Intermodulation Product Levels in Flame-Sprayed Materials

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Ford Aerospace (under contract with the Jet Propulsion Laboratory) completed a preliminary investigation on intermodulation product (IMP) levels of fiberglass-backed flame-sprayed surfaces. The purpose was to demonstrate the use of modified techniques and materials in combustion flame spraying of formed surfaces in reducing intermodulation products. The approach used improved metal wire stock without impurities or with smaller droplet sizes, used new high-temperature release agents, used wire stock with lower electrical resistance, and used variations in spraying distances, and intense buffing processes which amalgamate the material gaps and droplets in an effort to fabricate IMP-free light-weight and low-cost subreflectors. The study revealed positive material candidates with an IMP level around -150 dB, which is comparable to solid aluminum surfaces used as a reference.

I. Introduction

Ford Aerospace and Communications Corporation (FACC) (under contract with JPL) performed a study examining the intermodulation product (IMP) response characteristics of certain flame-sprayed materials and processing procedures. The purpose for this study was to demonstrate the feasibility of applying certain modified combustion flame-spray (metallizing) techniques and a number of materials for fiberglass-backed subreflector surfaces, used for the cassegrain microwave antennas, while avoiding the generation of impairing IMPs. The aim is to provide a method of producing at low cost, low IMP, and high efficiency, small-tolerance (RMS) and light-weight subreflectors. Material candidates were sought with characteristic IMP levels of -40 dB or below the antenna third sidelobe radiation level when radiated with multiple carriers at a power density approximating the antenna operating conditions. The study objective was to perform Lab tests on sample materials and fabrication procedures and to compare results versus conventional solid reflecting surfaces.

Past experience (Ref. 1) has shown that conventional flame-spray techniques using standard aluminum wire feed stock produce unacceptable IMP and noise problems when a multiple carrier uplink RF transmitter is used. Hence, a better approach is developed. This report describes the materials that were investigated, their method of fabrication, the test facility, the test procedure, and the test results and gives recommendations for future work.

II. IMP Mechanisms

The frequency F_i of a given intermodulation product resulting from two carriers of frequencies F_1 and F_2 ($F_1 < F_2$) is determined by the expression

$$F_i = NF_1 - MF_2 \quad (1)$$

where N and M are integers. The IMP order is defined as $N + M$. For example, the third, fifth, and seventh IMP orders can be written as follows.

$$\left.\begin{aligned} F_i(3) &= 2F_1 - F_2 \\ F_i(5) &= 3F_1 - 2F_2 \\ F_i(7) &= 4F_1 - 3F_2 \end{aligned}\right\} \quad (2)$$

Intermodulation product effects have been investigated since multiple frequency carriers were first introduced in space communications systems. Passive intermodulation products occur because some microwave components in radio-frequency systems, presumed to be linear, are in reality very slightly nonlinear. Transmit-to-receive isolations on the order of -150 to -200 dB are typically needed for high-power transmitter systems with sensitive receivers. For such systems, nonlinearities as little as 1 part/10^{10} may present a problem.

Three of the most predominant mechanisms for producing nonlinearties and intermodulation products are (1) electronic tunneling (a semiconductor action) through thin oxide layers separating metallic conductors at metallic junctions; (2) micro-discharge between microcracks, whiskers, or across voids in metal structures; and (3) nonlinearities associated with dirt, metal particles, and carbonization on metal surfaces. Each of these different mechanisms manifests itself in identical power laws and in nearly equal levels of IMP generation.

The nonlinearities responsible for the IMP are a result of the summation of many different microcurrent conduction processes. Microscopically, all surfaces are highly irregular and have a surface oxide layer between particles or droplets several angstroms thick. When two or more surfaces (particles) come in contact, rupture spots through the oxide coatings are formed, and very thin oxide layers separate the metals.

The nonlinearity will depend on the proportion of the conductive and displacement currents. For metal surfaces separated by thin oxide layers, less than 50 Å (50×10^{-10} m) nonlinear electron tunneling occurs. For thicker oxide layers, semiconductor current flow can take place. At high-power levels, low-level water vapor, weak gaseous plasma, and nonlinear processes in the material come into play. The observed IMP currents are a result of the statistical summation of the microcurrents from many different nonlinear contacts.

A nonlinear device is one that does not obey Ohm's law, and the relation of current and voltage for such a device is a curve that can be represented by a polynominal of a degree higher than one over a finite interval. Analysis made by FACC shows that third order intermodulation power is the predominant contributor to IMP interferences. Relationships are derived to show the magnitude of the third order IMP as a function of the magnitude of the power of two or more signals applied to the nonlinear device. Where all signal voltages are constant, the IMP power, P_i, is shown to vary with the carrier power ratio R as

$$P_i = \frac{R}{(R+1)^3} \quad (3)$$

In summary, IMPs result from nonlinear junctions where two or more carriers of given power ratio exist simultaneously and where the power of third order frequencies of the interference is sufficient to cause interfering sources.

III. Background

The detrimental effects of IMPs to JPL radio telescopes was described during the Voyager space program (Ref. 1). Past experience on flame-sprayed surfaces has shown that the unacceptable intermodulation and noise products, produced by conventional flame spray techniques, have resulted from one or all of the following conditions:

(1) Some *impurities* in the wire feed stock were included, typically, standard aluminum wire which contains up to 10% silicon impurities. These impurities cause undesirable coating of the sprayed aluminum particles (flakes), which create multiple resistive cells with local eddy currents and noise effects.

(2) The spray particles may have significant *oxide coatings*, developed during flight from the spray gun to the desired surface, resulting in noise generation.

(3) The low-temperature oxide-forming and *nonuniform spray pattern* of spray particles create a porous surface that, when power illuminated, results in IMP generation.

(4) The use of *incorrect spraying distances* which affects the porosity and oxide coatings referred to in (3), above.

(5) The use of a low-temperature "release agent" (a coating used for separating surfaces in the simulated female molds) causes excessive outgassing and thereby creates

local resistive cells with their accompanying eddy currents and noise effects.

(6) The selection of wire materials relative to the size of the sprayed particles is important. Other wire materials with good electrical characteristics, such as copper, silver, tin, zinc-tin, etc., have finer particle diameters – which at S- and X-band frequencies have a significant improved effect on IM products.

(7) Conventional techniques do not use intense *buffing*. Since flame-spray particles are laid down in semiflat flakes and are oxide coated in random (creating resistive cells and a porous surface), the application of intensive buffing of the finished surface may amalgamate the surface flakes together. Buffing will break down the interparticle oxide barriers and minimize the amount of porosity – especially in softer metals.

IV. Study Approach

The study approach is to avoid the past pitfalls mentioned above and to investigate the feasibility of significantly reducing the IMPs in the combustion flame-spray process by using a combination of pure wire-feed materials, high-temperature release agents, finer particle sprays, proper spray distances, different types of wire feed, and the amalgamating effects of intense buffing. In the future, the plasma flame-spray technique may be investigated to determine whether it can be adapted to NASA and DSN needs and is not included in this study.

V. Description of Material Samples

A number of flat flame-spray samples were fabricated as an approximation to the curved female mold used for forming the subreflector surface. The sample size was 30.5 cm X 30.5 cm with a 0.15-cm thick fiberglass backing. The samples were prepared by Antenna Systems Inc. (ASI), San Jose, California. The wire-feed materials were flame sprayed against a flat mold whose surface had been prepared with a high-temperature release agent. After the simulated mold had been metal-sprayed to a thickness of approximately 0.025 cm, the fiberglass backing was applied to the flame sprayed surface. The backing material was bonded and cured, and the sample was then removed from the mold. The release agent was removed using acetone.

A total of thirteen material samples was prepared as described in Table 1. Following the examination, processing, and testing of the first seven samples, certain handling procedures, test methods, and test criteria evolved which suggested that more meaningful results could be obtained by altering the original methods for the remaining samples. Pure tin was deleted from the list since flame spraying of this material constituted a health hazard.

VI. Test Conditions

The test conditions were set to approximate the operating power level of JPL antennas. The peak power density incident on JPL subreflectors was given as 5.4 W/cm^2. A test was configured to provide that power density as a minimum plus any margin the test facility would provide. Since IMPs from the flame-spray samples were the primary concern, the test configuration was designed to minimize or eliminate IMP contributions from the facility itself.

A means for mounting and supporting the test samples was constructed that would not in itself contribute to the observed IMP level. The holding fixture was a polyvinyl chloride (PVC) frame which supports the sample at 0.635 cm from the radiating aperture. PVC is used to eliminate metallic surfaces which are known IMP generators. The sample was held in proximity to the horn aperture to reduce radiation into the anechoic absorber which covers the interior of the test facility. This too was to reduce the background IMP of the measurement system. Figure 1 shows the sample holding fixture located in place within the test facility.

The radiating aperture was a 12.7-cm diameter conical horn which connects to the remaining IMP test facility providing the radiation and monitoring system. The transmitter, receiver, and recording/monitoring system used were at FACC IMP test facility located in Palo Alto, California. This facility was built to test IMPs having a level of -170 dBm from components radiated at multiple carrier power levels of +63 dBm into a free space environment. An RF-shielded anechoic test facility is also included that permits measurements in excess of -150 dBm from those power sources. The transmitter is a high-power amplifier capable of delivering 5 kW of carrier power. This level of power is necessary to provide a minimum of 2 kW at the feed interface following distribution losses through the facility waveguide and monitoring equipments. The frequency bandwidth covers 7.90 to 8.40 GHz. Most of the tests were run at a power level of 1 kW. This provided a power density level of 6.6 W/cm^2, exceeding the minimum required for the study. Attempts were made to increase the power level; however, the level of reflected energy (caused by the waveguide short presented by the flame-spray sample) into the receiver bandpass filter causes excessive heating of that component.

The receiving system has a noise figure of 1.5 dBm (105 K). This is achieved by including a Field Effect Transistor (FET) before the downconverter and spectrum analyzer. Since thermal noise power is -174 dBW/Hz at room temperature (290 K), a 10 Hz predetection bandwidth on the spectrum analyzer provided a theoretical noise power of -160 dBm. Also included in the test setup are a spectrum display and an equipment controller. These provided a swept display of all IMPs generated in the 7.25 to 7.75 GHz band. Those data were stored in computer memory, recorded on tape and by an $X - Y$ recorder. The modulated carriers which are used to drive the high power amplifier (HPA), the down converter local oscillators, and the spectrum analyzer are stabilized to 5×10^{-11} by an oscillator. This provided long term or swept measurement stability. Between 7.75 to 7.90 GHz at least 100 dB of rejection was provided by a separate bandstop filter. This prevented energy from the traveling wave tube (TWT) HPA passing through this window that would generate an IMP in the field effect transistor (FET) amplifier. Procedures are included to identify and isolate IMPs generated within the HPA.

Separate screen rooms having greater than -80 dB isolation were used between the receive test area and transmit area. These rooms prevent "floating" signals of the transmitter from influencing the low-noise receiver information. Figure 2 shows a block diagram of the FACC test facility. All tests were performed at room (ambient) conditions.

The recorded IMP level observed at each setting of the carrier frequencies was taken from a statistical average of ten separate readings. This was done to eliminate peaks, nulls, and equipment variations. As a result of this averaging process, each frequency measurement occurs over a 10-minute time period, and each test sample measurement occurs over a 90-minute time period.

No special facilities were required to perform the sample buffing, surface resistance tests, or porosity tests. Conventional equipment was used for each of these. A Kelvin Resistance Bridge was used for the simple surface resistance measurements. A 30X power microscope and light source were used in judging the sample porosity.

VII. Test Results

The flame-spray samples were sequentially tested for surface resistance, checked for porosity, IMP tested, buffed, and then retested. Initially the samples were tested, then buffed using various buffing techniques, and then retested. The data herein are grouped according to the sample identification in Table 1.

A. Buffing Procedures

One of the study objectives was to determine whether the observed IMP level could be reduced by intense buffing which causes amalgamation of the metal. If the IMP is a result of the material porosity or if it is a result of oxidation between globules of metal formed during the flame-spray process, the IMP level should be reduced following the amalgamation process.

Several buffing methods were examined. The first used a horse-hair brush wheel operated at very high speed. It was found that the heat developed from the brush was not adequate to cause distortion of the metal surface and no amalgamation occurred. The second attempt was to place the metal surface against a granite lapping plate. An orbital sanding machine was modified to accept the material sample during this process. Again, sufficient heat to cause amalgamation could not be developed, probably due to the heat sink effect of the granite block.

As a third attempt at buffing the flame-spray samples, a hard leather disk was fabricated and used on edge, similar to the horse-hair brush. This method proved to be too harsh and abrasive. The disk edge, which was approximately 1.2-cm thick, removed some metal from the sample, thus leaving large, unacceptable voids. The leather disk was then applied flat, using an automotive-type polishing machine. This method was marginally acceptable for certain metal surfaces. The pure aluminum (sample number 2, Table 1) was partially amalgamated by the leather-disk buffing process. Materials having a coarse surface (copper and silver, sample numbers 4 and 5) tended to load up the leather disk, thus significantly impairing the process. The pure zinc and tin/zinc materials (sample numbers 4 and 6) exhibited hard surfaces and large areas flaked off during the buffing process.

On examination of the above three buffing processes it was recognized that none of them yielded the desired result and a new trial was needed. A dry-lubricant Silicon Carbide polishing disk was tried, and it was found that grade-80 polishing agent provided significant improvement to the surface smoothness and its porosity and seemed to approach amalgamation somewhat more than the leather disk. The processing time was also significantly reduced. This buffing method was used on the remaining six samples (8 through 13).

B. Porosity Check

Samples 8 through 13 were checked before and after buffing for granularity and porosity. This examination was made by viewing the metallic surface in a darkened room while holding a high-intensity constrained light source to its fiberglass surface. The degree of porosity was a subjective judgment made by the test conductor with ranking from 1 to 5 (1 = no light showing through; 5 = significant light showing through). Porosity was helpful in determining the effectiveness of the buffing process. The results are shown in Table 2.

C. Surface Resistance Tests

Each sample was measured to determine its DC surface resistance before and following the buffing process. A Kelvin Resistance Bridge was used for these tests by placing two electrodes on the surface of the sample, spaced apart by a constant distance. The results are tabulated in Table 3 for comparative evaluation before and after buffing only. In general, materials having low resistance contribute lower system noise temperature. However, these measurements do not represent the actual dissipative loss associated with the metallic surface as described in Refs. 2 and 3[1]. A more accurate measurement technique such as the cavity resonator technique was developed by R. Clauss and P. Potter (Ref. 3).

D. Reflection Tests

One area of concern was the reflective quality of the samples following the buffing process. A test was added to determine the surface reflection to RF energy. A microwave reflectometer using an Automatic Network Analyzer was used to monitor reflected energy from an open-end waveguide placed flush to the sample surface. Table 4 lists the results of samples 8 to 13 before and after buffing for comparative evaluation only. Note that for a perfect reflector, the reflection coefficient should be zero. A different reflection measurement technique wherein each sample is placed at 45° slope from the radiating horn is contemplated for future work.

E. Intermodulation Products (IMP) Tests

The IMP results acquired from the measurements described in Section VI are plotted as a function of the receive frequency in Figs. 3-5. Each graph includes a frequency distribution. Fifteen carrier pairs were tested with carrier 1 frequencies ranging from 7.900 to 8.075 GHz and carrier 2 between 8.050 to 8.400 GHz. IMP 3rd order frequencies ranged from 7.40 to 7.75 GHz. An analysis of the results is given below.

1. System calibration. A reference calibration demonstrated the background IMP of the facility, holding fixture, and test equipment. The source horn was radiating into the anechoic room without a test sample plate in position. The calibration demonstrated (Fig. 3[a]) a background IMP level averaging -171 dBm over the receive frequency band.

Second, reference calibrations were made to demonstrate the inherent IMP level of the measurement system when a reference test plate (of known IMP purity) was substituted for the test samples. Two aluminum and copper plates, with dimensions identical to the flame-spray test samples, were mounted in the holding fixture and their IMP responses were measured. This calibration revealed (Figs. 3[b] and 3[c]) a nominal increase in the baseline IMP level. The increase is attributed to two factors: first, a concentration of incident energy on the chamber absorber in the proximity of the horn; and second, a significantly increased reflected energy into the monitoring microwave components (horn, orthomode junction, filters). Since IMPs increase at a rate of 3 dB per dB of incident power (Ref. 4), the reflected power level through the monitoring RF components is increased several fold when the calibration plates and the flame-spray sample plates are positioned over the horn aperture. Thus, the observed system IMP level increase in the calibration level was expected. The calibration data shown in Fig. 3 are accurate within ±5 dB of the indicated values. Thus, the two copper and aluminum plates exhibited generally comparable IMP signatures (~ -160 dBm).

2. Test samples. The results of the first seven flame-spray samples are shown in Fig. 4 where the general IMP level is observed between -100 and -170 dBm. Standard aluminum flame spray (sample 1, Fig. 4[a]) shows the largest IMP (-114 dBm); however the high-temperature release agent improves its performance significantly. The IMP performance of standard aluminum flame spray with high temperature release agent (Fig. 4[g]) is comparable (at -137 dBm) to the general trend of the other samples. IMP performance was plotted before and after buffing. When the 10 dB tolerance window (±5 dB) is considered, it was apparent that the samples performed generally the same except for the "standard" aluminum with low-temperature release agent (Fig. 4[a]). Pure zinc (Fig. 4[f]) and zinc-tin (Fig. 4[c]) appear as slight favorites within each group (~ -132 dBm).

The results of samples 8 through 13 are shown in Fig. 5. During the tests on these samples, the transmitter/receiver control software was modified (wherein each frequency was repeated ten separate times), and the transmitter power output was set at a constant 1 kW. The results show a closer correlation between sample tests than was observed from the previous seven samples and show consistent improvement in the measured IMP level when the buffing process was used although no significant change can be attributed to the double buffing process.

The measured tolerance was reduced to ±2.5 dB on samples 8 through 13 due to improved repeatability of measurements. This also is attributed to the modified measurement method.

The results of Fig. 5(a) also show that the 70/30 tin-zinc (at -134 dBm) performs better following the buffing procedure. Buffing apparently affected the tin-zinc (improves IMP

[1]See also C. W. Choi and G. S. Kirkpatrick, "Surface Resistivity Measurements for the JPL 34-m X-Band Antenna," Harris Corporation, Melborne, Fla., September 9, 1980.

from -134 dBm to -155 dBm) far more than any of the other samples tested. The pure aluminum sample in Fig. 5(b) measured low initial IMP (-156 dBm) and exhibited a lower value (average -158 dBm) following the second buffing procedure (with dry-lubricant silicon followed by leather disk).

The METCO Babbit™ sample in Fig. 5(c) and the pure aluminum with a 70/30 tin-zinc subsurface sample in Fig. 5(d) show generally the same mixed trend as the pure aluminum.

The two remaining samples (No. 12 and 13 in Figs. 5[e] and 5[f]) having overspray and material buildup to double thickness exhibited poor IMP response after buffing. No particular reason could be found for their higher IMP measurement.

VIII. Summary

It was learned that as a general class of materials, flame-sprayed fiberglass-backed laminates can be considered viable candidates as reflector surfaces in high-intensity microwave multiple carrier systems without excessive interference due to secondary emissions from intermodulation products. This rather board conclusion is supported by the overall low level (between -150 and -160 dBm) of IMPs observed from the present tests.

The flame-spray materials were exposed to a radiation density in excess of 6.6 W/cm^2 with selected tests exceeding 13 W/cm^2. Some materials (tin-zinc and pure aluminum) exhibited IMPs of -150 dBm when measured over a 6.3 percent frequency band. These levels are generally considered satisfactory for most receiving systems yet may be marginal for stringent JPL systems.

The study shows that buffing the flame-spray surface for some samples improved IMP performance; however, the results were mixed. General improvements of 10 dB were noted and may reach 20 dB (such as using tin-zinc in Fig. 5[a]). The "best" buffing process found was light polishing with a dry-lubricant silicon fine grit paper. Further buffing with hard leather provided only nominal improvement. Microscopic examination of the flame-spray material before and after the buffing processes revealed no conclusive evidence that the material had undergone amalgamation; the improvement may result from rupture of the oxide coating around the spray particles. Porosity tended to increase only slightly following the buffing process.

Taking the norm of multiple recordings of the IMP level at each frequency set improved the repeatability and thus the accuracy of the data. Setting the power at a constant level removed the 3 dB/dB slope from the data curve.

The study results showed a definite feasibility for some flame-spray materials for DSN antenna subreflectors. From an IMP consideration, the tested materials reveal positive candidates for that application. The selection of a specific material, however, should not be made without further technical and economical investigations. Until the observed IMP level from a sample material can be maintained at a value below the measurement system noise level, there is room for improvement. Indeed, as the material technology is enhanced, as was experienced during the current study, improvements can be made in the measurement methods to demonstrate even lower levels of performance. The areas envisioned for further work include the following:

(1) Plasma spray metallizing techniques result in surfaces whose characteristics may avoid many of the known sources of IMP generation. The process uses a combination of high-energy, high-velocity gas with an inert gas carrier to develop high-density, oxide-free, nonporous metallic surfaces.

(2) In fabricating a scaled subreflector, with a hyperbolic surface and testing for its IMP performance, material candidates should include tin-zinc and pure aluminum. In addition, comparative microwave reflective efficiency measurements should be made on the subreflector using a standard solid aluminum unit as a reference.

(3) The effect of local environment on selected candidate materials should also be considered prior to a final material selection. Weather effects, such as rain, ice, hail, humidity, dust, high- and low-temperature cycling, should be determined.

References

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3. Clauss, R., and Potter, P. D., "Improved RF Calibration Techniques: A Practical Technique for Accurate Determination of Microwave Surface Resistivity," *Technical Report 32-1526*, Vol. XII, Jet Propulsion Laboratory, Dec. 1972, pp. 59-67.

4. Chapman, R. C., Rootsey, J. V., Polidi, I., and Davison, W. W., "Hidden Treat: Multicarrier Passive Component IM Generation," AIAA/CASI 6th Communications Satellite Systems Conference, April, 1976. Montreal, Canada, Paper No. 76-296.

Table 1. Flame-spray samples

Sample Number	Description
1	Wire spray using "standard" aluminum wire (with 10% impurities) and a low-temperature release agent
2	Wire spray using pure aluminum wire, high-temperature release agent and no buffing
2(A)	Same as Sample 2 with buffing
3	Wire spray using pure zinc–tin wire, with high-temperature release agent
3(A)	Same as Sample 3
4	Wire spray using pure copper wire with high-temperature release agent
4(A)	Same as Sample 4 with buffing
5	Wire spray using pure silver, with high-temperature release agent
5(A)	Same as Sample 5 with buffing
6	Wire spray using pure zinc wire with high-temperature release agent
6(A)	Same as Sample 6 with buffing
7	Same as Sample 1 except using a high-temperature release agent
7(A)	Same as Sample 7 with buffing
8	A composite of tin/zinc in a 70/30 mix, with high-temperature release agent
8(A)	Same as Sample 8 after buffing
9	Repeat of Sample 2 above (pure aluminum) for repeat of measurements
9(A)	Repeat of Sample 2(A) above (pure aluminum) after buffing for repeat of measurements
10	Wire spray using METCO Babbit™ with high-temperature release agent
10(A)	Same as Sample 10 after buffing
11	Wire spray of pure aluminum as the surface area with a 70/30 tin–zinc as a subsurface backup material, with high-temperature release agent
11(A)	Same as 11 after buffing
12	Same as Sample 8 composite (70/30 tin–zinc) except flame-spray surface material thickness was increased to approximately 0.05 cm using an overspray
12(A)	Same as Sample 12 after buffing
13	Same as Sample 2 except flame-spray surface material thickness was increased to approximately 0.05 cm using an overspray
13(A)	Same as Sample 13 after buffing

Table 2. Porosity of some samples

Sample number	Material	Porosity	
		Before buffing	After buffing
8	70/30 tin/zinc	3	5
9	Pure aluminum	4	4
10	METCO Babbit™	5	4
11	Pure aluminum (with 70/30 backup)	2	2
12	70/30 (overspray)	1	1
13	Pure aluminum (overspray)	1.5	4

Table 3. Bridge Resistance of samples

Sample Number	Material	Resistance, ohms	
		Before buffing	After buffing
1	"Standard" aluminum (low-temp. agent)	0.0102	0.0114
2	Pure aluminum (high-temp. agent)	0.0127	0.0133
3	70/30 tin/zinc (high-temp. agent)	0.0038	0.0037
4	Copper (high-temp. agent)	0.0010	0.0010
5	Silver	0.0029	0.0028
6	Zinc (high-temp. agent)	0.0061	0.0065
7	"Standard" aluminum (high-temp. agent)	0.0150	0.0154
8	70/30 tin–zinc	0.0113	0.0105
9	Pure aluminum	0.0063	0.0065
10	METCO Babbit TM	0.0053	0.0051
11	Pure aluminum	0.0055	0.0060
12	70/30 (with overspray)	0.0033	0.0034
13	Pure aluminum (with overspray)	0.0004	0.0041

Table 4. Surface Reflection of flame-spray samples

Sample number	Material	Frequency, GHz	Reflection loss coefficient, dB	
			Before buffing	After buffing
–	Copper reflection plate	8.1	0.06	–
		8.4	0.01	–
8	70/30 tin/zinc	8.1	0.11	0.03
		8.4	0.11	0.01
9	Pure aluminum	8.1	0.43	0.08
		8.4	0.40	0.07
10	METCO Babbit TM	8.1	0.24	0.08
		8.4	0.36	0.04
12	70/30 tin/zinc with overspray	8.1	0.17	0.08
		8.4	0.09	0.08
13	Pure aluminum with overspray	8.1	0.23	0.02
		8.4	0.42	0.01

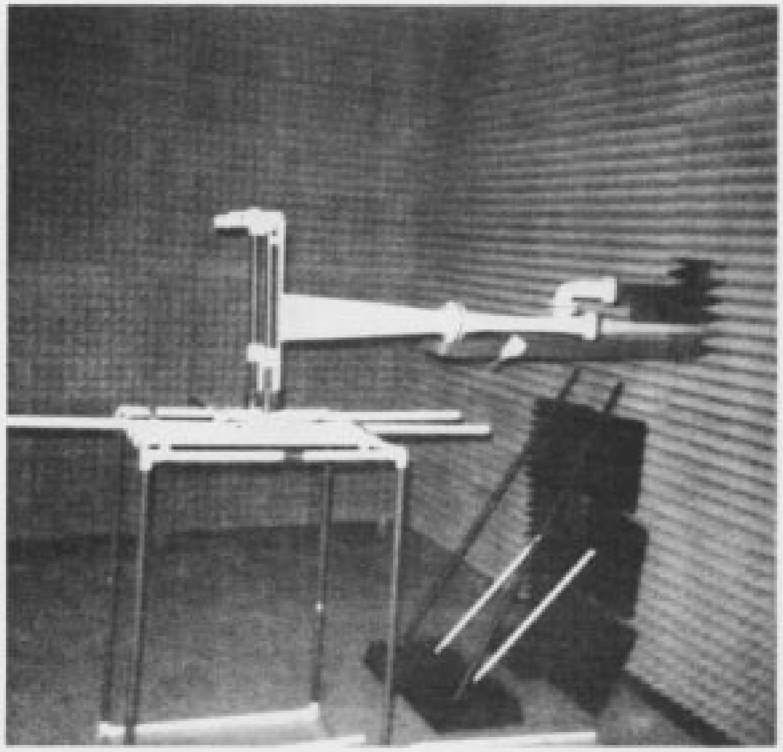


Fig. 1. Flame-spray test sample in anechoic chamber

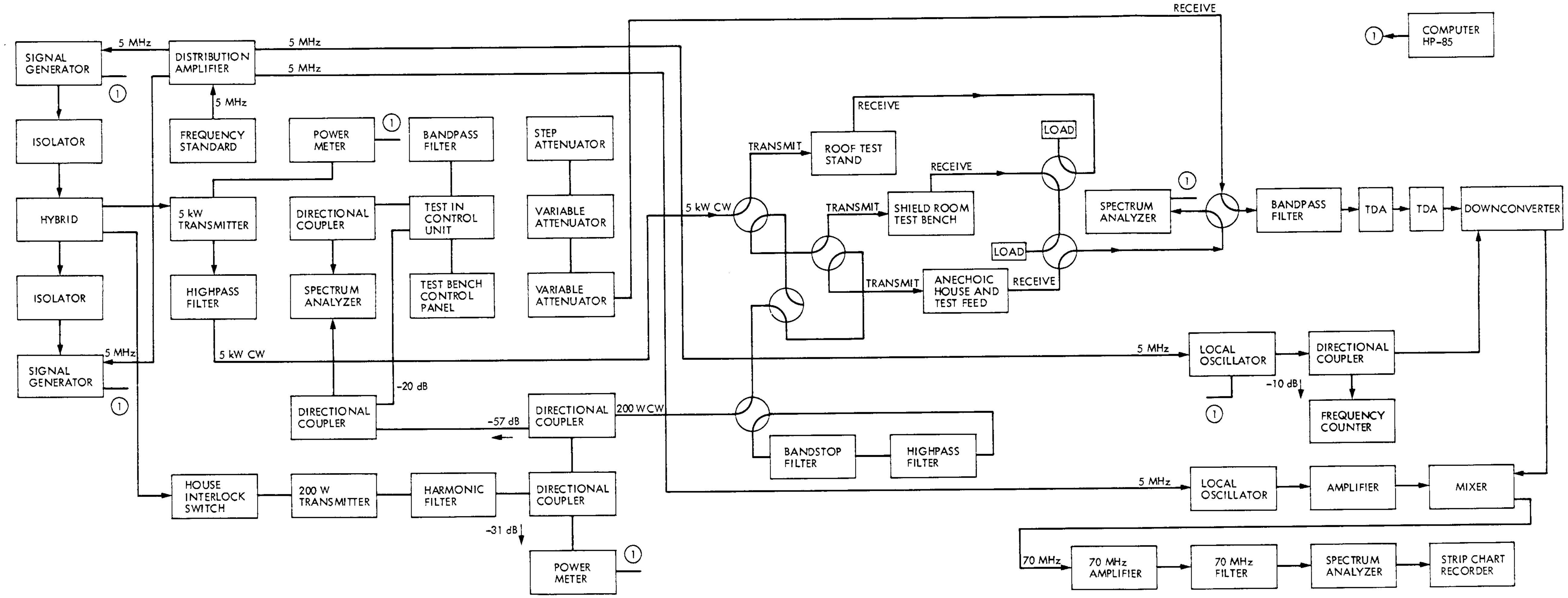


Fig. 2. IMP test facility at FACC

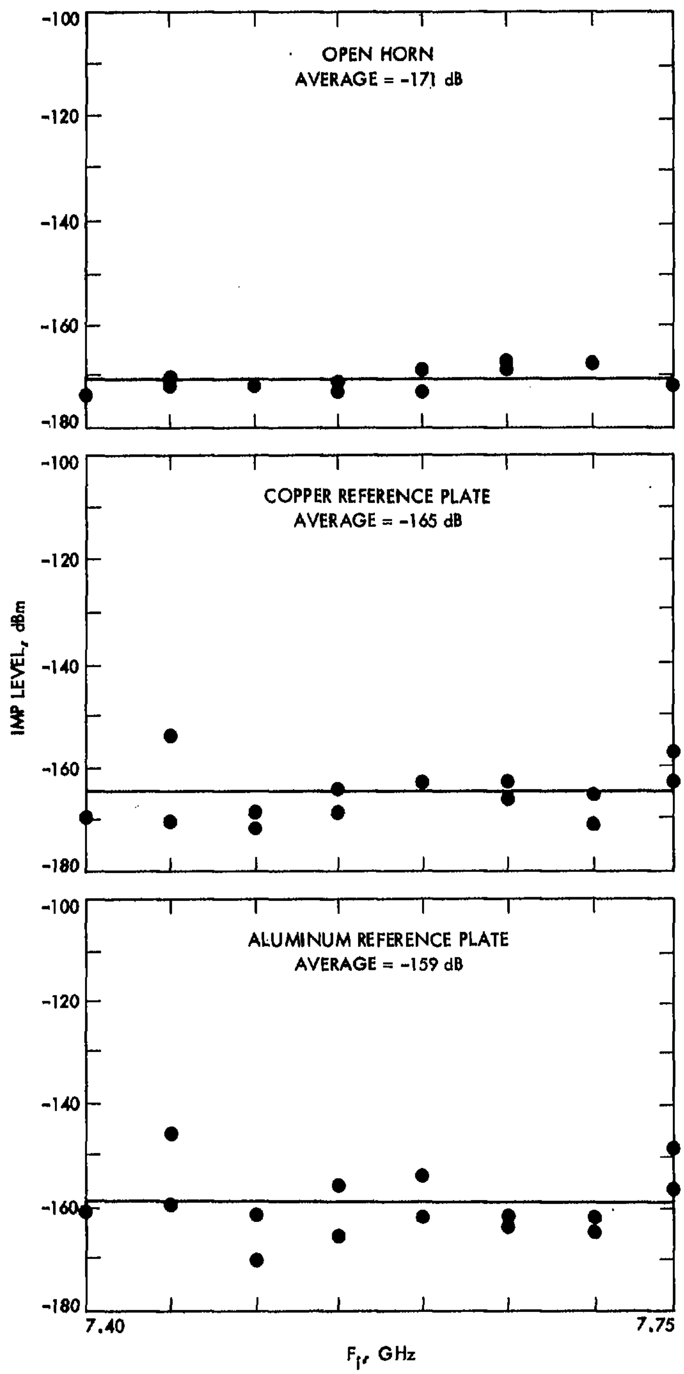


Fig. 3. IMP levels for facility and calibration plates

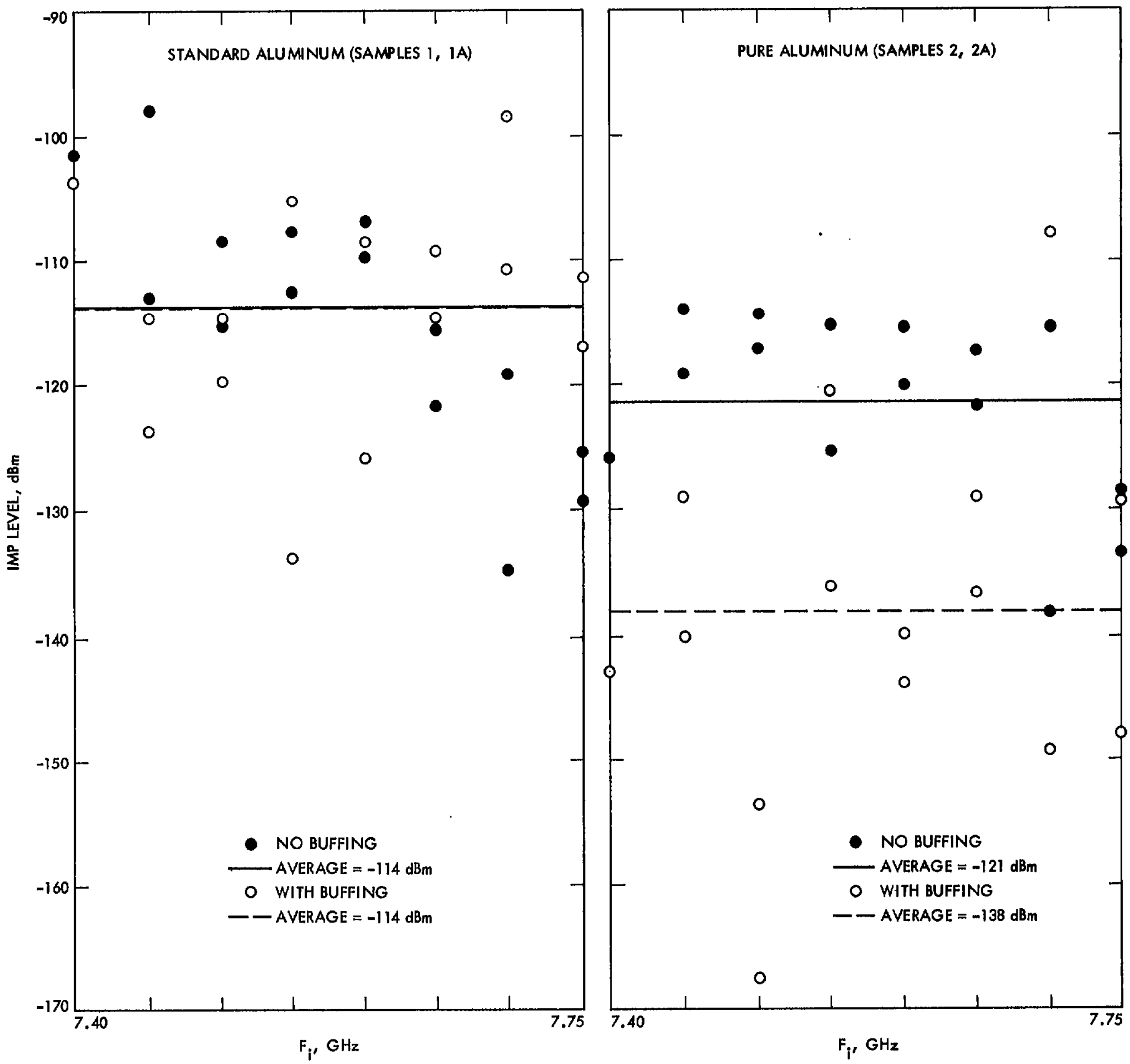


Fig. 4. IMP levels for samples 1 through 7 before and after buffing

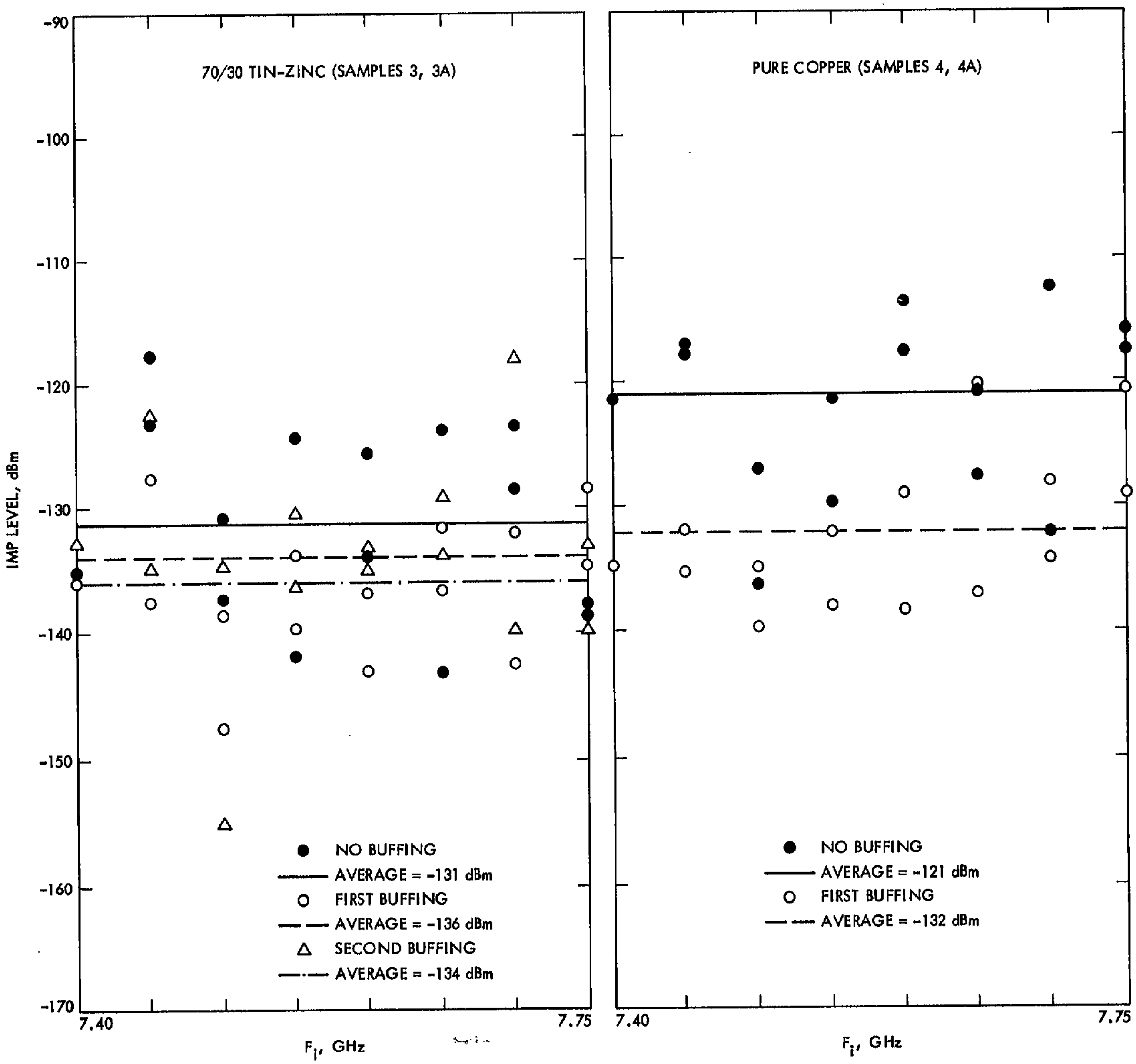

70/30 TIN-ZINC (SAMPLES 3, 3A)
PURE COPPER (SAMPLES 4, 4A)
IMP LEVEL, dBm
-90
-100
-110
-120
-130
-140
-150
-160
-170
7.40
7.75
F_I, GHz
NO BUFFING
AVERAGE = -131 dBm
FIRST BUFFING
AVERAGE = -136 dBm
SECOND BUFFING
AVERAGE = -134 dBm
NO BUFFING
AVERAGE = -121 dBm
FIRST BUFFING
AVERAGE = -132 dBm

Fig. 4 (contd)

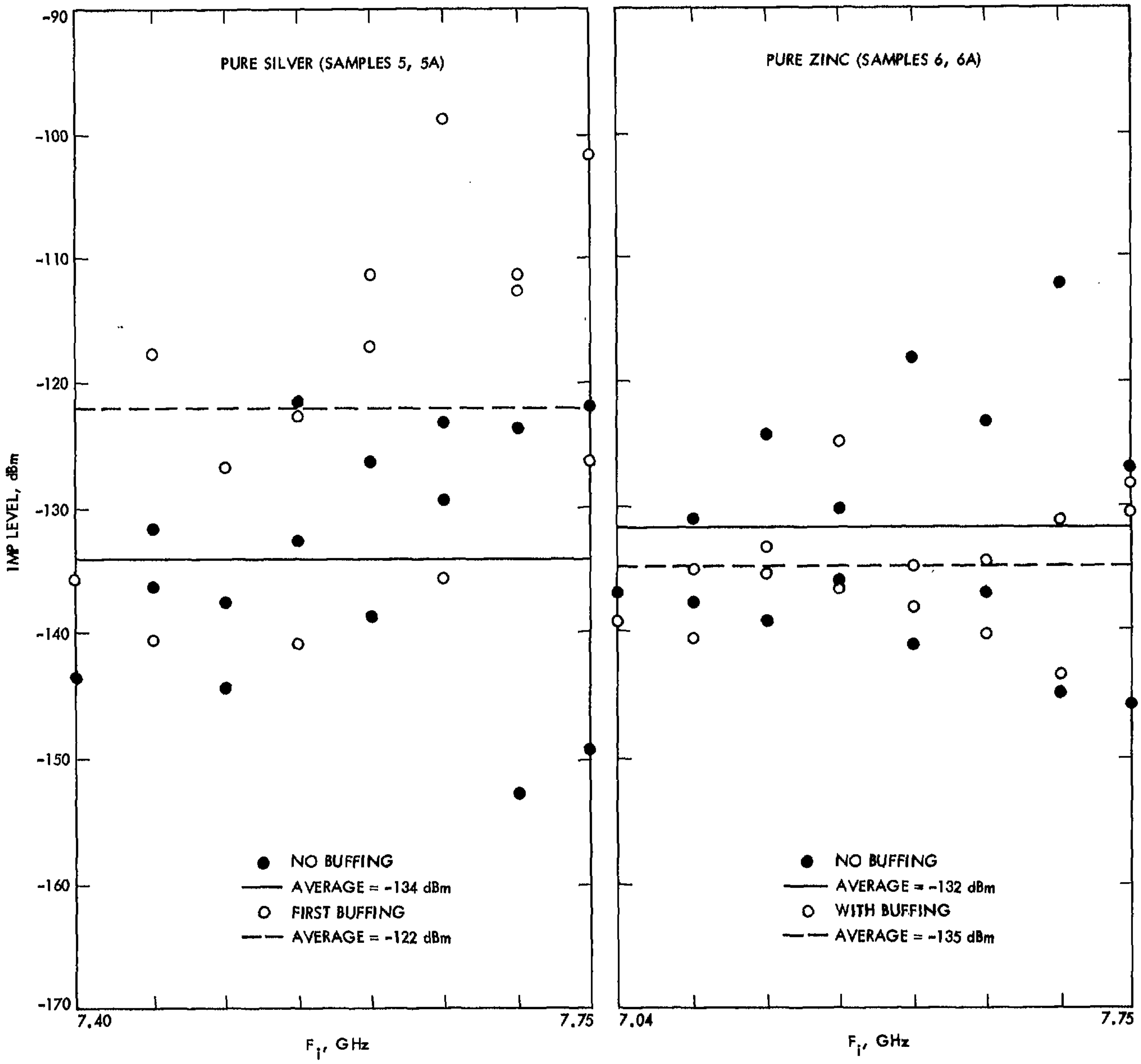
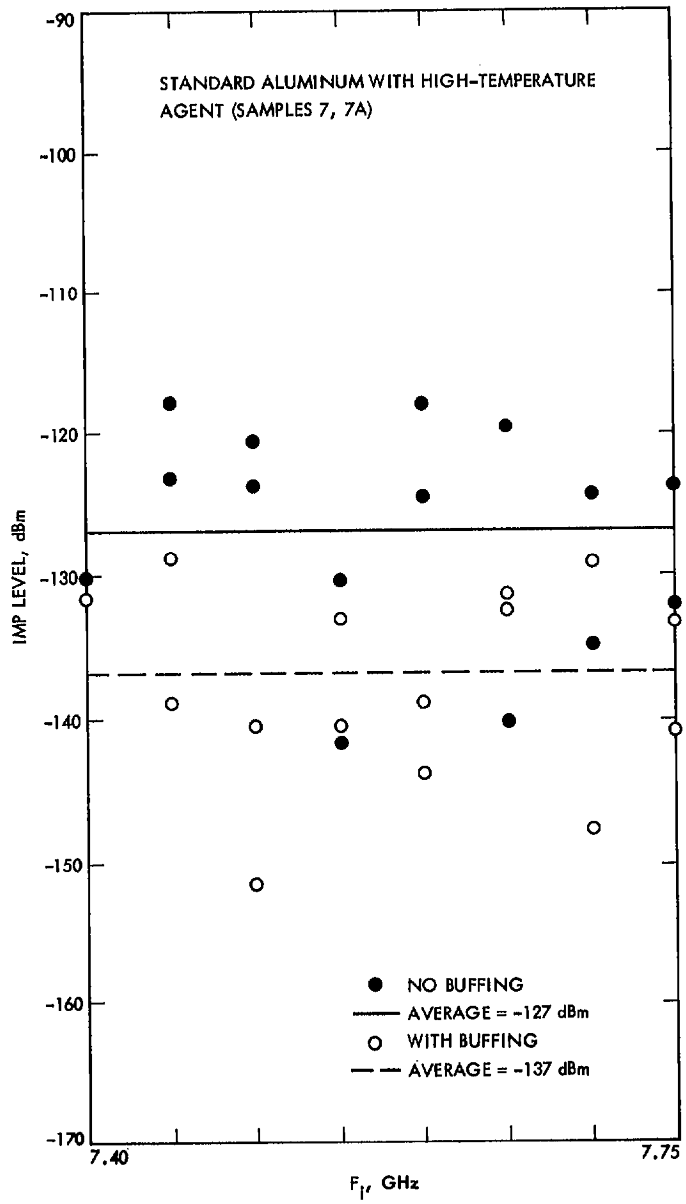

PURE SILVER (SAMPLES 5, 5A)
PURE ZINC (SAMPLES 6, 6A)
IMP LEVEL, dBm
-90
-100
-110
-120
-130
-140
-150
-160
-170
NO BUFFING
AVERAGE = -134 dBm
FIRST BUFFING
AVERAGE = -122 dBm
NO BUFFING
AVERAGE = -132 dBm
WITH BUFFING
AVERAGE = -135 dBm
7.40
7.75
7.04
7.75
F_i, GHz
F_i, GHz

Fig. 4 (contd)



STANDARD ALUMINUM WITH HIGH-TEMPERATURE AGENT (SAMPLES 7, 7A)
-90
-100
-110
-120
-130
-140
-150
-160
-170
IMP LEVEL, dBm
NO BUFFING
AVERAGE = -127 dBm
WITH BUFFING
AVERAGE = -137 dBm
7.40
7.75
F_I, GHz

Fig. 4 (contd)

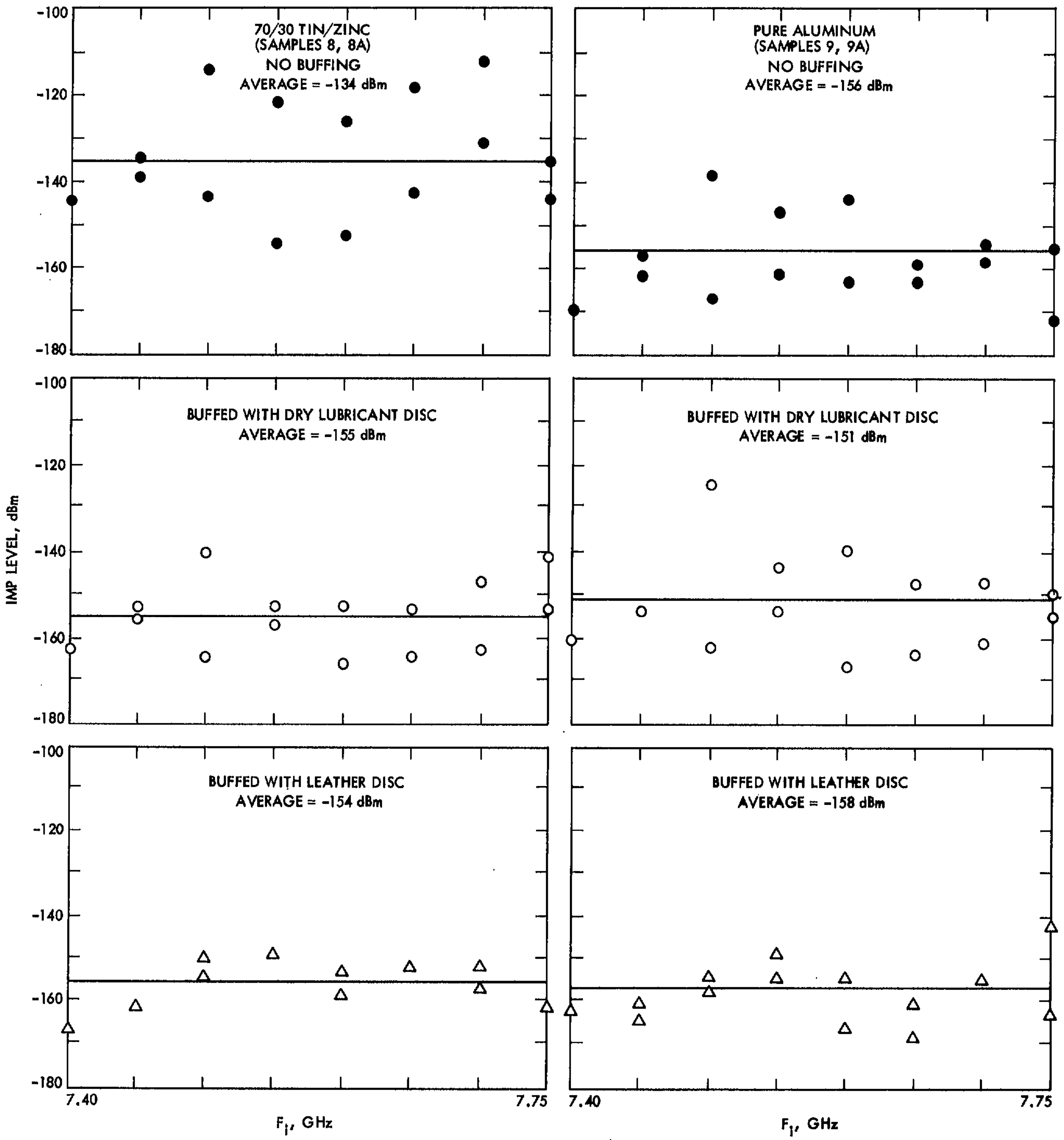


Fig. 5. IMP levels for samples 8 through 13 before and after buffing

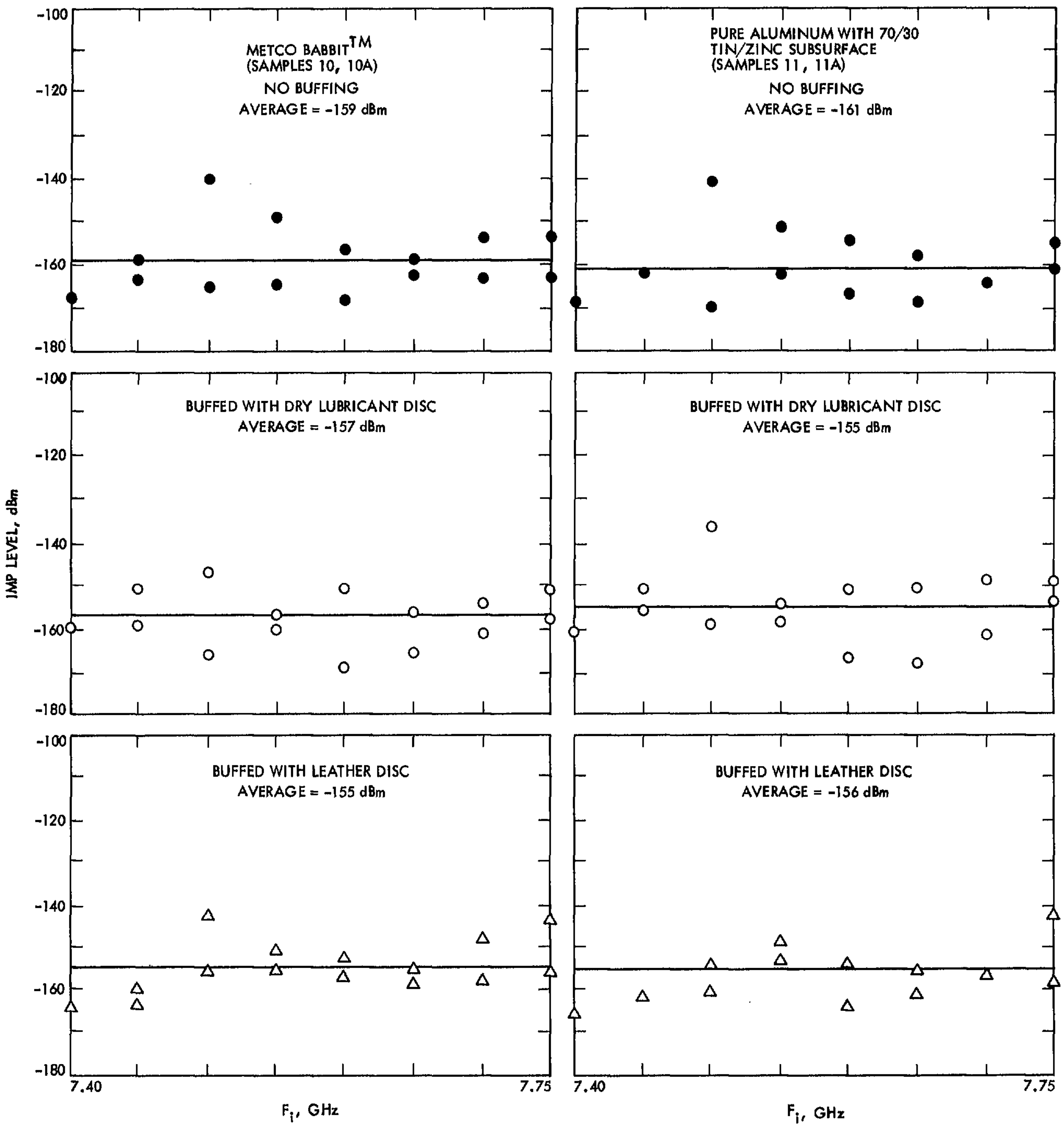

METCO BABBIT™
(SAMPLES 10, 10A)
NO BUFFING
AVERAGE = -159 dBm
PURE ALUMINUM WITH 70/30 TIN/ZINC SUBSURFACE
(SAMPLES 11, 11A)
NO BUFFING
AVERAGE = -161 dBm
BUFFED WITH DRY LUBRICANT DISC
AVERAGE = -157 dBm
BUFFED WITH DRY LUBRICANT DISC
AVERAGE = -155 dBm
BUFFED WITH LEATHER DISC
AVERAGE = -155 dBm
BUFFED WITH LEATHER DISC
AVERAGE = -156 dBm
IMP LEVEL, dBm
-100
-120
-140
-160
-180
7.40
7.75
F_i, GHz

Fig. 5 (contd)

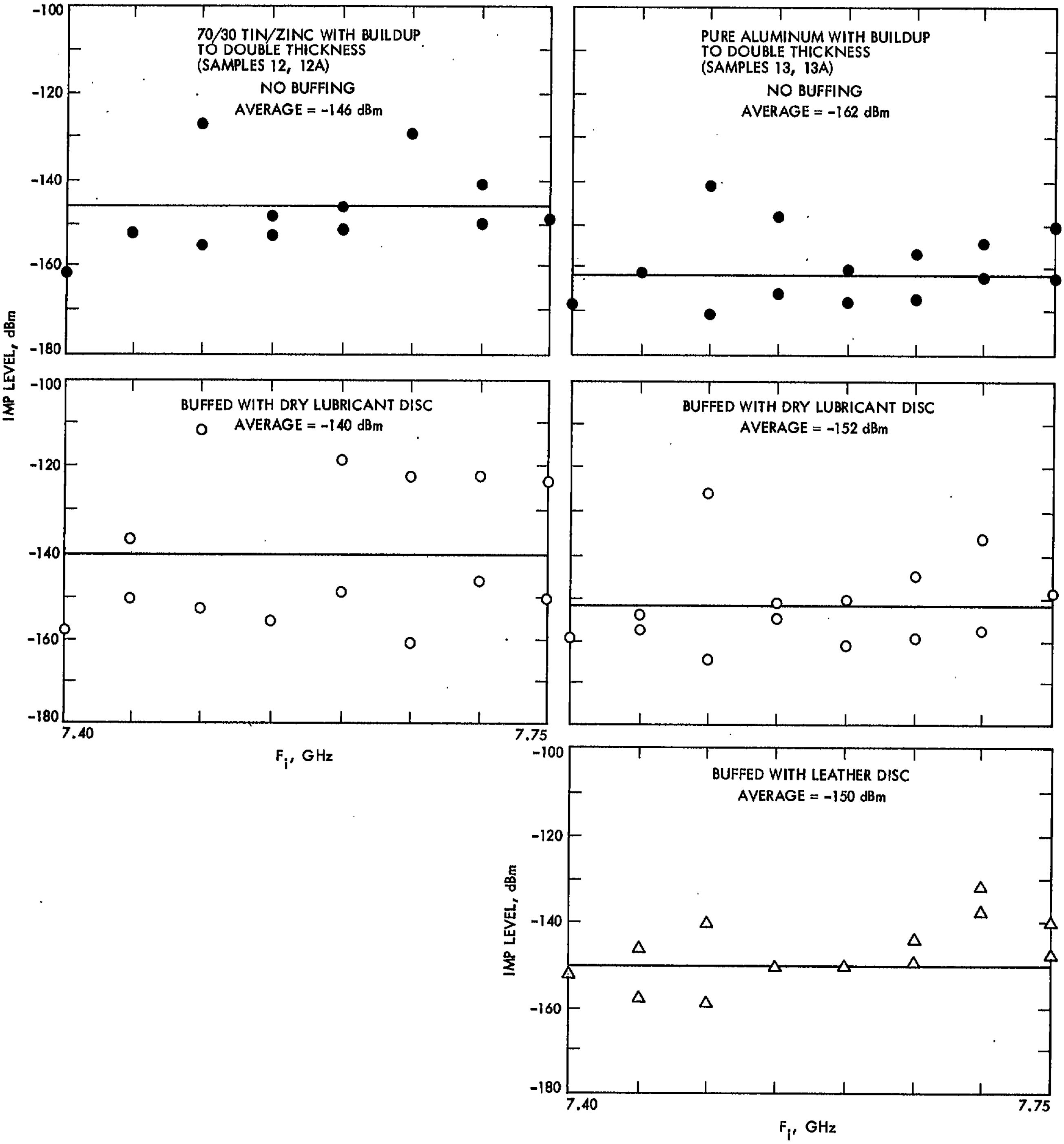

70/30 TIN/ZINC WITH BUILDUP TO DOUBLE THICKNESS (SAMPLES 12, 12A)
NO BUFFING
AVERAGE = -146 dBm
PURE ALUMINUM WITH BUILDUP TO DOUBLE THICKNESS (SAMPLES 13, 13A)
NO BUFFING
AVERAGE = -162 dBm
BUFFED WITH DRY LUBRICANT DISC
AVERAGE = -140 dBm
BUFFED WITH DRY LUBRICANT DISC
AVERAGE = -152 dBm
BUFFED WITH LEATHER DISC
AVERAGE = -150 dBm
IMP LEVEL, dBm
-100
-120
-140
-160
-180
7.40
7.75
F_I, GHz

Fig. 5 (contd)