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Report ECOM- 4226

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ADVANCED MEASUREMENT TECHNIQUES WITHIN SHIELDED ENCLOSURES

Robert L. McKenzie

DDC

June 1974

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This report summarizes the results of an experimental program to develop measurement techniques for obtaining accurate radiated interference data on electronic and electrical equipment when tested within the confines of shielded enclosures. Specific objectives were to investigate various observations, conclusions and recommendations evolving from prior work in this area.

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Although the initial measurements were made in a full size enclosure, most of the experiments were performed using frequency scaled cavities at frequencies up to and including the first resonant frequency.

With linear source and receive antennas, the severe E Field null observed by other investigators appeared at frequencies somewhat above fco/2 for the dominant waveguide mode. As noted by Mendez (IBM), the null moves toward the source as the frequency is increased. In addition, the location of the null relative to the source is a function of the enclosure geometry, the location of the source and the length of both the source and receive antennas. However, when either monopole was replaced by a loop the null did not appear. Also, the null was not observed with the monopole source antenna located on the bottom wall and a monopole receive antenna probing along the top wall.

Regardless of the antenna configuration, the standing wave at the first resonant frequency is a problem. Reasonable success in reducing the amplitude was realized by loading the cavities with lossy, vane attenuators.

PREFACE

The work under this program was performed at the U. S. Army Electronics Command, Fort Monmouth, N. J. It was conducted in support of Task 1S6 62701 D449 01, R & D Support for Radio Frequency Program, Under DoD Directive 3222.3, DoD Electromagnetic Compatibility Program, 5 July 1967, and AR 11-13, Army Electromagnetic Compatibility Program, 29 July 1969.

The fabrication work performed by John Leonard and the comments offered by Dr. Kurt Ikrath are acknowledged and greatly appreciated.

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1. INTRODUCTION.

1.1 Objectives.

The general objective of this program was to develop measurement techniques for obtaining accurate electromagnetic interference (EMI) data on electronic and electrical equipment when tested within the confines of shielded enclosures. Specific objectives were to experimentally investigate various observations, conclusions and recommendations evolving from prior work in this area such as that performed by the Georgia Institute of Technology (Georgia Tech)[1], the University of Pennsylvania (U of P)[2] and the International Business Machines Corporation (IBM)[3].

1.2 Background.

Test Method RE02 in MIL-STD 462, "Electromagnetic Interference Characteristics, Measurement of", requires that Electric Field (E Field) radiated emission tests be performed on equipment over the frequency range of 14 kHz to 12.4 GHz. It is generally necessary to make these measurements inside a shielded enclosure, particularly in populated areas, because of interfering signals, man made and atmospheric noise, and inclement weather. The electromagnetic compatibility (EMC) community is aware of the difficulty in making E Field measurements within an enclosure below approximately 400 MHz, that are meaningful, and can be duplicated in a differently configured enclosure or correlated with measurements made out of doors. Because of cavity and waveguide effects, the results are greatly influenced by the geometry of the enclosure, the test frequency and the exact location of the equipment within the enclosure.

As the electromagnetic environment within an enclosure, or cavity, will vary with frequency, it is necessary to consider the problem at several points in the spectrum; such as at frequencies below the first resonance, at resonance and at frequencies above the first resonance.

1.2.1 Frequencies Below the First Resonant Cavity Frequency.

Georgia Tech[1] observed that at frequencies much lower than the first resonant frequency, with the probe antenna close to the source the results were essentially the same as those obtained with measurements made out of doors. However, in general, at frequencies below resonance in the enclosure, severe E Field coupling nulls were observed as the probe antenna was moved away from the source. The position of those nulls, relative to the source, appeared to be frequency sensitive.

Mendez[3] later developed a mathematical analysis capable of predicting the location of the null and the relative signal strength versus distance from the source of the roll-off. His analysis shows that the null starts at the wall, moves toward the source as the frequency is increased, and disappears at the source at resonance. He experimentally validated the analysis, but did not specifically state the cause of the nulls.

1.2.2 First Resonant Cavity Frequency. (See Figure 1)

The resonant frequencies of a rectangular cavity are given by:[4]

$$f_{m,n,p} = \frac{C}{2}\left[\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{d}\right)^2\right]^{\frac{1}{2}} \qquad (1)$$

Where

f	=	Frequency in Hz.
C	=	Speed of light in meters.
a,b,d	=	Dimensions of enclosure in meters.
m,n,p	=	Mode integers, only one of which can be zero at one time.

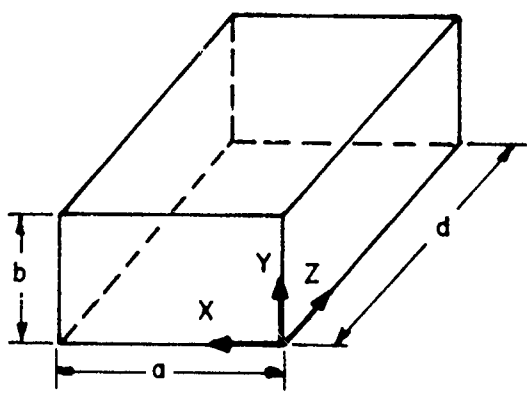


FIG 1

For example, if the enclosure dimensions are such that $b < a < d$, the lowest resonant frequency would be associated with a transverse-electric (TE) wave traveling in the Z direction ($TE_{1,0}$) and would be determined by setting m, n, p equal to 1,0,1 respectively. At this frequency ($f_{1,0,1}$) the $TE_{1,0,1}$ standing wave appears; the amplitude, of course, being a function of the enclosure figure of merit, or Q. In a typical enclosure this resonance will occur at a frequency below that at which absorbent materials are practical.

1.2.3 Frequencies Above First Resonance.

The higher order modes associated with larger values of mode integers produce many resonances at the higher frequencies. The highest resonant mode that will be excited will depend on the frequency at which the wall losses equal the radiated power. Above approximately 400 MHz, however, the use of absorbent materials on the walls of the enclosure is practical, and the "hooded antenna" technique developed by Georgia Tech[1] appears to be effective.

2. FACTUAL DATA.

2.1 Coupling and Antenna Impedance Measurements in a 16 X 8 X 24 ft. Shielded Enclosure.

Test Method RE02, MIL-STD 462, specifies that from 14 kHz to 30 MHz radiated electric field emissions shall be measured, at a distance of 1.0 meter from the test specimen, using a 41 in. rod antenna with matching network.

Georgia Tech[1] observed that at a distance of 1.0 meter or less from the source in their 8 X 8 X 20 ft. shielded enclosure, the measurement results appeared to be independent of the source location over the 1.0 to 30 MHz frequency range. Measurements repeated in an 8 X 8 X 12 ft. enclosure showed good correlation. In addition, both series of measurements were within 2 to 3 dB of those obtained in the open field. Above approximately 30 MHz there was no apparent correlation between measurements in the two enclosures. Two dipole antennas were used for these measurements.

In a first attempt to develop a general method for establishing this upper frequency limit for any size enclosure, and to investigate the behavior of the rod antenna, in a cursory manner, a series of E Field coupling experiments and antenna impedance measurements were performed in the 16 X 8 X 24 ft. shielded enclosure, available in the EMC Office.

2.1.1 E Field Coupling Measurements.

Two 41 inch rod antennas with Antenna Coupler CU-890/URM-85 were used as source and receive antennas. The 24 X 24 inch counterpoise normally associated with these antennas was not used in order to eliminate one unknown variable. The base of the couplers, resting on the plywood floor, were approximately 2.5 inches above the steel floor of the enclosure. Two 30 foot lengths of RG-5B/U cable were used to connect the antennas to the test equipment via feed-through connectors mounted on the enclosure walls. The test equipment remained outside the enclosure, and the coax cables were separated as far as possible to minimize cable coupling.

The appropriate Hewlett-Packard signal generator was used as the signal source and Radio Interference Measuring Set AN/URM-85 as the receiver. The signal generator output for a 10 dB reading on the AN/URM-85 output meter served as the indication of the coupling between the antennas. The higher the signal generator output, the less the degree of coupling; so for

graphing purposes the signs are reversed. That is, a signal output less than 1.0 mV is positive and a signal level greater than 1.0 mV is negative. This convention is followed throughout the report.

It was decided to make the initial measurements from 30 MHz, down to approximately 1.0 MHz. The specific values of 30, 25, 20, 15, 8.0 and 2.0 MHz were chosen because, at the time, it was believed that out-of-door measurements could be made at these frequencies.

2.1.1.1 Test Results and Discussion.

Figure 2 shows the results of relative E Field coupling measurements in the 16 X 8 X 24 ft. enclosure with the source antenna at various locations in the enclosure and the receive antenna located 3.0 ft. from the source. This approximates the 1.0 meter specimen-probe separation specified in MIL-STD-462.

At 15 MHz and below, the results are very close regardless of the location of the source. Above 15 MHz there is considerable variation particularly at 25 and 30 MHz.

Figure 3 shows the relative coupling versus distance at 25, 20, and 15 MHz with the source antenna located in the center of the enclosure, and the receive antenna probing the long axis with measurements made at 3.0, 3.5 and 4.0 ft. from the source. The coupling versus distance curve at 15 MHz is almost linear, while the 25 MHz curve illustrates the gross difference in measurement accuracy which can result from a slight displacement of the pick-up probe. Table I tabulates the maximum variation in relative coupling under four test conditions in the enclosure. It shows a maximum variation in coupling of 1.4 dB at 15 MHz and below, compared to 29.7 dB at 25 MHz and 23.7 dB at 30 MHz. At 15 MHz, and below, the results appear to be essentially independent of the source location.

Associated with each possible wave type in a rectangular waveguide there is a cutoff wavelength related to the cross-sectional dimensions of the guide in the following manner:[5]

$$\lambda_{co} = \frac{1}{\left[\left(\frac{m}{2a}\right)^2 + \left(\frac{n}{2b}\right)^2\right]^{\frac{1}{2}}} \qquad (2)$$

Where:

λ_{co} = Cutoff wavelength in meters

a = Width of guide in meters

b = Height of guide in meters

m, n = Mode integers

For transverse-electric (TE) waves m or n may be zero. In a guide in which the a dimension is larger than the b dimension, and letting m = 1 n = o yields the $TE_{1,0}$ mode which has the longest cutoff wavelength and thus, the lowest cutoff frequency. The wave type with the longest cutoff wavelength in a particular guide is often called the dominant mode.

Considering the 16 X 8 X 24 ft. enclosure as a waveguide:

$a = 16$ ft. $\lambda_{co} = 9.76$ meters

$b = 8$ ft. $f_{co} = 30.7$ MHz

$f_{co}/2 = 15.4$ MHz

For the Georgia Tech 8 X 8 X 20 ft. and 8 X 8 X 12 ft. enclosures:

$a = 8$ ft. $\lambda_{co} = 4.88$ meters

$b = 8$ ft. $f_{co} = 61.5$ MHz

$f_{co}/2 = 30.8$ MHz

In the three different size enclosures, the results of the E Field coupling measurements appear to be independent of source location at frequencies $f_{co}/2$ for the dominant mode, and below. Because of the high level of signal interference it was found to be impossible to make comparative open-field measurements.

The theoretical attenuation, L, in a length, d, for a waveguide below cutoff can be found by:[6]

$$\text{Loss (dB)} = 54.5 \frac{d}{\lambda_{co}} \left[1 - \left(\frac{f}{f_{co}} \right)^2 \right]^{\frac{1}{2}} \qquad (3)$$

For the 16 X 8 X 24 ft. enclosure:

$\lambda_{co} = 9.76$ m = 32 ft.

$f_{co} = 30.7$ MHz

$d = 1.0$ ft.

Theoretical loss at 15 MHz = 1.5 dB/ft.

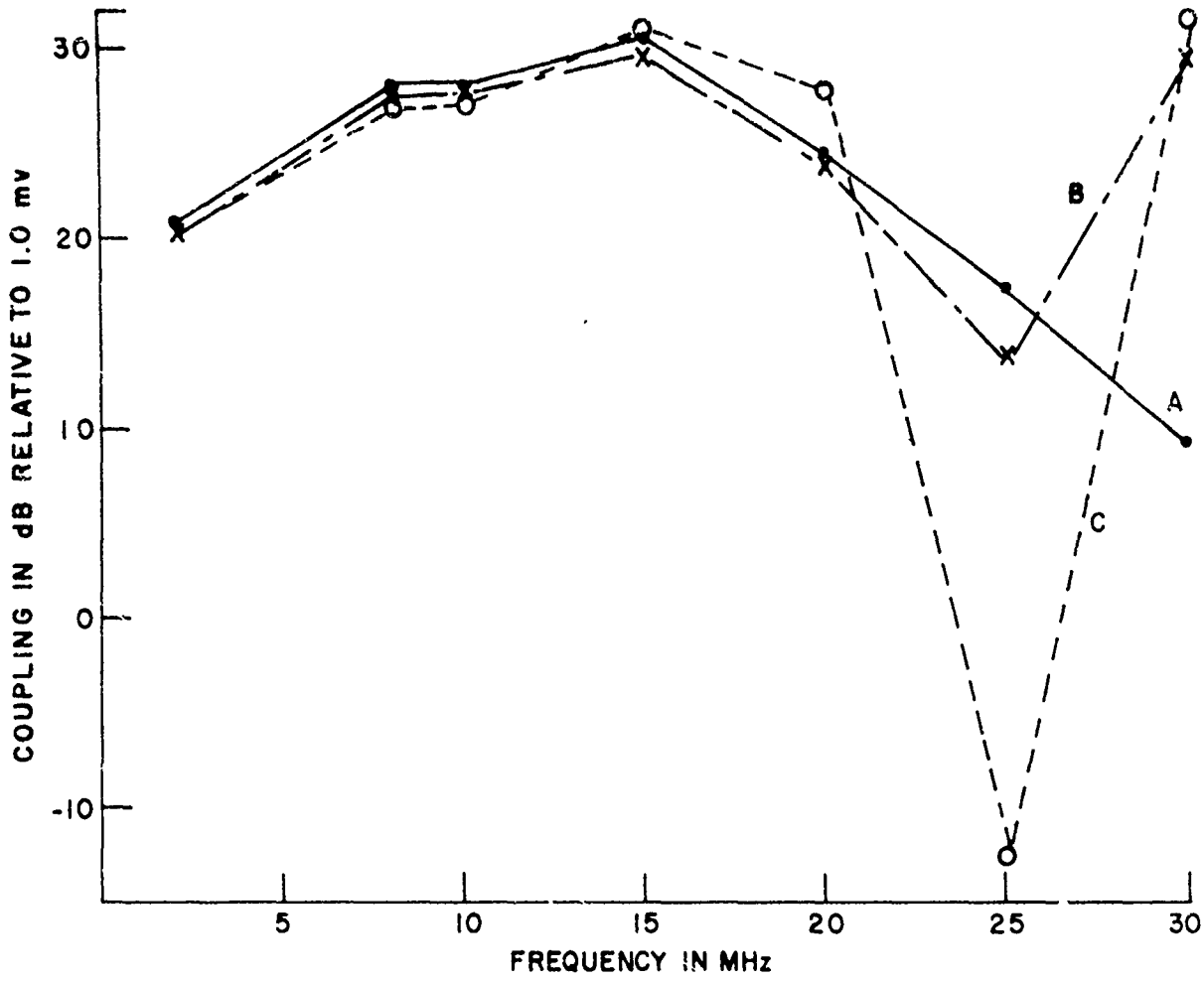
When $f << f_{co}$

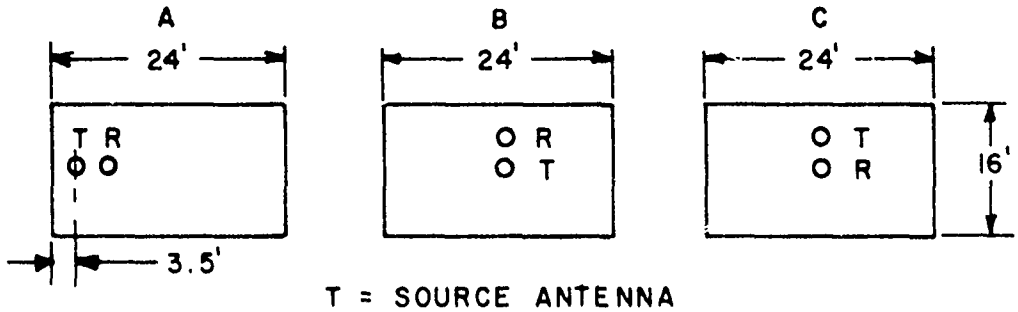
Loss (dB) = $54.5 \frac{d}{\lambda_{co}}$ - 1.7 dB/ft. which is the theoretical maximum.

Figure 4 shows that the loss at 15, 10, 8 and 2.0 MHz exceeds the theoretical maximum for a waveguide below cutoff.

A detailed examination of coupling data taken by Georgia Tech[1] in an 8 X 8 X 20 ft. rectangular enclosure shows the presence of coupling nulls at $f_{co}/2$, and below. However, the nulls are located far enough from the source so that measurements made at the 1.0 meter test distance appear to be reasonably close to those made in the open-field.

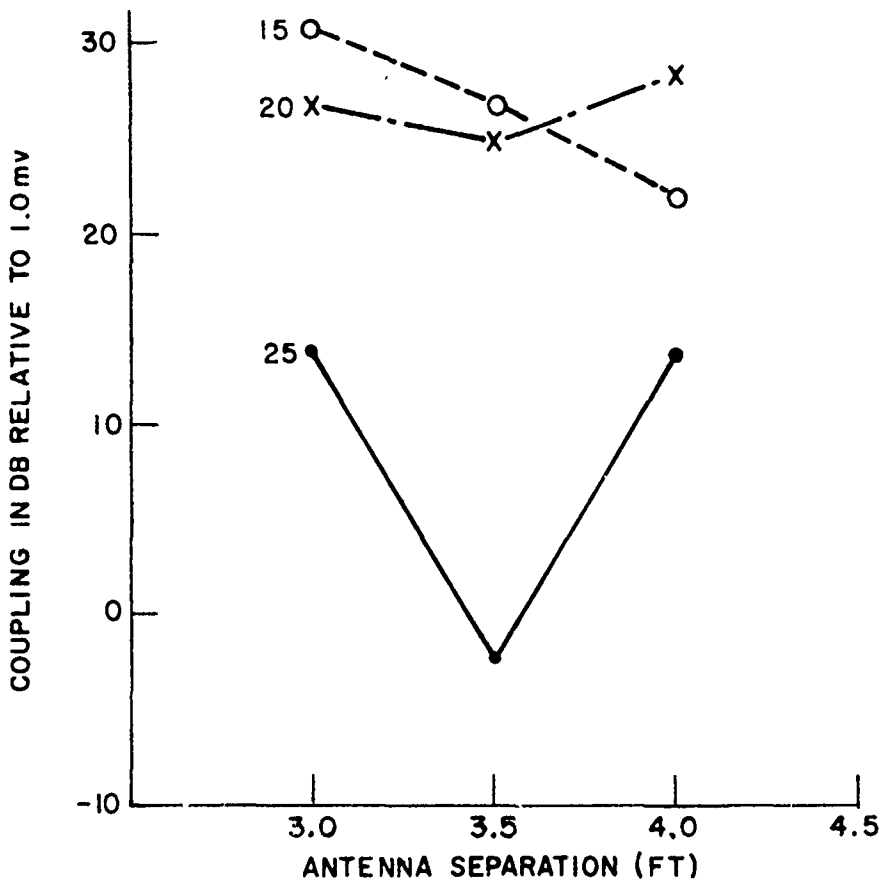
On the other hand, the Mendez curves[3] for a 20 X 10 X 20 ft. square enclosure show no null at $f_{co}/2$, and below. In both cases, however, the attenuation exceeds the theoretical waveguide below cutoff value.





T = SOURCE ANTENNA
R = RECEIVE ANTENNA

E FIELD COUPLING VS FREQUENCY
16 X 8 X 24 FT. ENCLOSURE
ANTENNA SEPARATION 3.0 FT
FIG. 2



RELATIVE E FIELD COUPLING
VS
ANTENNA SEPARATION
15, 20 AND 25 MHz

SOURCE ANTENNA IN CENTER
RECEIVE ANTENNA ON LONG DIMENSION CENTER LINE

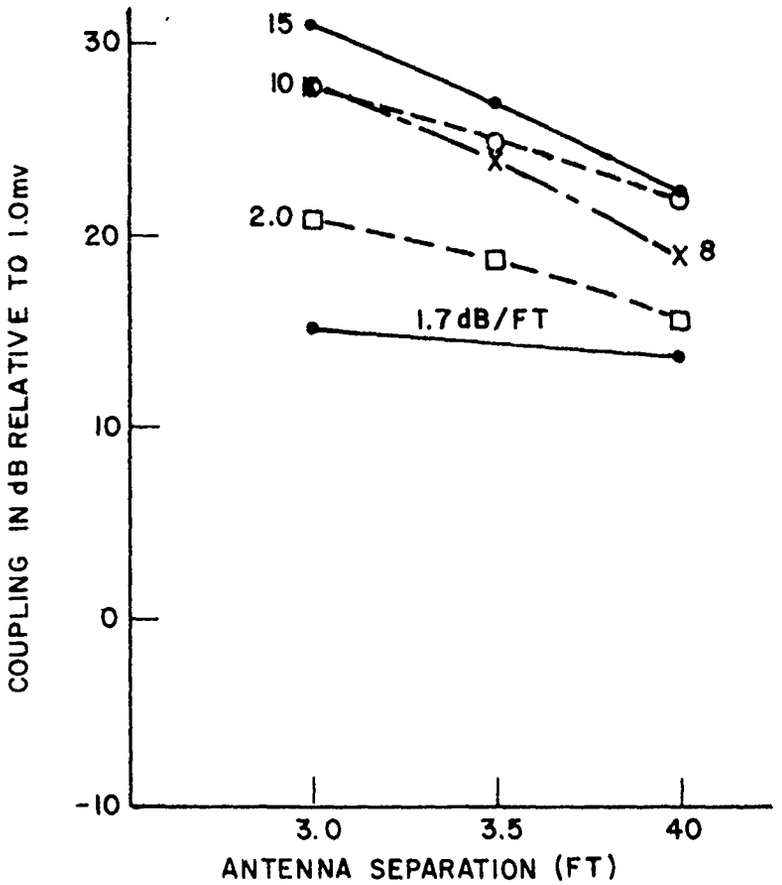
FIG 3

TABLE I

COUPLING IN dB RELATIVE TO 1.0 MV

FREQUENCY (MHz)	A	B	C	D	MAXIMUM VARIATION (dB)
2.0	+20.9	+20.4	+20.4	+20.4	0.50
8.0	+28.0	+27.5	+27.1	+27.3	0.90
10.0	+28.0	+27.7	+27.3	+27.5	0.70
15.0	+30.5	+29.4	+30.8	+30.8	1.4
20.0	+24.7	+24.4	+27.5	+26.6	3.1
25.0	+17.1	+13.8	-12.6	+13.6	29.7
30.0	+ 9.1	+29.1	+31.4	+32.8	23.7

NOTE: Test conditions A, B and C are the same as those shown in Figure 2. In D the source antenna was located at the center of the enclosure and the receive antenna was on the long dimension center line at a distance of 3.0 ft. from the source.



RELATIVE E FIELD COUPLING
VS
ANTENNA SEPARATION
2, 8, 10 AND 15 MHz

SOURCE ANTENNA IN CENTER
RECEIVE ANTENNA ON LONG DIMENSION CENTER LINE

FIG 4

2.1.2 Antenna Impedance Measurements.

2.1.2.1 Test Procedures.

Impedance measurements were made at the input to the CU-890/URM-85 Coupler with the 41 in. (1.04m) rod antenna located in the center of the 16 X 8 X 24 ft. enclosure. The initial measurements were made without the ground plane with the coupler resting on the plywood floor which corresponds to the configuration used in the E Field coupling measurements. As previously noted, this places the base of the coupler approximately 2.5 in. above the steel floor of the enclosure.

The measurements were repeated with the 24 X 24 in. ground plane in place, and the entire assembly mounted on the tripod normally used with the rod antenna. Measurements were made with the ground plane at heights of 29.75 and 42.5 in. from the plywood floor.

High level signal interference in this frequency range made it impossible to make comparative out-of-door measurements. As a substitute, impedance measurements were made on a 1.0 meter monopole mounted on a 34 X 34 in. ground plane, in the center of the enclosure, with the ground plane 24.5 in. above the plywood floor. It was theorized that if these results varied significantly from those obtained, out-of-doors, by Brown and Woodward,[7,8] it could be concluded that the terminal impedance of the 41 in. rod and coupler, when measured in an enclosure, would also deviate significantly from the out-of-door value.

Impedance values were measured with a Hewlett-Packard R.F. Vector Impedance Meter, Model 4815A connected to the antenna with a 11 ft. 4 in. section of RG-213/U coax cable.

2.1.2.2 Discussion and Test Results.

Table II summarizes the results of the impedance measurements made on the 41 in. rod with coupling network in the enclosure. Table III-A shows the results of the measurements on the 1.0 meter rod in the enclosure, and III-B tabulates the corresponding out-of-door values measured by Brown and Woodward.

Since both antennas are less than $\lambda/8$ at 30 MHz and below they should both represent a high capacitive reactance with a value inversely proportional to frequency. However, the coupling network used with the 41 in. rod is designed to "step down" the high reactance to a value more compatible with the nominal 50 ohm input impedance of interference measuring equipment.

Tables II-B and II-C with the ground plane 32.25 and 45 in., respectively, above the steel floor show there is very little change in impedance under those conditions. It should be pointed out, however, that the tip of the antenna was approximately 10 in. from the top of the enclosure, so that the data does not include the effect of any appreciable capacitive coupling to the top wall.

More significant is the fact that the changes in impedance magnitude and angle with frequency in Table II are extremely inconsistent, and contrary to theory for an electrically short monopole.

Results tabulated in Table III-A for the 1.0 meter antenna, without a coupling network, inside the enclosure are likewise inconsistent. A comparison of Tables III-A and III-B shows a significant difference in terminal impedance between measurements made out of doors by Brown and Woodward and those made in the enclosure.

Reference 2, pp. 57-58, contains additional comments on the use of the 41 in. rod antenna in a shielded enclosure.

TABLE II

41 IN. ROD ANTENNA WITH COUPLER

	A IMPEDANCE		B IMPEDANCE		C IMPEDANCE	
FREQ (MHz)	OHMS	DEGREES	OHMS	DEGREES	OHMS	DEGREES
30	150	-30	115	+74	112	+75
25	12	+60	4.4	+30	5.8	+20
20	27	-72	38	-77	40	-77
15	64	+68	47	+68	46	+75
10	38	+76	49	+69	50	+79
8	5	+17	5.6	+42	6.0	+45

A. No Ground Plane-Base of Coupler Resting On Plywood Floor - 2.5 In. Above Steel Floor of Enclosure.

B. With Ground Plane - Ground Plane 32.25 In. Above Steel Floor Of Enclosure.

C. Ground Plane 45 In. Above Steel Floor.

TABLE III

1.0 METER ROD ANTENNA

FREQ (MHz)	A IMPEDANCE OHMS	A IMPEDANCE DEGREES	B IMPEDANCE OHMS	B IMPEDANCE DEGREES
30	34	-84	180	-88.4
25	197	-84	190	-88.5
20	300	+82	210	-88.6
15	25	+85	245	-89.77
10	11	-84	300	-89.8
8	26	-88	350	-89.8

A. 34 X 34 In. Ground Plane 27 In. Above Steel Floor of Enclosure.

B. Out-Of-Doors Values Measured By Brown and Woodward (With Ground Plane)

2.2 Coupling Measurements in Frequency Scaled Enclosures.

2.2.1 Test Methods.

At this point for convenience and flexibility, it was decided to continue the experiments in small, frequency scaled cavities. Since the greater part of the Mendez data was formulated for a square enclosure, it was decided to perform the initial measurements in a 10 X 3 X 10 in. cavity in order to develop measurement techniques and a feeling for Mendez's work. However, since most shielded enclosures are rectangular rather than square, the majority of the measurements were performed in 10 X 3 X 17 in. and 10 X 3 X 12 in. cavities.

The standard test antennas were monopoles consisting of a 1.0 in. length of 1/16 in. diameter solid wire soldered to the center conductor of an M39012/21 coax connector. For the coupling measurements, the antennas were inserted into the cavities through a slot centered along the top

(10 in. wide) wall, and the shell of the connectors were grounded to the cavity. A slot oriented in this manner in a waveguide is theoretically a non-radiating slot for the $TE_{1,0}$ mode. The 1.0 in. monopole becomes 1/8 wavelength long at 1.5 GHz, so can be considered electrically short for these measurements, which were all below 1.0 GHz.

Again the appropriate Hewlett-Packard signal generator was used as the signal source, Radio Interference Measuring Set AN/URM-85 the receiver, and the signal generator output for a 10 dB reading indicated the coupling level.

2.2.2 Coupling Measurements - 10 X 3 X 10 Inch Cavity.

For the 10 X 3 X 10 in. Cavity:

a = 10 in., b = 3.0 in., d = 10 in.

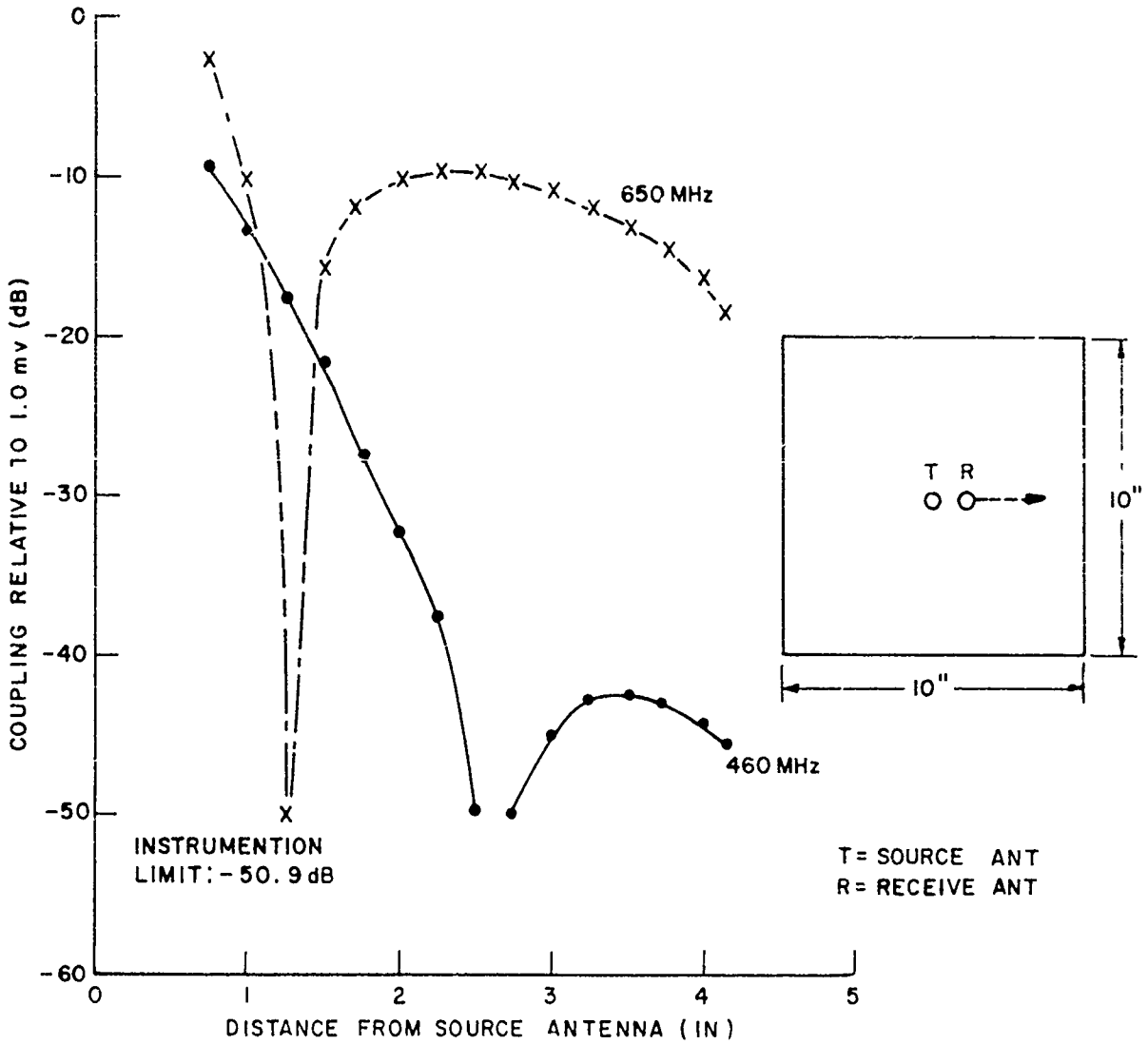
Dominant Wave ($TE_{1,0}$) Cut-off Frequency: 591 MHz

First Resonant Frequency ($f_{1,0,1}$): 837 MHz

A series of E Field coupling versus separation distance were made over the 460 MHz to 800 MHz frequency range. The source antenna was located at the center of the cavity, and the receive antenna was moved along the center line toward one of the side walls. The minimum separation distance between the antennas was 0.75 in. The E Field null was observed from 460 MHz to 700 MHz, was not present, or was closer than 0.75 in. from the source at 750 MHz, and up to 1.0 GHz had not reappeared. At 460 MHz, the null was located at a distance of 2.6 in. from the source, and moved to a point 0.9 in. from the source at 700 MHz.

Figure 5 shows relative coupling versus distance at 460 and 650 MHz. It should be pointed out that the -50 dB value shown on the graphs reflects the limit of the instrumentation, and in most cases the depth of the null greatly exceeded this value. Figures 6 and 7 compare "open field" measurements to those made in the cavity at 460 and 650 MHz. The "open field" measurements were made with the antennas mounted on a 10 X 17 in. ground plane located in the center of the 16 X 8 X 24 ft. shielded enclosure. Figures 5, 6 and 7 clearly illustrate the problems encountered in attempting to make meaningful measurements in shielded enclosures. For example: If measurements were made at a distance of 3.0 inches from the source which might conceivably correspond to the 1.0 meter test distance in a full size enclosure, the results at 460 MHz would be approximately 15 dB below and at 650 MHz approximately 9.0 dB higher than the "open field measurements. Figure 8 shows the position of the null relative to the source, versus frequency, from 460 to 700 MHz. The relationship is fairly linear over this frequency range.

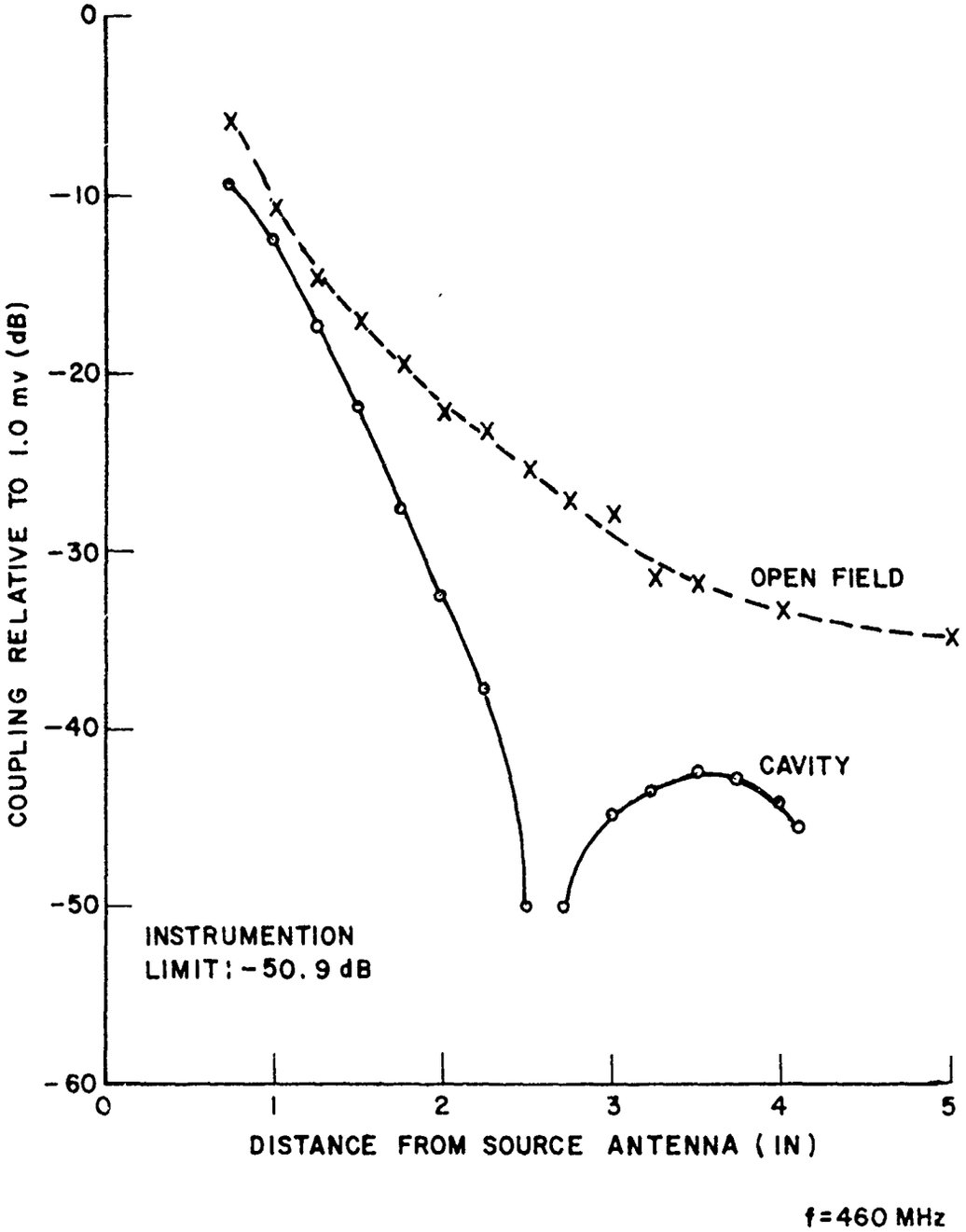
When the cavity was probed from the center to one corner, the null appeared at the same distance from the source as was previously observed. Thus, in a square cavity with the source antenna in the center, the null is apparently located along a radius around the source.



RELATIVE COUPLING
VS DISTANCE
10X3X10 IN CAVITY

SOURCE ANTENNA IN CENTER

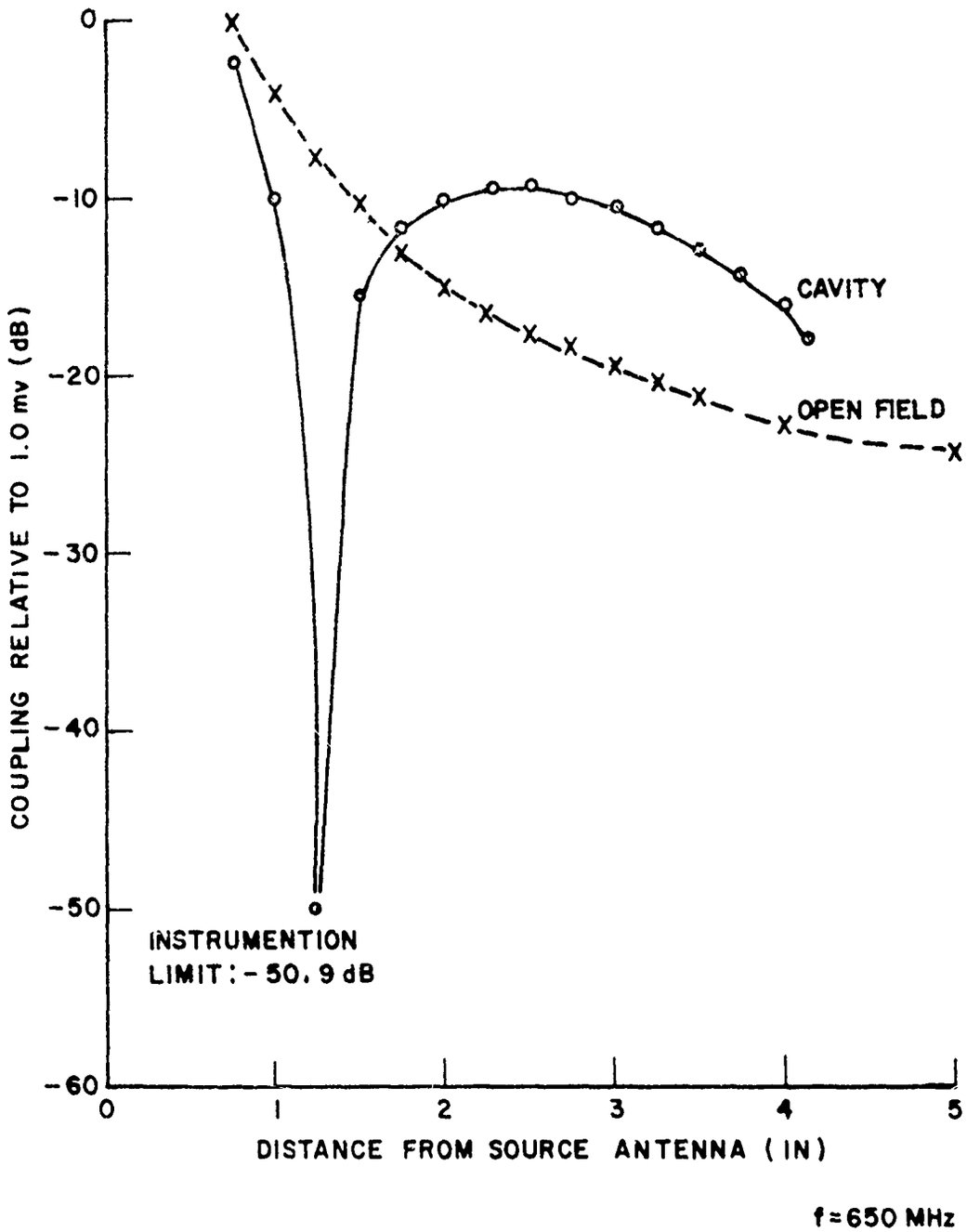
FIG 5



RELATIVE COUPLING
VS DISTANCE
10X3X10 IN. CAVITY

SOURCE ANTENNA IN CENTER

FIG 6

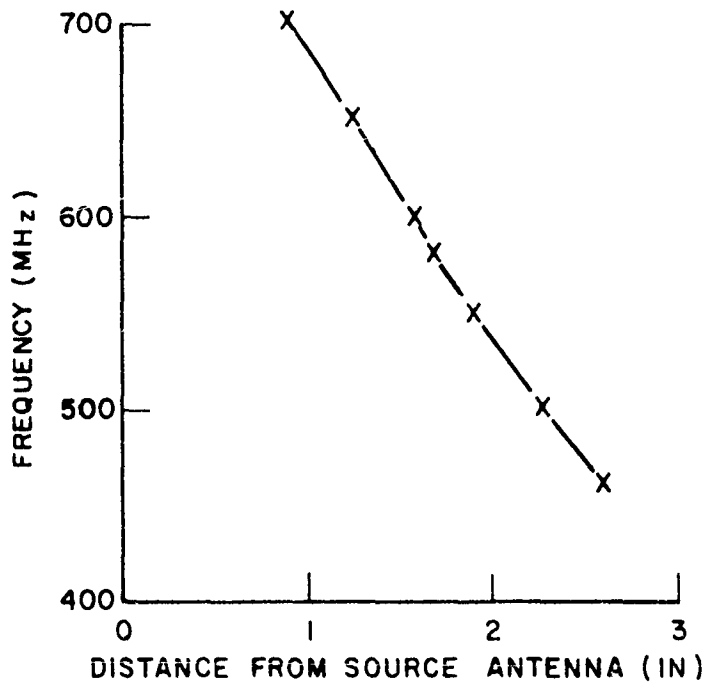


f = 650 MHz

RELATIVE COUPLING
VS DISTANCE
10X 3 X 10 CAVITY

SOURCE ANTENNA IN CENTER

FIG 7



LOCATION OF E FIELD COUPLING NULL
VS FREQUENCY
10X 3 X 10 CAVITY

SOURCE ANTENNA IN CENTER

FIG 8

2.2.3 Coupling Measurements - 10 X 3 X 17 Inch and 10 X 3 X 12 Inch Rectangular Cavities.

For the 10 X 3 X 17 in. Cavity:

a = 10 in., b = 3 in., d = 17 in.

Dominant Wave ($TE_{1,0}$) Cut-off Frequency: 591 MHz.

First Resonant Frequency ($f_{1,0,1}$): 685 MHz.

Second Resonant Frequency ($f_{1,0,2}$): 912 MHz.

For the 10 X 3 X 12 in. Cavity:

a = 10 in., b = 3 in., d = 12 in.

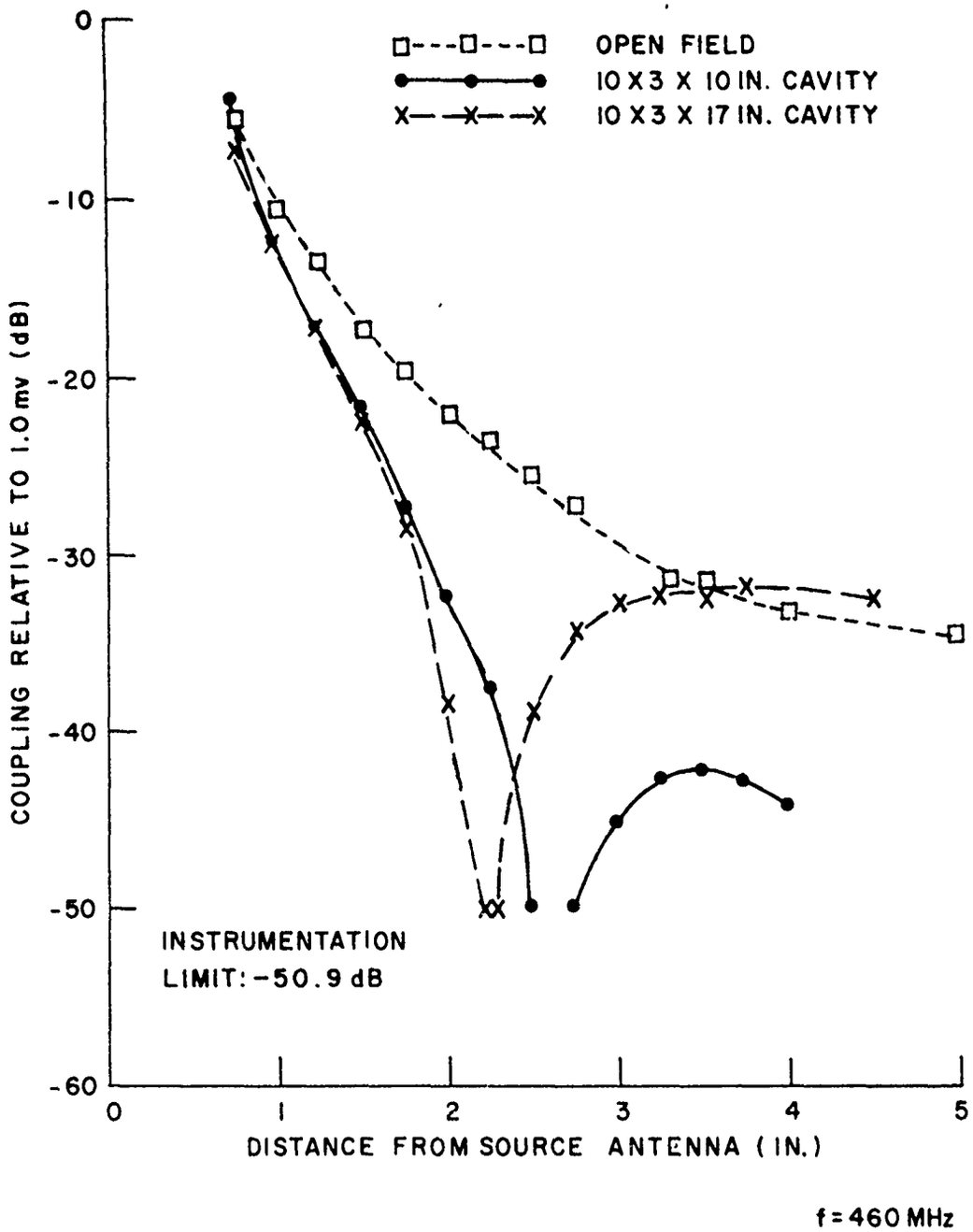
Dominant Wave ($TE_{1,0}$) Cut-off Frequency: 591 MHz.

First Resonant Frequency: ($f_{1,0,1}$): 768 MHz.

The initial measurements in the rectangular cavities were made with the source antenna located in the center of the cavity and the receive antenna probing along the long dimension center line. Again, the minimum separation was 0.75 in.

A comparison of the measurement results in the three cavities, with the source antenna in the center, indicates that the null is at a slightly different distance from the source in each of the cavities. Figure 9 shows the results of measurements made at 460 MHz in the 10 X 3 X 10 in. and 10 X 3 X 17 in. cavities. Figure 10 compares the results at 650 MHz in the two rectangular cavities. The 10 X 3 X 17 in. cavity is approaching resonance, which occurs at 685 MHz. The effect of resonance on radiated measurements is shown in Figure 11. Figures 9, 10 and 11 point out the almost unbelievable variation in readings that may be obtained in different size enclosures, even though the same test set-up is used and the source is in the same relative location.

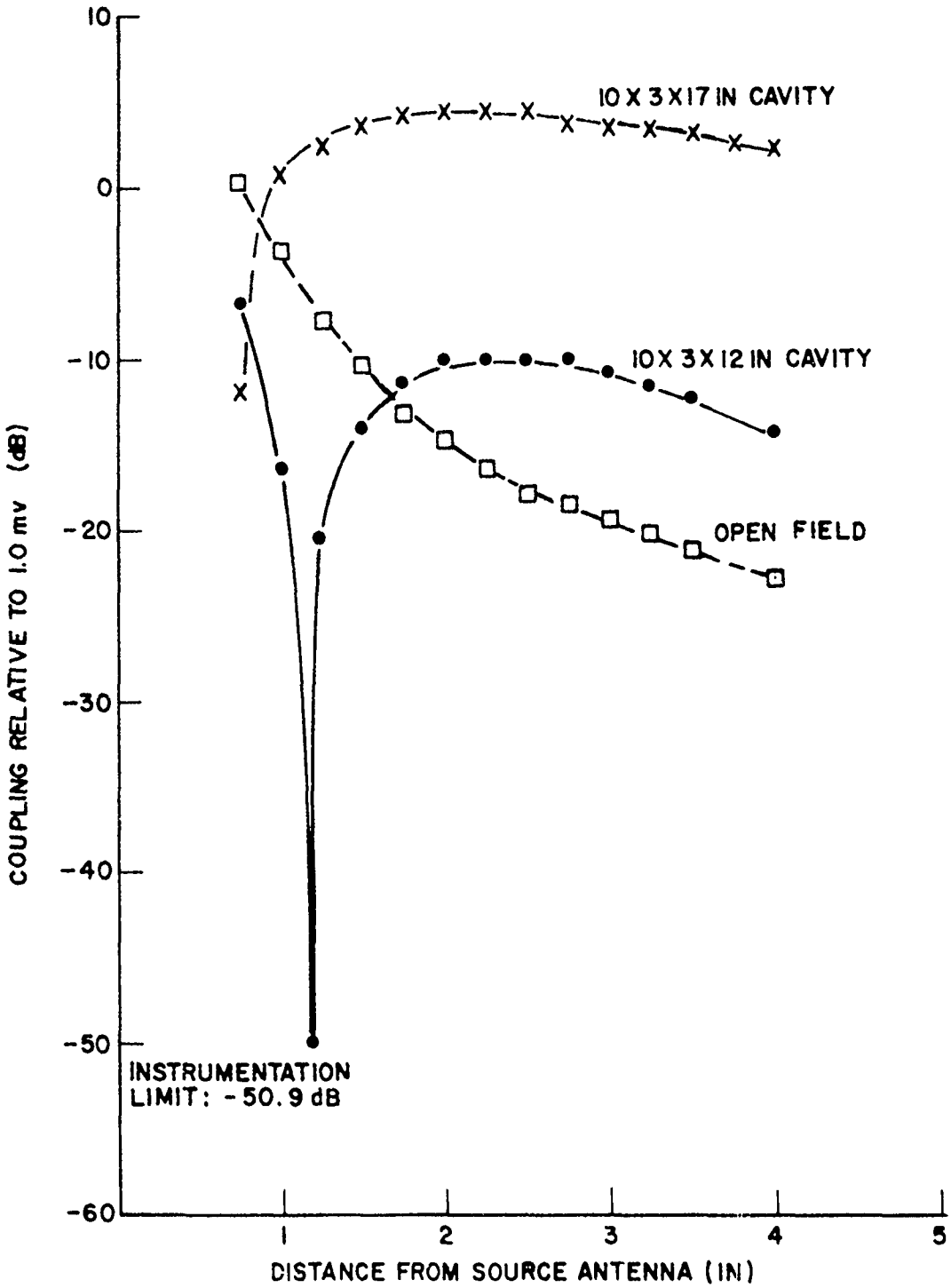
The relationship of frequency versus distance of the null from the source is again linear, for the most part, in the 10 X 3 X 17 in. cavity (Fig. 12). However, the slope is not the same as in the square cavity (Fig. 8).



RELATIVE COUPLING
VS DISTANCE
10 X 3 X 10 IN. AND 10X 3 X 17 IN. CAVITIES

SOURCE ANTENNA IN CENTER

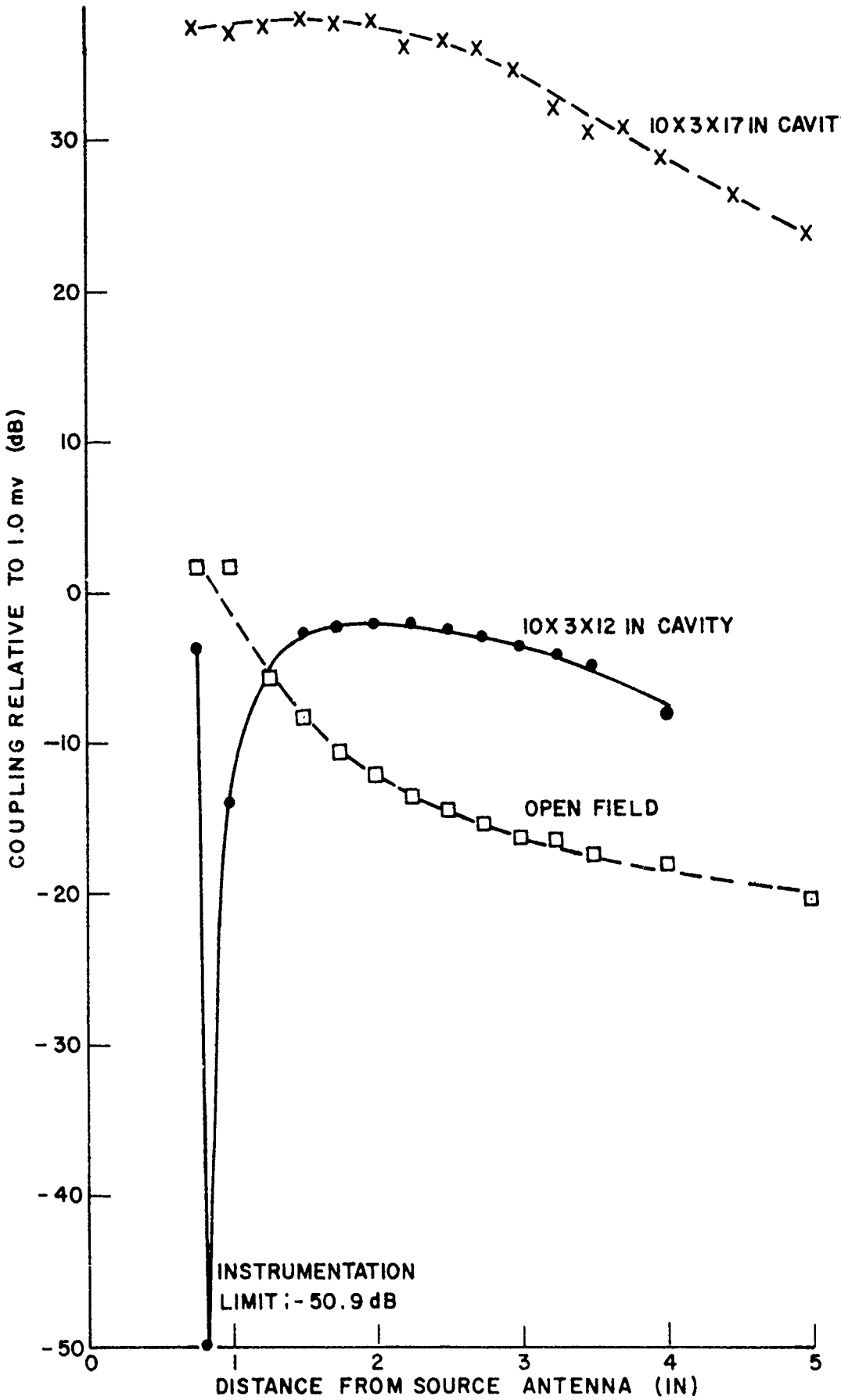
FIG. 9



RELATIVE COUPLING f = 650 MHz
VS
DISTANCE

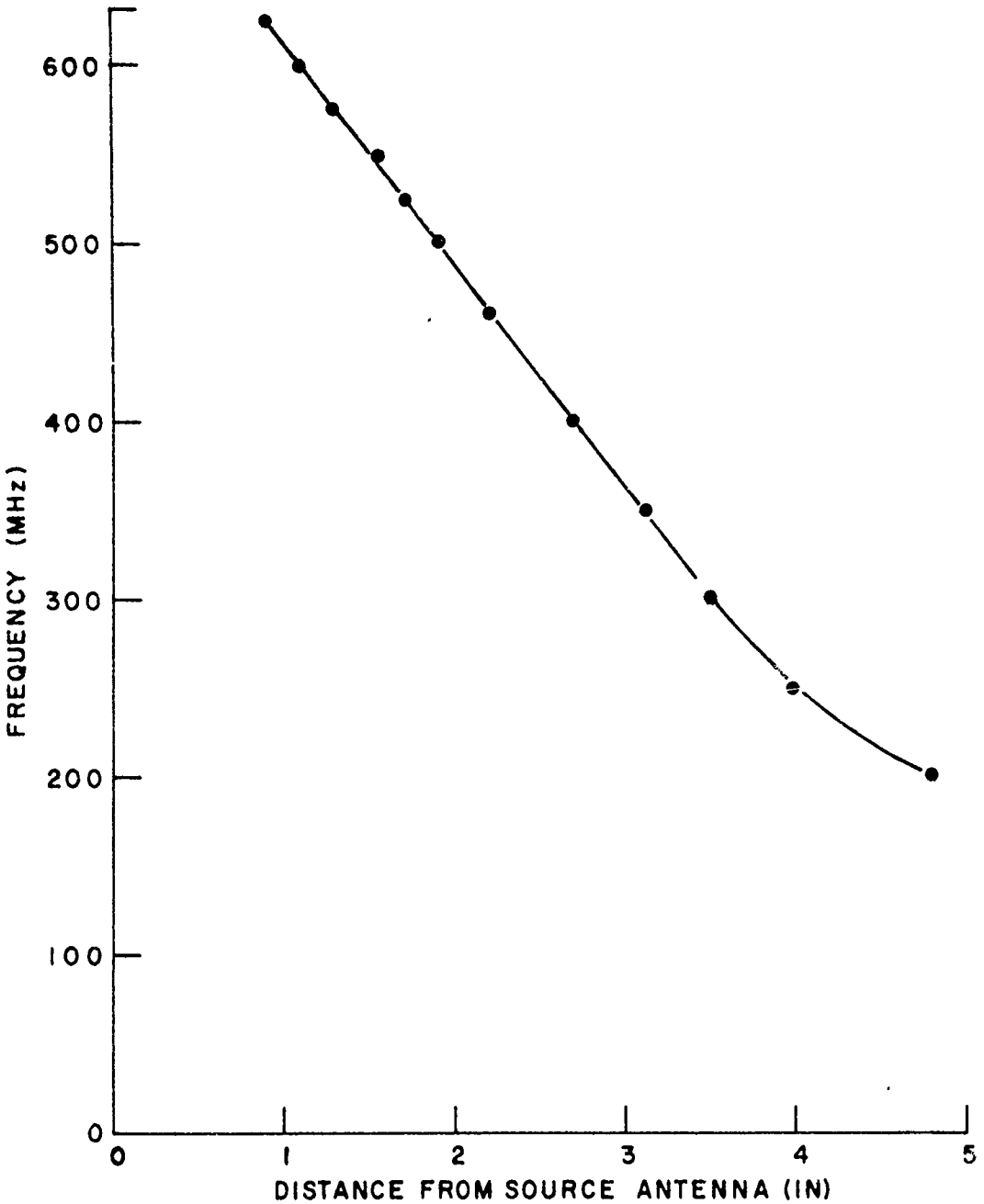
10 X 3 X 12 IN AND 10 X 3 X 17 IN CAVITIES
SOURCE ANTENNA IN CENTER

FIG 10



f = 685 MHz

FIG 11 RELATIVE COUPLING VS DISTANCE
10X3X12 IN AND 10X3X17 IN CAVITIES
SOURCE ANTENNA IN CENTER



LOCATION OF E FIELD COUPLING NULL.
VS FREQUENCY
10 X 3 X 17 CAVITY

SOURCE ANTENNA IN CENTER

FIG. 12

2.2.3.1 The Effect of Source Antenna Location.

Coupling measurements were repeated in the 10 X 3 X 17 in. cavity with the source antenna located 5.0 in. and then 1.5 in. from the center of one of the end walls and the receive antenna located on the long dimension center line. Figure 13 summarizes the results at 460, 500 and 600 MHz including the original data taken with the source antenna in the center (8.5 in.). The three curves are very similar, with the distance between the source and null increasing in a non linear manner as the source is moved toward the end wall. Figures 14 and 15 compare the coupling, with the source at 1.5 and 8.5 in. from the end wall, at 600 MHz and 250 MHz. At 600 MHz the curves diverge, and at 250 MHz which is below $f_{co}/2$ for the dominant wave, the curves are very close. This verifies observations on measurements made in the full size enclosure.

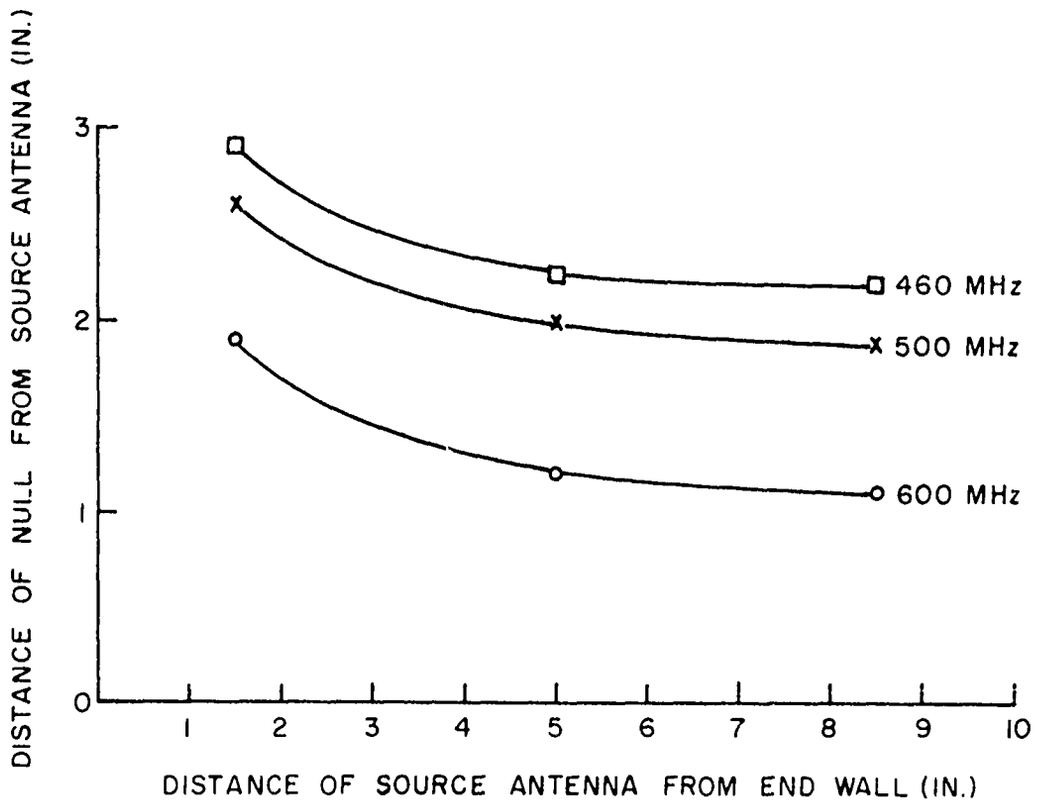
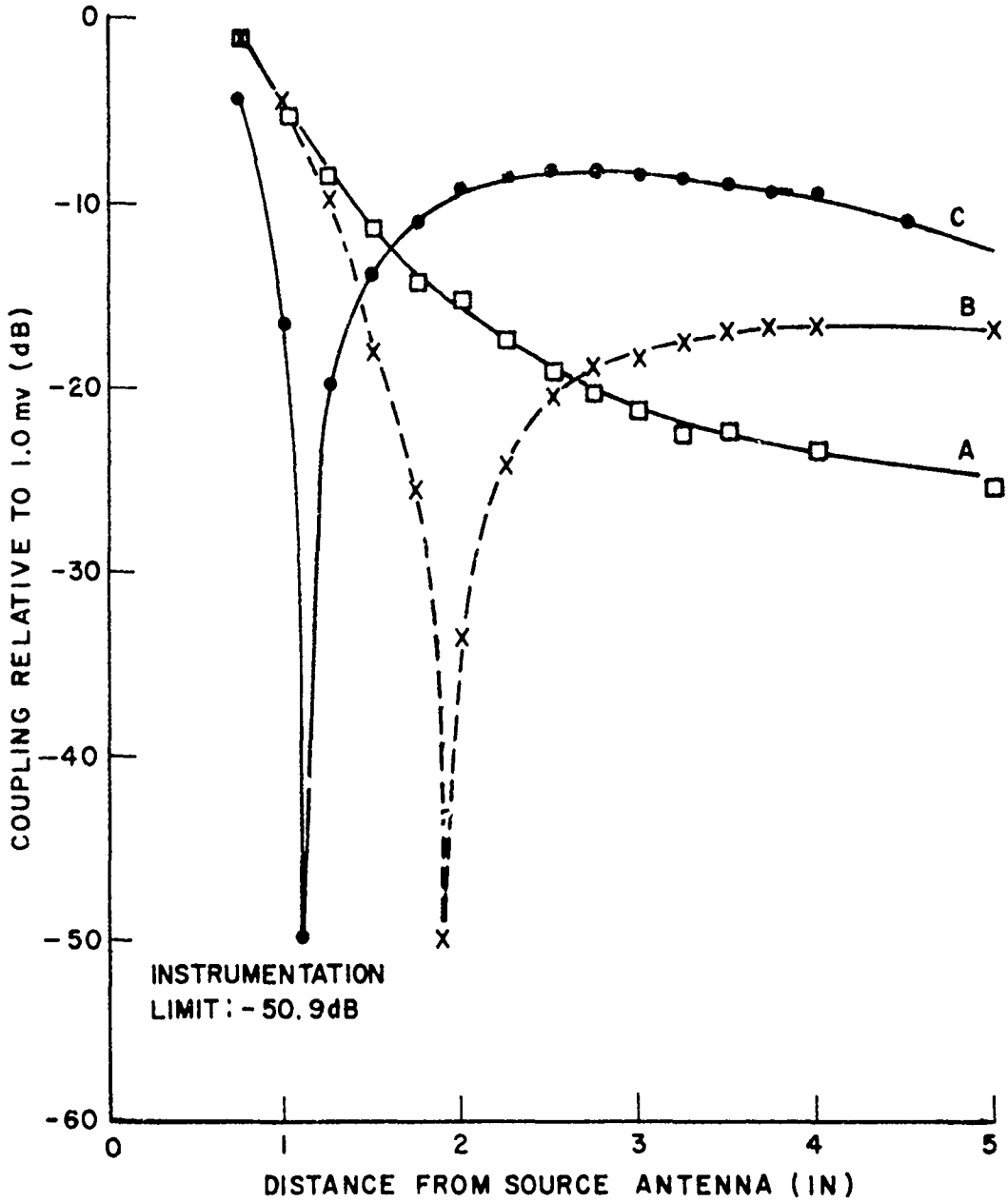


FIG. 13 EFFECT OF SOURCE LOCATION ON LOCATION OF COUPLING NULL IN 10 x 3 x 17 IN CAVITY



RELATIVE COUPLING

VS

DISTANCE IN 10X3X17 IN CAVITY

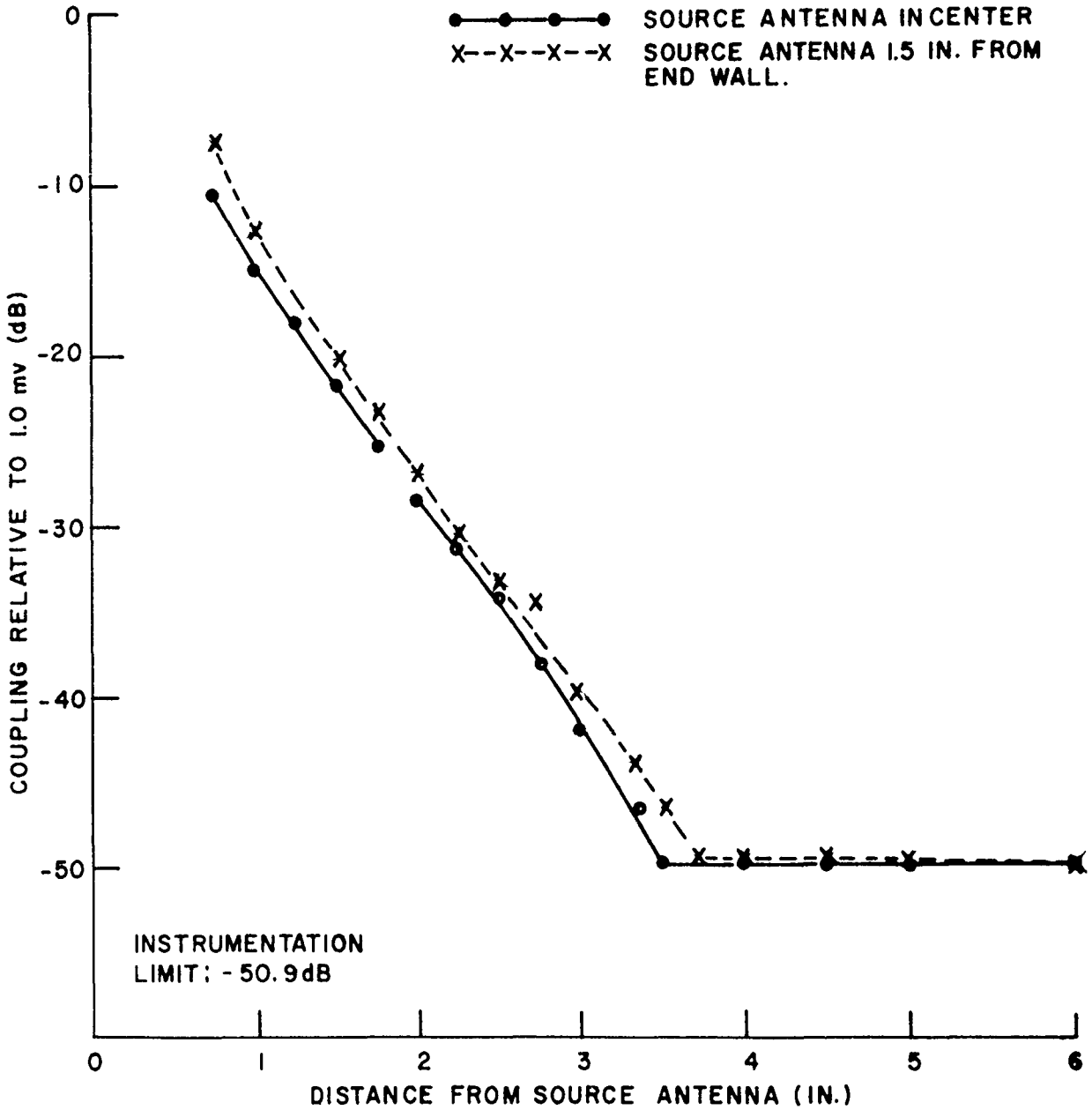
EFFECT OF SOURCE ANTENNA LOCATION AT 600MHz

A OPEN FIELD

B SOURCE 1.5 IN FROM END WALL

C SOURCE IN CENTER (8.5 IN FROM END WALL)

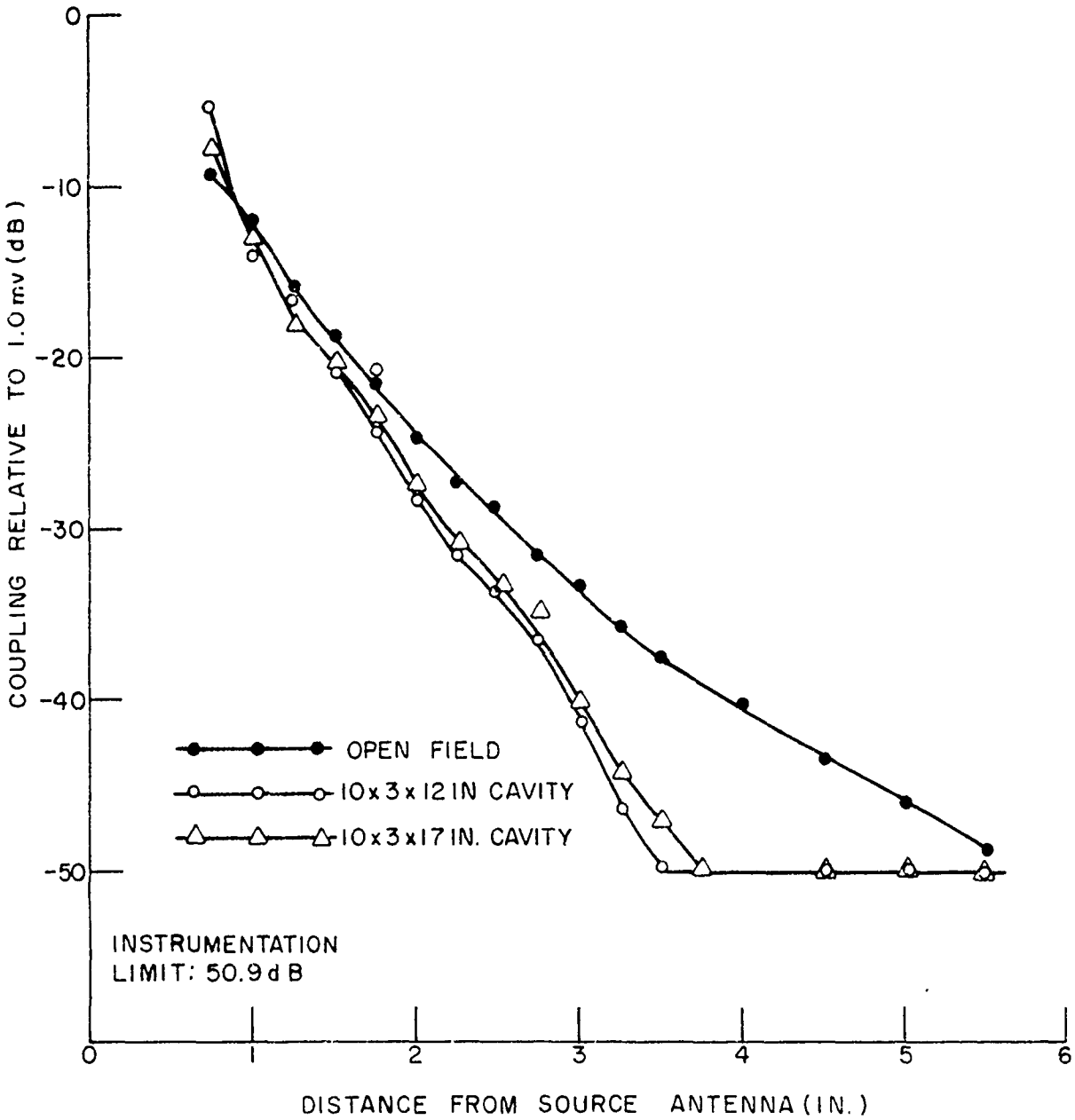
FIG 14



RELATIVE COUPLING
VS DISTANCE
10 X 3 X 17 IN. CAVITY

EFFECT OF SOURCE ANTENNA
LOCATION AT 250 MHz

FIG. 15A



RELATIVE COUPLING
VS
DISTANCE AT 250 MHz
STANDARD MONOPOLE ANTENNAS
SOURCE ANTENNA 1.5 IN. FROM END WALL

FIG. 15 B

2.2.3.2 The Effect of Source Antenna Length.

In order to investigate the possible effect of test specimen size on the E Field distribution, coupling measurements were made in the 10 X 3 X 17 in. cavity using a short (1/2 in.) monopole and then a long (2-3/16 in.) monopole as the source antenna. The source was located in the center of the cavity, and the receive antenna was the standard 1.0 in. monopole probing along the long dimension center line.

Figure 16 shows the null moving toward the source as the length of the source antenna is increased. Varying the length of the receive antenna has a similar effect, but the distances between the source and the nulls are somewhat different from those observed when the source antenna length was varied. At resonance, the long source antenna appears to load the cavity thus reducing the Q and the drastic effect of resonance, and interestingly, the coupling roll-off versus distance is quite linear (Fig. 17). During the above experiments the tip of the long antenna was approximately 5/16 in. from the opposite wall.

When the length of the source antenna was increased until the tip made contact with the opposite wall, the null appeared to move into the source and completely disappear.

Possibly as significant are the results shown in Figure 18. The source antenna was a standard 1.0 in. monopole located in the center of the cavity. The receive antenna was a long monopole, end loaded with a 1/2 X 3/4 in. piece of sheet copper. The "top hat" was approximately 1/16 in. from the opposite wall during the experiment. No coupling nulls were observed, and except for the "tail" at resonance (685 MHz), the curves are essentially linear up to a separation distance of approximately 4.0 in.

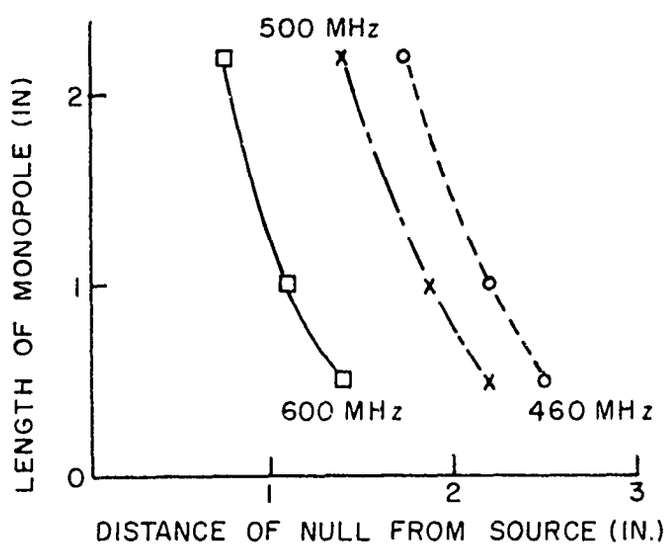
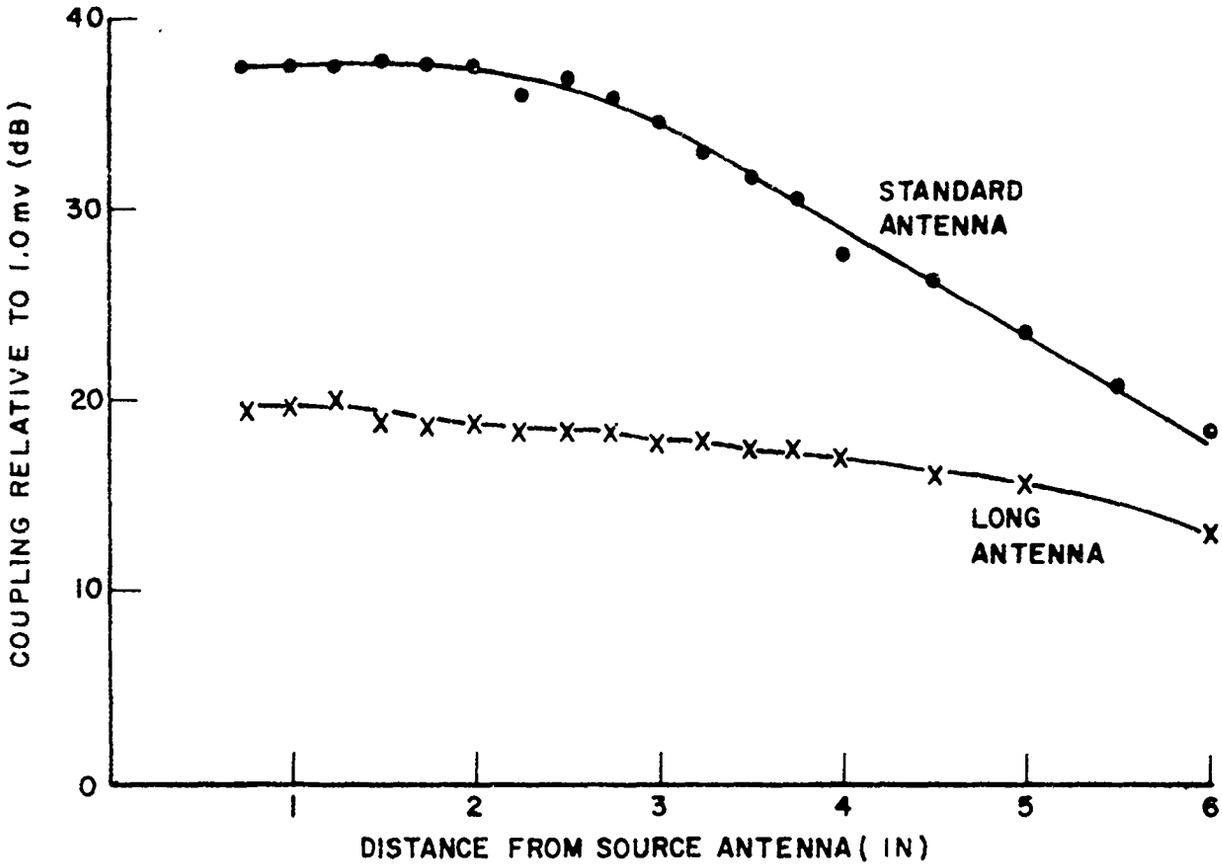


FIG. 16 EFFECT OF SOURCE ANTENNA LENGTH ON LOCATION OF NULL IN 10x3x17 IN. CAVITY SOURCE ANTENNA IN CENTER OF CAVITY



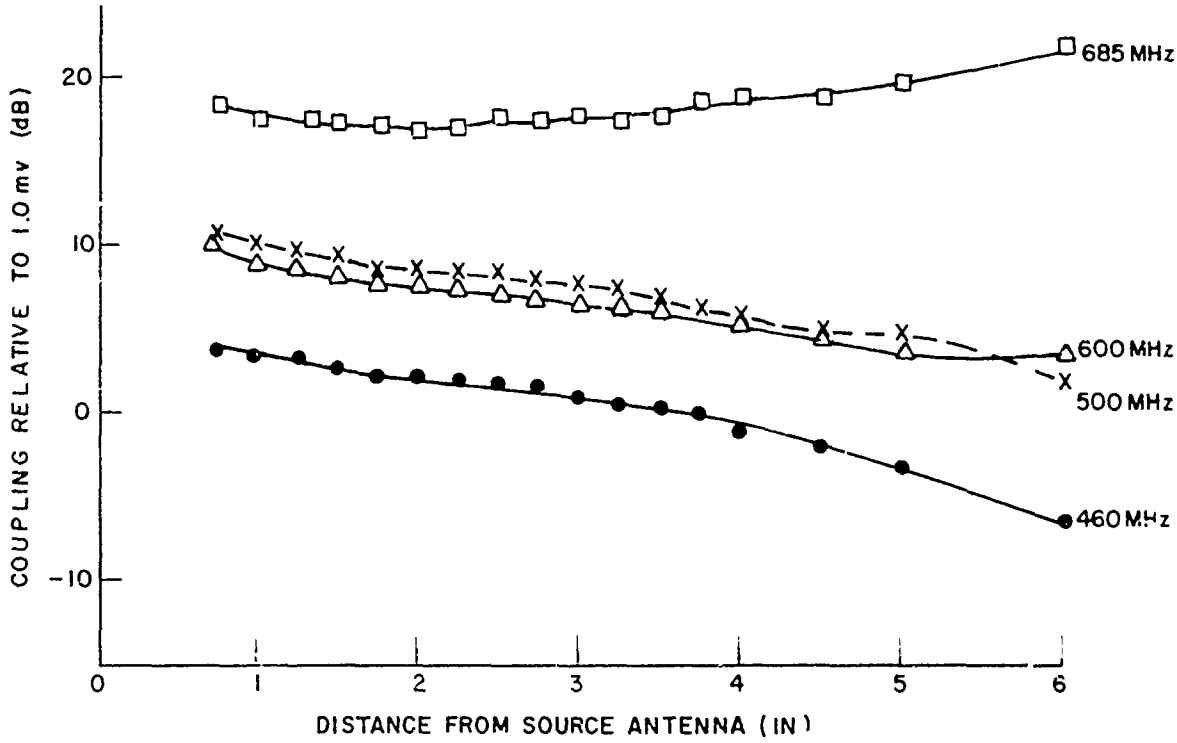
RELATIVE COUPLING

VS

DISTANCE IN 10X3X17 IN CAVITY

COMPARISON OF STANDARD AND LONG SOURCE
ANTENNAS AT f 1,0,1 RESONANCE (685 MHz)
SOURCE ANTENNA IN CENTER

FIG 17



RELATIVE COUPLING

VS

DISTANCE IN 10X3X17 IN CAVITY

LONG RECEIVE ANTENNA WITH "TOP HAT"
SOURCE ANTENNA IN CENTER

FIG 18

2.2.3.3 Ray Tracing.

In accordance with theory,[9] the propagation of the $TE_{1,0}$ mode in a rectangular waveguide is the result of two plane waves traveling in the guide simultaneously. Each wave follows an oblique path with multiple reflections from the walls. The angle at which these wave fronts travel is a function of the wavelength and the size of the guide. The direction of this wave motion is a ray drawn perpendicular to the wave fronts. From Figure 19, which shows only a single wave front, and letting θ equal the angle of the direction rays with respect to the axis of the guide:

$$\sin \theta = \frac{AB}{BC} = \frac{\lambda/2}{a} = \frac{\lambda}{2a}$$

$$\theta = \sin^{-1} \frac{\lambda}{2a} \qquad (4)$$

Where: λ = Wavelength in free space

a = Width of guide

Initially it was believed that full scale plotting of the direction rays at the various test frequencies might provide some insight into the cause and prevention of the E Field null. However, subsequent experiments (2.2.3.2) showed that changing the length of either the source or receiving antenna also changed the location of the null so this objective was abandoned. Nevertheless, it was decided to briefly investigate this technique, using the 10 X 3 X 17 in. cavity with the source antenna in the center as a model.

The angles were calculated and rays plotted for 625, 650 and 685 MHz. It appeared that as the rays were continued back toward the source, after reflecting from the end walls, that two rays which had undergone an odd number of reflections intersected at a point very close to where the null was actually measured. At 625 MHz, the rays reflected from the end walls near the corners; placing a wedge shaped baffle in only one corner reduced the depth of the null by approximately 20 dB. At the resonant frequency, 685 MHz, the rays went into the corners after one reflection from the side walls, and flat baffles in two of the corners reduced the resonant effect.

It should be pointed out that these baffles were relatively large. The wedge faces and flat baffles were five inches in length. "Breaking-up" the corners with smaller, one inch, baffles had very little effect.

2.2.3.4 Room Shaping.

Although it was not believed to be the ultimate solution, as a result of the observations noted in paragraph 2.2.3.3, it was considered desirable to investigate the effects of two possible room shaping techniques.

2.2.3.4.1 Reflecting Half-Cylinders.

The first investigation involved placing 10 polystyrene half-cylinders, covered with aluminum foil, along the four walls and in the corners of the 10 X 3 X 17 in. cavity. The radius of the half-cylinders was 1.0 in. which becomes a quarter wavelength at approximately 3.0 GHz. E Field coupling measurements were made using two standard monopoles with the source antenna located in the center of the cavity and the receiving antenna probing along the long dimension center line. This technique greatly reduced the depth of the E Field null above approximately 500 MHz, but, as might be expected, introduced a new standing wave pattern. Figure 20 compares the relative coupling with and without the reflectors at 600 MHz.

2.2.3.4.2 Wedge Shaped Baffles.

The second technique investigated was the effect of large wedge shaped baffles located against the two end walls. This configuration had very little effect on the E Field pattern, except at the resonant frequency.

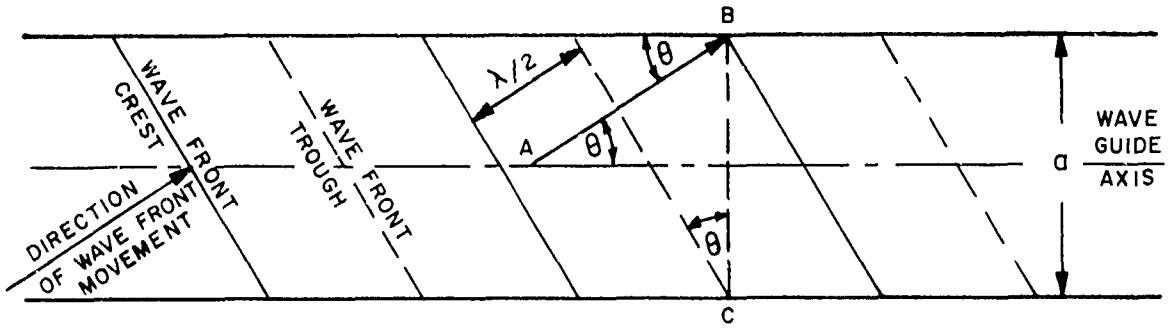
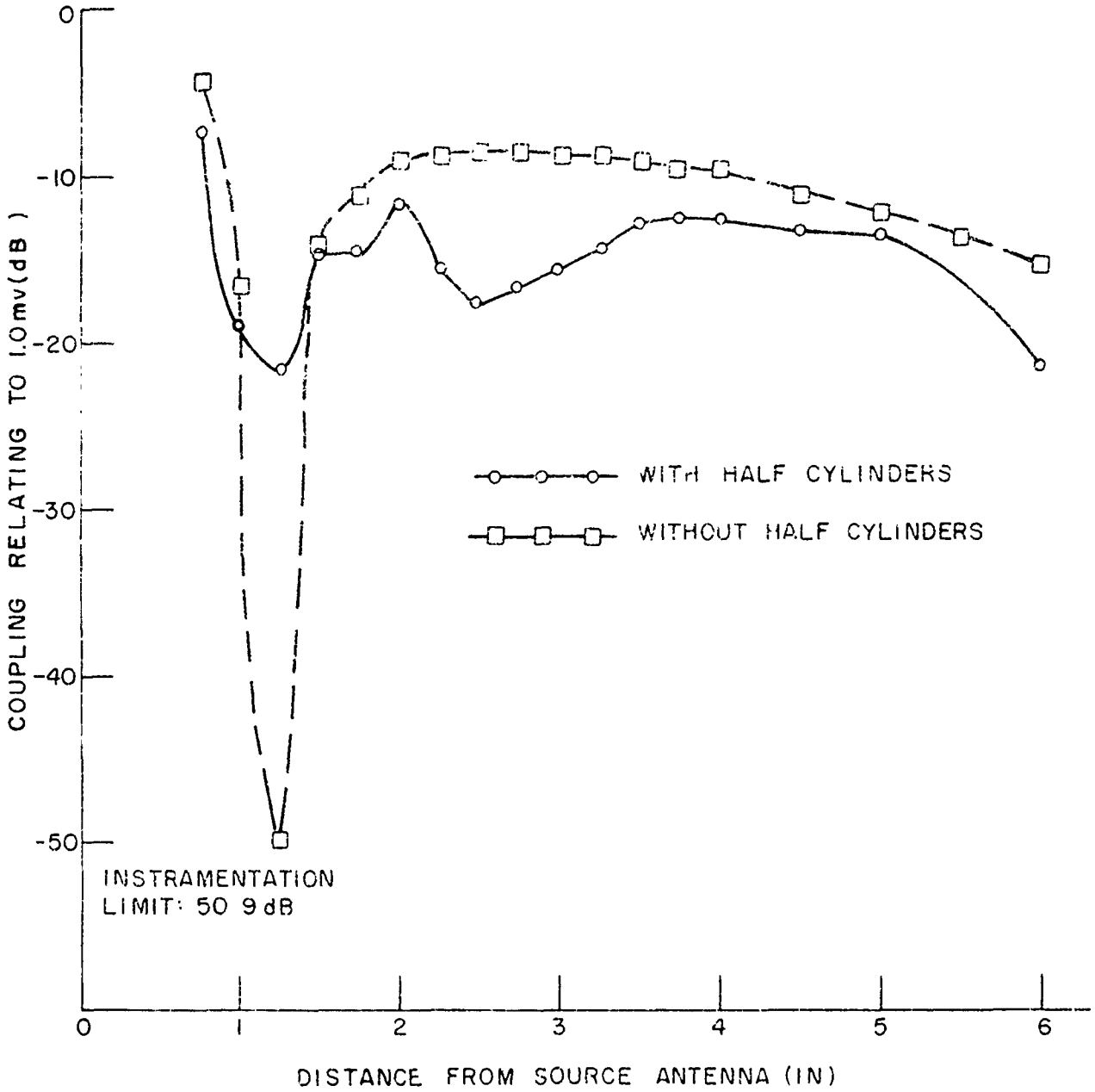


FIG. 19 SINGLE WAVE FRONT PROGRESSING DOWN WAVE GUIDE - REFLECTIONS NOT SHOWN



RELATIVE COUPLING

VS

DISTANCE IN 10 x 3 x 17 IN. CAVITY

SOURCE ANTENNA IN CENTER f = 600MHz

COMPARISON OF RESULTS WITH AND WITHOUT

REFLECTING HALF CYLINDERS

FIG 20

2.2.3.5 Monopole with Counterpoise.

2.2.3.5.1 Discussion.

Since the 41.0 in. rod antenna is normally used with a ground plane, or counterpoise, a 1.0 X 1.0 in. counterpoise was added to a standard 1.0 in. monopole in order to investigate its effect on measurement results. A series of experiments were performed in the 10 X 3 X 12 in. cavity over the 460 to 685 MHz range with a standard monopole located in the center of the cavity and the receiving antenna with counterpoise probing along the long dimension center line. The initial measurements were made in the normal configuration with receiving antenna shell grounded which placed the counterpoise 3/8 in. from the bottom wall. Subsequent measurements were made with the antenna at various distances above the wall.

2.2.3.5.2 Test Results.

The coupling null was observed in all cases except when the receiving antenna was far enough above the bottom wall so that the tip was 1/4 in. or less from the top. As the receiving antenna was moved toward the top wall, the null moved toward the source and finally disappeared. This effect was observed in previous experiments when the length of either the receiving or source antenna was increased (paragraph 2.2.3.2).

When the receiving antenna was moved above the ground wall, the coax cable extended into the cavity and cable coupling and ground appeared to have considerable influence on the results. Figure 21 shows the difference at 600 MHz, with the tip of the antenna 1/4 in. from the top wall between readings with the receiver coax grounded on the bottom wall and ungrounded. The cause of the rather abrupt break in the curves is not known.

2.2.3.6 Receiving Antenna on Opposite Wall.

2.2.3.6.1 Discussion.

Mortenson, et al,[10] recommended that the vertical E Field be determined by placing the test specimen on the floor in the center of the shielded enclosure and making the measurements with an E Field probe located on the top wall of the enclosure directly above the test specimen. In order to investigate this technique, E Field coupling measurements were made in both frequency scaled cavities with a standard monopole source antenna located at the center of the bottom wall, and a standard monopole receive antenna probing along the long dimension center line of the top wall.

2.2.3.6.2 Test Results.

The coupling versus separation distance curves at 460, 500, 600 and 685 MHz are plotted in Figures 22 and 23. No coupling nulls were observed, the curves are relatively smooth, and at 460, 500 and 600 MHz they are of a similar shape in both cavities, but with slightly different slopes. Figure 22 shows the effect of resonance at 685 MHz in the 10 X 3 X 17 in. cavity.

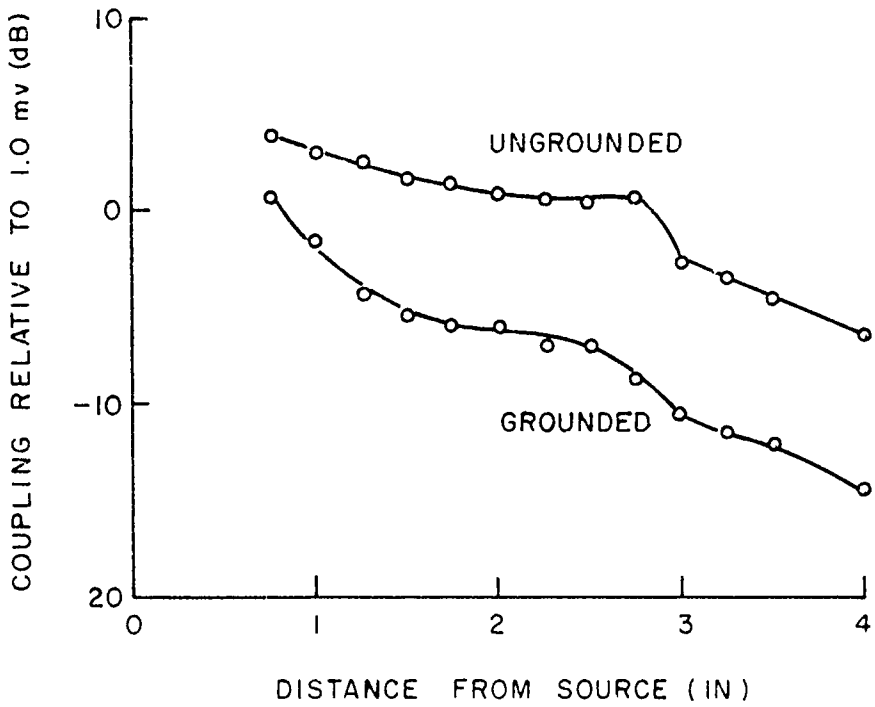
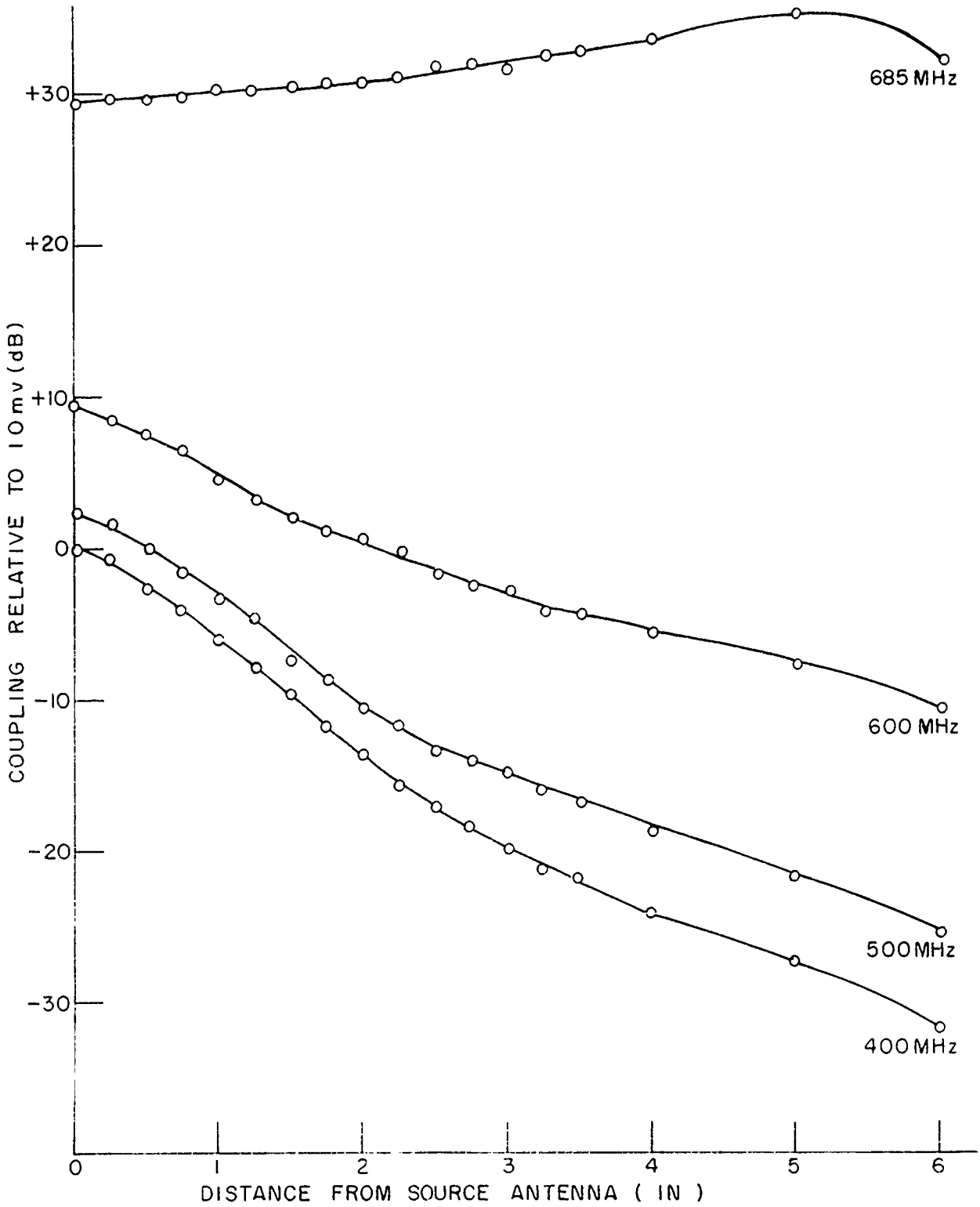
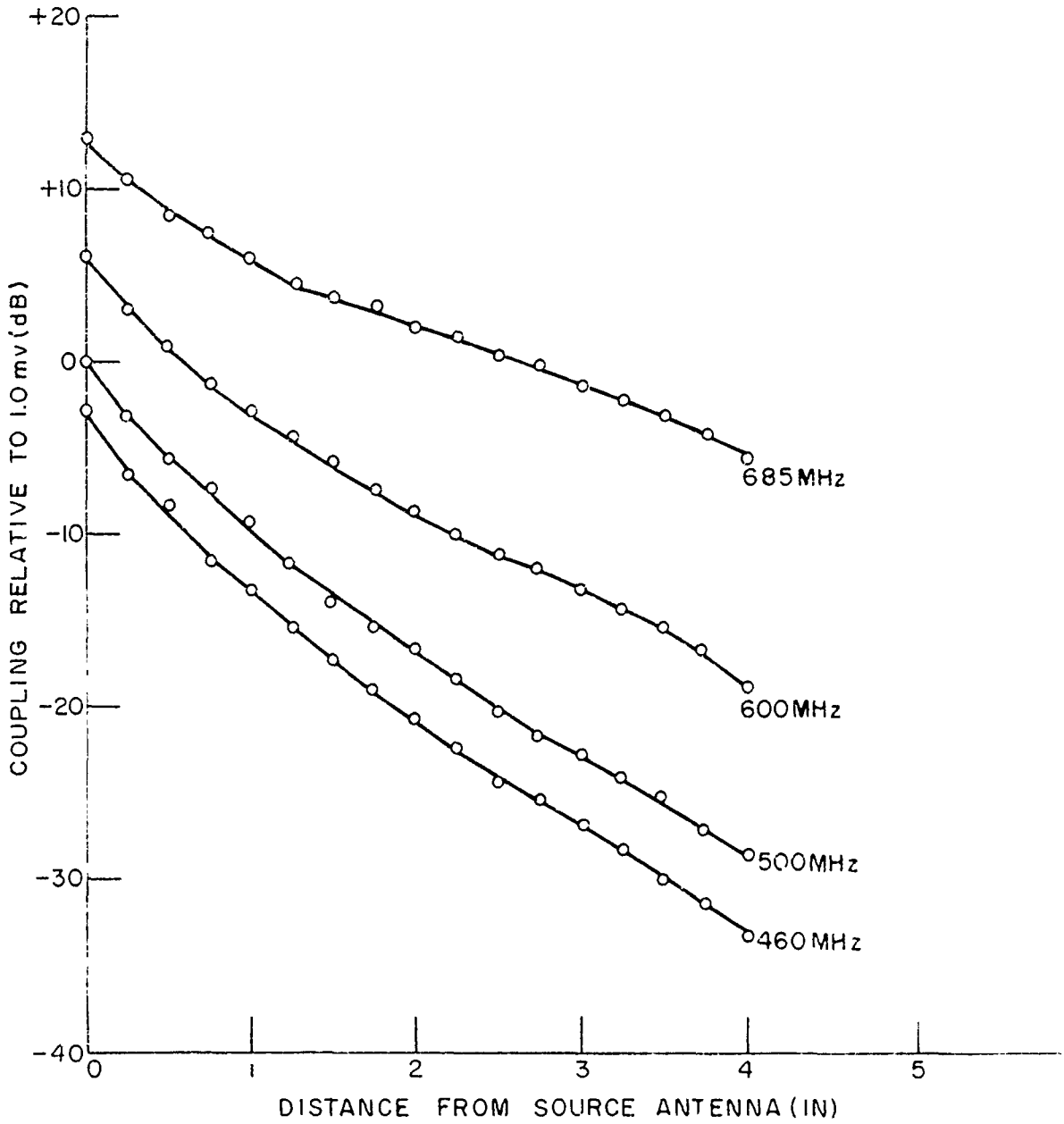


FIG 21 RELATIVE COUPLING AT 600 MHz IN 10 x 3 x 12 IN. CAVITY MONOPOLE RECEIVE ANTENNA WITH COUNTER POISE, ANTENNA TIP 1/4 IN. FROM OPPOSITE WALL



RELATIVE COUPLING VS DISTANCE
RECEIVE ANTENNA ON OPPOSITE WALL
SOURCE ANTENNA IN CENTER OF 10 x 3 x 17 IN. CAVITY
FIG 22



RELATIVE COUPLING VS DISTANCE
RECEIVE ANTENNA ON OPPOSITE WALL
SOURCE ANTENNA IN CENTER OF 10 x 3 x 12 IN. CAVITY

FIG. 23

2.2.3.7 Loop Coupling.

2.2.3.7.1 Discussion.

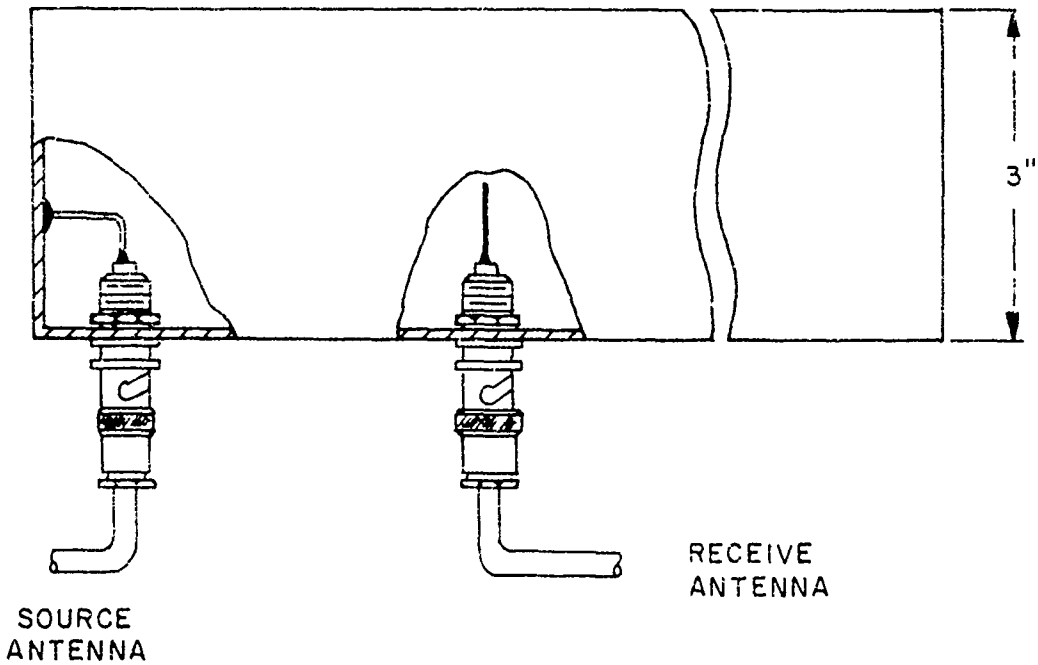
In order to investigate the radiation pattern within a cavity when it is energized by means of a low impedance loop instead of the monopole, a series of coupling measurements were made in the 10 X 3 X 17 in. and 10 X 3 X 12 in. cavities using a 3/4 X 7/8 in. single turn loop as the source and a standard test monopole as the receive antenna, both located on the long dimension center line. (See Fig. 24A and B).

Measurements were also made with a standard monopole as the source antenna and a 7/16 X 11/16 in. unshielded, single turn loop as the receive antenna in the 10 X 3 X 12 in. cavity (Fig. 24C). The source antenna was located at the center of the cavity and the loop on the long dimension center line. The center conductor side of the loop was facing the source during these measurements.

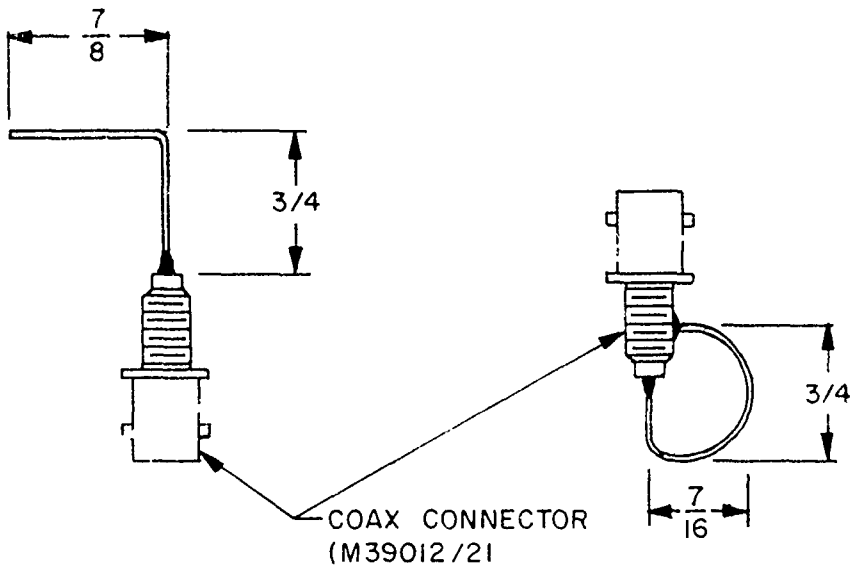
2.2.3.7.2 Test Results.

Figure 25 compares the results in the two cavities at 460, 500, 600 and 685 with the loop source antenna. No coupling nulls were observed, and with the exception of the 685 MHz (resonance) curve in the 10 X 3 X 17 in. cavity, they resemble the theoretical curves for a small loop developed in Ref. 11, page 16. At 460 and 500 MHz the curves are almost identical. At 600 MHz, which is approaching resonance in the 17 in. cavity, they start to diverge, and at 685 MHz there is wide divergence.

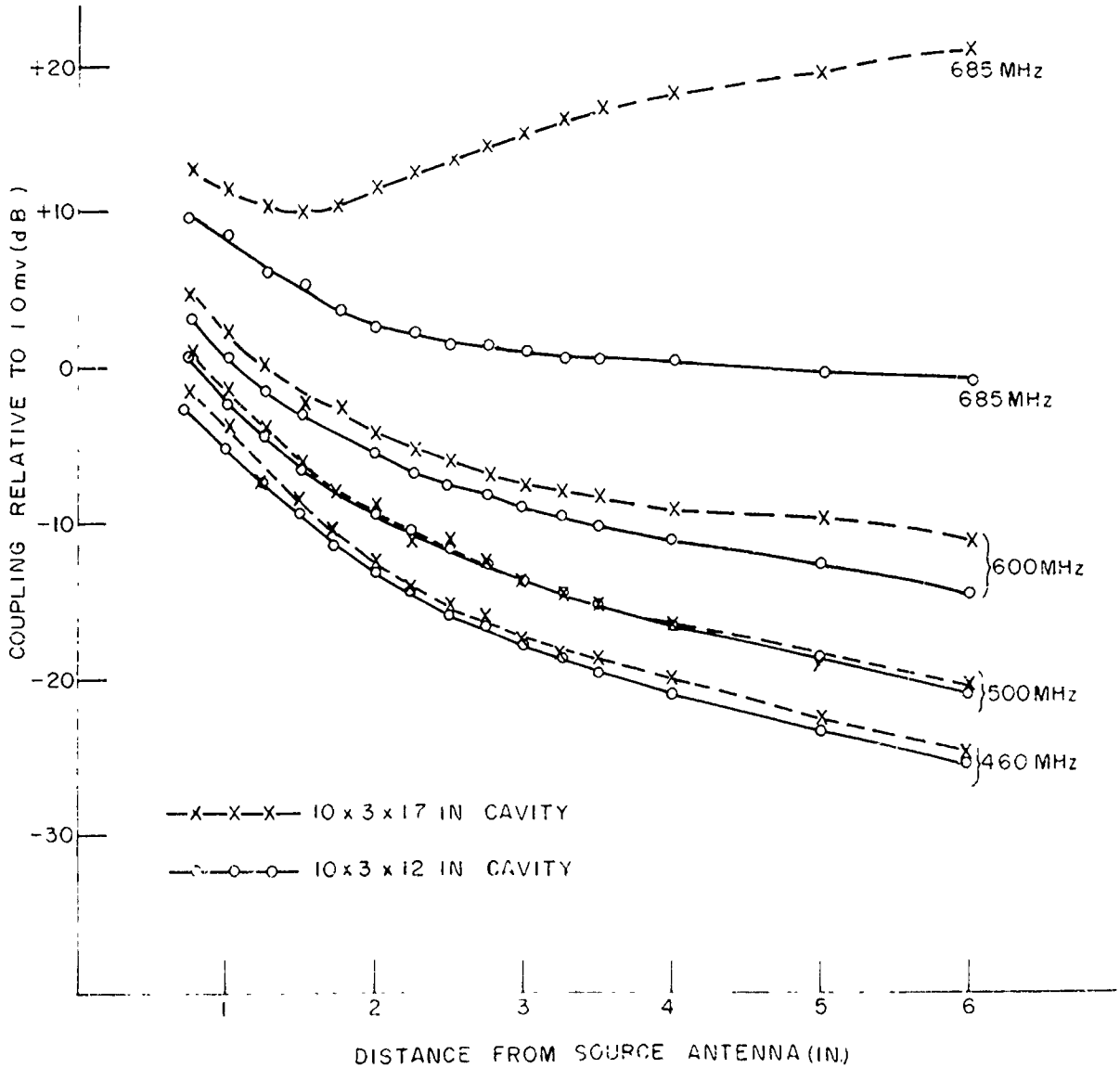
Figure 26 shows the relative coupling in the 10 X 3 X 12 in. cavity at 460, 500 and 600 MHz with the loop receiving antenna. Again there are no coupling nulls; however, the slope of the curves are steeper than in Figure 25. Whiteside and King[12] have concluded that unless the diameter of a singly loaded loop is equal to or less than 0.01 λ it will respond to the electric field as well as the magnetic field and with a diameter of 0.1 the response will be equal. The diameter of the receiving loop used was approximately 0.035 λ at 600 MHz which would imply that both fields were being sampled in this instance.


3"
RECEIVE
ANTENNA
SOURCE
ANTENNA

24-A

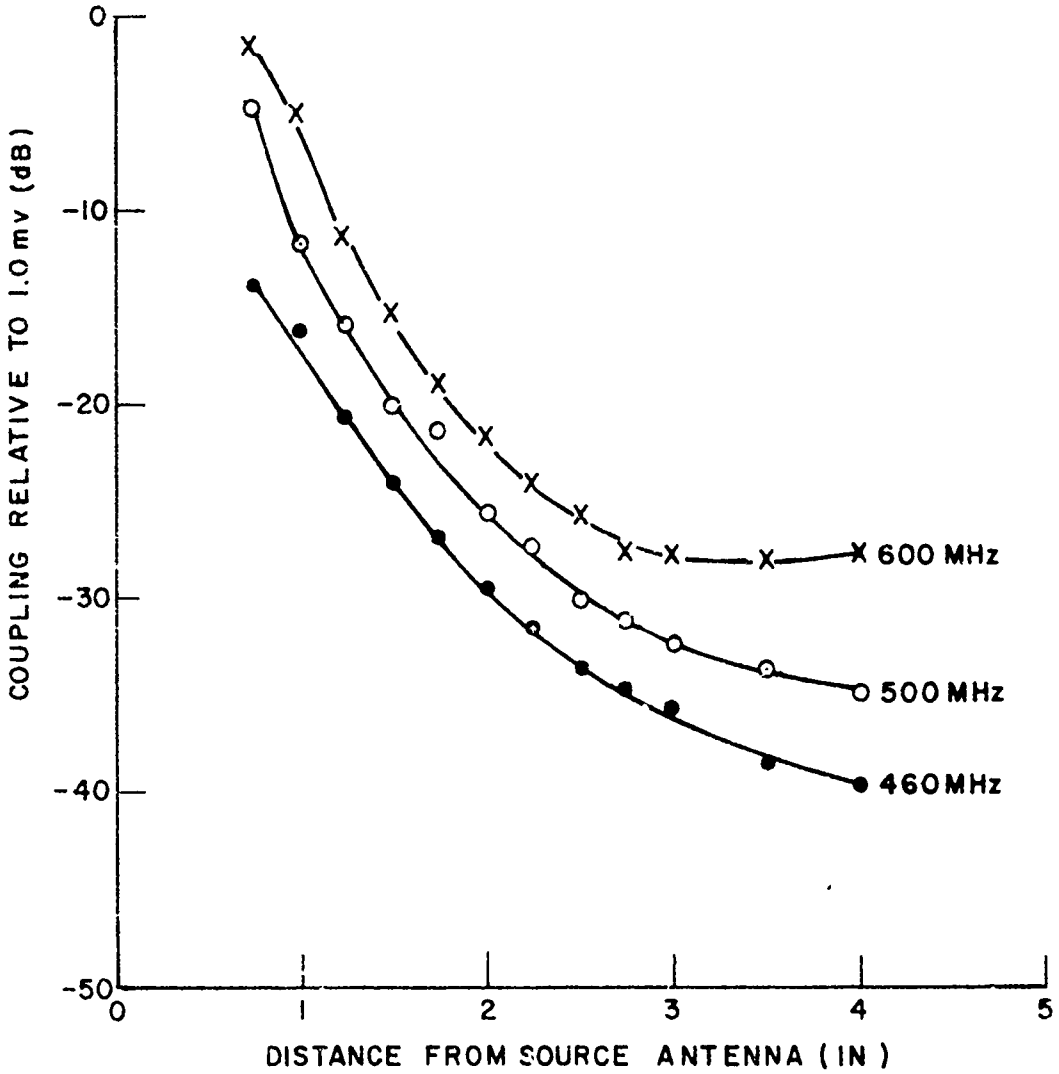

7/8
3/4
3/4
7/16
COAX CONNECTOR
(M39012/21

24-B 24-C



RELATIVE COUPLING VS DISTANCE
SINGLE TURN LOOP SOURCE ANTENNA LOCATED AT END OF CAVITY
STANDARD MONOPOLE RECEIVE ANTENNA

FIG 25



RELATIVE COUPLING

VS

DISTANCE IN 10X3X12 IN CAVITY

SINGLE TURN LOOP RECEIVE ANTENNA
STANDARD MONOPOLE SOURCE ANTENNA
LOCATED IN CENTER OF CAVITY

FIG 26

2.2.3.8 Vane Attenuators - Loop Loading.

2.2.3.8.1 Discussion.

Vane attenuators were constructed by coating triangular shaped pieces of 1/2 in. polystyrene foam with approximately a 1/16 in. thick coating of a one to one, by volume, slurry mixture of graphite and spackling compound. The initial coupling measurements were made with the source antenna located at the approximate center of the 10 X 3 X 17 in. cavity with two 7.0 X 2-7/8 in. attenuators located on the center line. (See Fig. 27). The measurements were repeated with six smaller 7.0 X 1.0 in. attenuators. Two were on the center line and four were slanted toward each of the corners. Coupling measurements were also made with the source antenna located 2-1/2 in. from one end wall with one 7.0 X 2-7/8 in. attenuator located on the center line.

In an attempt to load the cavity and at the same time to extract some of the energy so as to reduce reflections from the end walls, coupling measurements were made with single turn loop antennas connected to 50 ohm coaxial loads, located at the two end walls of the cavity. No data was recorded as the loops appeared to have a negligible effect on the E Field pattern, except at the resonant frequency.

2.2.3.8.2 Test Results (Attenuators).

The greatest improvement was obtained with the two 7.0 X 2-7/8 in. attenuators in the configuration of Figure 27. At 460 MHz, the null was still present, decreased in depth as the frequency was increased, and disappeared at 600 MHz.

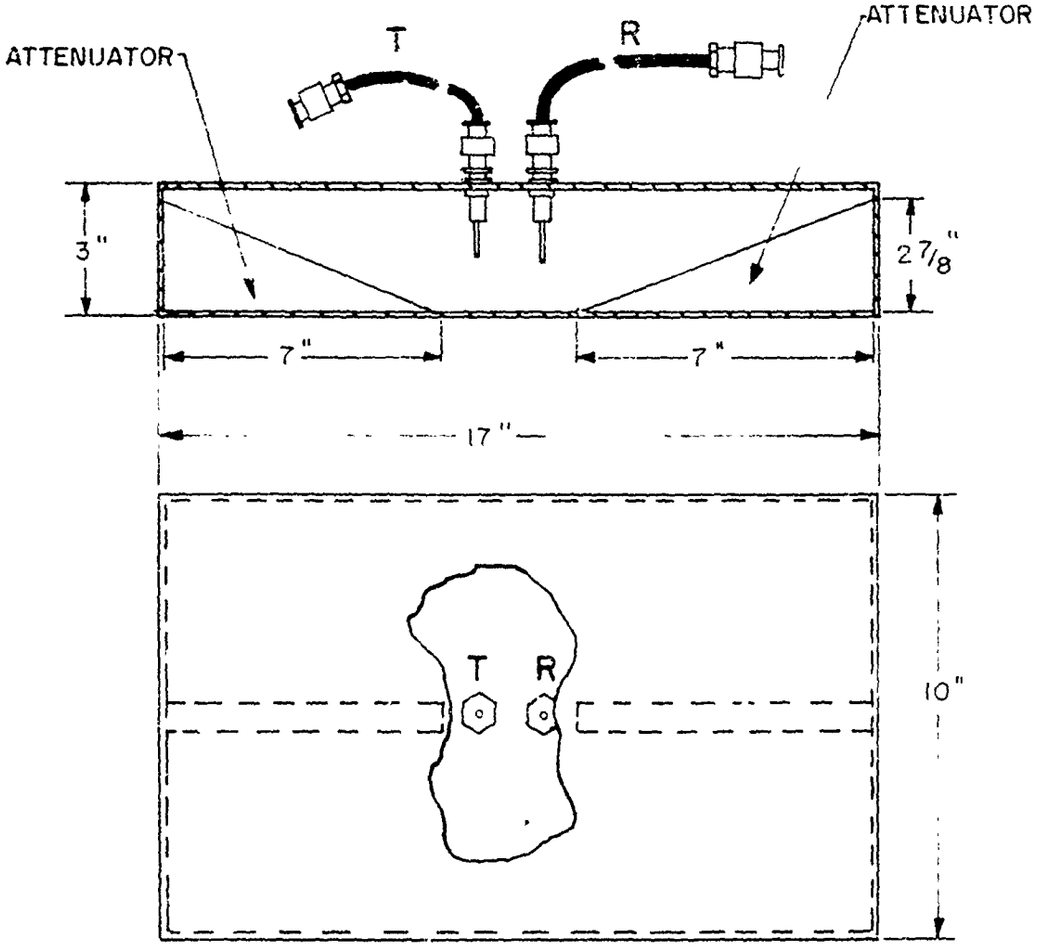
Figures 28 and 29 compare the relative coupling with and without the attenuators to the open field measurements at 600 MHz and 685 MHz (resonance). At 600 MHz the null was not present. However, the curve rises which would seem to indicate some reflections from the end walls. The improvement at resonance, 685 MHz was substantial. No attempt was made to optimize either the shape of the attenuators or the resistive material composition and thickness.

2.2.3.9 Simulated Equipment Case.

2.2.3.9.1 Discussion.

Since up to this time all of the E Field coupling experiments had been made with an antenna as the energy source, it was decided to investigate the E Field pattern of a simulated, poorly shielded equipment case to determine if the null and resonance effects are real-life problems.

A 2 X 3/4 X 3/4 in. aluminum box with a rather "leaky" bottom plate and a 1/8 X 1/2 in. slot cut in one side served as the equipment case. The box was excited by means of the signal generator and a 1.0 in. coaxial monopole with the shield grounded to the box (See Fig. 30).

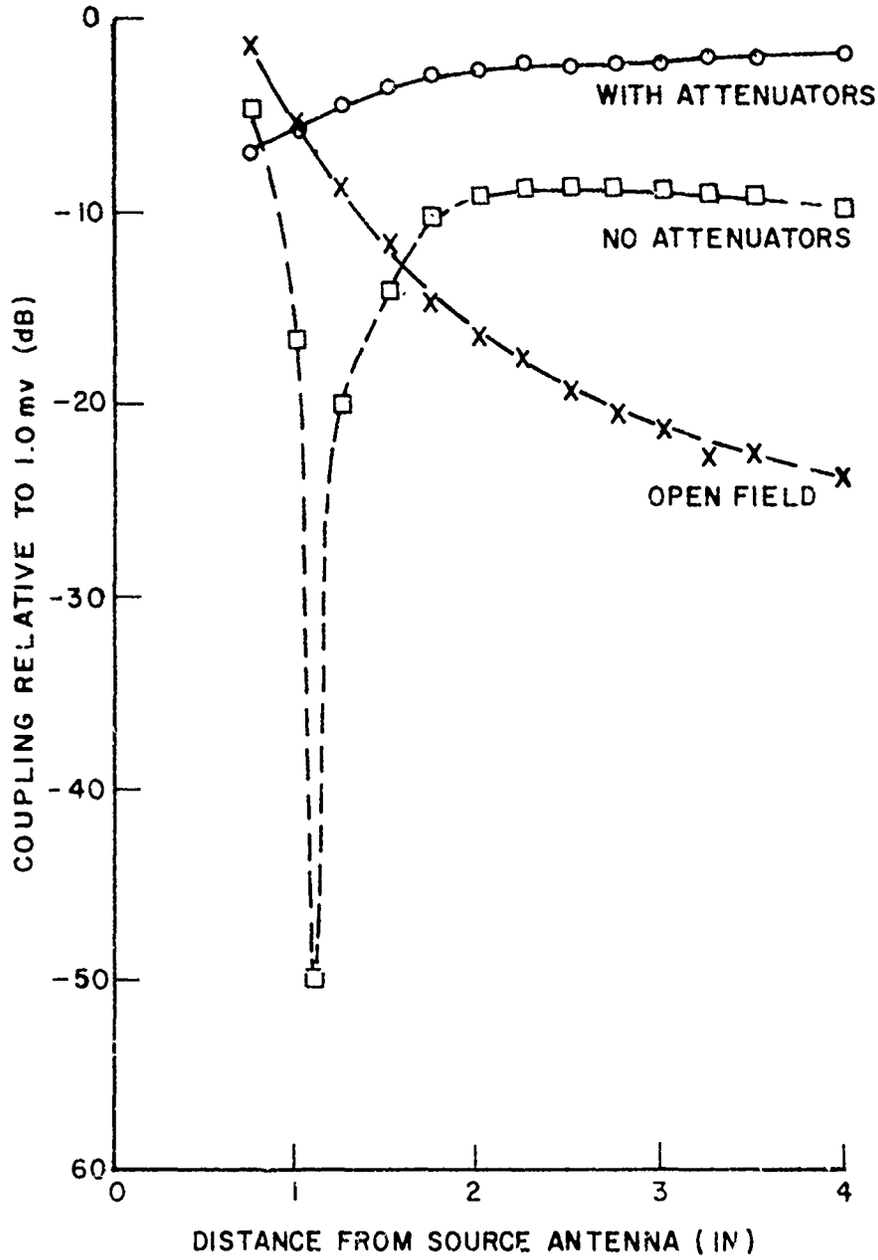


ATTENUATORS AND SETUP FOR INITIAL MEASUREMENTS

T = SOURCE ANTENNA

R = RECEIVING ANTENNA

FIG. 27



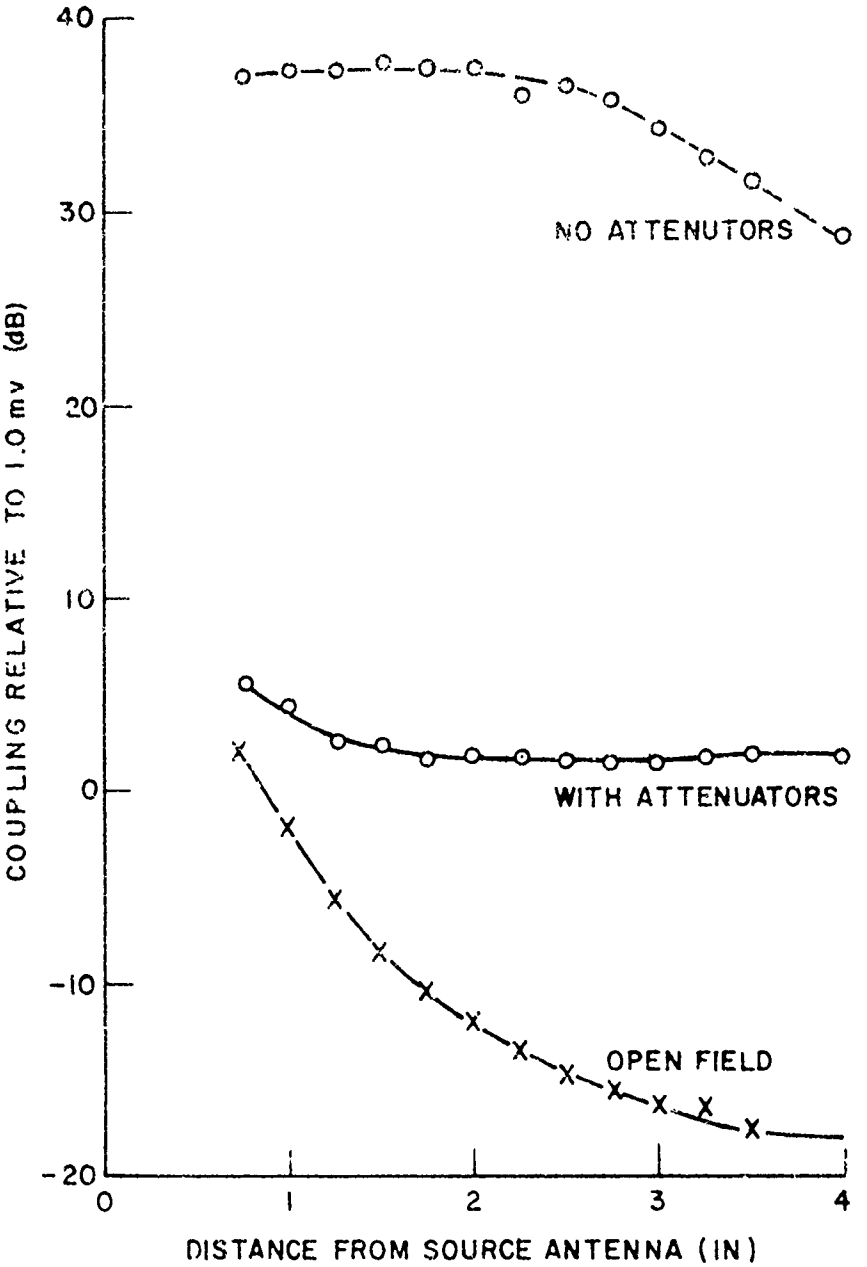
RELATIVE COUPLING f = 600 MHz

VS

DISTANCE IN 10X3X17IN CAVITY

COMPARISON OF RESULTS WITH AND WITHOUT ATTENUATORS
SOURCE ANTENNA IN CENTER

FIG 28



RELATIVE COUPLING f = 685 MHz

VS

DISTANCE IN 10X3X17 IN CAVITY

COMPARISON OF RESULTS WITH AND WITHOUT ATTENUATORS
SOURCE ANTENNA IN CENTER

FIG 29

E Field coupling versus distance measurements were made in the 10 X 3 X 12 in. cavity with the box located approximately 1.5 in. from the center of one end wall with a standard test monopole, located on the center line, serving as the receiving antenna. A series of measurements were made with the box ungrounded and also with the bottom of the box grounded to the cavity. In all of the measurements the slot faced the receiving antenna and was parallel to it.

2.2.3.9.2 Test Results.

The poorly shielded "equipment case" produced the same type of E Field patterns observed in previous experiments with the monopole source antenna. The exact location of the box had considerable effect on the location of the null and, thus, the degree of coupling at a particular distance from the source. As was anticipated, grounding the bottom of the box to the cavity considerably reduced the level of radiation.

2.2.3.10 Simulated Equipment Case - Loop Configuration.

2.2.3.10.1 Discussion.

In the experiments with the loop source antenna (paragraph 2.2.3.7), no coupling nulls were observed and the relative coupling versus distance curves were generally "well behaved" (Fig. 25). It was decided, therefore, to determine if the simulated equipment case would act like a loop if a grounding strap was connected from the top of the box to the end wall. The box was positioned in the 10 X 3 X 12 in. cavity so that the bottom was 0.375 in. from the bottom wall of the cavity and the front of the box, with slot, 1.75 in. from the center of one end wall. The coax cable from the signal generator was grounded to the box only. E Field coupling versus distance measurements were made, along the long dimension center line, with and without a 0.50 in. wide grounding strap connected from the top of the box directly to the end wall; thus forming a loop of sorts. A standard test monopole was used as the receiving antenna.

2.2.3.10.2 Test Results.

From Figures 31 and 32, which show the results at 625 and 685 MHz, it appears that, with the grounding strap, this particular box did couple into the cavity as a loop. No E Field nulls were observed, and the curves resemble those for the loop source antenna in Figure 25.

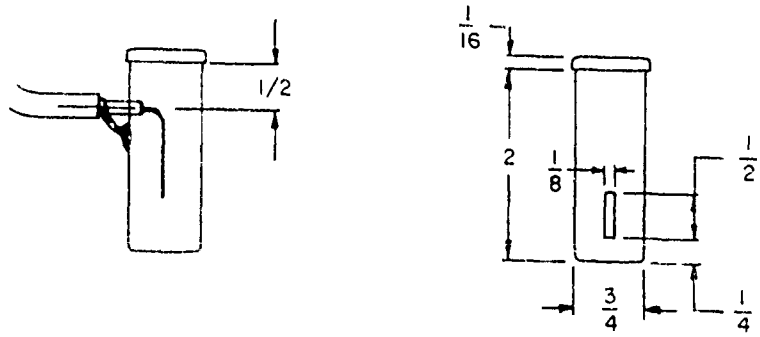
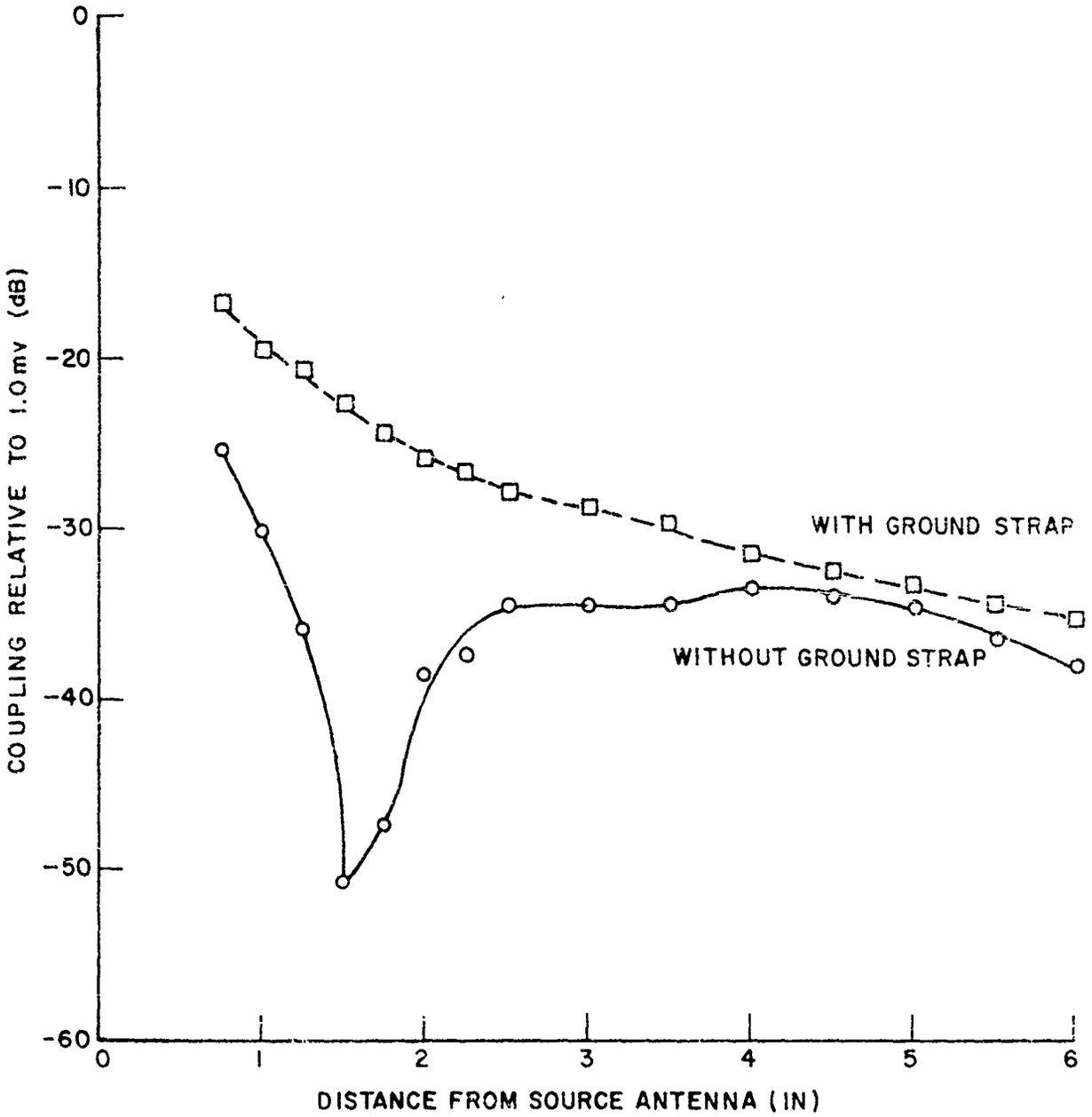


FIG. 30 SIMULATED EQUIPMENT CABINET



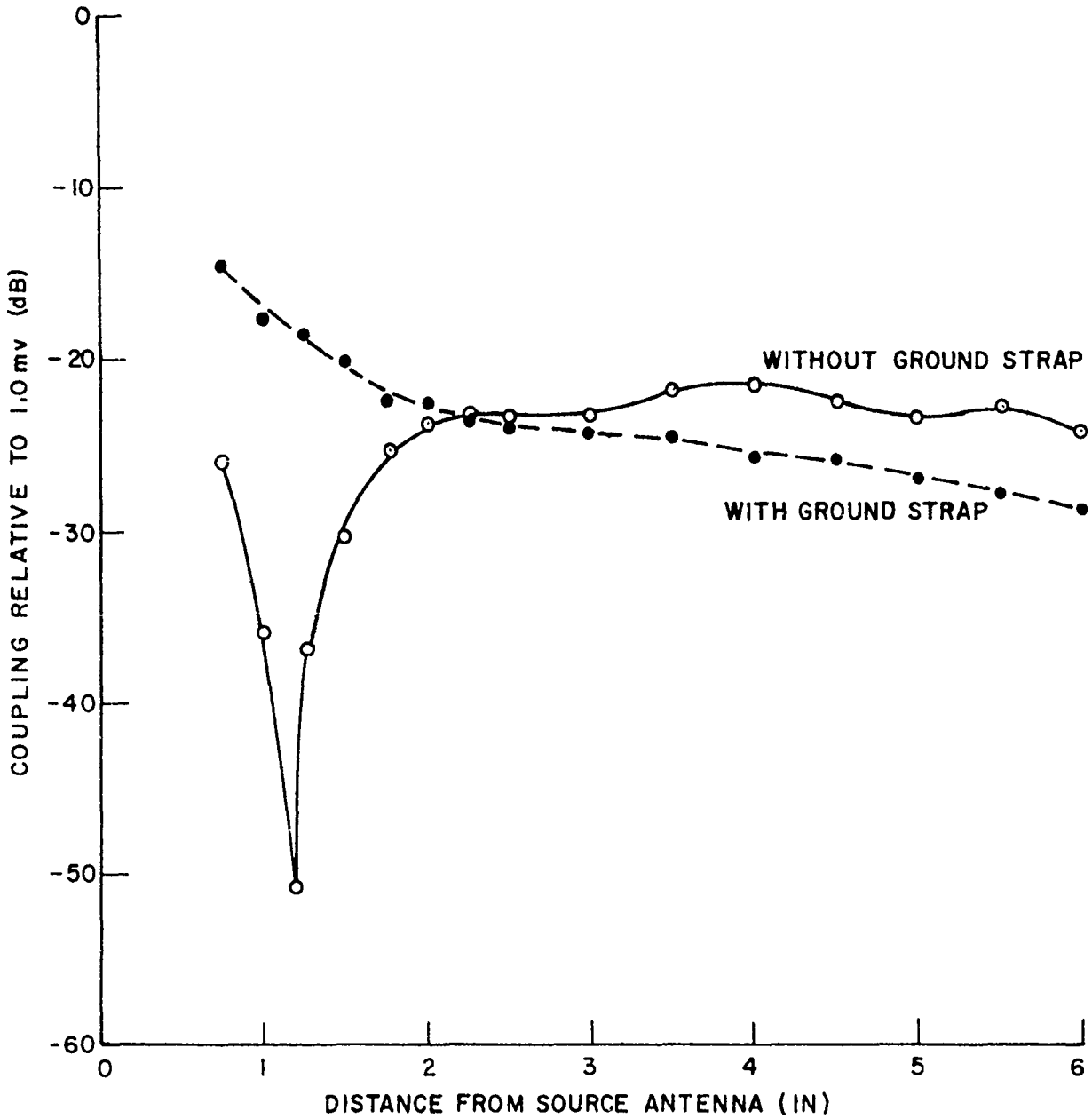
RELATIVE COUPLING f = 625 MHz

VS

DISTANCE IN 10X3X12IN CAVITY

SIMULATED EQUIPMENT CASE SOURCE
WITH & WITHOUT LOOP GROUND STRAP

FIG 31



f = 685 MHz

RELATIVE COUPLING
VS
DISTANCE IN 10X3X12IN CAVITY

SIMULATED EQUIPMENT CASE SOURCE
WITH & WITHOUT LOOP GROUND STRAP

FIG 32

2.2.3.11 Loop Source Antenna With Vane Attenuator.

2.2.3.11.1 Discussion.

It is obvious that it would be most desirable to be able to make measurements at all frequencies in various size enclosures with similar results. The curves in Figure 25, with the loop source, approach this condition except at 685 MHz, which is the first resonant frequency of the 10 X 3 X 17 in. cavity. In view of these results, additional coupling measurements were made in both cavities at 685 MHz with the loop source antenna and a 7 X 2-7/8 in. vane attenuator located on the center line at the opposite end.

The curves in Figures 22 and 23, using two monopoles with the receive antenna located on the opposite wall, are also quite close except at 665 MHz. Unfortunately because of equipment problems, it was not possible to investigate the effect of attenuators with the antennas in this configuration.

2.2.3.11.2 Test Results.

Comparing Figures 25 and 33 shows that the attenuator had essentially no effect on coupling measurements in the 10 X 3 X 12 in. cavity, and almost completely eliminated the resonant effect in the 10 X 3 X 17 in. cavity, bringing the two curves into close agreement.

2.2.3.12 Coupling Slots.

From the observations made in paragraph 2.2.2 regarding the absence of a coupling null in an "open ended waveguide", it was believed that if sufficient energy was coupled out of the cavity by means of coupling slots, and dissipated by some combination of waveguide below cutoff filters, absorbing loads and phase cancellation, all of the shielded enclosure problems would be resolved. This would admittedly be difficult to implement in a full size enclosure.

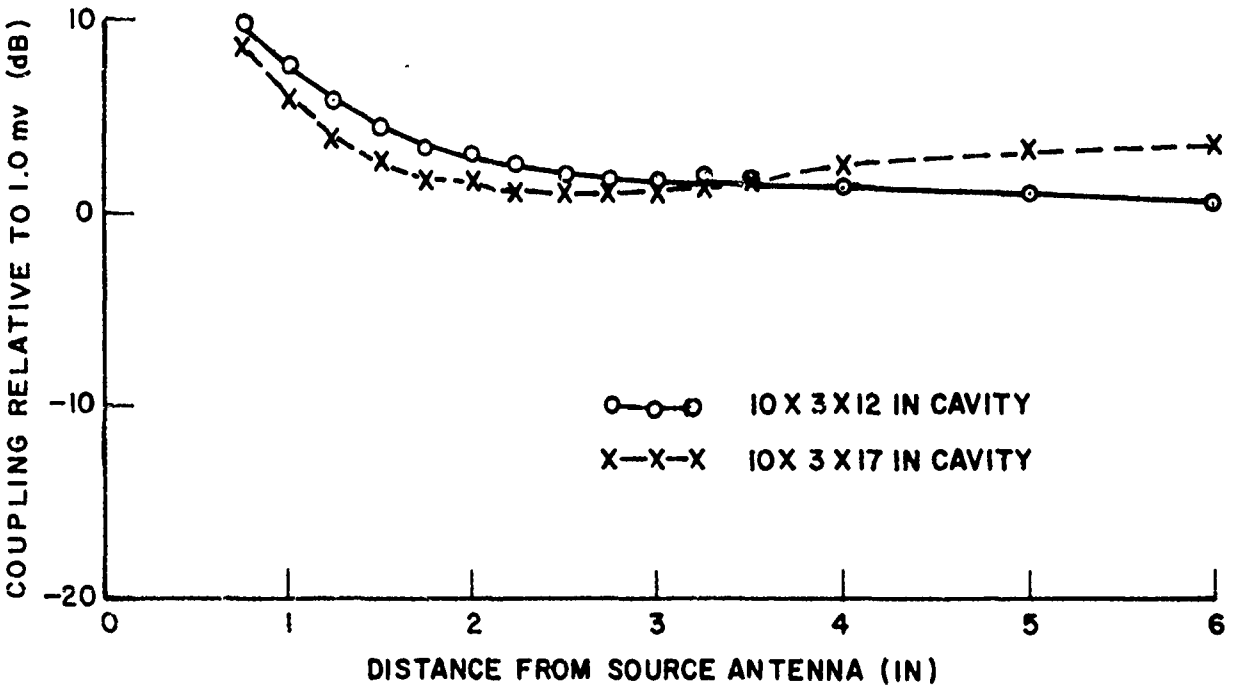
A series of experiments were performed, ignoring for the moment the problem of dissipating the coupled energy, with coupling slots at various locations on one of the broad walls, oriented perpendicular to the long dimension center line. This was carried to an extreme by completely opening up the end walls of the 10 X 3 X 17 in. cavity.

This technique proved effective at frequencies above the waveguide cutoff, approximately 600 MHz. However, below that, at 460 MHz for example, the coupling null, somewhat reduced, was generally quite evident.

2.2.3.13 Dipole Receive Antenna.

2.2.3.13.1 Discussion.

Georgia Tech Research Institute, in a related effort under subtask 1S7 62701 D449 01 67, used dipole source and receive antennas in most of their experiments. They also observed the coupling nulls and resonance effects. Since an actual test specimen might possibly more closely resemble



RELATIVE COUPLING

VS

DISTANCE

SINGLE TURN LOOP SOURCE ANTENNA
WITH VANE ATTENUATOR

FIG 33

a monopole, it was decided to investigate the E Field distribution pattern using a standard test monopole as the source and a dipole with balun, similar to those used by Georgia Tech as the receive antenna. A series of E Field coupling versus distance measurements were made over the 460 to 600 MHz range in the 10 X 3 X 17 in. cavity with the source antenna located at the center of the cavity and the receive antenna probing along the long dimension center line. The receive antenna was centered between the top and bottom walls and both antennas were parallel to the 3.0 in. walls.

2.2.3.13.2 Test Results.

The coupling versus distance varied considerably depending upon the location, or presence, of the ground for the dipole coax cable outer conductor. Measurements were made from 460 to 600 MHz under the following grounding conditions:

a. Outer conductor ungrounded.

b. Outer conductor grounded at end of cavity.

c. Outer conductor grounded 3.0 in. from dipole.

d. Outer conductor ungrounded - heavy mesh grounding strap connecting receiver to cavity.

At 460 MHz the results varied from a 50 dB null with the outer conductor grounded at the end of the cavity, to a 37 dB null with the receiving system ungrounded.

3. CONCLUSIONS AND RECOMMENDATIONS.

From the results of the experiments with the simulated equipment case source, and those performed using a standard monopole with counterpoise receive antenna simulating the 41 in. rod, the significant conclusion is that the E Field null and resonance effects are indeed "real-life" problems when performing radiated interference measurements in shielded enclosures, at least up to and including the first resonant frequency.

All of the data taken under this program and the data published by Georgia Tech[2] and Mendez[3] indicate that at fco/2 for the dominant wave, and below, the location of the test specimen in the enclosure is not critical and, provided the fco/2 condition is maintained, the results can be essentially duplicated in different size enclosures with the 41 in. rod antenna. If the null is present, it will be far enough from the source so as not to seriously influence measurements made at the 1.0 meter test distance. However, the results will be considerably lower than comparative open field measurements. In the frequency scaled enclosures, the relative E Field versus distance curves dropped off rapidly in a fairly linear manner, remaining very close to the open field curve up to a separation distance of approximately 1.5 in. This substantiates Georgia Tech's conclusion that, in a full size enclosure, measurements made close to the source (1.0 ft.) at the lower frequencies will be very close to the open field results. This suggests the possibility of making the measurements with a small probe closer to the test specimen than the presently specified 1.0 meter distance.

At frequencies somewhat above fco/2, with linear source and receive antennas, the severe E Field null starts to affect the measurement results. As the frequency is increased the null moves toward the source and generally disappears into the source by the time the first resonant frequency has been reached. The location of the null, relative to the source, is a function of the geometry of the enclosure, the location of the source, and the length of both the source and receive antennas. At a particular frequency as the source is moved toward the end wall in a rectangular cavity, the null moves away from the source, and as the length of either the source or receive antenna is increased, the null moves toward the source. In the frequency scaled 10 X 3 X 17 in. cavity using a long receive antenna with a "top hat", the null completely disappeared. Similar results were obtained with a long source antenna whose tip was very close to, or touched the opposite wall. Thus, it appears that the E Field null is not a result of antenna coupling to the walls, which had been considered a possible cause of the problem. Also, since the location of the null is a function of the source geometry, it would not be possible to "calibrate" a conventional enclosure with the null present; a technique which had been briefly considered.

The null was not observed with the monopole source antenna located on the bottom wall and the monopole receive antenna probing along the top wall. Also, when either the linear source or receive antenna was replaced by a loop no null was observed.

Unfortunately the exact cause, or causes, of the E Field null could not be determined. At frequencies above waveguide cutoff, absorbing energy at the ends of the cavity with attenuators or loops reduced, or eliminated the null depending upon the frequency. This would seem to indicate that reflections from the end walls were the culprits. However, at the lower frequencies absorbers had almost no effect. It is possible, therefore, that the null mechanism is a function of frequency.

The experimental work under this program has shown that, regardless of the source - receive antenna configuration, the standing wave at the first resonant frequency is a problem. Even in the frequency scaled 10 X 3 X 17 in. cavity with a relatively low Q, the standing wave at resonance was extremely high. Reasonable success was realized by loading the cavity with lossy vane attenuators which, as was previously mentioned, were also effective in either reducing or eliminating the null.

It appears that in a shielded enclosure, the terminal impedance of the 41 in. rod antenna with the CU-890/URM-85 coupler will vary significantly from theoretical and out-of-doors measured values, and will vary from one enclosure to another. It is reasonable to assume, therefore, that the antenna factor values specified for converting measurements to field intensity in dB above 1 μV/meter may not be valid for measurements made in a shielded enclosure. In addition, because of the relatively small size of the counterpoise, several investigators[2] have questioned the validity of the generally accepted effective height value of 0.5 meters for this antenna in the far field.

It is recommended that a program be conducted to (1) investigate the effect of grounding the 41 in. rod counterpoise to the floor of the enclosure, which is the latest requirement in MIL-STD 462, Notice 3, (2) investigate the effect of shielding the rod antenna, (3) determine if it is possible to calibrate an enclosure with the receive monopole on the opposite wall, (4) attempt to optimize material and shape of attenuators, (5) further investigate loop loading to reduce Q, (6) investigate the effect of a tapered enclosure, and (7) explore the feasibility of using a loop or some other configured antenna as the pickup probe.

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