NASA CR-168,253

NASA-CR-168253
19840016905

K-Band Latching Switches

Final Report

May 1984

Prepared for

National Aeronautics and Space Administration

Lewis Research Center
2100 Brookpark Road
Cleveland, Ohio 44135

Sales Number 37586
Contract Number NAS 3-22336

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7 1 1 RN/NASA-CR-168253
DISPLAY 07/2/1
84N24973*# ISSUE 15 PAGE 2327 CATEGORY 33 RPT#: NASA-CR-168253 NAS 1.26:168253 REPT-11982 CNT#: NAS3-22336 84/05/00 77 PAGES
UNCLASSIFIED DOCUMENT
UTTL: K-band latching switches TLSP: Final Report
AUTH: A/PIOTROWSKI, W. S.; B/RAUE, J. E.
CORP: TRW Electronic Systems Group, Redondo Beach, Calif. AVAIL.NTIS SAP: HC A05/MF A01
MAJS: /*DIELECTRIC PROPERTIES/*EXTREMELY HIGH FREQUENCIES/*MAGNETIC PROPERTIES/*SWITCHES/*WAVEGUIDES
MINS: / ACTUATORS/ CAPACITORS/ CIRCUITS/ FERRITES/ NICKEL COMPOUNDS/ PERMITTIVITY/ ZINC COMPOUNDS
ABA: A.R.H.
ABS: Design, development, and tests are described for two single-pole-double-throw latching waveguide ferrite switches: a K-band switch in WR-42 waveguide and a Ka-band switch in WR-28 waveguide. Both switches have structurally simple junctions, mechanically interlocked without the use of bonding materials; they are impervious to the effects of thermal, shock, and vibration stresses. Ferrite material for the Ka-band switch with a proper combination of magnetic and dielectric properties was available and resulted in excellent low loss, wideband performance. The high power handling requirement of the K-band switch limited the choice of ferrite to nickel-zinc compositions with adequate
ENTER:

1. Report No. CR168253	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle K-Band Latching Switches		5. Report Date 15 May 1984
		6. Performing Organization Code 11982
7. Author(s) W. S. Piotrowski and J. E. Raue		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address TRW Electronic Systems Group Redondo Beach, CA 90278		11. Contract or Grant No. NAS3-22336
		13. Type of Report and Period Covered Final Report
12. Sponsoring Agency Name and Address		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This final report describes the study, design, development, and test results of two single-pole-double-throw latching waveguide ferrite switches: a K-band switch in WR-42 waveguide and a Ka-band switch in WR-28 waveguide.

The design approaches for both switches are described. The K-band switch has high power handling capability in excess of 75 W CW and about 1 GHz bandwidth. The Ka-band switch, with 5 W CW power handling capability, has 2.5 GHz operating bandwidth. Both switches have structurally simple junctions, mechanically interlocked without the use of bonding materials; they are impervious to the effects of thermal, shock, and vibration stresses.

Ferrite material for the Ka-band switch with a proper combination of magnetic and dielectric properties was available and resulted in excellent low loss, wideband performance. The high power handling requirement of the K-band switch limited the choice of ferrite to nickel-zinc compositions with adequate magnetic properties, but with too low relative dielectric constant. The relative dielectric constant determines the junction dimensions for given frequency responses. In this case the too low value unavoidably leads to a larger than optimum junction volume, increasing the insertion loss and restricting the operating bandwidth.

This report also describes the efforts to overcome the materials-related difficulties through the design of a composite junction with increased effective dielectric properties, in addition to the efforts to modify the relative dielectric constant of nickel-zinc ferrite.

17. Key Words (Suggested by Author(s))	18. Distribution Statement

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
U	U		

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-C-168 (Rev. 10-75)

N84-24973#

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PREFACE

The work described in this report was performed in the Microwave Technology Department of the Electronic Systems Group of TRW's Electronics and Defense Sector. The work was performed under the direction of Dr. Cheng Sun, who gratefully acknowledges the principal contributions of Mr. Godfrey Anzic of the NASA-Lewis Research Center and Dr. J.E. Raue, Mssrs. W.M. Brunner, and W.S. Piotrowski of TRW.

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1. INTRODUCTION AND SUMMARY

This final report describes the development of two waveguide ferrite switches: a high power K-band switch in WR-42 waveguide and a high speed Ka-band switch in WR-28 waveguide. Also described are the efforts to improve the characteristics of ferrite materials for the K-band range. The nickel-zinc ferrites have excellent high power capability, and their magnetic and dielectric properties are nearly ideal for the design of high power, wideband, low loss circulators and switches at Ka-band. Their relative dielectric constant, however, is significantly too low to design these components at the lower K-band range, and leads to a too large junction volume, increased insertion loss, and degraded bandwidth performance. The analytical work, which disclosed the design problems caused by the too low relative dielectric constant, was verified by the design, fabrication, and performance measurements of an artificial composite junction consisting of a ferrite core and a ring fabricated from a high relative dielectric constant ceramic. The resulting junction, with significantly higher effective dielectric constant, produced the expected frequency responses from the analytically predicted dimensions and excellent, well-balanced isolation and VSWR performance. This approach resulted in increased insertion loss, however, caused by the dielectric discontinuity between the ferrite and the ceramic ring, nullifying the effects of the smaller junction volume. This effort demonstrated the need for a ferrite with higher relative dielectric constant for this frequency range; however, the required bandwidth and insertion loss improvements may be obtained only in a simple junction, fabricated from a homogeneous material with proper physical characteristics.

The results of this work were followed with efforts to modify the dielectric properties of the nickel-zinc ferrite. Several approaches were investigated during a 15-week development effort, and a substitution method of oxides with high polarizability into the NiO sites of the nickel-zinc composition resulted in several samples with significantly higher values of the relative dielectric constant. But, the rather large variations indicated that a greater effort would be required to achieve adequate process control and acceptable and repeatable results. The efforts to obtain the needed improvements will be continued as part of other ferrite materials developments.

The concurrent developments of two essentially similar components provide a comparison of not only the impact of the materials properties on the component performance, but also on the degree of design difficulty and the required level of effort. Logically, the nearly ideal material for the higher frequency Ka-band design simplified the effort and resulted in an excellent performance of isolators and switches. In contrast, the more modest performance of the lower frequency K-band switch was obtained at the cost of a significantly more difficult effort demonstrating the need for improvements in the area of ferrite materials technology.

The presently available ferrites were developed decades ago, long before present requirements could be anticipated. In a few exceptional cases, the combination of the magnetic and dielectric properties, as in the Ka-band, are nearly ideal and lead to outstanding component performance. Development of ferrite components during the past several years has resulted in rapid progress in design methods, which were predominantly oriented toward overcoming the limitations imposed by inadequate materials. However, the component performance is the result of proper correlation of the magnetic, dielectric, and transmission line characteristics, and the best design method cannot overcome the limitations imposed by grossly inadequate physical properties of materials. Further improvements of component performance require corresponding improvements of ferrite properties. In the specific case of high power K-band junction components, ferrites with significantly higher relative dielectric constant are needed.

The design of the K-band switch (Figure 1) was based on the approach which had proved successful in X-band switch development for DSSC-II and Landsat space programs and K-band switch development in WR-51 waveguide for NASA. The development objectives and the actual performance data are listed in Table 1.

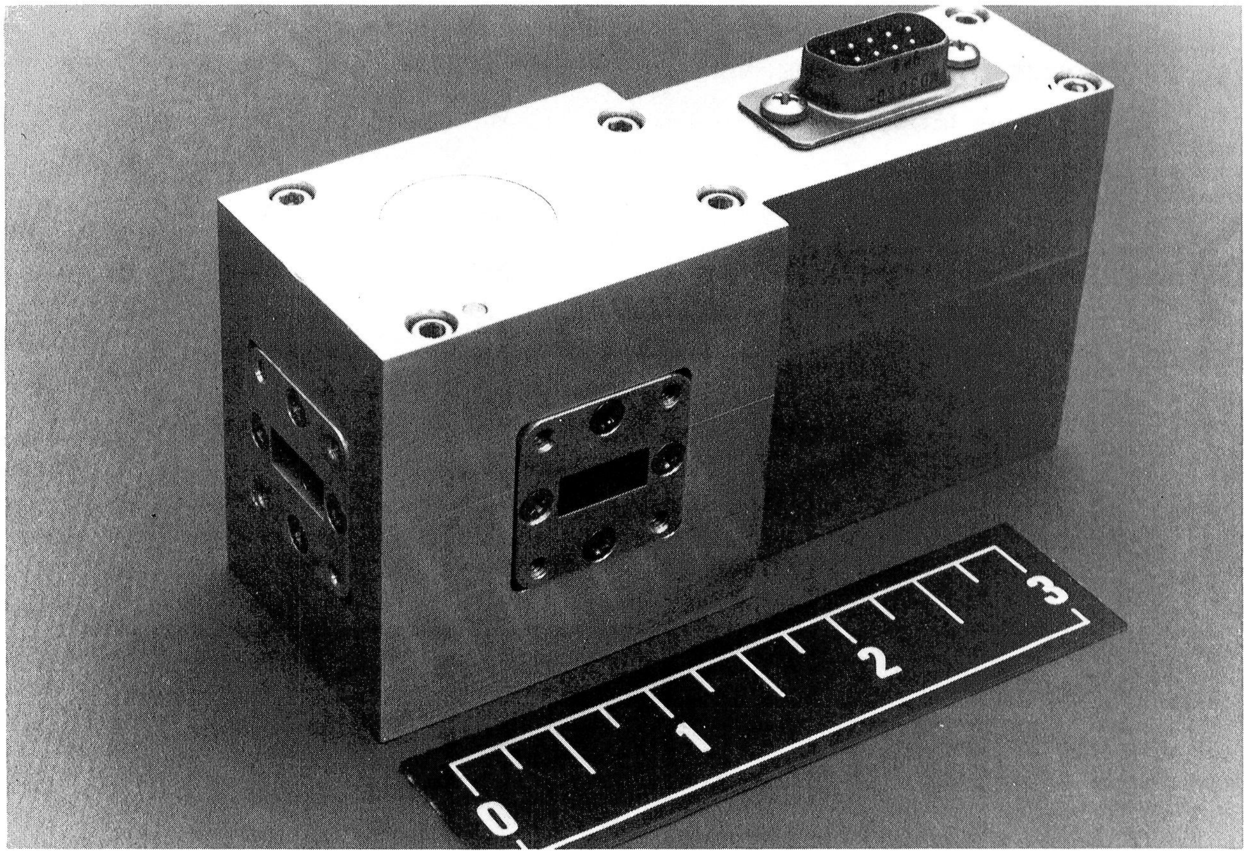

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Figure 1. K-Band Switch

Table 1. K-Band Switch Design Objectives and Performance

PARAMETER	DEVELOPMENT OBJECTIVES	ACTUAL PERFORMANCE
CENTER OPERATING FREQUENCY (GHz)	18.95	19.2
BANDWIDTH MIN (GHz)	2.5	1.0
CW OPERATING POWER (W)	75	NOT MEASURED*
OPERATING TEMPERATURE, MAX (°C)	56	56
NONOPERATING TEMPERATURE, MIN (°C)	-40	-40
WAVEGUIDE DESIGNATION	WR-42	WR-42
SIZE, MAX (CU. IN.)	10	8.4
SWITCH TYPE, LATCHING	SPDT	SPDT
INSERTION LOSS, MAX (dB)	0.25	0.4
ISOLATION, MIN (dB)	25	20 TO 25
ISOLATION, GOAL (dB)	30	-
VSWR, MAX	1.2	1.3
VSWR, MAX WITH 1.15 LOAD	1.3	1.3
PHASE LINEARITY OVER ANY 300 MHz OF PASSBAND (°)	5	< 5
SWITCHING TIME, MAX (μSEC)	80	50
SWITCHING POWER SUPPLY (Vdc)	24	24
SWITCHING POWER SUPPLY CURRENT, MAX (mA)	10	4.8

*TESTS NOT PERFORMED DUE TO LACK OF SUITABLE POWER SOURCES.

The development of the Ka-band switch shown in Figure 2, where ferrite material with nearly ideal properties was available, led to excellent performance, satisfying or exceeding the design objectives. These switches were provided with input isolators, increasing the input-output isolation of the isolator/switch assembly to a level in excess of 40 dB. The design objectives and the actual performance of the switches and the isolator/switch assemblies are listed in Table 2.

Table 2. Ka-Band Switch Design Objectives and Performance

PARAMETER	DEVELOPMENT OBJECTIVES	ACTUAL PERFORMANCE SWITCH	ACTUAL PERFORMANCE ISOLATOR/SWITCH
CENTER OPERATING FREQUENCY (GHz)	28.75	28.75	
BANDWIDTH, MIN (GHz)	2.5	2.5	
CW OPERATING POWER (W)	5	12	
OPERATING TEMPERATURE, MAX (°C)	56	56	
NONOPERATING TEMPERATURE, MIN (°C)	-40	-40	
WAVEGUIDE DESIGNATION	WR-28	WR-28	
SIZE, MAX (CU IN)	10	0.8	2.0
SWITCH TYPE, LATCHING	SPDT	SPDT	
INSERTION LOSS, MAX (dB)	0.4	0.25	0.4
ISOLATION, MIN (dB)	35*	20	40
ISOLATION GOAL (dB)	40*	-	40
VSWR, MAX	1.2	1.2	1.1 TYP
VSWR, MAX WITH 1.15 LOAD	1.3	1.3	1.2
PHASE LINEARITY OVER ANY 300 MHz OF PASSBAND (°)	5	5	
SWITCHING TIME (μSEC)	80	50**	
SWITCHING POWER SUPPLY (Vdc)	24	24	
SWITCHING POWER SUPPLY CURRENT, MAX (mA)	10	4.8	

* WITH INPUT ISOLATORS.

**ONE μSEC SWITCHING SPEED CAPABILITY WITH SUITABLE CONTROL CIRCUIT.

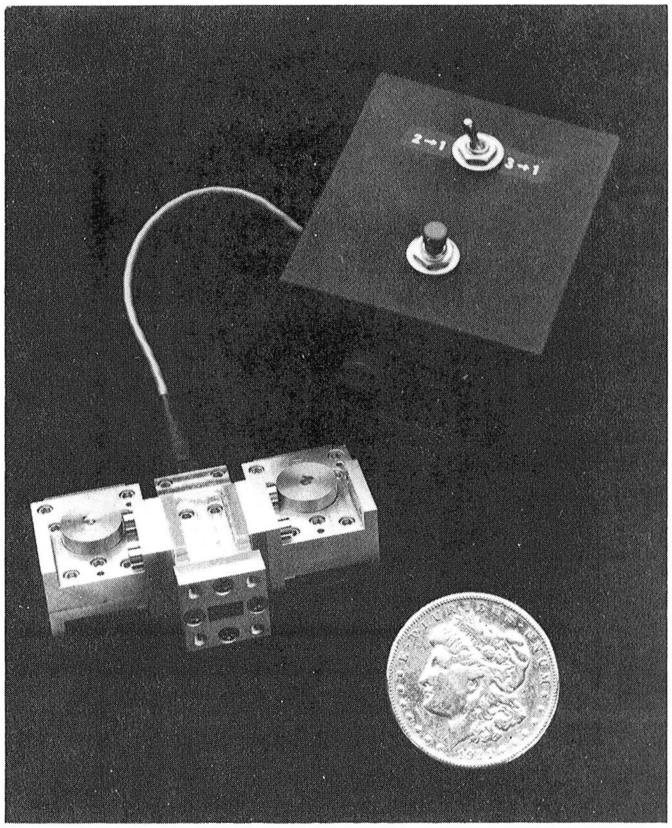

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Figure 2. Ka-Band Isolator/Switch Assembly

2. HIGH POWER K-BAND FERRITE SWITCH DEVELOPMENT

2.1 INTRODUCTION

The design approach of the high power K-band switch is based on the TRW patented[1] high power ferrite switching junction design, which has been previously qualified for DSSC-II and Landsat space programs. The same type of switching junction was also used in the WR-51 high power switches developed for NASA during 1980. The development of these WR-51 switches and multijunction circulators, required for other programs, disclosed unexpected difficulties in obtaining predicted bandwidth and insertion loss performance in this frequency range. These difficulties were unexpected because 0.1 dB insertion loss over full waveguide band has been obtained easily, not only at the lower X_L-band (7 to 10 GHz), but also over about 9 GHz of operating bandwidth at the much higher Ka-band frequency range (26.5 to 40 GHz). Considering the impact of this performance degradation at K-band not only on the high power switches, but also on the multistage solid state power sources then under development, we initiated a thorough investigation of this peculiar problem. By the time this current development program started, the analysis of the switch and circulator designs identified the significantly too low relative dielectric constant of the high power nickel ferrites used in these designs as a source of the difficulties. The initial efforts of the current K-band switch development were devoted to further detailed analysis and design of a composite junction to demonstrate experimentally the impact of the relative dielectric constant on the component design and performance.

2.2 FERRITE MATERIALS PROBLEMS

Materials selection and problems described in this section apply to the ferrite junction components with high power handling capability, low insertion loss, and wide operating bandwidth. Under these design constraints and at frequencies above 18 GHz, the only acceptable materials

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(1)Electronic Waveguide Switch, U.S. Patent No. 4,254,384, dated 3 March 1981 are nickel-zinc spinel ferrites. Garnets have too low saturation magnetization ($4\pi M_s$) to satisfy the bandwidth requirements, and magnesium compositions have a low power handling capability of up to about 20 watts. Some of the lithium ferrites with low saturation magnetizations have better dielectric properties (ϵ_r = 18, $4\pi M_s$ = 1100 gauss). These, with an adequate saturation magnetization in the range of 3500 to 4100 gauss, have too low relative dielectric constants and are not suitable for power levels in excess of 50 watts CW.

By coincidence, rather than by deliberate design, the nickel-zinc compositions developed decades ago and long before present requirements could be anticipated, have nearly ideal combinations of magnetic and dielectric properties for applications in several frequency ranges, such as the 26.5 to 40 GHz range, where performance with 0.1 dB insertion loss over about 9 GHz bandwidth is easily obtained. A similar performance at the lower K-band range is not possible with this type material because its relative dielectric constant is significantly too low. In this case, to obtain the frequency response determined by the relative dielectric constant of the ferrite, a large junction with distorted proportions leads to twice the insertion loss and a degraded bandwidth performance.

The impact of the relative dielectric constant on the performance of ferrite junction components has been largely ignored in the numerous theoretical papers concerned with general concepts and nearly exclusive emphasis on the magnetic characteristics. Experimental component developments at lower microwave frequencies started with a selected ferrite and optimized the junction dimensions to satisfy given (normally very modest) requirements. These experimental methods clearly had no capabilities to determine required materials properties, not only dielectric but also magnetic. After an examination of a number of existing components, J. Helszajn[(2)] writes, "This result also suggests that many junctions are constructed using materials with values of saturation magnetization which are too large for the ripple level and bandwidth of the device."

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(2)F.C.F Tan and J. Hejszajn, "Suppression of Higher Order Modes in Waveguide-Junction Circulators using Coupled Open Dielectric Resonators," MTT-24, 5-76, pp. 271-273.

The introduction of the circulator junction circuit concept, which considers the junction ferrite as a dielectric resonator whose length is a quarter or half wavelength long, is also inadequate to define the junction circuit properly because it does not yield a unique solution. But, when the junction ferrite is considered as a dielectric resonator supporting the propagation of two modes, the junction dimensions and the required physical properties of the ferrite material may be determined accurately. This TRW-developed design method reverses the previous design approaches, which started with the material selection and attempted to optimize the dimensions to satisfy the given requirements. The new method begins with the given design center frequency and operating bandwidth, and determines the resonator dimensions and required relative dielectric constant of the ferrite material and its saturation magnetization. The following example illustrates the dominant importance of the relative dielectric constant in the junction design with design center frequency of 21 GHz and operating bandwidth 18 to 24 GHz in WR-42 waveguide.

The optimum ferrite dimensions required for low insertion loss and adequate impedance match over the specified bandwidth are:

Ferrite R/L = 1.4
Ferrite length = 0.040 inches
Ferrite radius = 0.056 inches
Ferrite volume = 3.9408×10^{-4} inches

If the relative dielectric constant of the ferrite is $\varepsilon_r = 21$, the frequency responses of the dielectric resonator are:

Low frequency = 18.13 GHz
Center frequency = 20.994 GHz
High frequency = 23.855 GHz

If a ferrite with the relative dielectric constant $\epsilon_r = 13$ is substituted, the frequency responses would be:

Low frequency = 23.046 GHz
Center frequency = 26.682 GHz
High frequency = 30.319 GHz

If the ferrite with the relative dielectric constant $\epsilon_r = 13$ must be used because the proper value is not available, the ferrite dimensions must be increased and experimentally determined. These modified dimensions, in comparison with the optimum, analytically predictable values are:

	$\epsilon_r = 13$	$\epsilon_r = 21$
Ferrite length (inches)	0.056	0.040
Ferrite radius (inches)	0.075	0.056
Ferrite R/L ratio	1.34	1.40
Ferrite volume (in^3)	9.8960×10^{-4}	3.9408×10^{-4}

The modified ferrite has 2.51 times larger volume, leading to a proportional increase of the circulator insertion loss, and the badly distorted junction dimensions also cause degradation of the bandwidth performance. In addition, the impact on the design process should be noted. The circulator design with optimized material parameters is relatively simple, and the actual component performance closely conforms to the analytically predicted. But when the ferrite relative dielectric constant is only about half the required value, several experimental and time consuming design iterations are unavoidable. As a consequence, a poor performance is obtained at significantly more difficult effort and cost.

Recognizing the sources of the design difficulties in previous circulator and switch developments at K-band as materials-related problems has led to a two-pronged effort to obtain the necessary improvements. The purpose of the first part of this work was to confirm experimentally the accumulated analytic data, while the second part was devoted to an investigation of potential methods to improve the properties of ferrite materials.

2.3 MATERIALS MODIFICATION EFFORT

The increased insertion loss and reduced bandwidth of K-band circulators and switches, compared with similar junction designs at both the lower and higher frequencies, have been noted during previous developments. The reasons and sources of these design difficulties have not been identified, however, and the potential solutions have been thought to depend on improved design concepts. During a more recent development of K-band switches in WR-51 waveguide in 1980 the insertion loss and bandwidth performance, projected on the basis of previous results obtained at both the lower X-band and higher Ka-band frequencies and falling short of the design objectives, stimulated a more thorough examination of these unexpected design difficulties peculiar to the K-band range. After the previous development was completed and before the present task was initiated, examination and analysis were nearly completed, and the sources of component performance difficulties were identified as materials-related problems; specifically, the improper and significantly too low relative dielectric constant of the nickel ferrites used in the design of high power components in the K-band frequency range.

During the analysis phase, the causes of degraded bandwidth and insertion loss performance for the K-band high power ferrite components were examined and compared with other frequency bands. This effort led to several significant modifications and improved analytic methods, disclosing not only the source of the deficiencies, but also potential corrective measures.

Initially, the comparison of the junction dimensions, as related to the waveguide dimensions at X-, K-, and Ka-bands, indicated that the K-band junctions were significantly larger than the wideband, low loss X- and Ka-band designs. In our design, where the junction ferrites as circuit elements determining the frequency responses of the component are dielectric resonators, this clearly pointed to the relative dielectric constant of the ferrite as a major source of the problems.

The preliminary results were followed by a more detailed evaluation of other numerous available dimensional and performance data and design procedure changes. This was necessary because, in spite of the fact that the impact of the relative dielectric constant on the size of the circulator junction may seem obvious, the subject was never considered as significant in the large volume of technical writing during the past 30 years. Presenting it as a key design consideration, the aspect of the dielectric constant could be questioned on the basis of this long-standing treatment and the nearly exclusive consideration of magnetic properties as the most important design parameter.

Another important reason for a thorough analysis of this problem was the potential impact on further component performance improvements through progress in the materials technology. Historically, again the main thrust of the development has been exclusively on magnetic properties, but little progress has been demonstrated during the past two decades in this area due to challenging technical difficulties and lack of adequate funding. Potentially, with improved dielectric properties, an additional direction in materials technology could lead to the same objectives using technically simpler and more economical materials development methods.

The reasons for the absence of adequate consideration of the dielectric properties of ferrites in junction component design are that most of the technical papers do not even address the component design problems, but are mainly concerned with idealized, theoretical considerations, or the depth and sophistication of the generalized mathematical concepts. As such, they are of little or no value to the component designer. The few presentations with more practical purposes normally begin with a given existing material, concentrate on the obviously important magnetic properties, and consider the relative dielectric constant as a given, fixed design parameter. The objective of this method is to optimize component performance with what is available, but not necessarily to determine what is, in fact, required. With several significant improvements, TRW's design procedures were essentially similar. This approach, which accepts the "as is" condition without the search for what is really needed, tends to obscure the effects of the ferrite physical properties on component performance. In some cases, this process works very well because, by coincidence rather than conscious effort, most design parameters happen to be close to ideal, leading to outstanding component performance. Under more difficult circumstances this approach, which in effect states "we will do the best we can with whatever we have and accept whatever results we can get", is bound to fail. Clearly, a reversed approach, starting with the given requirements and aimed at establishing the precise materials physical parameters required to satisfy the design objectives, is a vast improvement.

TRW developed this more logical approach and implemented the necessary computer analysis. Our design procedure correlates the dielectric, magnetic, and transmission line impedance requirements. In this unified procedure, each characteristic may be introduced as a variable, and its effects are immediately apparent, presenting a clear picture of interactions between the variables. Even in the case where the design parameters are less than ideal, it simplifies the optimization of the design.

This improved analysis clearly indicated the dominant effects of the relative dielectric constant on component performance. The ferrite in a circulator or switch junction is, as a circuit element, a dielectric resonator supporting the propagation of two modes. The frequency separation between the resonances of these modes determines the operating bandwidth of the component. The separation of the resonances in a cylindrical resonator is controlled by the proportions of the cylinder, specifically by the radius/length ratio, while the dimensions for a given frequency response are controlled by the relative dielectric constant of the ferrite material. It is possible, therefore, to produce an infinite number of dielectric resonators with identical R/L ratios and identical frequency responses using a wide range of relative dielectric constants. The difference between these resonators will be only their volume, increasing as the relative dielectric constant is lowered.

Considering all other parameters equal, the circulator junction with larger ferrite resonators would have higher insertion loss than a junction with smaller ferrites, the loss being proportional to their respective volumes. In a circulator, for the loss measurement to have any meaning it must be measured with the junction nearly perfectly matched to the terminating waveguides. Combining the loss and impedance considerations should be adequate to perceive intuitively that to obtain both the optimum loss performance and impedance match, optimum junction volume must exist. As a consequence, the optimum value of the relative dielectric constant is also fixed.

The effects of the magnetic properties in the junction design have not been mentioned because selecting the adequate level of saturation magnetization of the ferrite is far simpler. Above 30 GHz, the selection is limited to ferrites with the highest available saturation magnetization of 5000 gauss. Below this frequency, care should be taken to avoid too high a value, which would cause high insertion loss at the lower frequency part of the circulator bandpass where the ferrites would be magnetically biased into the high absorption region of the material. To obtain a circulator response with well-balanced ripples in the VSWR and isolation performance, it is necessary to select a ferrite with saturation magnetization level adequate to provide phaseshift over a bandwidth equal to or wider than the frequency separation of the resonances of the dielectric resonator modes. Under these conditions, the dielectric modes are coupled to form a wideband response, when the junction is magnetically biased into saturation, in a manner similar to responses of two coupled amplifiers. A relatively wide range of the saturation magnetization, extending from about 2900 gauss to about 4200 gauss could be used in K-band junction component design.

The opposite is true for the relative dielectric constant. The proper value of this parameter, combined with a rather wide range of adequate saturation magnetiztion, results in a junction having 0.1 dB insertion loss over the full waveguide band. Within a comparatively narrow range of values of the relative dielectric constant, the circulator or switch performance may be optimized. However, the progressively larger deviation, especially toward the lower values, leads to a larger junction, higher insertion loss, and degraded bandwidth. Bandwidth performance degradation is caused by the unavoidable deviation from the optimum R/L ratio of the ferrites. A larger volume of the ferrite, caused by a too-low relative dielectric constant required for the given frequency response, is obtained by enlarging the ferrite radius. This reduces the bandwidth over which acceptable impedance match may be obtained.

Our specific problem with the 20 GHz range is caused by three coincidental requirements of high power, wide bandwidth, and low insertion loss, leaving little room for compromises and tradeoffs. With the presently available dielectric constant, a lower insertion loss may be obtained over reduced bandwidth, or a wider band performance may be provided with higher insertion loss. Neither is acceptable, so the dielectric constant correction is the only solution.

As mentioned, the relative dielectric constant of the ferrites has not been considered an important design parameter and there were no known previous efforts in the materials technology, except to improve the magnetic properties. As a result, TRW initiated an investigation to determine potential solutions of the problem using two approaches: (1) obtain modifications of the relative dielectric constant of the existing basic nickel ferrite compositions and (2) overcome the materials deficiencies by a design technique using composite junctions with artificially increased effective dielectric properties.

2.3.1 Composite Junction Design

This task produced significant results. It is a circulator junction design, where previously used ferrites with a too low relative dielectric constant were replaced by an artificially created composite structure intended to approximate the significantly higher relative dielectric constant required to obtain optimum junction proportions with reduced volume.

Several observations made during this task led to conclusions with a large impact on potential future performance improvements of ferrite components. These are:

- Results of this work provided conclusive evidence that the efforts in the ferrite technology area should be focused on control of dielectric properties. Previous developments were exclusively devoted to improvements of magnetic properties.
- Actual measured data confirmed the previous analytic work on the effects of a relative dielectric constant in the design of ferrite junction components.
- The relative dielectric constant of the ferrite is the dominant design parameter in the design of ferrite junction circulators and switches. It determines the frequency responses, the junction volume, and the insertion loss performance.
- The value of the relative dielectric constant of the ferrite affects the quality of component performance, far exceeding the effects of the magnetic properties which may be chosen from a relatively wide range.
- A properly chosen value of the relative dielectric constant leads to an excellent, analytically predictable performance in contrast to time consuming adjustments of dimensions and relatively poor performance when proper value is not available.
- The analytically predictable performance significantly reduces development time. The adjustment of the final impedance match required less than one day's effort in this design, compared with several weeks of experimental modifications when a ferrite with too low relative dielectric constant had to be used.

The design approach of the composite junction considers the junction ferrite as a capacitor, whose effective dielectric constant may be modified artificially in several ways. It may be reduced by replacing part of the ferrite cylinder with a spacer with a lower relative dielectric constant. It may be increased by placing a ceramic pin in the center of the cylinder, or a ceramic ring with a high relative dielectric constant on a ferrite core. In the latter case, the objective was to increase the dielectric constant; a design with a ferrite core and ceramic ring was used, as shown in Figure 3.

The problems expected with this deceptively simple approach included spurious responses in the circulator bandpass, caused by fabrication

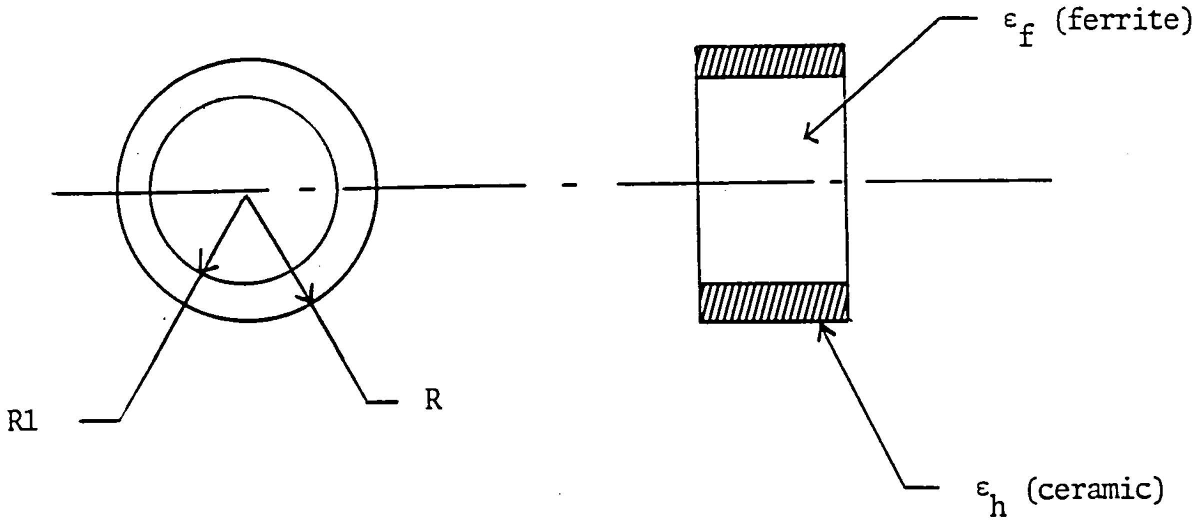

Figure 3. Configuration of Composite Junction Ferrite

tolerances and possible air gaps between the ferrite core and the ceramic ring, and the effects of the abrupt dielectric discontinuities between these parts. In the fabricated junction, the spurious responses did not appear, but the effect of the dielectric discontinuities was nearly twice the insertion loss of a homogeneous junction with comparable volume.

The value of the resulting effective dielectric constant of the composite junction may be obtained by considering the assembly as parallel capacitors and using the following simple relationship:

$$\varepsilon_{(eff)} R^2 = \varepsilon_f R1 + \varepsilon_h \; (R^2 - R1^2)$$

where:

$\varepsilon_{(eff)}$ = effective dielectric constant of the assembly
ε_f = ferrite relative dielectric constant
ε_h = ceramic relative dielectric constant
R = outside radius of the ceramic ring
R1 = ferrite radius

To obtain a basis for comparison, the composite junction was designed with an operating bandwidth similar to a previously developed K-band circulator. In this previous case, a ferrite with relative dielectric constant ε_r = 12.9 was used, leading to final ferrite dimensions having a radius = 0.150 in. and length = 0.112 in. The initially calculated ferrite dielectric spacer and transformer dimensions produced large frequency shift, poor impedance match, and, generally, an unbalanced and unacceptable performance. The ferrites were enlarged to lower the frequency to the required range and after several weeks of effort, performance was optimized; the results are shown in Figure 4. The swept frequency responses show 0.2 dB insertion loss (twice the 0.1 dB obtained at much higher Ka-band frequency range where a more suitable ferrite was available) and distorted and unsymmetrical VSWR and isolation ripples.

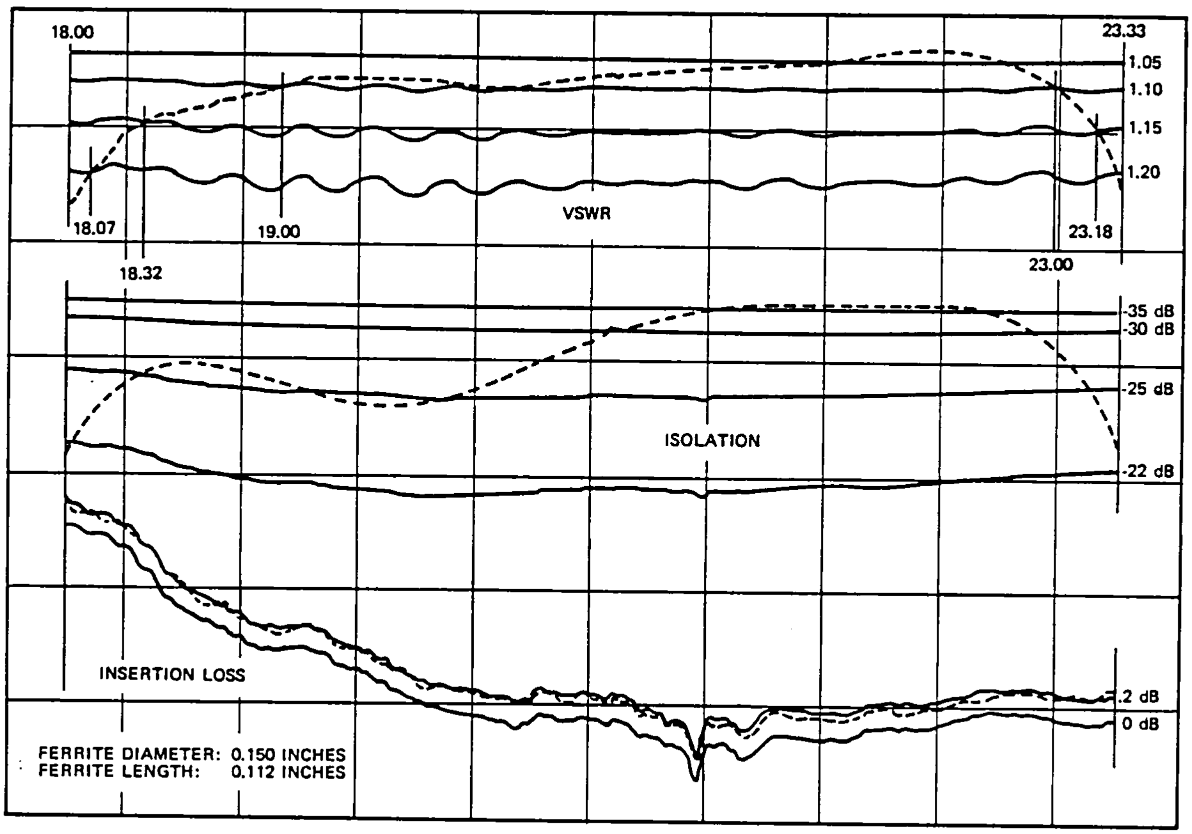

Figure 4. Performance of Circulator with Simple Low Dielectric Constant Ferrite Junction

Two composite junctions were designed using the same circulator design computer program. The first junction ferrite had a diameter of 0.136 inches and a length of 0.080 inches; the second had a diameter of 0.128 inches and a length of 0.080 inches. To minimize the cost of tooling and fabrication, the ferrite cores in each junction had a diameter of 0.100 inches and length of 0.080 inches. The impedance transformers were fabricated slightly longer than computed to allow for an adjustment of the VSWR and isolation levels in the center of the operating bandwidth. The ceramic rings were fabricated with the relative dielectric constant ϵ_r = 32. Preliminary measurements indicated an expected operating frequency range and, after the adjustment of the transformer lengths, the swept frequency responses shown in Figure 5, clearly demonstrated improved symmetry and balance of VSWR and isolation ripples over the previous design. The 0.25 dB insertion loss, caused by the dielectric discontinuities between the ferrite core and ceramic ring, would be significantly lower in a comparable junction volume fabrication from a homogeneous ferrite material. The volume of the 0.136 inch diameter junction was reduced to about 59 percent and the 0.128 inch diameter junction to about 52 percent of the original low dielectric constant design.

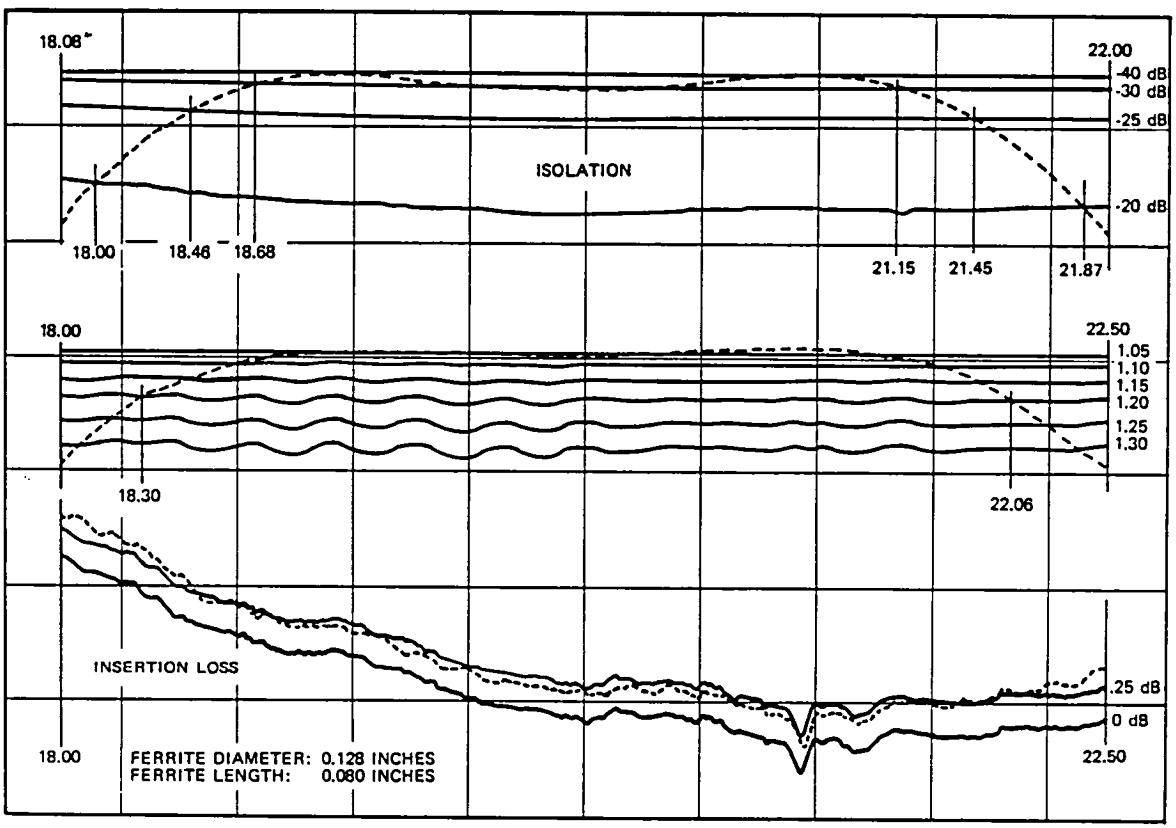

Figure 5. Performance of Circulator with Composite Dielectric Ferrite Junction

The increased effective dielectric constant of the junction permitted significant reduction of the junction volume for an essentially similar frequency response. The new junctions also demonstrated other improved characteristics:

- Nearly exactly the predicted frequency responses in contrast to troublesome frequency shifts in junction designs with improper dielectric properties.
- More accurate and predictable adjustments of the impedance matching transformers which determine the final performance level.
- Swept frequency responses displayed significant improvements in the balance and symmetry of VSWR and isolation ripples.

The composite junction is not a direct and equal substitute for a structurally and electrically simpler junction fabricated from homogeneous material with proper physical properties. The increased complexity and dielectric discontinuities are obvious disadvantages, also contributing to an increase of the insertion loss. But, the design concept proves the effects of ferrite parameters, especially the relative dielectric constant on the component performance, and provides conclusive and logical indications for the necessary development initiatives in ferrite materials technology.

2.3.2 Modifications of Ferrite Relative Dielectric Constant

The objectives of this effort included modifications to the dielectric properties of presently existing nickel ferrite compositions with high power handling capabilities for applications in wideband, low loss, high power junction circulators and switches operating in the K-band frequency range. As developed originally, ferrites with saturation magnetization levels in the range of 3000 to 4200 gauss (suitable for the K-band designs) displayed significantly too low values of relative dielectric constant to obtain junction ferrite proportions consistent with the operating bandwidth and insertion loss requirements.

Assuming an acceptable level of saturation magnetization, the bandwidth of a junction component depends on the radius/length ratio of the junction ferrite, but the ferrite in the junction circuit is a quarter- or half-wave resonator, and its length in a waveguide transmission line is restricted within relatively close limits with respect to the waveguide height. For this reason, to maintain the required ferrite R/L ratio, a similar restriction is also placed on the value of the relative dielectric constant. The significantly too low values of the present nickel ferrite compositions lead to an excessively large radius of the ferrite, distorting the R/L ratio and degrading the bandwidth, while the increased ferrite volume contributes to increased insertion loss. The design problems with the too low relative dielectric constant are especially troublesome in the K-band range in high power component design where nickel ferrites with the best power handling capabilities must be used.

TRW's general approach to the materials effort considered not only the objectives of the K-band switch development, but also the impact on other continuing work at other frequencies. Our background in the area of the ferrite materials technology was instrumental in both the recognition of the benefits of this work and in the assessment of risk and difficulties.

Considering the trend to higher frequencies, efforts were initiated in the area of ferrite materials technology several years ago. Our objectives included improvements of materials for applications in the 50 to 300 GHz frequency range. These initial efforts to resume development work of more than twenty years ago, and abandoned when the interest shifted to the lower microwave frequencies, were discouraging and disclosed several obvious difficulties such as technical problems, high costs and risks, the time consuming nature of this work, and a general lack of interest among the ferrite manufacturers. Technically, previous developments were limited to improving magnetic properties which are known as technically challenging. In addition, the trend to higher frequencies reduced the economic incentives to an unacceptable level. The materials for lower frequencies with a large sales volume and numerous potential commercial applications offered adequate incentives. Ferrite components at higher frequencies are not commercially practical because they are used only in limited quantities in space communications and military systems funded by government agencies. As a result, any further progress requires support from these agencies. In addition, lack of knowledge by ferrite manufacturers about specific requirements places the responsibility for any initiatives in this field on the component designers. The specific materials needs at K-band presented an opportunity to solve the current problem and develop potentially useful methods to modify the dielectric properties of ferrites at several other frequencies.

Another key consideration in this effort was the selection of a cooperating ferrite manufacturer. Our previous work in this area provided us with adequate knowledge about the capabilities of leading ferrite manufacturers and the individuals with the necessary background, interest, and motivation. The actual material formulation, processing, and measurements were performed by Countis Laboratories.

In the specific approach to the development of nickel ferrites with increased relative dielectric constant, TRW determined the best solution to be modifying the chemical composition, leading to a material with the required properties. Also considered was the possibility of obtaining acceptable results through simpler and less costly structural reconstitution methods. These included grinding and milling the existing ferrite, mixing with high relative dielectric constant additives, and re-sintering at reduced temperatures to prevent a complete reaction. Several samples produced by this method were unsuccesful in increasing the dielectric properties because the new material displayed a series-parallel arrangement of particles, where predominantly parallel alignment is required.

The possibility for modifying dielectric properties of existing basic nickel-zinc ferrite compositions was based on the assumption that an addition of elements with high polarizability to the present composition would modify the dielectric properties without materially affecting loss and magnetic characteristics. Several samples of experimental material confirmed this approach, but displayed an undesirably wide range of relative dielectric constants of 29, 60, and 102. The task to finalize the required material would require several months of work and would not be completed within the planned 15 weeks. To meet the new material requirement including 3400 to 4000 gauss saturation magnetization, 18.25 relative dielectric constant, and 0.001 dielectric loss tangent, additional time is required to establish the composition of the mixture and the sintering temperatures which critically affect the final properties.

2.4 JUNCTION DESIGN CONSIDERATIONS

The design of the K-band switching junction in the WR-42 waveguide is based on an approach established previously in space-qualified components at other frequencies and at K-band in WR-51 waveguide. As shown in Figure 6, the RF junction is magnetically biased by external (to the waveguide) switch drivers to obtain circulator action at the remanent magnetization level of the switch driver-RF junction assembly. The change in the circulator direction or the single-pole, double-throw RF switching action is controlled by the polarity of the current pulse through the coil within the switch driver; the switch is latched in its position by this current pulse.

The RF junction consists of two quarter-wave long ferrites and a dielectric spacer, housed in a dielectric sleeve located in the recess of the metallic transformer disk, which in turn indexes the junction assembly to the switch housing.

A gold foil with several skin current depth thicknesses forms the waveguide wall in the junction area and separates the switch driver ferrite from the RF junction, preventing RF leakage with a minimum of conductive material in the magnetic circuit. The foil thickness is kept to a minimum because the presence of the conductive material within the magnetic loop permits eddy currents during switching, increasing the required switching energy and reducing the switching speed. The design of the switch driver ferrites is presented in Section 2.5.

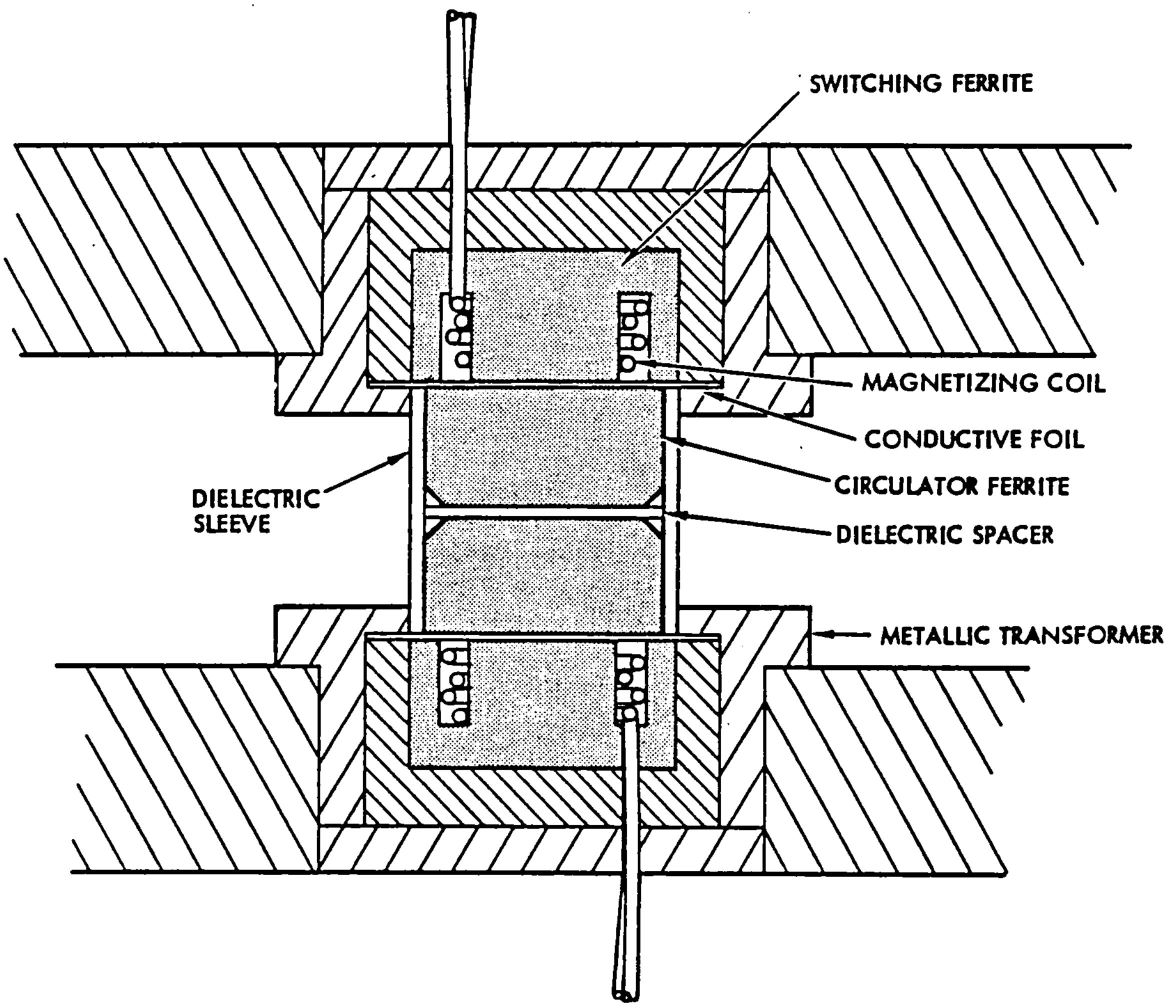

Figure 6. Cross-Section of Switching Junction Showing RF and Driver Ferrite Locations

The switching junction ferrite design is significantly more complex than the simple nonswitching circulator junction ferrite design. The task starts with the well-optimized circulator design to obtain a reasonable estimate of the key dimension: the length of the ferrite required to obtain adequate impedance match and isolation level. The new enlarged ferrite with an adequate cross-section to provide a return path for the magnetic flux is a dielectric resonator supporting the propagation of two modes whose resonances determine the operating bandwidth of the component when the junction is impedance-matched and magnetically biased. The two modes are coupled to form the familiar dual-ripple responses in VSWR and isolation similarly to the coupling of resonators in bandpass filters or coupled amplifiers. Ferrite materials with nearly ideal magnetic and dielectric properties simplified the task at X-band where a switching junction with about 0.15 dB insertion loss, better than 1.05:1 VSWR, and higher than 30 dB isolation performance has been developed. At K-band in the WR-51 waveguide a similar performance could not be obtained. The simultaneous requirements of high power and wide bandwidth eliminated from consideration all ferrites except the nickel-zinc materials with adequate magnetic characteristics but with about one-half the value of the required relative dielectric constant. In the WR-51 design, this led to a large junction with severely distorted proportions, nearly twice the expected insertion loss and degraded bandwidth.

During the current development, analysis of the previous design, which disclosed the material-caused difficulties, led to efforts to develop the necessary ferrite with an increased relative dielectric constant which is consistent with the bandwidth high power and insertion loss requirements. These efforts would have required significantly more time than could be included in this development to obtain adequate results, and the available approaches were reduced to the composite junction design or the design with existing ferrites. The composite junction could be justified in some simple nonswitching junction designs because, in comparison with the designs with a too low relative dielectric constant ferrite, it permits circulator designs with significantly improved impedance match and isolation performance at slightly higher insertion loss and structural complexity. In a larger switching junction the insertion loss caused by the dielectric discontinuities and the structural complexity make this approach unacceptable, leaving no other choice but to use the presently available nickel-zinc ferrite with known too low relative dielectric constant.

As expected, the optimization of the junction dimensions was difficult and required several time-consuming experimental modifications to obtain the performance shown in Figure 7.

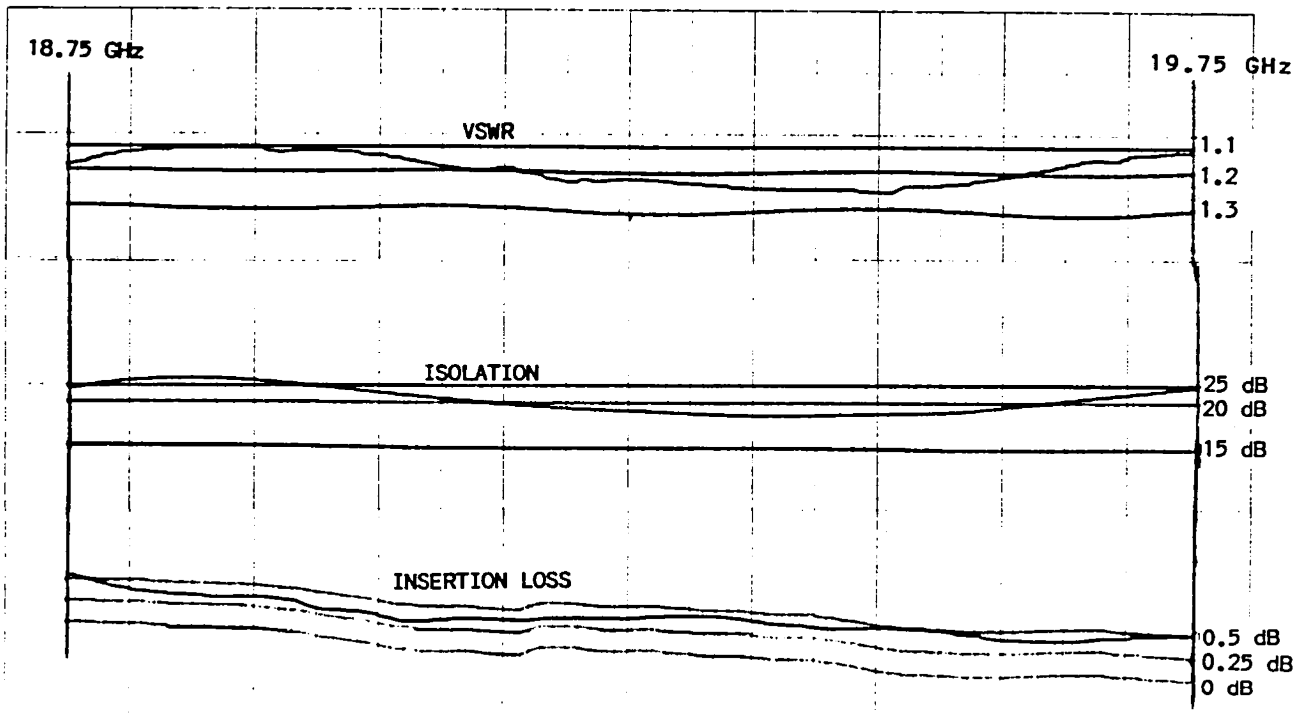

Figure 7. Swept Frequency Responses of Switch Serial No. 1 before Vibration Tests

2.5 SWITCH DRIVER DESIGN

The switch drivers which replace the permanent magnets of a circulator extend the capability of the junction with fixed direction circulation to that of a single-pole, double-throw switch. The current pulse through the winding establishes internal magnetization in the driver RF junction assembly, latching it at the remanent level, magnetically biasing the junction into circulation. A pulse with an opposite polarity repeats the switching and latching, reversing the direction of circulation.

The switch driver assembly shown in Figure 8 consists of a cylindrical ferrite sleeve enclosing a coil wound on a ferrite core. A closed magnetic loop of this electromagnet is formed by the contacting RF junction ferrite; when magnetized by a current pulse, it retains the internal magnetization within this closed loop at the remanent level. A ferrite material, suitable for the driver, should have low coercive field (Hc) and a square hysteresis loop characteristic, indicated by a high ratio of remanent over its maximum flux density (Br/Bm). The low coercive field (Hc), usually a few oersteds, ensures the low switching energy required, and a high level of remanent magnetization provides adequate bias for the circulator junction. In this specific switch design approach, where the switch drivers are placed externally to the waveguide circuit, both ferrite materials for the drivers and for the circulator junction are selected independently, allowing an optimum selection of materials for each function.

The ferrite material selected for the switch drivers is a lithium ferrite 5000 B, manufactured by Ampex Corporation. Its residual induction (Br) is 3700 gauss, Br/Bm ratio is 0.95, and its coercive field (Hc) is 4.2 oersteds, indicating good switching characteristics. Previous designs where similar lithium ferrites have been used required care in fabrication of the driver parts but did not present unusual problems in fabrication and heat-treatment. In the present case, the slightly smaller drivers with a thinner cross-section, combined with more brittle material, made the processing of driver parts nearly

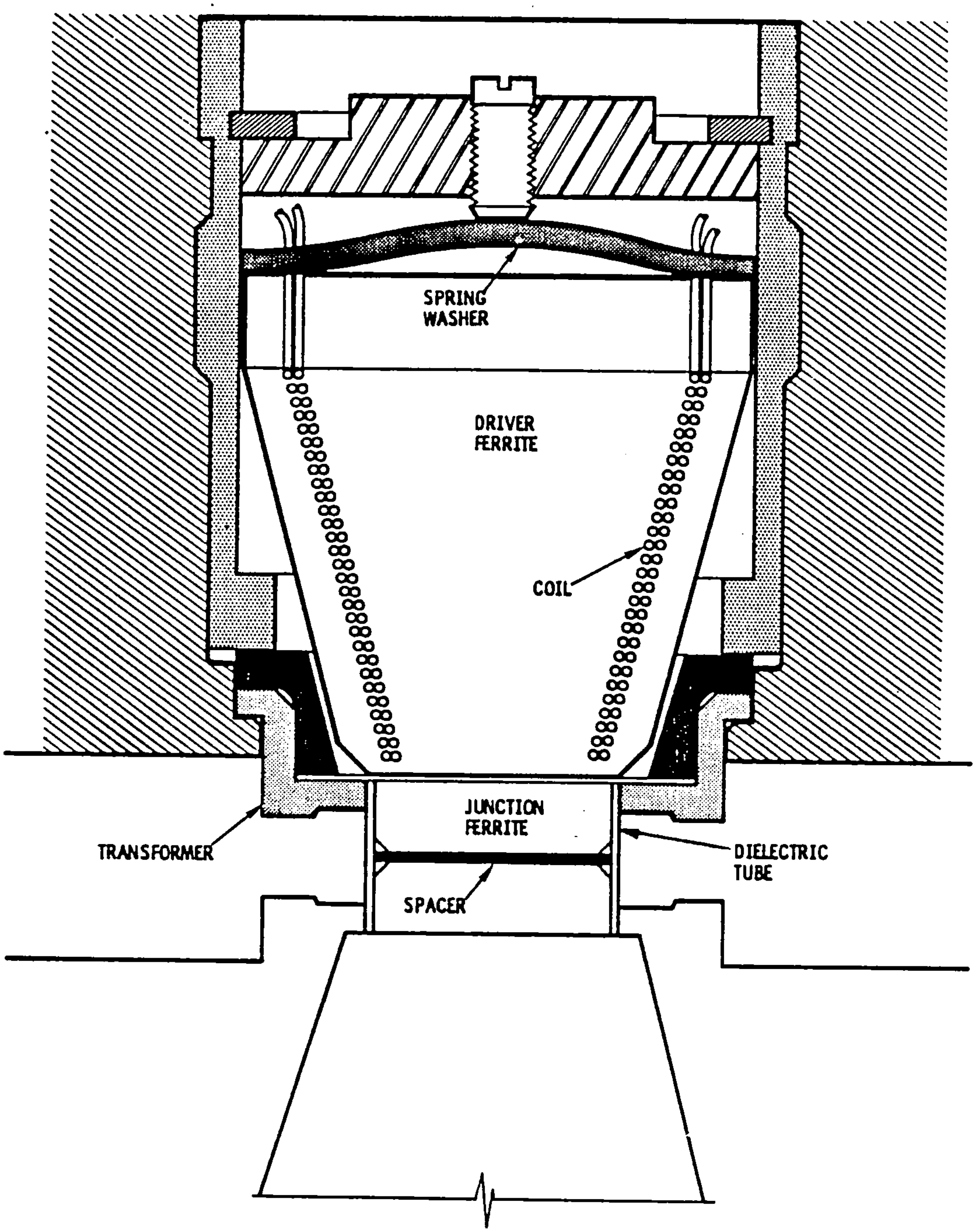

Figure 8. Configuration of Switch Driver Assembly

impossible. Part of the problem was the material; internal stress fractures could not be seen on the surface of the bar stock. To correct the problem, new material was purchased, and the cross-sections of the driver parts were increased beyond the requirements of the circuit to facilitate fabrication and heat-treatment processing.

The switch design with this type actuator requires an intimate contact of the switch driver with junction ferrites at all times and under all specified environmental conditions to prevent unlatching and loss of circulator action. This intimate contact is ensured by properly designed wavy-washer type springs which maintain the whole junction assembly under compression. Their resonant frequencies are much higher than the specified vibration test frequencies and in this way the thermal, shock, and vibration problems are effectively eliminated.

2.6 INSTRUMENTATION AND TEST SETUP

Electrical performance measurements of a circulator or switch under development include insertion loss, VSWR, and isolation and are normally accomplished with a simple reflectometer test set (Figure 9). The components of this test, with the exception of the waveguide load and detector, are standard commercially available equipment, maintained and calibrated by the TRW Metrology Department in accordance with the mandatory calibration procedures. Special care is used with the detectors and waveguide loads to ensure acceptable accuracy. This is necessary because the circulator is by definition a lossless and reflectionless device, and its actual performance is affected by reflections at all three ports. It may be measured as better than actual if the phasing of reflections is favorable, but more often a good performance is degraded by these reflections, especially the isolation measurements. The effects of the reflections on the accuracy of the isolation measurements may be seen in the graph shown in Figure 10. To minimize the range of measurement errors, we prepare our own waveguide loads and detector assemblies. The detector assembly shown in Figure 9 includes, in addition to a low reflection attenuator, a well-optimized circulator which dissipates even low-level reflections from the detector in its waveguide load. This improved reflectometer test set has been used during the development work and final performance measurements, including the thermal tests.

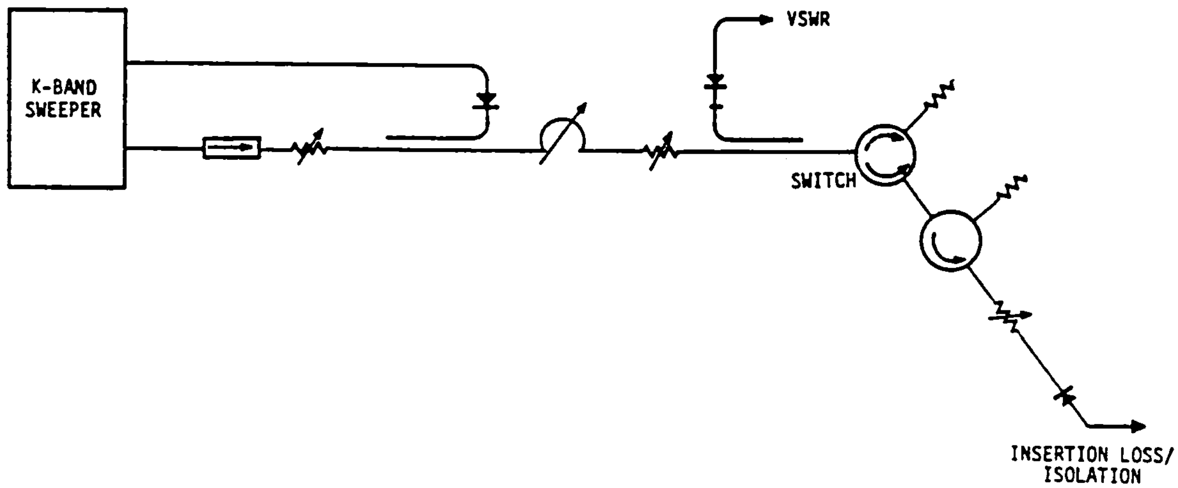

Figure 9. Schematic of K-Band Development Circuit

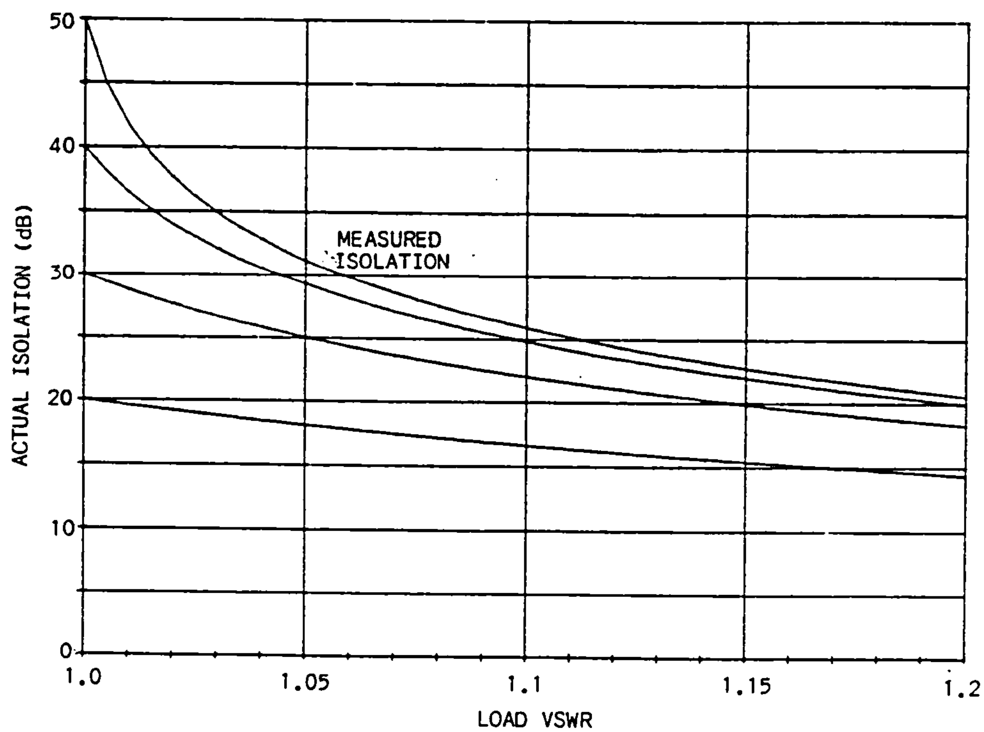

Figure 10. Degradation of Circulator Isolation with Load VSWR

2.7 SWITCH ACTUATOR CIRCUIT

The switch actuator is provided within the switch housing. All that is required to operate the switch is an external 24 Vdc power supply and two SPST switches or relays.

The actuator consists of two independent capacitor discharge circuits, one for each direction of circulation. Each circuit has a 188 μF capacitor, trickle-charged through a resistor, limiting the charging current to 5 mA, and a series dropping resistor, limiting the peak discharge current. The components of both circuits are combined on a single circuit board located in the cavity of the switch housing and protected from the effects of shock and vibration by special "formed in place" foam. Figure 11 is the schematic of the actuator circuit and the pin assignments of the nine-pin connector, while Figure 12 is the layout of the actuator circuit board.

The nominal value of the power supply voltage is 24 Vdc, but the switching may be completed with an input of 15 Vdc and longer capacitor charging time.

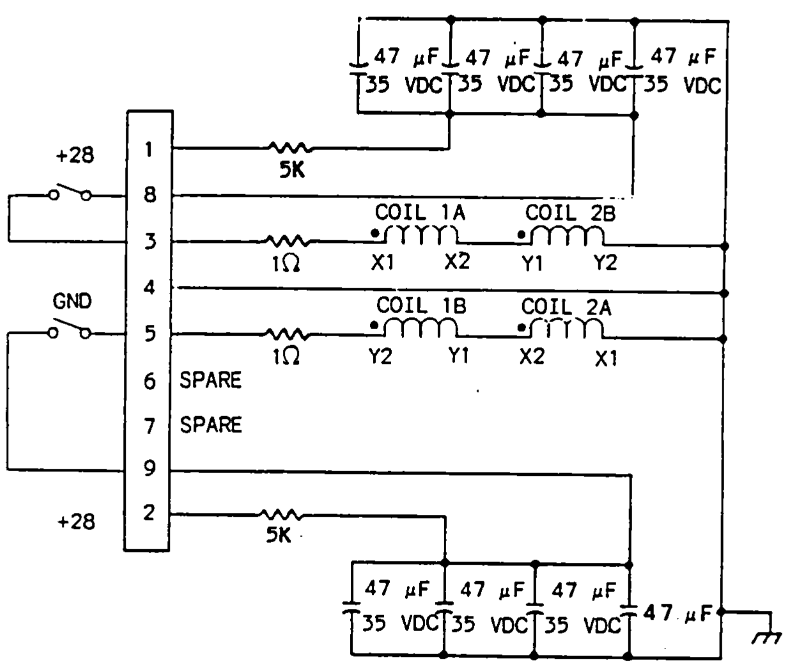

Figure 11. Schematic of Latching Switch Actuating Circuitry

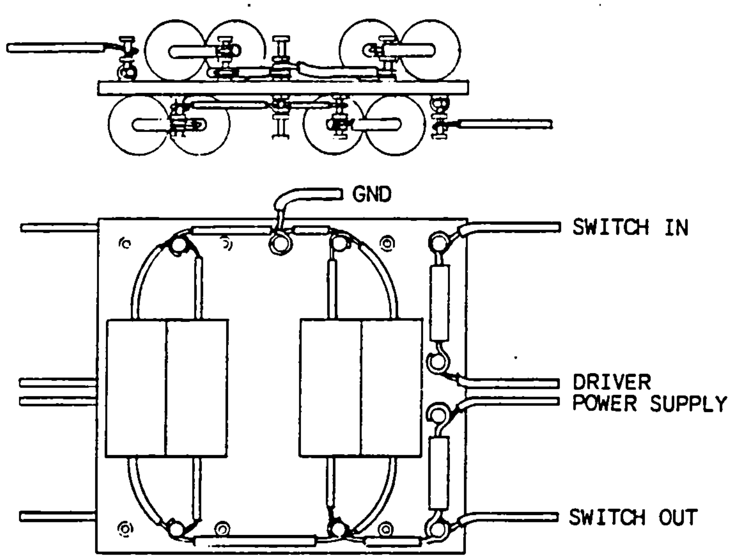

Figure 12. Board Layout of Switch Actuating Circuitry

2.8 RESULTS AND TEST DATA

Switch tests were performed in accordance with the test matrix shown in Table 3. Switch serial number two was temperature tested, while serial number one was vibration tested.

Figures 13, 14, and 15 are room temperature, swept frequency responses showing VSWR, isolation, and insertion loss, respectively. The thermal performance of switch serial number two is shown in Figures 16, 17, and 18. The thermal test was initiated by subjecting the switch to the survival temperature of -40°C for three hours. The temperature of the test chamber was then returned to room temperature (23°C) and the switch was connected for the return loss test. The test data taken at all three ports indicated no measurable deviations from the original acceptance test data. The temperature was increased to 56°C, stabilized for one hour, and the swept frequency responses were recorded. Then the temperature was lowered to 10°C, stabilized, and the swept frequency responses recorded. The temperature of the test chamber was then returned to room temperature level, and the initial reference levels were verified. The same procedure was repeated for the insertion loss test at all three ports.

Table 3. Test Matrix

TEST	SEQUENCE	REQUIREMENT / REFERENCE PARAGRAPH	VSWR 4.1.2	INSERTION LOSS 4.1.3	ISOLATION 4.1.4	AMPLITUDE VARIATION 4.1.5	PHASE DEVIATION 4.1.6	POWER HANDLING CAPABILITY 4.1.7	SWITCHING CIRCUIT CHARACTERISTIC 4.1.8
INITIAL FUNCTIONAL	1	4.1	X	X	X	X	X	(2)	X
VIBRATION	2	4.2		(1)					
POST VIBRATION FUNCTIONAL	3	4.1	X						X
THERMAL	4	4.2.2	X	X	X	X	X		X
FINAL FUNCTIONAL	5	4.1	X	X	X	X	X		X

(1) MONITOR ONLY
(2) GOAL ONLY (DEPENDS ON AVAILABILITY OF RF SOURCES)

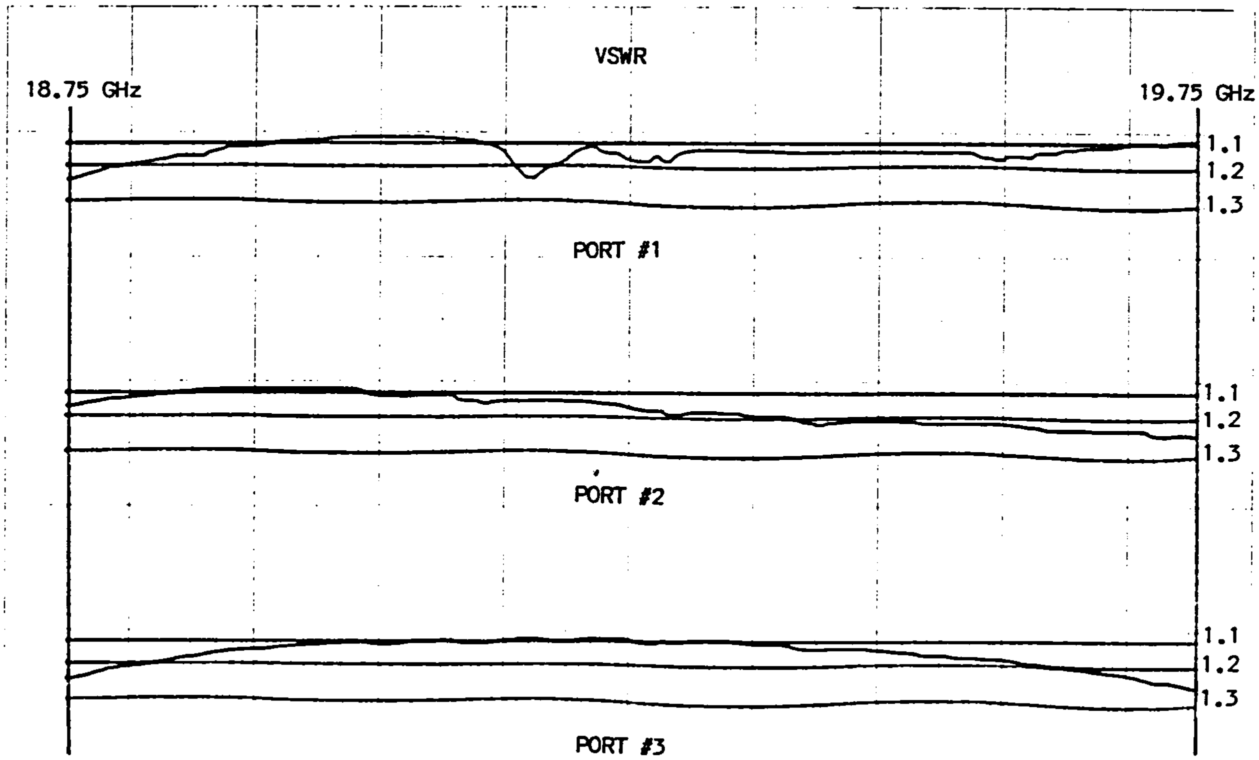

Figure 13. VSWR Swept Frequency Responses of Switch Serial No. 2

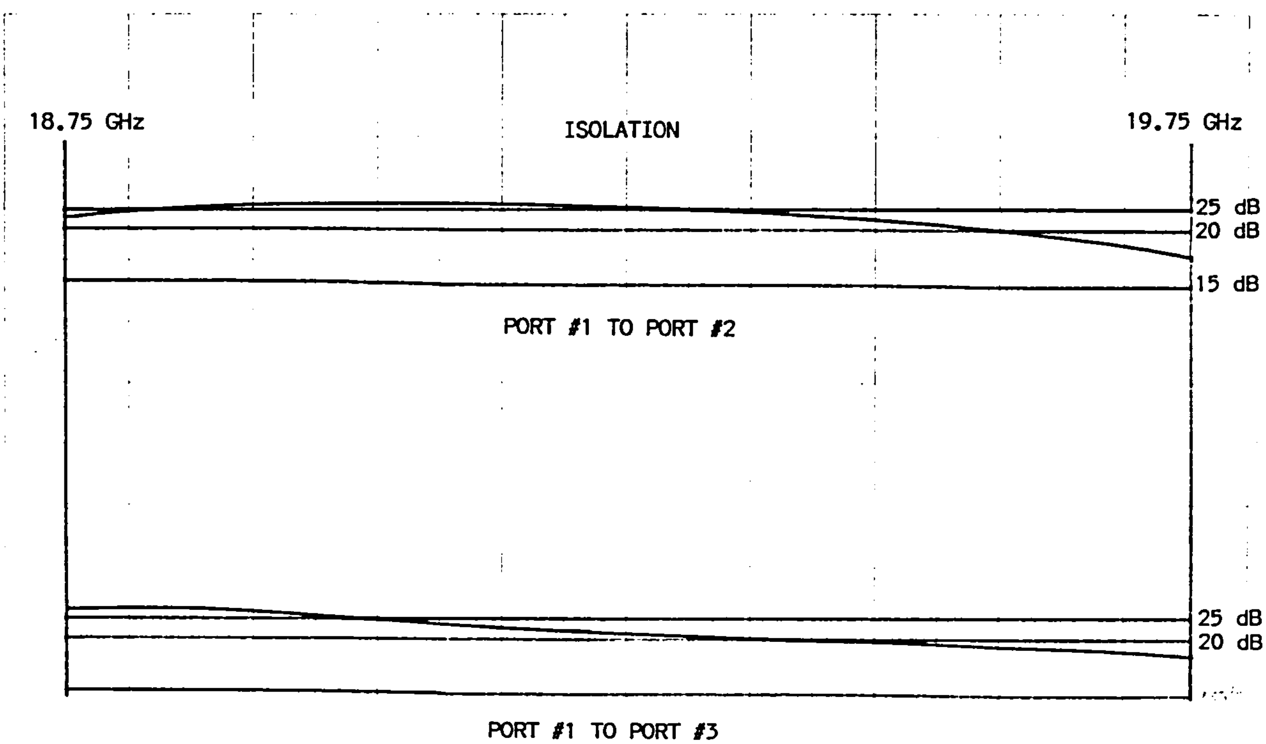

Figure 14. Isolation Swept Frequency Responses of Switch Serial No. 2

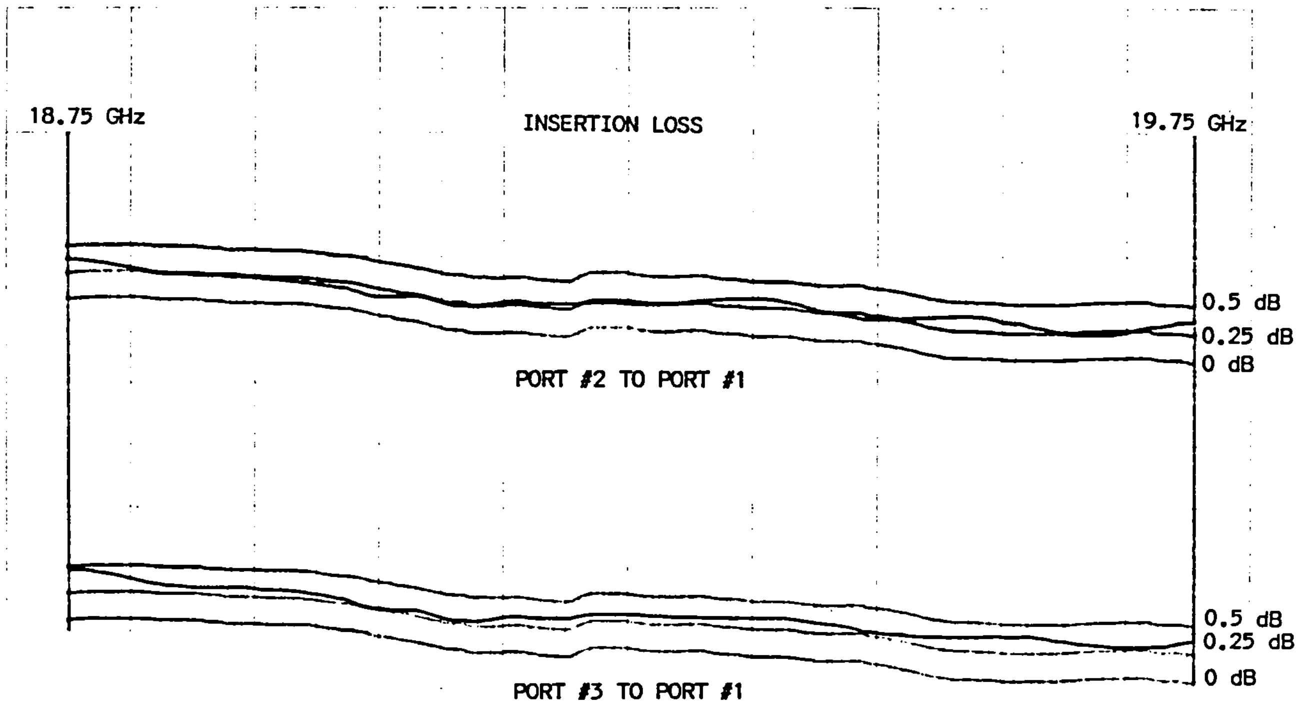

Figure 15. Insertion Loss Swept Frequency Responses of Switch Serial No. 2

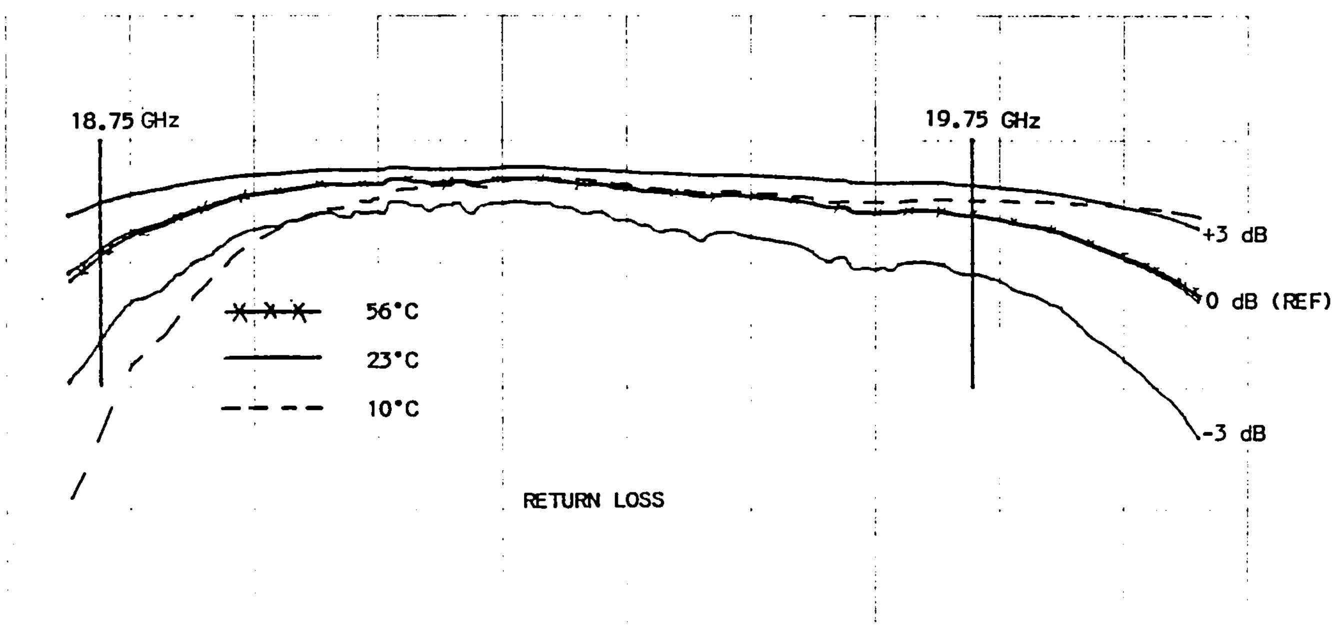

Figure 16. Thermal Performance of Switch Serial No. 2

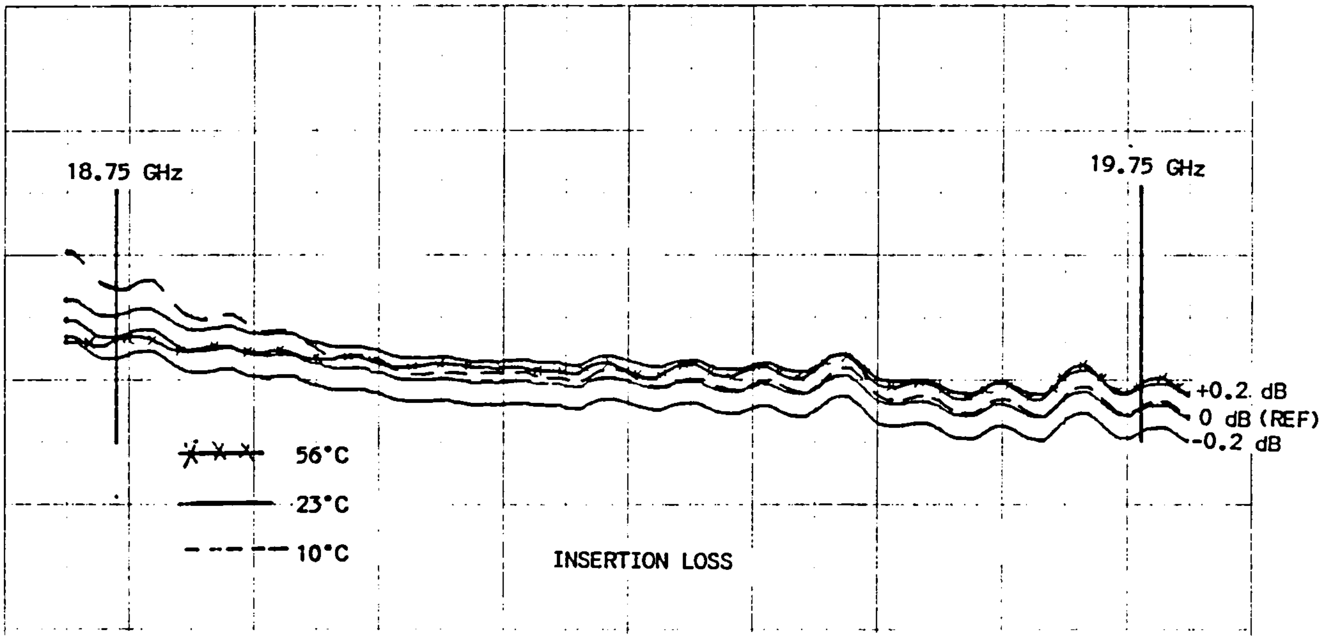

Figure 17. Thermal Performance of Switch Serial No. 2

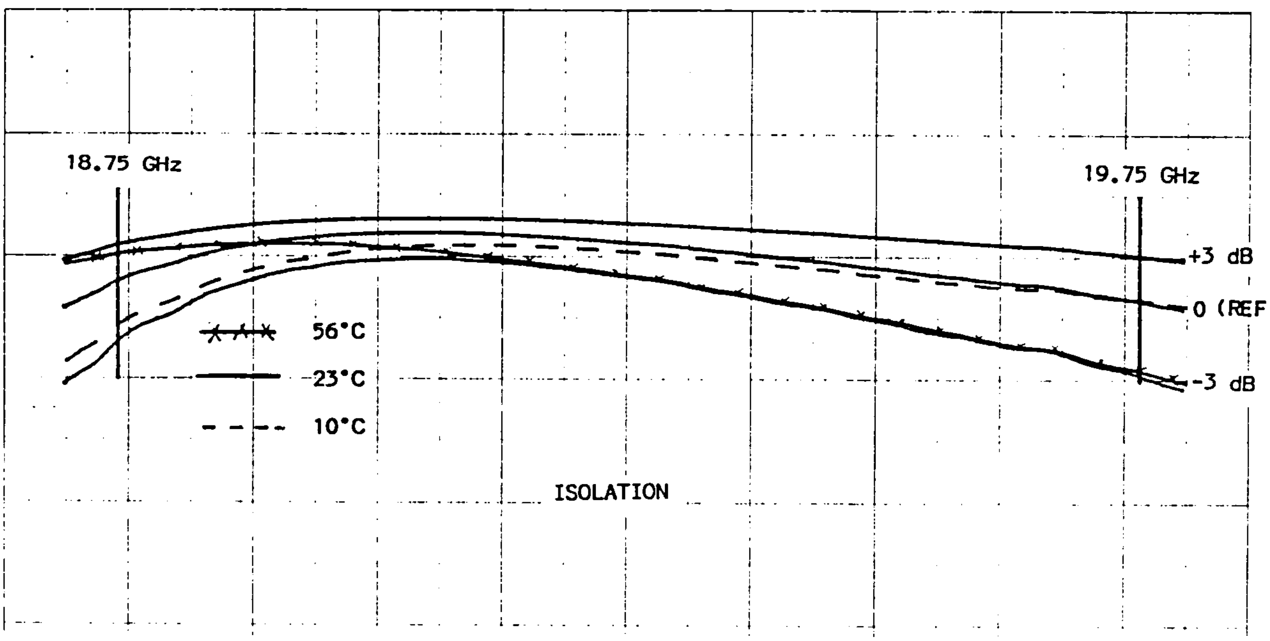

Figure 18. Thermal Performance of Switch Serial No. 2

A similar procedure was used during isolation and insertion loss tests. The swept frequency responses at 10°C and 56°C during the isolation and insertion loss tests were recorded after the swept frequency responses at room temperature were established as a reference. These responses at 10° and 56°C are shown as deviations from room temperature performance.

Switch serial number one was subjected to the specified levels of sine and random vibration test levels. Functional test data showing VSWR, isolation, and insertion loss before the vibration tests were shown in Figure 7. The switch was then subjected to the sine vibration test levels specified in the Statement of Work for three minutes along each of the three orthogonal axes. This test was followed by random vibration for three minutes along each of three axes. The sine and random test levels were monitored and recorded. The records of the sine and random input levels are shown for each test and each axis in Figures 19 through 24. After the vibration tests, the switch was subjected to the functional tests. The swept frequency test data of VSWR, isolation and insertion loss, shown in Figure 25 in comparison with the test data of Figure 7 before the vibration test, indicate that the switch is impervious to the specified vibration test levels.

The K-band switch outline is shown in Figure 26.

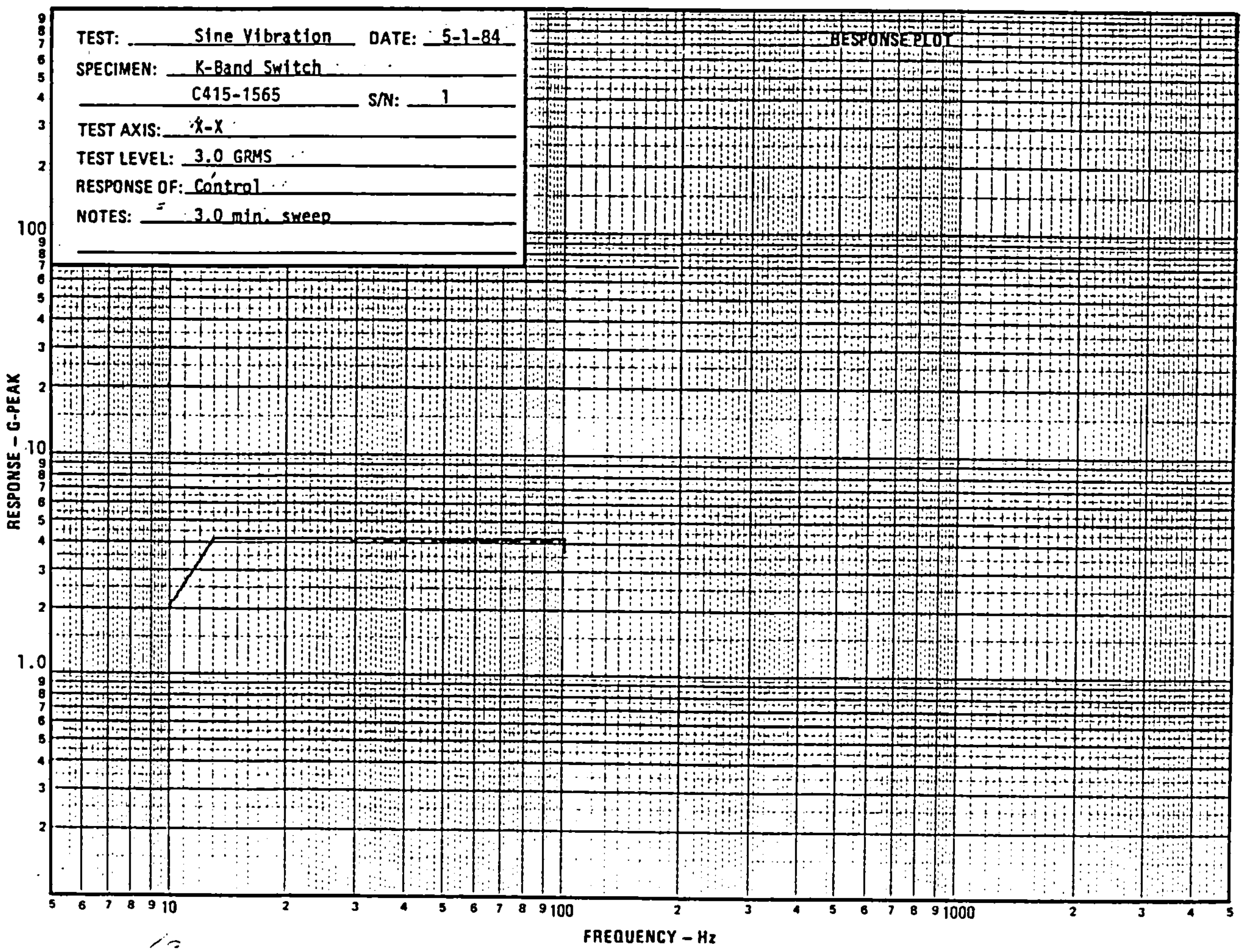

Figure 19. K-band Switch; Sine Vibration Test; Axis X-X

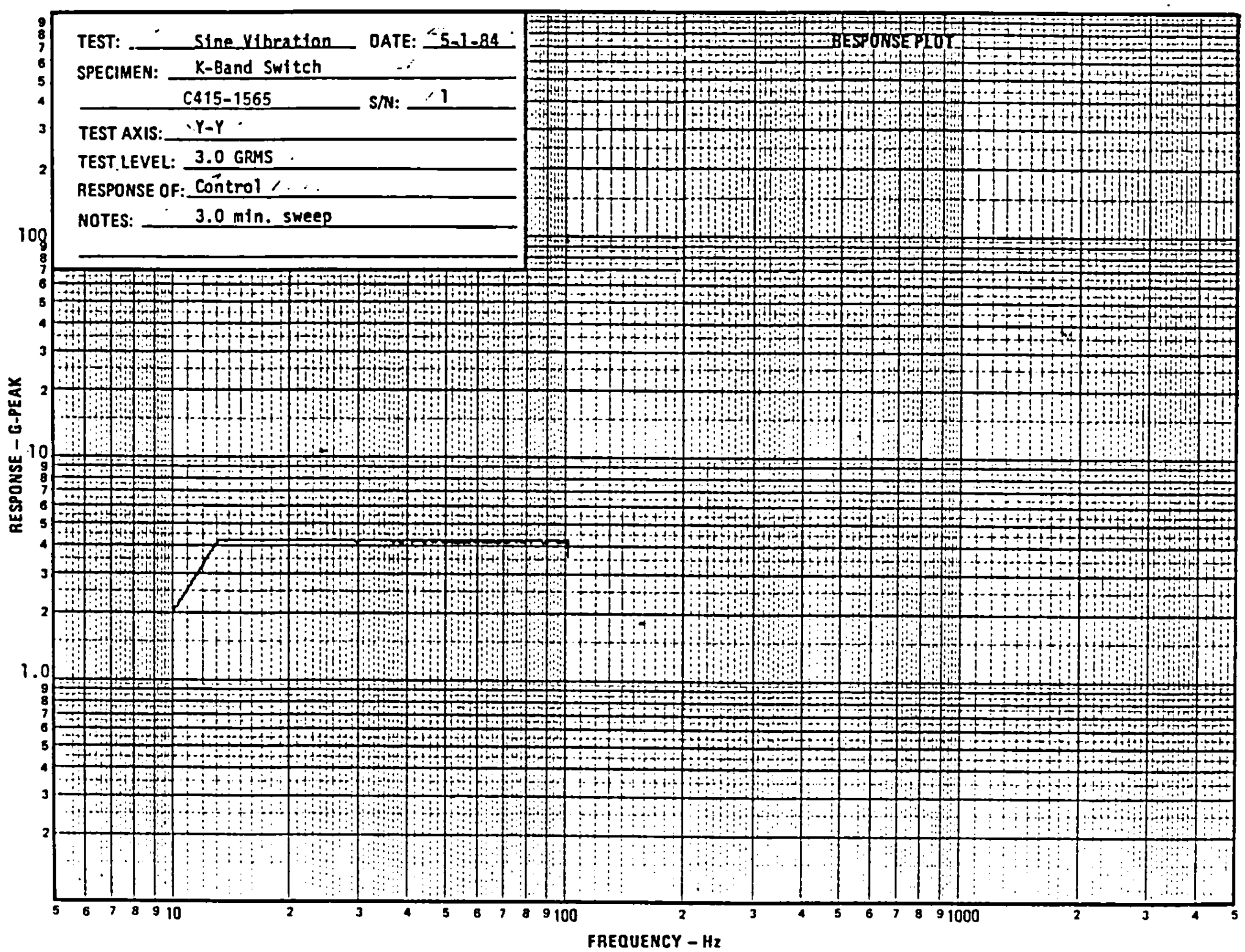

Figure 20. K-band Switch; Sine Vibration Test; Y-Y Axis

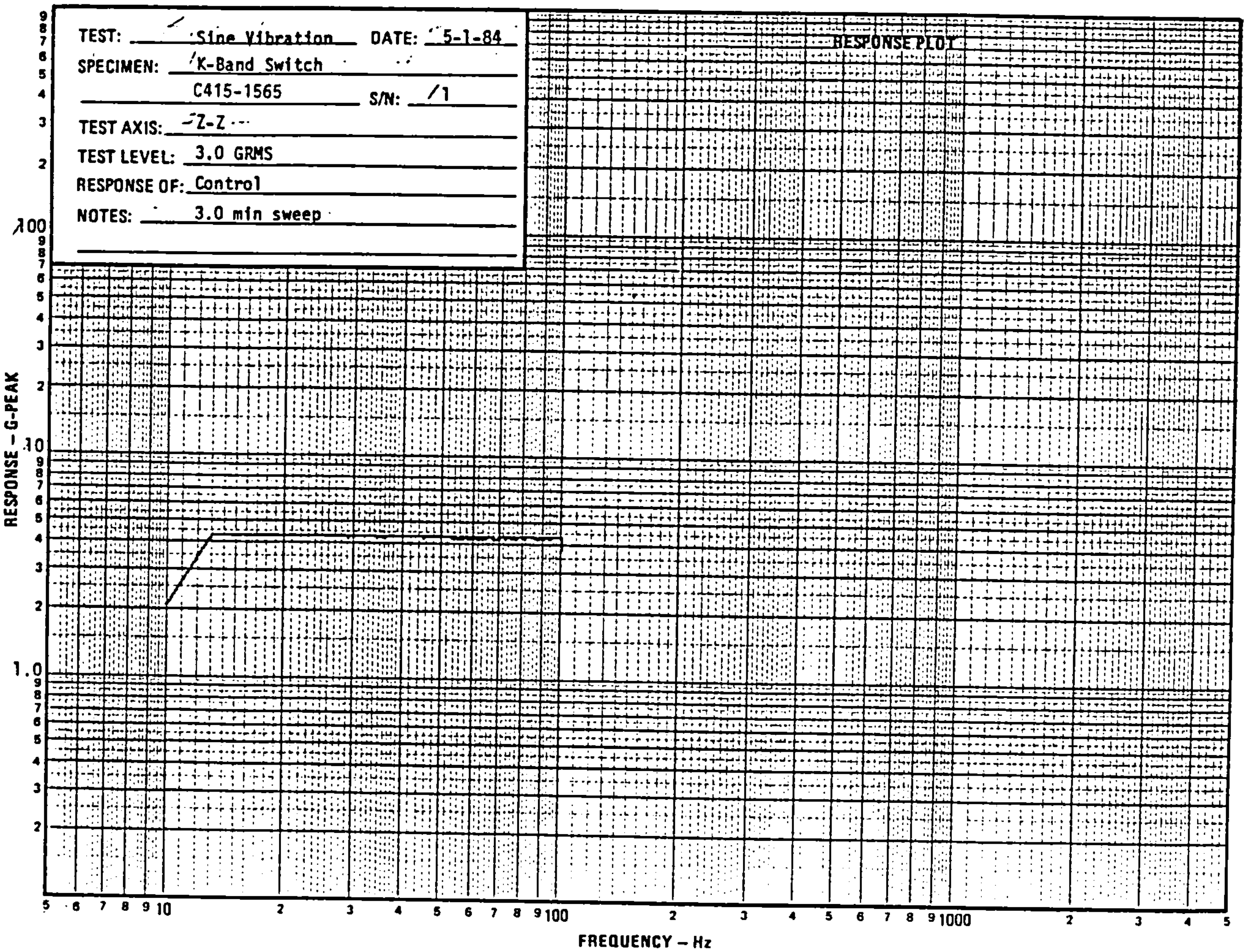

Figure 21. K-band Switch; SIne Vibration Test; Z-Z Axis

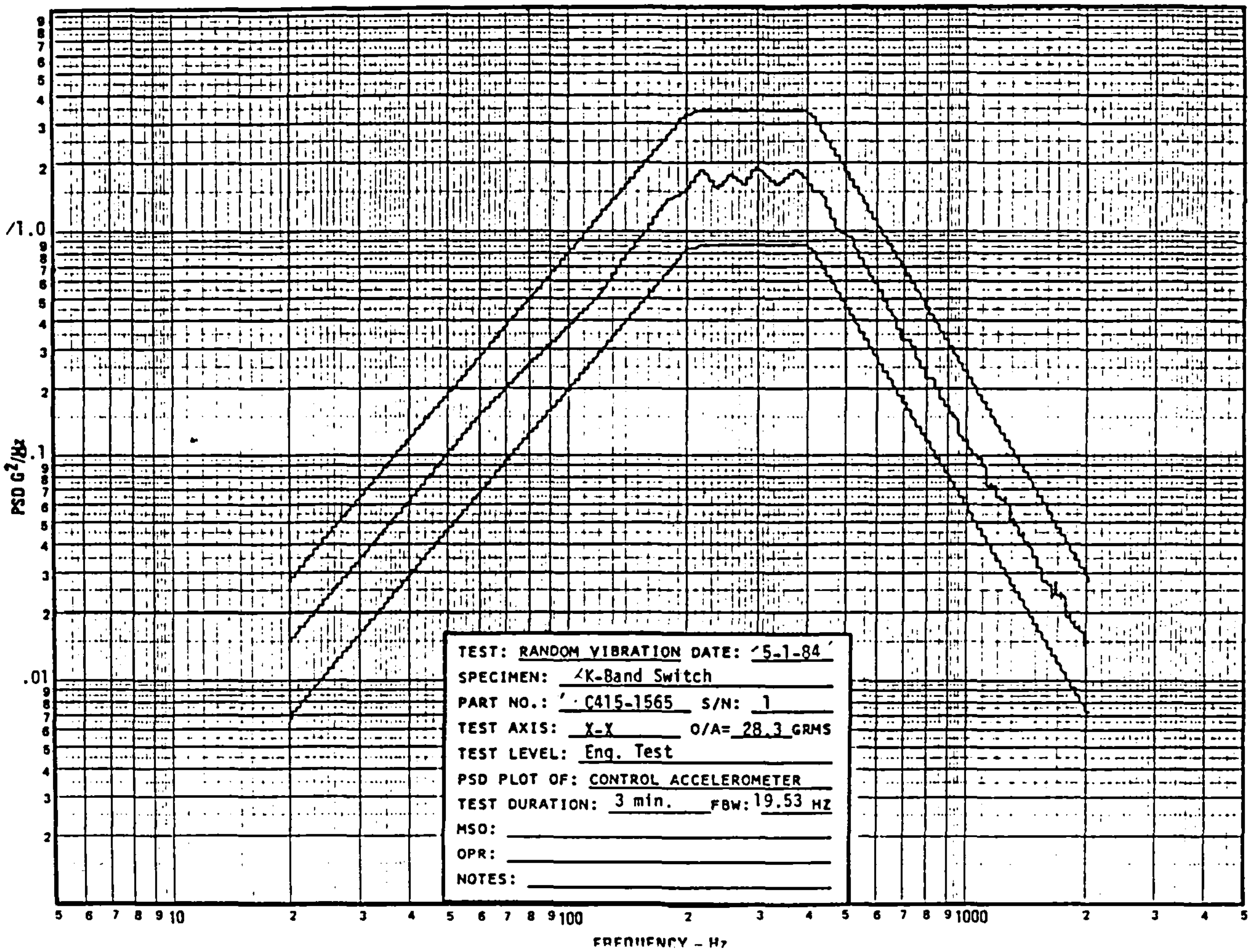

Figure 22. K-band Switch; Random Vibration Test; X-X Axis

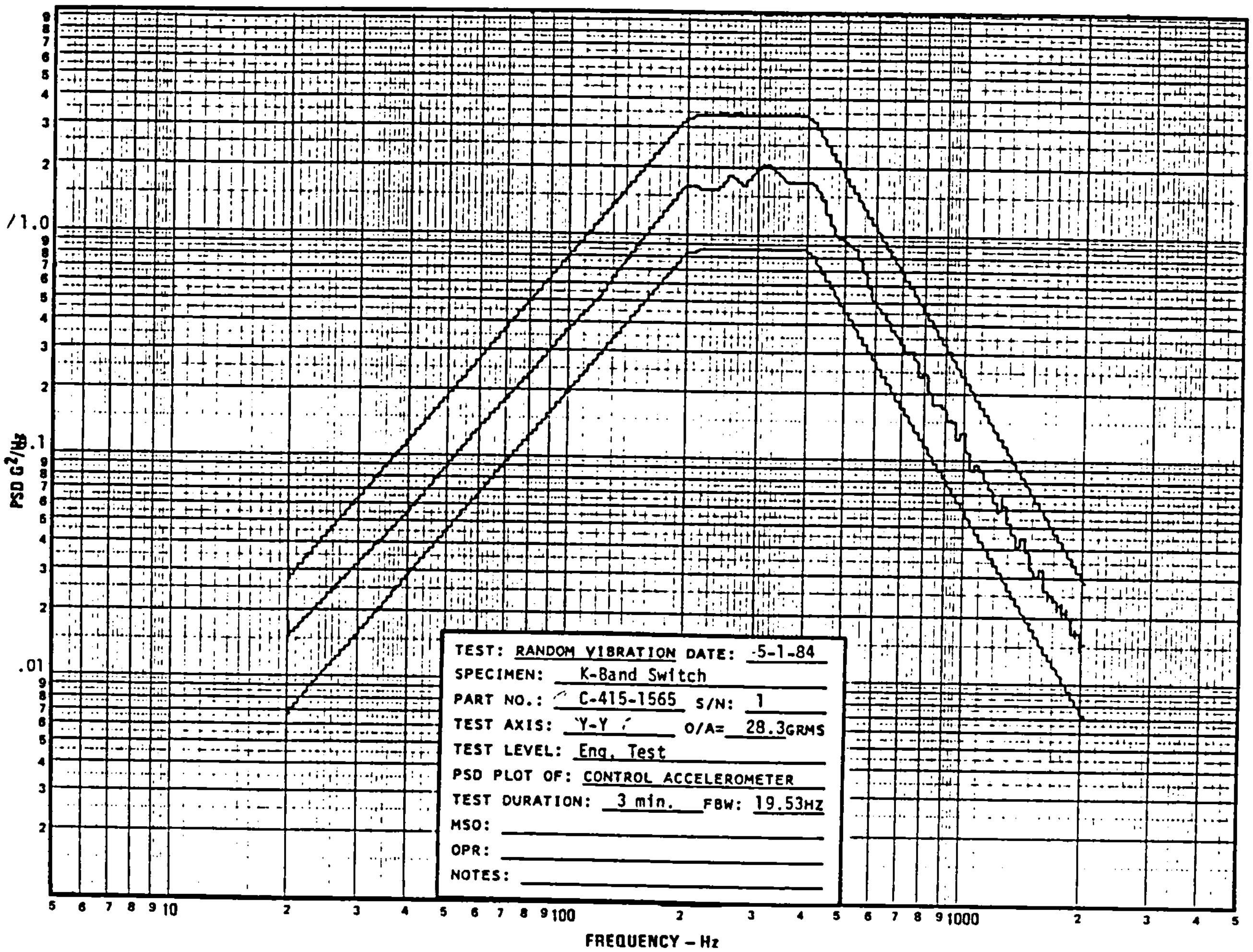

Figure 23. K-band Switch; Random Vibration Test; Y-Y Axis

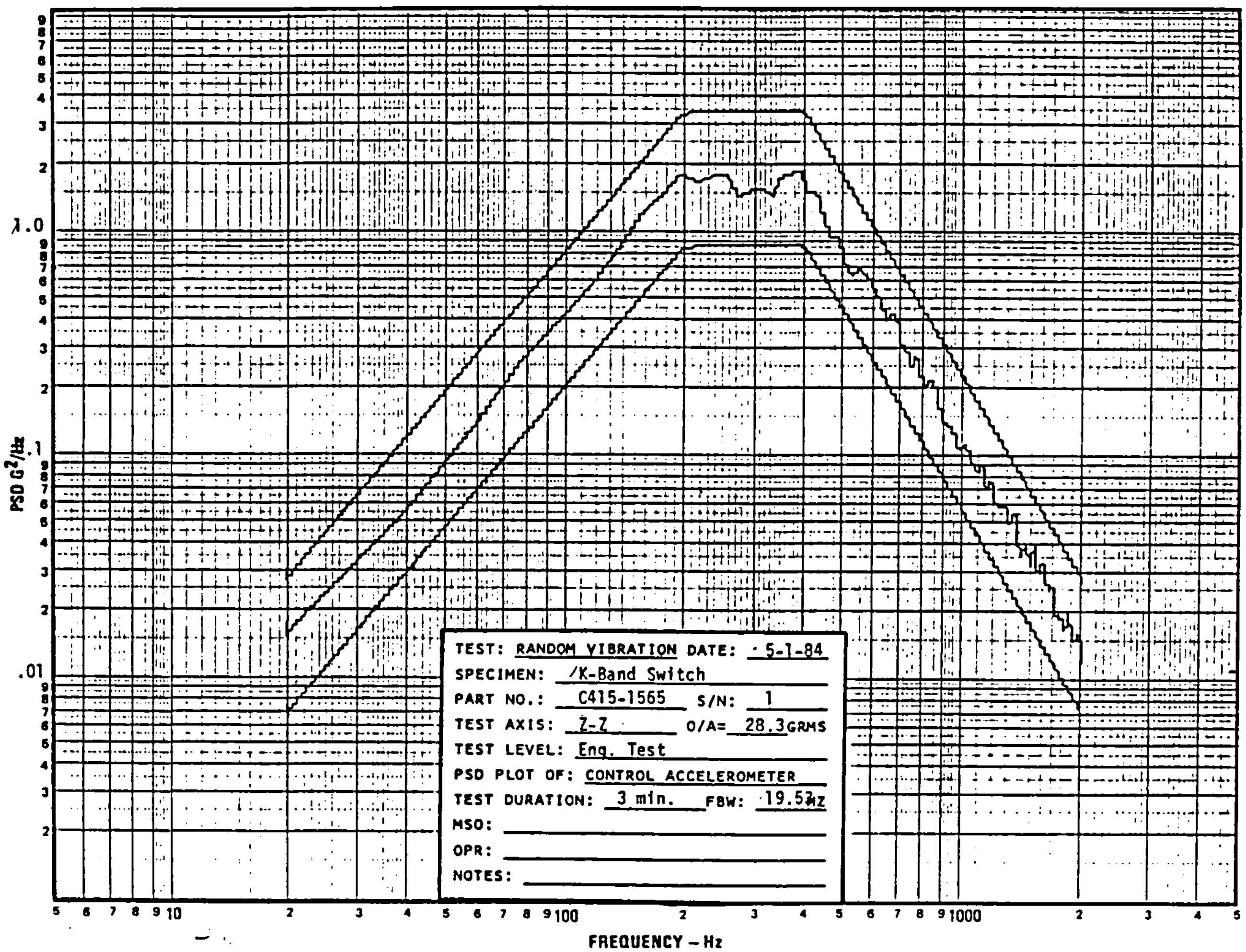

Figure 24. K-band Switch; Random Vibration Test; Z-Z Axis

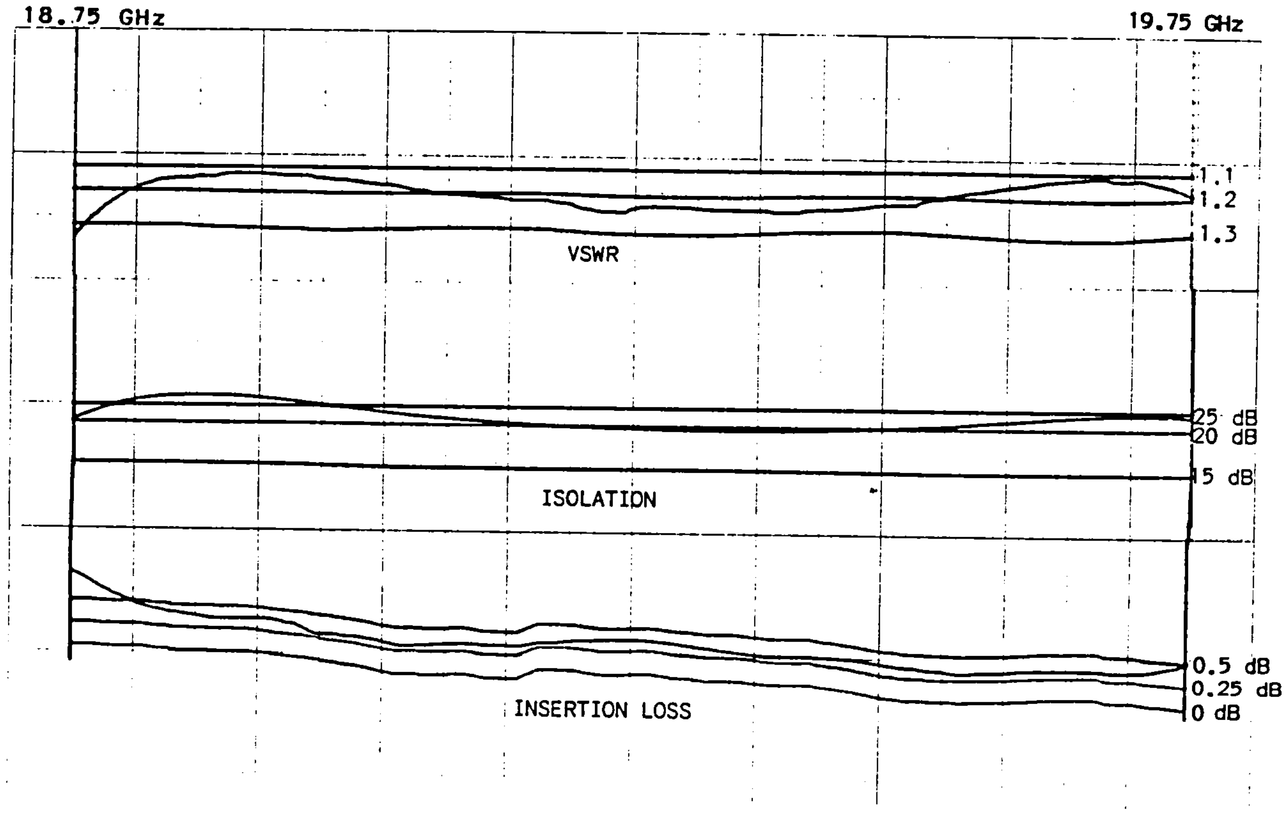

Figure 25. Swept Frequency Responses of Switch Serial No. 1
After Vibration Test

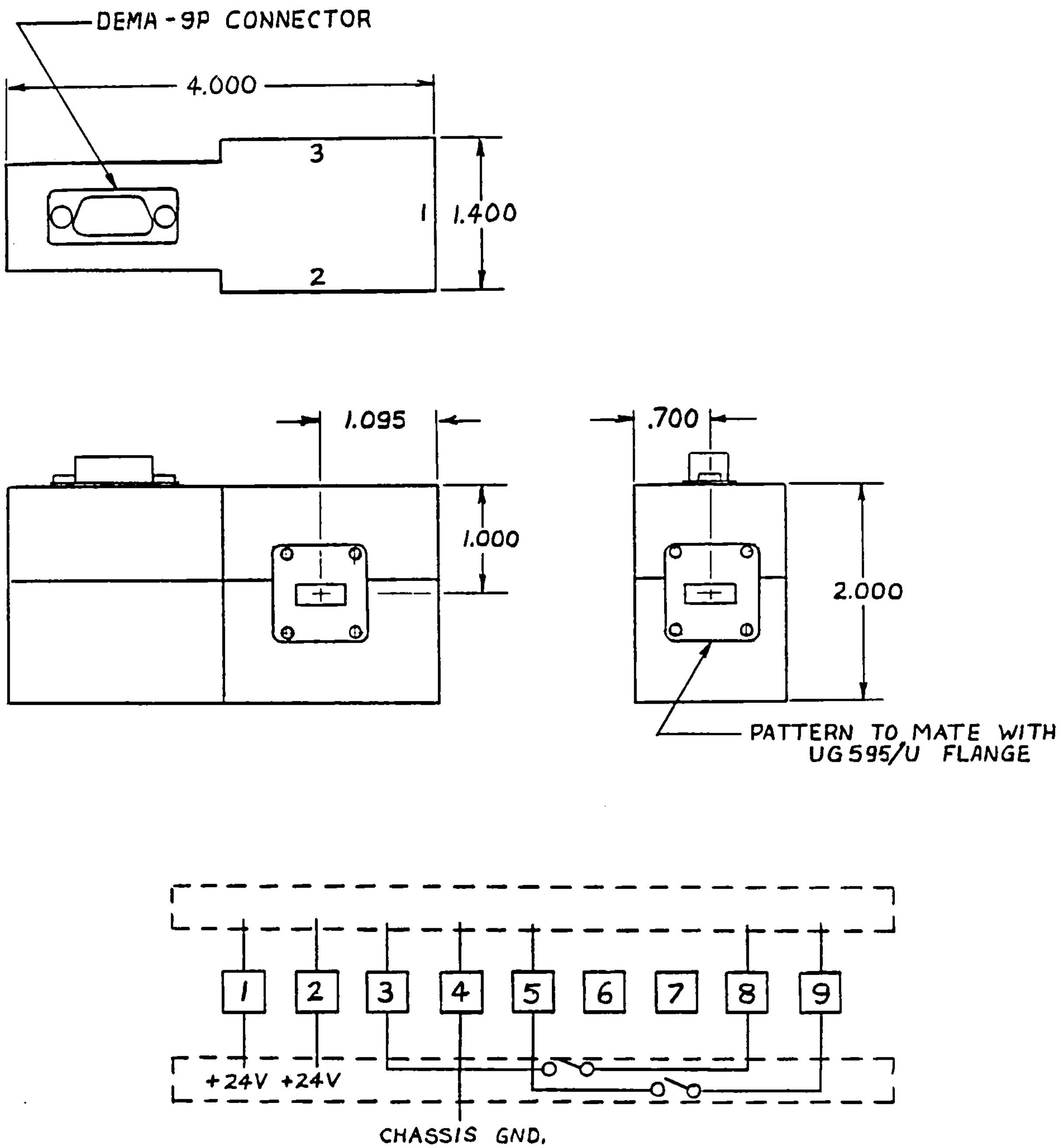

Figure 26. K-band Switch Outline

3. Ka-BAND SWITCH DEVELOPMENT

3.1 INTRODUCTION

The design approach for the Ka-band switches was finalized during the study and analysis phase of the development. Considering the moderate power handling requirements, available materials, and fabrication of critical components, the junction design with directly actuated ferrites and high speed switching capability was selected. The ferrite in this type junction is magnetically biased to circulation conditions and latched at its internal remanent magnetization level by a current pulse passing through a single-turn copper wire loop. The actuator loop is held in place in 0.005-inch diameter holes pierced through the ferrite by a laser beam.

In sharp contrast to the K-band switch development this task was significantly simpler. As noted in previous development, the component performance and the level of effort required to obtain an acceptable performance are strongly affected by the quality of the available ferrite materials. In the Ka-band case the ferrites with suitable physical properties for this frequency range simplified the design and optimization work and led to excellent switch performance.

3.2 JUNCTION DESIGN CONSIDERATION

The development of the Ka-band switching junction started with modifications of an existing circulator junction to provide optimum performance in the 27.5 to 30.0 GHz range. This modified junction provided the initial data for the design of the switching junction, and was used for the isolators with the Ka-band switches. It was also used in the detector assembly of the reflectometer test set. Performance measurements of ferrite junction components, especially the measurements of isolation, are effected by the reflections at the switch or circulator ports. To ensure accuracy of these measurements the test sets normally include special high quality waveguide loads and detector assemblies provided with attenuators and high quality circulators to minimize the reflections and measurements uncertainty. The swept frequency responses, isolation, VSWR, and insertion loss of the isolator junction are shown in Figure 27.

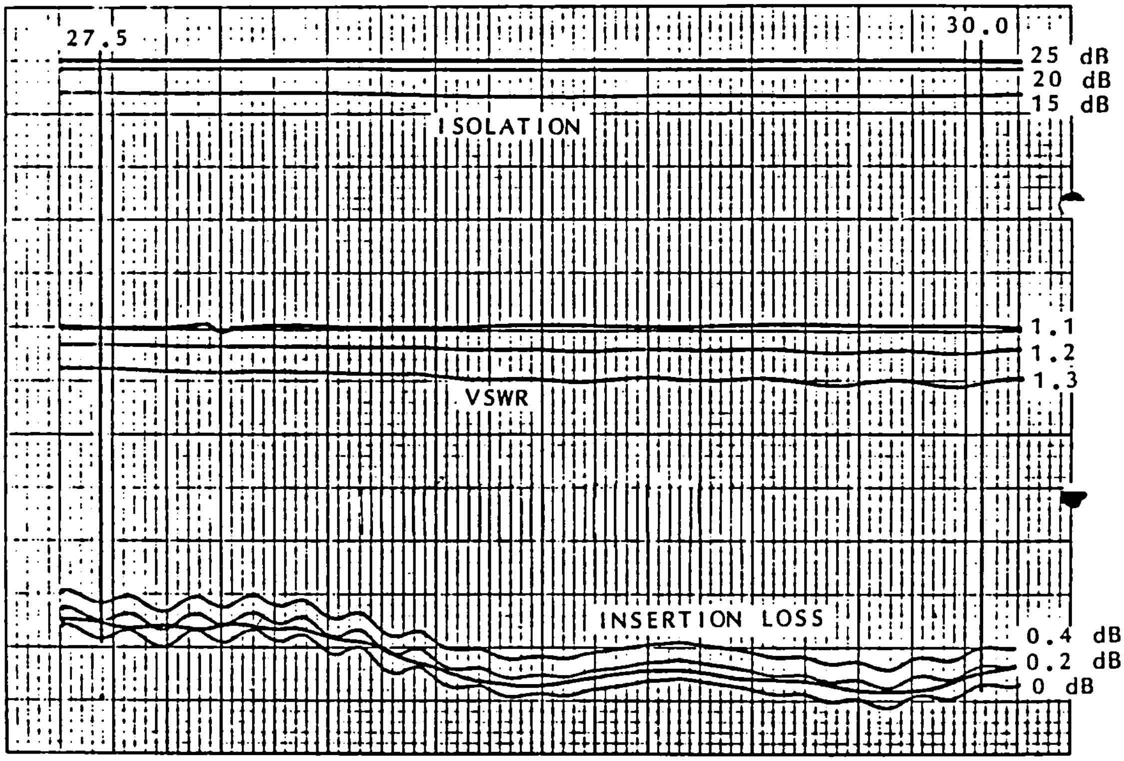

Figure 27. Swept Frequency Responses of Ka-Band Isolator

The switching junction ferrite design shown in Figure 28 starts with the data obtained from the circulator junction. The ferrite is increased to provide a return path for the internal magnetic flux. The innermost part of the junction ferrite provides the required volume to obtain circulation, but the increased ferrite volume, as a dielectric resonator, now supports a different set of propagation modes than were present in the smaller circulator ferrite. These new dielectric resonator modes determine the operating bandwidth of the switch; to obtain the required frequency response, the size of the ferrite is adjusted experimentally. In this particular case the initially

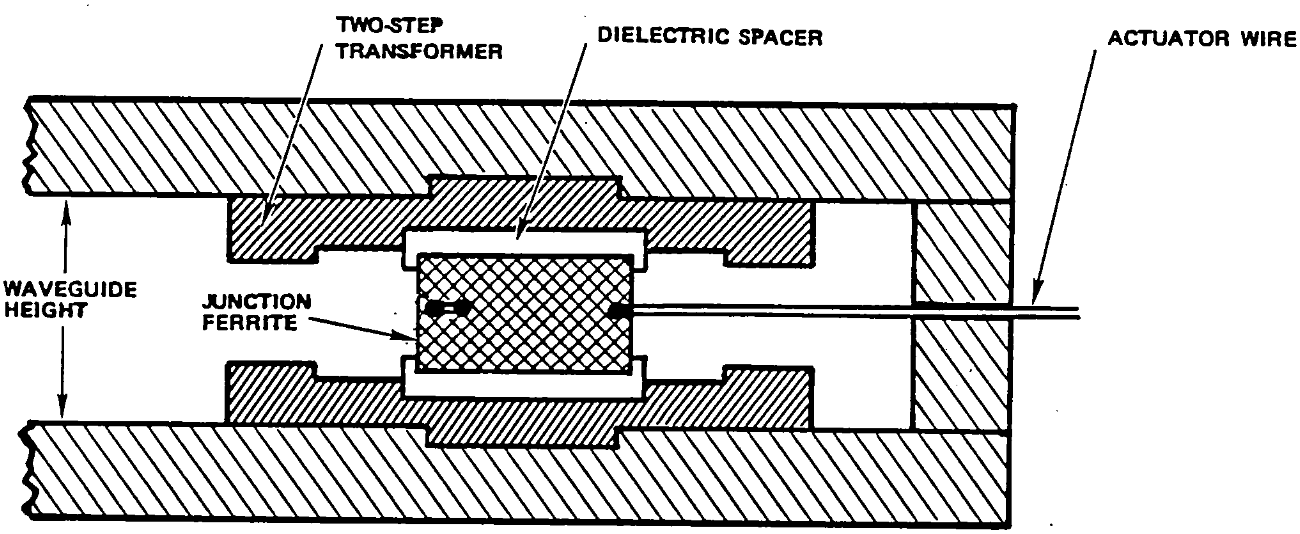

Figure 28. Switching Junction Configuration

calculated ferrite dimensions produced operating bandwidth at slightly higher frequencies, and the ferrite dimensions were increased to obtain the specified 27.5 to 30 GHz operating bandwidth. The junction is impedance-matched to the terminating waveguides with simple step transformation; the balance and amplitude of the ripples in the isolation and VSWR responses are obtained by adjusting the size of the dielectric spacers. The spacers electrically provide open-circuit at the faces of the junction ferrite, and structurally support and index the ferrite to the impedance step transformers. The transformers are, in turn, held in place in the geometrical center of the switch housing by a boss on the transformer and recess in the housing. This simple mechanical assembly ensures adequate protection for the junction under shock and vibration, and simplifies switch assembly by eliminating the need for epoxy bonding and high temperature cure.

As required, the switching junction is terminated to accept UG-595/U mating flanges of WR-28 waveguide; however, the junction may coincidentally also be terminated to accept WR-34 waveguide. This would not materially affect the switch performance, but because the WR-34 waveguide is larger and less lossy than WR-28, the performance could be improved from the present 0.4 dB to about 0.3 dB. The possibility for this optional design in either WR-34 or WR-28 waveguides exists only in the presently selected operating frequency range: below 27 GHz, only

WR-34 could be used, while above 30 GHz, WR-28 waveguide would be the proper choice. In the present operating band (27.5 to 30 GHz), the switch junction size and immediate area of the switch housing in the junction region are coincidentally such that the junction may be terminated with either waveguide. The slight advantage, as far as the insertion loss of the larger WR-34 waveguide is concerned, arises from the fact that the 27.5 to 30 GHz range falls nearly in the center of the 22 to 33 GHz waveguide operating band (far from cutoff, where its loss decreases), while the same switch range falls at the low frequency end of the WR-28 waveguide, where the waveguide loss is increasing. This coincidence was noticed during the breadboard development of the switching junction and the switch was evaluated in both waveguide configurations.

The Ka-band switches are provided with two isolators at the switch input ports. The isolator/switch assembly shown in Figure 29 also includes a switch actuator and connecting cables. Figures 30, 31, and 32 show the components of the assembly; the Ka-band switch, actuator and the Ka-band isolator, respectively.

The Ka-band switch is a single-pole, double-throw latching type. The isolators provided with the switches have standard TRW circulator junctions installed in special redesigned housings to provide adequate separation between the switching junction and the strong magnetic fields generated by the permanent magnets, used to bias the isolator junctions. The unused ports of the isolators are terminated in built-in waveguide loads.

The waveguide switch by itself is a single-pole, double-throw switch, and the RF power may be switched from any of its three ports as an input to any of the two remaining ports as an output. But once the isolators with fixed circulation directions are added, the operation of the isolator/switch assembly is limited to a specified mode, determined by the circulation direction of the isolators. In the present configuration, the isolator/switch assembly is intended to switch the RF power from one of the two ports, marked 2 and 3, to the common output

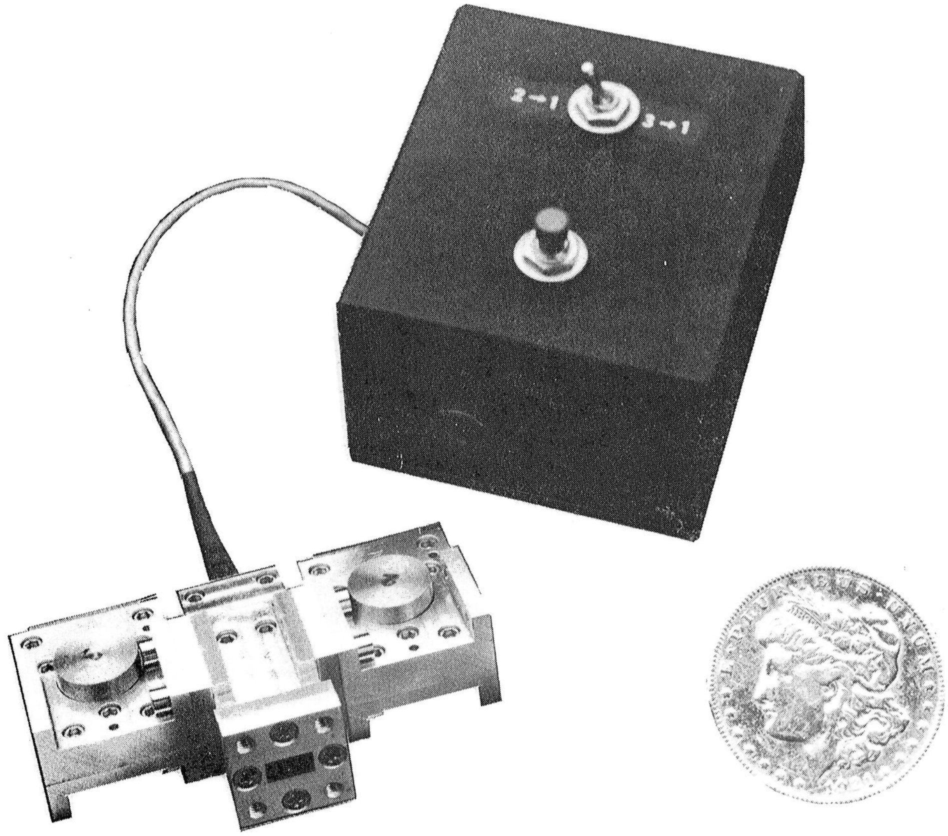

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Figure 29. Ka-Band Isolator/Switch Assembly

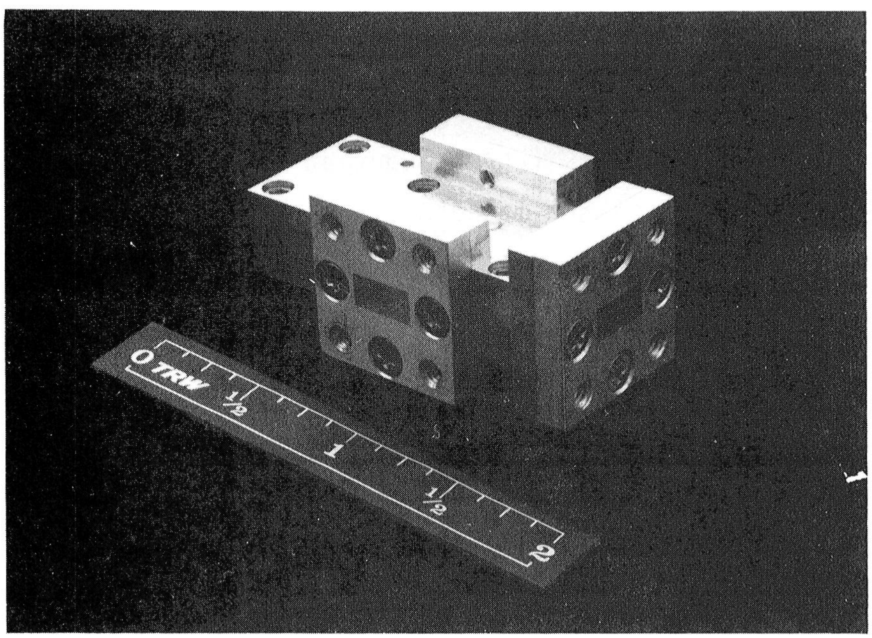

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Figure 30. Ka-Band High Speed Waveguide Ferrite Switch

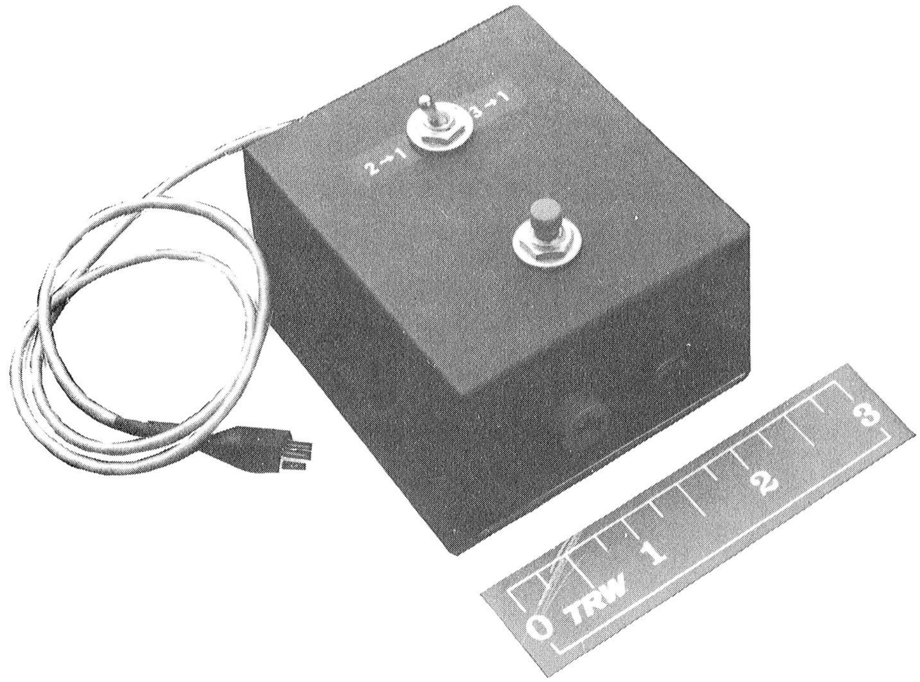

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Figure 31. Switch Actuator

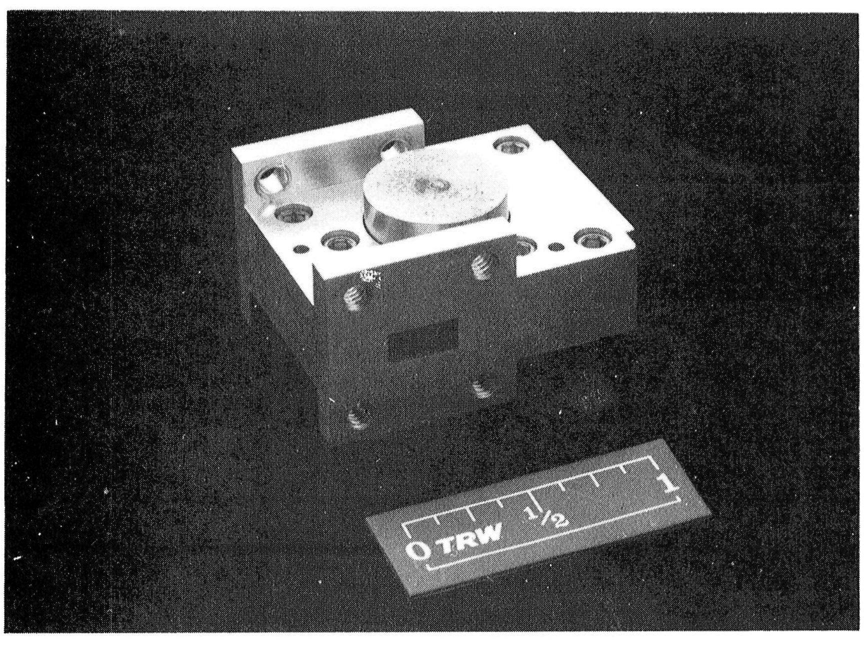

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Figure 32. Ka-Band Waveguide Ferrite Isolator

port, marked 1. This arrangement may be used, for example, to switch one of two redundant transmitters to an antenna.

The isolator/switch assembly provides well in excess of 40 dB isolation between the output and the input; but, because of the presence of the isolators, the isolation from port 1 to port 3 must be measured with the switch latched to provide transmission from port 3 to port 1. Similarly, the isolation from port 1 to port 2 is measured with the junction switched to provide low insertion loss path from port 2 to port 1.

The performance data under room temperature conditions, thermal performance, and the results before and after vibration tests are shown and discussed in Section 3.5.

3.3 INSTRUMENTATION AND TEST SETUP

The test setup for the development and final performance tests of the Ka-band isolators and switch was prepared and calibrated as described in Section 2.6 describing the K-band switch development.

3.4 SWITCH ACTUATOR CIRCUIT

The Ka-band waveguide ferrite isolator/switch is actuated and latched to transmit the RF energy from port 2 to 1 or from port 3 to 1 by a current pulse with proper polarity through the single-turn wire loop in the switching junction ferrite. The connection to the remote control switch, or relay, is provided by a polarized two-pin connector at the switch housing. The delivered isolator/switches are equipped with simple capacitor discharge control units and connecting cables. The switch control unit consists of a housing; momentary pushbutton switch; double-pole, double-throw toggle switch; a socket for connection to the 24 Vdc power supply; and a 188 μF capacitor, trickle-charged through a 5 KΩ resistor. The double-pole, double-throw switch position determines the polarity of the current pulse, and the pushbutton switch discharges the capacitor through the switch actuator loop, switching the direction of the RF power flow and latching the switch.

3.5 RESULTS AND TEST DATA

The isolator/switch tests were performed in accordance with the test matrix shown in Table 3. Serial number two was vibration-tested, both sine and random, while serial number three was temperature-tested.

Figures 33, 34, and 35 are room temperature swept frequency responses of isolator/switch serial number three showing VSWR, isolation, and insertion loss, respectively. VSWR is about 1.1:1, or better, over ~85 percent of the operating band, decreasing to about 1.23:1 at the low frequency end. Isolation between the output port 1 and input ports 2 and 3 of 43 dB exceeds the expected 35 dB requirements and 40 dB development objective. Insertion loss through two junctions (switch and isolators) varies from about 0.2 dB to 0.45 dB at the edges of the 27.5 to 30 GHz operating band. The swept frequency responses of the Ka-band waveguide switch are shown in Figure 36. The thermal performance of the isolator/switch serial number three is shown in Figures 37, 38, and 39.

The thermal test was initiated by subjecting the isolator/switch assembly to the survival temperature of -40°C for three hours. The temperature was then returned to room temperature (23°C) and the isolator/switch was connected for the return loss test. The test data was taken at the input ports 2 and 3 at room temperature (23°C) showing no measurable deviations from the original acceptance test data. The temperature was increased to 56°C, stabilized for one hour, and the swept frequency response recorded. Then the temperature was lowered to 10°C, stabilized, and the swept frequency response recorded. The temperature of the test chamber was then returned to room temperature level and the initial reference levels were verified. The same procedure was then repeated at the other input port. The swept frequency responses of the isolator switch during the thermal test are shown in Figure 37.

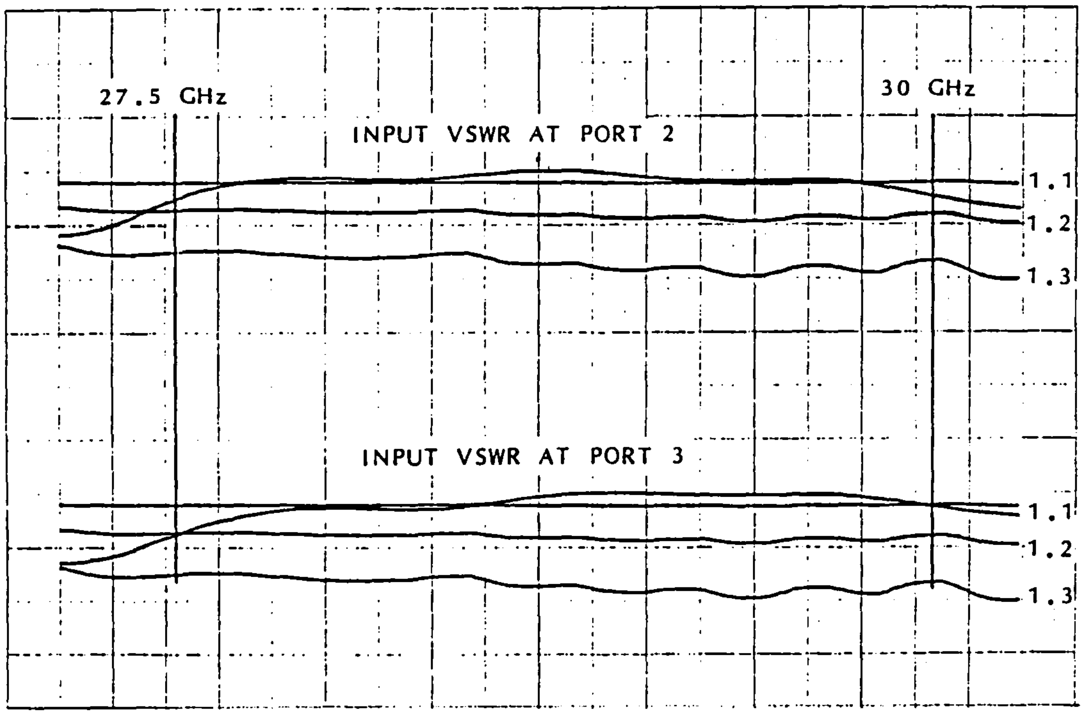

Figure 33. Performance of Ka-Band Isolator/Switch Serial No. 3

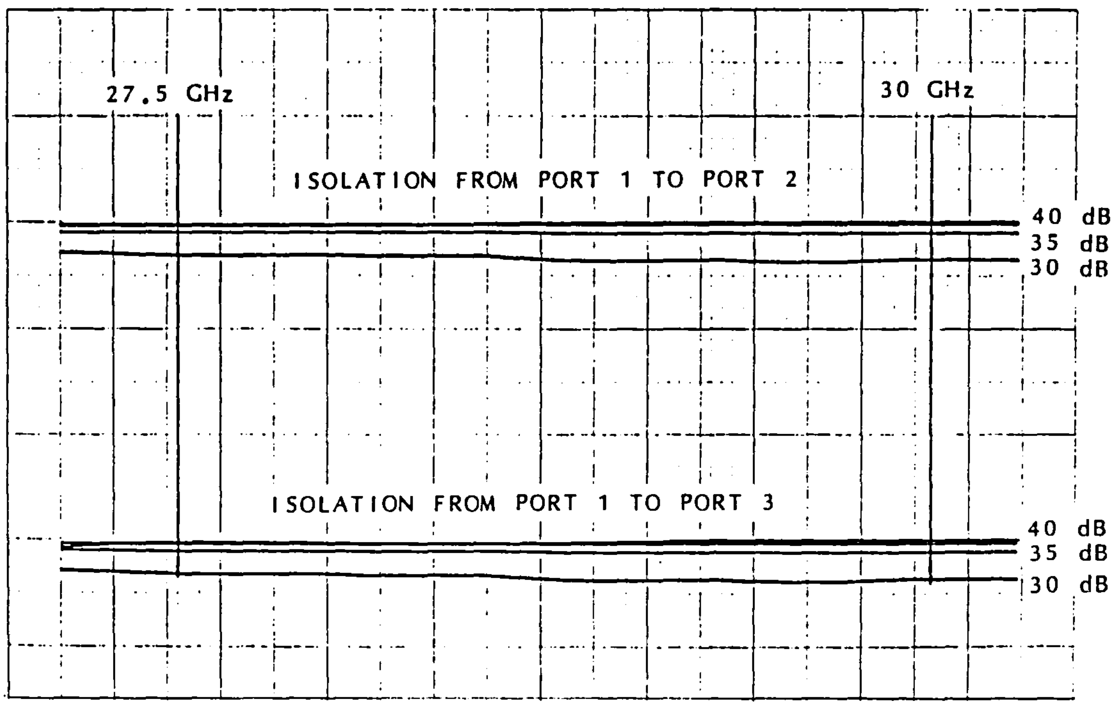

Figure 34. Performance of Ka-Band Isolator/Switch Serial No.3

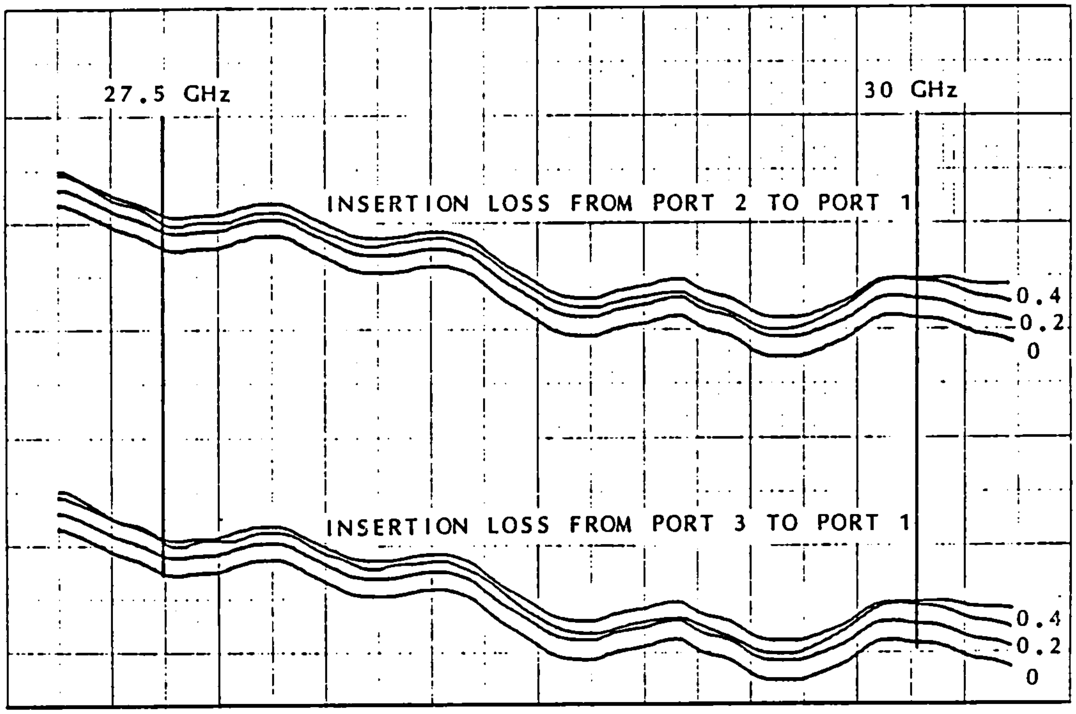

Figure 35. Performance of Ka-Band Isolator/Switch Serial No. 3

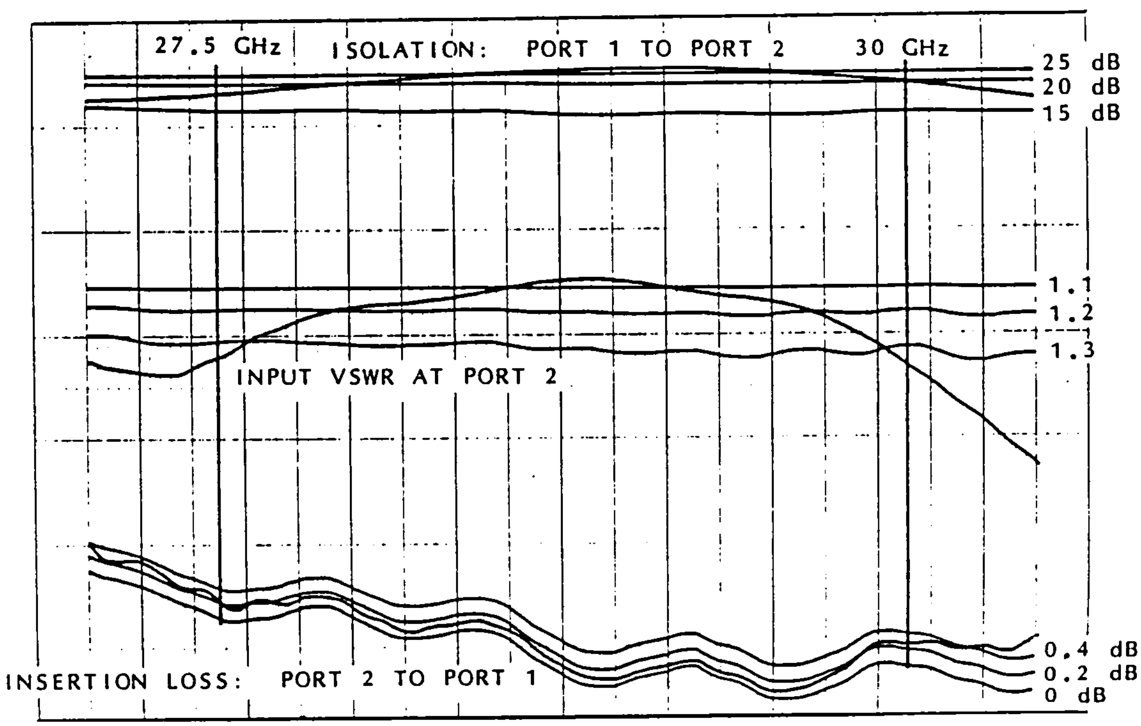

Figure 36. Swept Frequency Responses of Ka-Band Waveguide Switch

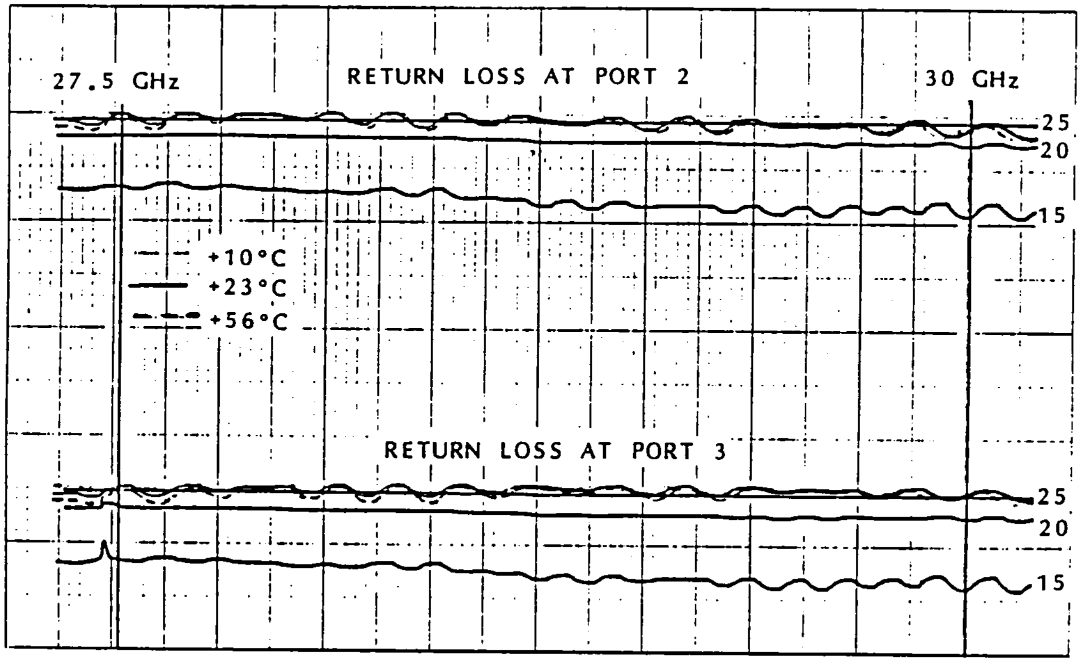

Figure 37. Thermal Performance of Ka-Band Isolator/Switch Serial No. 3

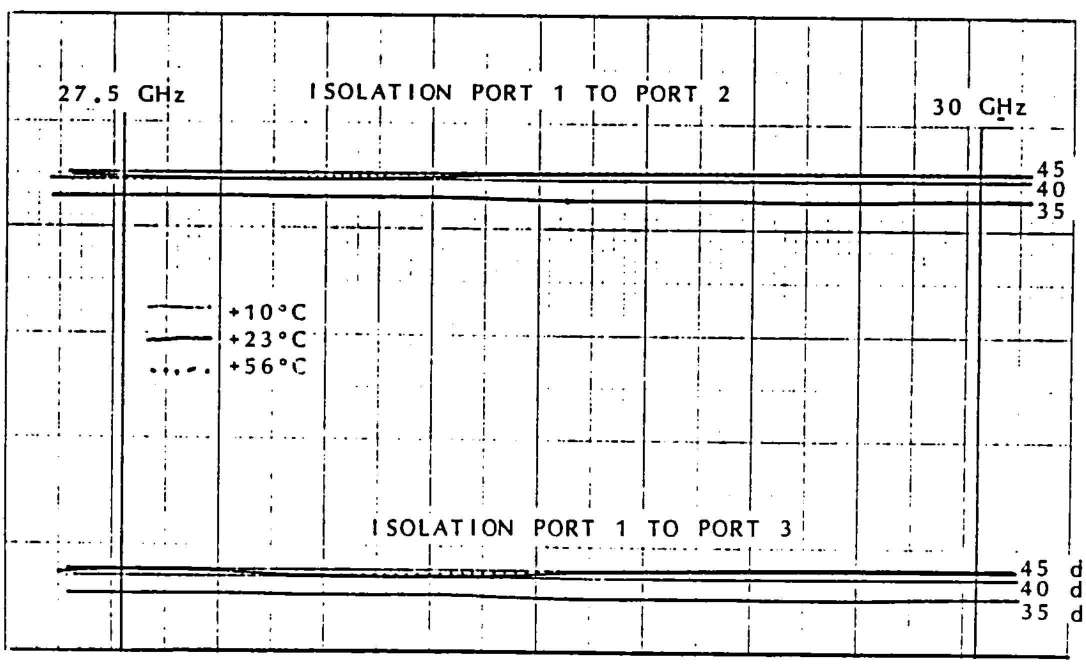

Figure 38. Thermal Performance of Ka-Band Isolator/Switch Serial No. 3

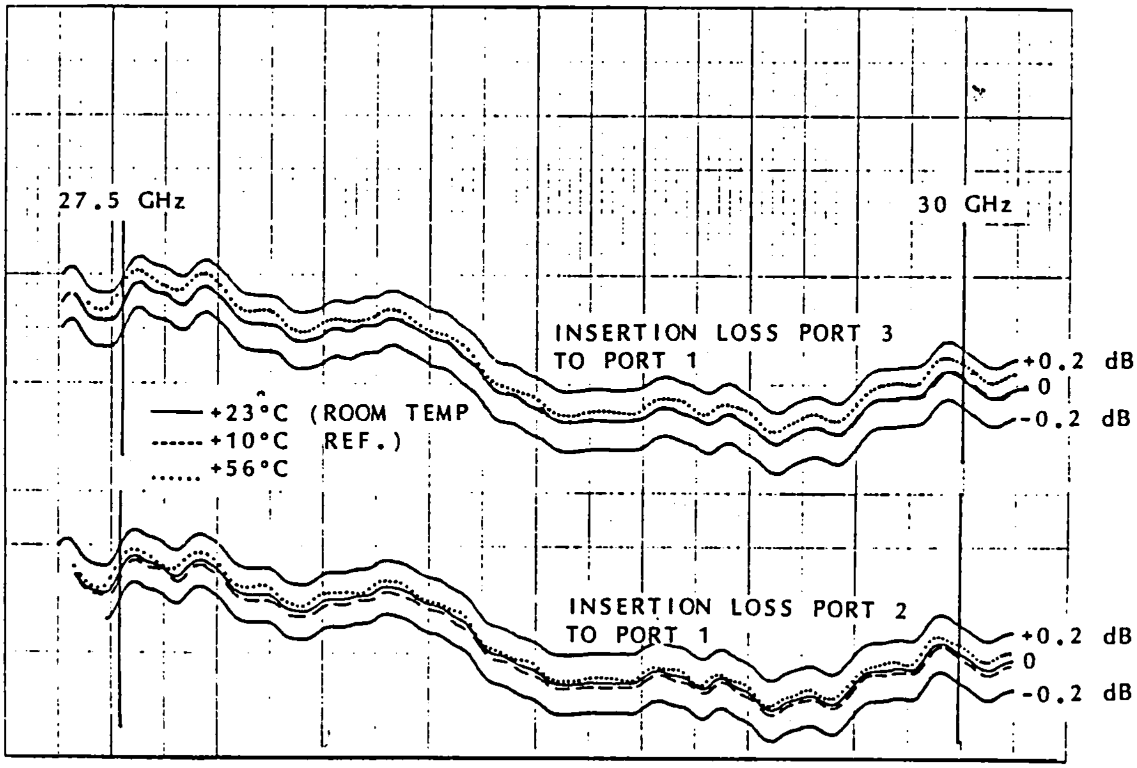

Figure 39. Thermal Performance of Ka-Band Isolator/Switch Serial No. 3

The isolation from output port 1 to input ports 2 and 3 was measured with the switch actuated to provide low loss transmission from port 2 and port 1 during the isolation test from port 1 to port 2 and similarly from port 3 to port 1 during the isolation test from port 1 to port 3. The swept frequency responses, recorded at room temperature (23°C), 56°C, and 10°C are shown in Figure 38.

The insertion loss from input ports 2 and 3 to output port 1 was referenced for better clarity of the test data to the insertion loss level at room temperature. The performance at 10 and 56°C was recorded after the swept frequency response at room temperature (23°C) was established as a zero reference and ±0.2 dB limits. The swept responses at 10° and 56°C are shown as deviations from room temperature performance in Figure 39.

The Statement of Work specified that the sine and random vibration inputs be applied simultaneously for three minutes in each of three orthogonal axes. It should be noted that this method was discontinued several years ago, and the current practice is to perform the sine and random vibration tests as two separate tests. The switch serial number 2 was first subjected to the sine vibration test input levels specified in the Statement of Work (3 G rms) for three minutes along each of the three orthogonal axes. This test was followed by the random vibration for three minutes along each of the three axes. The random vibration level of 28.3 G rms was monitored and recorded. The records of the sine and random vibration input levels are shown for each test and each axis in Figures 40 through 45.

After the vibration tests, the switch was subjected to functional tests. The swept frequency test data of VSWR, isolation, and insertion loss before and after the vibration test shown in Figures 46 and 47 indicates that the switch is impervious to the specified vibration test levels.

The protection from damaging thermal or vibration stresses is provided in all TRW ferrite junction components through a highly effective, yet very simple structural design. In the junction designs where the junction components are bonded with epoxy and rigidly mounted between the broad walls of the waveguide housing, the large difference of the coefficients of thermal expansion between the ferrite and the aluminum or copper alloy housing results in compressive stresses at low temperatures and tensile stresses at high temperatures. Also during the random vibration, especially at input levels exceeding 20 G rms, the

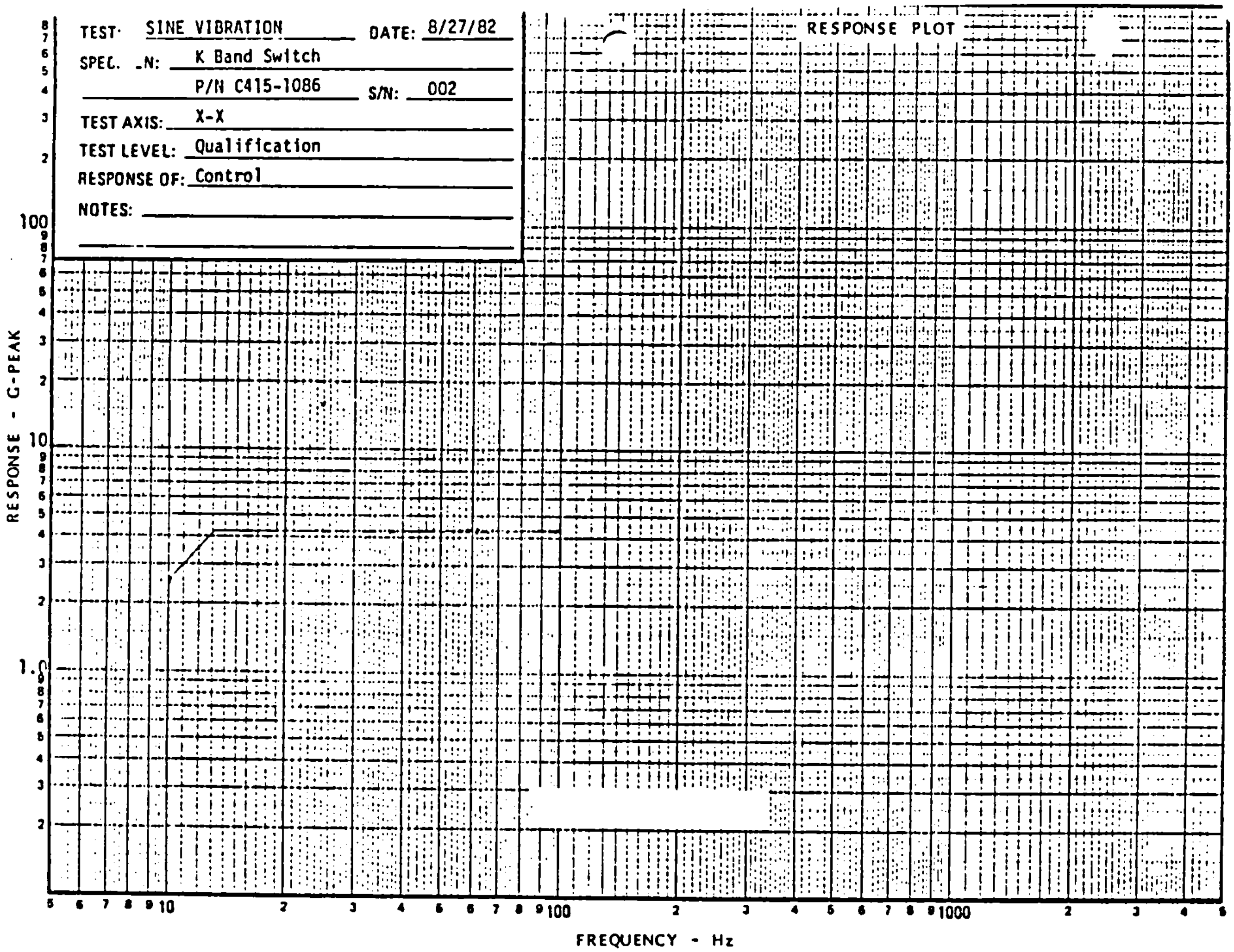

Figure 40. K-Band Switch; Sine Vibration Test; Axis X-X

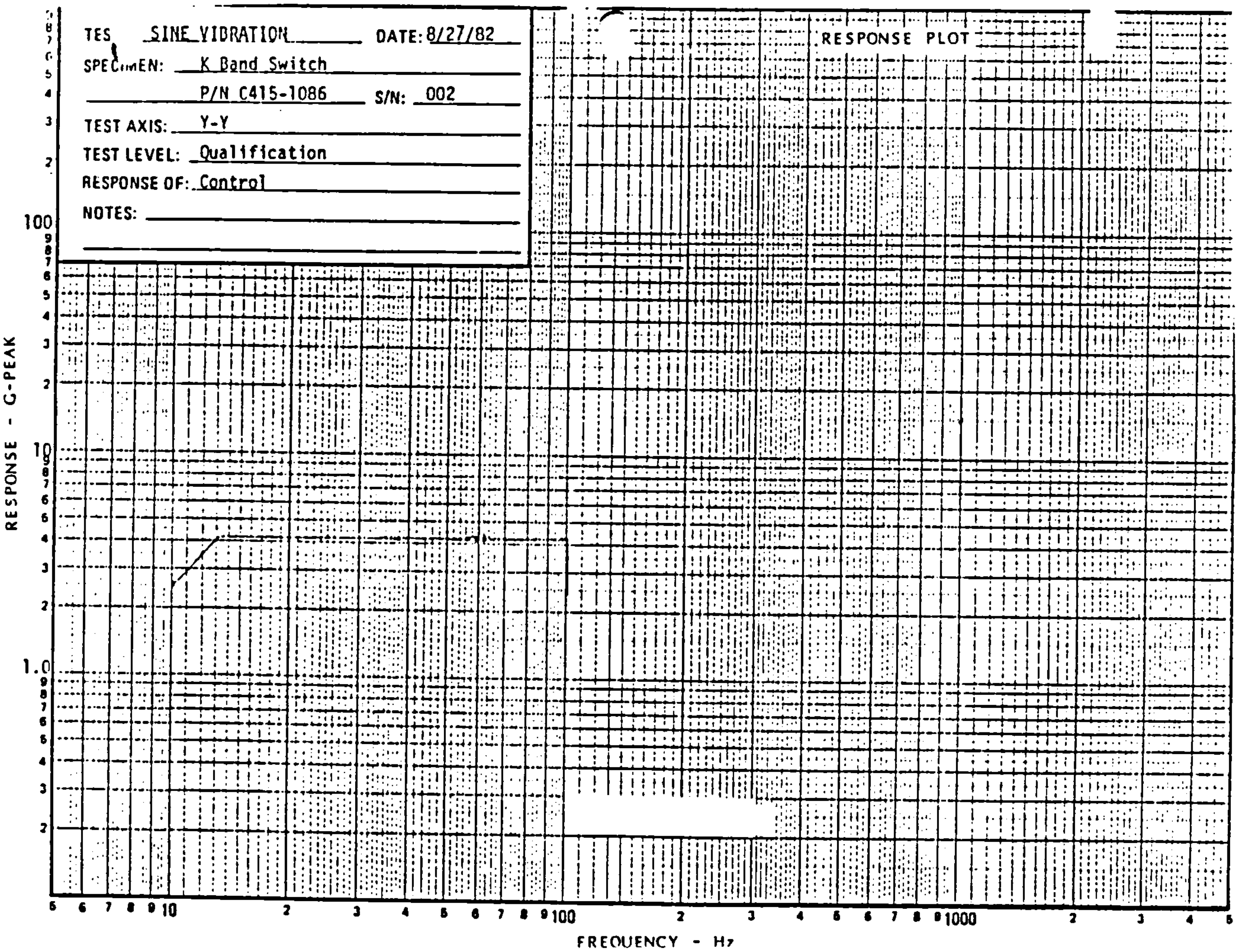

Figure 41. K-Band Switch; Sine Vibration Test; Axis Y-Y

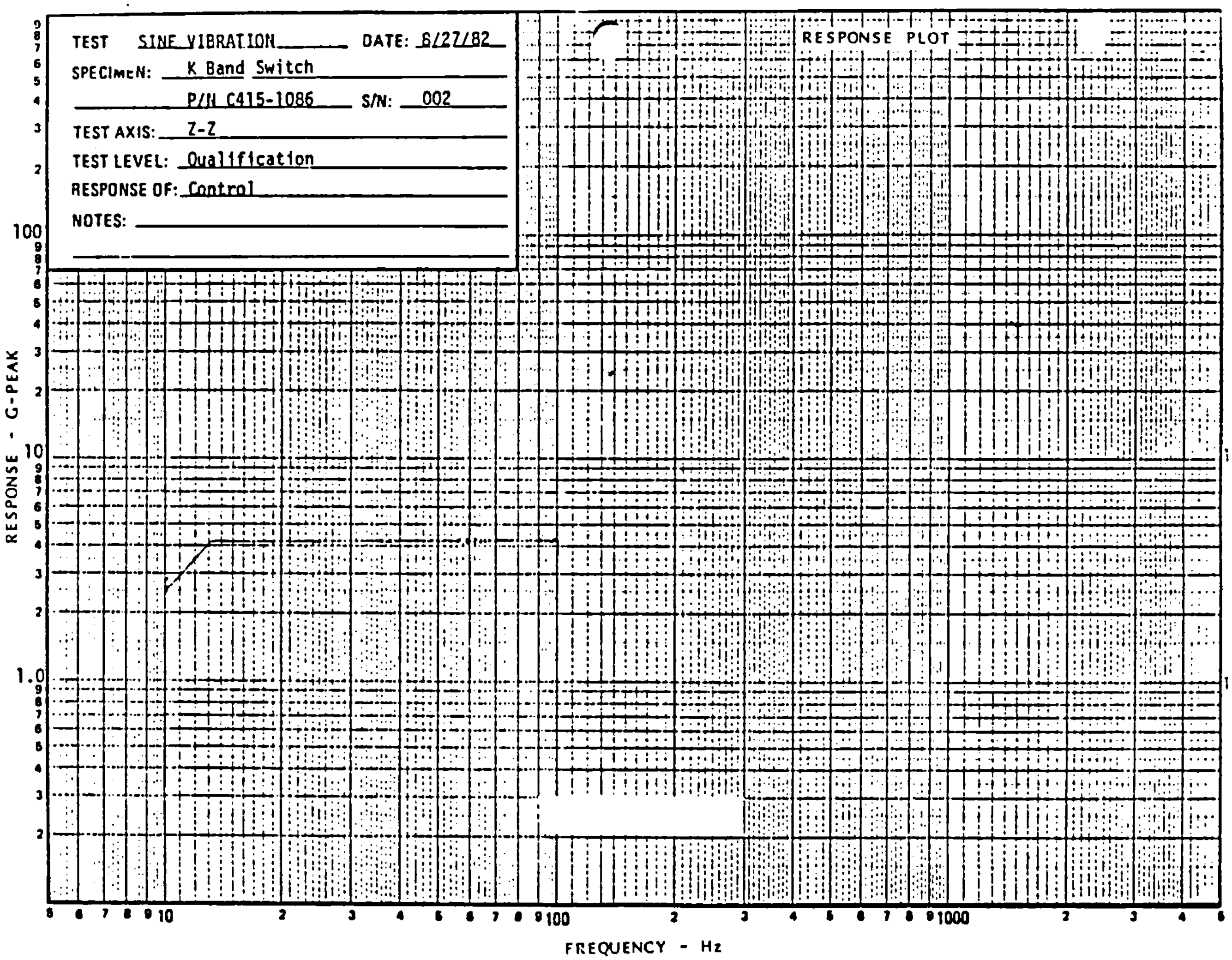

Figure 42. K-Band Switch; Sine Vibration Test; Axis Z-Z

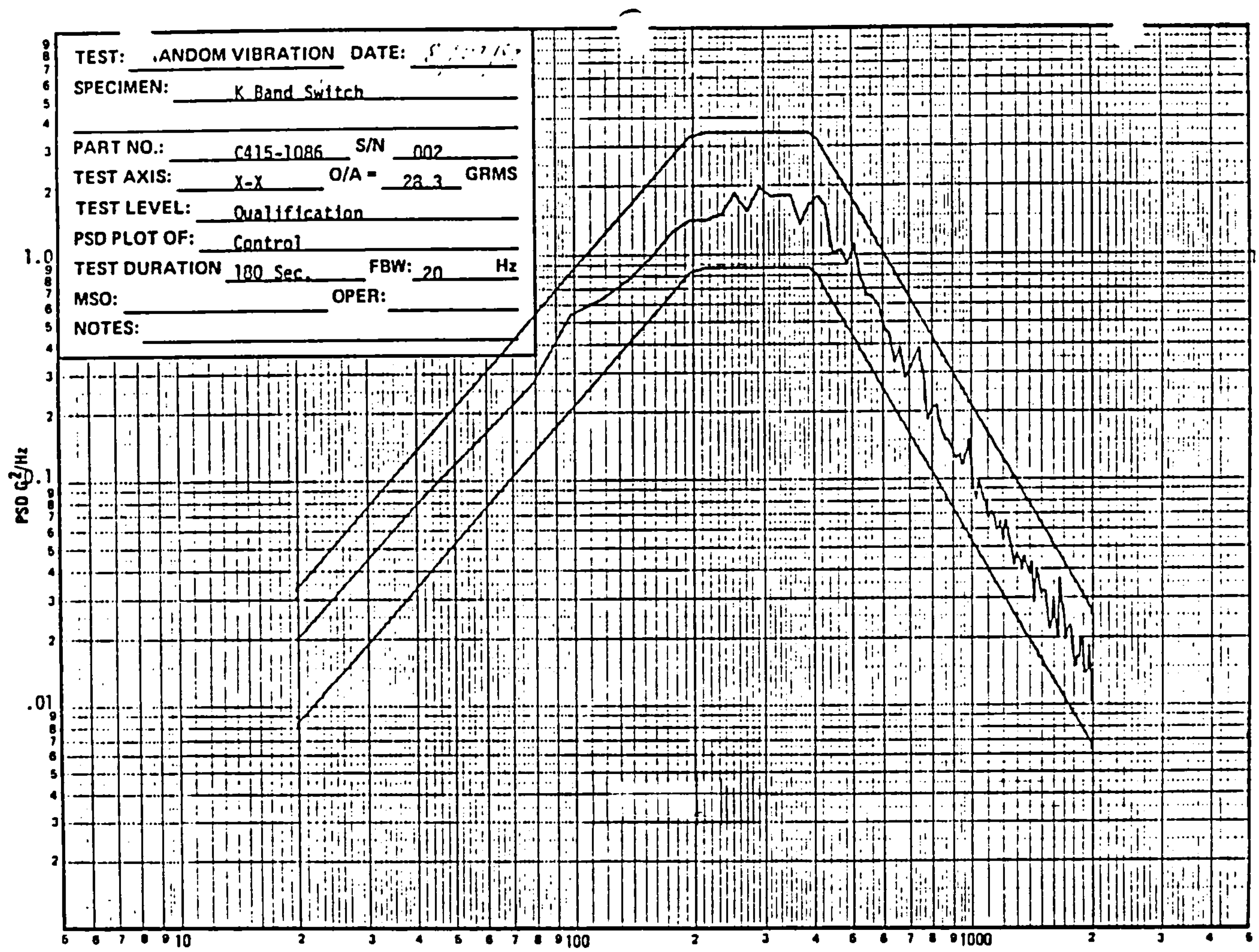

Figure 43. K-Band Switch; Random Vibration Test; Axis X-X

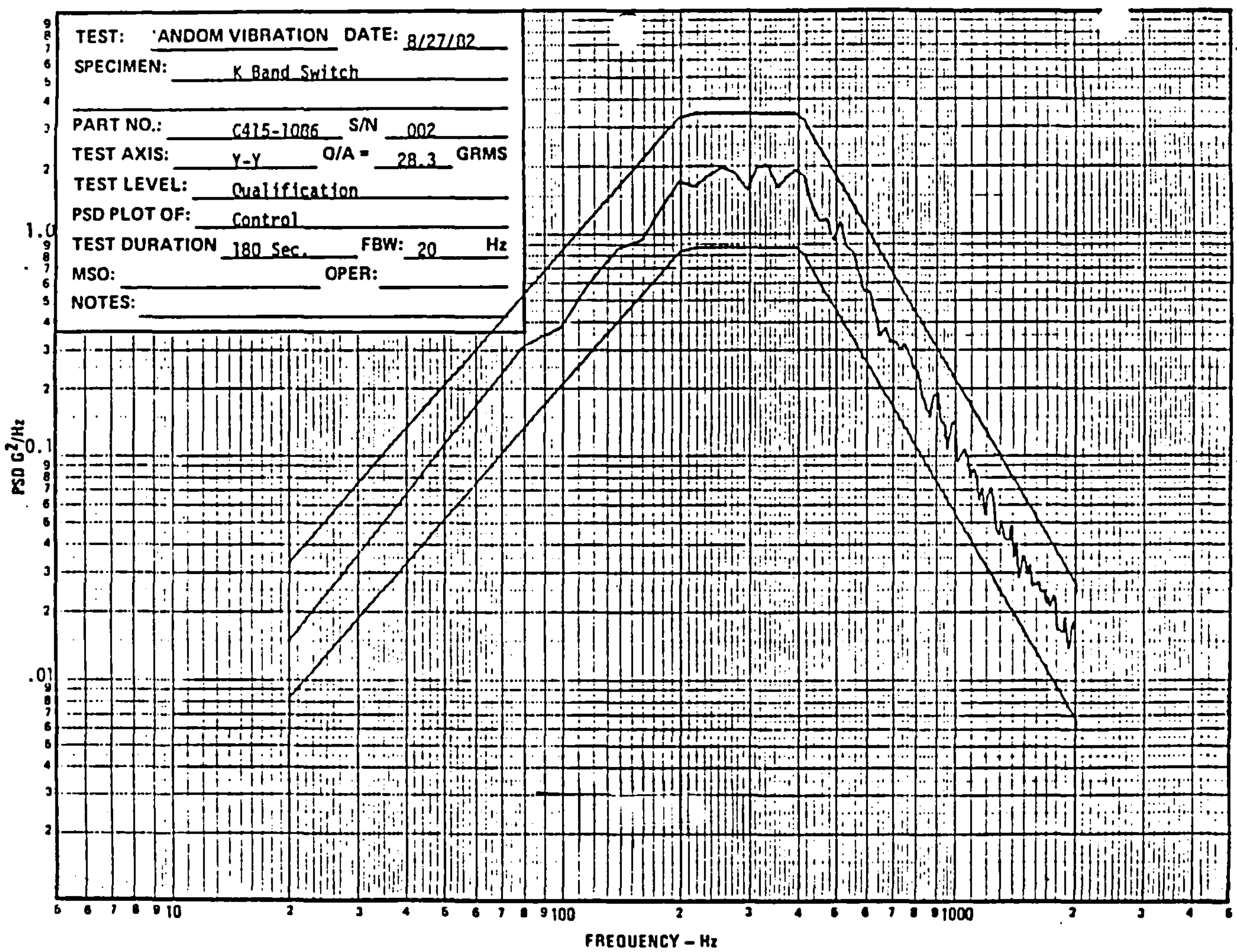

Figure 44. K-Band Switch; Random Vibration Test; Axis Y-Y

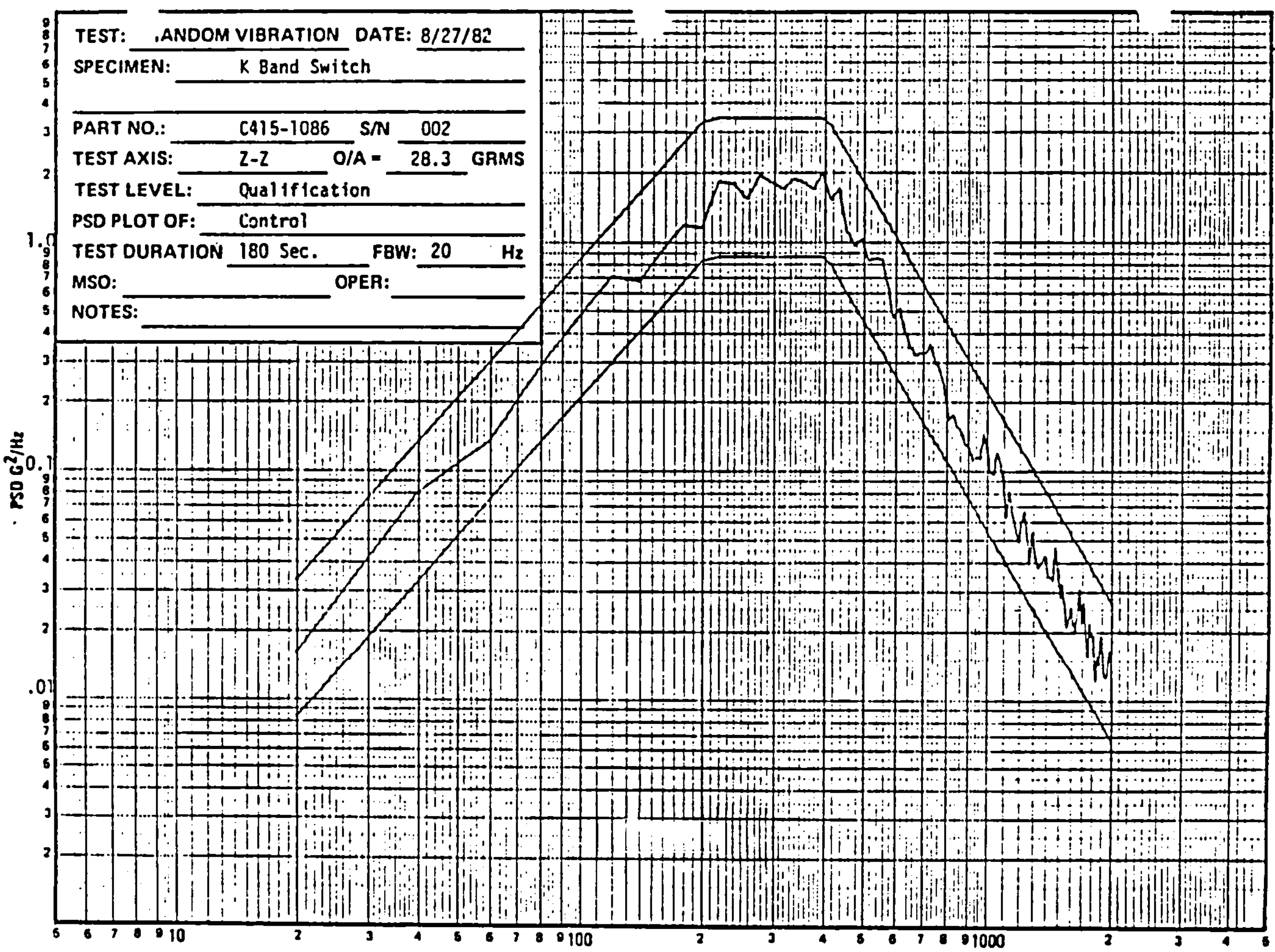

Figure 45. K-Band Switch; Random Vibration Test; Axis Z-Z

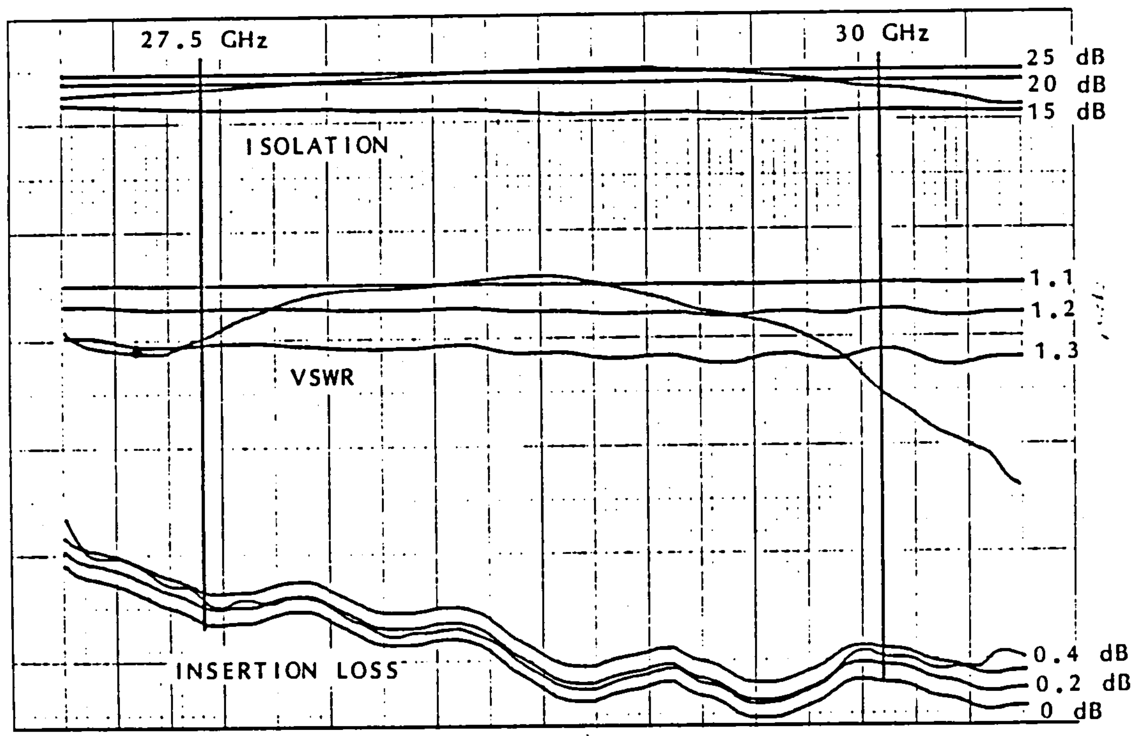

Figure 46. Ka-Band Switch Performance Before Vibration Test Serial No. 2

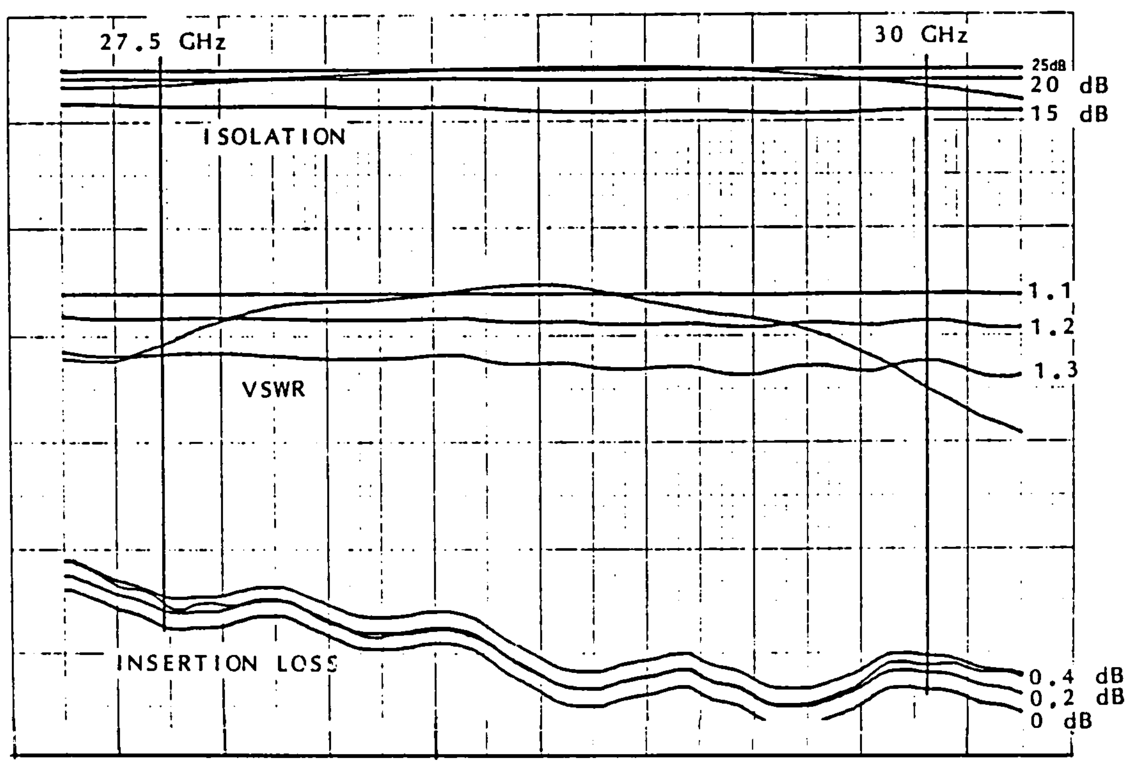

Figure 47. Ka-Band Switch Performance After Vibration Test Serial No. 2

bonded and rigid junctions have proved highly unreliable. The essential differences in the TRW junction construction are:

- Absence of any bonding materials
- Mechanical indexing and interlocking of junction parts to form junction assembly through a boss and recess joints
- High friction damping provided for critical junction parts
- Precise positioning of the junction within the component housing, ensuring a symmetrical and balanced electrical performance of all ports.

In addition to greatly simplified assembly, the boss and recess indexing provides high friction damping for the junction parts and completely eliminates the possibility of resonances within the frequency ranges of the vibration tests. The absence of these resonances precludes the transfer of high levels of destructive energy from the housing to the junction parts during shock and vibration. Numerous qualification tests performed to date on TRW ferrite components did not register a single problem or failure, demonstrating clearly the reliability of the structural design in providing an effective protection for junction parts normally considered brittle and fragile.

The final swept frequency responses, VSWR, isolation, and insertion loss are shown for serial number 2 isolator/switches in Figure 48 and for serial number 3 in Figure 49. The outline of the Ka-band isolator/switch assembly, including the schematic of the switch actuator connection is shown in Figure 50.

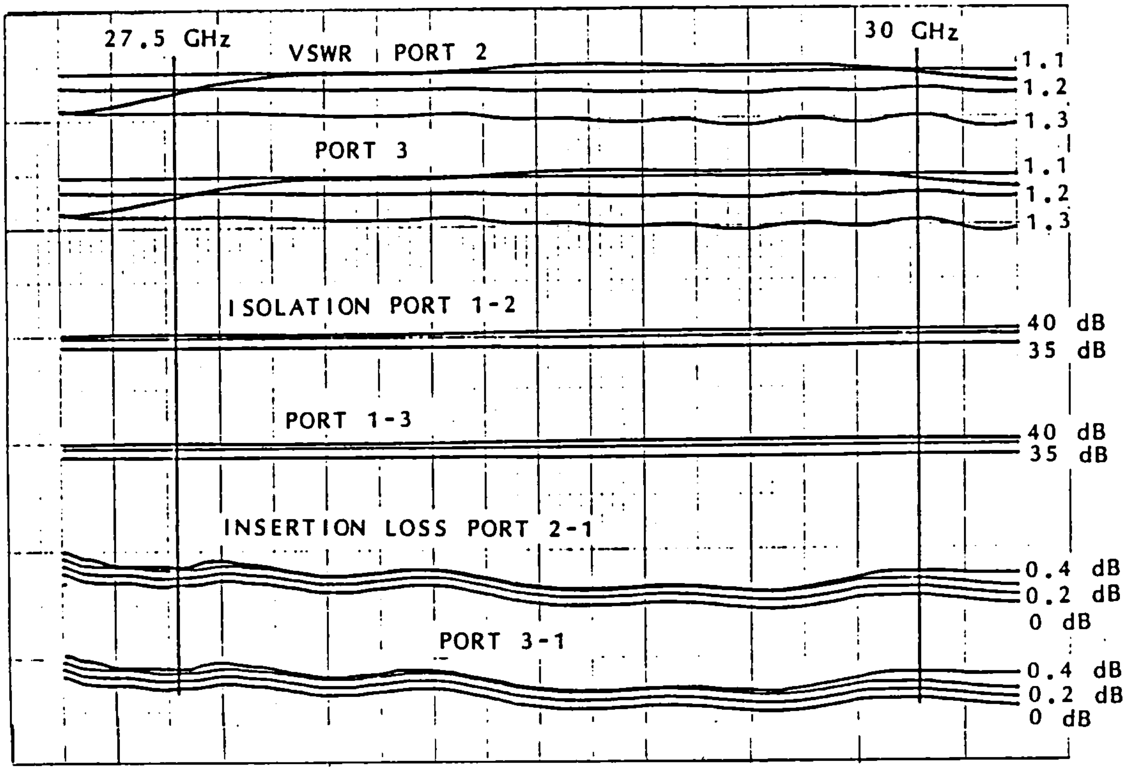

Figure 48. Ka-Band Isolator/Switch Performance After Environmental Tests, Serial No. 2

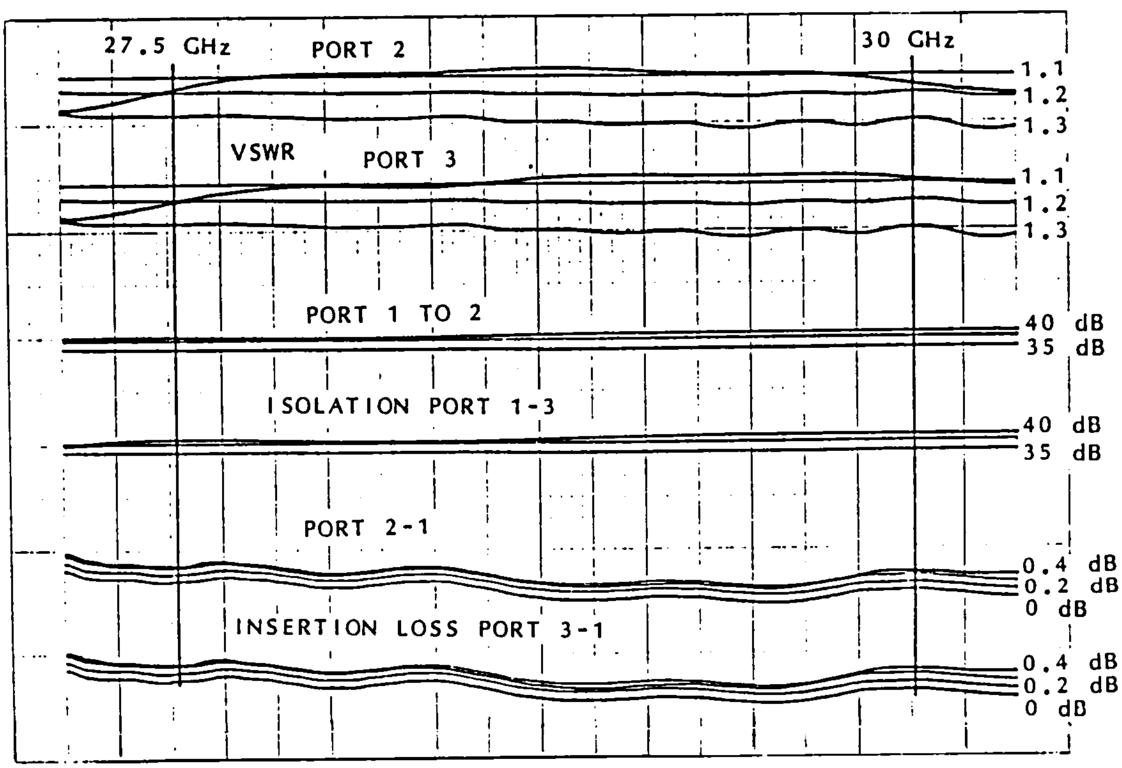

Figure 49. Ka-Band Isolator/Switch Performance After Environmental Tests, Serial No. 3

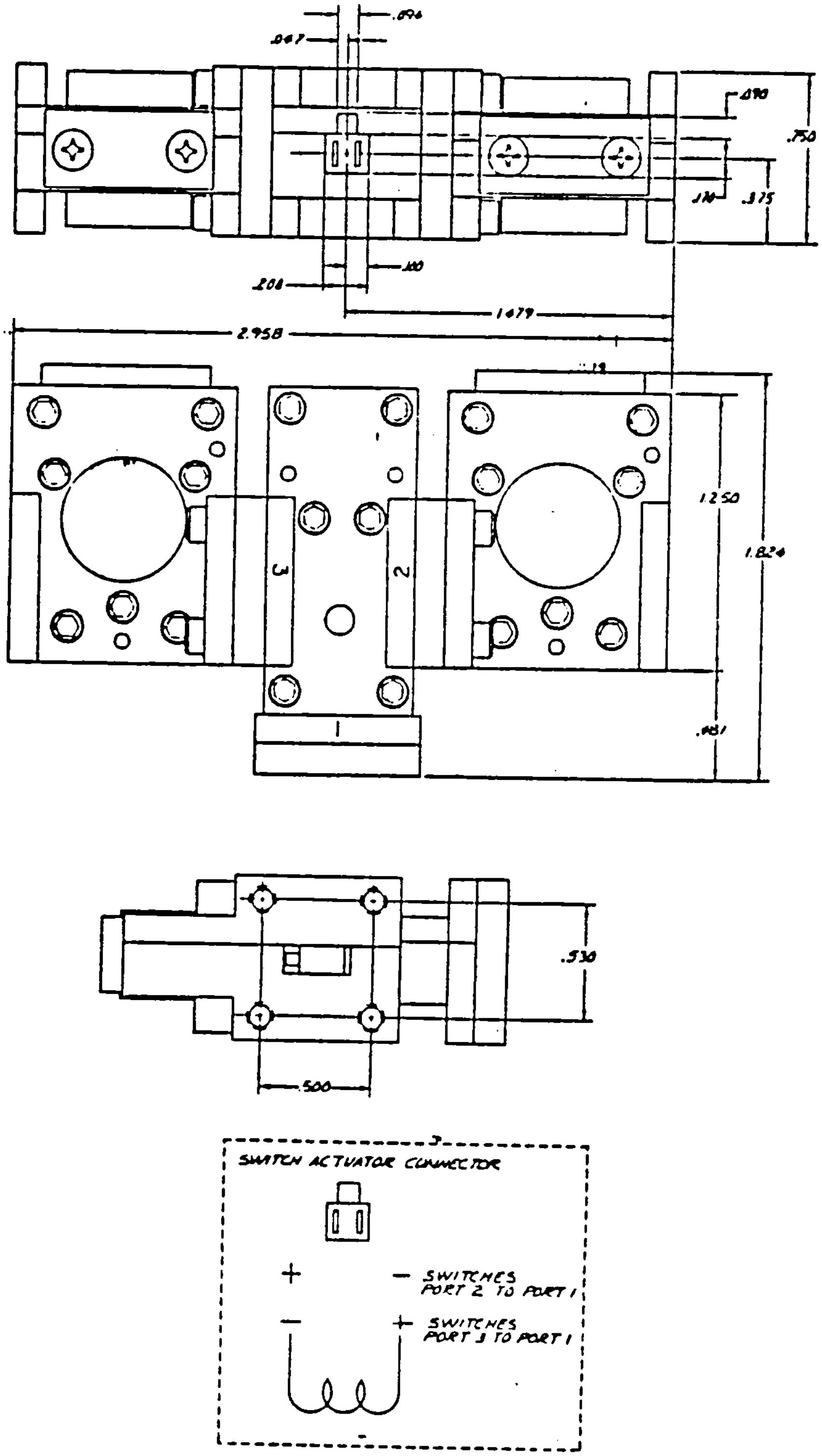

Figure 50. Ka-band Isolator/Switch Outline

4. CONCLUSIONS AND RECOMMENDATIONS

The development of the Ka-band waveguide ferrite switch resulted in a component design with excellent performance, which met or exceeded the electrical design objectives and environmental qualifications tests.

At the lower K-band range, difficulties encountered in meeting bandwidth and insertion loss objectives led to a thorough investigation of the problems which were found to be material-related. This effort led to several significant advances in the area of ferrite component design, including:

- The relative dielectric constant of ferrite, previously considered unimportant, was demonstrated to be the dominant design parameter.
- The relative dielectric constant determines the junction dimensions for given frequency response, junction volume, operating bandwidth, and insertion loss.
- The relative dielectric constant with significantly too low value leads to a large junction with distorted proportions, degradation of bandwidth, and insertion loss performance.
- Component performance for several frequency ranges, including frequencies above 50 GHz, may be significantly improved by modifications of ferrite dielectric properties. Previous efforts were devoted exclusively to increasing the saturation magnetization.
- Analytic design methods were modified to determine the material parameters to satisfy the performance requirements. Previous approaches permitted performance optimization only after the material was chosen, with primary emphasis on magnetic charcteristics.
- The analytic work disclosing the dominant effects of the relative dielectric constant has been verified experimentally by composite junction design.
- An examination of previous development efforts disclosed effects of material selection on component performance and development cost. Inadequate materials invariably led to poor performance and high development cost.
- An investigation of methods to modify and control the ferrite dielectric properties, in addition to experimental work, indicated these properties may be modified by additives with high polarizability.

The improvements resulting from the analytic approach identified the significantly too low relative dielectric constant of the nickel ferrite, which had to be used to satisfy the high power requirements, as the cause of the bandwidth degradation. The analytic work, verified by experimental measurements of the composite junction, also identified the relative dielectric constant as the dominant parameter in the design of junction components. This work was also instrumental in establishing new concepts to improve ferrite component performance through efforts in the ferrite material technology. Specifically, these improvements may be obtained by modifying the dielectric properties of ferrite materials. Until this time the relative dielectric constant of ferrites has been considered an unimportant design parameter, and the efforts in the area of ferrite materials technology were exclusively focused on the magnetic properties. The preliminary material efforts indicated that the dielectric properties of ferrites may be modified by adding elements with high polarizability. These new materials are needed to satisfy not only the design requirements at K-band, but also at all frequencies above 50 GHz, where to date increasing the saturation magnetization was deemed the only possible solution.

The concurrent developments of the K- and Ka-band switches, in contrast to separate efforts, attempted at different times and under different conditions, provided an unusual opportunity to evaluate the impact of ferrite materials properties on the component performance, degree of technical difficulty and development cost. Normally, a design effort of two essentially similar components for two frequency bands would be expected to be technically simpler at the lower frequency range and to produce slightly better performance results. This clearly was not the case in this development. The Ka-band effort, at higher frequency but with adequate material, was significantly simpler and led to excellent results. On the other hand, the K-band effort, excluding the analytic work and the material effort, was much more difficult and did not meet the design objectives. In retrospect, understanding the material's related problems, it is easy to see why these difficulties were underestimated.

The possibilities to identify and understand the sources of the material-related problems were obscured by the formerly used design procedures and the known excellent component performance at both higher and lower frequencies. The design approach, which started with the selection of material with proper magnetic characteristics, considered the relative dielectric constant as a fixed design parameter. This approach aimed at the optimum component performance with the selected material, and lacked the capability to determine what material parameters were, in fact, required to satisfy the given performance requirements. Where, by coincidence, the electric and magnetic properties were nearly ideal, excellent performance was easily obtained, while with the combination of dielectric and magnetic properties too removed from optimum (as in the K-band case), the design approach failed to produce the expected performance and could not positively identify the sources of the problem.

Three distinct improvements in the design process were necessary to fully recognize the impact of the relative dielectric constant. First was the introduction of the concept of the junction ferrite as a dielectric resonator, supporting the propagation of two modes. The resonances of these two modes, or their separation in frequency, determines the operating bandwidth of the junction. The second step was the recognition that the level of saturation magnetization must provide phaseshift over frequency range, which is larger than the frequency separation between the resonances of the dielectric resonator. Only under this condition may the two modes be coupled, in a manner similar to two coupled amplifiers, to produce a single wideband response with two ripples in isolation and VSWR responses. The third step was the reversal of the design process. Rather than selecting the material without being certain that it is, in fact, adequate to achieve the required performance, the improved approach first determines the values of the saturation magnetization and the relative dielectric constant required to produce the given frequency responses.

This analytic approach to verify the material requirements of existing components with excellent performance demonstrated that nearly ideal combinations of material properties were found for these designs strictly by coincidence. The presently available materials were developed decades ago and long before the present requirements could be anticipated. Several materials with adequate saturation magnetization for the K-band design are available, but their values of relative dielectric constant at $\epsilon_r = 13$ are significantly below the required value of $\epsilon_r = 18$, or higher.

Clearly, in applications where materials with the required physical properties are not available, a degraded component performance is unavoidable. In addition, this degraded performance is obtained with a higher degree of design difficulty and at significantly higher development cost.

In most current applications, especially in systems using solid state devices where wideband performance and low insertion loss of ferrite components are among the key considerations, the degraded ferrite component performance imposes major limitations on the system designs. These limitations may be removed and significant further progress obtained through efforts in the area of ferrite materials technology.