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CONFORMAL COATINGS FOR PRINTED WIRING BOARDS

by

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ABSTRACT

Conformal coatings have been used for years for moisture and corrosion protection, insulation, and ruggedization on printed circuit boards and terminal blocks. The materials that have been used range from epoxies, silicones and polyesters to polyurethanes. The conformal coating requirements of NASA's Kennedy Space Center, located on central Florida's east coast, are somewhat unique due to exposure to a wide variety of severe environments.

Although corrosion prevention and moisture intrusion are the critical requirements, the materials and components must also withstand the shock and vibrations associated with the Saturn V launches. This has led to the development of testing procedures for printed wiring boards, components, and coatings as complete systems instead of the usual separate item approach.

The present qualification program at KSC includes tests for resonance change after coating, insulation resistance, compatibility, fungus resistance, thermal shock, ruggedization, flourescence and flame resistance. The reasoning behind the selection of the particular test methods, the differences from the MIL SPEC and descriptions of the methods themselves are presented.

I INTRODUCTION

The need for conformal coatings for electrical components has existed since Thomas Edison worked with Eastman and others on films and coatings shortly after the development of the light bulb. Strangely enough, much of this work took place directly across the Florida peninsula from Kennedy Space Center at Fort Myers.

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Since that time engineers have used various substances for coating and protecting their circuits - for moisture proofing and corrosion protection, for insulation and short prevention, and for protection from handling and vibration.

Development of the Kennedy Space Center (KSC) thin-film conformal coatings[1] is only another step in the evoluation of such substances. In his early film developments, Edison worked with phenolics - one of the finest coatings ever developed. It remains today, one of the most widely used of all electrical insulating materials.

Many other plastics have been and are being used as electrical insulation coatings: polyesters, epoxies, silicones, and polyurethanes to name only a few. Each has its own particular strong points - and weaknesses.

During the early 1960's printed circuit boards were either coated with various epoxy coatings or left uncoated. Often the designer in considering the maintainability of the boards chose to use bare boards rather than chip away the epoxy to change components. During this time the polyurethanes, a discovery of wartime Germany, were being introduced into the United States and were first used as foams and potting compounds.

II MSFC BEGINS USE OF POLYURETHANE POTTING COMPOUNDS

About this time NASA's Marshall Space Flight Center (MSFC) began using polyurethanes for potting and cable molding. These potting materials were also applied to printed circuit boards since tests showed their physical characteristics - for potting - seemed good.

Since little was known about handling these new compounds, Marshall's Astrionics Laboratory, ESE Section, set up a training course right in their lab where the materials were qualified. They taught contractor and NASA technical personnel the peculiarities of the materials and how to mix, aerate, pot, mold and conformal coat.

III PROBLEMS WITH THE THICK COATINGS

About 1964 we began to realize that some of these materials had a tendency to crack even though carefully handled. We also realized that these thick potting materials, 20 - 25 mils thick, applied to circuit boards seemed to be shrinking or in some manner stressing the boards and components. This action, after some cycling of the equipment, cracked components and weak solder joints, especially Kovar lead joints, causing intermittent shorts which were difficult to locate. Also, difficulty was experienced with repair through the thick coating. Many engineers refused to allow these coatings to be used because of the great change in electrical characteristics after coating.

Aerospace contractors and equipment suppliers, too, had complaints about the coatings. Handling characteristics were poor. The coatings often had to be heated and dissolved before they could be mixed. After mixing, it was necessary to put them under a vacuum to remove entrapped air and other gases. This was a messy, expensive process which wasted expensive material and reduced the application life to less than an hour. In addition, boards entirely coated with these thick materials would not slide into standard slots. In order to eliminate this problem the edges of the boards had to be masked with tape. By timing these operations, we found that the time for masking and removing the tape was greater than the time required to apply the coating. Furthermore, the tape, when removed, often lifted or tore the edge of the coating. Since moisture penetration is greatest through the cut edges of the board, masking left bare the most vulnerable moisture paths.

Mixing usually took place after the masking since the coating had to be applied as soon as possible. This was further complicated because some of the materials often crystallized in the cans, had to be heated, melted and cooled to room temperature before mixing. Since the coatings were the consistency of thick syrup, more problems were encountered in thoroughly mixing the two components so that homogeneous polymerization could take place. Usually the material was poured into a second mixing container for final mixing to assure no unpolymerized resin was left on the sides of the container. After mixing for about twenty minutes, the mix was deaerated with vacuum pump and bell jar for ten to twenty minutes to remove entrapped air and other gases.

Application life of approximately two hours had been effectively reduced by these operations to approximately an hour with the loss of considerable material. Application was by brush, dip or spray but the only spray unit available cost $5,000 (now $8,000). This made spraying prohibitive except for the large manufacturer who could write off such an expenditure on a large contract. Often while brushing we have witnessed the material suddenly getting stiff or "gelling" half-way through a board application. Usually the board had to be scrapped. It was the usual practice to go over each board with a hot air gun, before the coating gelled, to level out bubbles and cover voids. Careful handling was required since the hot air could easily damage board or components. Often each side of the board had to be coated and pre-cured separately.

Cure time for these thick materials is 16 hours in an oven or 7 days at room temperature. Since most plastics electrostatically attract dust, this curing time required extensive "clean" areas or ovens to avoid foreign matter contamination during cure.

Many small electronic concerns contribute greatly to the NASA space programs in designing and manufacturing various components or systems. Most of the firms cannot afford the extensive facility investment of vacuum equipment, ovens and clean work areas required by these thick coatings. It not only penalizes the small manufacturer but is expensive to NASA and the taxpayer.

IV DEVELOPMENT OF THE KSC THIN-FILM COATING CONCEPT

In July 1965, two of us from KSC met with two engineers from MSFC and derived a different philosophy from that previously used. This approach was to design a material to do the job needed of conformal coatings rather than select a known potting material and try to adapt it to the printed circuit boards.

Our design requirements were for a material which would:

1. not appreciably increase the Q-factor of the board.

2. be tough and yet elastic.

3. provide sufficient moisture protection to maintain the insulation resistance and prohibit disruptive discharge.

4. not corrode the circuitry and components of the board.

5. be easy to apply with the minimum of equipment.

6. allow one mix to be used for a shift (4 to 6 hours).

7. cure quickly without need for extensive oven space

8. be thin enough to eliminate nearly all masking and allow the sealing of all board edges.

9. be fungus resistant.

10. be easily repaired.

11. be economical.

12. not shrink and crack components.

13. be transparent.

More than 30 available materials were screened by Bill Fussell and Raymond Flack at MSFC's ESE Lab. Of these, 11 materials were selected for preliminary testing. Three thin materials showed the most promising characteristics and were tested completely. Two of the 3 most used thick coating materials were also tested for comparison purposes. The report, "Evaluation and Comparative Analysis of Conformal Coating Materials," ESE-E-55[2], was published at MSFC in October 1966. We had already released KSC-QPL-183-1[3] in July 1966 at KSC listing the three materials which had met the requirements. The material specification, developed jointly by KSC and MSFC, written formerly as KSC-C-183 in August 1966, was later released as KSC-SPEC-Q-0001[4] in October under a revised numbering system. The procedure for applying the material, KSC-SPEC-E-0001[5], followed in November.

Added to the original requirements was one for a fluorescent dye or pigment which would not inhibit the transparency but would allow for simple and easy ultraviolet inspection for voids and defects. Accurate repetitive inspections of boards under normal light is almost impossible because of the transparency of some of the coatings. This fluorescent feature was picked up by the Army in Mil-I-46058[6].

Most difficult of the tests was that of "Q" or "storage factor" of charged components. The "Q-factor" is a ratio of reactance to the resistance of the electrical component or device, where reactance is the effect of capacitance or inductance and frequency combined.

During the latter part of this work we became aware of extensive research performed by Anthony J. Beccasio[7] of Motorola/Minneapolis for Anthony Orlowski of the U. S. Army Electronics Command, Fort Monmouth in preparation for publication of Mil-I-46058. In this work it was demonstrated that electrical equipment, subject to environmental stresses which would cause it to fail if uncoated, would operate satisfactorily when coated. This research proved, also, that the Q-factor changed very little with coatings up to 3 mils, but that as the coating thickness increased above 3 mils, the Q-factor increased at a rapid rate.

It was this change in Q-factor which had caused many engineers at KSC to reject the use of the thick coatings on printed circuit boards and led us to try thin coatings.

The electrical properties of the thick materials themselves are generally good but in conjunction with the boards, they are much less satisfactory - sometimes disastrous. This may be partially attributed to the thermal insulative characteristics of these materials in thick sections. They prevent the necessary dissipation of heat generated in electronic circuits. This may manifest itself in degradation of the coating which can result in the destruction of the board and components.

This is one of the many reasons we have stressed the testing and application of the conformal coating and printed circuit assembly as a packaged system instead of the testing of the coating as a material alone. Often the combined characteristics of the system are quite different from the sum of the characteristics of each separately.

Thin conformal coatings formulated especially for the purpose - as these were - are designed to be applied only a few mils thick. They cannot normally be cast in such shapes as to be readily tested like potting materials. We feel the only reasonable means of testing these materials is as coatings on printed circuit boards - not as unsupported film, although we have done some testing of the film alone.

Most of our characteristics are, therefore, based on this premise, that thin film and board act as a unit, and the specification and its tests use this concept.

During flammability tests[8] it was found that the generally used G-10 epoxy-glass type board material, when tested uncoated, was itself quite flammable. On the other hand, we found that fire retardant NEMA grade FR-4 board material (Mil-P-13949-GF) was the same price but had better cold-punching qualities. We therefore made FR-4 the standard board material to be used at KSC as well as making it the test board material.

V KSC RETESTS COATING MATERIALS AND REVISES SPECIFICATION

Since the original tests on our coatings were run in 1965 and 1966, and since many good coatings are continually being developed, we decided that requalification tests[9] should be performed and the specifications reviewed for adequacy. KSC's Materials Analysis Branch was requested to perform these tests in November 1967.

All samples submitted to us at the time were tested. These included the 2 thick coatings (which we do not recommend for the purpose): Hysol's PC-12 and Products Research Corporation 1538; the 3 previously qualified thin coatings, Magna's Laminar X-500-7C23WF, Epoxylite's 9653-3 and Coast Pro-Seal's 773; and 3 new one-component coatings, PRC's 1568, Furane's 8267-31 and Hysol's PC 18-04. (The Furane material can also be bought in aerosol cans.)

KSC-SPEC-Q-0001 (known as the "Q" spec) establishes the KSC requirements for conformal coatings suitable for application to printed circuit boards by dipping, brushing, or spraying. Its purpose is to assure satisfactory performance of assemblies over a frequency range of 50 to 200 megahertz and operation under high humidity conditions. The coatings are grouped by viscosity into three classes:

Class 1 - 10 to 99 centipoises
Class 2 - 100 to 249 centipoises
Class 3 - 250 to 500 centipoises

KSC-SPEC-Q-0001A (not yet released) differs from the original specification mainly in that it - like to Mil Spec - puts the responsibility for qualification testing upon the resin formulator or manufacturer. The basic requirements of both specifications are as follows:

1. Not highly toxic initially or after cure.

2. Minimum 35% nonvolatile content by weight.

3. Maximum difference in Q between coated and uncoated specimens from 50 to 200 megahertz under standard or hot-humid conditions is not to exceed 5 to 20 or 10 to 25, respectively.

4. Insulation resistance shall be a minimum of 1×10^{12} ohms at standard conditions and 1×10^{11} ohms after salt fog.

5. Boards will have no disruptive discharge, sparkover, or breakdown with a leakage rate of not over 5 microamps.

6. Coating will not support fungus.

7. Will not crack, blister, peel, wrinkle or lose adhesion due to thermal shock.

8. Will not separate or strip from the board.

9. Will have a usable application life of at least 4 hours. (Not specified in Mil-I-46058.)

10. Will not crack or cause cracking of joints or components - even fine intermittent opens - after vibration to 10Gs at frequencies of 10 to 2000 Hz. in three planes while operating.

11. Fluoresces under ultraviolet light and is transparent.

12. Flame resistant.

13. Relatively inexpensive and easy to apply.

14. Withstands severe abrasion.

Many of these requirements are self-explanatory but some require further explanation.

1. <u>Toxicity</u> - Most hydrocarbon resins are somewhat toxic but are generally formulated to reduce the degree of toxicity as low as possible and to assure no highly toxic residues are left after cure. Often the hardner - such as in epoxy formulations - is the most toxic substance, and the manufacturer will specify an excess of hardner to assure complete polymerization of the compound. In polyurethanes, the isocyanate moiety is the toxic ingredient. This grouping is extremely irritating and leads to profuse tearing. This irritating effect occurs at levels well below the toxicity levels and acts as an extremely effective warning system to the presence of free isocyanate.

2. <u>Solids Content</u> - The requirement for 35% nonvolatile content means 35% resin solids and 65% solvent. The previous conformal coatings used by NASA were 100% solid materials with

high viscosity. Many engineers believe that solvent-based coatings, as they evaporate, will leave pinholes in the coating. We once believed this, too. After more than three years of trouble-free experience with at least one of these coatings and after many tests, we now know that these thin solvent coatings go on bubble free and cure quickly without voids.

These 35% solids materials have much better handling characteristics, flow better, and do not entrap air, thereby eliminating the need for vacuum degassing.

3. Q-factor Change - Q or Q-factor, (Fig. 1) as previously stated, is the reciprocal of the dissipation factor. Mil-STD-202C, Method 306, calls it the Quality factor or the "storage factor" as it is the measure of the ability of the component or circuit to store energy compared to the energy it wastes. The "Q" expresses the ratio of reactance to effective resistance of a circuit or circuit element. This numerical ratio is considered a "figure of merit."

The formula for Q is:

$$Q = \frac{Q_1 \; Q_2 \; (C_2 - C_1)}{(Q_1 - Q_2) \; C_1} \qquad \text{when,}$$

Q_1 = meter reading for uncoated board (or component)
Q_2 = meter reading for coated board (or component)
C_1 = capacitance of uncoated board
C_2 = capacitance of coated board

4. Insulation Resistance - Insulation resistance needs no explanation but it is interesting to note that all samples passed the insulation resistance requirements for standard conditions. No results after salt fog are available because the salt fog equipment was not operative at the time of these tests.

5. Disruptive Discharge - No boards showed disruptive discharge and no significant leakage rates were recorded.

6. Fungus Resistance - Certification that the coatings met the fungus resistance requirements was received from the manufacturers under the previous "Q" spec. Since no fungi problems have been reported, it is assumed that this certification is sufficient. Mr. Orlowski (USAECOM) has set up an extensive fungus laboratory for the Army Electronics Command at Fort Monmouth. We will probably ask his help if problems arise.

7. Thermal Shock - Our test for thermal shock is different from the Mil Spec in that we require the heated test specimen to be plunged into a dry ice-alcohol bath. This simulates the effect of heat up from operation and a cryogenic spill on the circuit board.

8. Application Life - As already explained, the usable application life of at least 4 hours was required to allow a practical full-shift use for each batch. All of the thin coatings exceeded this limit. Many showed less than 25% change in viscosity in 4 hours.

9. Ruggedization - None of the thin coatings caused discontinuities in the circuit after vibration to 10Gs in three planes. We feel this "live" test - vibration of an energized circuit and monitoring by scope for three hours - will give us realistic simulation (Figures 2, 3 and 4). The "dead" test - with dummy components - does not allow for detection of slight cracks or intermittent opens, which are more troublesome than actual breaks.

10. Fluorescence - The use of a fluorescent tracer dye in the coatings has become a uniform requirement since it greatly facilitates circuit board inspection. Both blue and pink dyes are used and in varying hues. For example, Magna's blue tracer (Figures 5 and 6) is not noticeable in normal light, but fluoresces nicely under black light. Epoxylite's pink dye (Figures 7 and 8) is easily spotted in normal light but black light highlights defects and should definitely be used.

11. Flame Resistance - The flammability of the two thick coatings and the first three thin coatings as well as the Furane material was tested and reported in MAB report 800-67. These tests showed the superiority of the FR-4 fire retardant board material over the general purpose G-10 board. They also showed that the thick coatings tend to drip like burning tar and are, therefore, a dangerous fire propogation hazard. In gaseous oxygen, all of the boards and coatings acted very much the same - they burned profusely.

12. Ease of Application - The Furane 8267 material in aerosol can was easiest to apply. It would also be somewhat more expensive than the same one-part material. Epoxylite 9653-3 is next. The three one-part materials come next in ease of application: Hysol PC -18-04, PRC-1568 and Furane 8267-31. Pro-Seal 773 is somewhat harder to apply, and the two thick materials, PRC-1538 and Hysol PC-22 are the most difficult to apply.

13. Abrasion Resistance - The coatings were tested according to the requirements of the original "Q" spec. All failed except the PR-1538. Upon evaluation of the test and comparison to standard tests in use at other agencies, we felt the hardness of the abrasion wheel was too great and that a softer wheel should be used. This requirement is incorporated in the new "Q" spec.

14. Outgassing - There has been some interest in using three thin coatings in a space environment. Bob Stroud reports that Ball Brothers is using a Laminar X-500 material in their spacecraft with excellent results. Bob Murphy of MIT's Lincoln Labs also tested a number of their conformal coatings and qualified Laminar X-500. Therefore, we decided to test these materials for outgassing and in an oxygen environment (Table I). Although the samples had been aged for 9 months at ambient conditions, all solvent systems in the coatings could be identified. The exact amounts of outgassing could not be closely determined but PRC-1538, PRC-1568, and Uralane 8267-31 liberated the greater amounts of CO and CO_2. PRC-1538 degraded to a dark, gummy mass. This occurred after 240 hours at 150° in gaseous oxygen.

15. Reversion Test - No reversion of the coatings was noted at 100°F and 95% relative humidity. Pro-Seal 773 did discolor and blister. Hysol PC-18-04, Epoxylite 9653-3, Uralane 8267-31, PRC-1568 and Magna X-500 showed some blisters but no discoloration. PRC-1538 and PC-22 did not blister or discolor. All boards showed some green corrosion on the copper conductor. These boards were the vibration or ruggedization samples and it is felt that the brush coating left pin-holes. The normal dip coating should eliminate this condition.

VI CONCLUSIONS

Some of these tests have had to be strung out and sandwiched between launch operations. Some of the materials were not received in time to be completely tested, but despite the shortcomings of this series of tests, they have generally confirmed the earlier tests of MSFC ESE-E-55 performed by Fussell and Flack[2]. The requirements have remained essentially unchanged although the test methods have been modified somewhat.

Each of the materials has its own peculiar characteristics but it can be generally concluded that the qualified thin films - [redacted] - are equal or better than the thick coatings, does not significantly change the Q of the circuits, are much easier and cheaper to handle and apply, and does not have detrimental characteristics (Table II).

VII ACKNOWLEDGEMENTS

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*5. KSC-SPEC-E-0001 (formerly KSC-C-185), "Specification for Coating, Conformal (Polyurethane), Printed Circuit Assemblies, Procedure for." (November 30, 1966)

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7. "Conformal Coatings for Printed Circuit Assemblies," Department of Army Project No. 5999-0004 (July 1, 1961 - June 30, 1963); and "Conformal Coatings for Printed Circuit Assemblies, "Department of Army Project No. 5999-A005 (July 15, 1964 - January 15, 1965).

8. MAB 318-67, "The Evaluation of PRC-1538 and Magna Laminar X-500 for use as PC Board Conformal Coating Materials," (April 4, 1967); and MAB 800-67, "The Flammability of Selected PC Conformal Coatings in Air, 6.2 psia Q_2 and 16.5 psia O_2," (August 8, 1967).

9. MAB 1946-67, "Qualification Testing of Conformal Coating, (February 27, 1969) Materials Analysis Branch, Kennedy Space Center, Florida.

* This and other KSC specifications are available from the Kennedy Space Center Library, Specifications and Standards, Kennedy Space Center, Florida 32899.

J. M. "Mike" Fisher, Jr., was born in Brunswick, Georgia, on June 12, 1928. He studied chemical engineering as a Co-op at Georgia Institute of Technology (Georgia Tech), received the AB degree in sociology and psychology from Emory University in 1951, and the BS in civil engineering (sanitary) in 1954. Mr. Fisher has had a wide background in materials research, materials applications, market and industrial development. He joined Armco Steel Corp. in 1954 in market development and began and edited "Municipal Construction" magazine. In 1959 he joined Douglas Aircraft/Charlotte as Plastics Tool Engineer. He has worked in the plastics field as a Program Manager for Fairchild Stratos and at Douglas Aircraft/Tulsa as Project Manufacturing Engineer for Delta and Chief of Manufacturing Research. Joining NASA in 1964, he is Staff Engineer for Technology, Plans and Policy Office, Quality Assurance Directorate. As KSC member of the NASA Parts Steering Committee, Mr. Fisher is Chairman of the Task Group on NASA-wide Potting, Coating, and Sealing Problems.

Mr. Fisher is a member of Chi Epsilon.

Coleman J. Bryan was born in St. Augustine, Florida, on October 2, 1936. He received the BS degree in chemistry in 1958 and the MS degree in chemistry in 1961 from the Georgia Institute of Technology. In 1961 he was employed by Dow Chemical Company at Plaquemine, La., and worked in polymer research. He holds with Dow a patent for vinyl polymerizations. In 1963 he joined Melpar, Inc., Falls Church, Va., and did custom synthesis on polymers and fine organics. From 1966 to 1968 he was a materials engineer with Southern Research Institute, who supported NASA in its operation of the Materials and Failure Analysis Laboratories at Kennedy Space Center (KSC). In 1968 he joined NASA as a polymer materials engineer in the KSC Materials Testing Laboratory. He is responsible for planning, technical direction, and performance of testing programs related to polymers and their usage at KSC. He has publications in radiation chemistry and mechanisms of reactions.

Mr. Bryan is a member of the American Chemical Society.

Table I

Out-Gassing Studies in Oxygen Atmosphere

Coating	% Weight Change 5.5 psia	% Weight Change 16.5 psia	Color Control	Color 5.5 psia	Color 16.5 psia
PRC 1538	+0.040	+0.103	Colorless	Gummy and dark	Gummy and dark
PC-22	-0.048	-0.058	Colorless	Colorless	Colorless
Epoxylite 9653-3	-0.031	-0.038	Colorless	Olive	Olive
Uralane 8267-31	+0.026	+0.149	Light Pink	Pink	Red-Yellow
Magna X500	-0.033	-0.146	Colorless	Light Green	Light Green
Pro-Seal 773	------	-0.131	Pink	Burgundy	Burgundy
PRC 1568	+0.015	-0.035	Amber	Red-Yellow	Red-Yellow
PC 18-04	-0.032	-0.057	Colorless	Colorless	Colorless
Control	-0.025	-0.055	----	----	----

MAB 1947-67

Table II

Summary of Test Results on Conformal Coatings

Coating	Dielectric Test (Microamps)	Abrasion Test (gms lost/1000 Revolutions)	Specific Gravity	Viscosity (cps)	Application Life (hrs.)	Nonvolatile Content (Per Cent)	Fluorescence Color
PRC 1538	0	0.17	1.04	7840	1	99.9	Blue
Hysol PC-22	0	0.47	1.10	17200	1	99.9	Green
Epoxylite 9653-3	0	0.84	1.11	19.6	4	38.5	Blue
Uralane 8267-31	0	0.53	1.02	500	4	57.6	Orange
Magna X500	0	1.02	1.21	258	4	48.9	Blue
Pro-Seal 773	0	1.40	1.19	1040	4	79.5	Orchid
PRC 1568	-	1.58	1.08	41.4	4	43.3	Green
Hysol PC 18-04	-	0.62	-	-	4	-	Blue
Requirement KSC-SPEC-Q-0001	5 max.	0.2 max.	1.25 max.	10-500	4 min.	35 min.	Color not specified

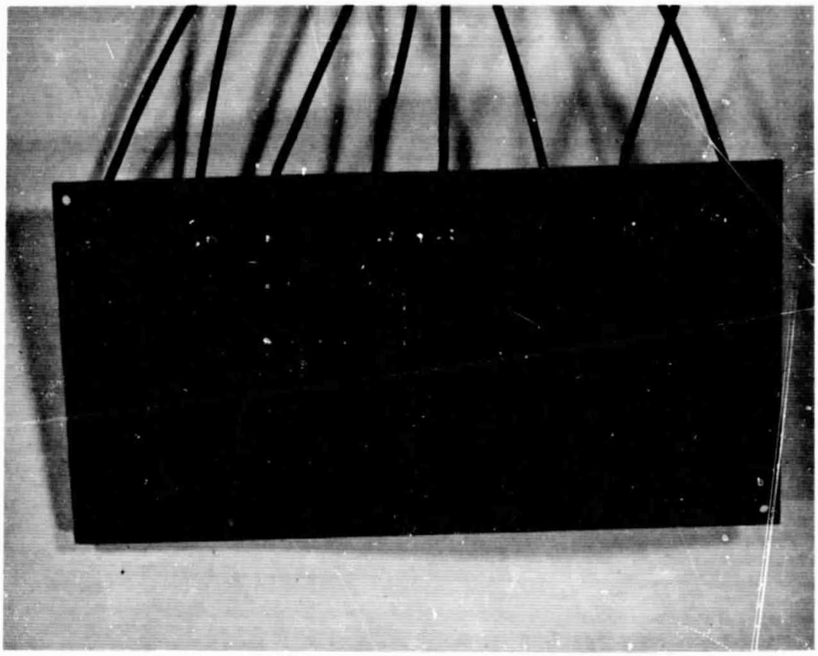

Figure 1

PC Board Layout Used for Q-factor and Dielectric Tests.

MAB 1947-67

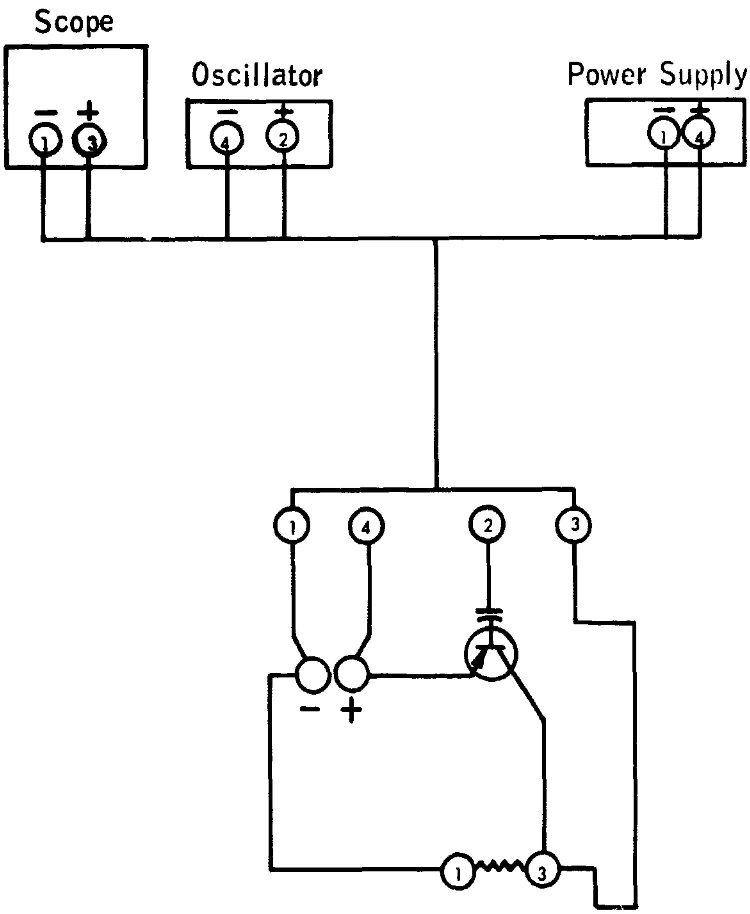

Figure 2

Test Circuit Schematic

MAB 1947-67

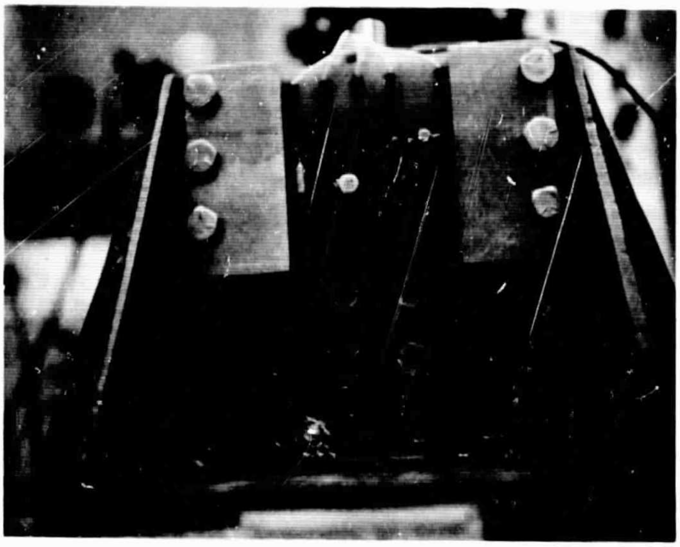

Figure 3

PC Test Circuit Mounted in the Vibration Test Stand.

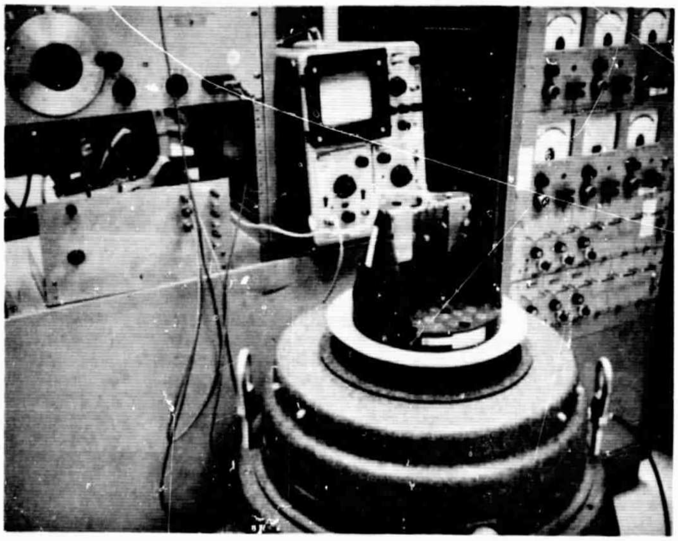

Figure 4

PC Test Circuit and the Electrical System Used to Provide Power and Monitoring Capability.

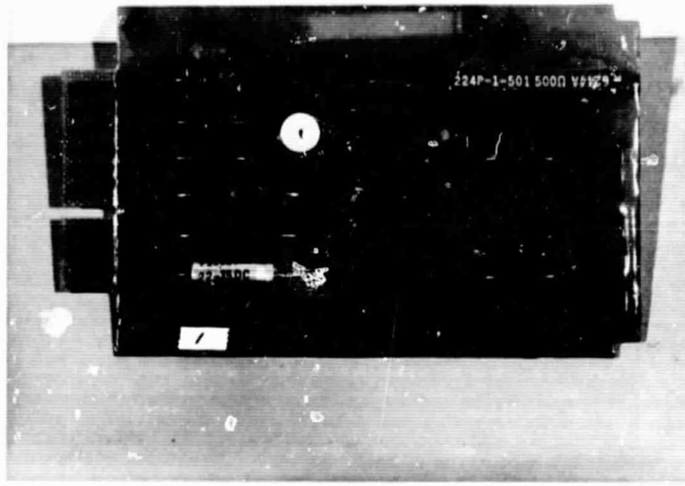

Figure 5

Magna's Laminar X 500(Blue Dye) on G-10 Type PC Board In Daylight

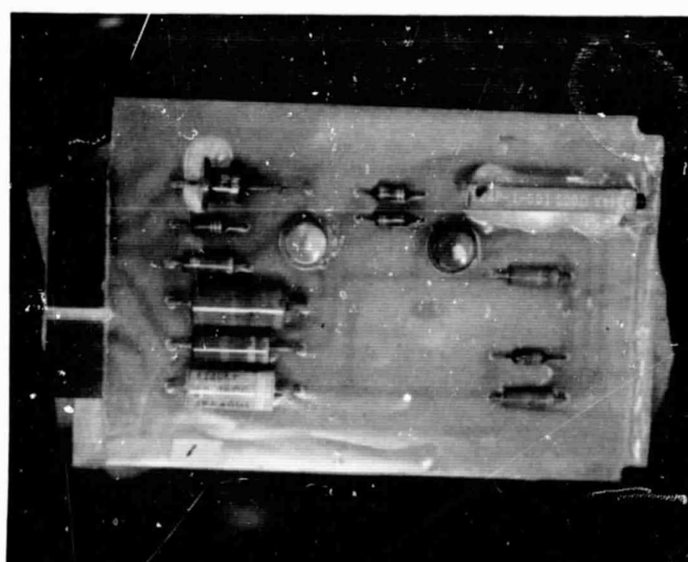

Figure 6

Magna's Laminar X 500 (Blue Dye) Under Black Light