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Attention: Mr. R. W. Blanchard, Chief
Electromagnetics Section, EF34

Reference: Contract No. NAS10-2639

Title: "A Study of Certain Propagation Anomalies in Radio Frequency Signals"

Subject: Monthly Progress Report No. 1, Project A-873
Covering the Period from June 30 to July 31, 1965

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Gentlemen:

The majority of the first reporting period has been devoted to: (1) obtaining and reviewing reports of prior studies of plasma media, (2) the development of measurement techniques suitable to the study of a plasma's electrical nonlinearities, (3) the acquisition of suitable plasma sources, and (4) the construction of a coaxial line RF-to-plasma coupler. The current plan of attack calls for in-line or in-guide measurements to determine the type of mixing (resistive or parametric), the magnitude of the products of intermodulation, and the power absorption characteristics for plasmas under near ideal conditions of control. A knowledge of these factors is essential in obtaining quantitative data through radiated measurements on hot plasmas and rocket exhaust flames.

The coaxial coupler consists of a 60 inch section of brass pipe, 2 1/2 inches in diameter, in which a fluorescent lamp configuration is coaxially mounted by two coax-taper end units. The end units slide on finger stock to accomodate various length tubes. They provide for power connections to sustain the plasma and for RF connection to the plasma through taper-matched N-type connectors. The line is presently completed but has not yet undergone testing to determine its functional characteristics.

During the next reporting period, the coaxial plasma coupler will be tested and, if its operation is satisfactory, measurements on electrically sustained argon plasmas will be conducted. In addition to these tests,

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waveguide-to-plasma couplers will be designed and built for tests at X-band. The waveguide couplers will be tested for satisfactory performance and measurements will be initiated on electrically sustained argon plasmas.

The literature reviewed included works by the authors: E. A. Desloge, Florida State University, 1964; S. Weisbrod, Pennsylvania State University, 1964; and O. E. H. Rydbeck, Pennsylvania State University, 1963. Desloge and Weisbrod were concerned with cross-modulation caused by the localized heating of the free electrons by a disturbing wave or high power. The heating changes the attenuation to a low amplitude wave and thus transfers any amplitude modulation on the high powered wave to the smaller amplitude wave. This effect occurs when the relaxation time is much greater than the carrier period but faster or of the same magnatude as the modulation period. The parameters normally associated with the degree of interaction are: electron density and collision frequency profiles, average kinetic energy of electrons, and a non-dimensional factor which is the fractional loss per collision of excess energy imparted to the electron by the disturbing signal. This type of interaction would not apply to intermodulation in general since the carrier periods are normally much faster than the relaxation rate.

Rydbeck approaches the phenomena of intermodulation from a parametric point of view in which the primary high powered signal is considered a "pump" and sum and difference frequencies are generated when a probing signal of small amplitude is propagated into the plasma medium. He demonstrates that the various product frequencies will be propagated out of the plasma at angles porportional to their frequency. In certain cases where the "pump" is a harmonic of the probing signal, degenerate parametric amplification occurs for the latter and is propagated back along the direction of incidence of the probing signal. This type of interaction is also a function of the electron density and velocity. Intermodulation over the entire frequency spectrum is possible through this type of interaction phenomena.

It might be noted that these studies are mostly theoretical with the exception of certain ionospheric measurements reported by Weisbrod. They apply generally to a three-component gas or plasma as related by the Boltzman transport equation and other associated relationships. The theories are not dependent on the manner in which the plasma is generated, although the absorption spectra and gyro-frequencies for the plasma may be influenced by the generation technique.

A report by F. R. Holmstrum of Stanford University, 1964 considers the theoretical impedance of an ideal plasma to radio frequencies. The impedance generally follows a spiral locus with changing frequency in the imaginary-real impedance plane. Conditions for stability and the impedance relationship to gyro-frequency are presented.

The erratic behavior of the intrinsic impedance of the plasma diode renders broadband matching rather difficult. If these effects are true in the case of the plasma in general, matching must be foregone and a method employed which will measure the absorbed power. This is most easily accomplished in a closed system such as used with in-coax or in-waveguide measurement techniques.

The closed systems to be employed in the current study will utilize fluorescent lamps as a convenient source of argon plasma. This is not meant to imply that fluorescent lamps are the object of this study. They are only the medium through which techniques will be developed for use in radiated measurements on actual oxy-hydrogen flame plasmas. It is known from prior measurement that argon plasma will produce intermodulation effects in sufficient quantity to obtain useful data.

Mr. R. W. Blanchard visited Georgia Tech, 22-23 July 1965, to discuss the progress and proposed avenues of approach in this propagation study.

Respectfully submitted:

[redacted]

R. D. Trammell, Jr.
Project Director

Approved:

[redacted]

D. W. Robertson, Head
Communications Branch

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ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

September 1, 1965

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National Aeronautics and Space Administration
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Attention: Mr. R. W. Blanchard, Chief
Electromagnetics Section, EF34

Reference: Contract No. NAS10-2639

Title: "A Study of Certain Propagation Anomalies in Radio Frequency Signals"

Subject: Monthly Progress Report No. 2, Project A-873
Covering the Period from August 1 to August 31, 1965

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Gentlemen:

The second reporting period has been devoted to the testing of RF-to-plasma couplers, both coaxial and waveguide, and to the collection of data on the coaxial coupler described in Monthly Progress Report No. 1. The measurements made during the period were exploratory in nature to determine 1) the available bandwidth, 2) the effects of warmup and aging on data repeatability, 3) the parameters which must be controlled and 4) the degree to which intermodulation is obtained. The measured data include the voltage standing wave ratio (VSWR) for all ports coupled to the plasma, the insertion loss through the plasma between any two ports, and the power levels of both the sum and the difference frequency products generated within the plasma as measured at the various output ports. It is believed that such data will establish the nonlinear generating properties of any plasma on which the measurements can be made even though certain anomalies which were encountered during first attempts at data reduction are not yet resolved.

Exploratory tests of intermodulation indicated the need for a relatively large isolation between the two signal generators in that the plasma's intermodulation products were rather small and generator intermodulation could have obscured the plasma-formed products. A two-isolated-port, four-terminal-hybrid was constructed such that the generators are isolated by 20 to 30 db with a nominal 6 db insertion loss to each of the other two ports. The insertion loss between the latter two ports is a

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nominal 6 db and provides a measurement port at the driven end of the plasma coupler. The hybrid performs over the band from 10 Mc to 1000 Mc.

Test Configurations: Waveguide sections and appropriate flanges have been acquired for tests to be conducted at X-band. These will be used to couple RF to both flame and electrically sustained plasmas. One section has been drilled to receive an eight-watt argon-plasma lamp at an angle of some 30 degrees. The lamp can be replaced by a section of Vicor tubing for flame-plasma tests. A standard propane torch was purchased to produce a fairly hot flame which can be funneled through the Vicor tubing into the waveguide-to-plasma coupler. This same technique can be used in coaxial type couplers. Consideration is also being given to the use of a standard acetylene torch as a source of flame plasma for testing purposes. A more extensive use of oxy-hydrogen flames than was originally planned is presently envisioned.

X-Band Tests: An X-band noise source which utilizes a DC-sustained argon-plasma tube, No. 6357, was examined as a possible source of plasma nonlinearity. The first test was directed toward coupling a UHF signal into the anode of the tube via a specially designed filter in an attempt to modulate the ionized plasma column passing through the waveguide. Testing of this setup failed to reveal any product generation between the UHF and microwave signals.

Two X-band signals were then fed into the section containing the plasma tube via a directional coupler. Limitations in the bandwidth of the test equipment prevent the measurement of second-order products for two X-band input frequencies; however, third-order products can be made to lie within the X-band region. No third-order products were detected.

The VSWR at the input to the section containing the plasma tube was measured and found not to exceed a value of 1.12:1 over the entire band. Insertion loss at X-band for the section with the tube ionized exceeded 20 db. Obviously, power is being absorbed by the plasma column; however, any products formed evidently undergo absorption to the degree that they lie below the minimum detection level for the test equipment (NF-112).

A radiated test was conducted on an open-flame placed in the path between two X-band horns. A dipole antenna oriented near the flame provided the UHF mixing signal. Again, no intermodulation terms were detected at the receiving horn. The result is not surprising as it is doubtful that much signal power was coupled to the flame by the UHF dipole.

A fourth test was conducted utilizing an eight-watt fluorescent tube passed diagonally through a section of X-band guide. The insertion loss of the section measured between 8.2 Gc and 10 Gc was observed to be around 10 db with the tube ionized. A UHF signal was applied to a loop coupler around the tube protruding from the guide section but no evidence of the UHF signal was apparent at the output of the waveguide section.

The totally negative results of these tests are not conclusive in that the power level of the UHF signal reaching the mixing region of the plasma column is not known. Future tests and coupling techniques will attempt to measure this quantity.

VHF/UHF Tests: The VSWR measurements obtained on the coaxial plasma coupler between 10 Mc and 2.4 Gc indicate a useable bandwidth from 10 Mc to 500 Mc, and from 900 Mc to 2.4 Gc. An apparent line resonance at 700 Mc prevents utilization of the frequency range from 500 to 900 Mc. Insertion loss for the 47 inch plasma column varies from around 12 db at 10 Mc to over 135 db at 1800 Mc, above which no data could be obtained. The loss is on the order of 40 db at 900 Mc, rising sharply thereafter. Both second and third-order intermodulation were measured in the band from 10 Mc to 500 Mc with +13 dbm input power from each generator. Second-order products were down some 53 db or more below the input levels while third-order products fell some 78 db below the input levels. These measurements were made through the 6 db hybrid at a common end of the coaxial coupler.

The loss sustained by generated products in escaping the plasma medium appear to be in proportion to their frequency by the same ratio as the frequency dependent insertion loss obtained when signals are passed through the plasma tube. This is based on equal power being generated at both the sum and the difference frequency of a given product of intermodulation as formed within the plasma. At present, the data are insufficient to establish the presence of parametric mixing forms, but the evidence indicates they are either very weak or nonexistent. In no case thusfar examined has the measured power level of the sum frequency exceeded that of the difference frequency for a common product of intermodulation. In view of the apparent attenuation of generated products, it seems unlikely that any measurements can be performed above 900 Mc using the 47 inch tube in the coaxial coupler. This may be an insight into the apparent lack of product generation at X-band frequencies, providing that the attenuation continues the steep ascent indicated by the data obtained with the coaxial coupler.

It has been noted that the current sustaining the argon arc varies with operating time (temperature most likely) and must be controlled for repeatable results. In general, increased current causes decreased attenuation and decreased intermodulation for the coaxial configuration. No comprehensive data have been assembled to verify and establish the range of these phenomena. Also noted is the fact that more intermodulation is obtained when the generators and receiver are connected to the negative end of a DC-excited fluorescent configuration than when connected to the positive end of the same configuration. The levels are larger than those obtained at either end of an AC-excited tube, possibly because either end of an AC-excited tube is negative only half of the time. A rarefaction of ion-recombination is evident at the negative end of the DC-sustained arc which possibly produces a region of higher nonlinear activity.

Future Effort: During the next reporting period, tests will continue on the coaxial coupler using argon plasma sustained by both AC and DC currents. Fluorescent tubes of the same diameter but shorter length than the presently used variety will be acquired for use in the coaxial line to determine the effect on attenuation to injected and internally generated signals. Tests will be devised to determine the loss sustained by frequencies above 1800 Mc in traversing an argon-plasma tube. Additional tests at X-band will be conducted at higher input power levels in an effort to obtain positive results of intermodulation. Loop and probe couplers will be utilized in the microwave effort.

Respectfully submitted,

[redacted]

R. D. Trammell, Jr.
Project Director

Approved:

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D. W. Robertson, Head
Communications Branch

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5 October 1965

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Attention: Mr. R. W. Blanchard, Chief
Electromagnetics Section, EF34

Reference: Contract No. NAS10-2639

Title: "A Study of Certain Propagation Anomalies in Radio Frequency Signals"

Subject: Monthly Progress Report No. 3, Project A-873
Covering the Period from September 1 to September 30, 1965

Gentlemen:

During the third reporting period, the primary effort has been channeled toward developing a means for coupling RF signals to an extremely hot plasma source. Radiated techniques are difficult because the plasma absorption-frequency characteristics prevent the use of frequency scaling techniques which correspond to the physically small flame-plasmas available for testing. The plasma column temperatures range between 7,000 and 30,000 degrees Kelvin and any materials inserted within the column would be severely damaged. Loop and helix couplers show promise in this regard since the plasma column need not touch the coupler and the loop or helix can be liquid cooled if necessary.

Intermodulation Measurements:

Intermodulation occurring in the receivers used to observe the mix products was found to have substantially affected the intermodulation measurements reported in Monthly Progress Report No. 2. The use of a notch filter in the signal path to the NFIM's eliminated the problem. New intermodulation data for the plasma coaxial line show only one case where the sum product exceeded the difference product for a given mix. This was only by one db, where for purely parametric mixing the ratio should have been 3.7 db. Of course the losses sustained by the signals in escaping the plasma media have a large influence on the results of such tests. Thus far, no technique has been devised to conclusively determine the relative losses sustained by signals of different frequencies in escaping the plasma media. Insertion loss data have not provided consistent results when correlated with the escape losses sustained by frequencies of a common mix. These results could indicate a combination of both resistive and parametric mixing.

A double hybrid network is being fabricated to provide isolation between all items of test equipment and to eliminate the need for the notch filters. This unit is designed to operate from 10 Mc to 1000 Mc and to provide 6 db of coupling loss between the plasma-coupler and either generator or NFIM. The time required for measurement will be considerably reduced with the application of this hybrid unit.

Coupler Development:

In Monthly Progress Report No. 2, consistently negative results were reported on a number of tests which were conducted in the area of interference generation by plasmas at X-band. A review of the situation indicated that a more intensive study of coupling techniques and devices should be undertaken before proceeding further.

The dimensions of the laboratory plasma columns are several thousand Debye lengths but are small relative to the lower frequency wavelengths of interest in this study. Frequency characteristics of the laboratory plasmas are similar to those of a rocket exhaust, varying from a plasma frequency (the frequency below which the plasma is conductive) of some 100 Mc to 10 Gc or so depending on the type of generating technique. For mixing to occur, power must be absorbed at both test frequencies. Consequently, couplers must be devised to create good power-transfer characteristics over a large bandwidth.

One of the suspected reasons for the failure to achieve mixing between an X-band signal and a signal in the HF region was ineffective coupling to the electrically-sustained plasma. Studies into possible coupling techniques have proceeded this month. Two multi-turn loop couplers were constructed around an eight-watt argon plasma tube. The change in coupling between the loops due to the tube being in the "ON" state as opposed to the "OFF" state was measured as a function of frequency and spacing between loops. The coupling change was measured from 900 Mc to 4000 Mc at three different spacings. The generalized behavior followed roughly the same pattern at each separation. In some frequency regions a decrease in coupling (8 to 10 db) occurred while in other regions an increase of similar magnitude was observed. The decrease in coupling occurred around 1100, 1800, and 3500 Mc while the more prominent increases were noted at 1600 and 1900 Mc. The coupling change as a function of spacing between loops was measured at selected frequencies. At 1100 and 1800 Mc (regions of maximum increase), the change was not significant. Nor was there much variation at 1500 Mc, a frequency where little effect (1 to 2 db) was caused by ionizing the tube. At 1000 and 2000 Mc the variation as a function of spacing was in the neighborhood of 10 db.

Another type of coupler which is being evaluated consists of a helical coil wrapped around the argon plasma tube. The tube and coil were placed inside a 2-1/2 inch copper pipe. Both ends of the coil were brought out through a Type "N" panel jack. The insertion loss as a function of frequency has been measured with coils of 10, 20, and 30 turns. The behavior is rather erratic above 2500 Mc. Insertion loss in the neighborhood of 10 db was measured between 500 and 2000 Mc.

The impedance into one end of the helix was measured with the other end terminated in 50 ohms. The VSWR for the 10-turn coil oscillates about 2.5:1 from 900 to 2000 Mc. The 20-turn coil reached a lower VSWR but exhibited a reduced bandwidth characteristic. The actual impedance of the 20-turn coil was measured and was found to be less than 50 ohms in the frequency range where the best match was obtained. The 30-turn coil was constructed in an attempt to raise the impedance closer to 50 ohms. No significant improvement in match was obtained. The impedance of the 30-turn coil was found to vary from $95.7\underline{/55^{\circ}}$ ohms at 450 Mc to $49.4\underline{/62.2^{\circ}}$ ohms at 1000 Mc to $29.2\underline{/12.9^{\circ}}$ ohms at 1800 Mc. The VSWR at selected frequencies for open and short circuit terminations were compared to that for a 50 ohm termination. Typically the short circuit termination resulted in the lowest VSWR of the three.

Techniques for coupling into weakly ionized media such as that produced by a propane torch are being investigated. A device consisting of 1-1/4 inch copper tubing with electric field probes extending into the center was constructed to enable a signal to be coupled in and out of a flame column. The coupling between the two probes was measured from 1 Mc to 1000 Mc. From 400 Mc to 1000 Mc, the attenuation characteristic was typically that for a waveguide below cutoff. Below 400 Mc, the attenuation exhibited a 6 db/octave decrease with frequency.

A flame column was directed up the axis of the tube so that both probes penetrated well into the flame. The propane flame alone caused little variation in the coupling between the loops. Rock salt (NaCl) was placed in the nozzle of the torch in such a position that it was ionized by the flame. The fuel was adjusted so that an even, medium yellow flame resulted. When the probes were coupled with this more highly ionized flame, the coupling was raised at frequencies below 100 Mc. The coupling between the probes increased 40 db at 1 Mc in the presence of the sodium flame; the increase was 20 db at 10 Mc with very little change noted above 100 Mc. The coupling exhibited as much as 10 db variation with normal flame fluxuations. Least attenuation occurs when the largest number of sodium ions are being released. The figures quoted for 1 and 10 Mc are the minimum changes that occurred at those frequencies upon application of the flame.

The effect of a high powered signal on the nonlinear properties of ionized media is of considerable interest. Efforts are underway to use a 100-watt, 10 to 15 Mc amplifier to couple large signals to flames, plasma tubes, and, later, to an oxygen-hydrogen rocket engine. A coupling network has been constructed to match the output impedance (50 ohms) of the amplifier to a multi-turn loop antenna. The field developed by this antenna should be as strong as any that might actually be encountered in the vicinity of a rocket exhaust and should accent any interference generation that might occur as the result of high power dissipation in an ionized media.

Future Effort:

The development and testing of various coupler configurations will continue during the next reporting period. Additional intermodulation data will be accumulated for the coaxial plasma line to provide better insight into the loss phenomena encountered by signals escaping the plasma media. Much of the data previously collected will be reduced such that power absorption and intermodulation rejection may be determined for electrically sustained argon plasma.

Respectfully submitted:

[redacted]

R. D. Trammell, Jr.
Project Director

Approved:

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D. W. Robertson, Head
Communications Branch

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Attention: Mr. R. W. Blanchard, Chief
Electromagnetics Section, EF34

Reference: Contract No. NAS10-2639

Title: "A Study of Certain Propagation Anomalies in Radio Frequency Signals"

Subject: Monthly Progress Report No. 4, Project A-873
Covering the Period from October 1 to October 31, 1965.

Gentlemen:

Effort during the fourth reporting period has been directed to the development and evaluation of coupling techniques. Continued effort was devoted to the construction of 3-db hybrids to minimize receiver and generator intermodulation. Various configurations of coaxial, helical couplers were evaluated.

Attempts to construct a 3-db, double-hybrid coupler for the frequency range from 10 Mc to 1000 Mc were largely unsuccessful. Resistive 6-db hybrids operated well in the double configuration, but the total loss through the two units was excessive for the required measurements. Three different 3-db hybrid connections were attempted using twisted-pair transmission-line windings on ferrite torroids. All three of these failed to exhibit sufficient isolation to prevent generator intermodulation. Smaller ferrite cores might have improved the operation of these units, but sufficient time for development and parts acquisition was not available.

Two Anzac model H1 hybrid couplers were purchased to facilitate intermodulation measurements in the frequency range from 5 Mc to 1000 Mc. The performance of these units according to specifications has been verified; they should minimize the problems of generator and receiver intermodulation over their specified range of operation.

Data obtained on 17-inch and 47-inch columns of glow-discharge plasma, confined within a coaxial coupler, indicate that most of the absorption and intermodulation activity occur in the dark regions (Faraday region, etc.)

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at the cathode end of the plasma column. The positive column appears to act as a fairly good conductor over the region from 10 Mc to 500 Mc. Insertion loss data on the 17-inch and 47-inch columns range from 10 db to 60 db and differ by only 1 to 3 db over the range from 10 to 1000 Mc. The dark regions for both tubes are approximately the same length while the positive column is considerably shorter in the 17-inch tube. The small relative difference in insertion loss between the two tubes indicates that the majority of the loss cannot be attributed to absorption in the positive column.

In Monthly Progress Report No. 3, the results of an investigation of two multi-turn loop couplers were discussed. Since the couplers are essentially antennas, the energy coupled from one to the other is a function of their radiation patterns at the particular frequency of investigation. The plasma appears as a good conductor in some frequency ranges. In these ranges, the radiation patterns of the loops will be altered by the plasma connecting the loops. The change in coupling between the two loops upon the addition of the plasma is due to the effect of absorption by the plasma and to the modification of the radiation patterns of the loops. The separation of these two factors is a difficult process.

A coaxial system circumvents some of the difficulties of loop antennas. An argon plasma tube was incorporated into a coaxial configuration by mounting it in a 2-1/2 inch copper pipe. The results of some of the tests made on an 8-watt fluorescent lamp were briefly discussed in Monthly Progress Report No. 3. Further tests were made to determine if the attenuation measured through the helical coupler was due to absorption by the plasma. In addition to absorption, the attenuation could have been caused by impedance mismatch at the input and output of the coupler. Another possibility was that energy was being radiated out the ends of the coaxial section. Up to 2000 Mc, the mismatch at both ends of the coil was not sufficient to account for more than 2-db of the attenuation that was measured. To check the possibility of radiation from the ends of the system, the VSWR at one input to the coupler was measured with the ends of the outer conductor enclosed with copper foil covers and compared with that obtained with the ends open. No significant differences were noted below 2400 Mc. Above 2400 Mc, the differences can be attributed to the propagation of circular waveguide modes. In view of these results, the attenuation measured below 2000 Mc is attributed to absorption by the plasma.

Another coaxial coupler configuration was constructed to accomodate a larger plasma tube. A 15-watt fluorescent lamp was positioned in the center of a 2-1/2 inch copper pipe. The pipe was made long enough to allow each end of the lamp to be no closer than one foot from either end. Four type N panel jacks were mounted on the outer wall to provide access every 10 cm along the lamp. The different access points allow measurements to be made in different regions of the plasma column.

Tests were made on a uniformly wound coil placed at two positions along the tube; one near one end of the tube and the other near the center. The coils consisted of 16 turns over a total length of 10 cm. Higher attenuation was measured on this tube than with the 8-watt lamp. Attenuation was in excess of 20 db from 400 Mc to 2000 Mc. Below 500 Mc the impedance match was better for the large coupler but deteriorated at 1500 Mc instead of 2000 Mc.

Another helix was wound over a 20 cm length with a logarithmic distribution of turns and tested with AC and DC excitation of the lamp. Attenuation measurements were made with the coil connected between ports 1 and 3. Port 1 is located approximately one-half inch from one end cap of the fluorescent lamp. VSWR measurements were made at ports 1 and 3 for each mode of excitation.

The first series of tests were made with 60 cps, 110 volt excitation. The attenuation was greater than that measured with the uniform helix, but this could be due in part to the greater length of the logarithmic helix. Improved impedance match was noted from 700 Mc to 2000 Mc. A lower VSWR was obtained below 500 Mc particularly at port 1 which is the open end of the logarithmic spiral.

Two series of tests were made with DC excitation; one with the electrodes of the tube near port 1 as the positive terminal and one with the polarity of the electrodes reversed. The attenuation patterns were similar. Two regions of very high attenuation were noted in both cases. Near 1500 Mc the attenuation was in excess of 70 db and near 3000 Mc the attenuation approached 50 db. The VSWR at port 3 in both cases reached extreme values at these frequencies. The VSWR at port 1 exhibited less severe excursions than that at port 3.

Arrangements have been completed for the use of an oxygen-hydrogen rocket engine. Instruction has been received on the procedure for running the engine. Procedures for the rapid procurement of oxygen and hydrogen gases necessary for the rocket engine are being clarified.

Effort during the next period will include intermodulation and harmonic measurements on coaxial and helix coupled glow-discharges in argon gas. Construction of a helical coupler for use with oxy-hydrogen flames at temperatures between 6000 and 7000 degrees Rankine will be undertaken and tests begun for VSWR and insertion loss. A further reduction of existing data will be accomplished for use with the more recently acquired intermodulation data.

Respectfully submitted:

[redacted]

for R. D. Trammell, Jr.
Project Director

Approved:

[redacted]

D. W. Robertson, Head
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Attention: Mr. R. W. Blanchard, Chief
Electromagnetics Section, EF34

Reference: Contract No. NAS10-2639

Title: "A Study of Certain Propagation Anomalies in Radio Frequency Signals"

Subject: Monthly Progress Report No. 5, Project A-873
Covering the Period from November 1 to November 31, 1965.

Gentlemen:

During this reporting period, a helical coupler has been fashioned and tested for use with an oxygen-hydrogen rocket exhuast. Significant harmonic and intermodulation products have been measured with helical couplers on glow-discharge plasmas of argon. It has been made reasonably apparent that harmonic and intermodulation product rejection is a function of total input power contained in the incident waves producing the product, though the range of significant power levels is presently unknown.

Glow-Discharge Tests:

Intermodulation and harmonic products were measured for a glow-discharge plasma of argon using the logarithmic helix coupler described in Monthly Progress Report Number 4. In all cases tested, the incident frequencies were admitted at port number 1. Excitation of the glow-discharge was accomplished with a constant current of 300 milliamperes, both AC and DC. No significant change in product generation was noted between the various modes of excitation which include reversing the flow of the direct current. Second harmonic rejection versus fundamental frequency is shown in Figure 1 for three modes of excitation with an input level of +12 dbm.

The levels of several products were measured at both the number 1 and number 3 ports of the helical coupler. A larger product level was found to exist at port number 3 for the cases tested. Consequently, the majority of data were obtained at port number 3. The apparent directivity may be a function of the type of coupler used rather than a property of the plasma

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medium itself. In the case of the coaxial coupler, the larger values of product level were obtained at the same port as was used to admit the incident frequencies. This result is in direct opposition to that noted for the helical coupler and indicates that the directivity of the products may be a function of polarization and/or incidence angle of the fundamental waves. Further testing is necessary to determine that such activity is a valid property of the plasma media.

The level of an intermodulation product generated within a plasma appears to be dependent on the total power level of the incident waves producing the product. The behavior appears to follow that of a common diode mixer if coupling difficulties are excluded. The primary difference lies in the range of input power levels over which intermodulation is significant.

If two signals are introduced and form a second order intermodulation product within a plasma, raising the level of either input by 1 db will raise the product level by 1 db. Raising both input levels by 1 db raises the product level by 2 db, etc. At least this general rule is valid over input power ranges between -2 and +10 dbm for the coupling conditions existing in the couplers being tested. Typical intermodulation levels for a total input power of 12 to 18 milliwatts appear in the table below:

HELIX COUPLED INTERMODULATION
PRODUCTS IN ARGON GLOW-DISCHARGE

INPUT f_1		INPUT f_2		$f_1 + f_2$		$f_2 - f_1$	
Mc	DBM	Mc	DMB	Mc	DBM	Mc	DBM
50	+8	230	+8	280	-30	180	-37
80	+9	200	+9	280	-30	120	-34
80	+9	120	+9	200	-31	40	-41
85	+9	115	+7	200	-31	30	-43
90	+7	110	+7	200	-31	20	-45
115	+7	185	+8	300	-36	70	-40
120	+9	180	+8	300	-36	60	-42
125	+9	185	+8	310	-37	60	-42
160	+7	240	+8	400	-40	80	-37
180	+8	220	+8	400	-38	40	-42
190	+8	210	+8	400	-38	20	-46
225	+8	275	+8	500	-53	50	-42

The random variations in sum and difference levels appears to be a function of the coupler's frequency characteristics rather than a definite indication of parametric mixing. Levels measured on a coaxial coupler show larger levels at the difference frequency in the majority of cases.

It is noted that the intermodulation products exhibit maximum levels of some 40 db below the total input power for the 18 milliwatt levels shown. At input levels of -2 dbm, the maximum product levels fall some 60 db below the total input power of 1.8 milliwatts. Based on the above observations, the maximum product levels at 180 milliwatts of input power would lie only 20 db below the input power level for equal input levels at both frequencies. Thus for a total input power of 0.2 watts, intermodulation would be a problem in glow-discharge plasmas.

The problem is made more difficult by the fact that only one of the input levels need be large to obtain efficient mixing within the plasma. If one signal has a level of 0.2 watts, intermodulation products will lie only 20 db below the smaller signal's level from noise to +10 dbm or better. These results are only theoretical at present because data are not available for inputs in excess of +13 dbm.

Rocket Engine Tests:

Tests on the oxygen-hydrogen rocket engine have produced only limited results since most of the available time was expended in developing a suitable coupler.

A coaxial-type coupler was constructed similar to the one found useful with the argon tube experiment. A 6 3/8" I.D. 3 foot long aluminum pipe was used as an outer conductor with the rocket exhaust acting as the center conductor. The pipe was positioned to axially align with the rocket nozzle. A helix was positioned in the pipe to enclose the path of the exhaust. Both ends of the coil were terminated in a type N panel jack.

The visible portion of the exhaust was estimated to be 14 to 18 inches long. A coil was constructed of No. 12 solid copper wire to a length of 16 inches. A 5-second run of the engine loosened the soldered connections to the rf connectors and melted the coil at one point. Another coil was constructed of 1/8" O.D. Copper capillary tubing that has a 0.07" hole in the center. This coil also experienced excessive heating during a 5-second run even though water was forced through the tubing.

The next coil was constructed of 3/16" O.D. copper tubing with approximately 1/8" I.D. The length was shortened to 8 inches. A water line attached to the end of the coil nearest the rocket provided adequate cooling even for runs as long as 20 seconds.

Once a useable coil was developed, tests to determine the level of harmonic generation in the exhaust were initiated. Tests were run for second harmonic generation from fundamental frequencies of 5 Mc to 115 Mc.

The harmonic level was found to vary too much to obtain a valid average reading on the NFIM (Singer NF-105). An X-Y recorder was employed to record the amplitude variations of the signal as a function of time. Calibration lines on the recorder enabled the excursions of the signal to be measured.

Figures 2 and 3 are copies of the recorded amplitude variations of the second harmonics of 20 and 40 Mc, respectively, as a function of time. Specific power levels at the NFIM input are indicated at the left margin of the figure. The very definite effect of the exhaust gases is apparent in the sudden increase in harmonic level immediately after firing. The residual level is that due the second harmonic of the signal generator which is not completely attenuated by the low-pass filters that were inserted for each test run. Also, part of this residual may be due to second harmonic generation in the input stages of the NFIM. The effect of the rocket ignition phase is observed in the interval before actual firing by noting that the level is higher than the residual.

The highest levels of any products are in the neighborhood of 90 db below the level of the fundamental. This means that the level of the harmonic at the NFIM is 90 db below the fundamental level at the generator. This result may be significant because the indication of the power absorbed by the plasma was immeasurably small, being in the order of 0.1 db of insertion loss created by firing the engine. If it were a 0.1 db insertion loss, the total incident power level would fall 17 db below the 0 dbm output level of the generator and the harmonic level would lie only 73 db below the fundamental level. Since -17 dbm represents a small amount of incident power for non-linear activity even within glow-discharge plasmas, the resulting low level of second harmonic generation may indicate a significant amount of second order activity within the oxygen-hydrogen plasma. Further testing will be necessary to establish the effectiveness of the coupler.

Future Effort:

During the next period, tests will continue on the oxygen-hydrogen engine to include the injection of alkaline materials for the simulation of solid rocket plumes. Tests will be conducted on the glow-discharge plasmas to determine that larger input levels will improve the second order generating efficiency of the plasma medium. Further reduction of existing data and correlation of results will be attempted.

Respectfully submitted:

[redacted]

R. D. Trammell, Jr.
Project Director

Approved:

[redacted]

D. W. Robertson, Head
Communications Branch

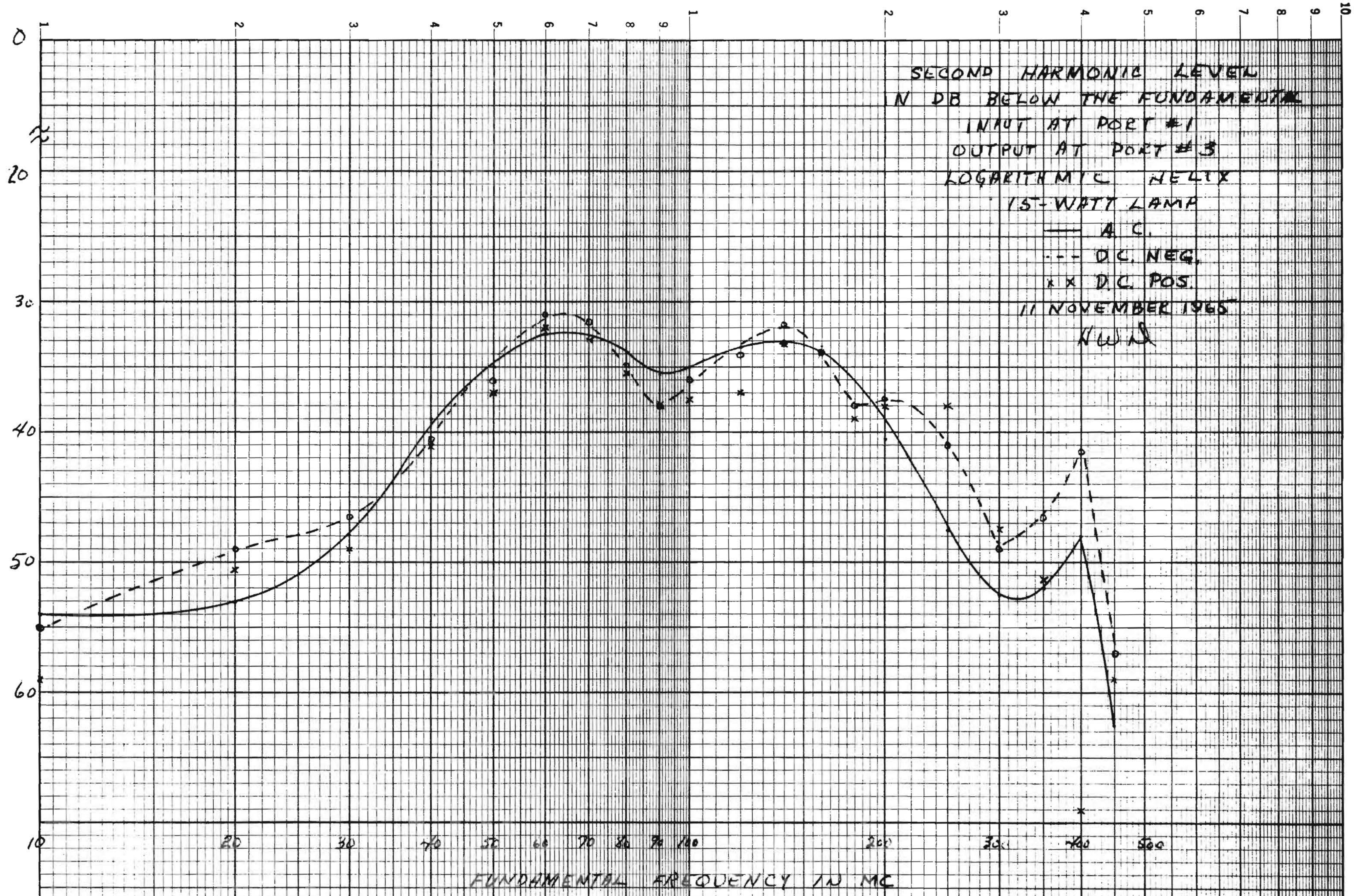

FIGURE 1. HARMONIC GENERATION PROPERTIES

Input Frequency: 20 Mc
Input Level: +10 dbm

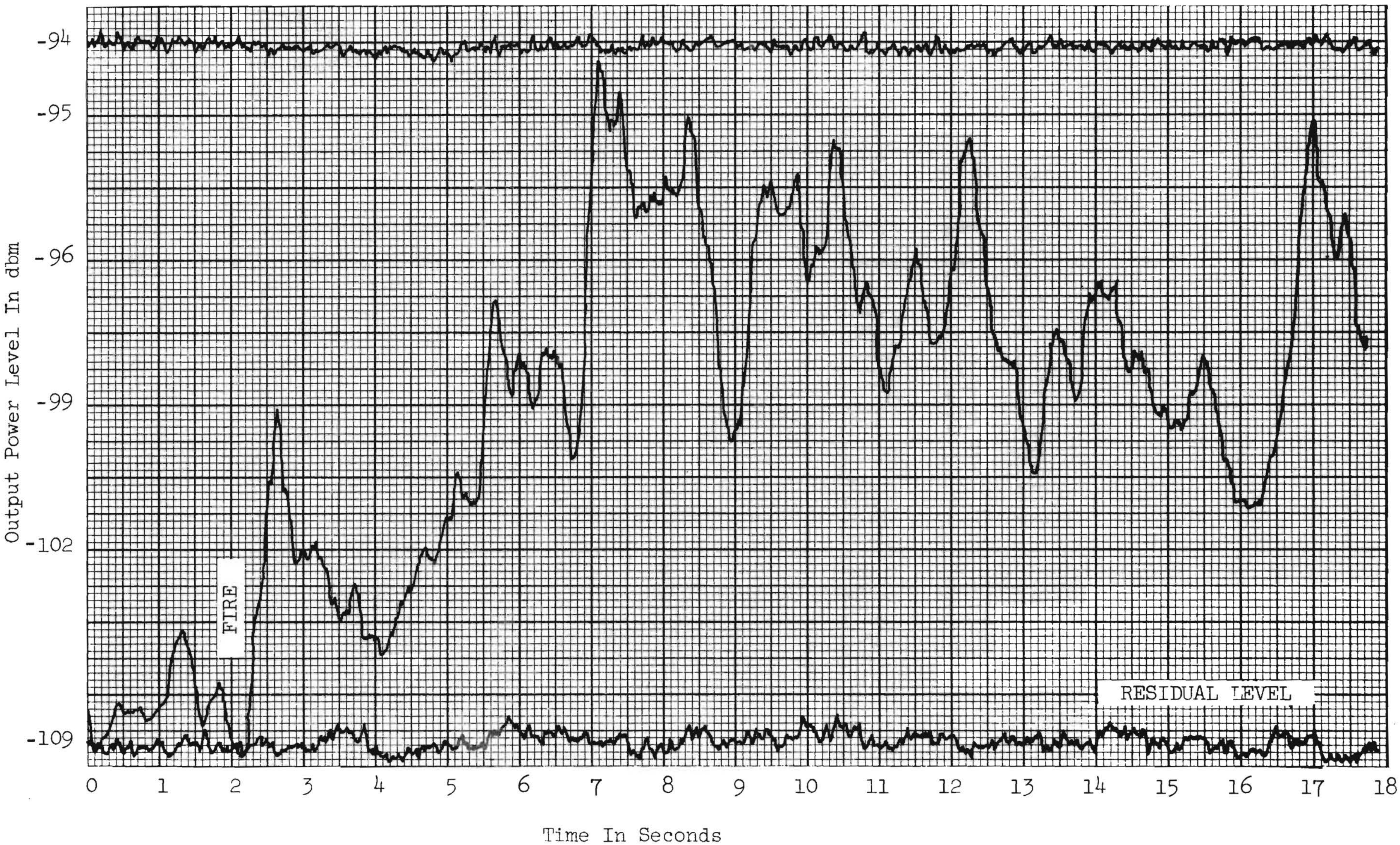

Figure 2. Second Harmonic Level Versus Time

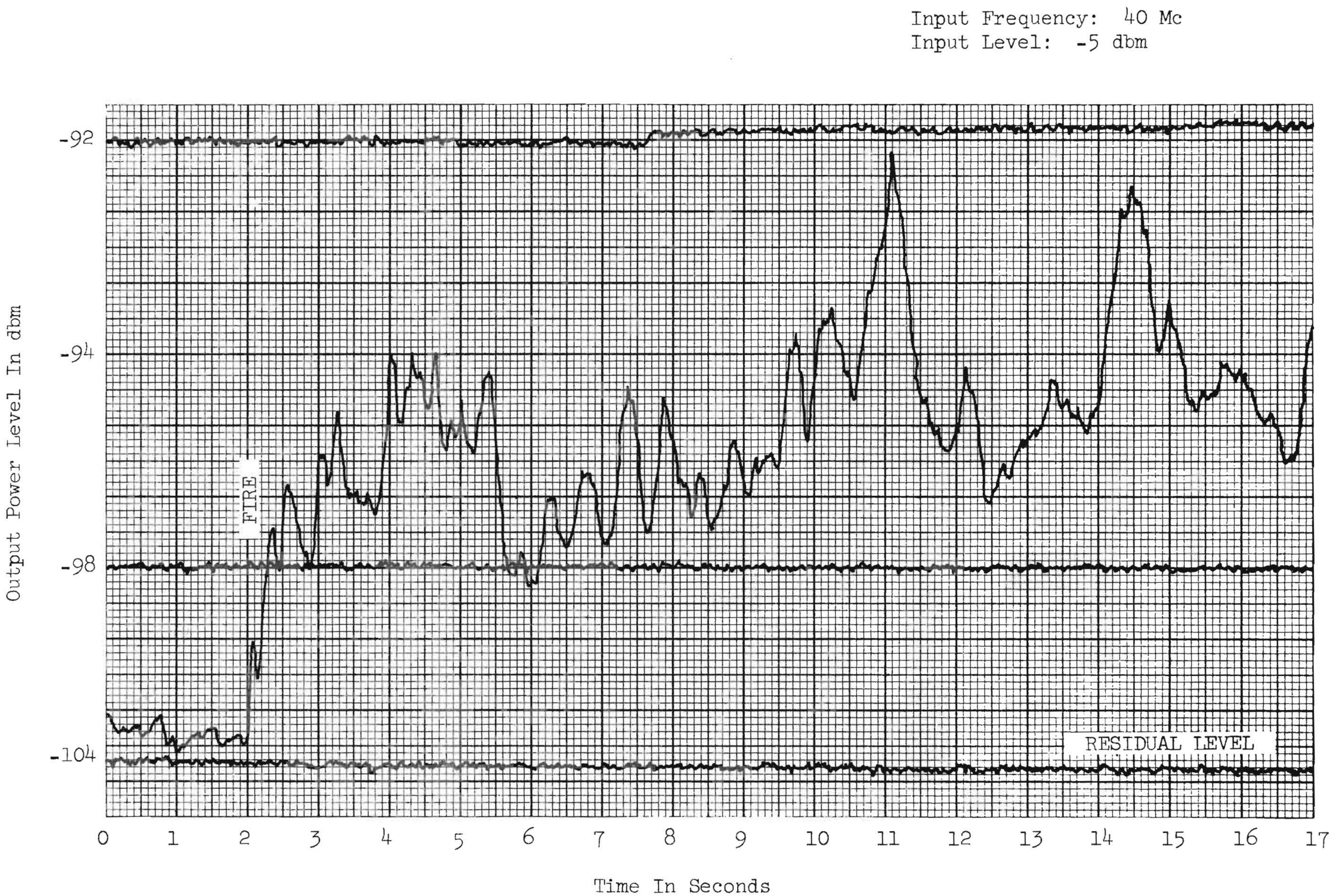

Figure 3. Second Harmonic Level Versus Time

FINAL REPORT

PROJECT A-873

A STUDY OF CERTAIN PROPAGATION ANOMALIES IN RADIO FREQUENCY SIGNALS

R. D. TRAMMELL, JR. AND H. W. DENNY

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30 June to 29 December 1965

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National Aeronautics and Space Administration
John F. Kennedy Space Center
Cocoa Beach, Florida

1965

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Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

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FINAL REPORT

PROJECT A-873

A STUDY OF CERTAIN PROPAGATION ANOMALIES IN RADIO FREQUENCY SIGNALS

By

R. D. Trammell, Jr. and H. W. Denny

CONTRACT NO. NAS10-2639

30 June to 29 December 1965

Prepared for
National Aeronautics and Space Administration
John F. Kennedy Space Center
Cocoa Beach, Florida

FOREWORD

This report was prepared at the Georgia Tech Engineering Experiment Station under Contract No. NAS10-2639 with the National Aeronautics and Space Administration, John F. Kennedy Space Center, Cocoa Beach, Florida. The materials contained herein present the results of a six-month experimental study of the nonlinear properties of plasma media.

The program was conducted under the general supervision of D. W. Robertson, Head, Communications Branch. Acknowledgement is made to Messrs. R. L. Fitzwilson and M. O. Bennett for their contributions in equipment construction and the measurement of the parameters required for this study.

Respectfully submitted:

[redacted]

Robert D. Trammell, Jr.
Project Director

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M. W. Long, Chief
Electronics Division

ABSTRACT

Two closed system methods for coupling rf to a plasma were developed and utilized to measure the nonlinear properties of glow discharge and flame plasmas. One coupling technique utilized the plasma column as the center conductor of an rf coaxial line. The other technique employed a helix surrounding the plasma column such that it could be used with hot flame plasmas.

Levels as high as -43 dbm of intermodulation signal were measured with argon glow discharge and two input signals of zero dbm. Level relationships between input and output signals were measured and extrapolated to predict the product generating efficiency for +30 dbm input levels. Measurements performed at a +20 dbm input level on the exhaust plasma of a small scale oxygen-hydrogen rocket engine provided evidence of second harmonic generation at levels of about -62 dbm. These tests were only marginally successful because of the low efficiency of the rf coupling to the plasma medium.

Tests were performed for incident signals between 10 MHz and 450 MHz and product signals between 10 MHz and 900 MHz. The close relationship of the physical parameters for glow discharge and flame plasmas indicate that intermodulation and harmonic generation due to the interaction of electromagnetic waves in a plasma may become a serious source of interference during launch vehicle flights. This is particularly true of plasmas generated by antenna breakdown in rarefied or plasma laden atmospheres.

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I. INTRODUCTION

The contents of this document comprise the findings of an initial study to establish an understanding of the phenomenon of intermodulation and harmonic generation of electromagnetic waves in plasmas as it applies to the potential threat of interference from nonlinear interaction in the plasmas created by launch vehicles. The purpose of the study was to provide the NASA with a knowledge of the intermodulation and harmonic levels which might be generated through the interaction of electromagnetic waves in plasma media, and to enable cognizant personnel to determine whether there is a potentially serious interference threat from this source. The scope of the research was to conduct theoretical and laboratory scale experimental investigations into the nature and magnitude of nonlinear interactions between electromagnetic waves in plasma media similar to those created by a launch vehicle during flight. Criteria for flight experiments and for a means to collect and record the information on the ground were included in this investigation for the future substantiation of laboratory findings.

The Luxemburg effect and subsequent investigations of plasma properties relating to nonlinear effects in plasmas indicate that the intermodulation products of electromagnetic waves can be generated within a plasma medium.[1,2,3] Intermodulation interference similar to that which occured during the prelaunch testing of Saturn launch vehicles might be generated within plasma media created by the launch vehicle during flight to the extent that a loss of transmitted data or control information would occur. Though several documents support this possibility, few indicate to what extent intermodulation will occur in a plasma and virtually none contain substantiating experimental data for frequencies below the critical frequency of the plasma. The present study was initiated to provide rudimentary data for predicting the extent to which interference might be produced by a plasma. This required the development of broadband rf couplers and special measurement techniques to provide experimental data indicating the level and other peculiarities of harmonic and intermodulation generation occurring in the plasma media. Glow discharge, flame, and seeded flame plasmas were tested at frequencies ranging from 10 MHz to 1000 MHz during the course of this study.

Several studies[4,5,6,7,8] in the past have evaluated the absorption and phase shift properties of plasmas in general and rocket exhausts in particular. Other studies[9,10,11] have investigated the nonlinear properties of plasmas. Barrett and Whitmer[12,13] have performed a mathematical analysis of the wave equation of an electromagnetic wave traveling through an idealized plasma. Their analysis retained the parameters which produce harmonics as an integral result of the wave traveling through the plasma, and is applicable to the efforts of this study in that it defines and organizes much of the problem. It serves to shed much light on the mathematical basis of harmonic generation. The study, though, is not sufficiently descriptive of the situation of concern in this report, in that it primarily treats the case $\omega_p/\omega \ll 1$, i.e., the plasma frequency* is below the frequency

*Plasma frequency designates that frequency above which the plasma is essentially transparent to an electromagnetic wave.

of concern. The highest harmonic levels predicted and measured in the study of Barrett and Whitmer were on the order of 110 db below the fundamental. The levels presented elsewhere in this report are considerably larger which indicates that their analysis is not sufficient to completely describe the situation studied under this contract.

The Luxemburg Effect[14] results from a condition whereby one signal is modulated by changes in the propagation medium which are produced by the same or another signal. The dielectric constant is actually changed through increased ionization of the medium brought about by one of the signals. The plasmas studied during this six month period probably generate harmonics through a combination of the above phenomena.

II. FACTUAL DATA

A. Analysis of Plasma Media and Coupling

Two forms of plasma generation were utilized in this study, the chemical reaction or flame and the glow discharge. Flame plasmas were generated by the common propane torch and by a small oxygen-hydrogen rocket engine. The glow discharge was readily available in the form of standard fluorescent-configuration argon lamps.

The small rocket engine utilized in the tests did not necessarily present the best model for studying the properties of an exhaust plume the size of that generated by a Saturn rocket. The dimensions of a Saturn rocket plume are such that it is many wavelengths long and several wavelengths across for frequencies in the 200 MHz telemetry band. It provides a large area for the interception of power from incident waves well below 200 MHz. The exhaust from the small scale engine is not sufficiently large to provide for useful power transfer at the frequencies of interest. Direct frequency scaling cannot be used because the electron concentration in the exhaust plasma is not sufficiently high to accept power at frequencies proportional to the flame size. The power absorbing capacity of the small exhaust can be improved by "seeding", i.e., injecting easily ionized materials into the plasma to increase the electron concentration. Measured data describing the distribution and magnitude of the electron concentration in the Saturn exhaust were not available for this study and, although the test plasmas were "seeded" with alkaline materials, no attempt was made to precisely control the electron concentration.

Additional knowledge of the electron concentration characteristics of the Saturn exhaust and development of a precise feed mechanism for seeding the small scale test plumes should permit, in future tests, direct frequency scaling and collection of applicable data in the laboratory.

Glow discharge plasma provided a good study medium for the purposes of this study for three primary reasons: 1) it is easily generated, controlled and contained, 2) it can be used to study various coupling techniques as its cylindrical shape is similar to the exhaust plume of a rocket motor, and 3) its physical parameters overlap those of flame plasmas even though its electron concentrations and temperatures are dispersed around a slightly higher average.[15] The nonlinear activity prevalent in a glow discharge plasma should be akin to that of a flame plasma providing that equivalent coupling conditions are assumed.

The first step taken in this study of plasmas was the development of an effective coupler. Two basic techniques are described along with a number of evaluation measurements in the Appendix. Both the "in-line" coaxial and helix couplers were useful in performing studies of glow discharge plasmas. The coaxial coupler was preferred when performing measurements below 300 MHz as its impedance provided a better match than the helix; however, the helix presented a better match above 700 MHz.

The helix coupler does not make actual contact with the plasma medium; therefore, it can be used for comparison studies on glow discharge and flame plasmas. The helical coupler behaves in a manner analogous to that of a conventional step-down transformer. With no plasma present, the coil has an impedance and insertion loss behavior pattern similar to the primary of a transformer with the secondary open. When the plasma column is introduced along the axis of the coil, power is coupled to the plasma. The primary impedance variations are as if the Q of the input had been lowered by putting a low resistance across the secondary. The frequency response is broadened and the impedance variations are smoothed out. Figure 1 demonstrates this behavior by showing how the standing wave ratios at the input of a helix coupler change when the glow discharge plasma was energized.

The coaxial coupler provided a very consistent match over a wide bandwidth and thus was utilized to examine many of the basic nonlinear generating qualities of a plasma medium. This technique provides coupling by launching a normal electric field wave down the plasma column. The field extends into the medium where it slows down and creates a tangential component. The tangential component provides for power transfer into the plasma medium in a radial direction. The total Poynting vector therefore slopes into the plasma medium and power transfer is accomplished. The plasma acts as a lossy center conductor in a coaxial transmission line.

B. Measurement Techniques and Results

Accurate measurement of the product signal levels generated in a plasma medium is difficult to achieve because the generating efficiency of a plasma is quite low for the input power levels available from standard signal generators. This is particularly true when all of the involved signals must be measured through the same coupler port. The large incident signals required to generate measurable product levels cause sufficient intermodulation in signal generators and radio frequency measuring sets

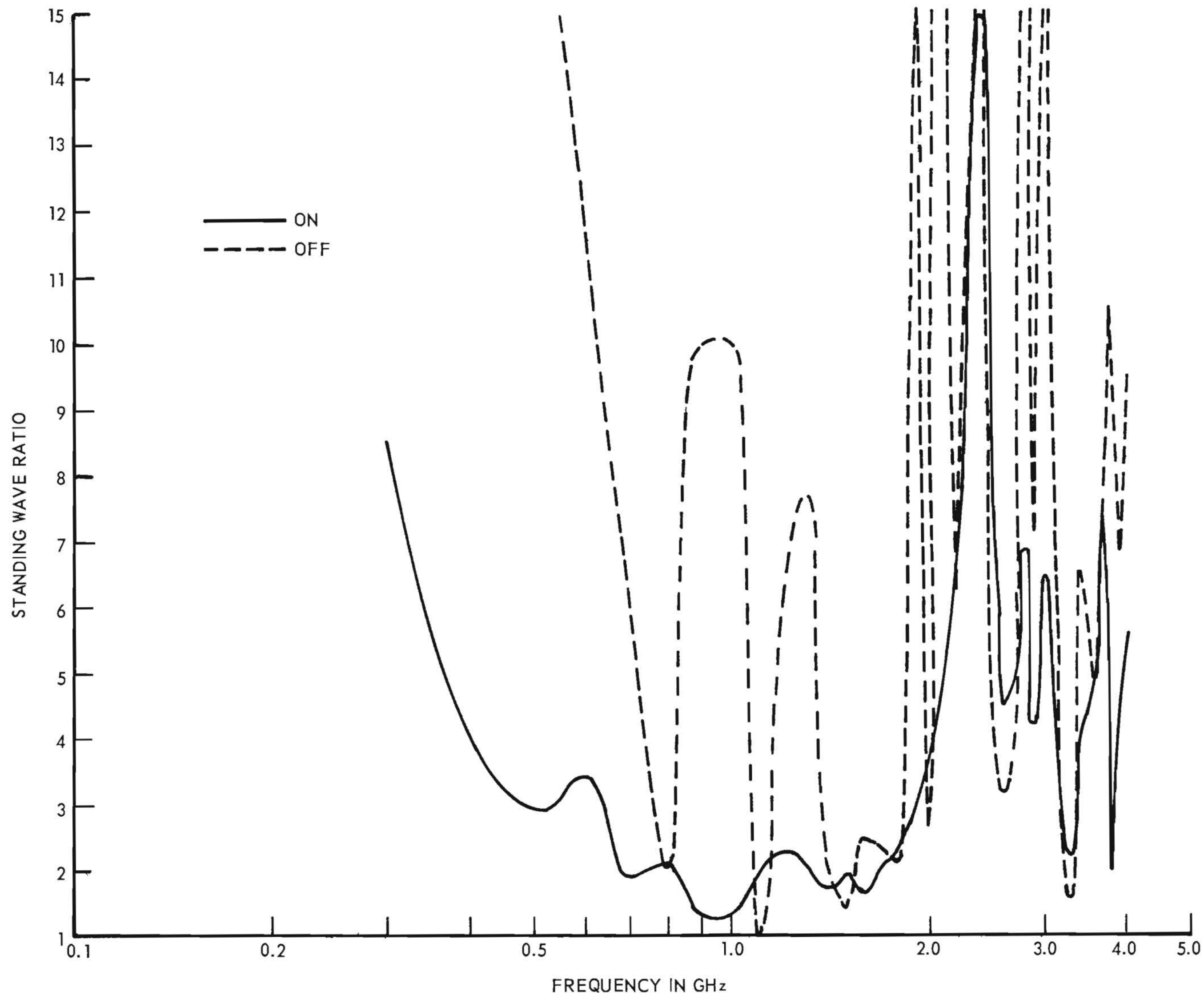


Figure 1. Comparison of the Standing Wave Ratio Patterns of the Helix Coupler for the Plasma Tube in the ON and OFF States.

(RFMS) to completely override the signals from the plasma unless a high degree of isolation is provided between equipments. Standard wideband methods of accomplishing the necessary isolation create excessive signal loss which defeats the experiment. Filter methods are expensive and excessively time consuming when many different test frequencies are utilized. A measurement technique suitable to the evaluation of nonlinear activity in a weakly active medium was developed using single or double 3 db wideband hybrids to provide sufficient isolation between equipments without seriously attenuating the desired signal flow. Two Anzac, Model H-1, 5 to 1000 MHz hybrids were used either singly or as a double hybrid by connecting them in series through the low impedance ports on a 25 ohm matching basis. This provided three 50 ohm ports and one 25 ohm port which were utilized according to the block diagrams of the various test setups described below.

Several test setups were required to perform the various measurements under consideration. Five typical setups are shown by block diagram in Figures 2 through 6. These will be referred to as plans 1 through 5 respectively. Where both the sum and the difference frequency are to be measured, two RFMS's are utilized for simultaneous readings. Standard EMC procedures were followed in obtaining the data and signal substitution was utilized instead of the calibrated receiver in determining accurate signal levels.

In order to determine that no equipment intermodulation would degrade the measurements, the hybrid setups were checked at each set of operating frequencies under full generator output (+13 dbm) with the plasma coupler replaced by a linear mismatch equal to the worst condition presented by the

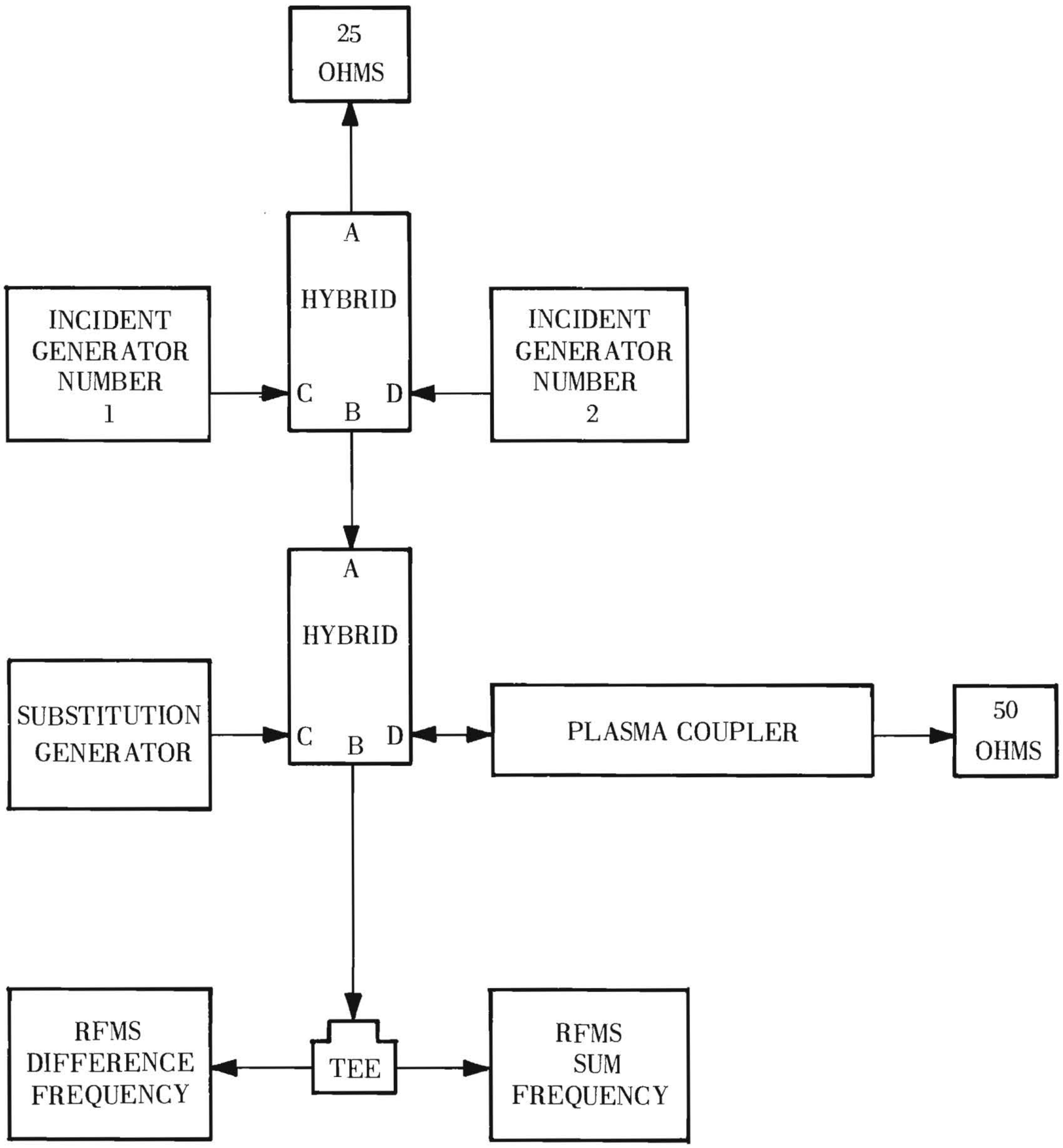


Figure 2. Setup for One-Port Intermodulation Measurements.

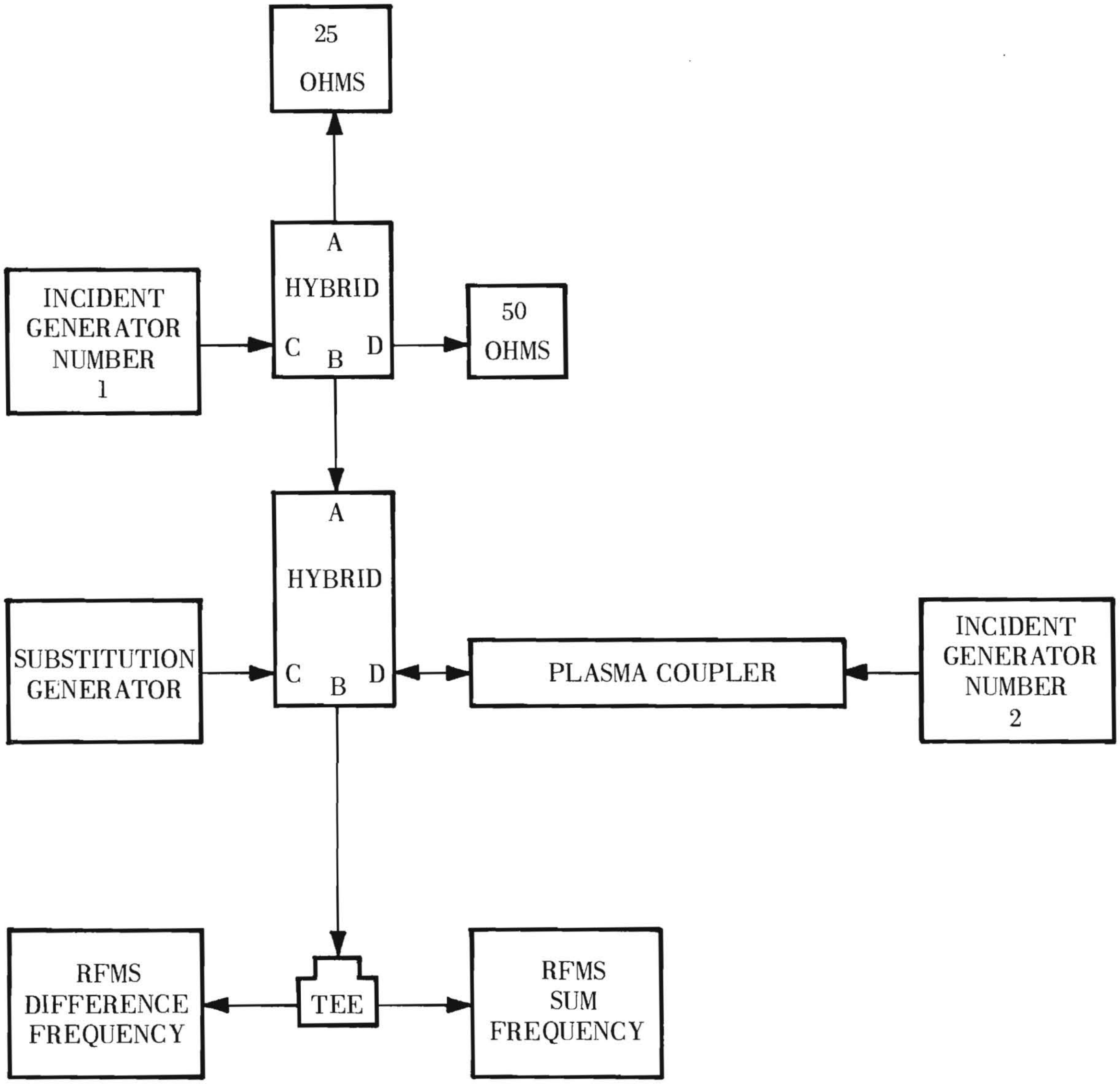


Figure 3. Intermodulation Measurements Setup for Two Generator Ports.

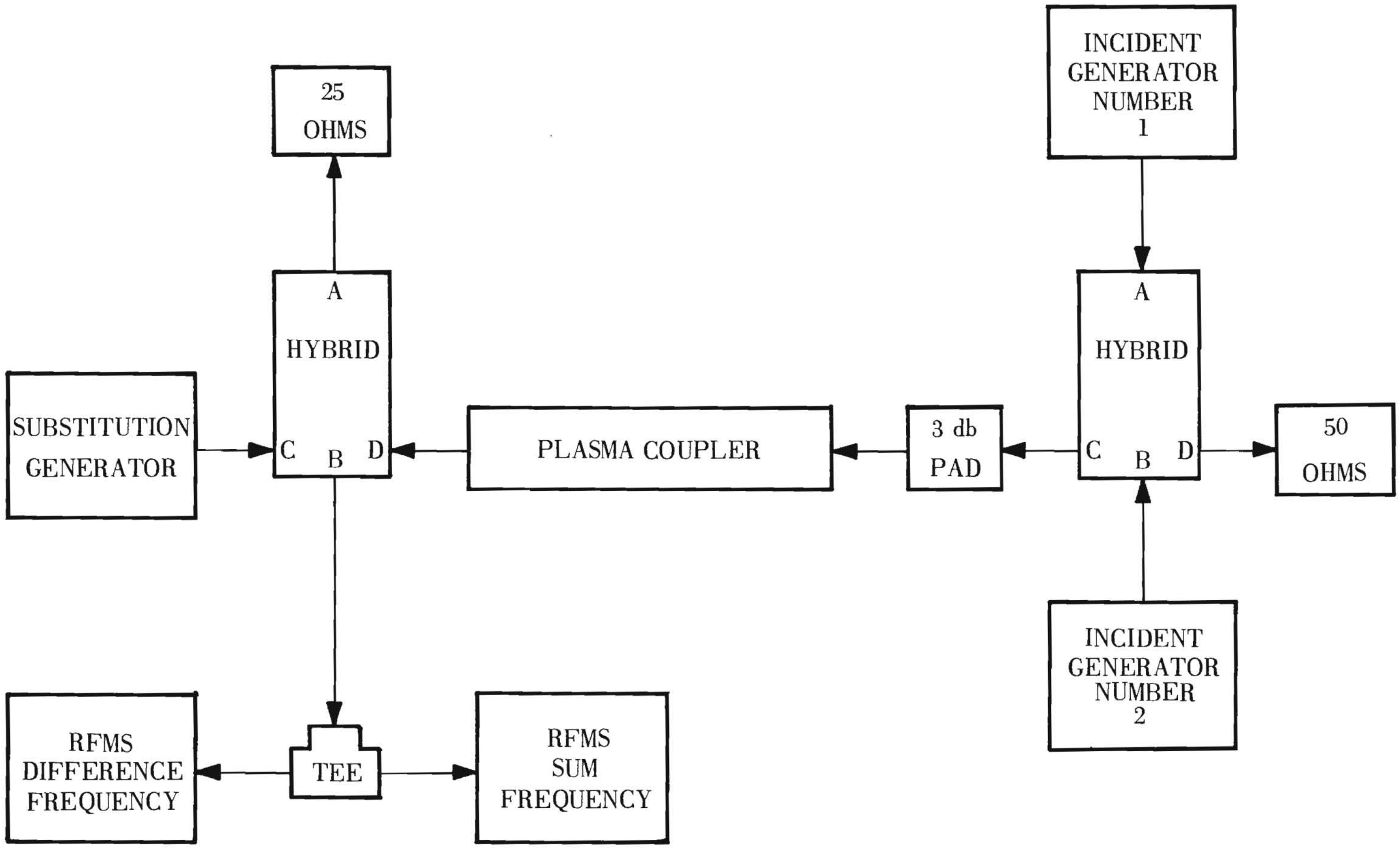


Figure 4. Intermodulation Measurements Setup for Separate Input and Output Ports.

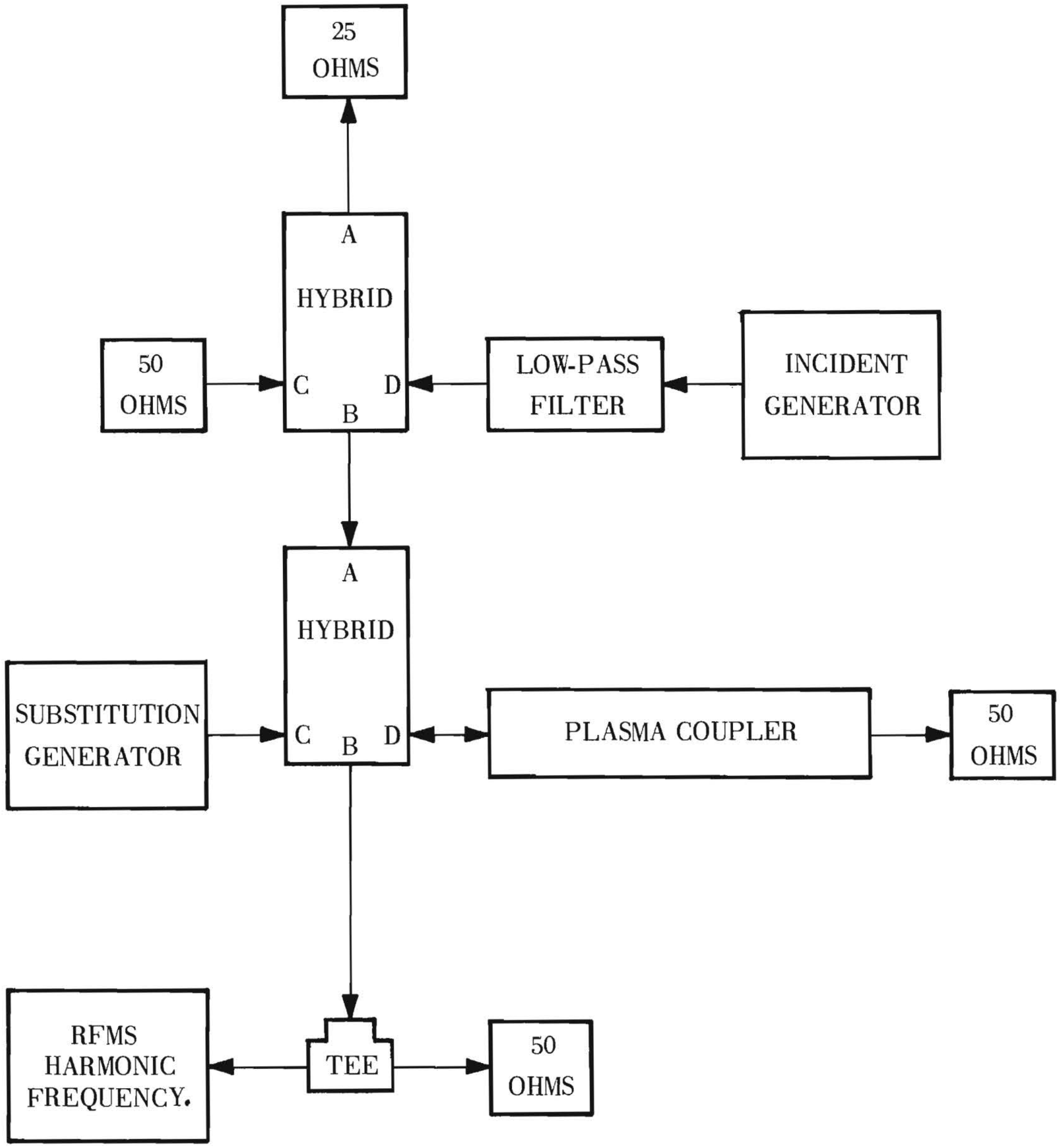


Figure 5. Setup for One-Port Harmonic Measurements.

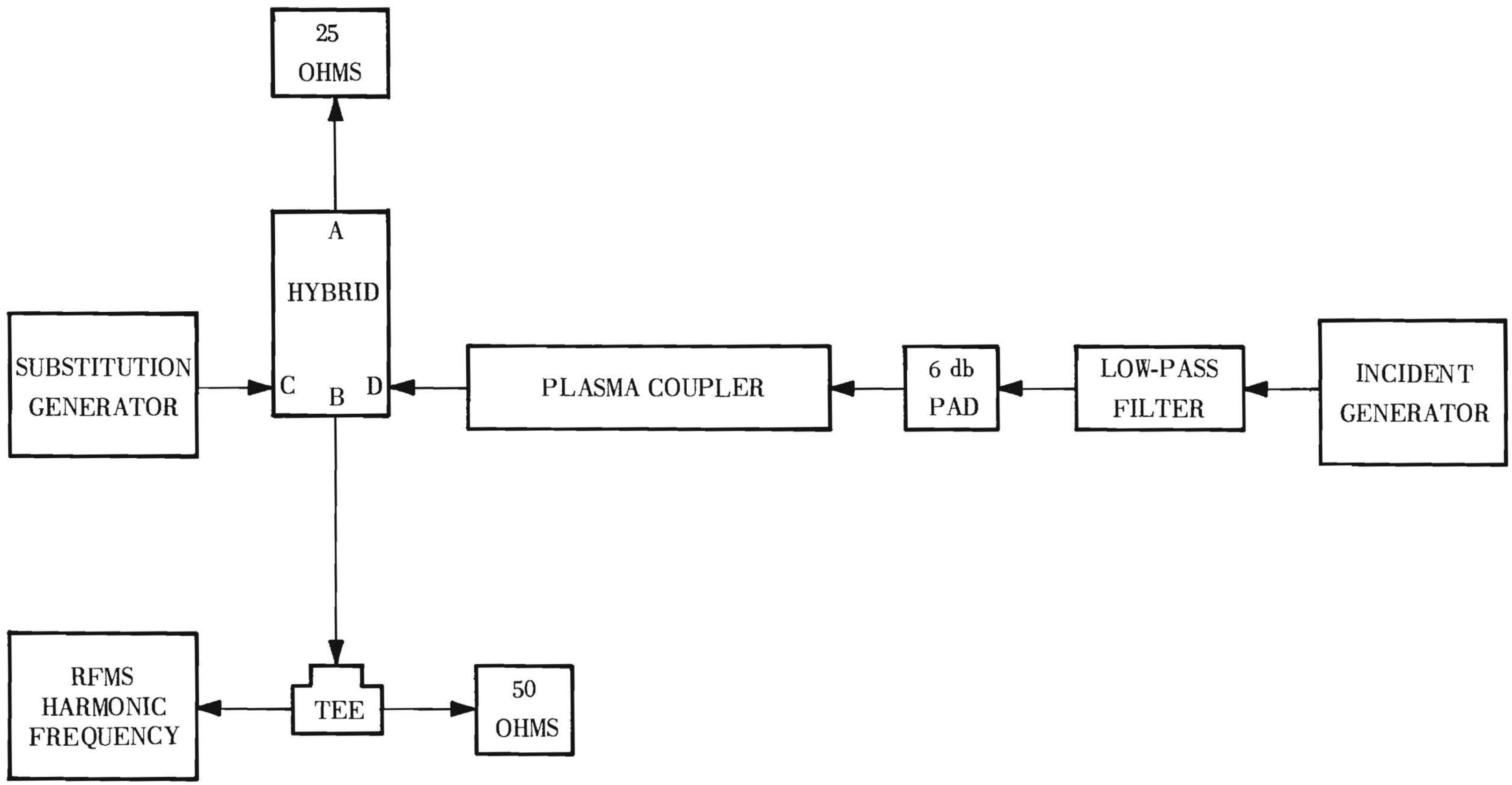


Figure 6. Harmonic Measurements Setup for Separate Input and Output Ports.

coupler proper. No spurious products were found to exceed a value of -84 dbm. With the plasma coupler replaced by a 50Ω termination, no spurious products were detected above the system noise level.

Intermodulation and harmonic levels were measured using the coaxial coupler with both 47 inch and 18 inch glow discharge tubes. Intermodulation data were obtained for up to twelve different frequency combinations for overlay and spacing information. These measurements were repeated, at least in part, for various coupling arrangements, power levels, and excitation conditions. Harmonic data were obtained for several frequencies under similar conditions for the correlation of intermodulation activity to harmonic order and diode behavior.

The largest intermodulation level measured on the coaxial coupler was -40 dbm at 280 MHz and was obtained with +5 dbm input levels at 50 MHz and 230 MHz. The largest harmonic level was -47 dbm at 100 MHz and was obtained with a +5 dbm input level at 50 MHz. The variation of second order intermodulation and harmonic signal level with changes in the input power level are shown in Figures 7, 8, and 9. The intermodulation curves with a unit slope were obtained by holding a 115 MHz incident signal constant at +2 dbm and varying a 185 MHz incident signal from +2 dbm to -18 dbm in 1 to 5 db steps. The intermodulation curves having a slope of 2 were obtained by concurrently varying the 115 MHz and the 185 MHz incident signals in 1 to 5 db steps from +3 dbm to -13 dbm. The second harmonic curve was obtained by varying a 50 MHz incident signal in 1, 2, and 5 db steps from +5 dbm to -13 dbm. All of the above data have been corrected for losses introduced by the test setup and indicate the input-output efficiency for

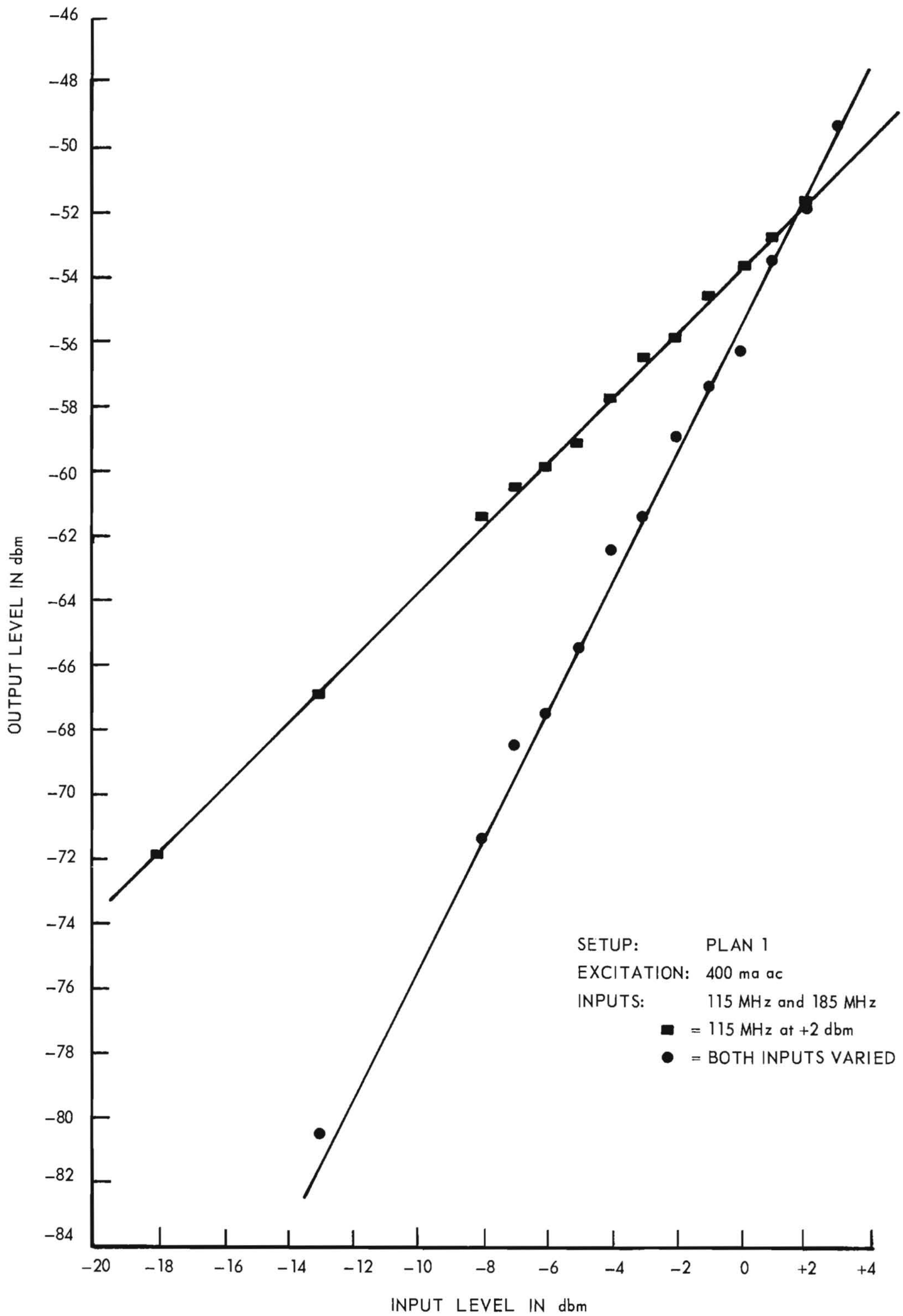


Figure 7. Difference Signal Behavior with Change of Input Level.

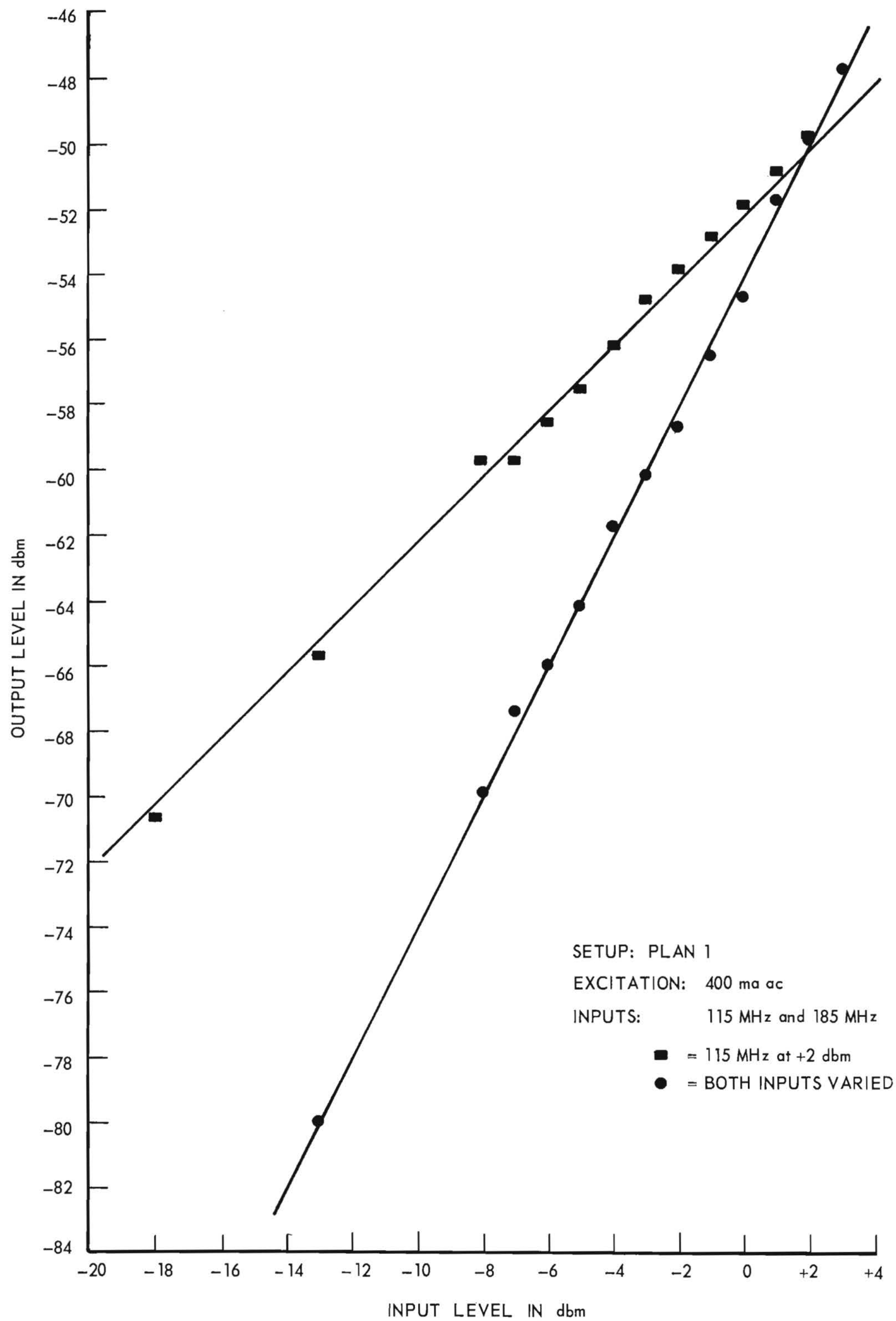


Figure 8. Sum Signal Behavior with Change of Input Level.

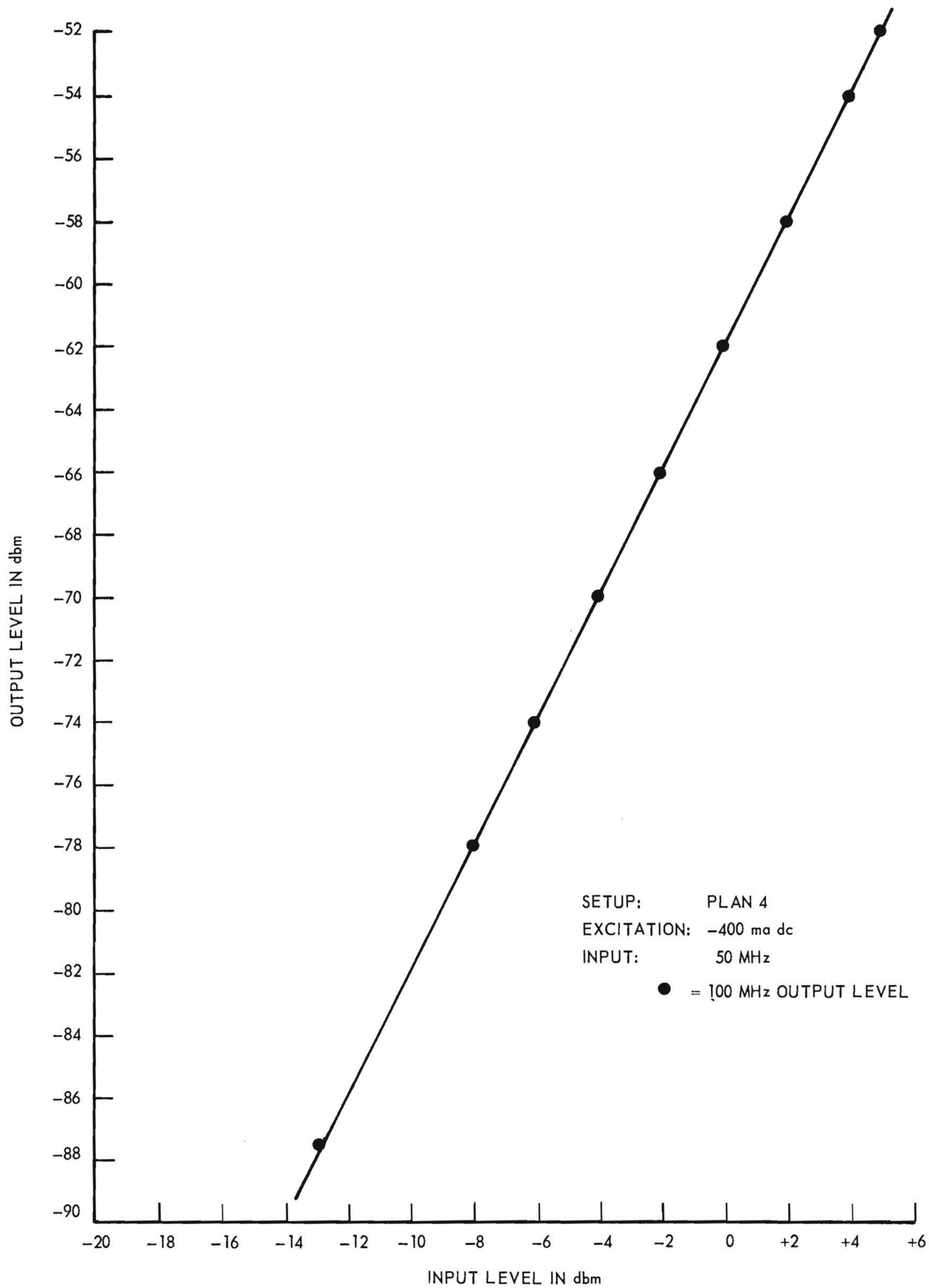


Figure 9. Second Harmonic Signal Behavior with Change of Fundamental Level.

the plasma medium at the incident power levels represented. Within the measurement error for the data, these variations are linear 1 to 1 and 2 to 1 proportionalities with respect to input power.

The effect of changing the excitation current, and consequently the column voltage, on the intermodulation and harmonic signal levels is shown in Figures 10 and 11. These data could not be accurately corrected for reflection loss because no data are currently available on the SWR for changes in the excitation current. The variation in SWR is not thought to be large for currents above 100 ma.

Though some third order intermodulation and harmonic measurements were successfully completed, the range of input levels over which valid data could be obtained was severely limited. Consequently, no data are available to show the third order variation with input level. For normalization purposes, it was assumed that all third order product levels increase at a rate of 3 to 1 with respect to total input signal level.

Two third order intermodulation products were measured concurrently with the second order intermodulation product resulting from the same pair of incident signals. These data appear in Table I.

TABLE I

MEASURED SECOND AND THIRD ORDER INTERMODULATION LEVELS

PRODUCT	INPUT f_1		INPUT f_2		SUM		DIFFERENCE	
	MHz	dbm	MHz	dbm	MHz	dbm	MHz	dbm
$f_1 \pm f_2$	90	+4.6	140	+5.4	230	-46.9	50	-45.7
$2f_1 \pm f_2$	90	+4.6	140	+5.4	320	-76.4	40	-70.8
$f_1 \pm 2f_2$	90	+4.6	140	+5.4	370	-75.2	190	-73.4

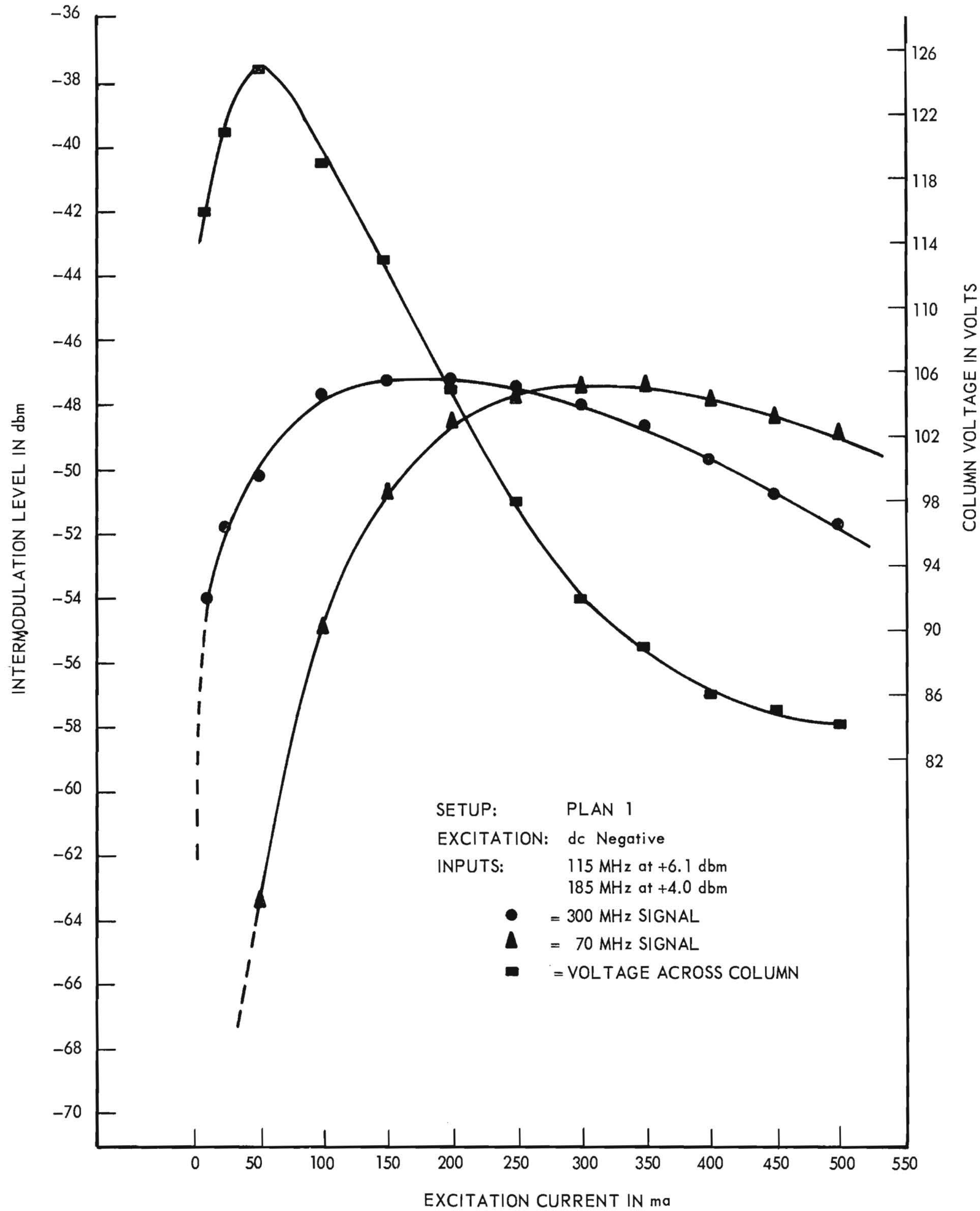


Figure 10. Intermodulation Signal and Excitation Voltage Behavior with Change of Excitation Current.

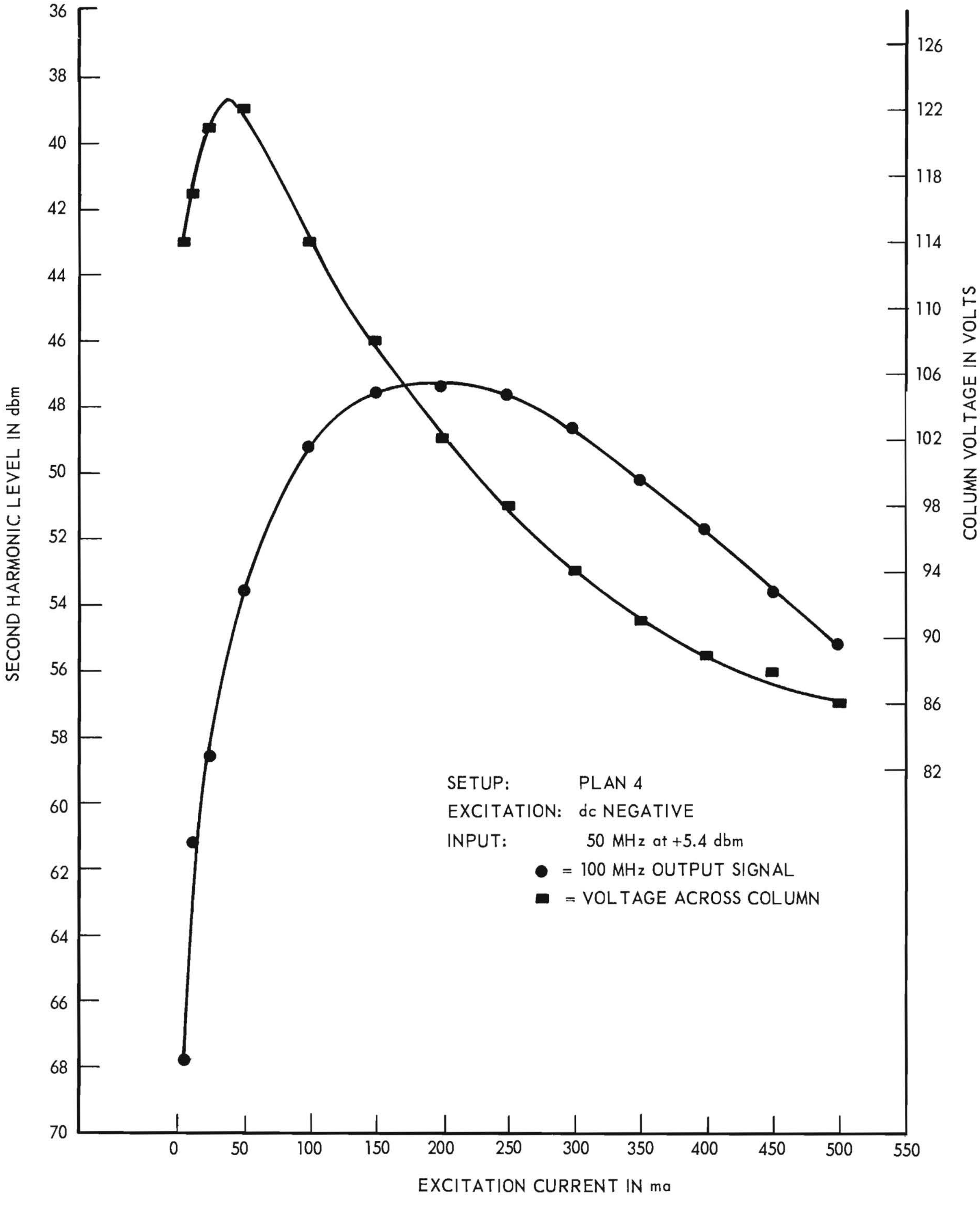


Figure 11. Second Harmonic Signal and Excitation Voltage Behavior with Change of Excitation Current.

Typical second order intermodulation levels measured for other frequencies within the coaxial coupler's bandwidth appear in Table II. A total of some

TABLE II

MEASURED SECOND ORDER INTERMODULATION LEVELS

INPUT NO. 1		INPUT NO. 2		SUM		DIFFERENCE	
MHz	dbm	MHz	dbm	MHz	dbm	MHz	dbm
50	4.0	230	4.4	280	-45.2	180	-46.5
80	4.0	200	5.6	280	-43.5	120	-44.9
85	6.1	115	5.8	200	-45.0	30	-47.2
90	6.2	110	5.9	200	-43.9	20	-46.2
115	6.1	185	4.0	300	-44.5	70	-46.4
120	2.0	180	3.9	300	-48.7	60	-52.4
125	1.5	185	3.2	310	-51.1	60	-53.3
160	4.7	240	4.4	400	-50.9	80	-45.8
190	0.6	210	0.5	400	-57.3	20	-48.8

300 different harmonic and intermodulation levels were measured using the coaxial coupler and measurement plans 1 through 5. The data were normalized to a zero dbm input level and then averaged by sum and difference product or harmonic within each data group. The mean sum and difference levels were then averaged to give the mean level of the intermodulation order for comparison with the common harmonic. These data appear in Tables III and IV.

In order that the peculiarities of the nonlinear activity within a plasma might be ascertained, the product levels measured at the coupler output had to be corrected for losses incurred while traveling from the

TABLE III

AVERAGE SECOND ORDER INTERMODULATION LEVELS FOR ZERO dbm INPUTS

TUBE	PLAN	EXCITATION		SUM/DIFF.	SUM	DIFFERENCE	IM AVERAGE
		ma	v	db	dbm	dbm	dbm
47C	1	-400	86 dc	+0.2	-55.9	-56.1	-56.0
47C	2	-400	86 dc	-0.7	-74.0	-73.3	-73.7
47C	2	400	80 ac	-2.7	-77.9	-75.2	-76.5
47C	3	-400	86 dc	-1.2	-79.0	-67.8	-73.4
47C	3	400	80 ac	-8.1	-81.5	-73.4	-77.4
47F	1	400	80 ac	-2.9	-63.7	-60.8	-62.3
47F	1	-400	80 dc	+1.0	-59.0	-60.0	-59.5
47F	1	510	80 ac	-5.2	-58.5	-53.3	-55.9
47F	2	510	80 ac	-4.9	-75.0	-70.1	-72.5
47F	3	510	80 ac	-1.4	-78.8	-67.4	-73.1
18H	1	-300	44 dc	+7.0	-51.1	-58.1	-54.6
18H	1	300	44 ac	-3.8	-58.5	-54.7	-56.6
18H	1	+300	40 dc	+0.1	-76.2	-76.3	-76.3
18H	3	300	43 ac	-6.9	-67.7	-60.8	-64.3

TABLE IV

AVERAGE HARMONIC LEVELS FOR ZERO dbm INPUT

TUBE	PLAN	EXCITATION ma	EXCITATION v	2nd HARMONIC dbm	3rd HARMONIC dbm	4th HARMONIC dbm
47C	4	-400	80 dc	-65.4	-106.9	---
47C	4	+400	81 dc	-77.2	-106.8	---
47C	5	-400	80 dc	-85.5	-126.4	---
47C	5	+400	80 dc	-95.4	---	---
18H	4	300	43 ac	-59.9	- 81.0	---
18H	5	300	43 ac	-72.5	-104.7	-133.5

TABLE V

AVERAGE HARMONIC LEVELS INCREASED BY TUBE ABSORPTION LOSS AT HARMONIC FREQUENCIES

TUBE	PLAN	EXCITATION ma	EXCITATION v	2nd HARMONIC dbm	3rd HARMONIC dbm	4th HARMONIC dbm
47C	4	-400	80 dc	-44.4	- 87.0	---
47C	4	+400	81 dc	-56.3	- 84.9	---
47C	5	-400	80 dc	-64.5	-106.4	---
47C	5	+400	80 dc	-74.4	---	---
18H	4	300	43 ac	-44.6	- 67.0	---
18H	5	300	43 ac	-56.0	- 85.5	-112.0

point of generation to the coupler terminal. This loss is difficult to separate unless the generation point is defined. It was reasoned that products generated within a plasma should experience absorption from traveling in the medium before reaching the output terminal, and that this absorption would be in proportion to the absorption experienced by a signal of like frequency in passing through the coupler. Since the exact point of generation was not known, the exact proportion of loss could not be calculated. For the purposes of this portion of the study, the absolute level was not significant and the total absorption loss was used to correct the data to the point of generation regardless of the actual location of that point. The corrected average product levels for zero dbm inputs, appear in Tables V and VI. The need for data on helical coupler types pre-empted the further accumulation of data concerning the actual region of product generation and the question of parametric activity.

Once the helix coupler was determined to be an effective device for coupling rf to a plasma column, measurements were performed to evaluate the harmonic and intermodulation generating properties. The logarithmic helix was used as the coupler for all of the following tests on glow discharge plasmas as it exhibited the better impedance and coupling properties over the frequency range of primary interest. As both ends of the coupler were accessible, measurements were made at both terminals to see if there might be any discernible effects caused by propagation along the plasma. As mentioned in the Appendix, port 1 is the "open" end of the logarithmic spiral and port 3 is the "tight" end.

TABLE VI

AVERAGE SECOND ORDER INTERMODULATION LEVELS INCREASED BY TUBE ABSORPTION LOSS AT PRODUCT FREQUENCIES

TUBE	PLAN	EXCITATION		SUM/DIFF.	SUM	DIFFERENCE	IM AVERAGE
		ma	v	db	dbm	dbm	dbm
47C	1	-400	86 dc	+ 4.9	-34.1	-39.0	-36.6
47C	2	-400	86 dc	+ 4.1	-52.2	-56.3	-54.3
47C	2	400	80 ac	+ 3.8	-57.4	-61.2	-59.3
47C	3	-400	86 dc	- 5.9	-57.3	-51.4	-54.3
47C	3	400	80 ac	- 1.6	-61.0	-59.4	-60.2
47F	1	400	80 ac	+ 1.8	-37.2	-39.0	-38.1
47F	1	-400	80 dc	+ 3.0	-43.5	-46.5	-45.0
47F	1	510	80 ac	+ 2.9	-38.7	-41.6	-40.0
47F	2	510	80 ac	+ 2.1	-53.6	-55.7	-54.7
47F	3	510	80 ac	- 4.4	-57.5	-53.1	-55.3
18H	1	-300	44 dc	+11.9	-35.7	-47.6	-41.7
18H	1	300	44 ac	+ 2.0	-42.5	-44.5	-43.5
18H	1	+300	40 dc	+ 5.1	-60.8	-65.9	-63.4
18H	3	300	43 ac	- 2.4	-52.8	-50.4	-51.6

Harmonic levels were measured with the glow discharge sustained with ac and dc excitation. For all of the data shown, the input signal was applied at port 1. Port 3 was also tested as the input port and generally no difference was detected. The curves in the Appendix show that there are cases where the impedance match is different for the two ports. Depending upon the frequency of the input signal, the power loss due to mismatch could affect the harmonic coupled out or the actual level generated by affecting the level of fundamental coupled into the plasma.

There was a significant difference in the level of harmonics as measured at the two ends of the coupler. A hybrid was utilized to discriminate against harmonics coming directly from the signal generator when the harmonics generated in the plasma were being measured at port 1. The resultant data have been corrected for losses in the hybrid and mismatch loss at the coupler. Table VII is a presentation of the harmonic levels through the fourth order after normalization to a zero dbm input level. Table VIII is a tabulation of the normalized harmonic levels when the fundamental is applied at port 1 and the harmonics are measured at port 3. Figures 12 and 13 show the variation of the levels of the second and third harmonics, respectively, with frequency. The harmonic levels at port 3 are plotted in db below the fundamental input at port 1. Note that both curves are plotted using the fundamental frequency as the independent variable. This means that the level actually represented by the curve is that produced at the second or third frequency multiple depending on the harmonic number.

The variation in the harmonic power output as a function of fundamental input power was tested. Figure 14 shows the rate of harmonic power increase

TABLE VII

HARMONIC GENERATION PRODUCTS IN A GLOW DISCHARGE PLASMA WITH INPUT AND OUTPUT MEASURED AT THE SAME END OF HELIX COUPLER

A. EXCITATION: I = 300 ma ac
V = 45 v ac

FUNDAMENTAL MHz	FUNDAMENTAL dbm	SECOND HARMONIC dbm	THIRD HARMONIC dbm
10	0	-70.7	- 99.9
20	0	-66.4	- 97.0
30	0	-60.7	- 92.0
40	0	-65.1	- 99.9
50	0	-59.2	-103.4
60	0	-57.7	- 92.6
70	0	-61.3	- 92.0
80	0	-62.9	-100.1
90	0	-64.0	-100.0
100	0	-53.6	- 93.7
120	0	-67.6	-102.4
140	0	-70.1	-108.8
160	0	-64.5	-101.7
180	0	-62.5	- 97.5
200	0	-66.6	-103.8
250	0	-66.7	- 93.9
300	0	-64.4	-107.2
350	0	-74.8	---
400	0	-69.4	---
450	0	-73.7	---
AVERAGE LEVELS (30 MHz to 500 MHz)		-63.1	- 98.8

(Continued)

TABLE VII (Continued)

HARMONIC GENERATION PRODUCTS IN A GLOW DISCHARGE PLASMA WITH INPUT AND OUTPUT MEASURED AT THE SAME END OF HELIX COUPLER

B. EXCITATION: I = 300 ma dc
V = 44 v dc
Port 1, Negative

FUNDAMENTAL MHz	FUNDAMENTAL dbm	SECOND HARMONIC dbm	THIRD HARMONIC dbm
10	0	-72.0	- 93.8
20	0	-70.1	- 97.0
30	0	-60.7	- 92.3
40	0	-66.1	-103.8
50	0	-60.6	-110.8
60	0	-56.0	- 93.4
70	0	-59.3	- 94.3
80	0	-62.1	- 97.7
90	0	-63.1	-109.9
100	0	-54.6	-103.7
120	0	-68.5	-103.5
140	0	-71.5	-104.5
160	0	-65.2	-116.0
180	0	-66.7	- 96.3
200	0	-71.3	-101.1
250	0	-69.1	- 94.0
300	0	-64.7	- 92.9
350	0	-64.3	---
400	0	-64.1	---
450	0	-70.4	---
AVERAGE LEVELS (30 MHz to 500 MHz)		-63.9	-102.7

(Continued)

TABLE VII (Concluded)

HARMONIC GENERATION PRODUCTS IN A GLOW DISCHARGE PLASMA WITH INPUT AND OUTPUT MEASURED AT THE SAME END OF HELIX COUPLER

C. EXCITATION: I = 300 ma dc
V = 44 v dc
Port 1, Positive

FUNDAMENTAL		SECOND HARMONIC	THIRD HARMONIC
MHz	dbm	dbm	dbm
10	0	-75.9	- 96.9
20	0	-59.7	-103.0
30	0	-58.1	- 91.7
40	0	-79.0	-106.3
50	0	-60.2	-110.7
60	0	-55.2	- 90.3
70	0	-60.8	- 92.7
80	0	-63.1	-105.3
90	0	-51.9	- 99.0
100	0	-56.9	- 96.3
120	0	-70.4	- 95.0
140	0	-64.4	- 97.0
160	0	-65.6	-104.4
180	0	-49.9	- 88.0
200	0	-63.2	- 94.9
250	0	-62.5	- 87.8
300	0	-61.8	-104.9
350	0	-62.8	---
400	0	-63.7	---
450	0	-65.3	---
AVERAGE LEVELS (30 MHz to 500 MHz)		-61.5	- 99.0

TABLE VIII

HARMONIC GENERATION PRODUCTS IN A GLOW DISCHARGE PLASMA WITH INPUT AND OUTPUT MEASURED AT DIFFERENT ENDS OF HELIX COUPLER

A. EXCITATION: I = 300 ma ac
V = 45 v ac

FUNDAMENTAL MHz	FUNDAMENTAL dbm	SECOND HARMONIC dbm	THIRD HARMONIC dbm	FOURTH HARMONIC dbm
10	0	-64.7	-101.9	-136.0
20	0	-66.0	-102.5	-140.8
30	0	-62.2	- 95.7	-139.1
40	0	-56.8	- 98.2	-134.4
50	0	-54.3	- 89.9	-128.5
60	0	-51.0	- 88.1	-122.0
70	0	-51.0	- 87.7	-126.1
80	0	-52.0	- 91.4	-120.3
90	0	-52.1	- 93.3	-131.9
100	0	-49.1	- 89.3	-124.2
120	0	-54.3	-102.1	-142.0
140	0	-54.7	-102.7	-143.4
160	0	-52.6	-105.1	-135.1
180	0	-60.8	-109.0	-140.8
200	0	-51.8	-104.5	-148.2
250	0	-70.3	-118.8	---
300	0	-78.6	-123.3	---
350	0	-81.5	---	---
400	0	-80.6	---	---
450	0	-97.2	---	---
AVERAGE LEVELS (30 MHz to 500 MHz)		-55.2	- 94.9	-129.8

(Continued)

TABLE VIII (Continued)

HARMONIC GENERATION PRODUCTS IN A GLOW DISCHARGE PLASMA WITH INPUT AND OUTPUT MEASURED AT DIFFERENT ENDS OF HELIX COUPLER

B. EXCITATION: I = 300 ma dc
V = 44 v dc
Port 1, Negative

FUNDAMENTAL		SECOND HARMONIC	THIRD HARMONIC	FOURTH HARMONIC
MHz	dbm	dbm	dbm	dbm
10	0	-65.4	- 95.9	-129.7
20	0	-67.1	- 98.7	-141.3
30	0	-63.1	- 97.8	-146.1
40	0	-58.6	-103.0	-141.9
50	0	-54.4	- 90.1	-117.9
60	0	-48.7	- 88.1	-120.8
70	0	-49.3	- 86.7	-127.4
80	0	-52.1	- 93.6	-133.9
90	0	-53.8	- 96.4	-136.4
100	0	-51.3	- 96.6	-135.0
120	0	-52.2	- 97.9	-136.2
140	0	-51.2	- 92.8	-133.1
160	0	-53.3	- 97.7	-142.5
180	0	-56.3	-103.0	---
200	0	-57.1	-104.5	---
250	0	-60.0	-121.2	---
300	0	-75.1	-124.1	---
350	0	-75.5	---	---
400	0	-73.0	---	---
450	0	-87.5	---	---
AVERAGE LEVELS (30 MHz to 500 MHz)		-54.4	- 94.6	-132.8

(Continued)

TABLE VIII (Concluded)

HARMONIC GENERATION PRODUCTS IN A GLOW DISCHARGE PLASMA WITH INPUT AND OUTPUT MEASURED AT DIFFERENT ENDS OF HELIX COUPLER

C. EXCITATION: I = 300 ma dc
V = 44 v dc
Port 1, Positive

FUNDAMENTAL		SECOND HARMONIC	THIRD HARMONIC	FOURTH HARMONIC
MHz	dbm	dbm	dbm	dbm
10	0	-70.0	- 98.8	---
20	0	-64.5	-100.8	-138.7
30	0	-62.0	- 96.4	-131.9
40	0	-58.9	-100.1	-143.8
50	0	-54.9	- 92.4	-129.4
60	0	-47.5	- 88.4	-114.3
70	0	-49.4	- 87.3	-127.1
80	0	-52.1	- 92.1	-131.8
90	0	-53.0	- 92.1	-133.9
100	0	-50.5	- 93.1	-131.2
120	0	-55.3	-101.1	-140.6
140	0	-50.7	- 94.0	-124.5
160	0	-52.6	- 98.6	-145.2
180	0	-46.8	- 89.9	---
200	0	-58.1	-101.9	---
250	0	-63.5	-110.8	---
300	0	-71.8	-127.4	---
350	0	-79.8	---	---
400	0	-98.2	---	---
450	0	-90.8	---	---
AVERAGE LEVELS (30 MHz to 500 MHz)		-54.0	- 94.1	-131.6

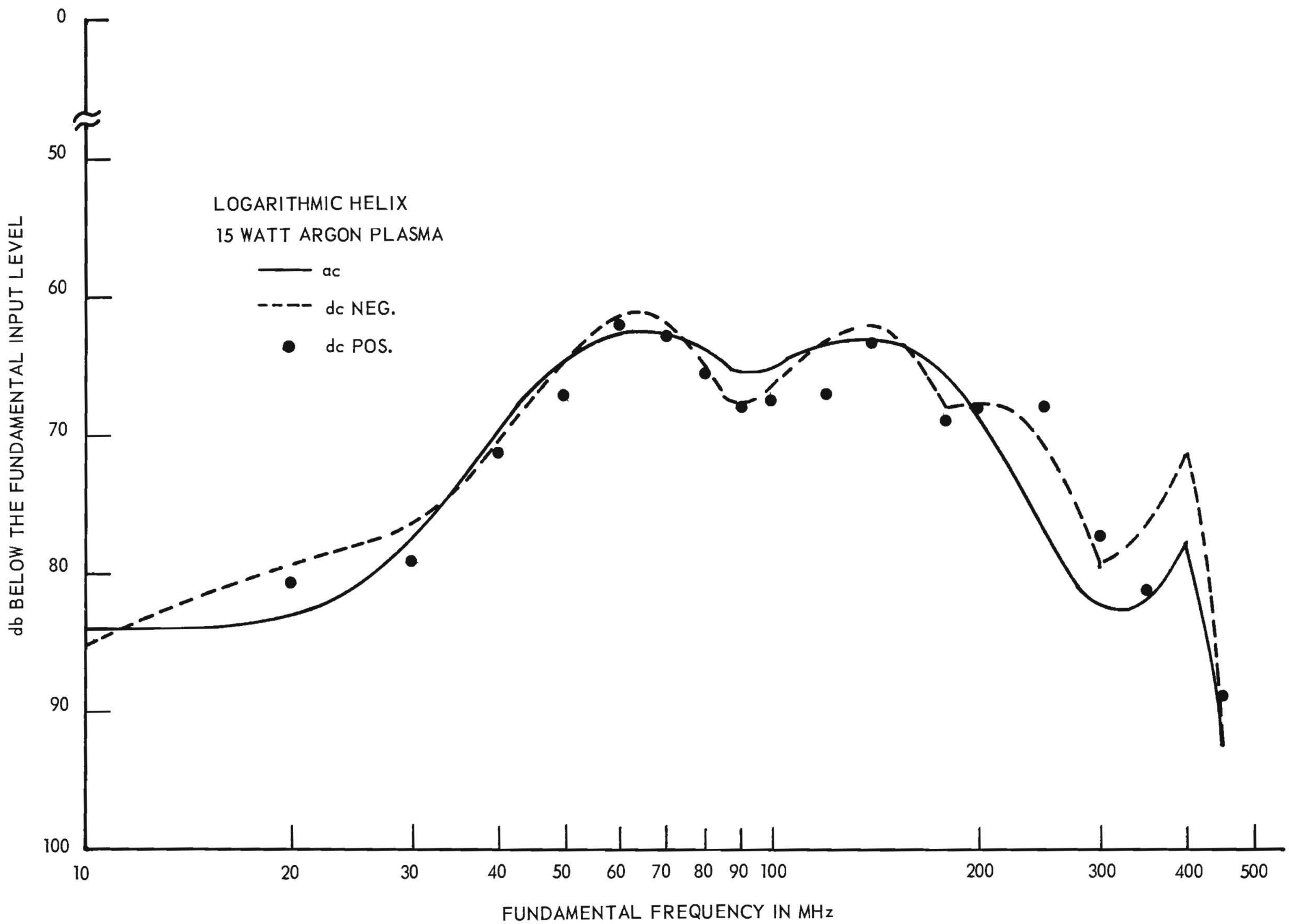


Figure 12. Second Harmonic Level Versus Frequency as Generated in a Glow Discharge Plasma.

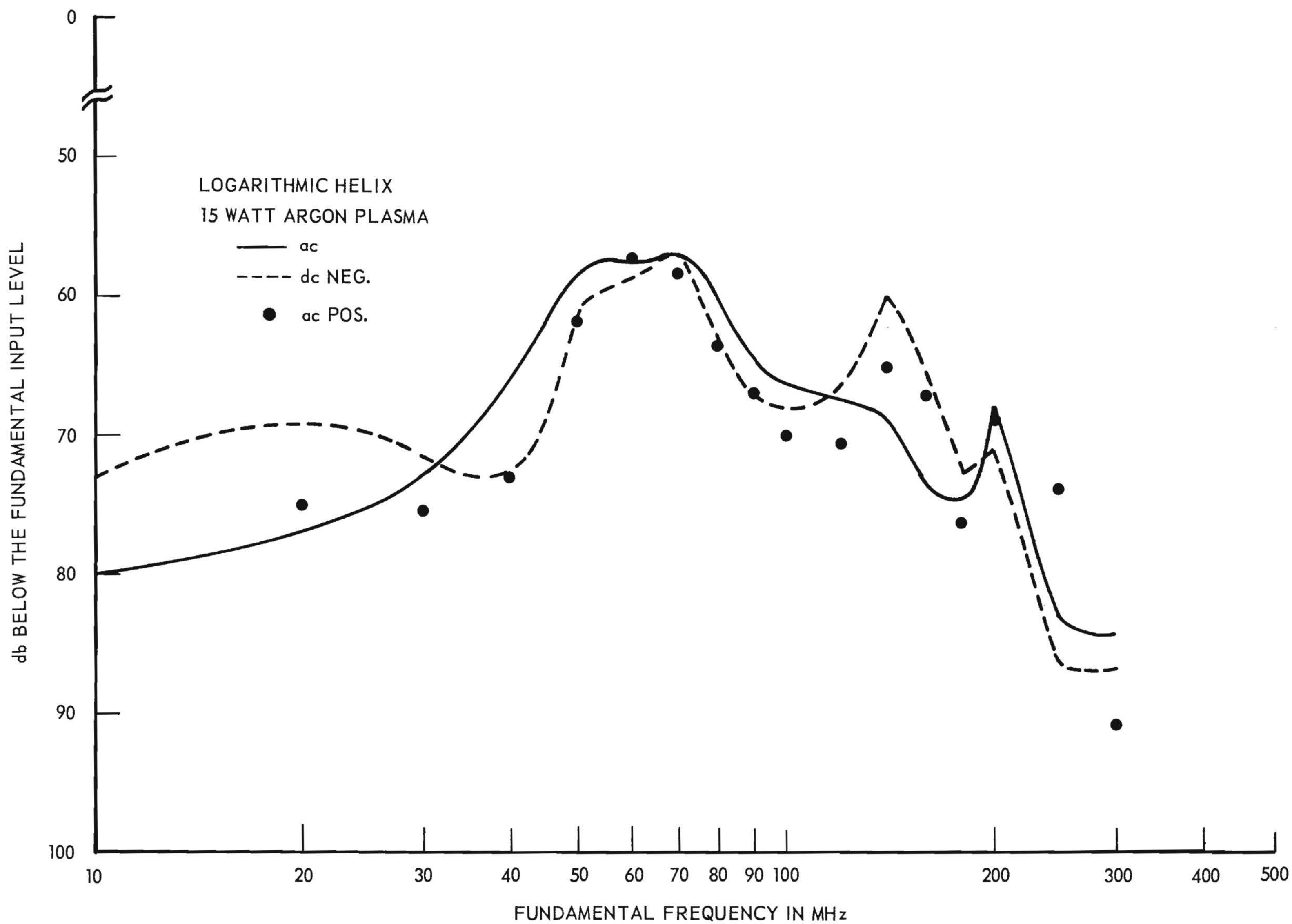


Figure 13. Third Harmonic Level Versus Frequency as Generated in a Glow Discharge Plasma.

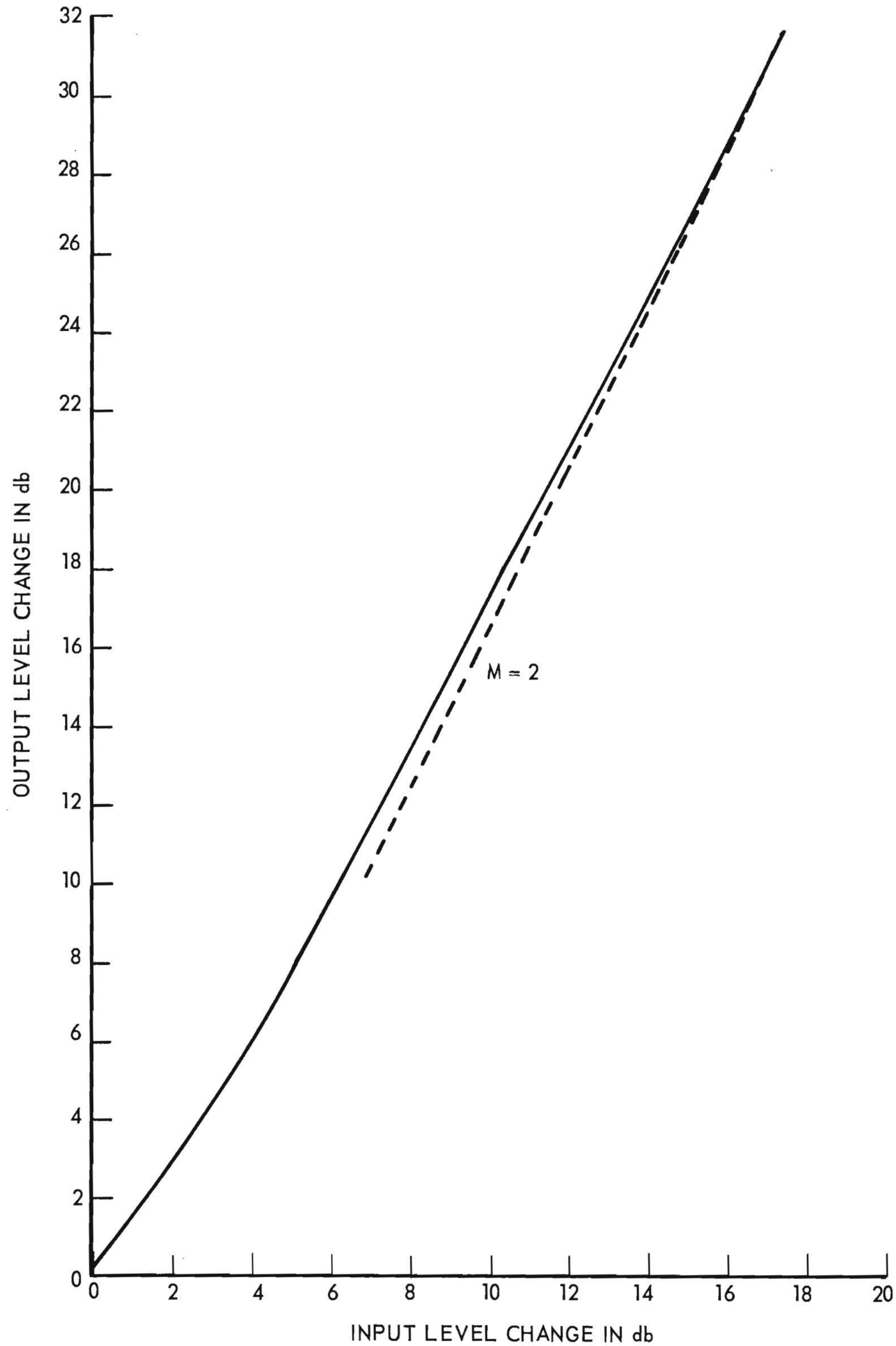


Figure 14. Second Harmonic Level Variation with Increase in the Fundamental Input Level in a Glow Discharge Plasma.

with increase in input power. Also shown on the graph for reference purposes is a line with slope of 2 which corresponds to an ideal power law harmonic generation. The decrease in slope of the harmonic generation curve at the lower input levels indicates that the harmonic level out of the plasma is approaching the residual level that results from the feed through of harmonics produced by the signal generator.

The effect of current flow through the plasma on the harmonic level was investigated by measuring the level for various excitation currents. The current was ranged from a value just necessary to sustain the glow up to 400 ma. Only a small change in harmonic level resulted from varying the excitation current over a 10:1 range.

Sum and difference products were measured for two input signals ranging in frequency from 10 MHz to 300 MHz. Table IX shows the second order intermodulation levels after normalization to zero dbm input levels for f_1 and f_2. Figure 15 shows the variation of the difference frequency, (Δf), where Δf is equal to 300 MHz, as f_1 increases in frequency. Both f_1 and f_2 were maintained at +13 dbm input levels. For all these intermodulation tests, f_1 and f_2 were isolated from each other with a broadband hybrid.

An oxygen-hydrogen rocket engine was investigated with regard to the nonlinear activity in its exhaust gases since the rocket exhaust is a more appropriate model of the conditions exhibited by an actual missile. The electron densities produced by the small rocket are not necessarily akin to the magnitude of those produced by a Saturn rocket because the latter uses an organic fuel constituent. The small engine, however, does exhibit a mach 7 shock structure and temperatures to 6000° Rankine.

TABLE IX

NORMALIZED INTERMODULATION LEVELS FOR THE HELICAL COUPLER AND ARGON GLOW DISCHARGE

				300 ma at 45 v ac		-300 ma at 44 v dc		+300 ma at 44 v dc	
INPUT F_1		INPUT F_2		SUM	DIFFERENCE	SUM	DIFFERENCE	SUM	DIFFERENCE
MHz	dbm	MHz	dbm	dbm	dbm	dbm	dbm	dbm	dbm
10	0	300	0	-48.0	-49.0	-49.4	-50.3	-49.4	-52.4
50	0	230	0	-46.1	-52.8	-46.7	-47.0	-46.7	-48.6
80	0	200	0	-47.1	-51.4	-48.3	-52.3	-48.2	-50.0
80	0	120	0	-48.6	-58.3	-47.8	-56.4	-48.3	-56.3
85	0	115	0	-47.7	-57.3	-47.3	-57.2	-46.4	-55.0
90	0	110	0	-46.1	-60.1	-46.6	-57.9	-45.1	-56.1
115	0	185	0	-50.8	-56.3	-47.5	-52.9	-42.9	-48.0
120	0	180	0	-51.6	-58.5	-47.4	-53.2	-44.6	-49.6
125	0	185	0	-52.7	-59.0	-47.8	-54.5	-44.4	-50.4
160	0	240	0	-54.7	-52.9	-52.0	-52.9	-51.2	-52.1
180	0	220	0	-53.4	-58.0	-57.3	-56.6	-48.2	-51.2
190	0	210	0	-53.9	-62.8	-58.3	-58.3	-50.1	-54.9
225	0	275	0	-68.9	-57.9	-67.6	-57.0	-65.7	-56.3
AVERAGE LEVELS				-51.5	-56.5	-51.1	-54.4	-48.6	-52.4

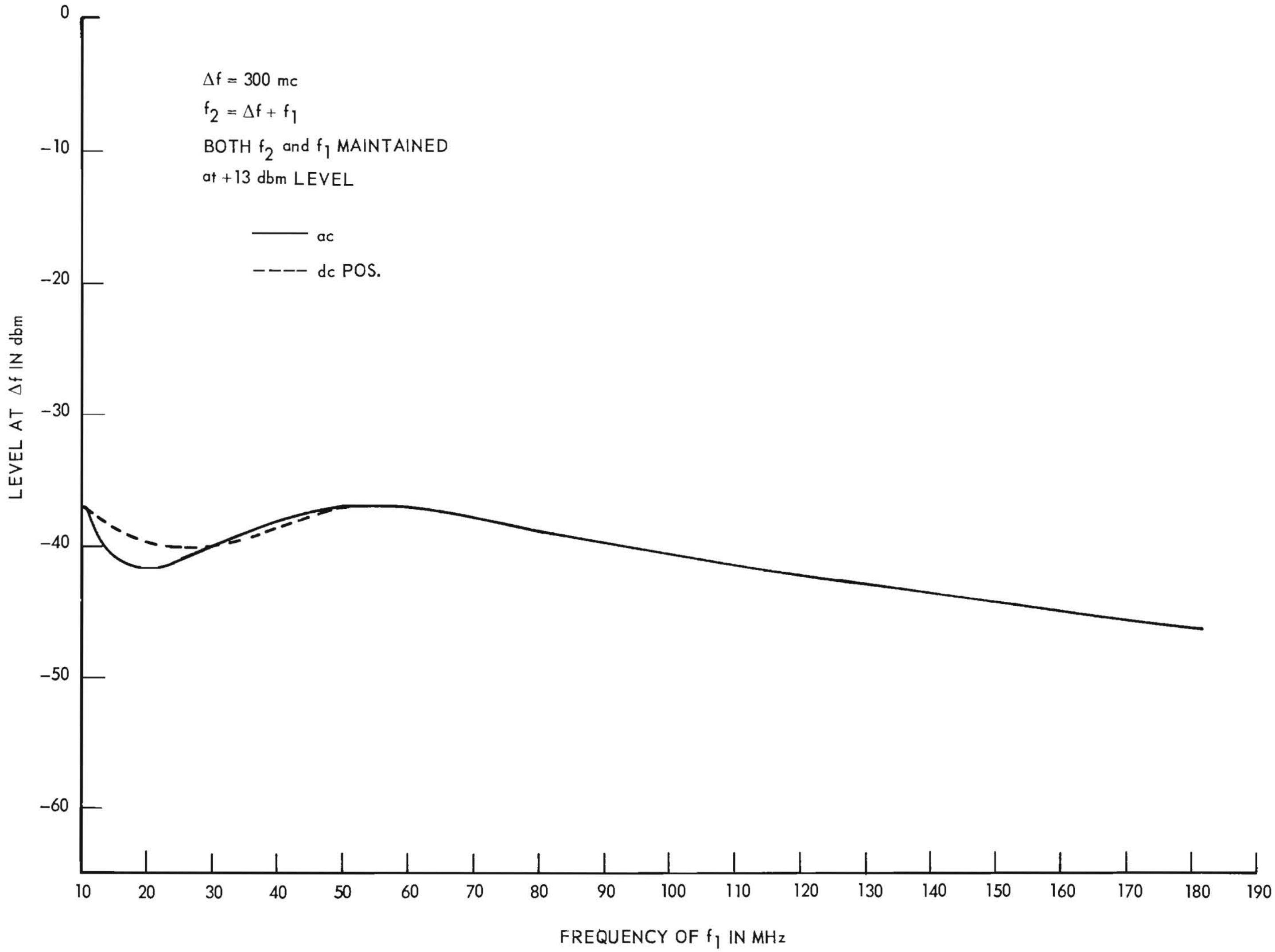


Figure 15. Level of the Difference Frequency, Δf, as a Function of One of the Intermodulation Frequencies, f_1.

Harmonic generation capabilities were investigated using the helical coupler described in the Appendix. Figure 16 is a reproduction of a recording made of the amplitude of the output of the RFMS when tuned to 40 MHz. A 20 MHz signal at +17 dbm was applied to the coil during the run. The generator second harmonic was attenuated with a low-pass filter. This figure seems to indicate that appreciable nonlinear activity is present. This was indeed thought to be the case until further investigation revealed a strong 40 MHz noise component with no input signal present. A recording of this 40 MHz component is reproduced in Figure 17. The amplitude levels shown on Figure 17 are higher than those on Figure 16. The variations in signal levels over the duration of the run are much greater in the noise spectrum than in the "harmonic" run (27 db as compared to 10 db). The absolute levels shown on the figures are not important per se because the gain control on the RFMS was probably not at identical settings since the recordings were made several days apart.

In the course of the investigation of the noise components at various frequencies, a strong 60 Hz component was observed in the signal. This led to a questioning of the ignition system. The system for igniting the gases prior to and during the firing phase consists of a high voltage step-up transformer which generates a spark between a probe and the rocket housing near the exhaust. This spark gap is a very efficient noise generator and was responsible for the strong components measured up to 80 MHz. Figure 18 is a recording made of a firing cycle with an input signal of +20 dbm at 20 MHz applied to the coupler. The one second time interval (t_1 to t_2) prior to firing shows the effects of the arc and small amount of burning hydrogen during the ignition phase. At firing, time t_2, a large spike

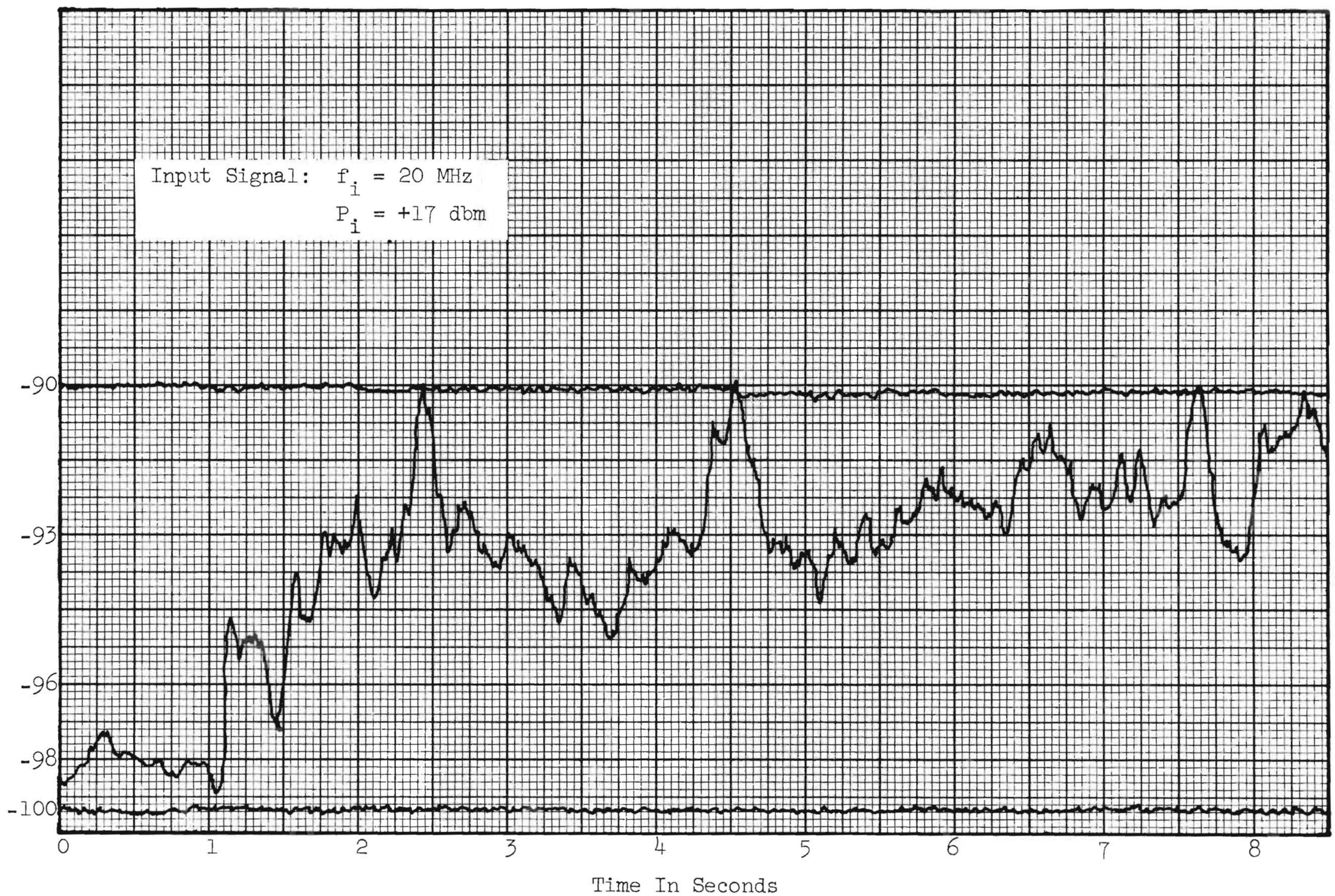


Figure 16. Recording of the 40 MHz Output Component of the Exhaust Coupler.

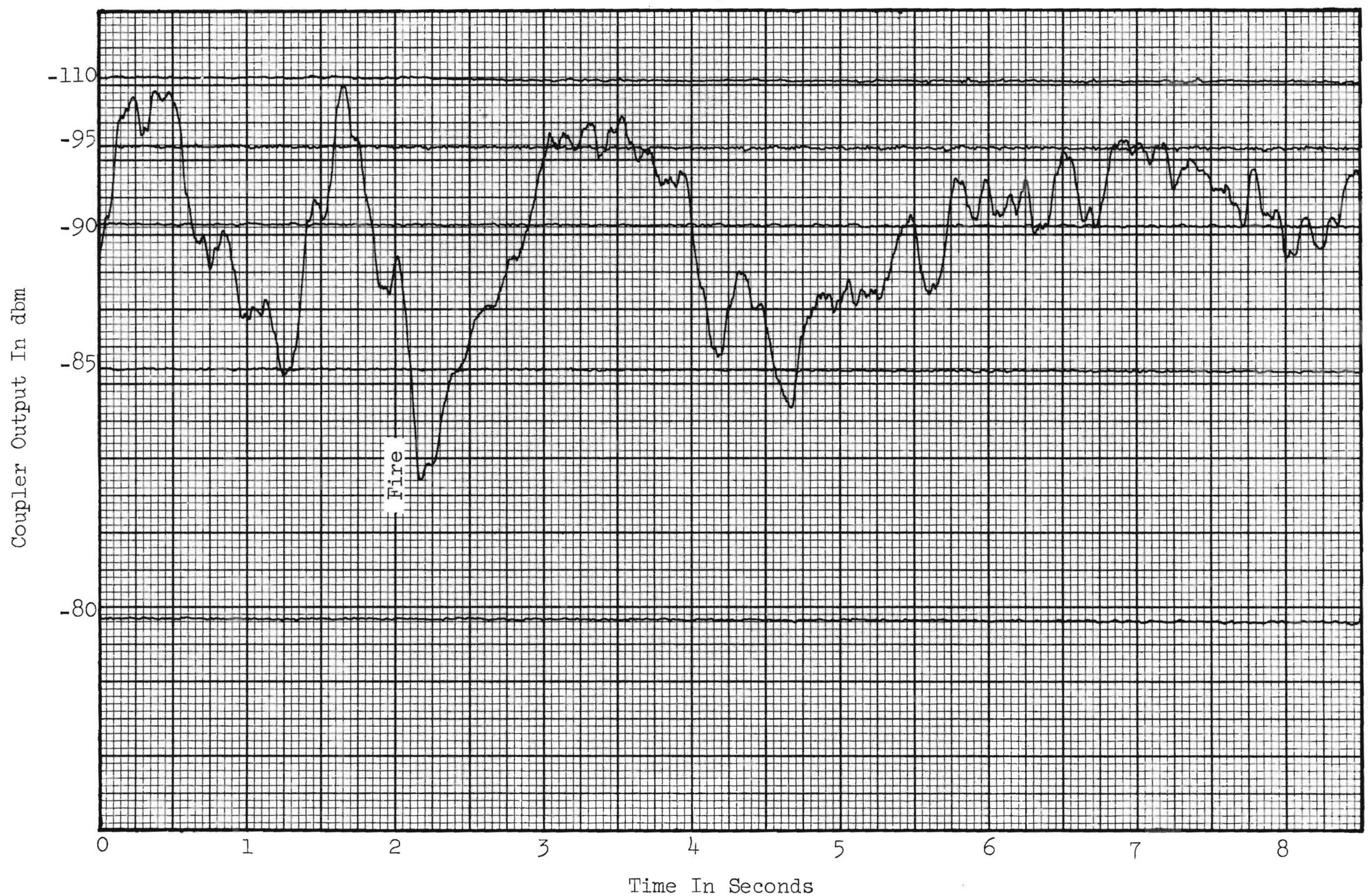


Figure 17. Recording of the 40 MHz Noise Component In the Signal Output of the Exhaust Coupler.

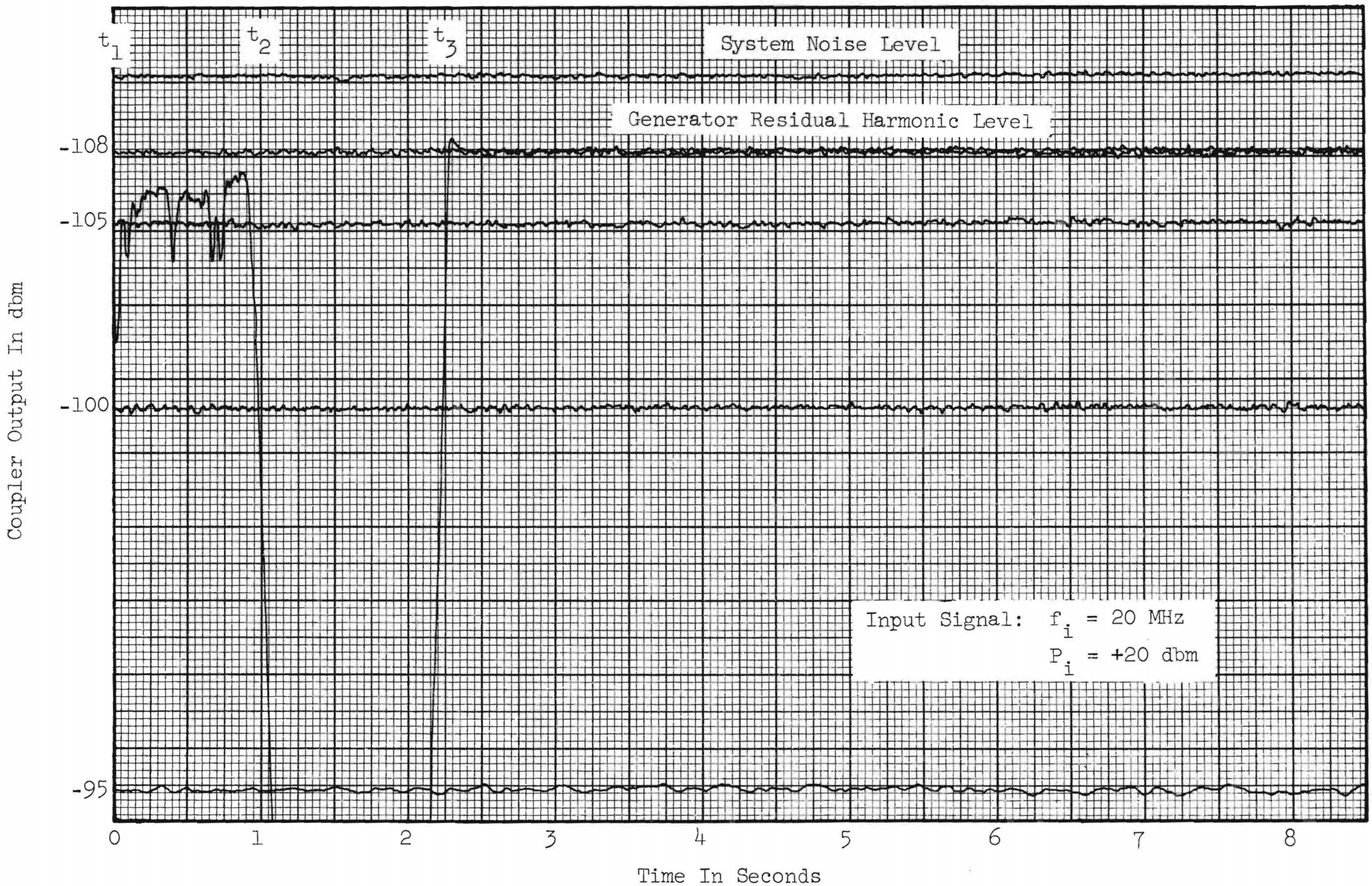
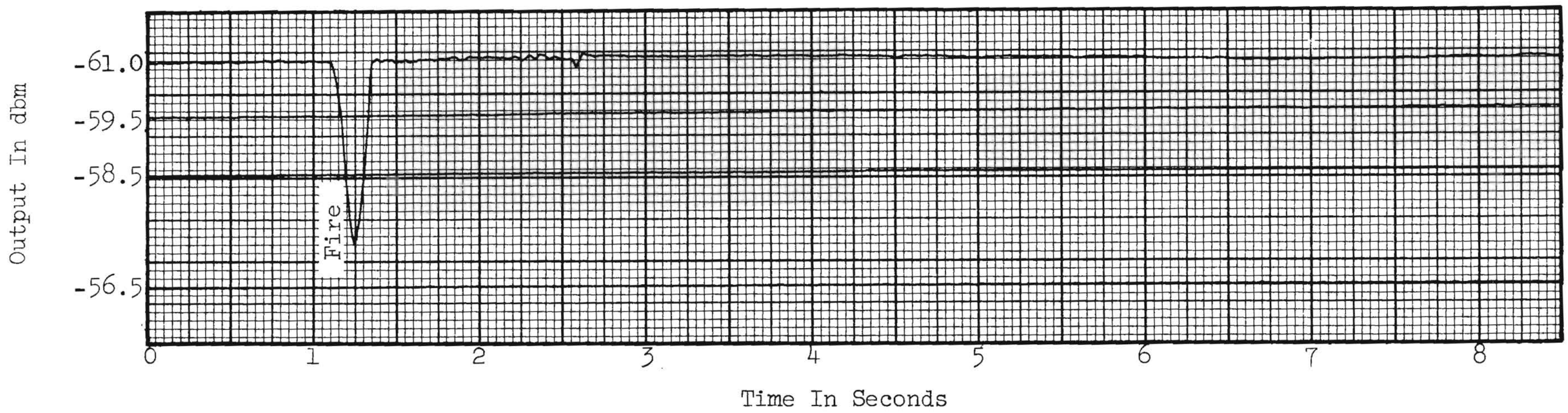


Figure 18. Effects of Ignition Coil on 40 MHz Output Signal from the Exhaust Coupler.

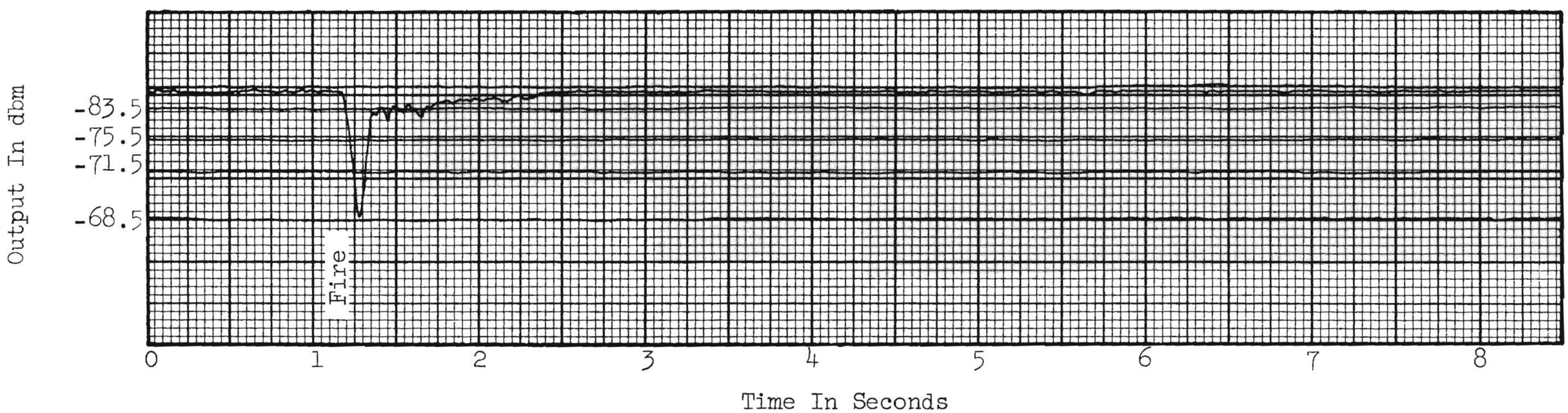
occurs in the output of the coupler. This is probably generated by the shock wave structure of the mach 7 gases escaping from the exhaust. Although some harmonic generation may occur due to the shock wave, the signals are difficult to distinguish from the noise components at the same frequency. On Figure 18, time t_3 shows the effect of de-energizing the ignition coil. The engine continued to run for the duration of the test. Since the total signal dropped to the residual level upon de-energization of the arc, it is evident that the output signal was a product of the ignition system.

The curves of Figure 19a show the recorded response at 10 MHz of a 5 MHz input signal at +20 dbm power level. The reference levels show that the power level of this output signal is much higher than the levels recorded in Figures 16 and 17. Note for one thing that the signal fluctuations visible previously during the ignition phase (the time prior to firing) have been overridden by the signal voltage.

The recording of Figure 19b shows the noise voltage from the coupler with the RFMS at the same adjustments of 19a. The magnitude of the signal is at least 12 db below that with the 5 MHz signal present. This would seem to indicate that the signal level in 19a is due in part to harmonic generation. The spike of output signal in both cases coincides with the passage down the coupler of the shock wave which is generated by the initial blast of burning exhaust gases. The tip of the signal spike is not necessarily the true power level because the response time of the recorder is on the order of a few cycles per second and probably will not follow the rise of the signal. The indications are that harmonic products as well as strong



A. With 5 MHz Signal Applied



B. No Signal Applied

Figure 19. Output Responses At 10 MHz For (A) A 5 MHz Input Signal and (B) No Input Signal.

noise components are generated in the shock wave; these two signals are difficult to separate in the data obtained.

Aluminum is an alkali metal which ionizes readily in a high temperature atmosphere such as that found inside the exhaust plume of the rocket engine. The power feed system, which is described in the Appendix, was used to spray aluminum powder, Fisher Scientific No. A-559, into the exhaust plume. The amount of powder added was controlled by the pressure of the carrier gas. A very accurate quantitative measure of aluminum in parts per million was not performed. Figure 20 is a 17 second recording of the signal output from the coupler with an input signal of 10 MHz at +20 dbm. The engine was fired and the ignition spark turned off before the recorder was started. The 20 MHz residual level from the signal generator is -72 dbm. The coupler output began to increase at approximately 12 to 15 seconds after the engine was fired. After the output leveled off, the input power level was reduced 10 db and the output decreased 20 db which verifies that true harmonic generation was occuring. This 20 db decrease lowered the output level below the residual level, but the latter would decrease 10 db with a 10 db decrease in the input because it also passes through the attenuator.

C. Analysis of Data

The harmonic and intermodulation levels measured at the output ports of the coaxial and helical couplers using glow discharge plasmas are sufficiently large to produce interference in ordinarily sensitive receiving equipment. The trend of the levels with increasing input power points to the probability of more efficient mixing at even higher input levels.

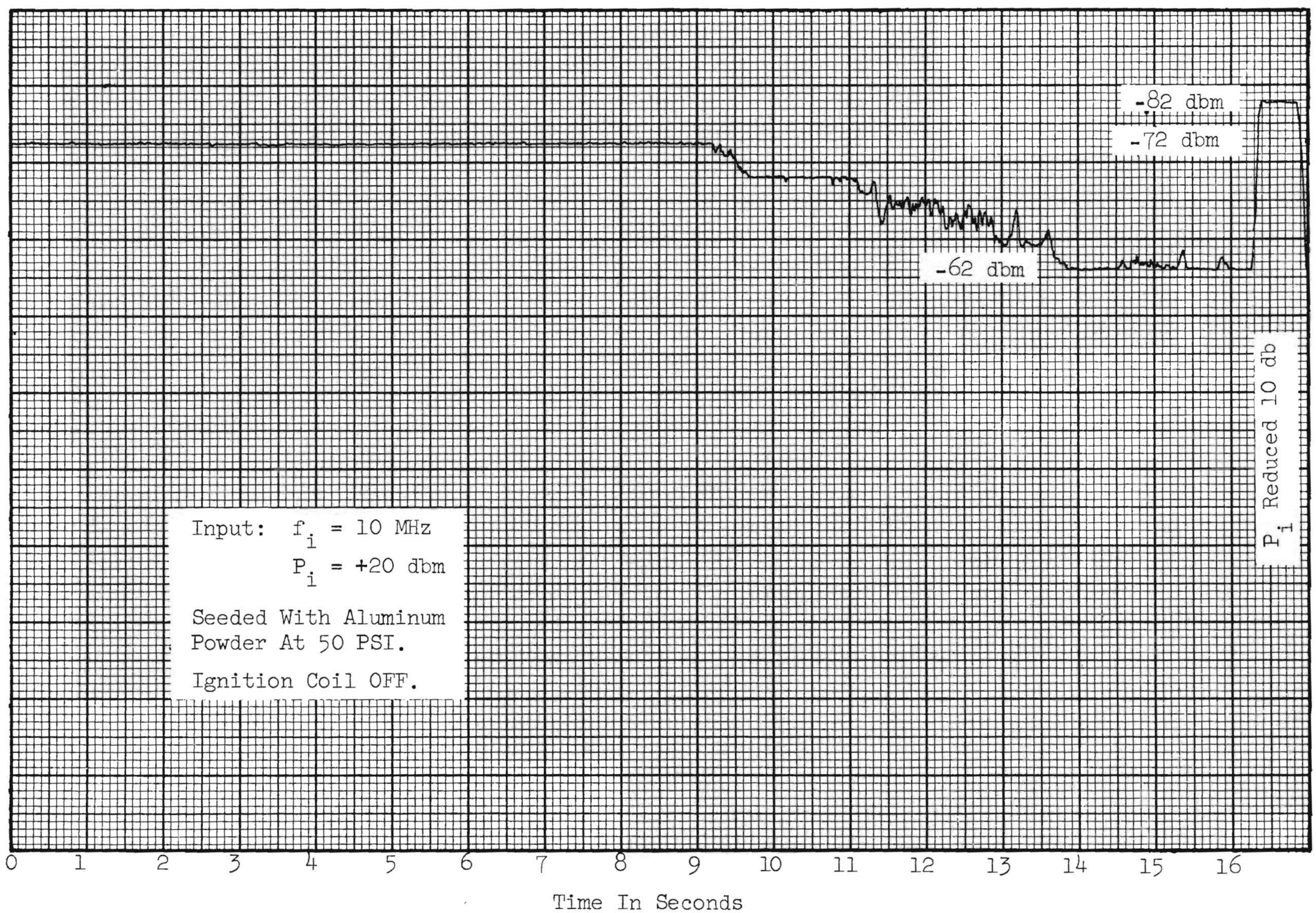


Figure 20. Output Response At 20 MHz With the Exhaust Seeded With Aluminum Powder.

Curves B and C of Figure 21 are extrapolations of the data shown in Figure 8. They indicate the levels of intermodulation to be expected for incident power levels up to +35 or +40 dbm with the coaxial coupler. Curve A is a plot of the output limit above which no product level can extend. The curve is actually a plot of the absorbed incident power treated as though it were an output. If curve C actually remains linear through +30 dbm at the input, curve D is the locus of intermodulation levels to be expected when one incident signal is fixed at +30 dbm and the other is variable. These levels fall a fixed level below that of the variable input signal. It is obvious that the level of the largest intermodulating signal determines the efficiency with which intermodulation products are formed. The efficiency will increase with input level until the limit of linear proportionality is reached.

Curve E is extrapolated from the point representing the largest second harmonic level measured with the helix coupler. It will be shown later that second order intermodulation levels are 6 db larger than second harmonic levels. Point G is 6 db above the second harmonic level such that curve F represents the locus of intermodulation levels which are predicted for the helix coupler when one incident signal approaches a +30 dbm power level.

Though it is not plotted in Figure 21, an assumed 3 for 1 increase in third order intermodulation product level would cause third order products to be significant at a +30 dbm input level (-5 to -10 dbm).

These suppositions are based on common diode mixer theory which the plasma appears to parallel over the range of input levels that were

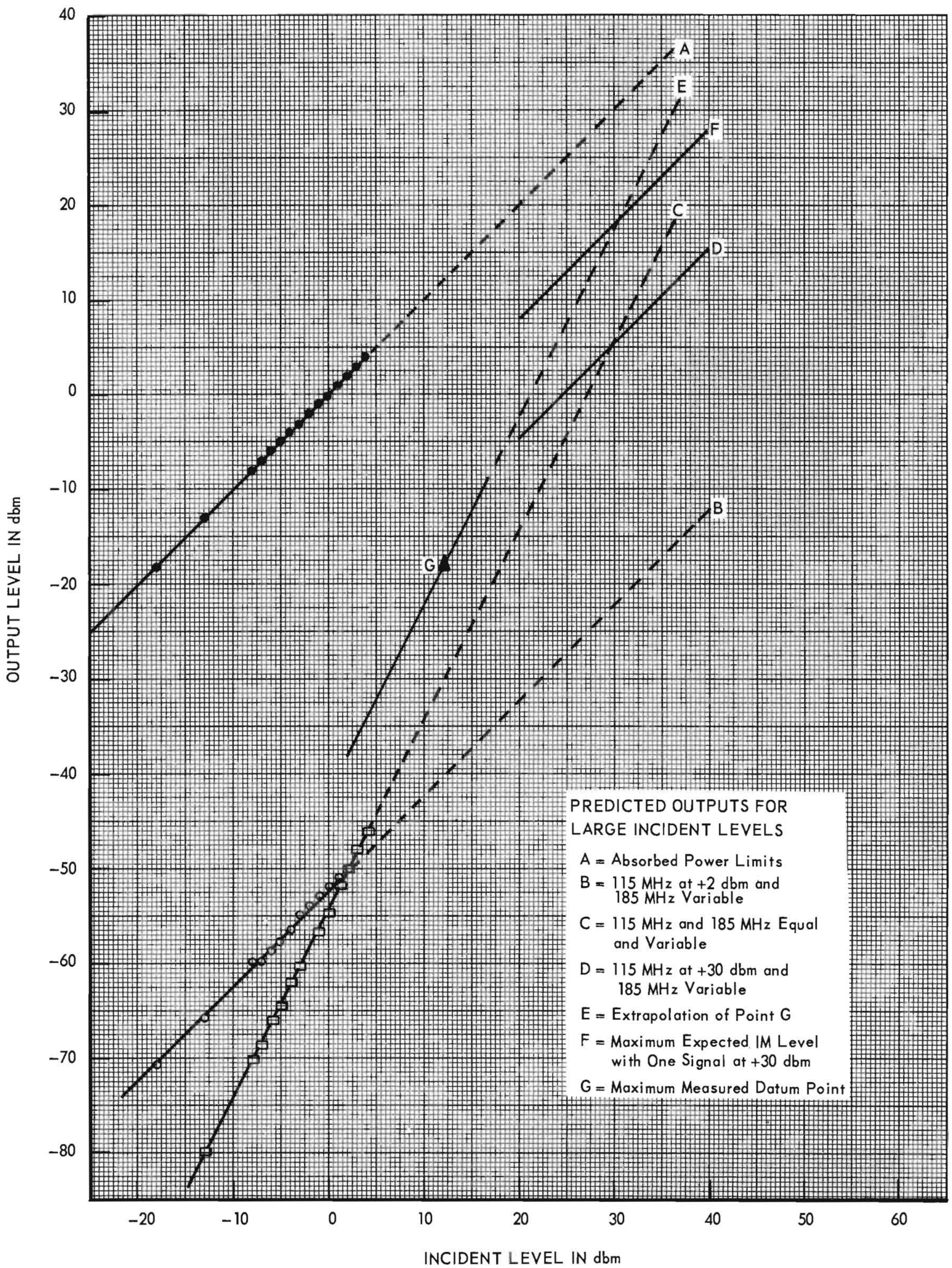


Figure 21. Prediction of Harmonic and Intermodulation Levels for Conditions where One Incident Signal Approaches 1 Watt.

available for testing. Of course the upper limit of linear proportionality may be considerably below the absorbed power limit because of energy conversion to heat.

If the second harmonic levels of Table V are compared with the intermodulation averages of Table VI for equivalent test conditions, an average difference in level of 5.9 db is noted. This indicates that the levels of the intermodulation products for equal incident signal levels will exceed the harmonic levels generated by some 6 db. Diode theory[16] predicts a 6 db ratio in the direction of the average measurements as corrected to the point of generation. The theory further indicates a 9.5 db gain of the $2f_1 \pm f_2$ or $f_1 \pm 2f_2$ intermodulation products over the third harmonic. Precisely equivalent test conditions were not available for this comparison because the third order intermodulation test was performed on tube 47F for which no harmonic data are available. Comparison to tube 47C indicates a 15 to 17 db ratio which is reasonable considering the variations between tubes.

The data of Table VI were generated primarily to determine parametric behavior. The SUM/DIFF. column presents the ratio of average power levels between the sum and difference frequency signals. Parametric activity would be indicated by positive ratios in this column. The fact that the ratios for plan 1 are always positive and those for plan 3 are always negative indicates that a directivity of signals by frequency is occuring rather than parametric mixing. The larger portion of the sum frequency signal propagates to the common input port while the larger portion of the difference frequency signal propagates away from the common input port. When the two input signals are introduced from opposite ends of the coupler (plan 2) the mean intermodulation signals at either end of the coupler provide positive sum to difference signal level ratios in all cases tested. This may be a positive indication of parametric activity even though the ratios are barely larger than the estimated measurement error.

The data from which the averages of Table VI were taken generally indicated some degree of correlation between the sum to difference signal magnitude and frequency ratios even though the proportion was not exact. Such behavior indicates either signal directivity in rough proportion to frequency or partial parametric activity. The fact that plan 2 always yields positive ratios biases the controversy on the side of partial parametric mixing. However, the negative amplitude ratios obtained with plan 3 are correlated to frequency and average a larger absolute magnitude than the positive ratios obtained with plan 1.

One of the major factors leading to the generation of Tables V and VI is indicated in the SUM/DIFF. column of Table III. For these averages of normalized measured data, the sum to difference magnitude ratios are chiefly negative, a situation which is not the direct result of any form of mixing presently known. It was presumed that the ratios became negative because a higher percentage of transmission loss occurred at the sum frequency. A common generation point and equal travel in the medium were assumed for both the sum and difference signal. Thus the absorption loss for the coupler at each respective frequency, having been assumed proportional to the losses incurred by products generated within the medium, was used to generate Tables V and VI.

Other factors of latent interest are noted in the data of Tables III and IV. Before proceeding with these, however, a discussion of the peculiarities of the insertion loss characteristics of the various plasma configurations is in order. The difference in insertion loss for ac and dc excitation is only a matter of 1 or 2 db out of 10 to 50 db of loss. The loss appears essentially independent of the signal direction regardless of the type of excitation. The difference in the insertion loss for 18 inch and 47 inch tubes is 1 to 5 db out of 10 to 50 db of loss. The latter fact may seem strange until it is noted that the excitation voltage across the shorter tube is on the order of one half the voltage on the larger tube for the same current flow. A difference in gas pressure for the two tubes is indicated which causes a greater proportion of loss per unit length in the shorter tube.

A difference of 10 or 12 db in the level of second harmonic generation is noted with a reversal of the dc excitation current using plans 5 or 4 respectively and tube 47C. The third harmonic level was relatively unchanged by the same reversal of excitation current. The difference in any harmonic level generated using either plan 4 or plan 5 with common excitation lies between 18 and 20 db, a value roughly equal to the average tube insertion loss over the frequency band utilized. The value of loss indicates that with either positive or negative dc excitation, the majority of harmonic generation takes place in the region where the incident wave first contacts the plasma media. The measured harmonic has either traveled down the plasma column suffering the 18 to 20 db attenuation (plan 5) or propagated back to the incident port with little loss (plan 4). If it were assumed that the incident waves traveled the distance of the tube prior to creating the product, the measured difference in level between plans 4 and 5 would have been twice the insertion loss for the second harmonic and thrice the insertion loss for the third harmonic. The difference in second harmonic level generated with positive or negative dc excitation thus appears to stem from a difference in the magnitude of second order activity at the two ends of the plasma column for the coaxial line coupling technique. Third order activity would appear to be independent of the excitation polarity.

The second order intermodulation products for tubes 47C and 47F appearing in Table III indicate a condition similar to that found for the second harmonic. Here again, the average tube loss represents the difference in average intermodulation level between plan 1 and either plan 2 or plan 3. The levels obtained using the latter two plans are essentially equal for equal excitation. Plans 1 and 3 are analogous to plans 4 and 5 of the harmonic case and are analyzed in an identical manner, keeping in mind that both input signals will suffer attenuation with travel in the medium. Plan 2, however, is slightly different in that the region of primary generation must occur near the end at which the products are measured. If it were not so located, both the signal entering through the measurement end and the product signal returning to that end would suffer the average insertion loss of the tube. The result would be a difference of twice the tube insertion loss between the levels from plans 1 and 2. It is indeed unfortunate that no positive dc excitation values are available for plan 2 such that this hypothesis could be further verified. The data for tube 18H is not as well correlated to the 16 db average insertion loss of the shorter tube but the direction of the data does not discount the results obtained on tubes 47C and 47F.

An interesting point is noted in the average 3 db reduction in level with ac rather than negative dc excitation. This is reasonable in that the region of primary generation falls on the negative end of the column half of the time. The resultant power level should be roughly half since the positive end generation is some 10 to 12 db below that of the negative end. It should be further noted here that the phosphor coating on standard fluorescent tubes does not appear to contribute to the nonlinear activity or insertion loss and VSWR characteristics of the plasma medium. This is evidenced from the data for tubes 47C and 47F. The former was phosphored and the latter was not. All of the 18 inch plasma tubes were phosphor coated standard fluorescent tube configurations.

The harmonic and intermodulation levels measured with the helical coupler were performed on tube 18I which is of the same type as tube 18H used with the coaxial coupler. This provided a correlation factor between the coaxial and helical types of rf coupling to the plasma medium.

The data shown in Tables VII and VIII indicate that the majority of the generated harmonic signals are propagated away from the input port for the helical coupler. The differences in average harmonic level for the two ends of the coupler varied between 4 and 10 db, depending on the particular harmonic and mode of plasma excitation. The averages, however, were computed for comparison with the coaxial coupler averages and did not take account of frequencies above 500 MHz at any harmonic or below 30 MHz at the fundamental. The majority of change in level with direction took place at the high end of the band and was oppositely oriented to the general trend. The levels of signals traveling the entire length of the helix were higher at the low end and middle of the band but much lower at the high end of the band. Figures 12 and 13 indicate this high frequency roll-off. The result is consistent with an increased absorption loss to the harmonic signal at the higher frequencies as evidenced by the steeply rising insertion loss characteristic of the coaxial coupler at frequencies above 300 MHz.

Comparison of the largest harmonic averages obtained with the helix and coaxial couplers indicate a 5 db increase in second harmonic, a 13 db decrease in third harmonic, and a 4 db increase in fourth harmonic generation for the helix coupler. The large variations in product level with different modes of plasma excitation which were noted for the coaxial coupler were not evidenced by the helical coupler. Variations in the average level of up to 4 db were the maximum noted for the helical coupler with the various excitation modes.

Comparison of the harmonic data of Table VIII with the intermodulation data of Table IX indicates that the intermodulation levels are generally larger than the harmonic levels. The comparison of averages does not show the theoretical 6 db difference; however, the warped bandwidth of the helical coupler can have a considerable effect on this average because the data fall differently within the frequency range. The coaxial coupler is felt to provide a more significant result in this regard.

The average sum to difference signal ratios for the data in Table IX are positive which indicates either signal directivity in proportion to frequency or parametric tendencies. Since the data were obtained for plan 3 only, there is no indication as to which is the true cause for the positive ratio. The noted directivity of harmonic products lends increased consideration to the theory of signal directivity in proportion to frequency. In passing, it is interesting to note that the level of the sum product for the 115 MHz and 185 MHz input signals with positive dc excitation falls on curve E in Figure 21 as was predicted from the maximum measured harmonic level for the helical coupler.

The majority of tests run on the engine exhaust were performed before the large noise components generated by the ignition arc were discovered. All of those which were run with the arc energized are subject to doubt as to the harmonic content present in the results.

There was oblique evidence that harmonic generation occurred in the exhaust. The second harmonics appeared to be at least 80 to 90 db below the applied signal. At first glance, this indicates a much lower degree of nonlinear activity than was evidenced by the glow discharge plasmas. However, considerably less power was being coupled into the plasma as the insertion loss directly attributable to the influence of the exhaust was on the order of 0.5 db or less, whereas the insertion loss caused by the glow discharge was 10 db or more.

There has been speculation that the levels required for efficient nonlinear activity within plasma media do not exist in close proximity to a launch vehicle during liftoff and flight. It might be noted that the Saturn carries a 5 kw peak power radar altimeter and a 400 watt C-band beacon in addition to several 4 to 20 watt transmitters. A rough calculation of the electric field strength at zero dbm for the glow discharge couplers yielded a maximum incident strength of 0.112 volts per cm. Strengths of this magnitude could be produced by the 5 kw altimeter at distances to 200 meters from the antenna in the direction of the rear of the vehicle. Though this might produce nonlinear activity in the exhaust plasma of the rocket, a more inherent danger exists through nonlinear activity generated in antenna breakdown corona, or other plasma media which may engulf the receiving and transmitting antennas of the vehicle. Breakdown of transmitting antennas in rarefied or plasma laden atmospheres is considered a factor in data transmission loss, and being a glow discharge, could create an efficient nonlinear mixing medium in addition. Its close proximity to the receiving and transmitting antennas would most assuredly present interference potentialities in a crowded spectrum.

D. Criteria For Full Scale Tests

In order to test for nonlinear activity in the flame or other plasma media during the flight of a vehicle, a receiver with high rejection to spurious and intermodulation responses must be utilized as a frequency sensitive voltmeter aboard the vehicle. At least one such receiver should "look" directly into the flame from a position near the rear of the vehicle. Another should have its antenna in the neighborhood of the other vehicle receiving antennas. The sensitivity of the receivers should be equal to or better than that of receivers normally aboard the vehicle. The receivers should be fixed-tuned to a frequency which may result from the intermodulation of two or three of the more powerfully transmitted signals originating on board the vehicle.

The detected output levels of the receivers should be recorded aboard the vehicle and transmitted to the ground via a data link after a moderate time delay. The delay will assure that any activity which occurs during a period of data dropout will not be lost. Since it is very likely that nonlinear activity will be highest during dropout periods, some delaying technique is required to assure detection.

The ground receiving station should record the delayed signal from the vehicle as level versus flight time so that any intermodulation detected may be correlated to other events occurring during the flight. Tests should be made prior to ignition to determine the ambient level of intermodulation and the proper operation of equipments.

A typical test condition might be the measurement of the second order intermodulation product between the altimeter beacon at 1610 MHz (f_1) and the ODOP at 960 MHz (f_2). The detection receivers aboard the vehicle could be tuned to the difference frequency signal ($f_1 - f_2$) occurring at 650 MHz both at the rear of the vehicle and in the region of the antennas. The output of each receiver would be delayed and transmitted to the ground via data link where the output of each receiver would be recorded as level in dbm versus flight time. These level indications would occur as pulses at the altimeter repetition rate in that the interference signal could be generated only when the altimeter was transmitting.

The relative levels indicated by the two receivers would indicate where the nonlinear activity was occurring. The relationship between these levels and the time of flight would indicate the source of the intermodulation. Larger signals from the rear constitute flame mixing while larger levels at the antennas indicate a plasma sheath or antenna breakdown, depending on the time of flight as compared to data dropout and other recorded phenomena.

It may be practicable to monitor two intermodulation products simultaneously either using two separate receivers at each location or switching one receiver between two frequencies at a specified rate. If so, the third order product between the ODOP at 960 MHz (f_1), the UDOP at 900 MHz (f_2), and the altimeter at 1610 MHz (f_3) might be measured. This results from tuning the detection receivers to the pulsed ($f_1 + f_2 - f_3$) product at 250 MHz and handling the resulting data in the manner prescribed above. Alternate arrangements might include additions of transmitters other than those normally aboard the vehicle which could be aimed directly into the flame.

III. CONCLUSIONS AND RECOMMENDATIONS

The coupling techniques developed for this study provided for wideband testing of the nonlinear generating properties of plasmas. The variation of harmonic and intermodulation product levels with changes in input level as well as the comparison of average intermodulation and harmonic levels has indicated a close correlation between common diode mixer and plasma nonlinear behavior. Extrapolation of the measured data has indicated that conversion losses of only 12 db might be expected from a plasma medium when one of the intermodulating signals has a level of +30 dbm. Special test data indicate that either a directivity of signal in proportion to frequency or a semiparametric form of mixing occurs as a result of propagation of electromagnetic waves in plasma media. They also evidence varying degrees of absorption of the product signals by the plasma media after generation. The efficiency of nonlinear generation in plasma media as well as the degree of directivity and reabsorption of generated products appears to be dependent upon the polarization of the incident signals.

Though problems were encountered in coupling rf into a flame plasma, sufficient coupling was obtained to give a clear indication of second harmonic generation within the flame. As a result of this study, it is felt that plasma media could become a source of interference due to the formation of harmonic and intermodulation signals through the propagation of electromagnetic waves within the medium. This is considered a definite possibility when the plasma media will engulf the antennas of the vehicle as in the case of antenna breakdown corona.

Full scale testing will involve considerable expense in that the on-board receivers must be of a quality comparable with a noise and field intensity meter. It is recommended that further laboratory tests be conducted prior to in flight testing in order to more closely model the full scale situation. In this regard, more efficient coupling arrangements should be developed so that a large percentage of the applied signal is absorbed by the exhaust plasma. The techniques of frequency scaling by seeding should be investigated so that an accurate accessment of the degree of scaling may be determined and radiated measurement techniques employed. In addition, studies of the electron concentrations in the various Saturn exhaust plumes should be investigated and made available so that the required degree of seeding may be calculated for scaling purposes. The limits of linear proportionality with increasing input level should be experimentally determined prior to the expense of full scale tests since this is a basic assumption in the consideration of nonlinear generating efficiency. A study of antenna breakdown corona should also be conducted to determine the generating properties of this medium.

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V. APPENDIX

A. Philosophies of Measurement

In order to obtain a reasonable evaluation of the nonlinear activity in a medium, the utilized (absorbed) incident signal power as well as the total product signal power must be measured. A technique which accounts for all the incident signal power must obviously be used. For the frequency range of interest in this study (10 MHz to 1000 MHz) the requirement was most easily accomplished through the use of "in-coax" coupling techniques which contain all of the electrical energy and allow for its measurement at specific ports. In addition to electrical containment, the coupler must provide a very broadband coupling characteristic in order that parametric tendencies might be adequately evaluated.

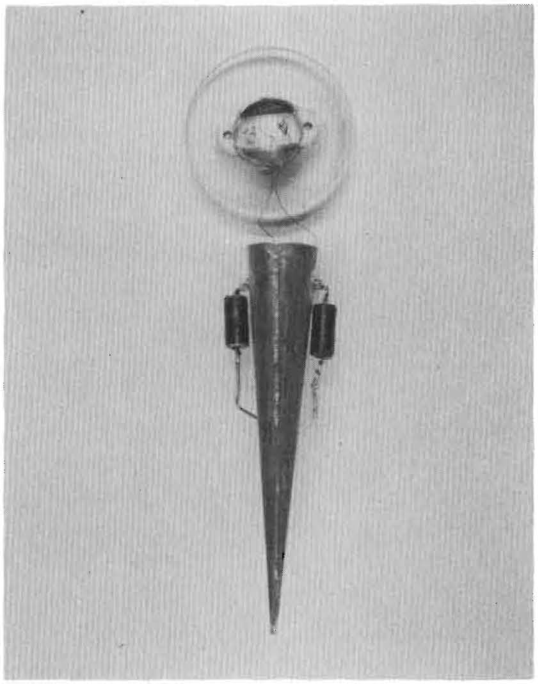
In the parametric mixing case, the sum and difference frequencies produced by a given product will occur at power levels proportional to the frequency of the particular signal. The existence of a parametric tendency can be determined if the power levels of both the sum and the difference frequency signals of a given mix can be measured accurately enough to correlate the frequency and power ratios. The larger the frequency ratio can be made, the greater the ratio of power levels will become for the parametric case. With an overall power measuring accuracy of ±2 db, the frequency ratio must be at least 5 to 1 or larger. Ratios larger than this provide for a greater degree of confidence in the measured results and were therefore desired in this study.

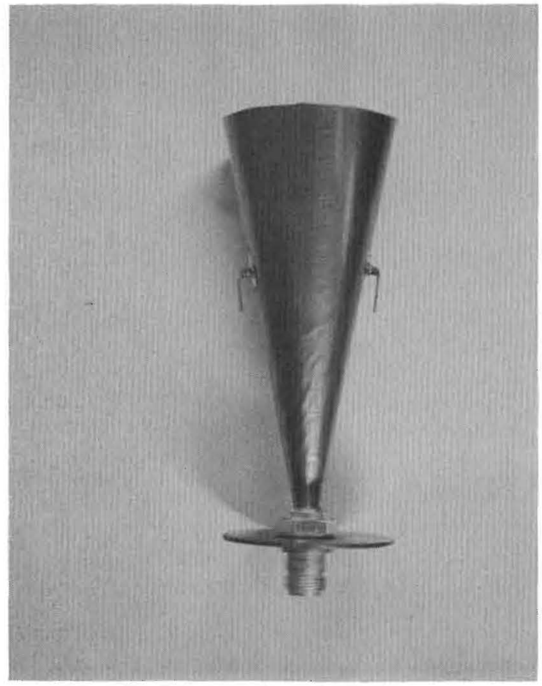
B. Coupler Development

The investigation of techniques for the broadband coupling of rf signals into a plasma medium was the most time consuming task undertaken in this study. Two suitable coupling techniques were developed using glow discharge in argon as a convenient source of plasma. The glow discharge tubes used for this purpose were 8 watt, 15 watt, and 40 watt fluorescent tube configurations, both with and without phosphor, excited by controlled direct and alternating currents.

The first coupling technique attempted utilized the plasma column as the center conductor of a 2 1/2 inch, 50 ohm coaxial line. Each end of the plasma tube was terminated through a taper-transition unit to a type N panel jack. The terminating units were arranged to slide on finger stock into the ends of the outer conductor such that tubes of various lengths might be accomodated. The construction details of the taper-transitions showing the chokes used to admit the glow discharge ignition and sustaining currents are shown in Figure A-1. The coaxial line resulting from this configuration provided a useful 50 ohm match over the frequency range from 10 MHz to 700 MHz as indicated by the VSWR and insertion loss curves shown in Figure A-2. These data were obtained using a 47 inch copper center conductor in place of a plasma tube to check the behavior of the taper-transition end units.

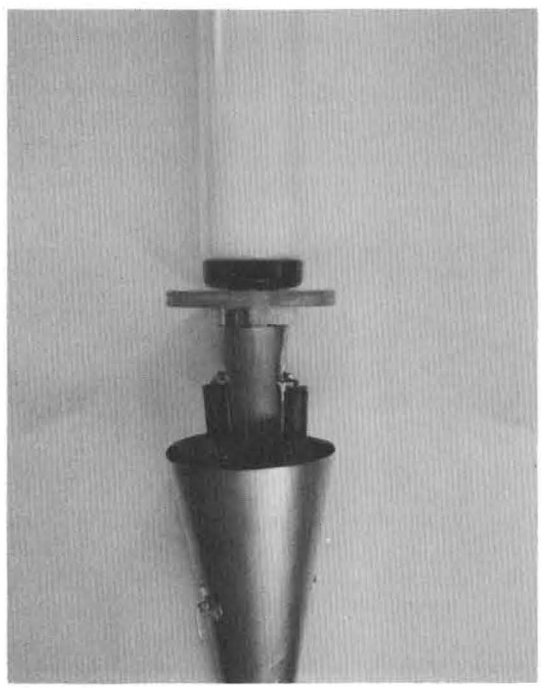
The VSWR and insertion loss values were measured at selected frequencies between 10 MHz and 1000 MHz for several 47 inch and 18 inch plasma tubes. Typical values for these quantities are shown in Figures





INNER COAXIAL TAPER

OUTER COAXIAL TAPER



SUPPORT SHELL

ASSEMBLY DETAIL

Figure A-1. Construction Detail of Taper-Transition Units.

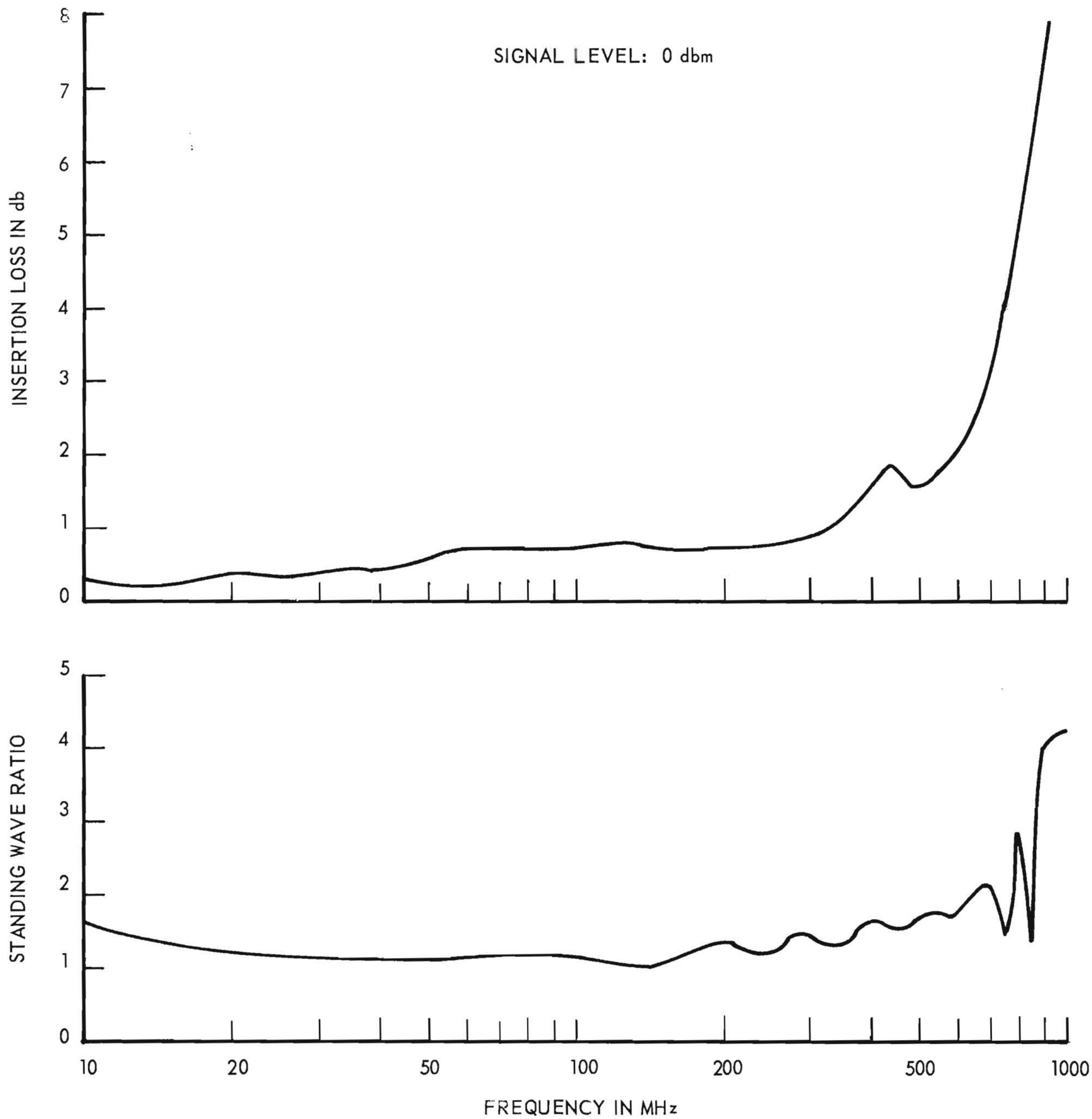


Figure A-2. Bandwidth Characteristics of Coaxial Line.

A-3 and A-4. In general, the useful bandwidth ranged from 10 MHz to 500 MHz for this coupler. The reflection loss at each terminal was derived from the VSWR measurements and subtracted from the measured insertion loss to provide a curve of the absorption characteristic of the plasma. Curves of reflection loss and absorption loss are shown in Figures A-5 and A-6. These curves are necessary for correcting subsequent measurements of intermodulation or harmonic level to arrive at the generating properties for the plasma medium and the true rejection values for the various harmonic and intermodulation products.

The coaxial coupler provided for excellent bandwidth and a high degree of power absorption by the enclosed plasma. However, the technique is totally unsuited for application to a flame plasma with a shock structure and a high temperature. The investigation of suitable techniques for coupling rf signals to a flame plasma was initiated by studying the influence of a glow discharge plasma on the coupling between two loops. Two multi-turn loop couplers were constructed around an 8 watt argon plasma tube. The change in coupling between the loops due to the tube being in the "ON" state as opposed to the "OFF" state was measured as a function of frequency and spacing between loops. The coupling change was measured from 900 MHz to 4000 MHz at three different spacings. The generalized behavior followed roughly the same pattern at each separation. In some frequency regions a decrease in coupling (8 to 10 db) occurred while in other regions an increase of similar magnitude was observed. The coupling change as a function of spacing between loops was measured at selected frequencies. The results were erratic and inconclusive. At

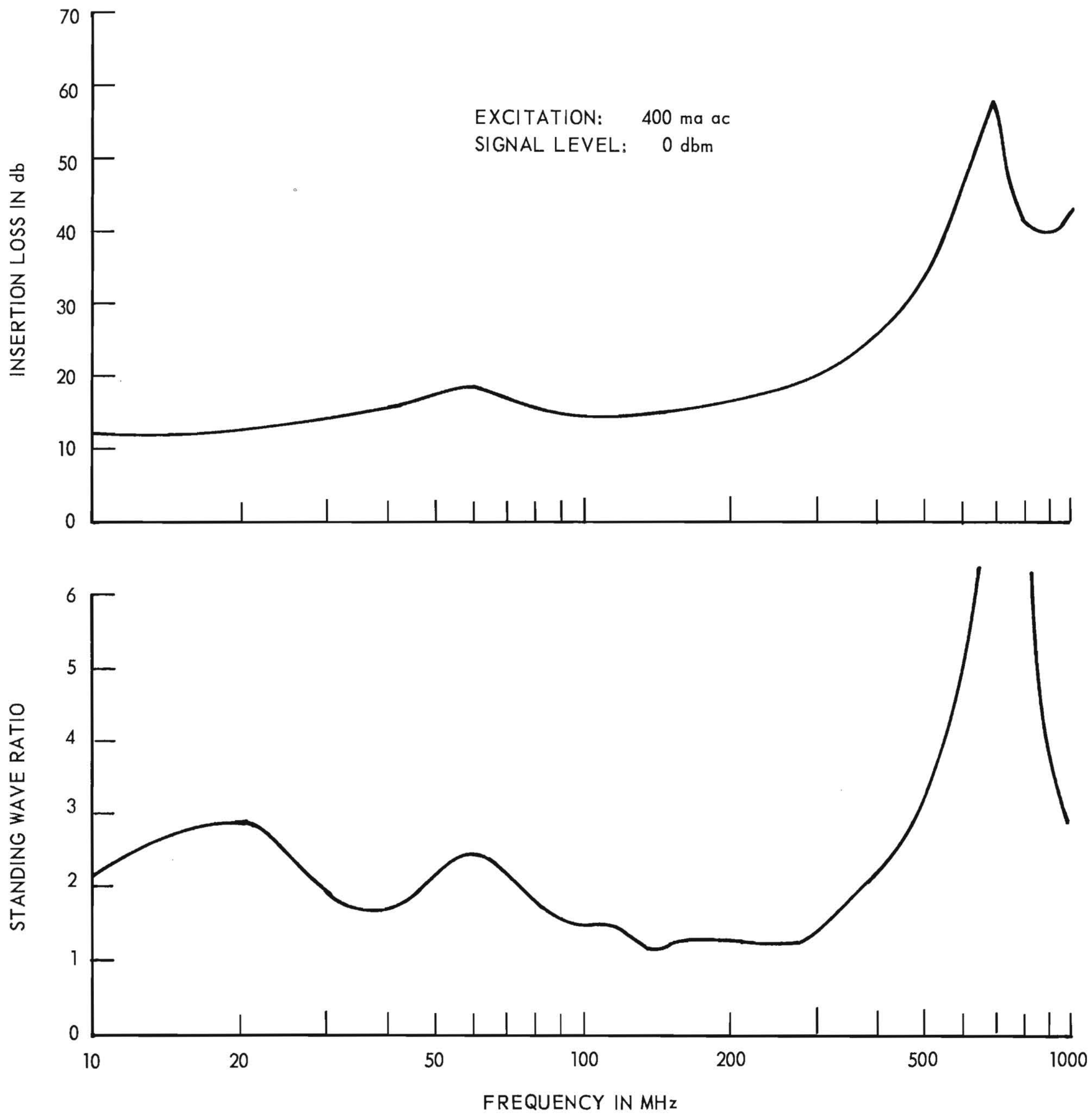


Figure A-3. Typical Bandwidth Characteristics of 47 Inch Coaxial Coupler.

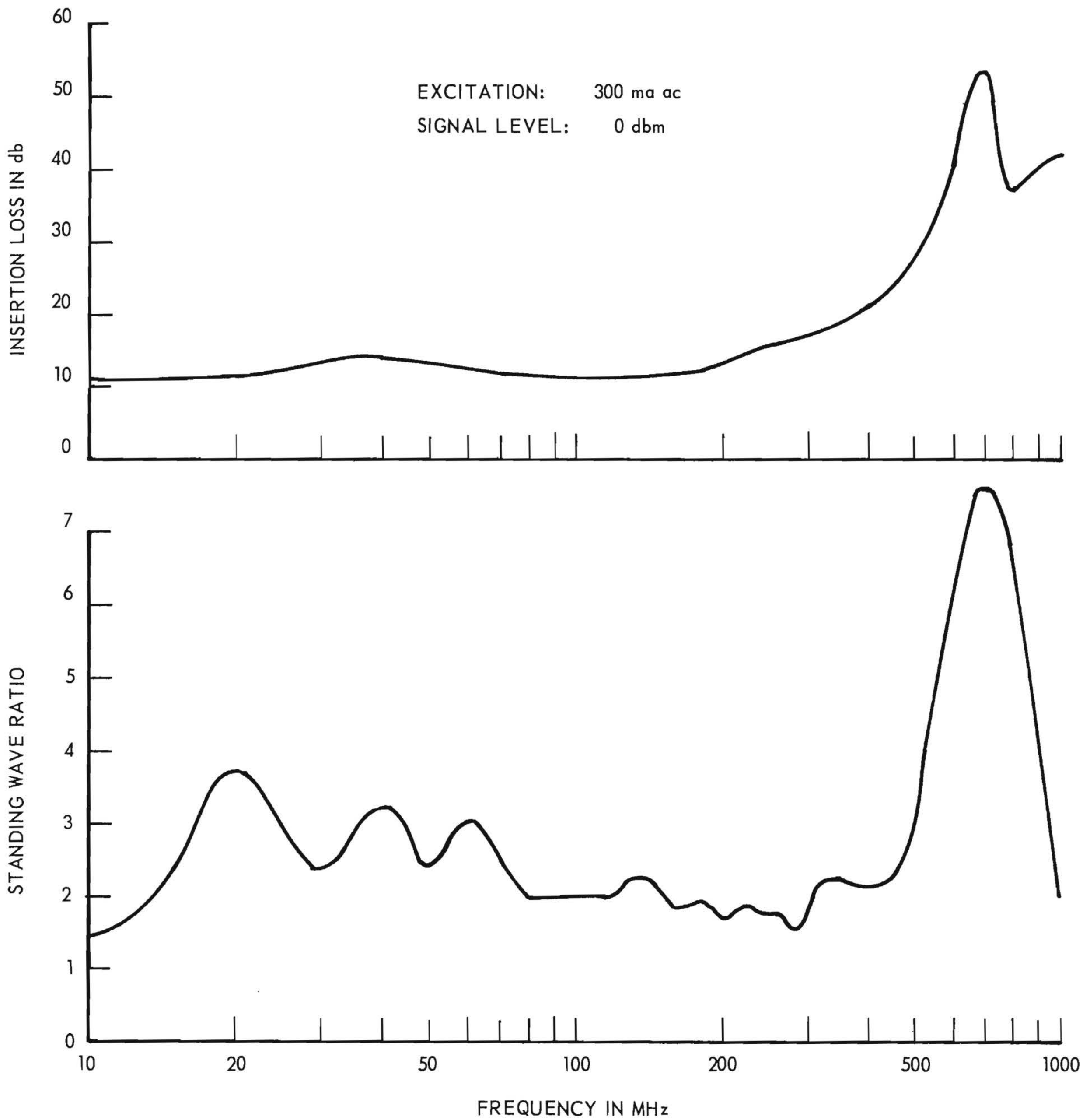


Figure A-4. Typical Bandwidth Characteristics of 18 Inch Coaxial Coupler.

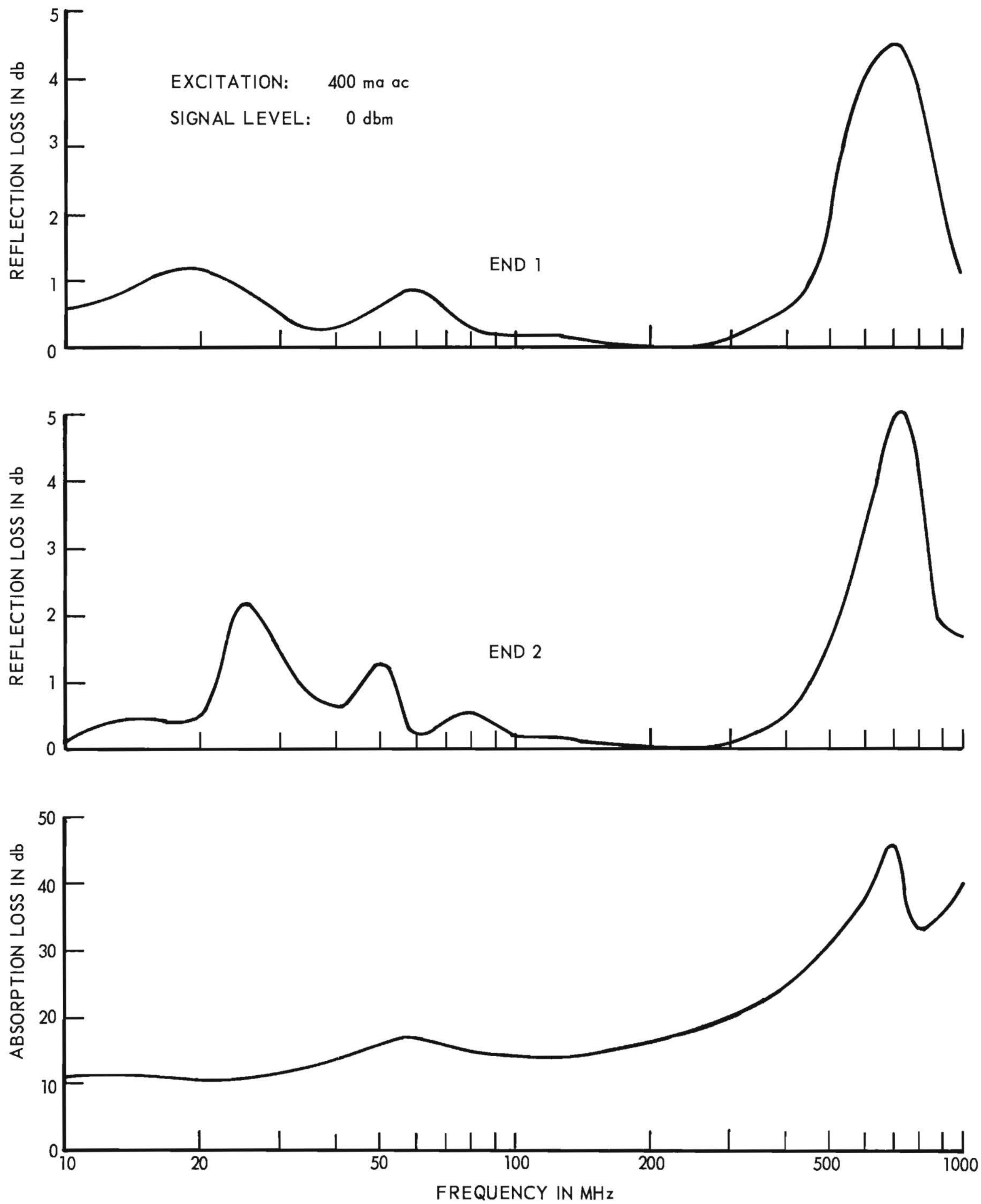


Figure A-5. Typical Reflection and Absorption Losses for 47 Inch Coaxial Coupler.

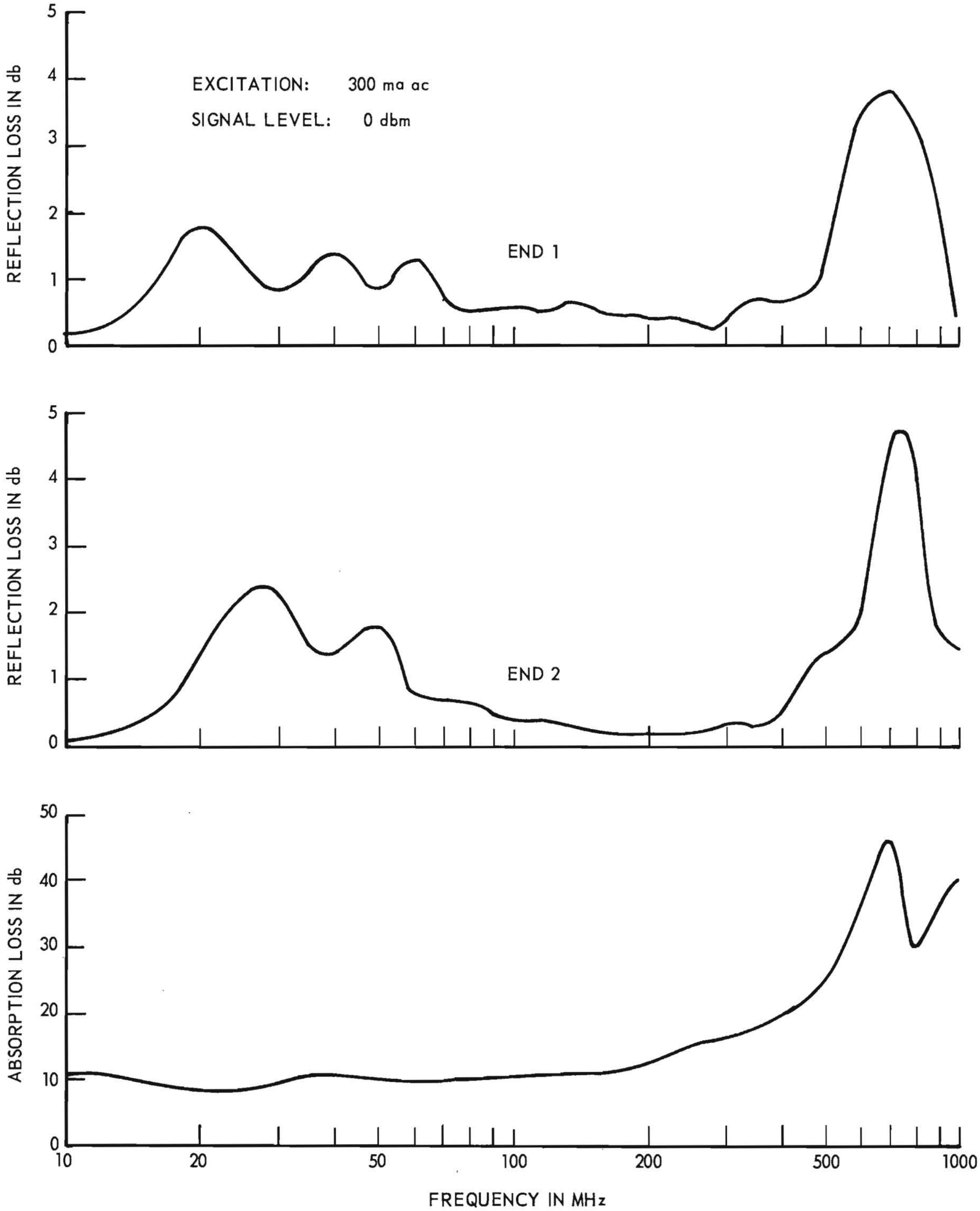


Figure A-6. Typical Reflection and Absorption Losses for 18 Inch Coaxial Coupler.

certain frequencies, no change in coupling was evident while at other frequencies as much as 10 db variation was noted.

Since the couplers are essentially antennas, the energy coupled from one to the other is a function of their radiation patterns at the particular frequency of investigation. The plasma appears as a good conductor in some frequency ranges. In these ranges, the radiation patterns of the loops will be altered by the plasma connecting the loops. The change in coupling between the two loops upon the addition of the plasma is due to the effect of absorption by the plasma and to the modification of the radiation patterns of the loops. The separation of these two factors is a difficult process.

A helical structure was the next coupler to be investigated. The coupler was constructed by wrapping a spiral of wire around an argon plasma tube and then mounting the tube along the axis of a 2 1/2 inch copper pipe. Both ends of the coil were brought out through the wall of the pipe via a type N panel jack. The distance between centers of the panel jacks was 10 cm. Over this distance coils of 10, 20, and 30 turns were constructed and tested.

Figure A-7 shows the measured insertion loss of the 30 turn coil alone, i.e., the plasma tube not energized. The insertion loss is primarily caused by impedance mismatch as is evidenced by the close correlation between the insertion loss and VSWR curves. Figure A-8 shows the greatly improved impedance behavior when the tube is energized. Less than 2 db of the insertion loss is due to mismatch from 400 MHz to 2000 MHz. The helix performs well as a coupler to the plasma in this same frequency

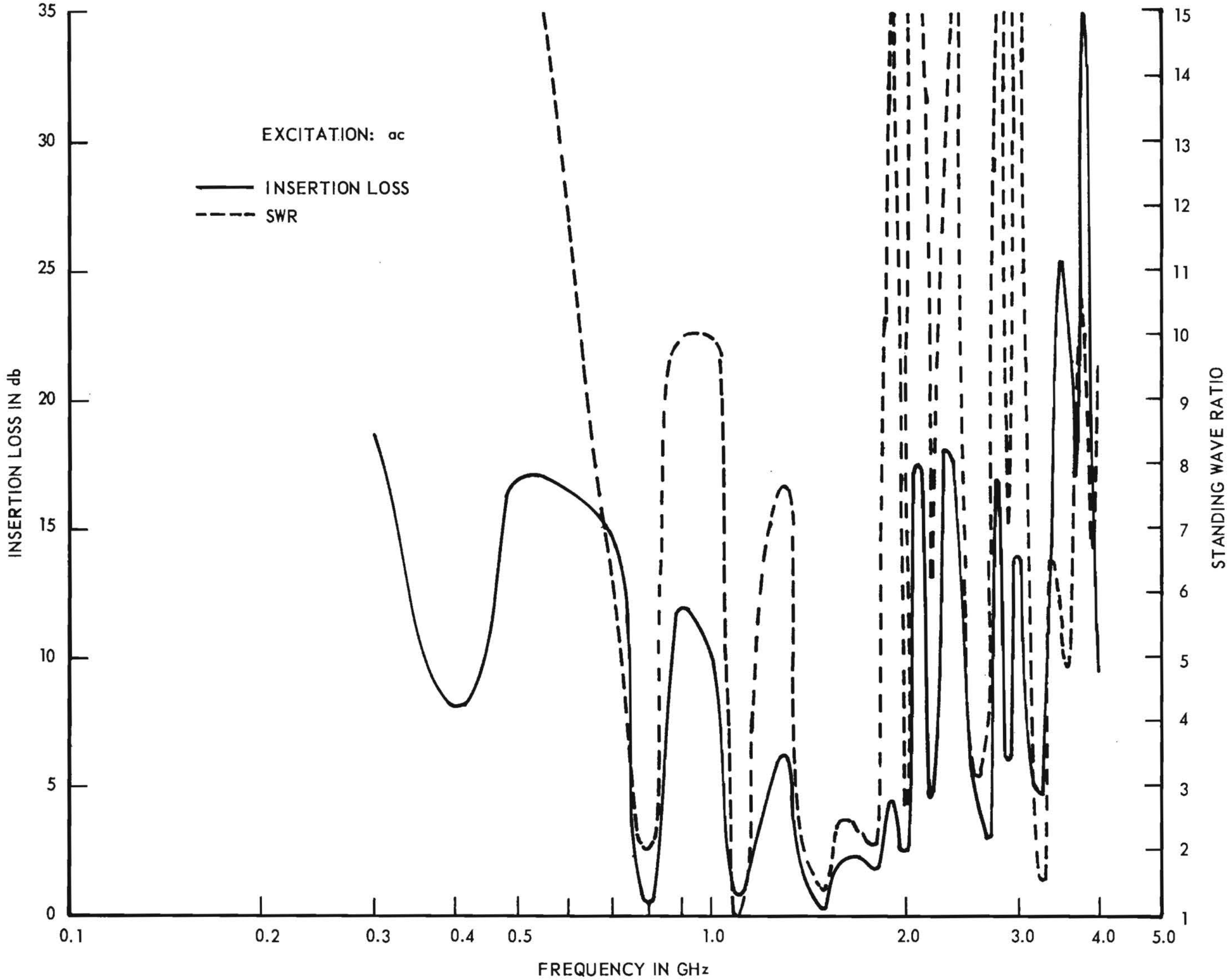


Figure A-7. Insertion Loss and VSWR Behavior of 30 Turn Helix Coupler with Tube Not Energized.

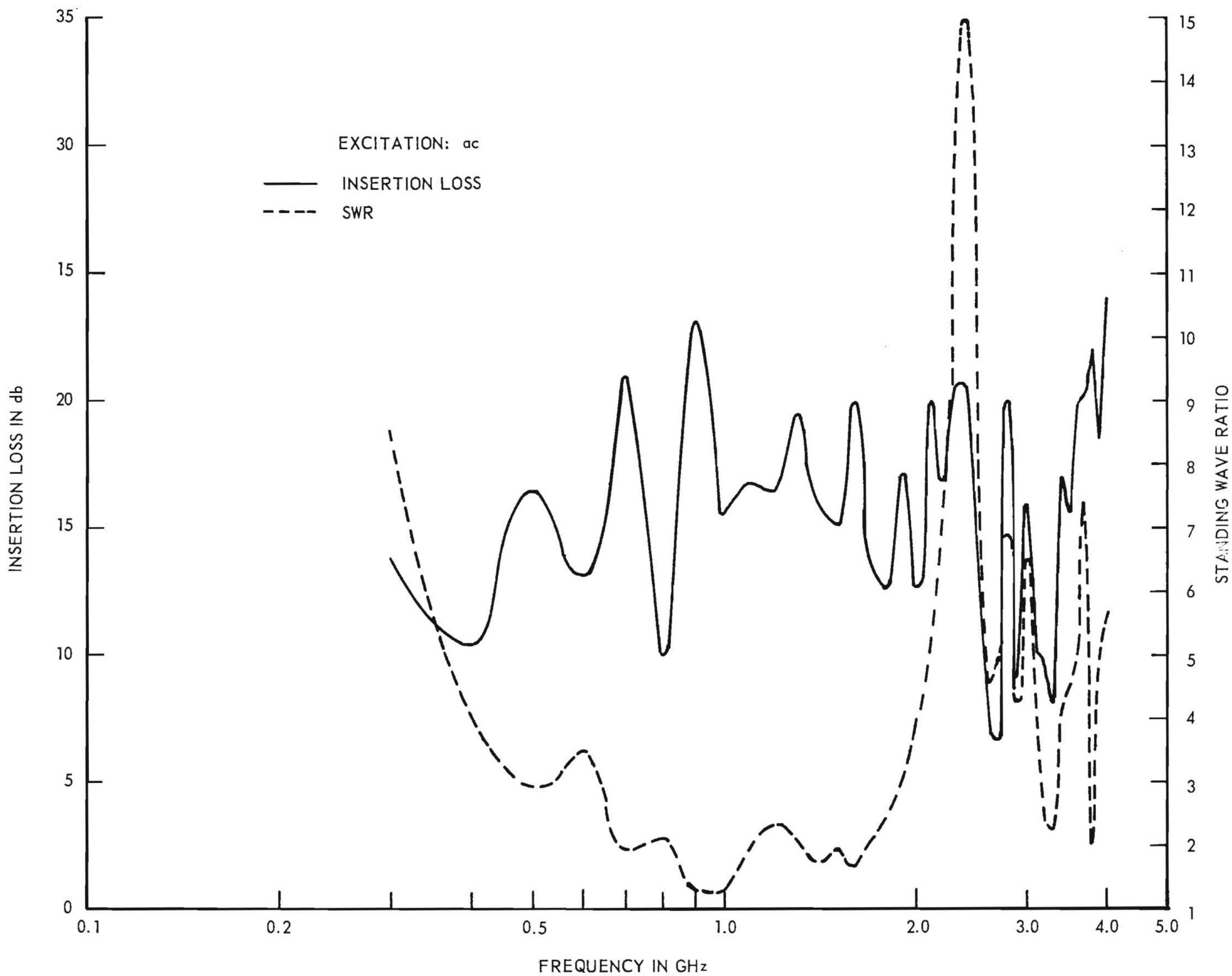


Figure A-8. Insertion Loss and VSWR Behavior of 30 Turn Helix Coupler with Tube Energized.

range. The attenuation is on the average about 15 db which represents a power absorption of 97% by the plasma.

The insertion loss measured through the helix may be due, all or in part, to three causes. Mismatch loss has been established as not being a major portion of the measured quantity. Actual absorption by the plasma is the desired result. Since the above measurements were performed with the ends of the copper cylinder electrically open, there existed the possibility that the power was radiated out the ends. To establish whether or not this was the situation, covers for the ends were fashioned from copper foil and tightly secured. The VSWR looking into the coil was measured with the covers in place. It was assumed that if the field configuration inside the cylinder was compatible with radiation from the ends, then the presence of the foil covers would change the configuration and shift the VSWR-frequency curve. Figure A-9 shows no significant difference in the VSWR curves under both conditions up to 2300 MHz.

The actual input impedance was examined more closely for all three (10, 20, and 30 turns) coils. The impedance into one end of the helix was measured with the other end terminated in 50 ohms. The VSWR for the 10-turn coil oscillated about 2.5:1 from 900 to 2000 MHz. The 20 turn coil exhibited a lower VSWR over a narrower bandwidth. The impedance of the 20 turn coil was less than 50 ohms in the region of best match. The 30 turn coil was constructed in an attempt to raise the impedance, but no significant change in match was obtained. The impedance of the 30 turn coil was found to vary from $95.7\ \underline{/55^{\circ}}$ ohms at 450 MHz to $49.4\ \underline{/62.2^{\circ}}$ ohms at 1000 MHz to $29.2\ \underline{/12.9^{\circ}}$ ohms at 1800 MHz.

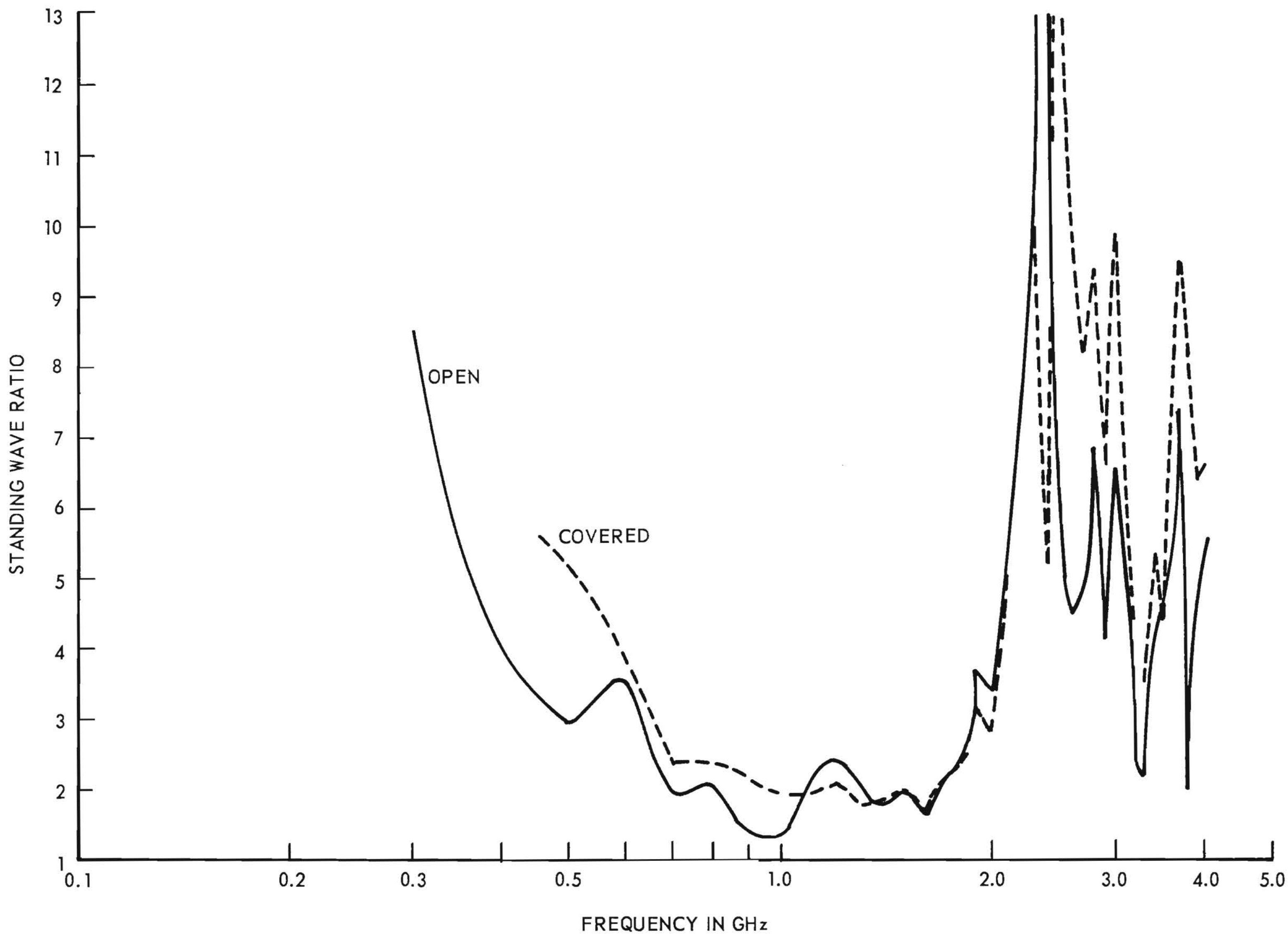


Figure A-9. VSWR Versus Frequency for 30 Turn Coupler with Ends of Outer Conductor Capped and Uncapped.

The VSWR at selected frequencies for open and short circuit terminations were compared to that for a 50 ohm termination. Typically the short circuit termination resulted in the lowest VSWR of the three.

Another coaxial coupler configuration was constructed to accomodate a larger plasma tube. A 15 watt argon plasma tube was positioned in the center of a 2 1/2 inch copper pipe. The pipe was made long enough to allow each end of the tube to be no closer than one foot from either end. Four type N panel jacks were mounted 10 cm apart on the wall to provide access over different ionization regions along the plasma column.

Tests were performed on a uniformly wound coil placed at two positions along the tube; one near one end of the tube and the other near the center. The coil consisted of 16 turns over a total length of 10 cm. Attenuation and VSWR measurements were made on the coil between two different pairs of ports. Figure A-10 shows how the attenuation varied with frequency when the coil was positioned between ports 2 and 3. (Port 1 is located so that its center lies about 1 cm from the end cap of the lamp.) Comparing these results with those of Figure A-7, the greater absorption of the larger tube is evident over the frequency range of 500 MHz to 1500 MHz. Over this same range, the power absorption by the plasma was in excess of 99%.

The impedance variations at each terminal of the coil are shown also in Figure A-10. Some improvement over the coil of Figure A-8 can be seen below 500 MHz but the overall bandwidth is reduced.

Another helix was wound with a logarithmic spacing of the turns over a length of 20 cm. Measurements were made on the coupler with ac and dc

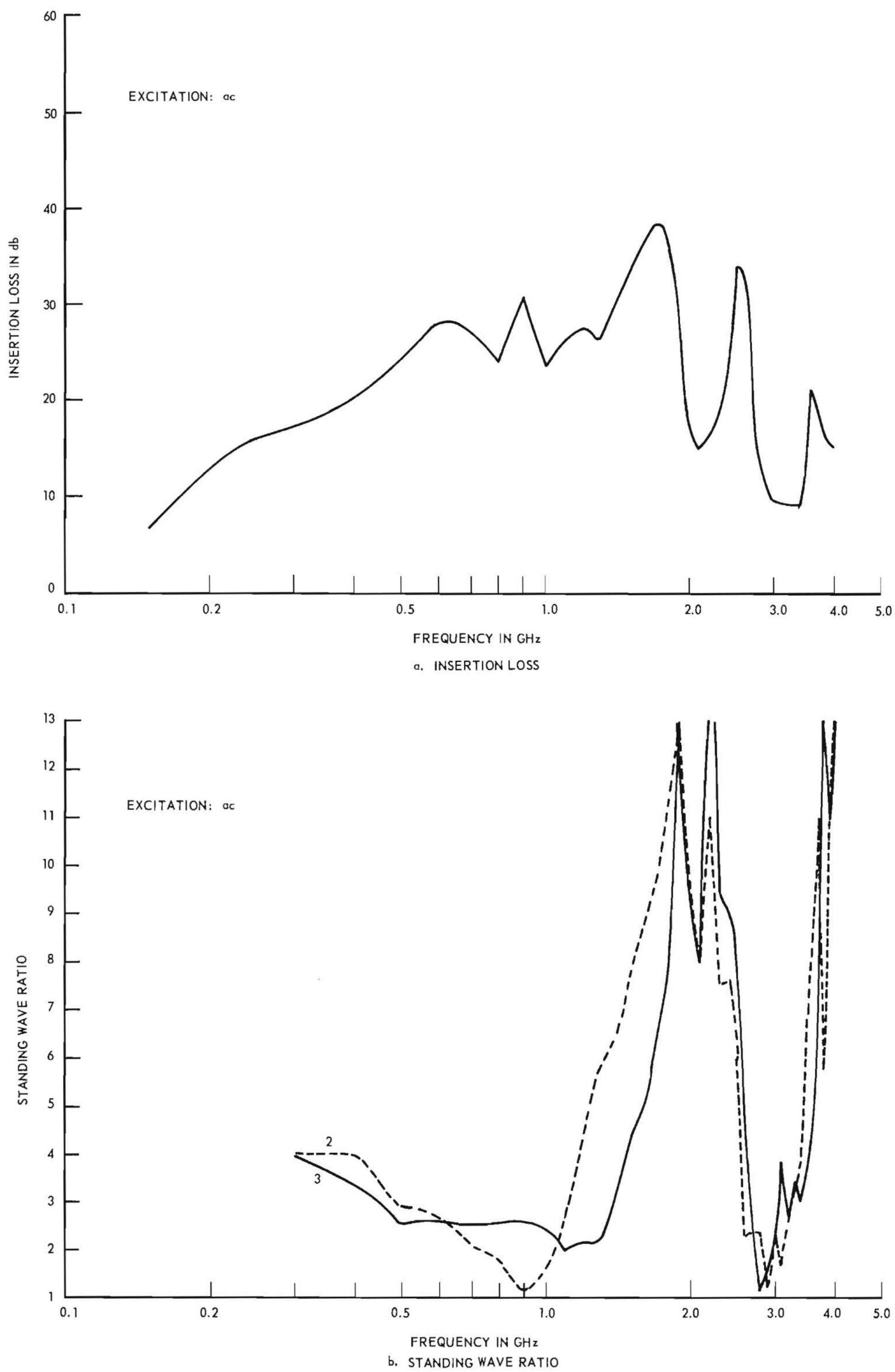


Figure A-10. Performance Curves of a Uniform, 16 Turn Helix Around an Argon-Plasma Lamp.

excitation of the plasma. The dc tests were made both with the coil spanning the dark regions and spanning only the positive glow column.

Figure A-11 demonstrates the performance of the coupler with ac excitation. On this figure, the curve labeled "1" represents data taken at port 1 which was at the open end of the logarithmic helix. The impedance match at port 1 exhibited an improved frequency performance over the impedance at port 3. Even considering the VSWR excursions between 1000 MHz and 2000 MHz, the attenuation up to 1800 MHz is primarily due to absorption by the plasma column.

Similar measurements were made with dc excitation. Figure A-12 shows the attenuation and VSWR performance of the coupler with the electrodes near port 1 as the negative terminal. The impedance variations are much more extreme than with ac excitation. A large peak in insertion loss occurs near 1700 MHz and is probably due primarily to the severe mismatch in this region. Note that, in general, the insertion loss (and absorption) is slightly less than with ac excitation. Figure A-13 shows that the performance when terminal 1 is positive is not greatly different than when negative. The parallel performance with both polarities is probably because the length of the helix is sufficient to extend beyond the dark region well into the glow regions.

The results of tests to this point indicated that a helix coupler was a usable technique for performing experimental evaluations of various types of plasmas. Since the coil does not make actual contact with the plasma medium, it can be used for comparison studies on glow discharge and flame plasmas.

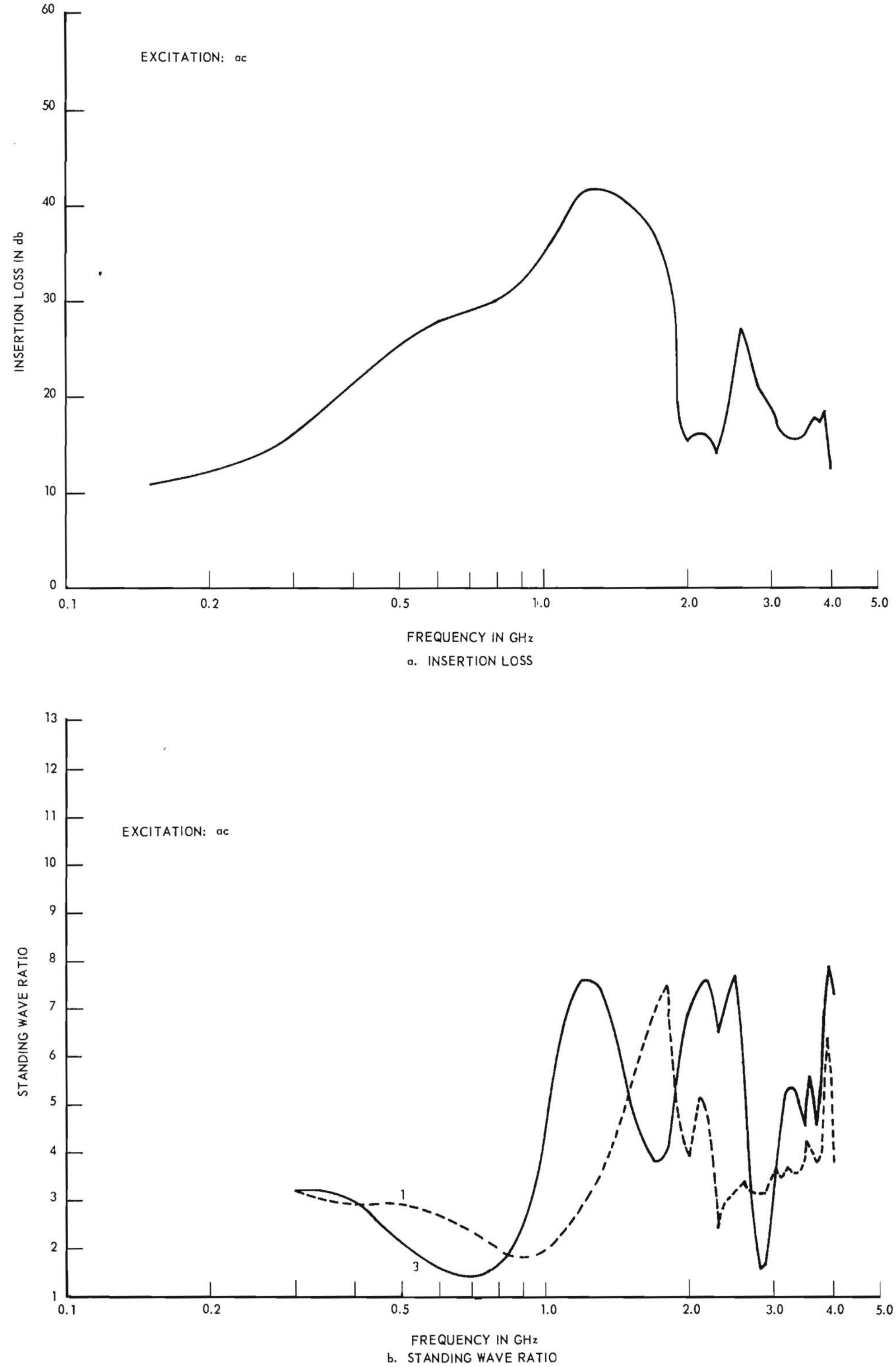


Figure A-11. VSWR and Insertion Loss Behavior with Frequency of the Logarithmic Helix with ac Excitation of the Plasma.

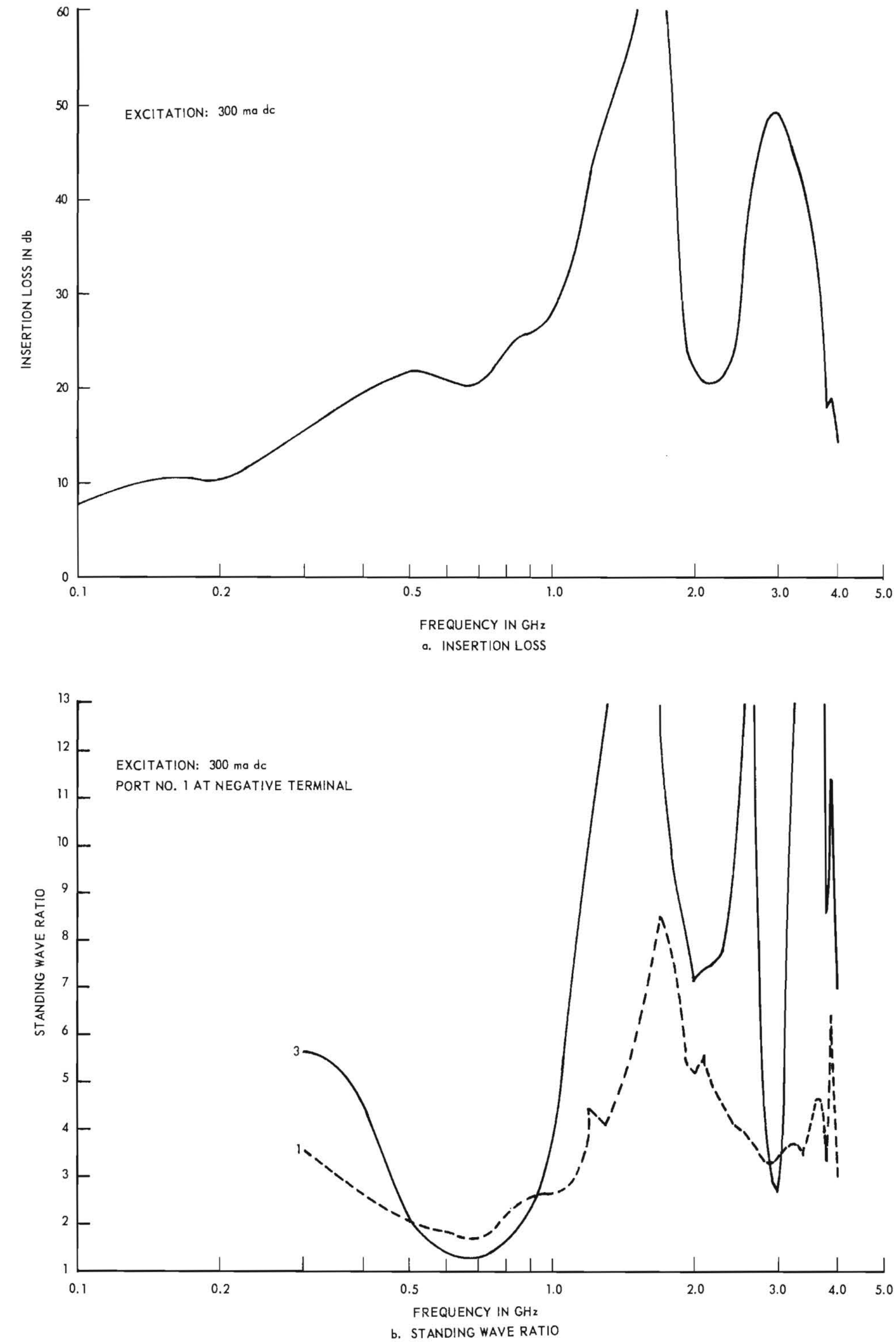


Figure A-12. Performance Curve of the Logarithmic Helix with Negative dc Excitation of the Plasma.

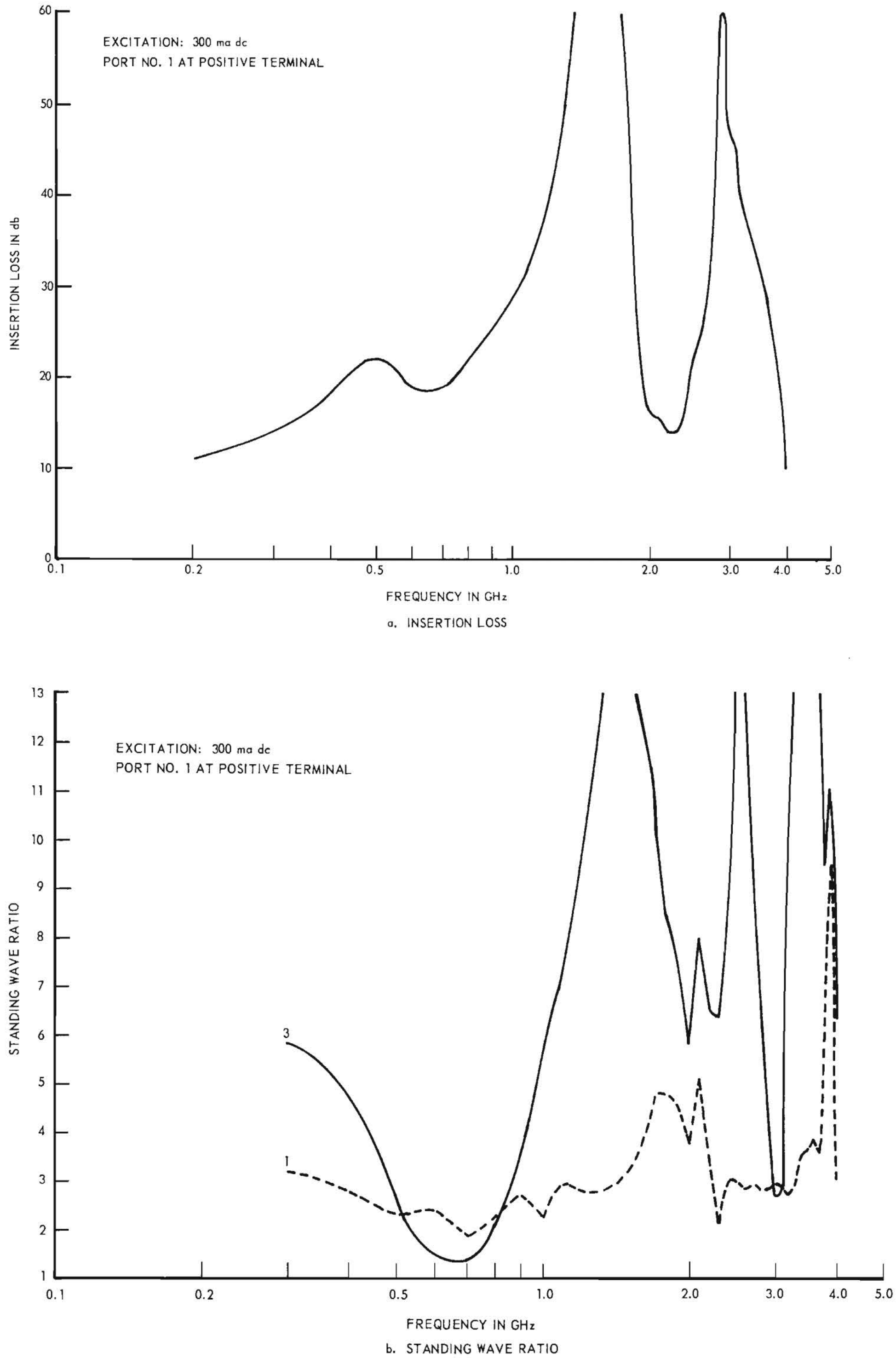


Figure A-13. Performance Curves of the Logarithmic Helix with Positive dc Excitation of the Plasma.

Prior to evaluating the helix as a coupler to a plasma generated by an oxygen-hydrogen rocket engine, preliminary tests were run using probes in a lower temperature flame. A device consisting of 1 1/4 inch copper tubing with electric field probes extending into the center was constructed to permit a signal to be coupled in and out of a flame column. The coupling between the two probes in the absence of a flame was measured from 1 MHz to 1000 MHz. From 400 MHz to 1000 MHz, the attenuation characteristic was that typical for a waveguide below cutoff, as can be seen on Figure A-14. Below 400 MHz, the attenuation exhibited a 6db/octave decrease with frequency.

A flame column produced by a propane torch was directed up the axis of the tube so that both probes penetrated well into the flame. The flame alone caused little variation in the coupling between the loops. Rock salt ($NaCl$) was placed in the nozzle of the torch in such a position that it was ionized by the flame. The fuel was adjusted so that an even, yellow flame resulted. When the probes were coupled with this more highly ionized flame, the coupling was raised at frequencies below 100 MHz. The coupling between the probes increased 40 db at 1 MHz in the presence of the ionized sodium flame; the increase was 20 db at 10 MHz with very little change noted above 100 MHz. The coupling exhibited as much as 10 db variation with normal flame fluctuations. Maximum coupling occurs when the largest number of sodium ions are released. The numbers quoted for 1 and 10 MHz are the minimum increases in coupling that occurred at those frequencies upon application of the flame.

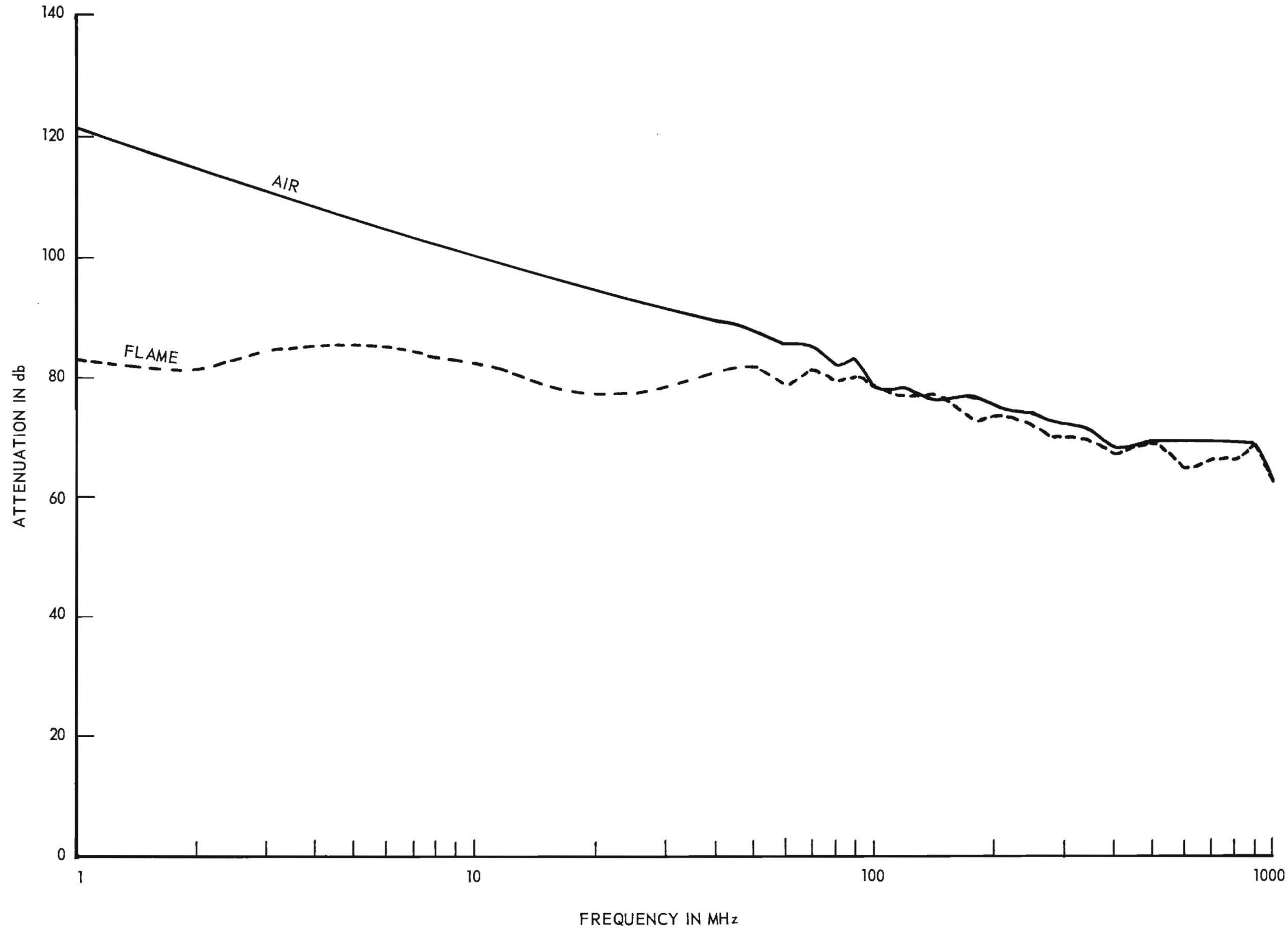


Figure A-14. Attenuation Versus Frequency Between Two Electric Field Probes Coupled in a Flame.

Electric field probes may be used as a coupling technique for use with low temperature flames such as that produced by the propane torch. The temperatures generated in the oxygen-hydrogen flame are sufficient to melt most conventional probe materials. For this reason the helix coupler was deemed to be more appropriate for making measurements on the small rocket exhaust.

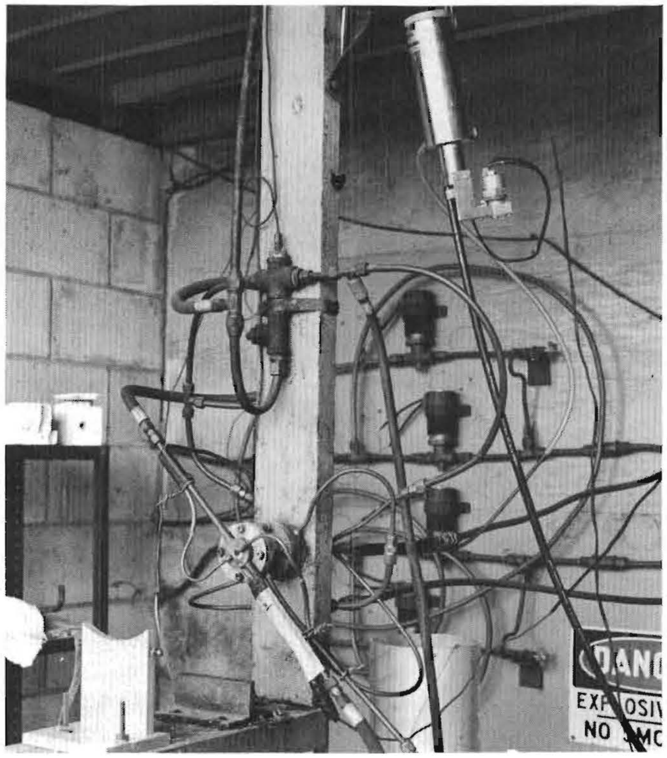
A coaxial type coupler was constructed similar to the one found useful with the argon tube experiment. A 6 3/8" I.D., 3 foot long aluminum pipe was used as an outer conductor. The pipe was positioned to axially align with the rocket nozzle. A helical coil with both ends terminated in a type N panel jack was positioned in the pipe to enclose the path of the exhaust.

The visible portion of the exhaust was estimated to be 14 to 18 inches long. A coil was constructed of No. 12 solid copper wire to a length of 16 inches. A 5-second run of the engine melted the soldered connections to the rf connectors and melted the coil at one point. Another coil was constructed of 1/8 inch, O.D., copper capillary tubing that had a 0.07 inch diameter hole in the center. This coil also experienced excessive heating during a 5-second run even though water was forced through the tubing.

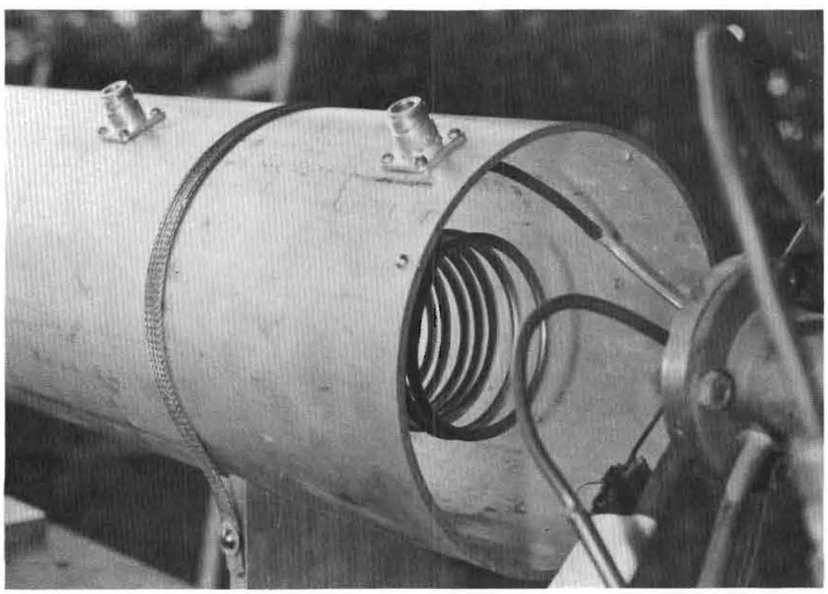
The next coil was constructed of 3/16 inch, O.D., copper tubing with approximately 1/8 inch I.D. The length was shortened to 8 inches and a water line attached to the end of the coil nearest the rocket provided adequate cooling for runs as long as 20 seconds.

A powder feed unit was obtained to investigate the effects of seeding the exhaust. The feed unit consists of a cylinder which holds the powder of the seeding material. A vibrator keeps the powder from packing which would stop the powder flow. An inert gas, such as dry nitrogen, is used as the carrier to transfer the powder to the exhaust plume. A dry nitrogen supply with a proper pressure regulator was procured along with a solenoid valve which permitted remote control of the feeding. Photographs of the rocket engine, the feed unit, and the coupler appear in Figure A-15.

Two coupling techniques were developed during the course of this study. The coaxial line and helix couplers provided good power transfer to argon glow discharge over a total range from 10 MHz to 1000 MHz. No comprehensive data are presently available indicating the effectiveness of helix coupling to small flame plasmas.



a. ENGINE



b. COUPLER

Figure A-15. Photographs of the Oxygen-Hydrogen Rocket Engine and the Helix Coupler.