad [5]$$

or

$$W_a = \gamma_{lg} (1 + \cos\theta) \qquad [6]$$

If the contact angle is zero, the solid is completely wetted by the liquid, and only partially wetted if the contact angle is finite.

The wetting of a surface during the impact of insects can be explained by either type of wetting described above. However, in both types of wetting, the contact angle between the liquid and solid surface depends in part on the surface energy of the solid. Increase of the contact angle means that the liquid becomes more wettable over the solid surface and the contact area (solid/liquid interfacial area) is increased.

III. Experimental

1. Road Test with Old and New Samples

In past studies (3,4) road tests have been performed to collect insects. The polymer samples were glued on aluminum strips and mounted on either an aluminum or a PVC half cylinder. The half cylinder was then mounted on the top of a car and driven at high speed (approximately 58 ± 3 ml/hr) in a given area where a large number of insects were expected to be present. It was determined that a large experimental error could be introduced during the road test caused by a variable insect flux.

To detect the presence of such errors, road tests were performed on May 27, July 9, and July 20 of 1987 driving from Blacksburg, Virginia to Princeton, West Virginia and back. Twenty-six 1 x 9 in. aluminum strips were mounted on a 4 in. OD (outside diameter) half cylinder which was then mounted on the top of a car. The number of insects sticking on each strip was counted

visually and recorded. By comparing the number of insects sticking on each aluminum strip, the insect density distribution across the half-cylinder was obtained.

The results from the three road tests are given in Table I. Nonuniform insect distribution across the half cylinder resulted in each of the three tests as shown in Figures 2 and 3. The average deviation (in percent) for each strip from the average number of insects collected during each road test and all three road tests was calculated using equation [7] and the results and plotted in Figure 4.

$$PD = [N_i - N_{al}]/N_i \qquad [7]$$

where PD is the average deviation (in percent), N_i is the average number of insects and N_{al} is the number of insects on a given aluminum strip. The value of N_i in turn is given by the total number of insects on all aluminum strips divided by the number of aluminum strips. As shown in Figure 4(d), smaller deviations for most strips were obtained by combining all three cases, but a deviation of ± 20% is still too large to assume a uniform insect distribution across the half-cylinder in the road test.

Since all three road tests showed a nonuniform insect density (insect flux) distribution across the half-cylinder, a new arrangement of sample strips developed. In the previous studies (3,4) both sample and control (aluminum) strips were mounted in a random manner for each road test. For example, three strips each of aluminum, FCE (fluorocarbon elastomer), polyurethane, Viton[R], and neoprene were mounted on the half-cylinder in a random manner. However, this method can lead to possible experimental error since all three strips of any one type of sample could be mounted in a

position where the insect density may be low or high. The chance of mounting a sample at a high or low insect density position can be reduced by running a road test with only one type of sample with an equal number of aluminum controls.

Five FCE samples used in the previous studies (3,4) and four SBR (styrene butadiene rubber) samples received from U. S. Army - Fort Belvoir were investigated to study the relationship between an insects sticking on the and the modulus of elasticity. Thirteen 0.75 x 6 in. strips of each FCE were washed, dried, and adhesively bonded with cyanoacrylate to 1 x 9 in. aluminum strips. Six 0.75 x 6 in. strips of each SBR were adhesively bonded to 1 x 9 in. aluminum strips with cyanoacrylate and the surfaces were washed by wiping with "Kemkit" wetted with acetone.

The sample and control strips were mounted on the aluminum half cylinder as shown in Figure 5, and the road tests were performed listed in Table II driving from Blacksburg, Virginia to Glen Lyn, Virginia and back. The number of insects sticking on each strip was counted visually and summed. Instead of comparing the absolute number of insects, the normalized percent (NP) for each sample was calculated by equation [8].

$$NP = \frac{\text{total number of insects on sample strips}}{\text{total number of insects on aluminum strips}} \times 100 \quad [8]$$

Thus, the NP value for the aluminum is always 100%.

During the road test on September 8th, four extra strips - two aluminum strips and two sample strips of teflon tape mounted on spongy double-sided mounting tape (TTD) - were added. Two 0.75 x 6 in. strips of plumbing-quality teflon pipe thread tape (teflon tape) were attached on two 1 x 9 in. aluminum strips using 0.75 x 6 in. 3M Scotch double-sided mounting tape. Strips designated TT prepared by mounting 0.75 x 6 in. teflon pipe thread tape on the

aluminum strip with 0.75 x 6 in. non-spongy 3M Scotch double stick tape. Teflon tape was used as received without washing the surface.

After the small NP value for the TTD sample was calculated, additional road tests were performed with seven strips each of TTD and TT on September 5th, and thirteen strips each of TTD and TT on September 18th and 20th, respectively with same number of aluminum strips driving from Blacksburg to Glen Lyn. The main reason for preparing the teflon tape sample in two different ways was to study whether the small NP value for the TTD stripe tested on September 8 was due to the sponge-like mounting tape beneath the teflon tape or the teflon tape itself. The number of insects sticking on each strip was counted visually and summed, and the values of NP were calculated.

2. SEM Analysis and Contact Angle Measurements

SEM photomicrographs of the polymer samples and aluminum surfaces before impact of insects were taken to study the surface topography. Approximately 0.5 X 0.5 in. disks of FCE samples were washed with a solution of TIDE^R in deionized water, rinsed with deionized water at least ten times, and dried in a vacuum oven overnight at room temperature. SBR samples were wiped with "Kemkit" wetted with acetone and dried in the atmosphere for at least three hours before taking SEM photomicrographs. Teflon tape samples were analyzed as received without washing the surface. All sample disks were sputter coated with gold using an Edwards S150B sputter coater for 2 minutes at 45 mA. SEM photomicrographs of samples were taken using an ISI SX-40 scanning electron miccroscope at various magnifications.

The contact angles of 1 x 1 in. disks of washed FCE and SBR samples and unwashed teflon tape were measured with deionized water using an NRL contact angle goniometer. Two µl of water were placed on the sample surface and

contact angles measured at both sides. An additional 2 μl was added to the original drop and the advancing contact angle was measured. This procedure was repeated two more times so that the total volume of water on the sample surface was 8 μl. Contact angles of each sample were measured at a minimum of four different locations on the sample surface and the average contact angle was calculated.

3. Insect Impact Simulation Using "Air-Gun"

After the velocity of the particle exiting from the end of the "air-gun" was determined to be 60 mph at a pressure of 10 psig, further improvements on the "air-gun" were made to obtain a more uniform velocity distribution over the entire sample target. The improved "air-gun" consists of a PVC pipe (12' length; 3" diameter), a T-connector (3" diameter); and, a rectangular plexiglass duct (4' length; 4 x 8 in). Uniform air velocity distribution across the duct was observed using a small quantity of flour as described in the previous study (4).

In the present study, a sample holder (target) has been developed which will be placed inside the duct as shown in Figure 6. As shown in Figure 7, a 3.5 x 14 in. aluminum strip is bolted onto the sample. After compressed air was introduced to the "air-gun" by fully opening the valves, a small quantity of powdered dry-ice was placed in the feed chute (T-connector) to study the air profile inside the duct and across the aluminum mounted on the sample holder. The process was video taped.

For further simulation with the "air-gun", a preliminary study of insect distribution across the sample holder (target) was performed by introducing a large number - approximately 100 or 150 - of fruit flies (Drosophilia) into the "air-gun" where they were accelerated to a high velocity. The insect flux

equal to the number of insects on a given area of the aluminum sheet was determined.

IV. Results and Discussion

1. Surface Analysis

As shown in Table III the contact angles of water on the FCE and SBR surfaces are similar, so that the surface energy of these samples are expected to be very close to each other. It is noted that the contact angle of water on teflon tape is 121° so that the surface energy is expected to be lower than any of the other samples used. The main difference then between the five FCE or the four SBR samples, is the modulus of elasticity. Thus, any difference in the insect sticking between these two groups of samples could be due to the modulus of elasticity.

SEM photomicrographs of aluminum, the SBR and FCE samples and teflon tape are shown in Figure 8. SEM photomicrographs of FCE and SBR samples show fairly homogeneous and smooth surfaces with different sized holes. The surface of the aluminum is fairly rough and has different sized holes and cracks. The surface of the teflon tape is different from any of other sample surfaces. There are spots (or islands) which are smooth and homogeneous with no holes, and these spots are connected by ridges which are parallel to each others and form different sized gaps.

2. Road Test

The NP values for each FCE and SBR sample was calculated as described in the experimental section above and are listed with the modulus of elasticity of the polymer in Tables IV and V, respectively. There appears to be at best only a small difference in the value of NP between any of the FCE or SBR samples and the control (aluminum) is observed. Values of NP are plotted as a

function of modulus of elasticity for the FCE and SBR samples in Figures 9 and 10, respectively. These curves are different from the curve obtained from the previous study (14) in which the FCE samples showed a practically linear relationship with a positive slope between the total number of insects sticking on the FCE surface and the modulus of elasticity. It is not clear why the curves obtained from the previous study are different from the present study. Perhaps the former curves which were obtained from only five runs per sample have a larger experimental error than the thirteen runs of the present study. It is still questionable whether there is a correlation between the sticking of insects on the FCE and SBR surfaces and the modulus of elasticity of polymer samples. Perhaps the kinetic energy of the impacting insect is so high that the effect of elasticity for the high moduli materials used is negligible. Further studies using the "air-gun" at lower velocity of incoming insects might be able to give more definitive results of the elastic effect on the sticking of insects.

The NP value for TTD from the road test on September 8th is only 8% which is much lower than 100% of control. However, this result was obtained from running only two TTD strips, so the results from the September 9th, 19th, and 20th tests using the TTD and TT samples are considered more reliable. As shown in Table VI, <u>the NP value of both the TT and TTD samples is < 50% which is the greatest reduction observed in any test since the study began</u>. A possible reason for such a large reduction in the number of insects sticking on the TT and TTD samples is the smooth and low surface energy teflon tape surface which reduces sticking of the fluid from the impacted insect and the tape surface. The further small reduction in the NP values for the TTD sample may be due to the sponge-like mounting tape which provides good elasticity that it absorbs a large amount of the kinetic energy of the incoming insect.

Thus, the momentum of the impacting insect is rapidly reduced by the mounting tape, so that the bursting of the insect can be prevented.

The fact that insects were observed to stick on all surfaces used in the road test is prima facie evidence of molecular contact (adhesion) between the insect fluid and the surface. High velocity air has two affects on sticking, namely, increasing the rate of drying of the insect fluid leading to increased viscosity and forcing the insect fluid to spread over the surface. The reason for the observed change in the sticking of insects due to the surface energy (TT or TTD compared to FCE or SBR) can be explained as follows. Insects impacting on the sample surface at high velocity during the road test will burst open. The insect fluid can be wetting or nonwetting depending on the surface energy of the solid surface. Drops of insect liquid on the low energy surface (TT or TTD) will have less contact area due to less wettability, and will require a larger force to spread over the surface. Thus, drops of insect liquid on the lower surface energy solid tend to be ball up, and the chance of being blown off the surface by the incoming airflow is greater, so that the number of insects sticking onto the surface is decreased.

3. Air Gun

A small quantity of powdered dry ice was poured into the feed chute and blown across the length of the "air-gun". The paths of the powder stream passing through the rectangular pipe and across the sample holder (See Fig. 6) were observed. No evidence of the dry ice stream near the pipe walls was observed, and the undisturbed powder stream had a fairly uniform density of dry ice across the middle portion of the pipe. Thus the air flow inside of the circular pipe was assumed to have reached steady state with a uniform velocity distribution across the pipe. An additional incoming air flow between the circular and rectangular pipes did not appear to effect the air flow exiting from the circular pipe.

After a large number of fruit flies were accelerated to a high velocity in the "air-gun", they were impacted on to the target which was placed at the end of the duct. The insect flux across the sample target as measured by the number of stuck insects was uniform in the horizontal direction. This is a significant conclusion. It was demonstrated that a non-uniform flux was obtained during the road test leading possibly to invalid conclusions regarding the effects of surface energy and modulus of elasticity on the extent of insect sticking. An air-gun has been designed and tested giving a uniform insect flux which should lead to unambiguous conclusions of the effects of surface energy and in the elasticity on insect sticking.

V. Summary

No significant reduction in the sticking of insects on either the FCE or the SBR surfaces was observed. No correlation was observed between the NP values for either the FCE or the SBR samples and the modulus of elasticity of these samples. The large reduction of insect sticking on the Teflon surface was obtained whether the tape was supported by a sponge-like mounting tape or by double stick tape. In both cases, the NP value was < 50%. This reduction is assumed to be due to the low surface energy of Teflon.

A uniform air profile inside the duct was observed even after the sample holder (target) was placed in the "air-gun". A uniform insect distribution across the sample target in the horizontal direction was observed.

VI. Future Work

The following recommendations for future work are listed:
1. Study the relationship between sticking of insects on both the FCE and SBR surfaces and the modulus of elasticity using the "air-gun".

2. Study the sticking of insects on the teflon tape using the "air-gun" and live fruit flies.

3. Obtain the insect velocity exiting from the end of the "air-gun".

4. Obtain a better understanding of the sticking mechanism by investigating other types of polymers and filming using a high-speed camera.

References

1. Shaw, D. J., **Introduction to Colloid and Surface Chemistry**, Butterworths & Co. (Publishers) Ltd. 1985.

2. Adamson, A. W., **Physical Chemistry of Surfaces**, John Wiley & Sons, Inc., 1982.

3. Yi, O., Chitsaz-z, M. R.; Eiss, N. S. and Wightman, J. P., "Factors Affecting the Sticking of Insects on Modified Aircraft Wings", NASA-LaRC. Semi-Annual Report, February, 1987.

4. Yi, O.; Chitsaz-z, M. R.; Eiss, N. S. and Wightman, J. P., "Factors Affecting the Sticking of Insects on Modified Aircraft Wings", NASA-LaRC, Annual Report, August, 1987.

TABLE I. INSECT DISTRIBUTION ACROSS THE HALF-CYLINDER
USING ALUMINUM STRIPS

Position of Aluminum Strips from Left Edge of the Half Cylinder	Number of Insects			
	May 28	July 4	July 20	Total
1	6	17	51	74
2	9	25	49	83
3	5	12	45	62
4	3	9	64	76
5	5	17	42	64
6	2	29	46	77
7	6	21	46	73
8	3	19	35	57
9	4	23	43	70
10	3	23	38	64
11	7	23	39	69
12	6	17	56	79
13	8	28	47	83
14	6	18	50	74
15	6	18	55	79
16	6	14	50	70
17	10	13	45	68
18	7	27	42	77
19	8	22	46	78
20	7	18	44	69
21	6	15	43	64
22	4	17	43	64
23	4	25	38	67
24	4	19	43	88
25	4	15	52	71
26	3	12	44	59

TABLE II. DATES AND TIMES WHEN ROAD TESTS WERE PERFORMED

Sample	Date (1987)	Time
FCE-A	August 6	19:45 - 21:30
FCE-B	August 9	20:00 - 21:45
FCE-C	August 10	20:10 - 21:40
FCE-D	August 11	19:30 - 21:32
FCE-E	September 2	19:17 - 20:48
SBR - 3C	September 3	19:37 - 21:15
SBR - 7C	September 3	19:37 - 21:15
SBR - 26	September 8	19:33 - 21:00
SBR - 17B	September 8	19:33 - 21:00

TABLE III. CONTACT ANGLE OF WATER ON THE SAMPLE SURFACE

Sample	Contact Angle (°)
FCE-A	93.2 ± 1.9
FCE-B	93.0 ± 3.0
FCE-C	98.7 ± 1.8
FCE-D	98.5 ± 2.2
FCE-E	99.4 ± 2.4
SBR-17B	94.6 ± 2.0
SBR-7C	95.1 ± 1.8
SBR-26	95.5 ± 2.0
SBR-3C	99.6 ± 2.6
Teflon Tape	121. ± 1.

TABLE IV. MODULUS OF ELASTICITY (ME) AND NORMALIZED PERCENTAGE (NP)

OF FLUOROCARBON ELASTOMERS (FCE)

Sample	ME (psi)	NP(%)
FCE - A	193	87
FCE - B	408	91
FCE - C	141	94
FCE - D	197	99
FCE - E	421	99

Note: Moduli of elasticity (ME) given above are at 200% elongation and were
provided by Personnel at 3M.

Normalized percentage (NP) is calculated by

$$NP = \frac{\text{total number of insects on sample}}{\text{total number of insects on aluminum}} \times 100$$

TABLE V. MODULUS OF ELASTICITY (ME) AND NORMALIZED PERCENTAGE (NP)

OF STYRENE BUTADIENE RUBBER (SBR)

Sample	ME (psi)	NP(%)
SBR - 3C	693	97
SBR - 7C	931	91
SBR - 26	734	79
SBR - 17B	709	82

Note: Moduli of elasticity given above are at 200% elongation and were
provided by personnel at Fort Belvoir, VA.

Normalized percentage (NP) is calculated by

$$NP = \frac{\text{total number of insects on sample}}{\text{total number of insects on aluminum}} \times 100$$

TABLE VI. NORMALIZED PERCENTAGE (NP) OF TTD AND TT

Sample	NP(%)	
TTD	38(a)	26(b)
TT	45(a)	31(c)

a. Road test performed on September 9, 1987 with 7 strips each of TTD and TT and 14 strips of aluminum.

b. Road test performed on September 18, 1987 with 13 strips each of TTD and aluminum.

c. Road test performed on September 20, 1987 with 13 strips each of TT and aluminum.

Note: TTD is teflon pipethead tape supported by sponge-like mounting tape, and TT is teflon pipethread tape supported by double stick tape.
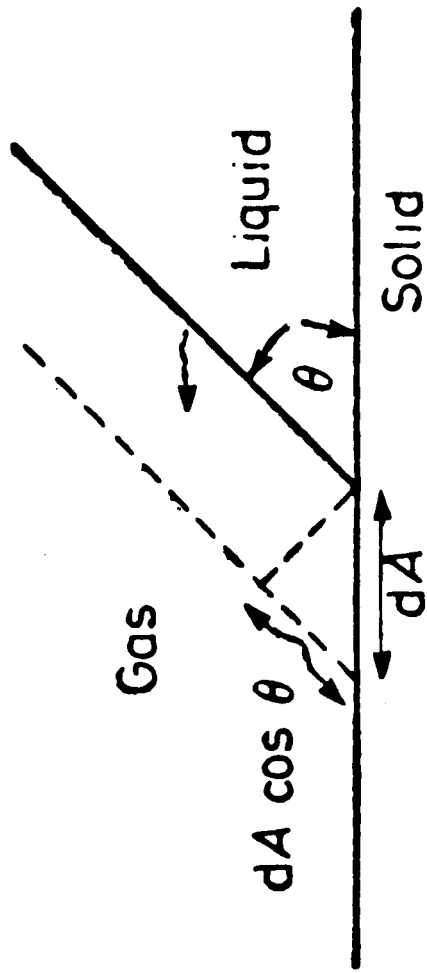
Figure 1. Illustration of spreading wetting at equilibrium
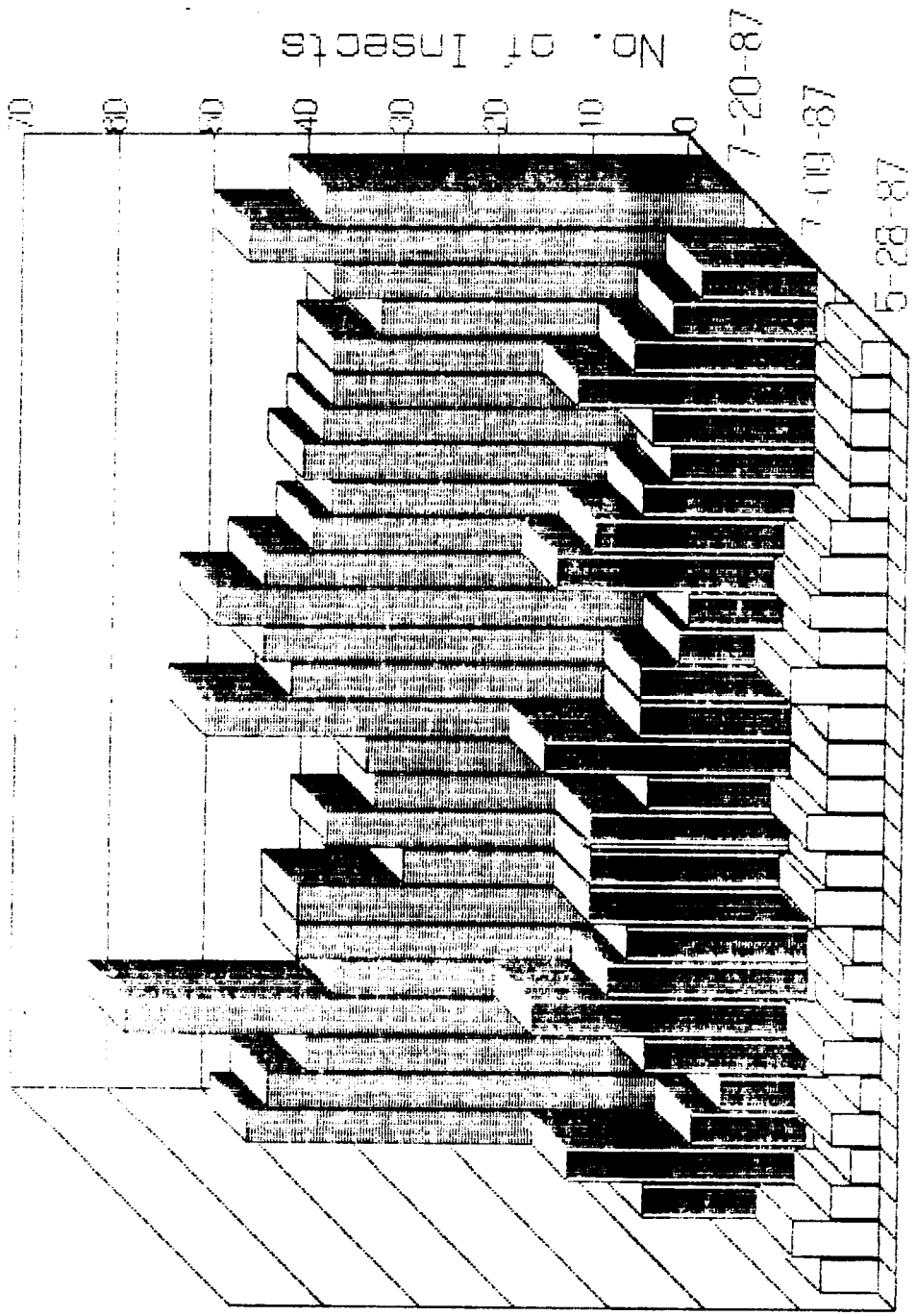
Figure 2. Study of insect distributions across the Semi-Cylinder using aluminum strips on three different days.
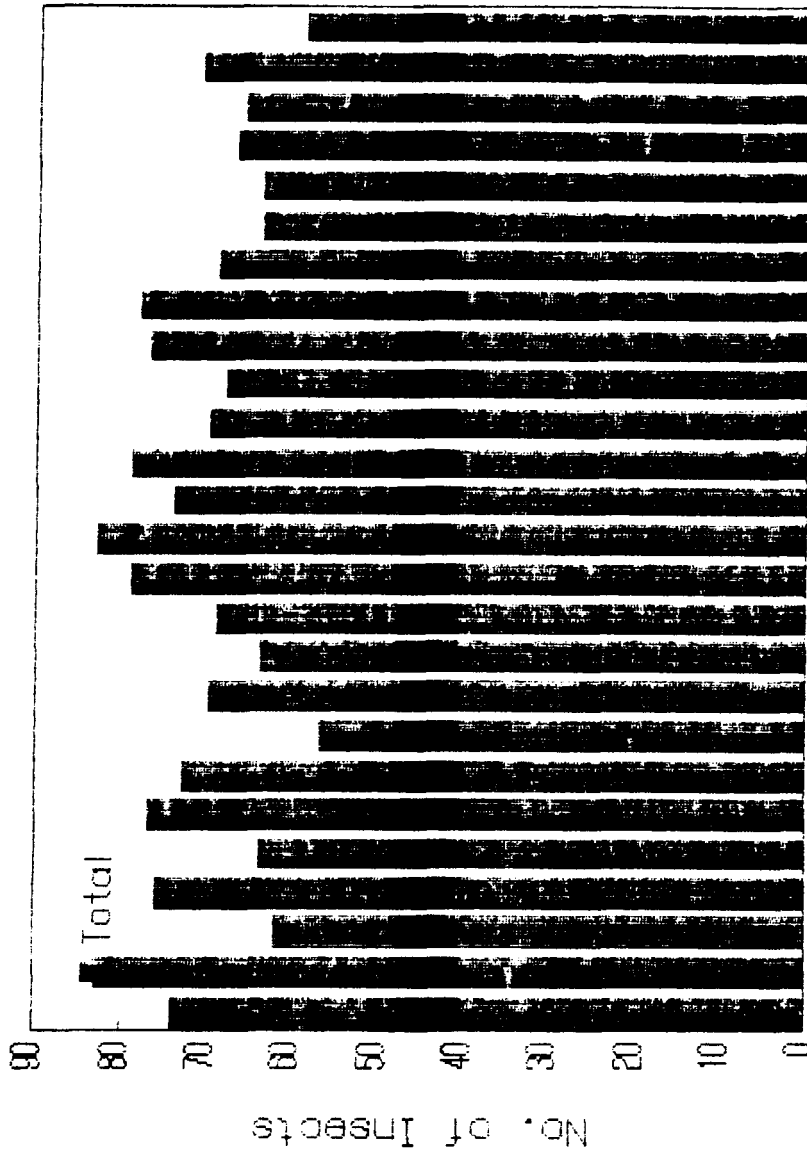
Figure 3. Insect distributions across the semi-cylinder (sum of results from three road tests).
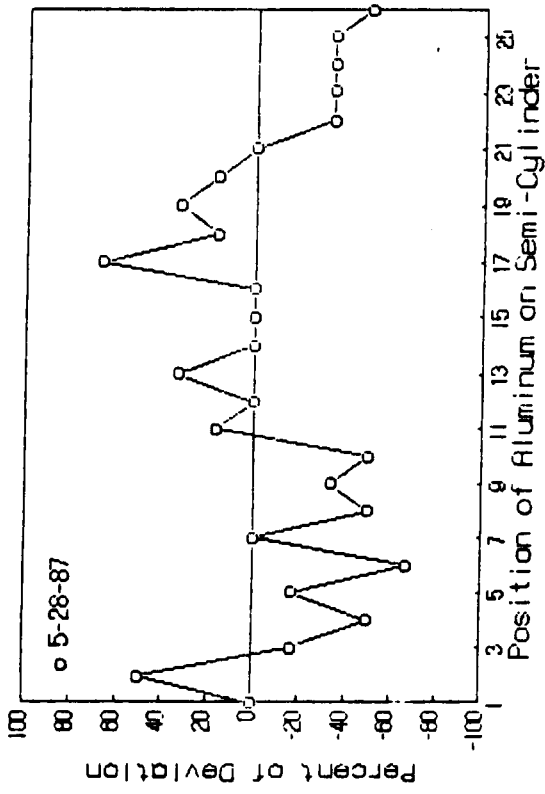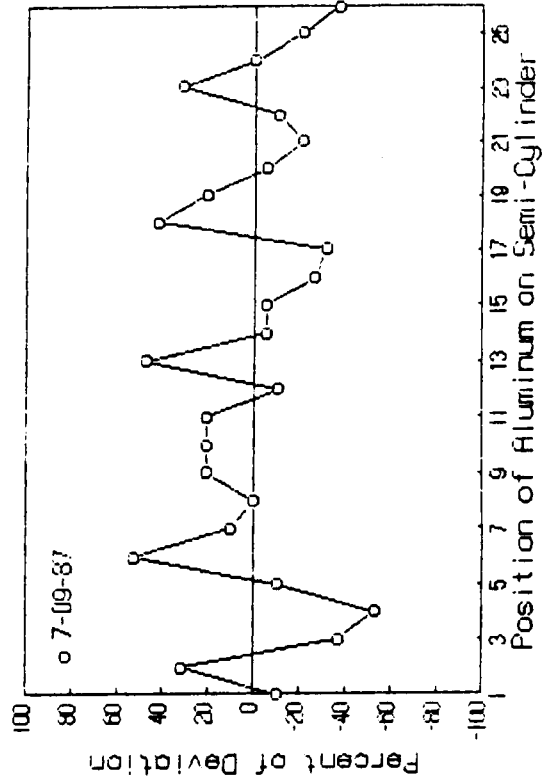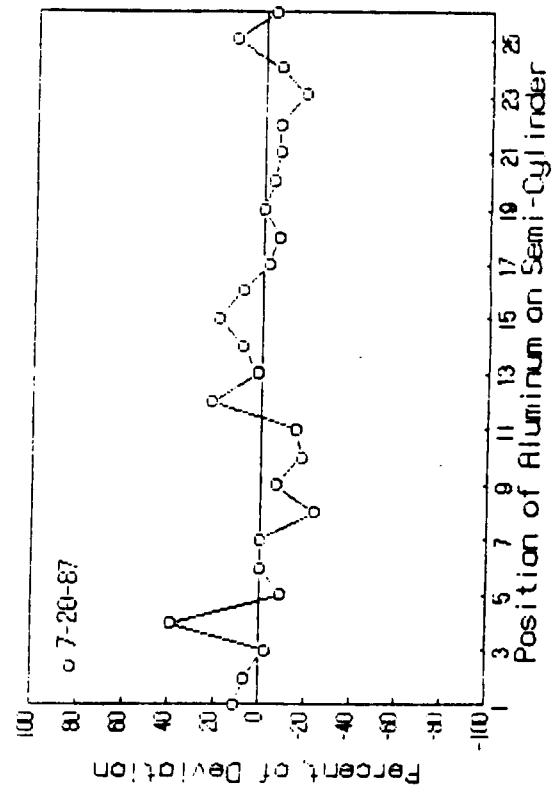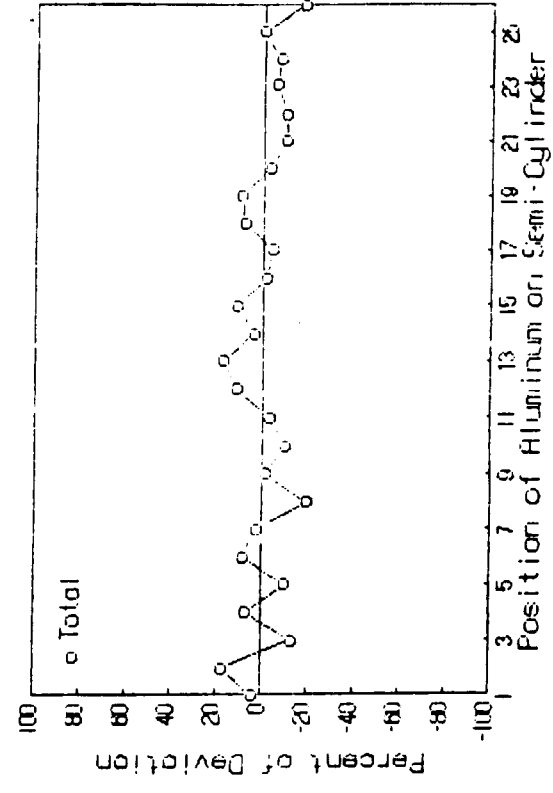
Figure 4. Deviation from the average number of insects sticking on each aluminum strip.

aluminum strip
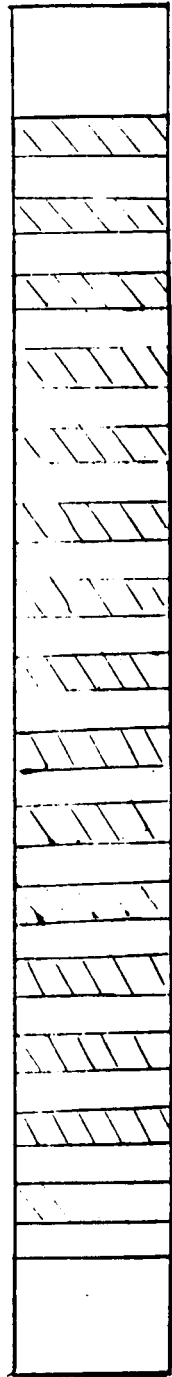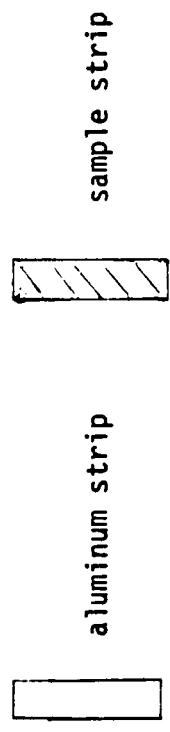
sample strip

Figure 5. A new arrangement of aluminum and sample strips across the half-cylinder.
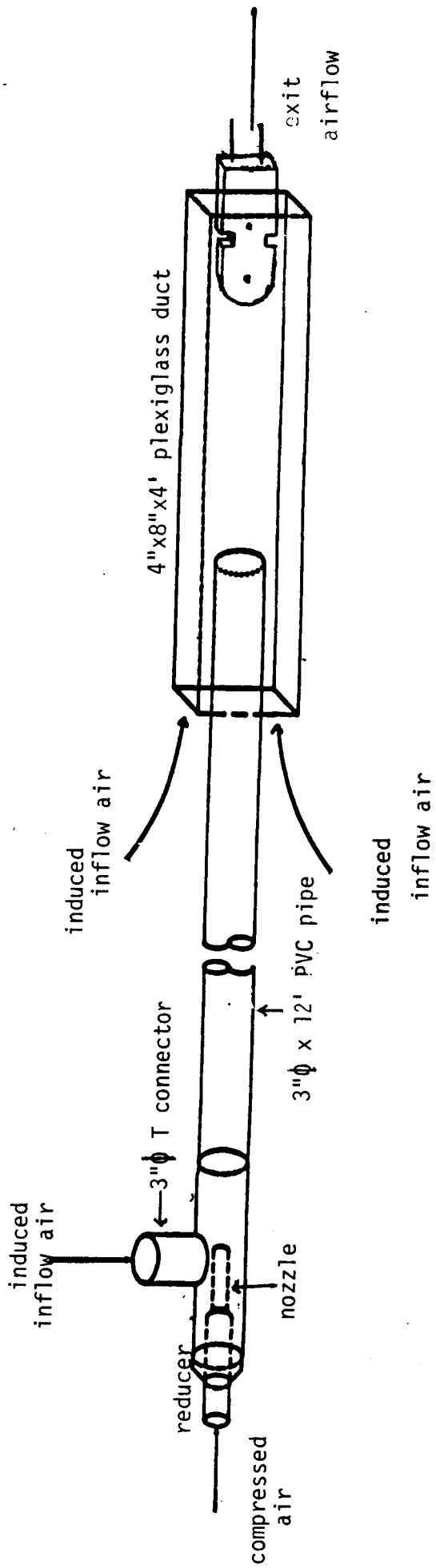
Figure 6. Schematic diagram of the improved "air-gun" with the sample holder (target).

quarter-inch holes
for support in air-gun
by threaded rods

θ

wood body

aluminum sheet held
by bolts in channel

aluminum sheet
(sample mount)

sample

aluminum
control

θ
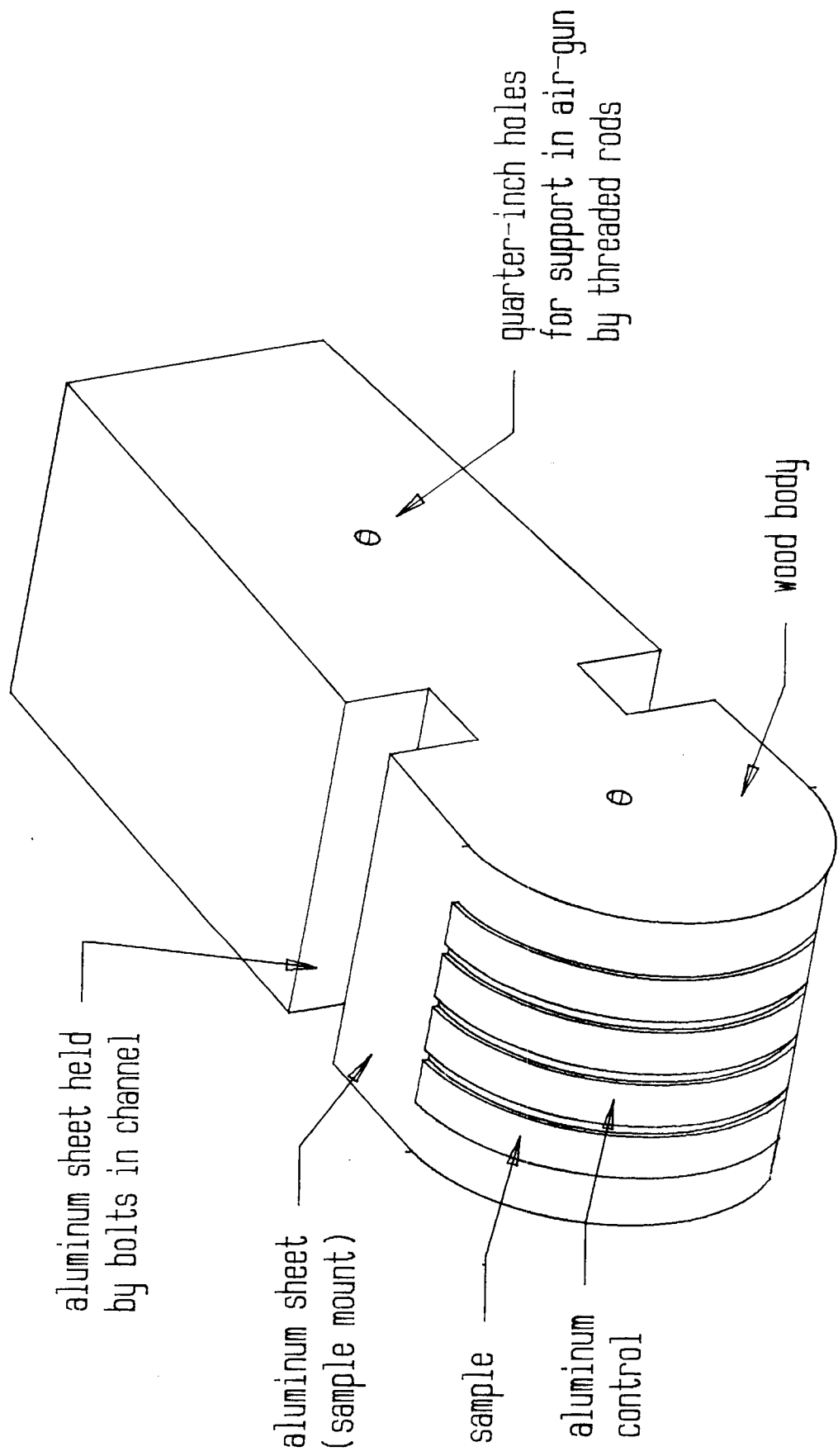
Figure 7. Sample holder (target) used to mount sample and aluminum control in "air-gun".
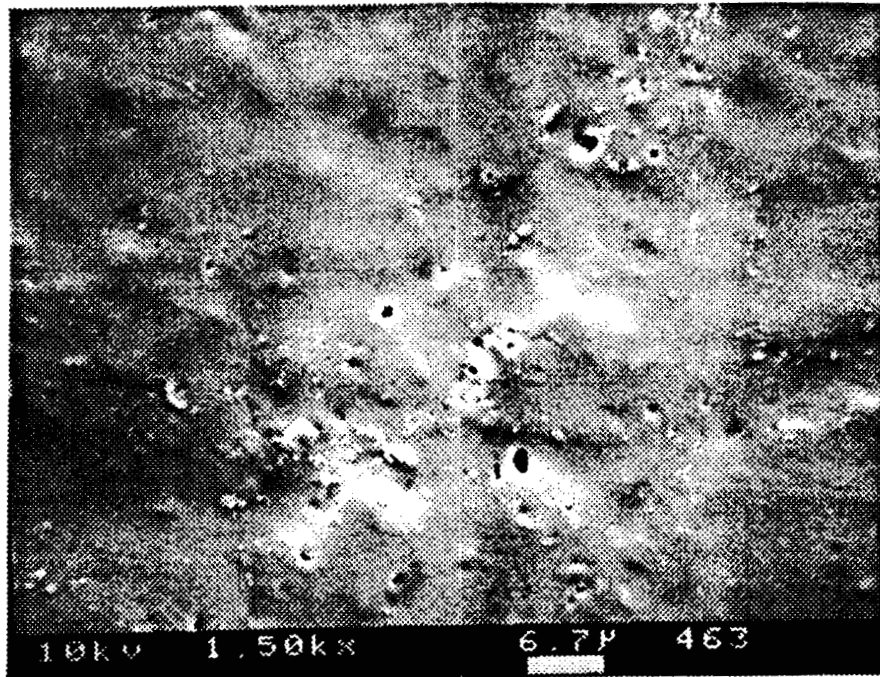
a) FCE-A
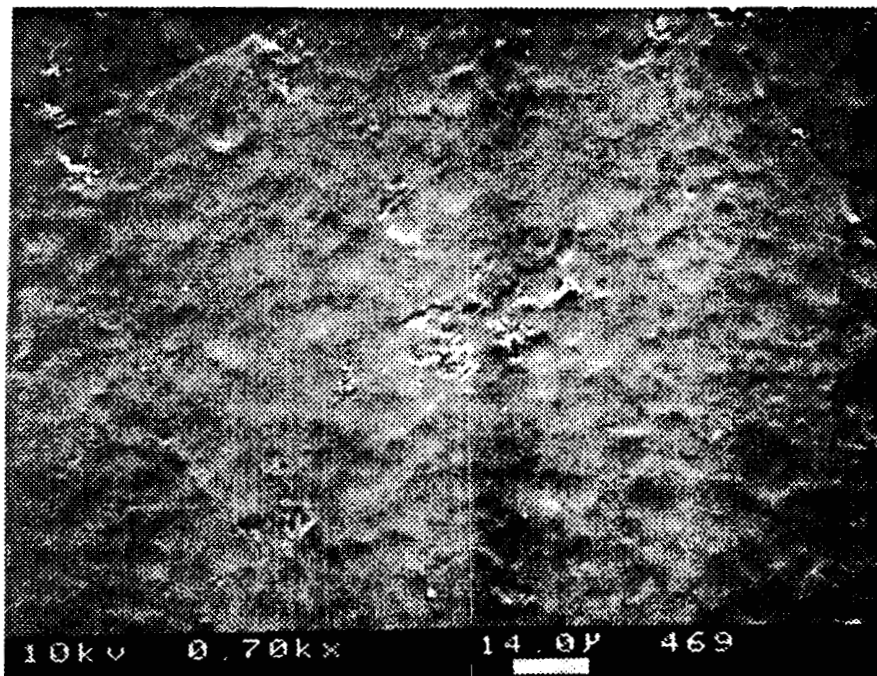
b) FCE-B

Figure 8. SEM photomicrographs of samples from road tests.
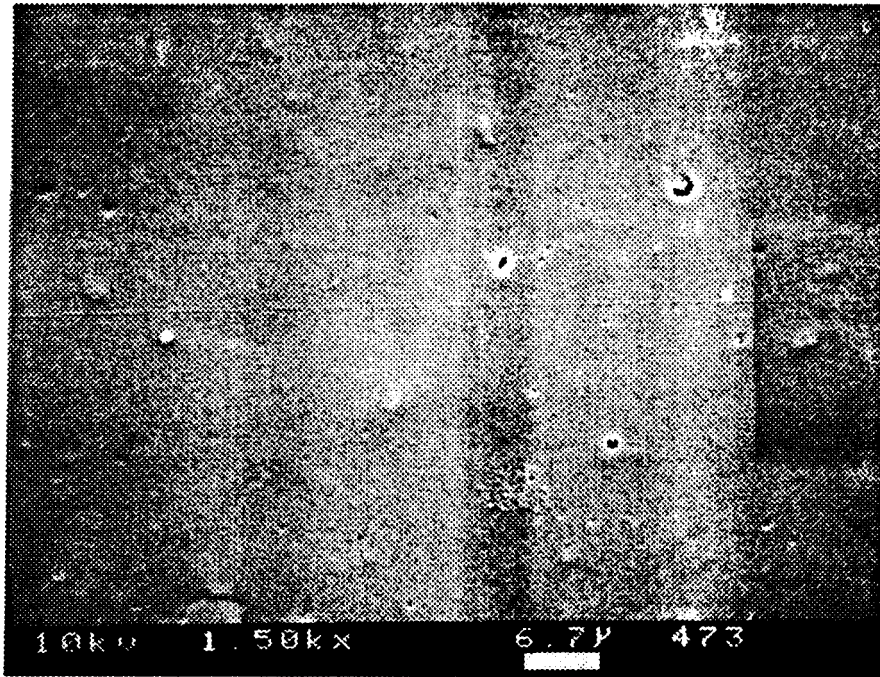
c) FCE-C
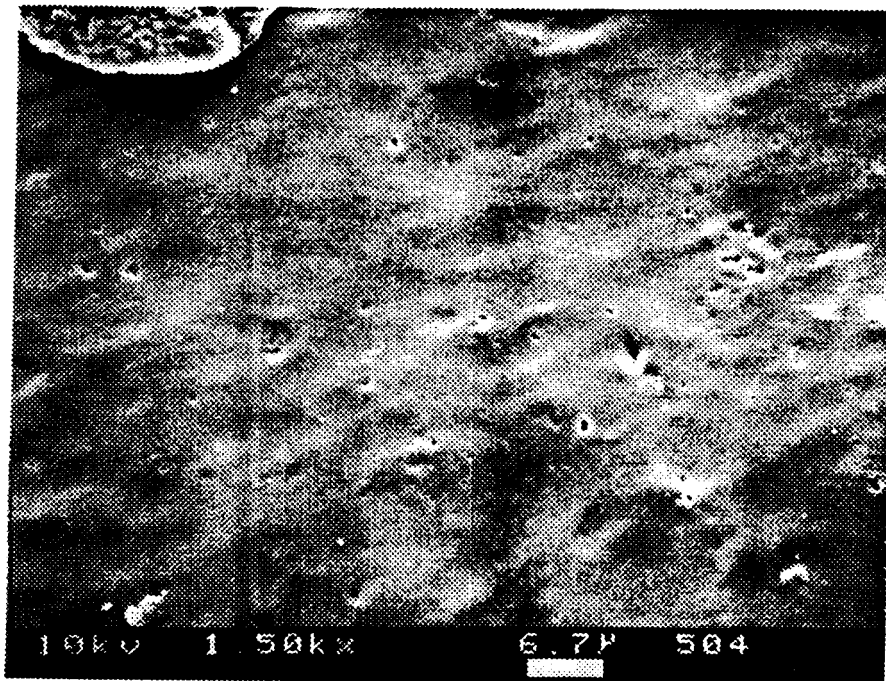
d) FCE-D
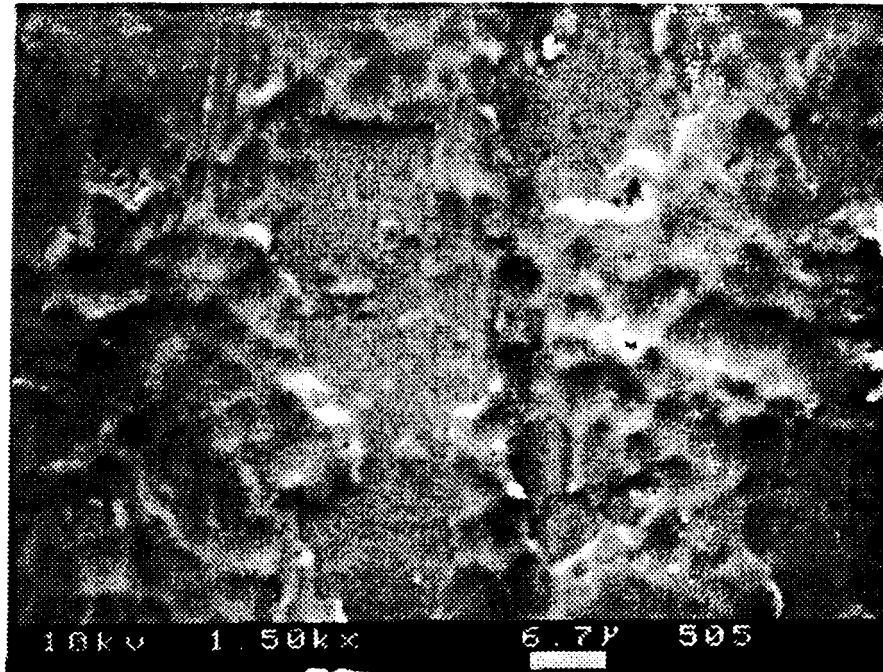
Figure 8.   Continued

e) FCE-E
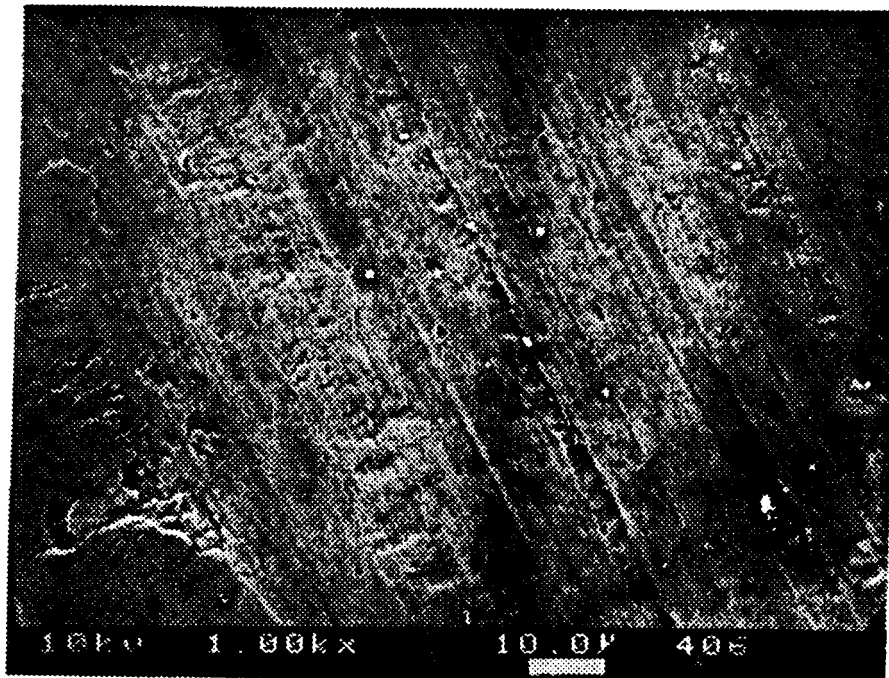
f) Aluminum

Figure 8. Continued
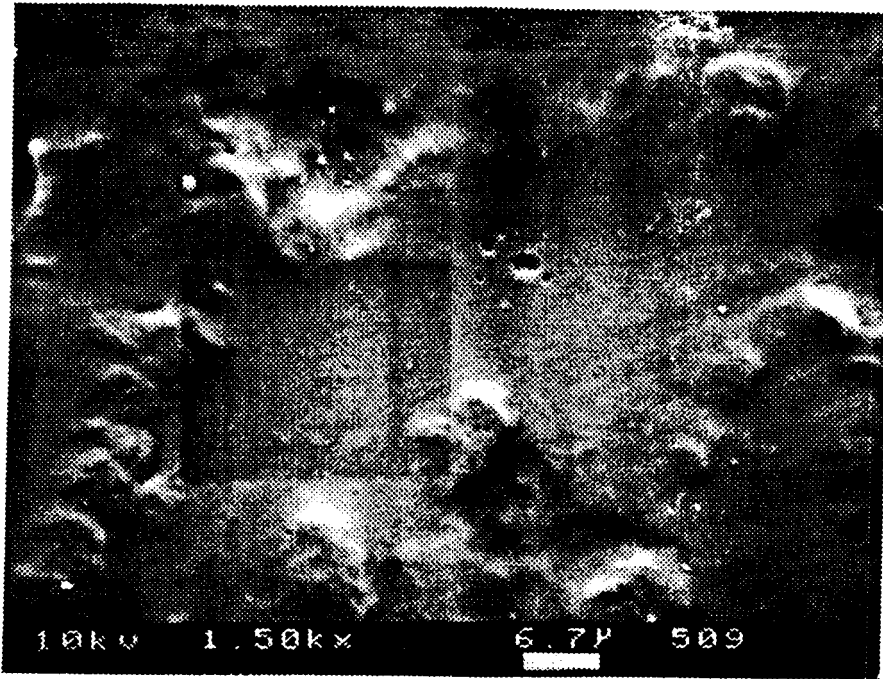
g) SBR-3C
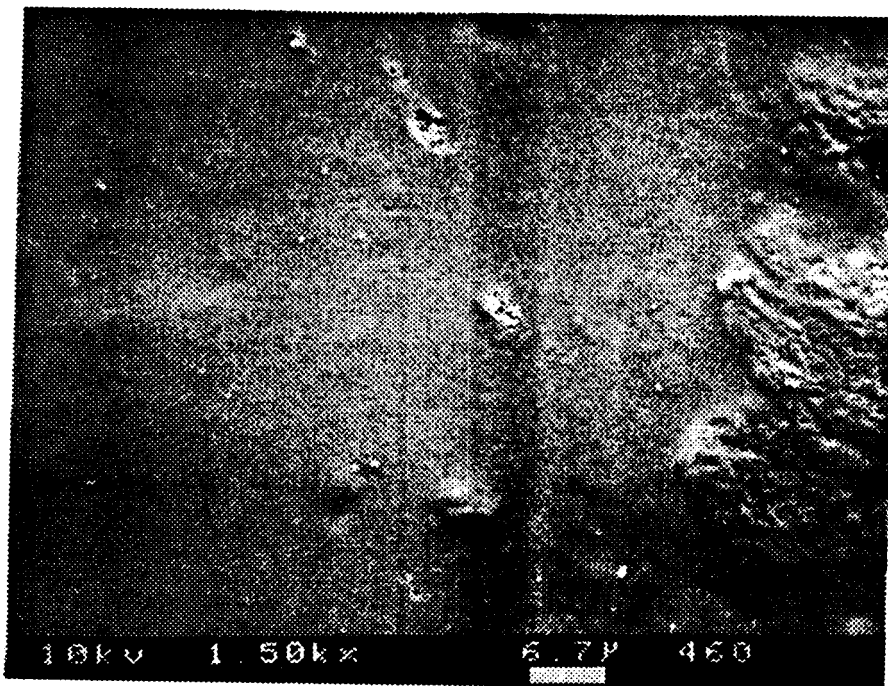
h) SBR-7C

Figure 8. Continued

i) SBR-26
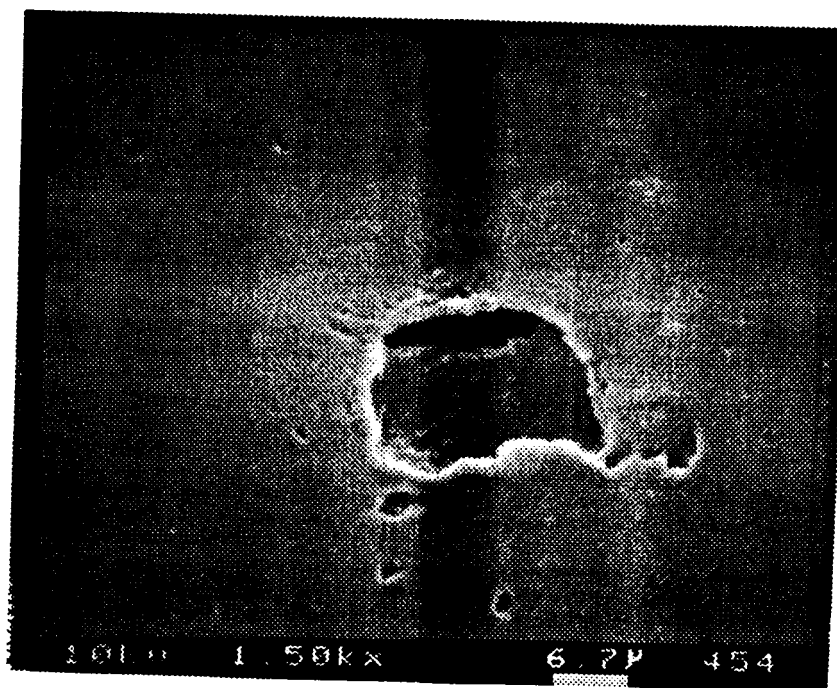
j) SBR-17B

Figure 8. Continued
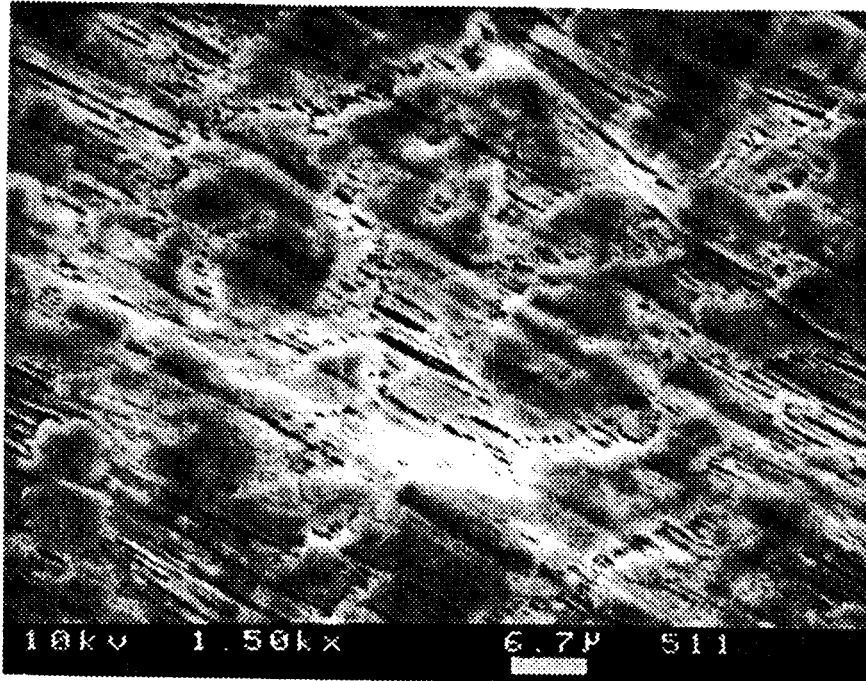
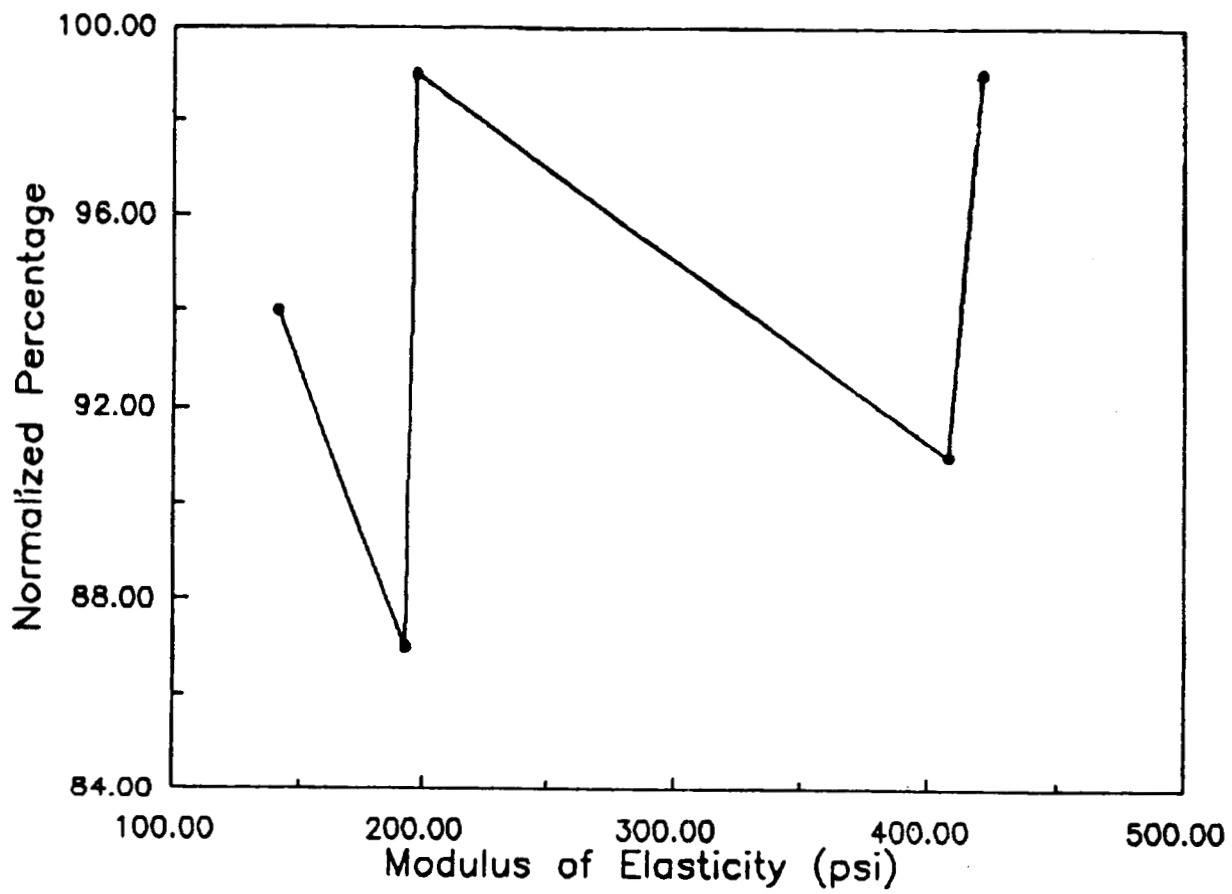h) Teflon tape

Figure 8. Continued

Figure 9. Normalized percentage of insects sticking on the FCE samples as a function of modulus of elasticity.
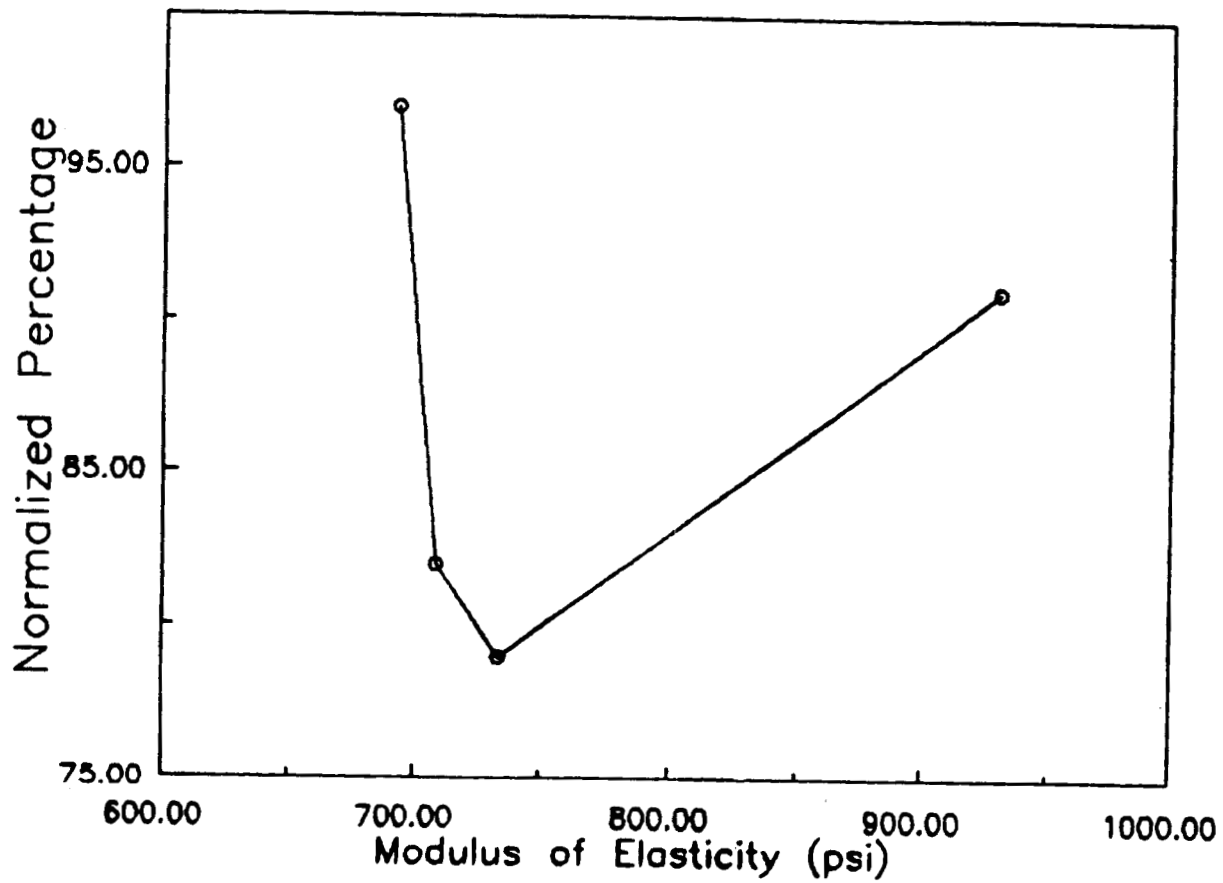
Figure 10.   Normalized percentage of insects sticking on the SBR samples
             as a function of modulus of elasticity.