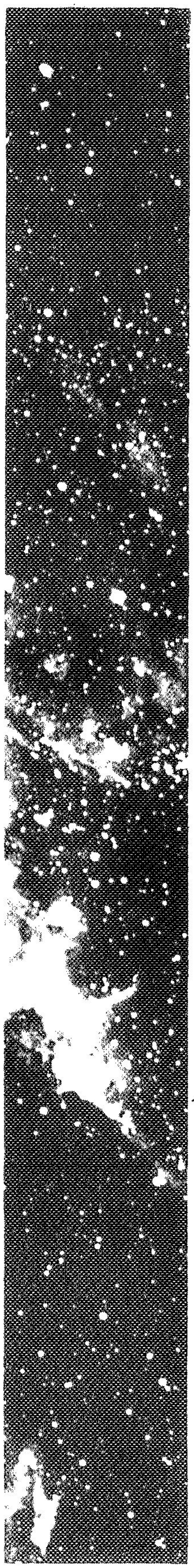
30 JULY 1969

SPACE SYSTEMS



MULTIKILOWATT TRANSMITTER STUDY FOR SPACE COMMUNICATIONS SATELLITES

Volume II
Technical Report
Phase II

Prepared For
GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINSTRATION
HUNTSVILLE, ALABAMA

Under
CONTRACT NAS 8-21886

GENERAL ELECTRIC

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TECHNICAL REPORT

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SPACE SYSTEMS ORGANIZATION

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ABSTRACT

The Phase II study of the Multikilowatt Transmitters for Space Communications Satellites Program investigated several key technology areas pertaining to high-power transmitters. The principal objective was to identify engineering solutions and technology alternatives for achieving a high-voltage, high-power transmitter capability in space. The areas investigated were:

1. High voltage and power effects in a satellite environment
2. UHF-AM-TV high-efficiency amplifier breadboard
3. Supporting areas which may critically influence the overall transmitter system

The high-power study investigated materials effects in electrical breakdown in a satellite environment, concluding with recommended materials for fabricating transmitters and power conditioners. DC and RF circuits were analyzed in terms of electrical requirements for typical transmitter types, including considerations for electrical breakdown suppression and materials to eliminate or minimize breakdowns.

A comparison study of high-efficiency amplifiers, initiated in the Phase I Study, was continued with two AM, high-efficiency amplifier circuits. The Doherty was selected over the Chireix Outphasing for breadboarding on the basis of apparent less complexity. Three low-power breadboard configurations are described: a UHF interdigital cavity type, a UHF 2-cavity amplifier, and a 30-MHz discrete-component simulator. The latter two provided good Doherty operation, but require further optimization effort to achieve the maximum efficiency.

The supporting technology areas studied included monitor and protective circuitry for both dc and RF subsystems, thermal control design approaches for the transmitter and power conditioner, and approaches for space qualification of high-power transmitter tubes. In addition, a qualitative evaluation of the validity of scaling low-power experimental and analytical results to a high-power level indicated caution should be exercised where electrical

breakdowns may be encountered, since some phenomena are not predictable due to the lack of pertinent data.

The study concluded with a recommended direction of continuation, based on results of this study. The two major areas were to develop a high-power, high-efficiency amplifier breadboard, and to initiate testing of key RF components in a high vacuum. Supplementary areas recommended for further effort were initial fabrication of power conditioners and thermal control heat pipes, and the initiation of tube life testing.

The results of the Phase I and II study efforts indicated no critical areas which would prevent the development of high-power, high-voltage space transmitters. However, the design problems are complex, and an early start is necessary if a space-qualified transmitter is to be available in the early or mid-1970's.

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SECTION 1

OBJECTIVES

The Multikilowatt Transmitter Study for Space Communications Satellites has as a major objective, the placing of a high-power satellite transmitter in space in the early 1970's. The efforts to date have been to identify critical problem areas which could potentially delay the transmitter development, and to make initial assessments of the design and development directions, particularly for a space TV broadcast satellite system. The major objectives of the early studies were to examine key systems, subsystems, and components to identify techniques and approaches for developing optimum flyable transmitters for space systems. After the preferred approaches are determined, the program is to develop the hardware for a selected mission, including the complete space-qualified transmitter with its supporting subsystems.

Phase I of the Multikilowatt Transmitter Study Program, an analysis phase, had a main objective of defining and analyzing technologies for high-power TV transmitter operation in a satellite environment. In this study, an extensive tradeoff analysis to identify preferred transmitter configurations, a conceptual design study of three typical configurations, and the identification of key technology problem areas were the outputs. The list of key technology problem areas was the basis for formulating the Phase II study of critical techniques.

The Phase II study extended the study on problem areas to evaluate the most difficult problems, resulting in an assurance that solutions to the problems are feasible within the state of the art for a 1970 transmitter development. Specifically, the study was to analyze selected critical technique and component areas in high-power space transmitters and supporting subsystems to ascertain and identify proper engineering solutions, and to define approaches and alternatives for achieving the program objectives. The three major problem areas addressed were the analysis of high-power and high-voltage technologies in a space environment, the feasibility of a high-efficiency UHF AM-TV power amplifier, using a breadboard demonstrater, and the evaluations of critical supporting subsystem areas which are vital to long-duration, high-reliability, mission requirements. Supplementary study objectives for Phase II included:

1. Fabrication of experimental circuitry for the UHF, high-efficiency AM amplifier, which is of sufficient novel design that it is not amenable to analytical analysis as determined in the Phase I study. Scaled-down components were utilized to demonstrate the principles at a low-power level.

2. Provide plans, schedules, and estimates of risks for establishing sources of components not presently qualified or proven; concern was for dc and RF components which may require unusual specifications for operation in a space vacuum.

3. Tests, simulations, and breadboarding plans should be defined where scaling up of ratings or operational characteristics are questionable in a vacuum environment. (This objective was approached qualitatively to identify areas which should be considered for experimental tasks in the subsequent phases of the program.)

To accomplish these objectives, the Phase II study was structured to cover the following areas:

1. High power in space
   a. Materials evaluation
   b. DC technologies
   c. RF technologies
   d. RF components and circuits
2. High efficiency UHF amplifier
   a. Selection of preferred amplifier
   b. Breadboard and test (Doherty amplifier)
3. Supporting technology analysis
   a. Monitor and protective circuits
   b. Thermal control design guidelines
   c. Tube qualification test plans
   d. Scaling to high powers
4. Task integration and recommendations

With the completion of these task studies, a breadboard of a satellite TV transmitter with several kilowatts of power output is next to be undertaken. Simultaneously, all other tasks relating to long life, reliability, and operation in the satellite space environment would be implemented. Thus, the program direction will continue towards a flyable satellite high-power transmitter, following a schedule for activation in the early 1970's.

SECTION 2
STUDY APPROACH

2.1 BASIS FROM PHASE I STUDY

The Phase I study of the Multikilowatt Transmitter Study program was to define and analyze technologies for high power transmitter operation in a satellite environment. This study included a parametric analysis of all potential transmitter types, identifying pertinent parameters and using the parameters of efficiency, weight, and cost as a function of transmitter power, modulation, and tube type for selecting optimum transmitter configurations. The study continued with conceptual designs of three representative transmitter configurations covering electrical, thermal, and mechanical designs. The final task of the study was to identify the key technology problem areas which should be resolved before initiating a prototype transmitter development program. The several tasks will be reviewed briefly to show their contributions to the final key technology problem areas.

The initial task involved a survey of all transmitter devices and a parametric analysis of transmitter types using these devices. The coverage of the program included: frequency bands of 0.7-0.89, 2-3, 8.3-8.5, and 11.7-12.7 GHz; FM and AM TV in all bands; single and multiple channel operation; applicability of TV standards; and a 1970 availability for transmitter devices. Using five device types (gridded tubes, klystrons, TWT's, CFA's, and solid state), the parameters of efficiency, weight, and cost were determined as a function of power output for all appropriate transmitter configurations, frequency bands, and modulations. Efficiency was considered the most critical parameter, while weight and cost data were largely secondary in significance (except for solid state systems which suffered from low device gain and the necessity for much drive circuitry). The transmitter parametric data were combined with similar data for the uplink receiver, power conditioner, and thermal control devices to develop "system" efficiency, weight, and cost data. These three supporting subsystems were considered to be the most influential in identifying preferred overall systems; other subsystems would have relatively little impact on transmitter selection and were not considered in this study.

Three typical transmitter configurations were selected from the parametric analysis for conceptual design studies, covering the electrical, thermal, and mechanical design approaches. The three configurations selected as representative were:

UHF-AM	1.	Linear CFA-15 KW, one channel
	2.	Gridded Tube - 5.5 KW (peak) per channel, 4 channels
S-Band FM	3.	Linear Beam Tube - 2.5 KW per channel, 8 channels.

These were selected on the basis of high efficiency and other desirable factors including low weight, low cost, and tube availability.

A typical result in terms of an artist's conception of the physical layout for 4-channel gridded tube transmitter (the second of the three systems) is shown in Figure 2-1. This transmitter uses Doherty high-efficiency amplifier output stages to achieve an efficiency about 50% greater than that obtainable with the conventional Class B linear amplifier stages.

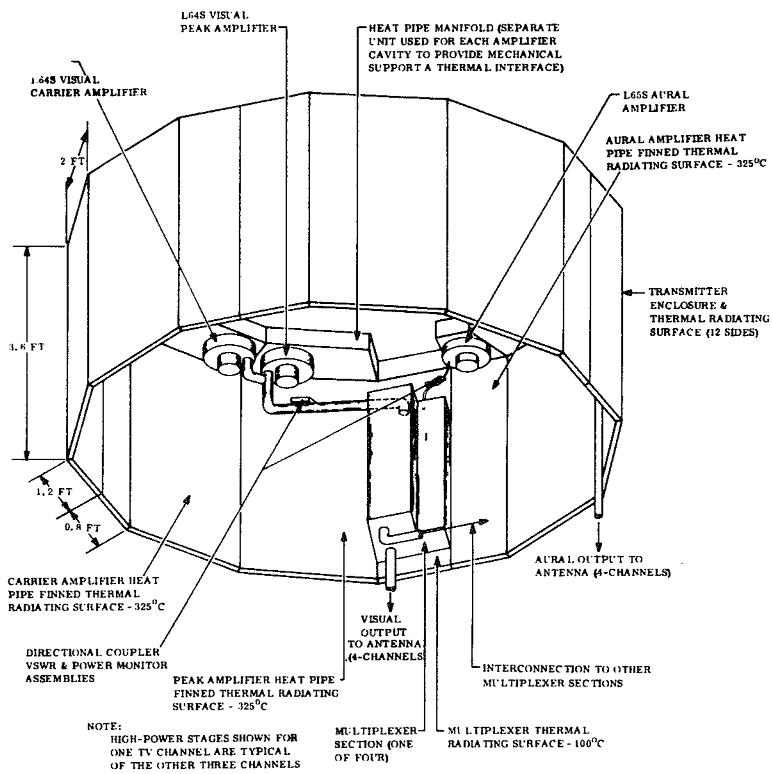


Figure 2-1. Mechanical Arrangement of Four-Channel Gridded Tube Spacecraft TV Transmitter Using 5 KW Doherty Amplifiers

A list of component, technique, and system/interface problems that must be investigated in greater depth before initiating a program to develop a prototype high power space transmitter evolved from the several task studies. Lists of topics in each of three major problem categories are indicated in Table 2-1. The items with asterisks are the ones included in the Phase II study. Additional items are either being covered in related programs (high efficiency and high power in transmitter tubes) or were judged to be less urgent and were deferred for future consideration (space TV standards and mechanical requirements, for example).

Table 2-1. Key Techniques and Problem Areas from the MKTS I Study

I. COMPONENTS	II. TECHNIQUES	III. SYSTEMS AND INTERFACES
a. Tubes and Devices	a. High Power Technology	*a. Power Conditioner for
1. High Power	*1. Materials	1. AM visual-channel transmitter
2. Efficiency	*2. DC and AC	2. FM visual-channel transmitter
*3. Life and Space Qualification	*3. RF	*b. Thermal Control
b. RF Components	b. RF Device Utilization	*c. Monitor and Control
*1. High Power	*1. Diplexing	d. EMC
*2. Electrical Performance	*2. Multiplexing	e. Space TV Standards
3. Implementation	*3. Power Combining	f. Mechanical Requirements
*4. Thermal Control	*4. VSB Generation	g. Test facility requirements
c. Monitor and Protective Circuits	*c. High Efficiency AM Circuits	h. Ground Receivers
*1. Sensors	d. Energy Storage* and Controlled Carrier	
2. Reliability	e. Multi-channel Audio	
	*f. Thermal Control	
	g. Redundancy	

*Included in Phase II Program

2.2 PHASE II PROGRAM APPROACH

The Phase II MKTS program was organized along three main lines of effort, each of which relate to the key technique problem areas of Table 2-1 as follows:

Problem Area	Table 2-1 Reference
HIGH POWER IN SPACE	
Materials Evaluation	II a 1
DC High Power Technology	II a 2, II d, III a
RF High Power Technology	I b 1, II a 3
RF High Power Components	I b 1, I b 2, II b 1, II b 2, II b 3, II b 4
HIGH EFFICIENCY UHF AMPLIFIER	II c
SUPPORTING TECHNOLOGIES	
Monitor and Protective Circuitry	I c 1, III c
Thermal Control Design Guidelines	I b 4, II f, III b
Tube Space Qualification	I a 3
Scaling Effects	(added)

The additional areas of Table 2-1 not covered will be evaluated in other related programs, or will be considered for elements of a future study in the MKTS program.

The Phase II program, based on the above tasks, was sequenced to permit the three major task areas to be studied independently, but with interfacing as required to obtain a coherent set of results. As the program approached its conclusion, the results of the studies were integrated into a set of program recommendations for Phase III which would lead eventually to a prototype development program.

The Phase II basic program outline is based on the above listing; the general basis for selecting and emphasizing the items listed are:

1. High Power in Space. Problems of electrical breakdown in the space environment, especially inside the satellite, are of utmost concern. Many electrical breakdowns have been observed (Reference 9), and only be eliminating these problems can a high-power transmitter ever operate successfully in space. The high-power study encompassed considerations for materials effects in a space

vehicle environment with the resulting effects in high-voltage high-power dc and RF circuits. This information makes the development of a reliable space transmitter more certain, and the confidence in meeting system objectives much greater. Thus, materials information is critical to the initiation of a high-power development program for both dc and RF circuitry in a broadcast satellite.

2. High Efficiency AM Breadboard Amplifier. A number of studies on microwave tubes for space are being pursued (References 21, 24, 27, 28, 30) but production of these tubes is some time in the future. The initial breadboard was a UHF gridded tube AM-TV amplifier whose selection was based on the advanced developmental status of high efficiency 2.5 kW triode, a type not being considered elsewhere. However, for this investigation phase, a low-powered triode was to be used in the high-efficiency circuit required for an acceptable level of efficiency. The Phase I study suggested that the Chireix Outphasing and the Doherty circuits be selected for further study, with breadboarding of the preferred circuit to follow.

3. Three Supporting Technologies. Monitor and protective circuitry is a major concern since the transmitter will be in an unmanned satellite and an electrical breakdown (temporary or permanent) must not be catastrophic by causing other functional subsystems of the satellite to become inoperative. Thermal Control Support is required to insure effective temperature control of all elements, since power dissipated inside the satellite must be conducted by some means to a radiating plate on the vehicle surface. The third support area of Tube Qualification Testing Requirements was included since the highest power tube qualified for space is presently a 100-watt S-band TWT by Watkins-Johnson. Testing requirements for space qualification at higher power levels are not well defined. Finally, the question of establishing testing requirements where analysis and low power testing cannot be safely extrapolated to high power systems was addressed.

4. Integration and Recommendations. The final task was to integrate and evaluate results of the individual task studies, formulating a logical and effective program continuation directed at an early flyable space transmitter. This study is presently emphasizing UHF-AM which is primarily of value for UHF-TV where the spectrum conservation of AM over FM is a significant factor. Adaptability to FM-TV appears to involve no problems of consequence which won't be solved in the AM amplifier development.

2.3 SCOPE OF EFFORT

The overall program was oriented to provide answers to the more urgent problem areas which might limit early development or the performance of a high-power space transmitter. The program as outlined above was judged to be adequate to identify the nature of the problems and to provide well-founded solutions and recommendations. In the high power realm, for example, the materials evaluation was centered about a list of materials supplied from the dc and RF high-power technology studies; the list is expected to be sufficiently inclusive for selecting suitable materials for all transmitter and subsystem components. The high power dc studies were directed at the power conditioner, which is the most significant equipment involving dc power. The power conditioner was treated parametrically, with later emphasis on the requirements for a gridded tube transmitter. The RF circuitry study was directed toward the three transmitter configurations of the Phase I study as listed in Section 2.1. The results included some general considerations of RF breakdown problem areas, since other transmitter configurations and components may be desirable for some future mission.

Only one high efficiency breadboard amplifier was developed and tested, operating at a power level under 100 watts. The preliminary amplifier selection study was a comparison of two high-efficiency amplifiers, the Chireix Outphasing and the Doherty circuits, with the latter receiving preference.

Supporting study areas were directly related to the types of equipments and concepts required to implement a high-power transmitter development. The monitor and protective circuit study concentrated on voltages of a few kilovolts in three to five kilowatt transmitters, but covered general dc and RF protective techniques. Thermal control guidelines were directed at cooling the recommended power conditioner configuration and the RF circuitry for the three transmitter configurations considered in the Phase I study. General outputs that can be adapted to other specific designs were also derived. Tube qualification testing requirements were considered generally, but directed toward UHF tube types, emphasizing requirements for space missions from which specific test formats should be developed.

A recommended plan for program continuation incorporated the outputs of the several tasks in the study, their inter-relations, and external inputs that would be directly influential in developing a high-efficiency, high-power TV transmitter for space. The areas requiring further efforts were divided into one group for early implementation and a second group that is less urgent on the overall time scale, as in the Phase I program.

2.4 PROGRAM PLAN

2.4.1 PROGRAM MAP

The basic program approach was discussed previously in Section 2.2. This section will expand briefly on the Task Descriptions, covering each of the tasks as shown in Figure 2-2. Results and Conclusions are summarized in Section 3, Recommendations in Section 4, and Technical Details are provided in Section 5.

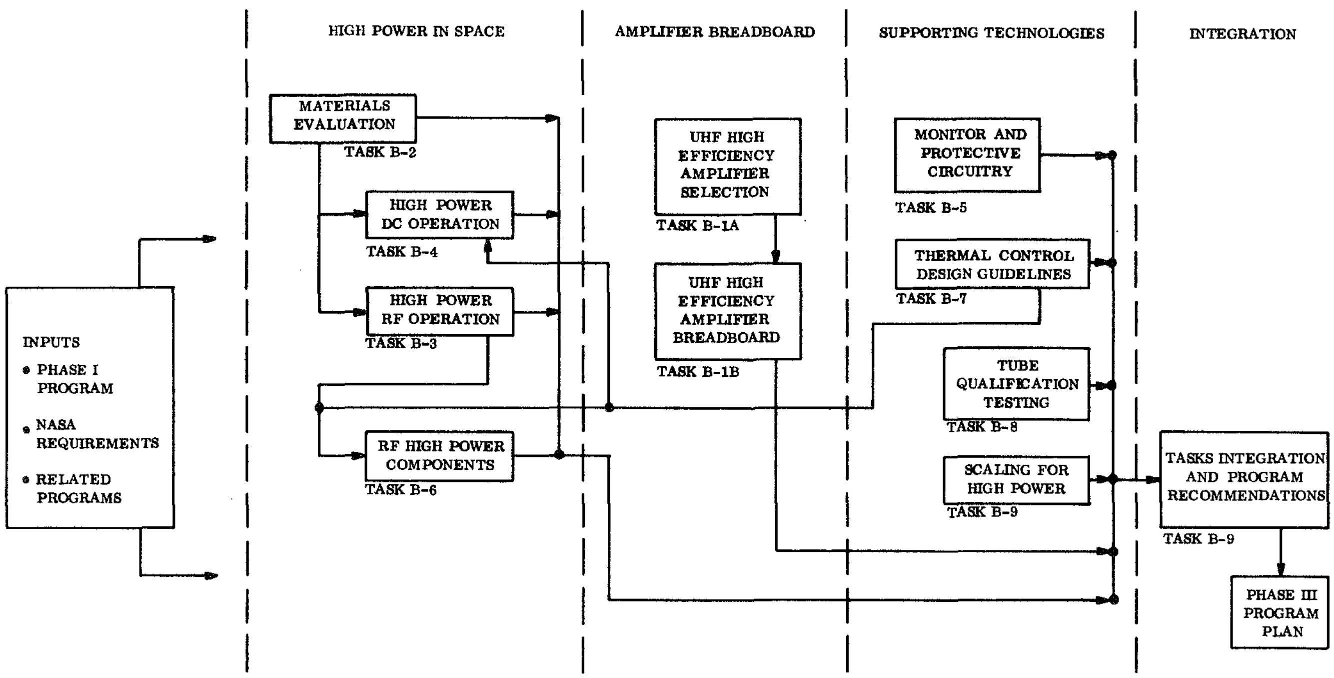


Figure 2-2. Program Map for Multikilowatt Phase II Study

2.4.2 HIGH POWER IN SPACE

2.4.2.1 Materials Evaluation (Task B-2)

This task is to identify and characterize materials for critical areas in high power satellite-borne transmitters and associated power conditioners. Recommendations will be made for specific materials to use and/or to avoid, and enclosure comparisons for "open," pressurized, and potted arrangements for operation in the space vacuum. In addition, outgassing, sublimation and condensation, and RF multipactor effects will be analyzed.

2.4.2.2 High-Power DC Technology (Task B-4)

This is to determine the components and circuit requirements for a satellite dc-to-dc power conditioner with solar array input, with output to provide a single high voltage for an AM-TV amplifier. Also to be considered are component development requirements, and materials evaluation results so that electrical breakdowns will be avoided.

2.4.2.3 High-Power RF Technology (Task B-3)

This task is to determine breakdown modes and conditions for high-power RF in a satellite environment. This includes outassing effects, sublimation, and especially multipacting (which only applies to high frequency RF circuits in vacuum. Means for minimizing breakdowns in coaxial and waveguide components at all frequencies and power levels of interest are to be covered.

2.4.2.4 High Power RF Components (Task B-6)

The RF components required for the three transmitter configurations assumed in the Phase I study (Section 2.1) are to be determined, and the characteristics of these components, both physical and electrical, derived after the breakdown conditions are defined in the above task. The breakdown characteristics from both outgassing and multipacting are then to be assessed, with recommendations for minimizing breakdowns.

2.4.3 HIGH EFFICIENCY UHF AMPLIFIER

2.4.3.1 High Efficiency Linear Amplifier Selection (Task B-1A)

The task objective is to analyze high-efficiency amplifiers selected from the Phase I study (Reference 19), and to recommend a preferred one for breadboarding. Previous recommendations indicated the Doherty to be the best compromise although the Chireix Outphasing circuit is also considered a likely contender.

2.4.3.2 High Efficiency Amplifier Breadboard (Task B-1B)

The amplifier selected above, after customer approval, is to be breadboarded using tubes below the 100 watt level to show high efficiency performance for TV and similar application. Recommendations for operations at about the 5 kW sync peak output level will be included.

2.4.4 SUPPORTING TECHNOLOGIES

2.4.4.1 Monitor and Protective Circuitry (Task B-5)

The Multikilowatt Transmitter study is vitally concerned with transmitters in long life unmanned satellites which are likely to be serving several purposes (perhaps a multiple channel TV system). The critical breakdown points in the transmitter must be monitored, and protective circuitry included to eliminate the possibility of a single breakdown aborting the entire mission. Techniques for monitoring and fault detection, power removal, fault analysis, and correction are involved.

2.4.4.2 Thermal Control Design Guidelines (Task B-7)

Specific techniques to remove heat from a power conditioner and from a transmitter are of interest. The latter problem largely will concern RF component transmission line heating; tubes have been considered in other programs. Heat pipes and direct conduction are the basic means of control to be evaluated.

2.4.4.3 Tube Qualification Study (Task B-8)

Space systems involve unique environmental characteristics, both during launch and in space, so the requirement for transmitter tubes to operate effectively for long periods of time while subjected to these environments is very critical to a reliable system. Test plans for establishing the necessary space qualification tests are to be determined; life testing is a major factor in the study.

2.4.4.4 Scaling to High Power (Task B-9)

Each task report is to be reviewed to determine possible problems in scaling results to the high-power system in space. Recommendations are to include requirements for possible supporting test programs.

2.4.5 TASKS INTEGRATION

2.4.5.1 Tasks Integration and Program Recommendations (Task B-9)

This task will provide follow-on recommendations for developing a high-power space TV transmitter for a UHF-AM mission. The recommendations will encompass experimental confirmation of theoretical conclusions where critical dc and RF components and subsystems are involved. Additional tests based on uncertain scaling of analytical results and of low-power to high-power operations will be considered.

2.5 CONSTRAINTS AND LIMITATIONS

Since each task noted above could easily become an extensive study in itself, the study was directed toward solving the most critical aspects of the problems. The levels of efforts established for the several tasks were such that the major problems areas would be adequately evaluated. The RF tasks were directed at the three transmitter types selected in the Phase I study (Section 2.1); the subsystems were directed more towards the gridded tube UHF transmitter, the type selected for breadboarding in the current study phase.

The Materials Evaluation considers a list of typical required materials prepared by personnel on the other high-power study tasks, and the prime effort was directed toward those materials. The question of venting, pressurizing, and potting of equipment was approached qualitatively since no definite input data from high power space experience was available. The dc study of high-power effects was directed largely toward power conditioners while the RF study was basically concerned with the RF components that would be required for the three transmitter configurations selected in the Phase I program.

The breadboard amplifier was limited to a low-power Doherty circuit which required no special cooling techniques and no high-power drivers or power supplies. Preliminary circuit evaluations were limited to the Doherty and the Chireix Outphasing.

The area of supporting technologies was generally concerned with the requirements arising in the other tasks. That is, the monitor and protective circuitry involved mostly a single dc voltage power conditioner for the gridded tube transmitter; RF monitoring was more general and results were applicable to all types. Thermal control design was performed previously on other programs for tubes (See Reference 16); the effort here considered heat removal from the power conditioner and the thermal losses in the RF components of high-power RF systems. Tube qualification test planning was investigated in a general way, and should be adaptable to all tube types.

The intent in placing bounds on the study was to narrow the scope to result in as effective a program as possible within scheduling constraints and to arrive at definition of a near-future transmitter for space TV broadcasting or other space application requiring multikilowatt transmission.

2.6 OUTPUTS EXPECTED

The outputs from this study form the basis for a program to develop a high power transmitter, a major subsystem for a satellite TV mission. The results will, therefore, be directly applicable in specifying a transmitter with all its attendant subsystems, and in specifying materials and techniques to optimize the transmitter for long-life operation.

2.6.1 HIGH POWER IN SPACE

The Materials Evaluation study is primarily intended to provide:

1. A list of preferred and unacceptable materials for dc and RF equipments.
2. An evaluation of open versus pressurized and potted fabrication.
3. The bounds on electrical breakdown to be expected.

Based on this and related technical studies, the High Power DC study should provide:

4. Design guidelines for a space power conditioner, including components, circuit and materials used in construction.

The High Power RF study is directed to supply:

1. An assessment of the RF breakdown problems in a high-power space transmitter.

2. Techniques to minimize or eliminate electrical breakdowns.

3. Design data for special RF components, including vestigial sideband filters, multiplexers, and power combiners.

4. Test recommendations to verify vacuum performance.

2.6.2 BREADBOARD UHF AMPLIFIER

The expected results cover two aspects:

1. A comparison of the more significant high efficiency AM-TV amplifiers.

2. An operating breadboard amplifier with power level of 20 to 100 watts to demonstrate performance of the selected high efficiency type.

2.6.3 SUPPORTING TECHNOLOGIES AND COMPONENTS

The supporting areas should produce the following:

1. A compilation of monitor techniques to detect electrical faults.

2. Basic circuits, such as the crowbar, to minimize damage from a breakdown.

3. Decision logic factors for compensating for faults.

4. Application methods for using heat pipes and direct conduction for cooling power conditioner, RF amplifier, and RF circuits.

5. List of recommended procedures for qualifying a tube for a space mission.

6. Validity of scaling all task results to high-power space systems with test requirements to validate where necessary.

2.6.4 RECOMMENDATIONS

Recommendations from the final integrating task of the study will include:

1. Amplifier configuration to pursue for an AM TV transmitter at UHF.
2. Transmitter design factors for a complete TV transmitter.
3. Development program for special RF components
4. Test plan for verifying performance of high power dc and RF components in a vacuum environment, equivalent to that expected within a satellite.
5. Sets of specifications for associated subsystems and their interfacing, and for purchasing components which are critical to the transmitter operation including the tubes, TV components, and dc components.

2.7 DEFINITION OF TERMS

Most terms in this report are defined as required, or are generally well known. The following list will clarify a few terms which might be unique to certain technological areas, or used a little differently than usual:

1. Outgassing. The effusion of disolved water and gasses in a material subjected to a vacuum or high temperature (or both). These outgas products usually have low vapor pressures.
2. Sublimation. The erosion of materials when molecules leave the surface as a consequence of vacuum and thermal agitation; vapor pressures are usually high and the process is of long duration, continuing until the material disappears.
3. Multipacting. A resonance phenomenon whereby an electron, accelerated between two plates by an alternating electric field, arrives in time to dislodge secondary electrons just at a time when the ac field reverses polarity. Thus clouds of electrons will build up and oscillate between the two plates in synchronism with the ac voltage. (The condition may be aggravated by outgassing, sublimation, and surface contamination.)

4. Paschen's Law. Relates voltage, gap length, and breakdown pressure; varies with gas type and electrode shape.

5. Torr. mm Hg

6. Diplexer. Combines visual and aural RF channels in TV transmitter output (usually used only with AM visual signals)

7. Multiplexer. Combines multiple TV channels into single transmission line.

SECTION 3

RESULTS AND CONCLUSIONS

3.1 HIGH POWER IN SPACE

3.1.1 NATURE OF THE PROBLEM

Concern over high power breakdown in a space environment is indicated clearly in a review covering 83 high voltage problems surveyed in a NASA study (Reference 9). During the period from 1961 to 1968 the problem included, among others, the following types of failures:

1. Corona and glow - 26
2. Arcover - 40
3. Multipacting - 1

The low number of multipactor failures is probably due to the relatively few missions involving high RF voltage equipment. Pressure was specified in about half of the cases, and in these the failures were equally divided between atmospheric pressure failures and very high vacuum failures, below 10^{-4} Torr. The specific causes of the failures were listed as follows:

1. Outgassing - 13
2. Insulation - 8
3. Circuit configuration - 6
4. Entrapped gas - 5
5. Contamination - 3
6. Pressure leak - 2
7. Environment plasma - 1

The significant parameters that influence electrical breakdowns include the following phenomena:

1. Electric field strength
2. Pressure (Paschen's law applies)
3. Temperature
4. Frequency (electrical strength decreases with increasing frequency)
5. Electrode geometry (sharp edges and points are especially bad)
6. Type of gas
7. Radiation environment
8. Plasma in space

Each of these factors was of concern in the overall study of electrical breakdowns.

3.1.2 MATERIALS EVALUATION

The materials evaluation study considered the basic breakdown mechanisms due to outgassing and sublimation. Multipacting effects were considered, but the major effort for this breakdown mode is covered in the RF studies, Section 3.1.4. The second area involved the packaging techniques for use in high power space equipment, and the final area covered recommended materials for space transmitters and related subsystems.

3.1.2.1 Outgassing and Sublimation

Materials, particularly organic and dielectric, contain dissolved gasses and water acquired in manufacture and by association with the atmosphere. In space, these dissolved materials migrate through the material and are drawn from the surface, thus gradually disappearing. However, materials themselves also tend to sublime, or errode, continuously in a high vacuum until the material has disappeared. Table 3-1 lists several typical materials, indicating the outgassing and sublimation for the periods, temperatures, and sample sizes listed. The equivalent pressure of the outgassing is not a well established parameter; it

Table 3-1. Loss From Materials - Outgassing Plus Bulk Loss

Material	Temp. (^{o}C)	Time	Configuration	Loss
Preferred				
BeO (Ceramic)	1340	1 yr.	flat surface	lose 10^{-5} cm
MgO	540	1 yr.	flat surface	lose 10^{-5} cm
Kapton H-film	200	4 days	film	1.8%
Teflon	100	5 days	1/8" sheet	0.01%
Not Preferred				
Silicone Grease DC-11	125	1 day	---	4.7%
Epoxy FM-1000	120	5 days	0.0043 inch film	5.5%
Polyolefin-Themofit CRN (Clear)	125	1 day	---	0.8%
Fiberglass Laminate G-7	130	14 days		2.6%
		1 day		1.3%

depends heavily on enclosures as well as the materials themselves. A purely open configuration, normally not encountered in real life, would encounter typical pressures from epoxies on the order of 10^{-4} Torr initially, and would be reduced by a factor of 10^{2} in one or two days at 100^{o}C. The pressure in a completely enclosed volume would build up until most of the dissolved gasses were released, resulting in a pressure well into the unsafe regions.

Identifying safe pressures requires utilization of Paschen's law. This law indicates the variation of breakdown voltage with electrode spacing and air pressure. Gas content, temperature, and electrode configuration also enter into the picture. Electrode spacings normally used in ground-based equipment are generally acceptable for open or vented systems in space if the pressure is less than 10^{-4} Torr. Figures 3-1 and 3-2 show Paschen's curves with practical working coordinates; the first figure indicates the desirability of keeping the equivalent pressure due to outgassing and sublimation well below 10^{-4} Torr. The very small spacings cannot be used due to vacuum arcs, in which metal whiskers form on the metal surfaces and eventually cause an arc or a serious corona discharge. The second figure substantiates the great concern for positively avoiding sharp electrodes; the data is for sharp points, but any other sharp projection will encounter similar problems.

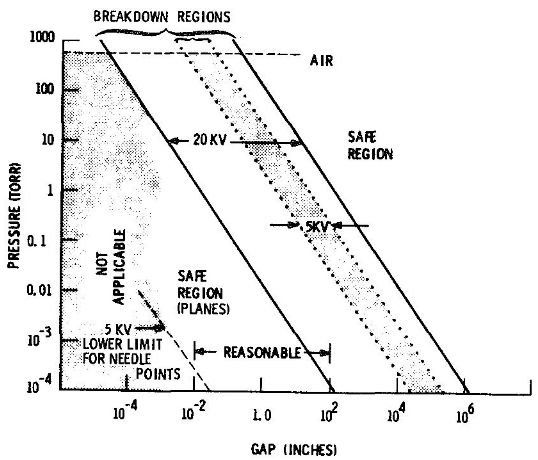


Figure 3-1. Breakdown Gaps - Planes

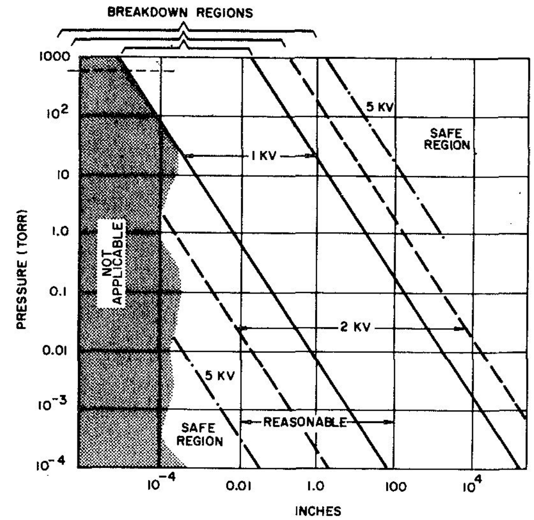


Figure 3-2. Breakdown Gaps - Points

3.1.2.2 Multipacting

Another electrical breakdown problem area, multipacting, is a phenomenon in which electrons oscillate between two planes in synchronism with the applied RF voltage and frequency. Certain conditions must exist before this can occur: an electron accelerating from one plate to the other must dislodge more than one secondary electron, on the average, so that there is a buildup of an electron cloud. In addition, the voltage must be at a correct value to accelerate the electron from one surface to the opposite surface in just a half cycle period so that the secondary electron dislodged will be accelerated in the opposite direction on the next half cycle. (Higher-order modes for odd multiples of this frequency also produce multipacting.) Figure 3-3 shows the general effect of multipactor buildup. Multipacting occurs only at high RF frequencies, so it will be considered in more detail in the RF High Power section, Section 3.1.4.

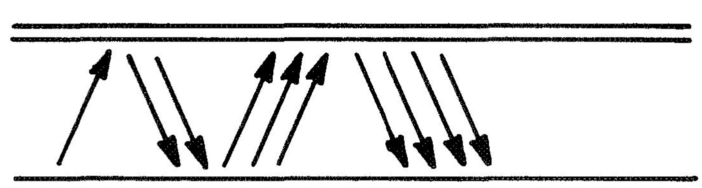


Figure 3-3. Multipacting Buildup

3.1.2.3 Enclosure Considerations

There is a lack of experimental data on the operational reliability for methods of "enclosing" high power equipment in a space system. Three enclosure techniques were considered qualitatively in this study: open, pressurized, and potted. The most likely key decision points in each were identified, and a preference derived on the basis of these key points as they appear to influence the system operational requirements. The pressurized and potted systems each have what appears to be an incorrectable breakdown mode while the open construction only requires an initial break in process. In particular, a pressurized system developing a slow leak will become inoperable for an unacceptably long period of time before sufficient outgassing products can escape. Potted systems can generate permanent pockets in the materials that accumulate outgassing products causing continuing breakdowns; in addition, the potting material itself is subject to permanent arc paths that will make the equipment inoperable. The various factors included in the consideration are listed in Table 3-2.

Reasonable assurance of acceptable operation of an unpressurized system depends on eliminating the breakdown modes possible in a high vacuum. An initial "bakeout" period is mandatory. Its duration will be related to the materials used and a gas sensor will be necessary to ensure sufficiently complete outgassing before operating the equipment. Heaters may be required to raise the temperature of certain materials that might otherwise outgas too slowly for the "bakeout" interval. Sublimation of materials, including metals, outgassing from other subsystems that may not be baked-out adequately, vacuum arcs resulting from metal whiskering and

Table 3-2. Enclosure Design Approaches

	"Open" or Unpressurized	Pressurized	Potted
Good	Simple Fabrication Most Reliable (After Initial Bakeout)	No Breakdowns Easier Shielding Controlled Environment for Testing/Operating	High Dielectric Strength and Smaller Spacing Constant Environment
Bad	Requires Initial Bakeout" in Orbit EMC Sublimation Continuous Other Subsystems May Outgas Vacuum Arc Intercept Plasma	Leak Would Soon Abort Mission Heavier Terminals Exposed to Vacuum of Space Sublimation Particles Enclosed	Fabrication Fault Not Observable Material May Outgas Into Voids Material Change with Time

subsequent arcing, and plasma interception are additional problem areas of an open design. These breakdown types are considered to be non-permanent in effect, and will not be destructive if monitor and protective circuits are included to turn off critical stages before damage can be caused.

3.1.2.4 Materials Recommendations

Recommended materials for use in a space system include specific ones required for transmitters and power conditioners. A relatively broad list of materials commonly used was generated (Reference 7) and analyzed on a preferred/not preferred basis. The metals were judged on sublimation rates and tendencies to whisker; non-metals were less well characterized, but were judged generally on outgassing and sublimation rates. Table 3-3 lists the metals in order of increasing sublimation. Four were rejected due to a very high tendency to whisker. The non-metals recommendations are generally in keeping with low-breakdown

Table 3-3. Materials Recommendations

Metals		Non-Metals	
Recommended (In Order of Increasing Sublimation)	Not Recommended (Heavy Whiskering)	Generally Preferred	Generally Not Preferred
		(Low Outgassing, Fast Outgassing, Low Sublimation)	(High Outgassing, Slow Outgassing, High Sublimation)
Tungsten	Tin	Ceramics	Silicone Grease
Tantalum	Antimony	Steatite	Epoxies
(Carbon)	Zinc	Mica (Early Outgas Large)	Rosin (Solder Flux)
Rhodium	Cadmium	Alumina	Impregnated Paper
Nickel	Alloys of Same	Fused Quartz	Polyethylene
Nichrome		Magnesium Oxide	Fiberglass (Varies)
Iron		Teflon	Mylar
Chromium		Kapton	
Gold		Beryllium Oxide	
Copper		Some Conformal Coatings	
Beryllium			
Aluminum			
Silver			

likelihood criteria, but additional data would be very desirable to assess the bakeout period required and to determine which materials result in too large an "atmosphere" for safe operation in space.

3.1.2.5 General Conclusions

The general conclusions from the materials study are:

1. The preferred design approach for fabrication of the transmitter is an open unpressurized system.

2. A bakeout period will precede high power operation to minimize the possibility of an electrical breakdown by driving off the major outgassing products as rapidly as possible.

3. All terminals with high voltage should be physically large and well rounded to minimize corona effects.

4. Outgassing breakdown data and the effects of partial enclosures on localized gas pressures are not well determined, and experimental evidence on breakdown conditions should be obtained.

5. Materials should be selected carefully. Metals should have low whiskering tendencies and low sublimation. Non-metals should have low outgassing or easily removed outgassing and low sublimation.

3.1.3 DC HIGH POWER TECHNOLOGY

The dc high power technology study concerned the dc-to-dc converter that raises the 100-volt input from a solar array to the high voltage required for the transmitter output stage. Parametric data was obtained on components, and design concepts were directed at a 3.2 kw, 3.5 kv supply for a Doherty-type gridded tube amplifier.

3.1.3.1 Components for Power Conditioner

The basic elements of a power conditioner are the input filter, switching devices to generate square waves, transformer, rectifier, output filter, and control circuits. The components to achieve a high efficiency of conversion were considered in some detail.

3.1.3.1.1 Input Filter

Uses L-C filter designed to obtain a low current ripple within the conditioner and a low ripple voltage reflected back into the solar array; typical filter values are 0.5 h and 700 μfds; weight is about 3 pounds and efficiency 95 percent.

3.1.3.1.2 Switching Devices

DC inputs are converted to square waves by transistors or thyristors (SCR's); tubes might be applicable for source voltage in the order of kilovolts. The Delco 2N2583 transistor is one of the best devices. Losses in various devices as a function of frequency are shown in Figure 3-4; about 4 kHz was selected on a system basis. SCR's would be efficient only at low frequencies, but here the transformer efficiences are poor. Efficiences are about 98 percent for a pair of transistor switches. (After this report was completed, a high efficiency SCR switching circuit was discovered. Changes in the present recommendations will probably be significant if this new circuit operates as expected.)

3.1.3.1.3 Transformers

Transformer design was checked parametrically for various input and output voltages, power levels, frequencies, and loss tolerances. Weight was found to decrease at higher frequencies but efficiency dropped off rapidly. Weight as a function of a specified frequency and efficiency are shown in Figures 3-5 and 3-6, while the equivalent efficiencies at various frequencies are shown in Figure 3-7. A lower limit of 97 percent was assumed for transformer efficiency, with a 98 percent objective; thus an operating frequency of 2 to 4 kHz is best, and the further calculations were based on the latter figure. Transformers in the 20 kv output region tended to have weights of 25 to 50 pounds for the power and efficiency ranges considered; insulation problems should be evaluated in more detail to reduce these rather exorbitant levels where 20 kv is nominal.

3.1.3.1.4 Rectifiers

The output L-C filter is a major weight item for an AM-TV transmitter where the power conditioner capacity is keyed to some average requirement less than the peak transmitter power requirement. For example, a typical average power requirement is 3.2 kw for a

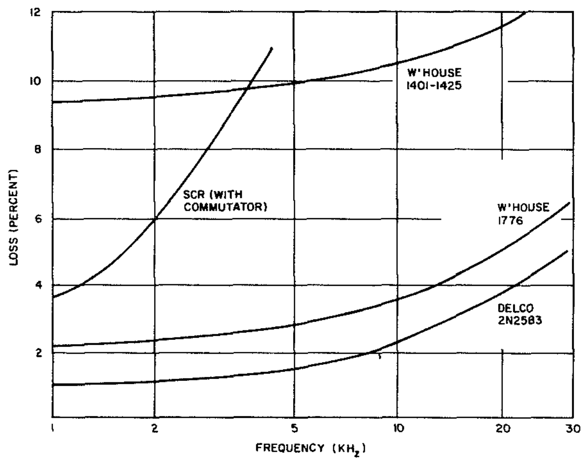


Figure 3-4. Switch Losses

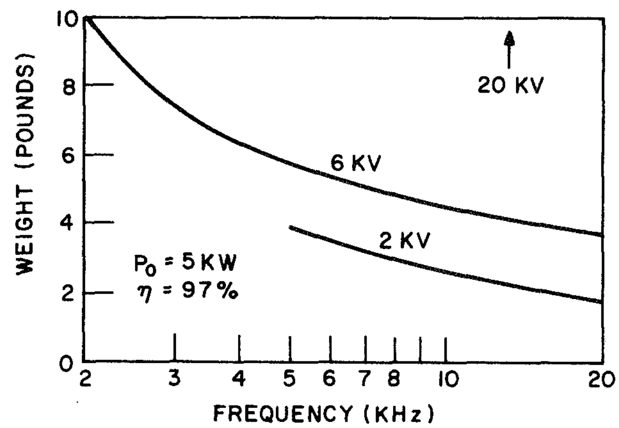


Figure 3-5. Transformer Weight Versus Frequency

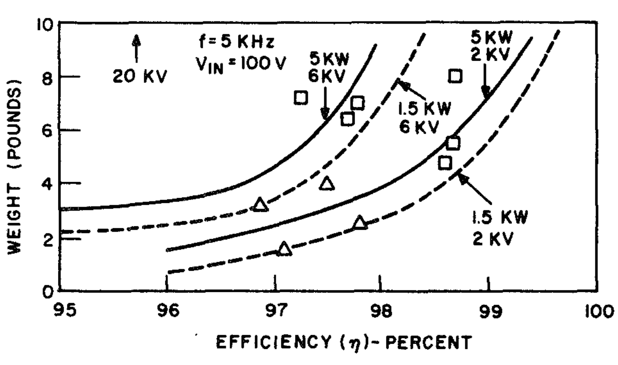


Figure 3-6. Transformer Weight Versus Efficiency

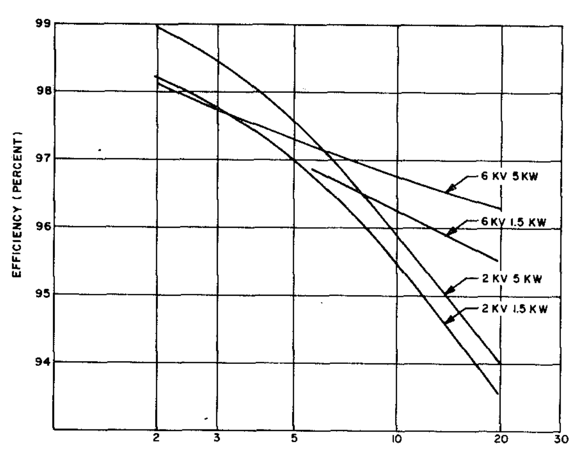


Figure 3-7. Transformer Efficiency Versus Operating Frequency

transmitter providing 1.6 kw RF output, equivalent to a 5.0 kw sync peak output. Thus, the conditioner must supply a peak dc power of roughly 8 kw (considering efficiency in the transmitter at the sync peak power level). The preferred method is to include enough capacitor storage to supply the peak power for short periods. The capacitor will recharge during low demand (nearly white TV picture) intervals. Typical L-C values are 3.4 h and 13.2 μfd for a 3.5 kv output voltage and 16 h with 2.6 μfd for a 7.5 kv output, both for 3.2 kw average demand. The filter problem is size and weight; weight will constitute 40 to 65 percent of the total equipment weight. Means for reducing the size of the filter include a controlled-carrier approach in which the transmitted carrier power is reduced but waveform proportions are retained to keep total power within the capability of the conditioner.

3.1.3.1.6 Control Circuits

Standard circuits are satisfactory. The controlled-carrier concept may change the design somewhat, which will require additional study.

3.1.3.2 Power Conditioner Circuit and Configuration

The power conditioner circuit is composed of modules of about 1 kw each, based on an input voltage of 100 volts with 10 amperes of current. A 3 to 4 kw conditioner would thus use four modules. The high voltage is based on series connections of the transformer secondary windings, and high voltage rectifiers operate as though they were a single transformer. The elementary circuit, where each transformer in a module is only required to provide one-fourth of the total volts, or 875 volts for a 3.5 kv supply is shown in Figure 3-8. This eases the breakdown problem somewhat within each module and the transformers having the lower peak voltages can have less insulation requirements.

The basic reason for adopting multi-modules is switching device efficiencies. Switching losses would be greater and efficiency would be less if transistors were paralleled. In addition, the average transistor life would probably be significantly reduced.

The power conditioner operating parameters were determined for a 3.2 kw output, 3.5 kv supply. Overall efficiency is on the order of 88 percent with the 98 percent efficient

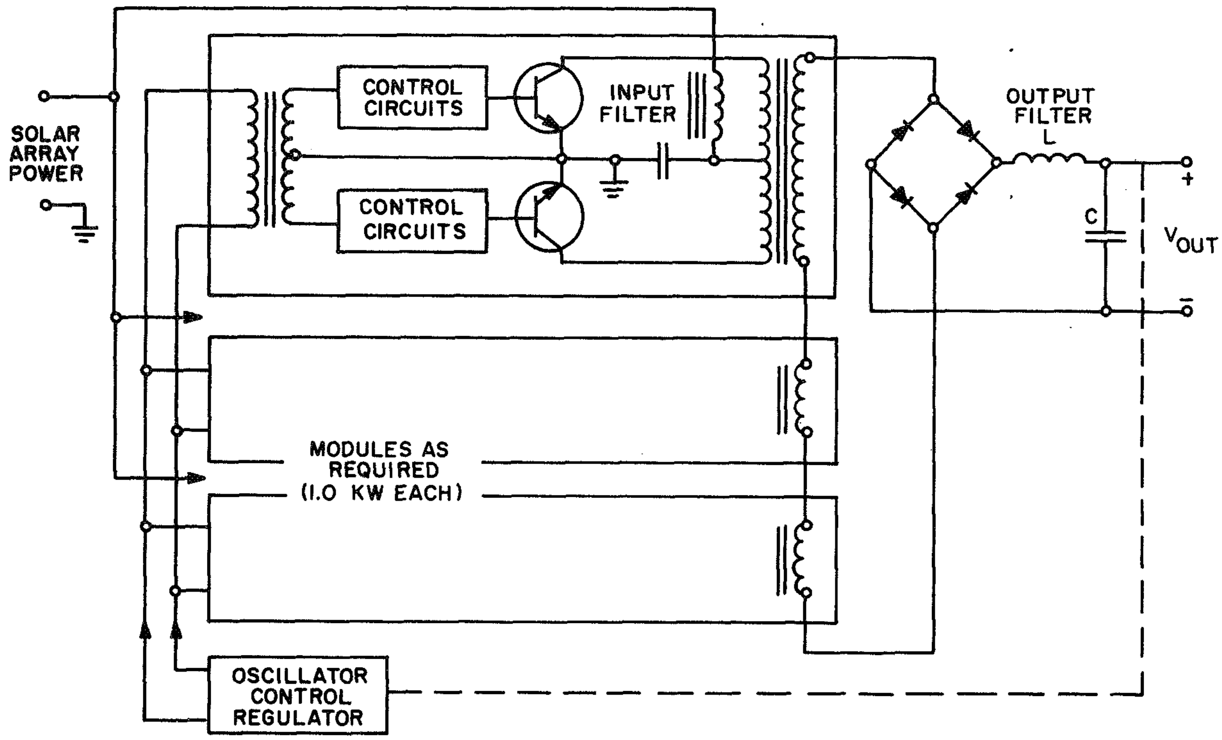


Figure 3-8. Power Conditioner

transformer, thus requiring 3.63 kw source power. A conservative evaluation of device performance indicated a 2 percent loss in transistors and rectifiers. Filters also have losses of about 2 percent each. Losses are converted to thermal energy which then must be removed in the same manner as all other dissipations. This conditioner can provide 2 percent regulation, an internal frequency of 4 kHz, and an internal current ripple of 5 percent. An open design is generally recommended with possible potting of isolated terminals for operating both in the atmosphere, for pre-launch testing, and in the high vacuum of space.

Mechanically, the power conditioner weights 110 pounds, of which 71 pounds is the output L-C filter. (The output filter is thus about 20 lb/kw while the rest of the conditioner is 11 lb/kw.) Filter weight reduction therefore is a major design factor to consider. The chassis for four modules (which may actually be integrated into a single assembly) is 30 x 14 x 6 inches.

3.1.3.3 General Conclusions on Dc Technology

The conclusions from the studies leading to the above results were:

1. Transistor switches should be used with one pair to a module to obtain high efficiency. This limits current in each module to 10 amperes input; each module has a 1 kw capability for a 100 volt input.

2. Secondaries of high voltage transformers within individual modules should be placed in series for high voltage applications.

3. Additional design efforts should be applied to transformers where voltages will be over 6 kv to reduce weight.

4. Output filters for AM energy storage should be re-evaluated; the techniques for using controlled carrier to reduce the energy storage filter are of considerable interest and should be investigated.

5. Recommended materials should be used; non-metal listing should be reviewed frequently, and additional investigations made to determine suitability for dc circuitry where data is uncertain.

3.1.4 RF HIGH POWER TECHNOLOGY

The possibility of electrical breakdown in high power RF circuitry also exists. Corona and arcing may occur with a tenuous gas present, multipacting can occur in RF components, and insulation can break down.

3.1.4.1 Corona and Arcover

Breakdown problems in a transmission line or RF components are similar to dc breakdown; Paschen's law generally applies. This law has been adapted to cover breakdown in various transmission line types. Typical breakdown powers as a function of gas pressure and waveguide height are shown in Figure 3-9, where the frequency effect also enters in terms of normalized recommended limits. Operation will usually occur somewhere between the recommended frequency limits shown, and the minimum breakdown power for rectangular waveguide here is on the order of 1000 watts. This is less than the power levels being considered, indicating that the RF equipment must not operate during the pressure ranges indicated. The worst conditions occur in ranges from 0.14 Torr for half-height UHF waveguide to 1 Torr for X-band standard waveguide. Thus operation should be avoided during ascent and until an initial bakeout period has removed most of the outgassing. The waveguide systems should be vented to eliminate the possibility of plasma accumulation within the guide, and to ensure that sublimating and outgassing after the bakeout interval can escape and not build up into a gas pocket.

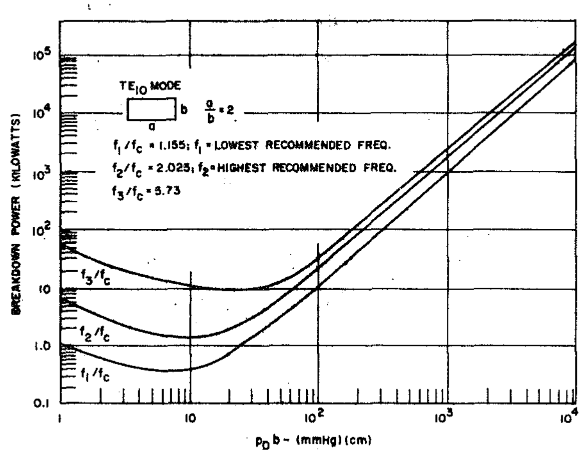


Figure 3-9. Arcover and Corona Breakdown Power in Waveguide

3.1.4.2 Multipacting

The multipacting phenomenon, mentioned in Section 3.1.2, is of considerable concern at RF since it operates independently of outgassing. Outgassing, if present, would aggravate the situation. The conditions for multipacting to occur are:

1. Pressure less than 0.1 Torr
2. Secondary emission coefficient greater than unity
3. Frequenty, voltage, and plate spacing related as:

$$d_{cm} = \frac{k \cdot \sqrt{V} \cdot (n_{odd})}{f(MHz)}$$

where k is about 12 (theoretical) and the n_{odd} indicates the order of multipacting modes possible. That is, the electron may take 3/2 cycles to cover the distance between plates rather than 1/2. Modes to 9/2 appear to provide a threat.

Analysis is complicated somewhat since the above relation does not have to be precisely satisfied, and an even broader range of action appears in practice. In addition, insulators will multipact as well as metals. Typical experimental data on the relation of RF voltage to the frequency-gap size product is indicated in Figure 3-10 for flat plates of copper and teflon and for coaxial lines. The coaxial line data shows the possibility of using a bias to eliminate the multipactor problem.

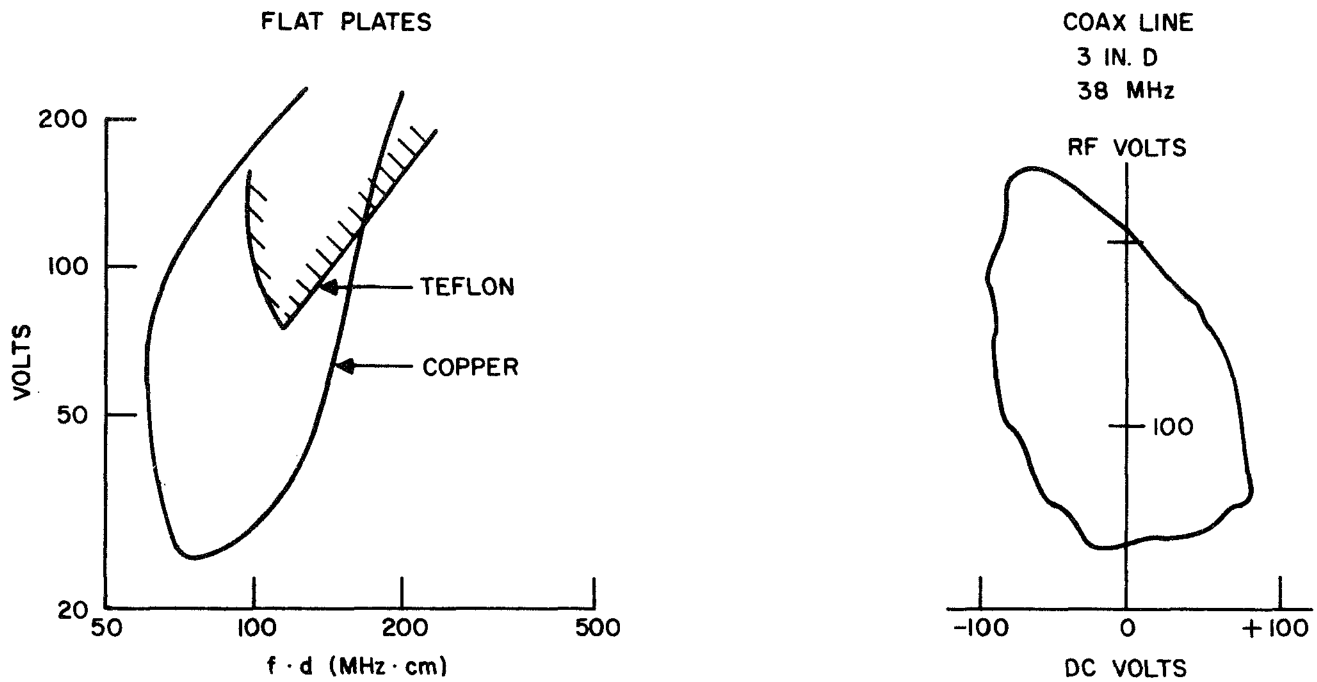


Figure 3-10. Multipacting Regions

3.1.4.3 Frequency Effect on Dielectrics

Most high frequency components produced commercially utilize materials that will stand up well at the required power levels. However, if potting or vacuum windows were to be included the electrical breakdown data would be of considerable concern. Typical reductions of electrical stress capabilities are indicated in the brief listing in Table 3-4.

3.1.4.4 General Conclusions

The conclusions on RF High Power Technology will be included in the overall RF general conclusions, Section 3.1.5.6.

3.1.5 RF HIGH POWER COMPONENTS

Defining the high power RF components and their capabilities was accomplished for the three transmitter configurations used in the Phase I study (see Section 2.1) determining the RF assemblies required by each and identifying components and their operational requirements.

3.1.5.1 Transmitter Systems

3.1.5.1.1 Eight-Channel S-Band FM TWT Transmitter

One of the three systems selected for conceptual design studies in the Phase I study was an eight-channel FM-TV transmitter using 2.5 kw output TWT's. The elementary block diagram of Figure 3-11 indicates the channel requirements. The 36 MHz wide FM channels with 12 MHz guard bands were found to be too close together for a reasonable size multiplexer with 30 dB isolation, and the decision was made to provide two multiplexers, each handling every other channel in the spectrum. This procedure results in 60 MHz separation, but requires two harmonic filters and two antennas. This appears to be a better approach at S-band than the very large multiplexer that otherwise would result. The overall system approach is shown in Figure 3-12.

Table 3-4. Electric Strength of Materials (volts/mil)

Material	60 Hz	100 MHz
Porcelain	232	60
Steatite	523	56
Alumina	298	69
Teflon*	850	143
Glass Cloth/Epoxy	774	Overheat

*Frequency has a dramatic effect on insulation electric strength

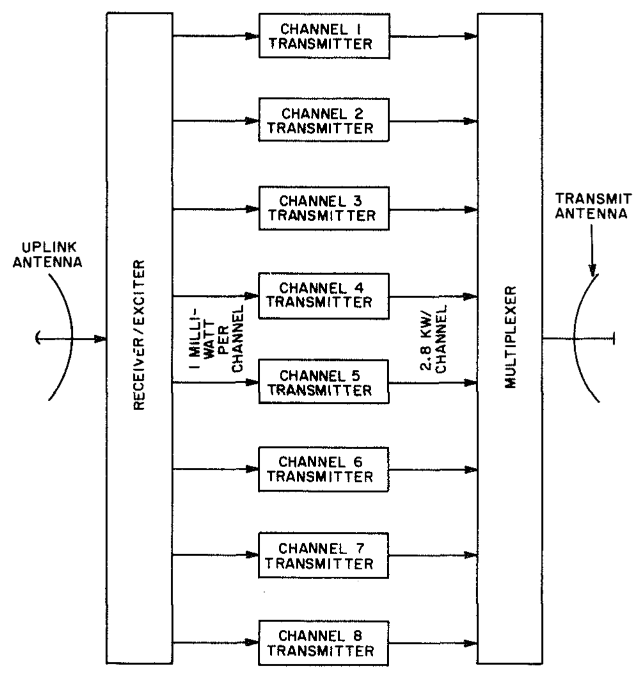


Figure 3-11. S-Band Eight-Channel FM TV Satellite Transponder

The monitor and protective requirements are indicated and are discussed in the supporting areas, Section 3.4.1 and 5.5.

The performance of this particular circuit includes:

1. Power Output - 2.5 kw per channel
2. RF Loss - 11%
3. Phase uncertainty - 2.1°
4. Weight - ground type equipment: 105 pounds (high end of band) or 176 (low end of band)
   - space design about 40% less weight
5. Volume - 2.6 ft^3 at high frequency end of band
   4.7 ft^3 at low end
6. Hot spot temperature - 23° above cold plate
7. No separate isolator required

The RF assembly will be discussed in Section 3.1.5.2.

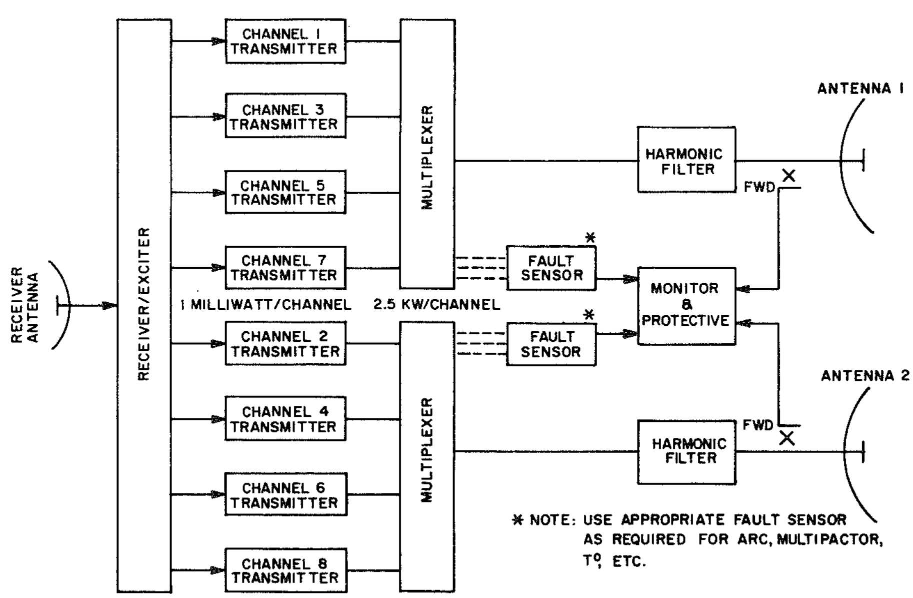


Figure 3-12. Eight-Channel FM Multiplexer Using Separate Antennas

3.1.5.1.2 Four-Channel UHF AM Gridded Tube Transmitter

The second configuration used four transmitters of 5 kw sync peak output power each, and is based on using advanced type triodes in Doherty high-efficiency amplifier circuits. The basic circuit is the same as half the eight-channel configuration, but is complicated by having separate visual and aural RF channels that must be combined in a diplexer for each channel. Thus, the multiplexer/diplexer of the circuits in Figures 3-13 and 3-14 will be somewhat larger and heavier than for an FM transmitter. A weight analysis indicated that half-height waveguide is lighter and much smaller than coaxial line for the RF assembly. In addition, a vestigial sideband filter and a color subcarrier image filter, peculiar to AM-TV transmitters, are required in each of the four channels. An isolator may be required in the output circuits if the VSWR, which appears to be marginal, is too high in the actual transmitters.

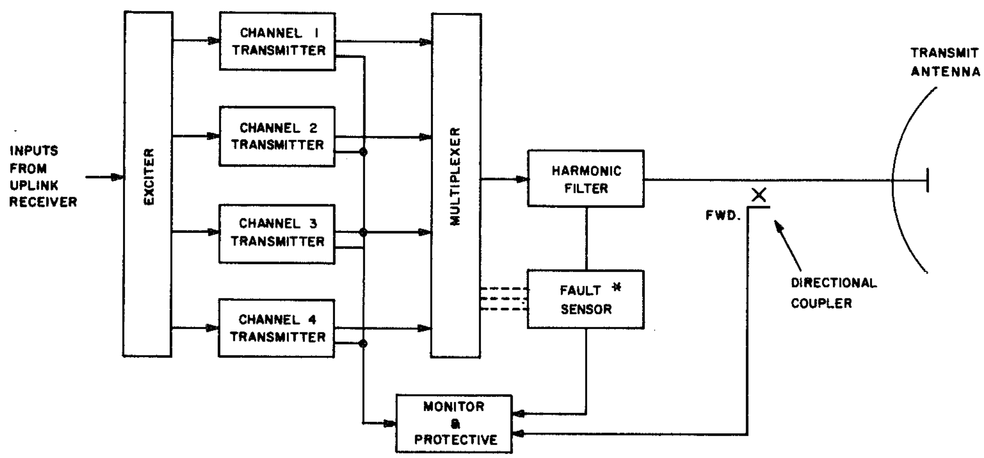


Figure 3-13. Basic Four-Channel Transmitter Block Diagram

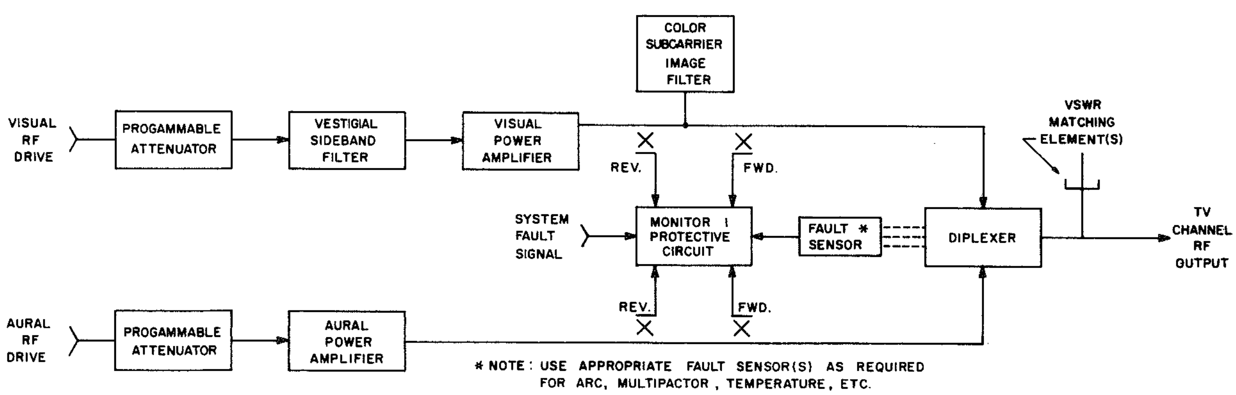


Figure 3-14. Circuit for a Typical High Power TV Channel

The general performance of this four-channel transmitter is:

1. Power out - 5 kw sync peak (visual) per channel
2. RF loss - average 13%
3. Phase stability - 3^{o}
4. Amplitude stability - marginal without isolator
5. Weight - ground type equipment: 784 pounds
   - space design about 40% less weight
6. Volume - 46 ft^3
7. Hot spot temperature - 13^{o} above cold plate
8. Channel isolation - 30 dB with 30 MHz guard band
9. Isolator required if load VSWR is worse than 1.15:1
10. May not require harmonic filter with linear amplifier

The applicable RF assembly is in Section 3.1.5.2. One variation of this transmitter to be considered is the use of separate antennas for the separately multiplexed visual and aural signals, which would reduce the RF losses to one-half that indicated above as well as reducing RF circuit weight substantially. However, UHF antennas are large and two antennas might not be preferred over the diplexing arrangement within the multiplexer.

3.1.5.1.3 One-Channel UHF AM CFA Transmitter

The third of the three transmitter systems is a 15 kw sync peak AM type using a UHF linear CFA. This tube is not yet available but was considered as a reference for comparing other system performance as well as a future candidate transmitter. The circuit, therefore, is very similar to one of the channels of the gridded tube type, as shown in Figure 3-14. However, the CFA tube has different requirements.

Because of the reverse transparency of the CFA, it is important that load reflected signals be attenuated rather than again amplified after reflection from the VSB filter and driver stage. An isolator (circulator and load) is included between the VSB filter and the CFA input terminal. Figure 3-15 indicates the RF circuitry arrangement, which details the diplexer arrangement and shows the monitor circuitry. A harmonic filter is required in addition to the VSB filter and the dual color subcarrier image rejection filters.

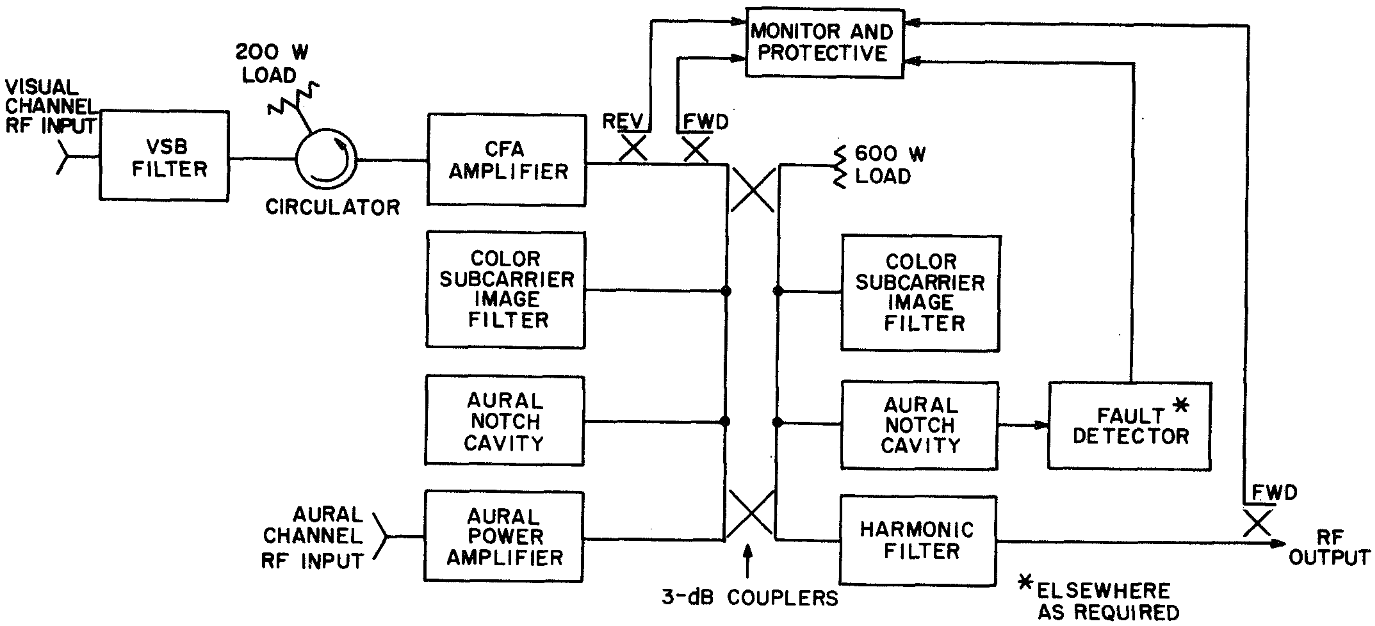


Figure 3-15. UHF Single-Channel AM Transmitter - 15 kw Sync Peak

Circuit performance is as follows:

1. Output - 15 kw (visual) sync peak

2. Loss in RF circuitry - 10%

3. Coaxial line used (if multipacting eliminated)

4. Circulator required (at CFA input)

5. Weight - 124 pounds (ground type equipment)
   - reduced about 40% for space equipment

6. Volume - 3.4 ft^3

7. Hot spot temperature - 25^{o}C above cold plate

3.1.5.2 RF Assemblies for Transmitters

3.1.5.2.1 Multiplexer for Eight-Channel Transmitter

A number of possible configuration can be considered, ranging from a separate antenna for each channel to an eight-channel multiplexing circuit to feed all eight channels to a single antenna. The compromise selected was two four-channel multiplexers with two antennas; the eight-channel multiplexer was much too large for a space system. The circuit is based on the use of 3 dB directional couplers with bandpass filters to provide the interchannel isolation required. The S-band circuit, whether based on WR 340 waveguide for operation near 3.0 GHz or the WR 430 guide nearer the 2.0 GHz end of the band, would use sidewall 3 dB hybrids, six in each of the two multiplexers, and inductive iris type filters, also six for each four-channel multiplexer. The resulting circuit arrangement is shown in Figure 3-16. The average loss is about 5 percent of the transmitter power; the same arrangement could be used for the UHF system with about the same losses. Components of the multiplexer are discussed in Section 3.1.5.3.

3.1.5.2.2 Multiplexer/Diplexer for UHF Four-Channel Transmitter

The multiplexer circuit for AM TV systems is complicated by the diplexing of the visual and aural RF signals in each channel. In addition to the six 3 dB couplers and the six bandpass filters as mentioned above for a four-channel multiplexer, eight additional couplers and eight aural notch filters are required. Half-height WR 1150 waveguide components have been recommended for this circuitry, and the general component approach is the same as for the S-band case. Figure 3-17 shows the overall RF circuit required. The average loss for this circuit is about 10 percent. The aural notch filters are band reject types; the visual channel filters are four-section inductive iris bandpass types.

An alternative circuit uses two multiplexers as in the previous eight-channel case with one multiplexer handling the four visual RF signals and the other the four aural RF signals. The system would then require two antennas, but the RF losses would drop to 5 percent. A small reduction of multiplexer weight would result, but at the expense of the added antenna weight.

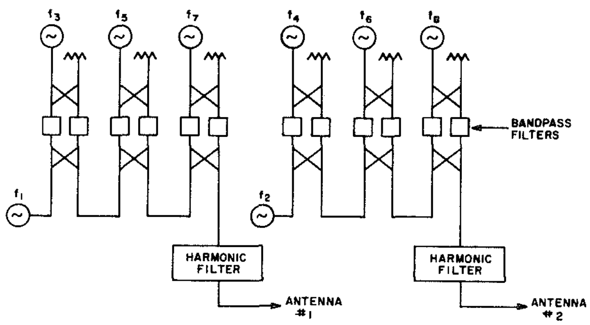


Figure 3-16. S-Band Multiplexer Configuration for Two-Antenna System Employing Hybrid Diplexers

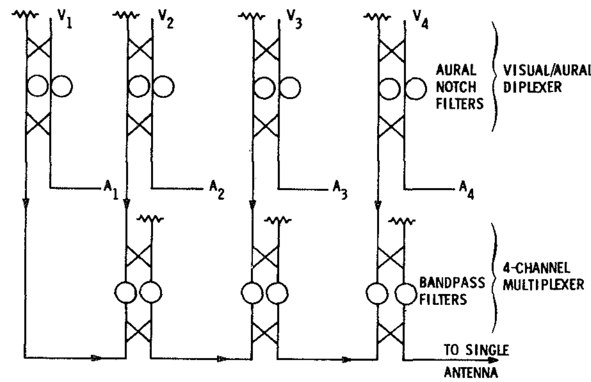


Figure 3-17. Four-Channel UHF Multiplexer Configuration Employing Single Antenna with Single Polarization

3.1.5.2.3 Diplexer for Single Channel UHF AM CFA Transmitter

The single channel UHF AM amplifier requires only a diplexer to combine the visual and aural RF signals. The diplexer is made up of two 3 dB hybrids and two aural channel notch filters that reject the aural RF signal and transfer it to the output terminal of the antenna. The color subcarrier image filters are placed within the diplexer to minimize their effects on the VSWR at the CFA. Figure 3-15 indicated the components used in the diplexer. Coaxial components are used since there is no multiplexer requirement and the very large four-cavity visual channel bandpass filters are not used. The notch filters may be stub types, which are considered under components in Section 3.1.5.3. The losses in the diplexer are about 6 percent in the visual channel and 8 percent in the aural channel.

3.1.5.2.4 Vestigial Sideband Filter for AM Transmitters

The VSB filter is to reject the lower sideband of the AM RF signal below 0.75 MHz. One approach is to use a series of notch filters stagger-tuned over the rejection band. A typical circuit, showing two 3 dB couplers and three pair of notch filters, is indicated in Figure 3-18. The attenuation characteristic and resulting VSWR are included in the figure. This is typical of the VSB filters used commercially; it has a weight of 54 pounds and occupies about a cubic foot of volume. The passband loss is about 12 percent, but the loss is on the driving power and represents only a relatively few watts. The components within the unit are coaxial construction for an input-type VSB filter.

The amplifier output losses with an input VSB filter are primarily those of the diplexer and the color subcarrier image filter. A comparison of the input and output type VSB filter circuits for the one-channel CFA transmitter shows:

	Input VSB Filter	Output VSB Filter
Visual Power Loss (%)	6	12
Aural Power Loss (%)	12	12
Weight (less multiplexer) per channel (lb)	232	950

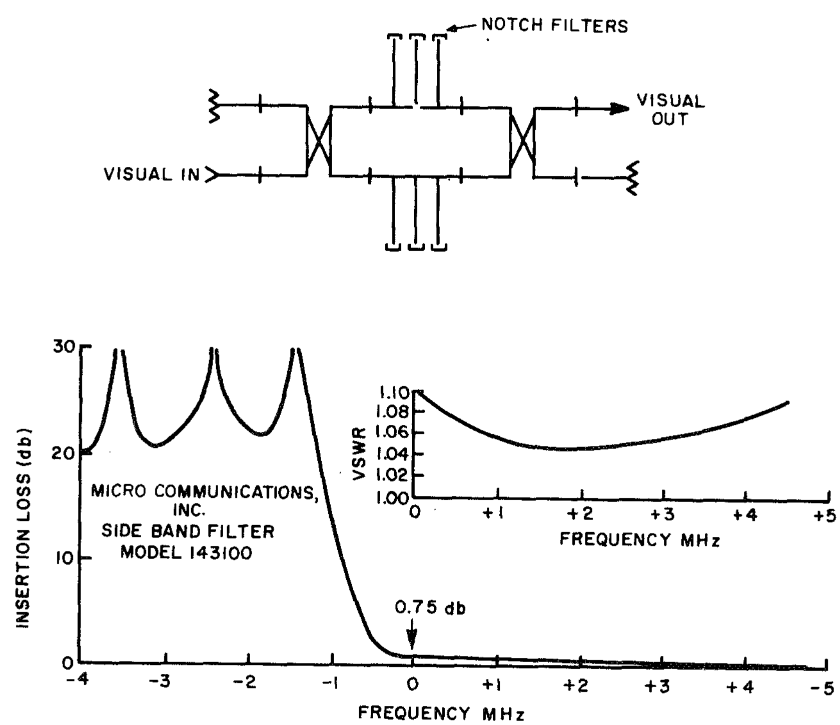


Figure 3-18. Circuit for Microwave Communications, Inc. Model 43100 VSB Filter

These weights may be reduced by up to 40 percent in a space design where light weight is an objective.

3.1.5.2.5 Color Subcarrier Image Filter for AM Transmitters

The color image filter reduces the subcarrier lower sideband to at least -42 dB (referenced to the 20 kHz upper sideband average level). The VSB filter reduces the image signal to between 20 and 30 dB below the reference, per Figure 3-18. The CI filter is a single-cavity, stub-type rejection filter, either waveguide or coax, whichever is used in the system. A typical commercial coaxial unit weighs 18 pounds, but can be made lighter by judicious use of weight-lightening design techniques. Waveguide types are slightly heavier than coaxial. Loss in this filter is expected to be about 1 percent. Stub filters are discussed further in the following section on RF components.

3.1.5.3 RF Components

The components listed below are those used in the various RF assemblies and systems described above.

3.1.5.3.1 Transmission Lines

The lines recommended for use in the three transmitter configurations are:

Band	Frequency Range	Line	Dimensions
8-channel S-Band	2.6 to 3.0 GHz	WR 340 Guide	3.4 x 1.7 in.
	2.0 to 2.6 GHz	WR 430 Guide	4.3 x 2.15 in.
UHF	0.7 to 0.9 GHz	Half-Weight WR 1150 Guide	11.5 x 2.875 in.
UHF	0.7 to 0.9 GHz	Air Core Coax	3-1/8 in. diam.

For low power driving circuits, the following may also be used:

Band	Frequency Range	Line	Dimensions
S-Band	2.0 to 3.0 GHz	Air Core coax	1-5/8 in. diam.
	2.0 to 3.0 GHz	Teflon Core coax	7/8 in. diam.
UHF	0.7 to 0.9 GHz	Air Core coax	1-5/8 diam.

3.1.5.3.2 Harmonic Filters

Harmonic filters are of two types: absorptive and reactive. Pure reactive filters may set up large VSWR's at harmonic frequencies since they present a reactive load impedance. An absorptive pad may be placed between the tube output and the reactive filter. The absorptive type can have less attenuation than if the reactive type weren't used at all, but VSWR's are maintained within reasonable limits. In addition, this arrangement would remove the high VSWR's of the reactive filter and have less signal loss than a purely absorptive type. This simple arrangement is shown in Figure 3-19.

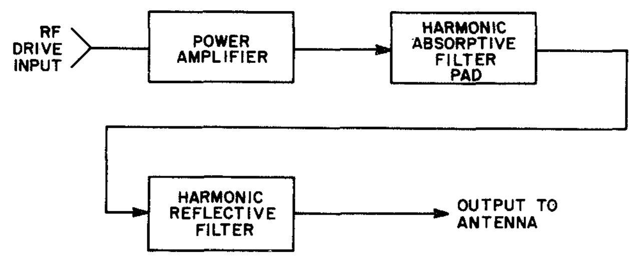


Figure 3-19. Use of an Absorptive-Type Harmonic Filter as Impedance Matching Pad

Typical waveguide and coaxial type reflective filters are shown in Figure 3-20. One difficulty that may appear is that these filters are subject to multipacting, particularly the coaxial type used in the UHF single channel 15 kw transmitter. Thermal control measures will be necessary since the filters will have high harmonic losses.

The absorptive filter can be the "leaky wall" type in which irises permit harmonics to pass into cavities having absorbing material. A waveguide type is shown in Figure 3-21. This may have relatively light attenuation and be used as a pad for the reactive type filter, or may be designed to accomplish the entire task of absorbing the harmonic power without additional circuitry. The latter would weigh considerably more than the combination filter. A coaxial version of the leaky wall filter is also available.

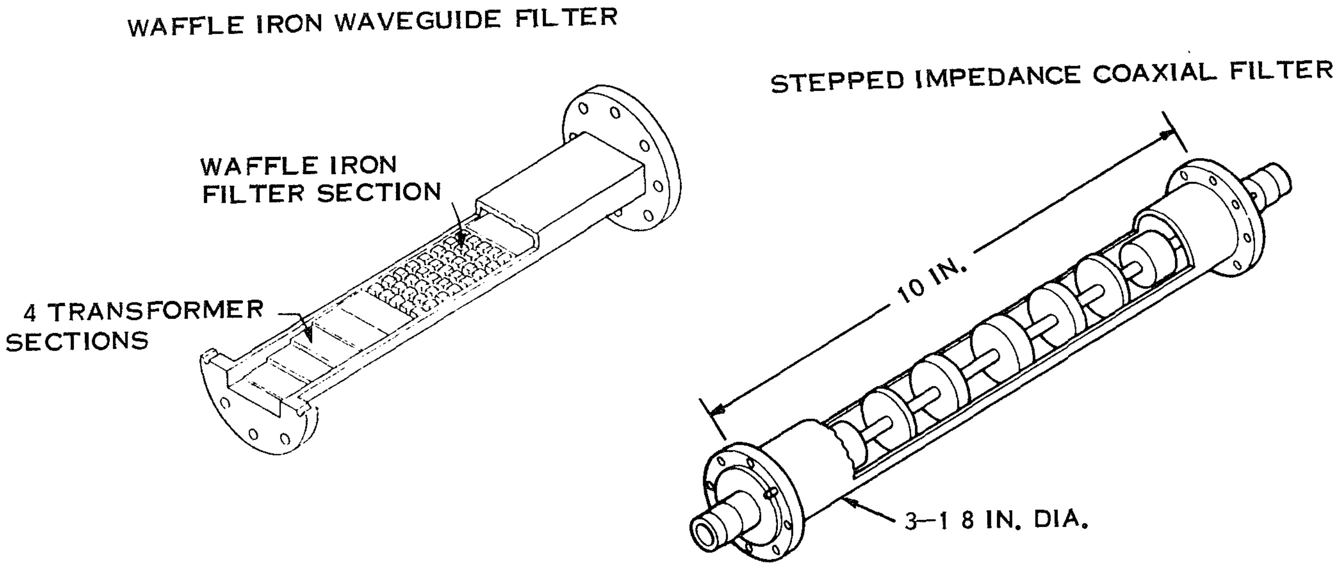


Figure 3-20. Examples of Waveguide and Coaxial Reflective Filters

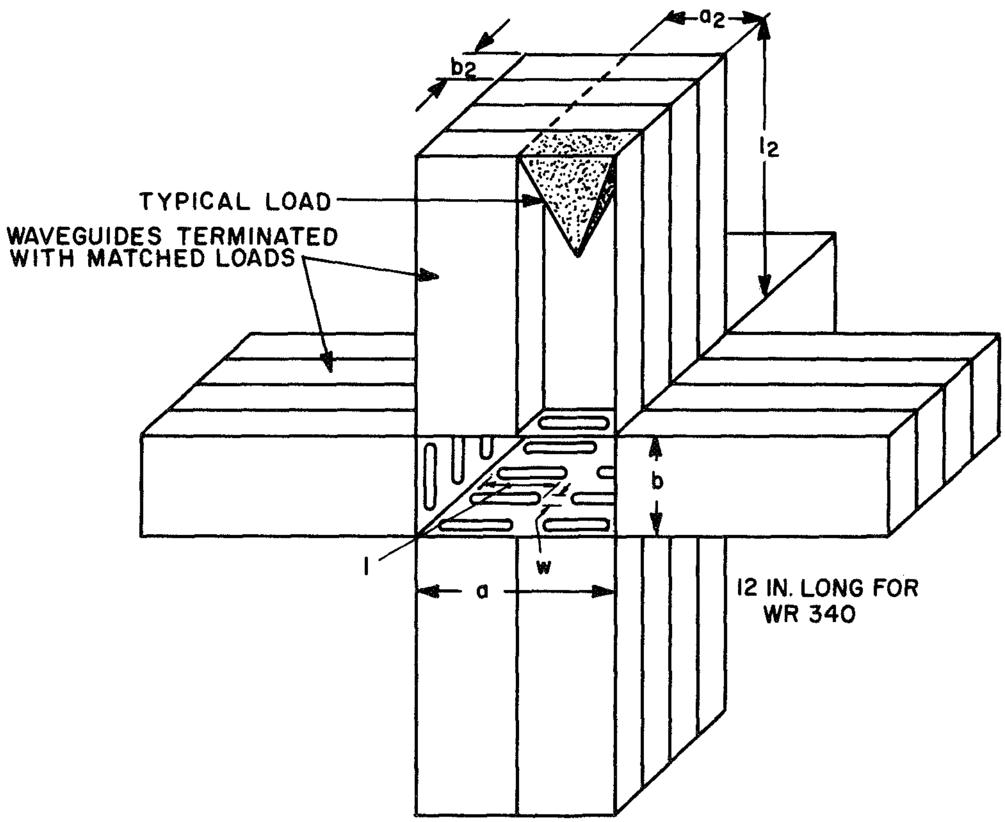


Figure 3-21. Typical Construction of a Leaky Wall Dissipative Waveguide Filter

3.1.5.3.3 Hybrids

For power combining and dividing, 3 dB hybrids are used. They also constitute a major part of multiplexers and diplexers as considered in Section 3.1.5.2. Standard waveguide couplers are the sidewall and topwall short slot types, shown in Figure 3-22. These have low losses per unit (0.5 percent) with coupling variations of 2 percent in amplitude and up to 3 degrees in phase.

Two common types of hybrids are available for coaxial UHF systems. The slab-line type and branch-line types are shown in Figure 3-23. There are only small performance differences between the two. The branch type made up of 1/4 wavelength lines is likely to have poorer VSWR's at harmonic frequencies and might require additional harmonic filtering.

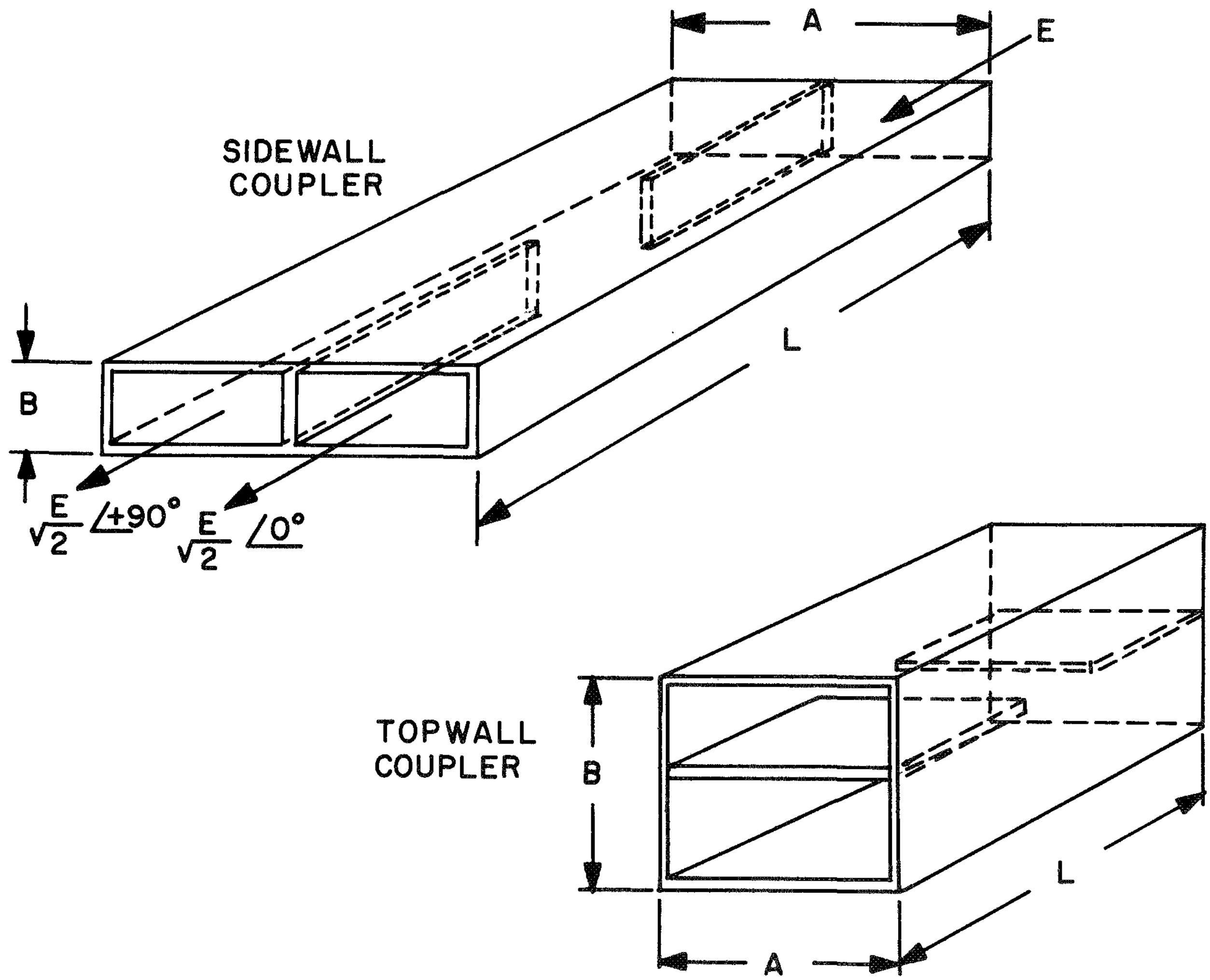


Figure 3-22. Waveguide 3 dB Short-Slot Hybrid Coupler

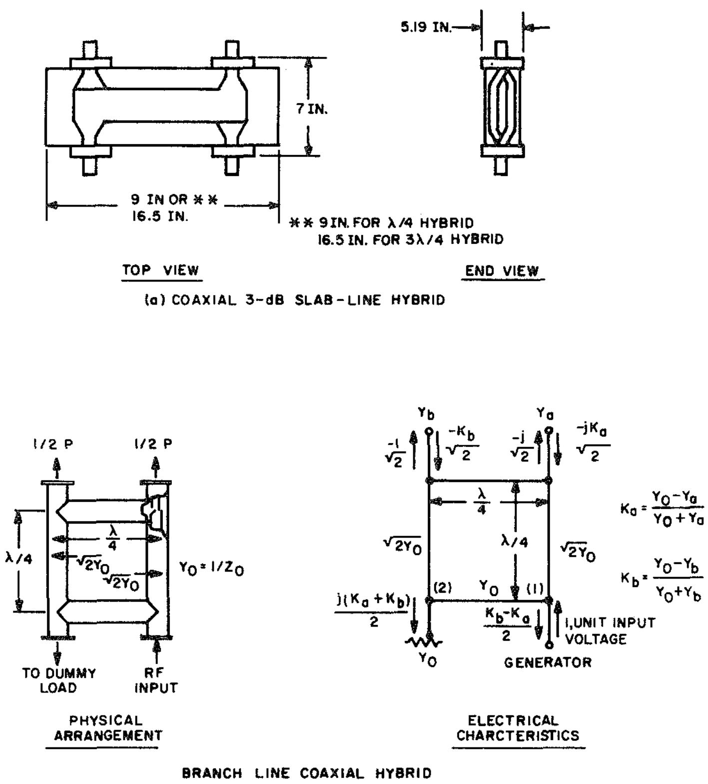


Figure 3-23. Coaxial Hybrid Couplers

3.1.5.3.4 Bandpass Filters

Bandpass filters are used in the multiplexers to pass the desired channel and to reflect all other channels when used as shown in Figure 3-16. S-band RF system filters are inductive-iris types with four cavities. The same general type is used for either S-band or UHF waveguide assemblies. Aditional cavities could also be included although four cavities appear to be sufficient. The filter can also be realized in a coaxial configuration; both are shown in Figure 3-24. Diplexer operation is usually acceptable with single cavity filters since the aural channel bandwidth is quite narrow. This would apply to both coaxial or waveguide filters.

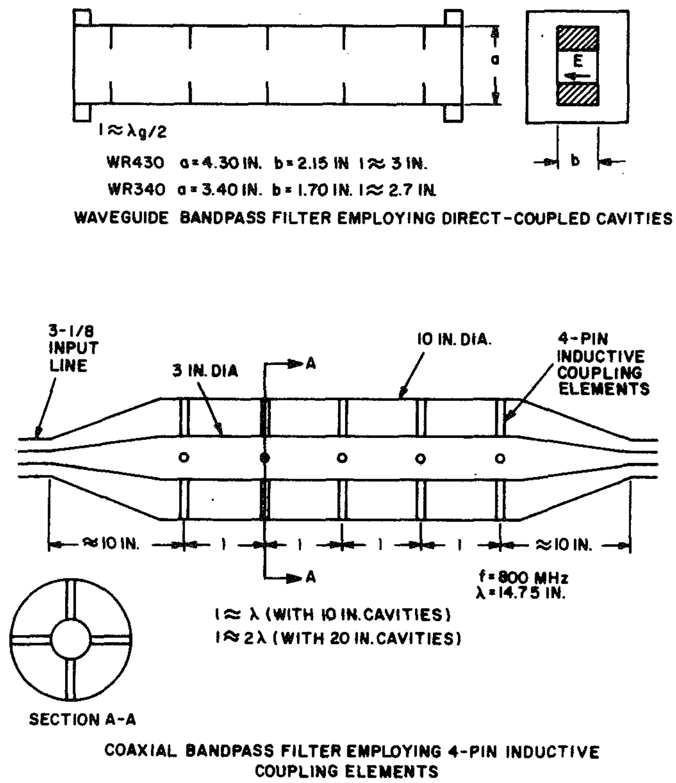


Figure 3-24. Bandpass Filters

3.1.5.3.5 Notch Filters

Notch filters, which reject an RF signal, are used in diplexers designed to route the narrow aural channel away from the visual channel RF circuitry and to the antenna, and for color subcarrier image rejection. A typical filter is a 1/2 wavelength stub on a coax or waveguide line; the design of a practical type filter is shown in Figure 3-25.

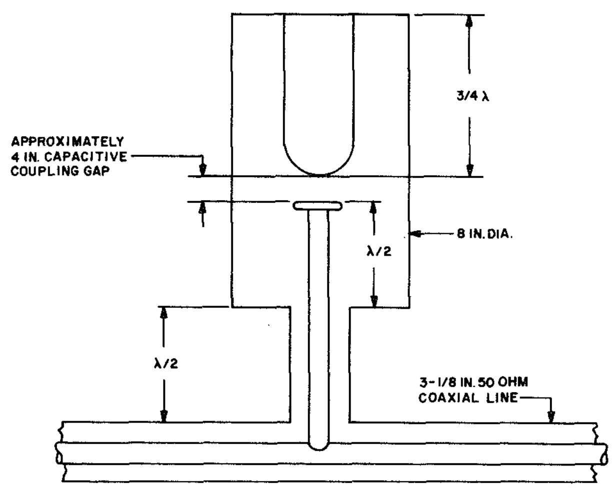


Figure 3-25. Schematic Diagram of Coaxial Notch Filter

3.1.5.3.6 RF Loads

In the circuitry using 3 dB hybrid couplers, primarily the multiplexers of Figures 3-16 and 17 and diplexers of Figures 3-15 and

17, loads are shown on the unused terminals. The loads usually absorb harmonics and unwanted reflected power from the output line. Both coaxial and waveguide loads may be required, depending on the frequency and circuit used.

Coaxial loads will require a resistive film or material on the center conductor, with a suitable taper section for impedance matching. The absorbed power will be converted into heat that must be conducted to thermally radiating plates. Figure 3-26 shows two coaxial loads, one for smaller power levels connected directly to a heat sink, and the second with a heat pipe built into the center conductor to transfer heat to remotely located heat sinks. Typically, a coaxial load weighs a few pounds. Waveguide loads are also possible, using lossy materials or film resistors to convert the RF into thermal energy; the waveguide can the be terminated with a cold plate or a heatpipe, depending on heat level and location limitations on the radiating cold plate. Figure 3-27 illustrates two waveguide load types. Power requirements vary from 25 watts for the S-band circuitry to as high as 600 watts for the CFA UHF transmitter.

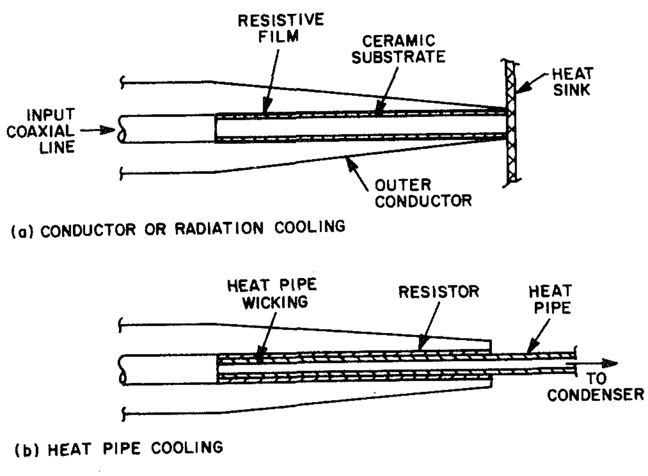


Figure 3-26. UHF Coaxial Loads

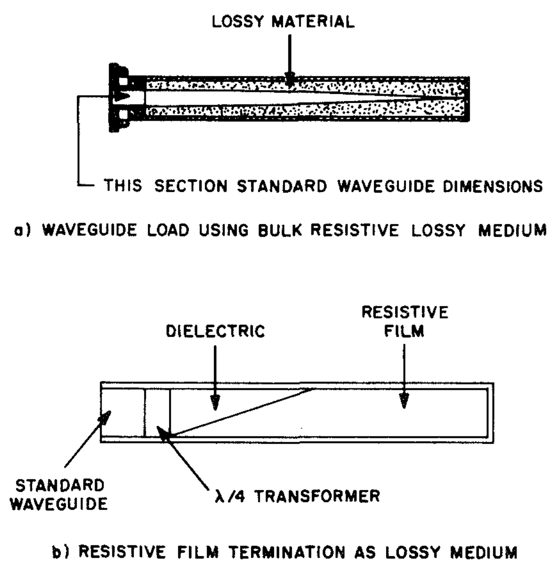


Figure 3-27. Waveguide Loads

3.1.5.3.7 Isolators and Circulators

A circulator was shown in the CFA driver line in Figure 3-15; this would be a conventional stock components, with a suitable 600 watt load. Except for materials used in the construction that might outgas and cause electrical breakdowns, the component has no critical characteristics. A similar isolator (circulator with load) might be required for the gridded tube amplifier output although this has not been established as yet. Again, conventional components would be used.

3.1.5.4 High Power Electrical Breakdown

In considering electrical breakdown, arc-over and corona, due to local gas pressures, and multipacting effects were given most attention. Arc-over and corona will occur whenever the gas pressure is within certain limits. RF voltages will usually be less than the dc voltages in the TWT and CFA transmitters. The gridded tube RF voltages at the anode will swing up to almost twice the supply voltage but it uses a lower supply voltage. The net effect is that there should be little difficulty in any of the three configurations if the gas pressure is low, preferably below 10^{-5} Torr where dc problems are not encountered. A problem in the RF system is the inherent nature of waveguide and coax to enclose volumes in which gas pockets may collect. Vents will have to be located wherever an outgassing material exists, such as in the RF loads. Vents should also be located in the transmission lines at strategic places to ensure that metal sublimation will not accumulate and that any outgassing materials will be exposed to the vacuum for dispersal.

Multipacting breakdown depends on the relations between electrode spacing, electric field, and RF frequency. It can also occur in modes that have odd multiples of the gap spacing of fundamental-mode multipacting. Each of the RF components considered was evaluated and multipacting possibilities determined for up to nine times the fundamental multipacting mode (an electron would take 4.5 cycles of RF to cross between electrodes). The components of particular concern, which include several coaxial components plus waveguide harmonic filters, are listed in Table 3-5; these should be checked thoroughly in a high vacuum before installing in a transmitter. All other components will not multipact within the operating ranges considered in this analysis, but a high vacuum check on the final system should be included to confirm this.

Table 3-5. Summary of Multipacting Conditions

Component	Operating Conditions: Power (kw)	Operating Conditions: Voltage* (Max. kv)	fd (MHz-cm)	Multipacting Voltage Range (kv)	Comments
3-1/8 inch Coax (700) MHz)	15	0.87	1575	0.55-5	May multipact in high order modes
Waffle-Iron (S-band) Filter	2.5	0.4	700	0.25-1.3	Multipacting likely
	4 @ 2.5	1.6	700	0.25-1.3	Multipacting likely
Waffle-Iron (UHF Filter)	5.0	0.57	700	0.25-1.3	Multipacting likely
	4 @ 5 ea. + 4 @ 0.5 ea.	3.0	700	0.25-1.3	Multipacting likely
	15	0.99	700	0.25-1.3	Multipacting likely
Coaxial, Stepped Inner Conductor (UHF)	15	0.87	500	0.18-2.4	Probably will multipact
Waveguide Hybrid Sidewall (UHF)**	4 @ 5 ea. + 4 @ 0.5 ea.	7.98	5000	7.5 - 30	Slight chance of multipacting in high order modes
Coaxial Hybrid, Slab Line (UHF)**	15	0.78	500	0.18-2.4	Probably will multipact
Coaxial Hybrid Branch Line (UHF)**	15	0.71-0.87	1210 & 1575	0.4-3.0	May multipact in high order modes
Coaxial Aural Notch Diplexing Filter (UHF)	1.5	14.5	6700	13-30	May multipact in high order modes
Circulator, 7/8 inch Coax (UHF)	0.2	0.2***	390	0.15-1.5	May multipact in the fundamental or 3/2 mode

*Voltages are for unity VSWR. Multiply by VSWR for actual operating voltage and check multipacting range.
**Voltages are calculated for multiplexer service.
***Voltage includes reflection from a short-circuited port to simulate worst case condition

3.1.5.5 Thermal Control of RF Circuitry

Thermal control of the RF absorbed energy is generally not a difficult problem due to the relatively low power losses (10 to 20 percent of the tube losses) and the distributed nature of the surface where heat is generated. However, the transmitter system must be designed to remove the heat before an accumulation would raise the temperature of the circuitry and result in line and cavity distortions. A cold plate attached to the broad side of the guide will suffice for most waveguide components. For coaxial components, low heat flux may be brought out on $\lambda/4$ stubs that are directly attached to a cold plate. High losses such as in the multiple-cavity bandpass filters may require the use of heat pipes as coax center conductors, except where high temperatures must be permitted. The RF loads are perhaps the worst problems, and here again the question of tolerable temperatures arises. As an example, the 600 watt load on the 15 kw CFA transmitter will assume a temperature near 475°C with only conduction cooling, but will hold to 125°C with a heat pipe built in. Filter absorption also tends to heat the coax center conductors, ranging from 232°C in a notch filter to 325^{o}C in a harmonic filter with conduction cooling. Thus, a problem exists and suitable techniques will have to be incorporated to ensure thermal compatibility.

3.1.5.6 General Conclusions

From the foregoing, the following general conclusions were extracted:

1. The three transmitter configurations from the Phase I study are suitable for design into a satellite system as far as the RF circuitry is concerned.

2. The eight-channel S-band FM-TV transmitter should use two four-channel multiplexers, each feeding a separate antenna.

3. The four-channel UHF-AM-TV transmitter could have lower losses if the visual and aural channels were multiplexed separately and applied to separate antennas, but two antennas would be required.

4. RF circuitry is determined for each of the three transmitter configurations; data is obtained for conventional components that could be improved for space systems by special design efforts.

5. The four-channel, one-antenna UHF gridded tube transmitter would use half-height WR 1150 waveguide; the one-channel CFA UHF transmitter would have less weight with coaxial lines and components; the S-band transmitter uses waveguide for all output RF circuitry.

6. Multipacting is likely in only the waffle-iron filter for the S-band system. This filter is also susceptible to multipacting at UHF in waveguide and coaxial configurations. Coax line itself may multipact in high order modes, and six coaxial components in particular are considered to be susceptible to multipactor breakdown.

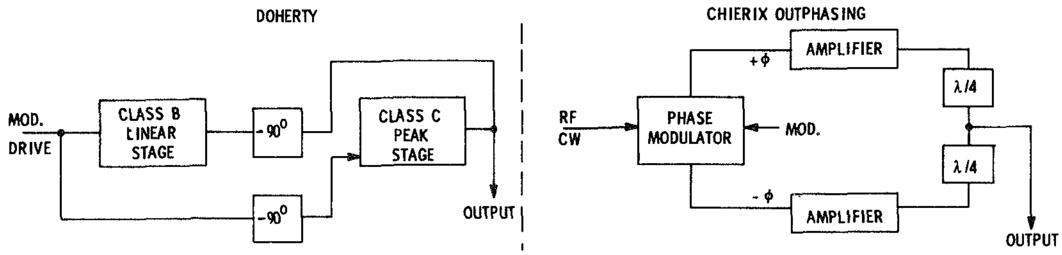
7. Thermal control is required, but is not a difficult problem except perhaps in the loads that terminate the unused terminal of hybrid couplers.

3.2 UHF AMPLIFIER BREADBOARD

3.2.1 COMPARISON OF AMPLIFIER TYPES

The two amplifiers selected as best for high efficiency operation for AM TV at UHF, as determined from the Phase I study, were the Doherty and Chireix Outphasing. These were evaluated further to determine which factors in each were advantageous and which were undesirable, identifying the most important features and determining which circuit should be breadboarded.

The Doherty circuit was preferred since it was relatively insensitive to phase instabilities, was simpler, and could use an input type VSB filter (see Section 3.1.5.2.4). Figure 3-28 summarizes this situation. The Chireix Outphasing could provide the required operation, but by virtue of its process of obtaining an AM output signal from two input phase modulated signals, it is sensitive to both phase and amplitude aberrations and would most likely require two feedback loops to linearize. It is more complex since it requires two matched amplifier chains instead of the single chain in the Doherty, and can use only an output type VSB filter, which is heavier and lossier than an input type. The Doherty selection for breadboarding was based largely on the complexity consideration.



BLANKING LEVEL (75% V): ± 2.5% SYNC PEAK

AMPLITUDE SENSITIVITY	4.45% MIN	3.3 - 6.8%
PHASE SENSITIVITY	7° - 11°	1.5° - 3°
LINEARITY	ONE FEEDBACK LOOP ENVELOPE	TWO FEEDBACK LOOPS ENVELOPE CHANNEL EQUALIZATION
COMPLEXITY	TWO STAGES	TWO OR MORE STAGES TWO AMPLIFIER CHAINS TWO PHASE MODULATORS
VSB FILTERS	INPUT LOW WEIGHT	OUTPUT DOUBLE WEIGHT

Figure 3-28. Amplifier Comparisons

3.2.2 THE INTERDIGITAL DOHERTY AMPLIFIER

The breadboard amplifier was designed to produce about 50 watts peak output, using a pair of Y1692's in an interdigital type RF circuit. This type of circuit uses a series of posts and the cavity volumes. Figure 3-29 shows the amplifier as developed; the interdigital structure provides the 90-degree phase shift required for Doherty operation. The inputs also have a 90-degree difference, generated by an external 3 dB hybrid coupler that also divides the input drive power between the two tubes. An additional output coupling circuit was added to provide a better load match to the amplifier.

Unfortunately, the developmental Y1692 tubes varied substantially in characteristics, particularly in the plate-grid capacitance. The tuning range of the amplifier was not sufficient to permit optimum operation without rebuilding the amplifier, which wasn't possible in this program. The efficiency achieved is about the same as would be expected from a Class B linear amplifier, shown in Figure 3-30. Maximum efficiency at 40 watts output was about 47 percent, indicating that operation was generally quite poor. However, with a careful redesign and a better established tube, this circuit should provide the required efficiency, and it should be considered some time in the future for possible high power breadboarding.

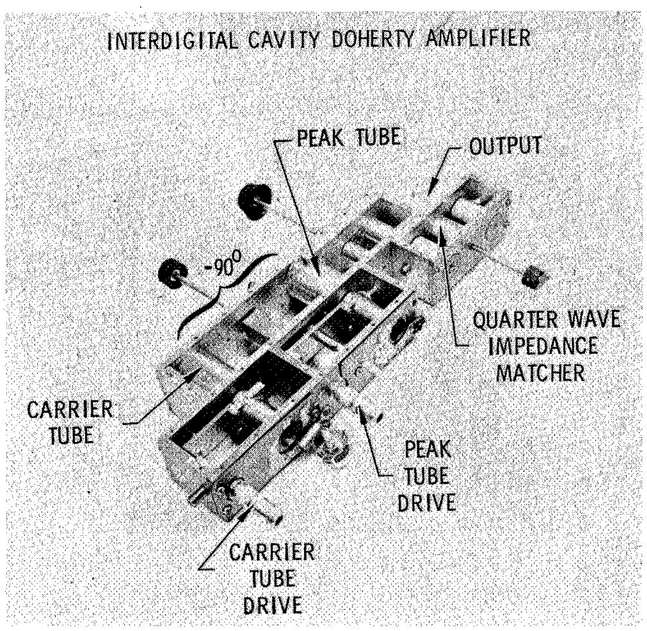


Figure 3-29. Interdigital Cavity Doherty Amplifier

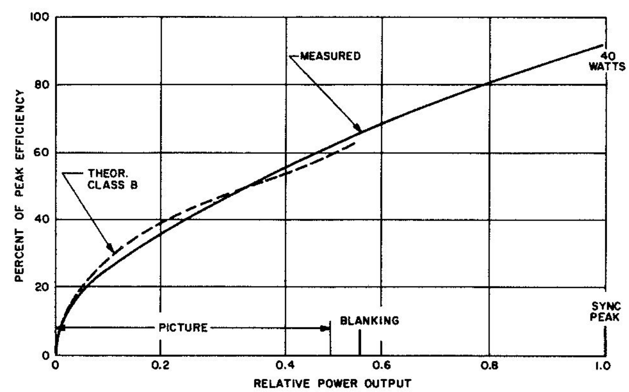


Figure 3-30. Doherty Operation of Interdigital Cavity Amplifier

3.2.3 THE TWO-CAVITY DOHERTY AMPLIFIER

A low power Doherty circuit using 2C39 tubes with commercial cavities was evaluated in an independent program, to determine Doherty performance at UHF. The 2C39 tubes are well standardized but do not provide the high efficiency desired in a final Doherty demonstration amplifier. The amplifier breadboard is shown in Figure 3-31. This has the 90-degree phase shifter line between cavities (a 50-ohm line in this case) and the independent input lines that are preceded by a 3 dB power splitter which also provides the required 90-degree phase shift between the input signals. Adjustment of couplings and tuning can be accomplished over a wider range here, although the tuning was not a problem since the cavities were designed to operate with the 2C39 tubes.

Doherty operation was obtained with this amplifier. Measured values of efficiency as a function of output power are shown for a single Class B stage and for the Doherty amplifier (as well as the theoretical Doherty efficiency) in Figure 3-32. Theoretical performance

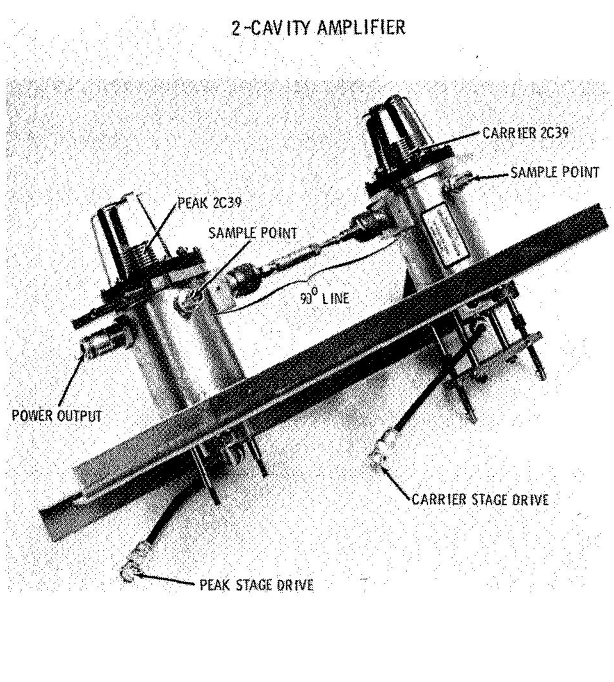


Figure 3-31. Two-Cavity Doherty Amplifier

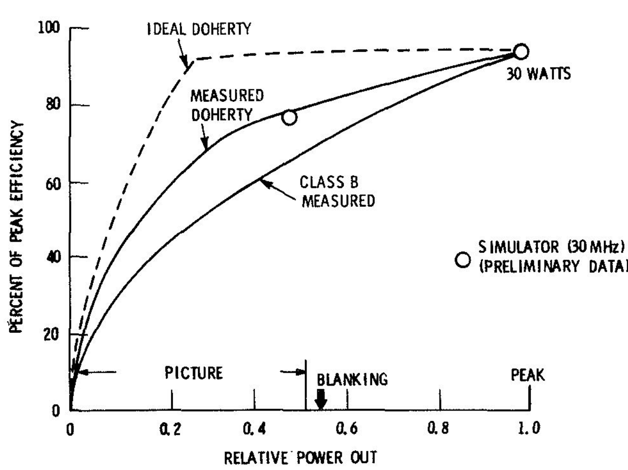


Figure 3-32. TwoCavity Doherty Efficiency

will probably not be obtained since it does not include the paralleling losses of the two tubes and the lossy-capacitor effect of the peak tube when it is idling (at inputs under one-half peak input voltage). However, it is known that the peak tube was not operating in an optimum manner and the load impedance of the carrier tube was not varying properly. Thus, optimizing methods for Doherty circuit operation are an early future objective.

3.2.4 30 MHz DOHERTY SIMULATOR

Achieving optimization of Doherty operation could be accomplished by a computer program that incorporates the factors involved in a grounded-grid Doherty amplifier, using characteristic curves of tubes rather than approximations in terms of tube constants. However, a simulator at 30 MHz was selected as being more realistic and capable of providing data more closely adaptable to an actual UHF amplifier. The simulator was devised to use lumped constants, which can be varied more easily and confidently, to determine the optimum operating parameters of a grounded-grid Doherty amplifier. Figure 3-33 shows the amplifier breadboarded. Two GL7913 tubes are used, providing a maximum output of 4 to 5 watts. The biases, drive signals, load coupling, and 90-degree lines are variable over wide ranges.

The initial data obtained from the simulator showed Doherty operation. This circuit was developed recently in an independent program. Operation has not been optimized, and further effort will be required. Data showed that performance was about comparable to that of the two-cavity amplifier. The power output variation as a function of input power is shown in Figure 3-34. Note that the peak efficiency was about 70 percent, suggesting that good peak operation was obtained, but intermediate levels were not up to optimum theoretical values. The intent is to use the simulator to determine optimum drive and bias relations, and to confirm the magnitude of efficiency reduction (estimated at about 10 percent) when the input signal is below the cutoff of the peak stage (which acts as a lossy capacitor to the carrier stage). In addition, the coupling of the 90-degree line can be simulated to include the coupling probe impedance effects.

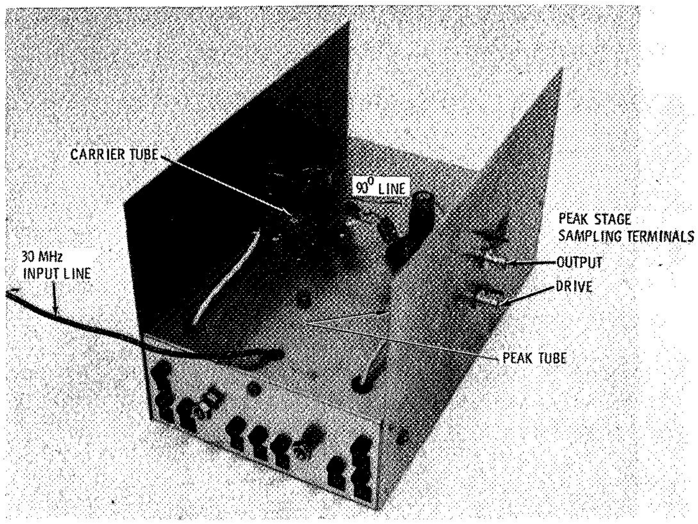


Figure 3-33. Doherty 30 MHz Simulator

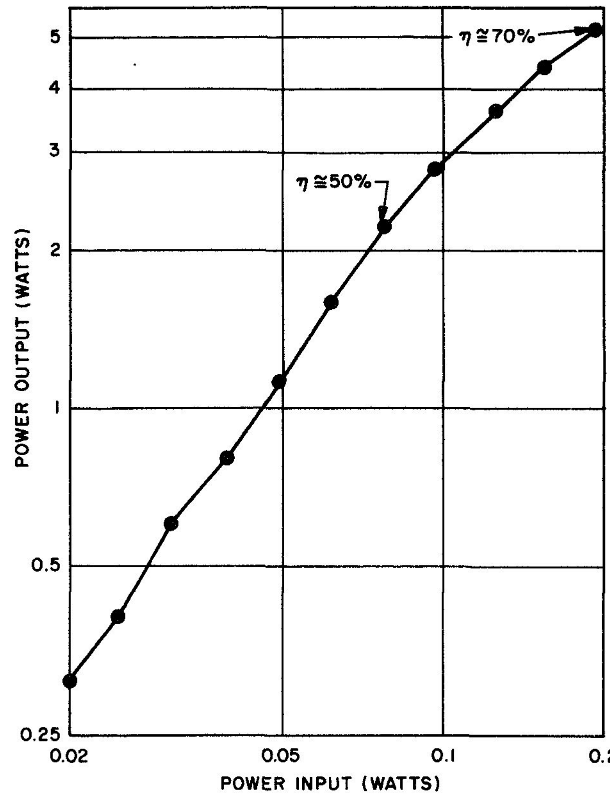


Figure 3-34. 30 MHz Simulator Preliminary Data Run

3.2.5 GENERAL CONCLUSIONS

The following general conclusions were derived from the results indicated, and will be considered in formulating a recommended future program:

1. The Doherty amplifier can provide improved efficiencies over a conventional Class B stage for AM TV amplifiers at UHF.

2. Circuits have not been optimized to date, but can be improved by obtaining basic design data from a low frequency simulator and adapting results to the UHF amplifiers.

3. The interdigital circuit has some mechanical advantages, but is considered too inflexible except where well-standardized tubes can be incorporated. Initial high power amplifiers should be developed with the conventional cylindrical cavities.

4. The Doherty circuit has not been sufficiently analyzed in literature to permit an optimized analytical design prior to breadboarding; the grounded-grid UHF circuit is best optimized at this time by an appropriate simulator program as mentioned previously, or by a computer program not yet developed.

3.3 SUPPORTING SUBSYSTEMS

A considerable number of satellite subsystems will be related to the TV satellite transmitter, but three are relatively critical and received an early evaluation within this program. Monitor and protective circuitry, thermal control guidelines, and tube qualification testing are considered here; other related subsystems are deferred until a later system study.

3.3.1 MONITOR AND PROTECTIVE CIRCUITS

A problem in high power transmitters is to ensure that an electrical fault, either a dc or an RF breakdown, will not destroy the amplifier or reflect into another subsystem to obstruct its performances. Frequently, an internal arc in a tube will not be destructive if the high voltage is removed immediately. This usually permits the tube to be restarted. RF breakdowns may or may not be repairable, depending on their cause, but will clear if the RF drive is removed.

3.3.1.1 Dc Monitor and Protective Circuits

Crowbar circuits are used in dc supply lines for dc protection. These are so devised that a large current in any of the high voltage lines will trigger the crowbar circuit, which will short the high output voltage to ground while the circuit breaker at the power supply input is removing the prime power. The shorting device on the high voltage is usually a triggered spark gap that can handle large quantities of current for short time intervals, or energy sufficient to reduce the tube voltage well below the minimum arcing potential, shutting the tube off in a microsecond or less. The voltages that should be crowbarred on various types of transmitter tubes are the collector and cathode voltages, or anode voltage in the case of the gridded tube. The beam voltage on the klystron is crowbarred rather than the collector. After the crowbar circuit has removed the critical voltages, the other tube voltages should be reduced or removed in order to implement a restart procedure following approved procedures. A restart attempt will ascertain the ability of the tube to continue operation after the arc has been extinguished.

The crowbar circuit, which includes an overcurrent sensor, a triggered spark gap directly across the high voltage terminals, and a breaker to remove the prime power is shown in

Figure 3-35. Tubes requiring two or more separate voltages must have a crowbar circuit for each terminal, and all must be triggered whenever an overcurrent indication is detected. The spark gap will be self extinguishing, and an attempt to return the tube to operation can be made as soon as the spark gap has ceased operation. An immediate repetition of the breakdown would require an evaluation of the situation and a decision on how to proceed. A vacuum arc due to whiskering usually does not involve permanent damage and the tube can be operable immediately without further likelihood of breakdown.

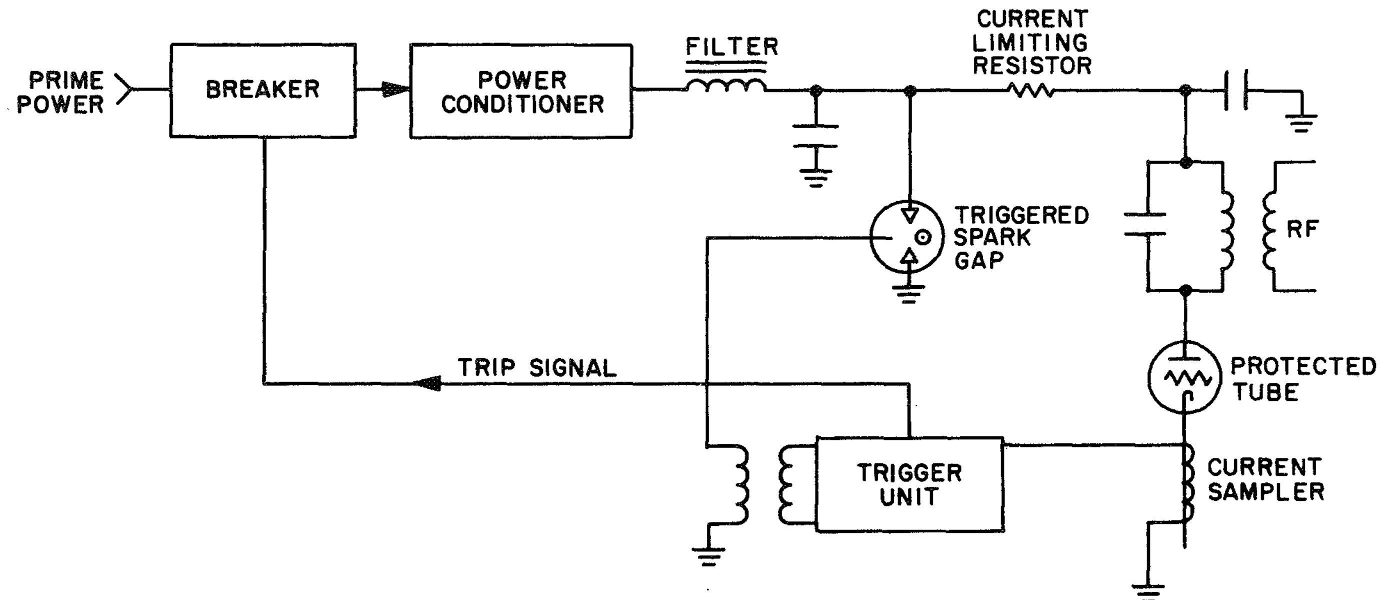


Figure 3-35. Dc Current Monitor and Crowbar Circuit

3.3.1.2 RF Monitor and Protective Circuits

RF circuitry electrical failures may result from outgassing or other gaseous materials in a waveguide, or from multipacting which depends only on electrons being present. Three monitor methods are discussed which may be appropriate to the RF circuits.

Many arcing situations result in an arc that emits visible or near visible light; detection is then possible with a photodiode, provided that the photodiode is looking into the part of the guide in which the arcing occurs. This approach may be somewhat cumbersome in a complex waveguide configuration. Such a photodiode circuit, which will cause the RF drive signal to be removed and thereby extinguish the RF arc when one appears, is shown in Figure 3-36.

A second technique for electrical breakdowns relates only to multipacting. Here the "arc" is the oscillation of a cloud of electrons between the upper and lower surfaces of a waveguide or between equivalent electrodes for other RF components. Detection can be accomplished with a small positively biased electrode located just above a small opening in the surface of the waveguide. The current flow to this electrode indicates the degree of multipacting encountered. A basic circuit for this purpose is also shown in Figure 3-36.

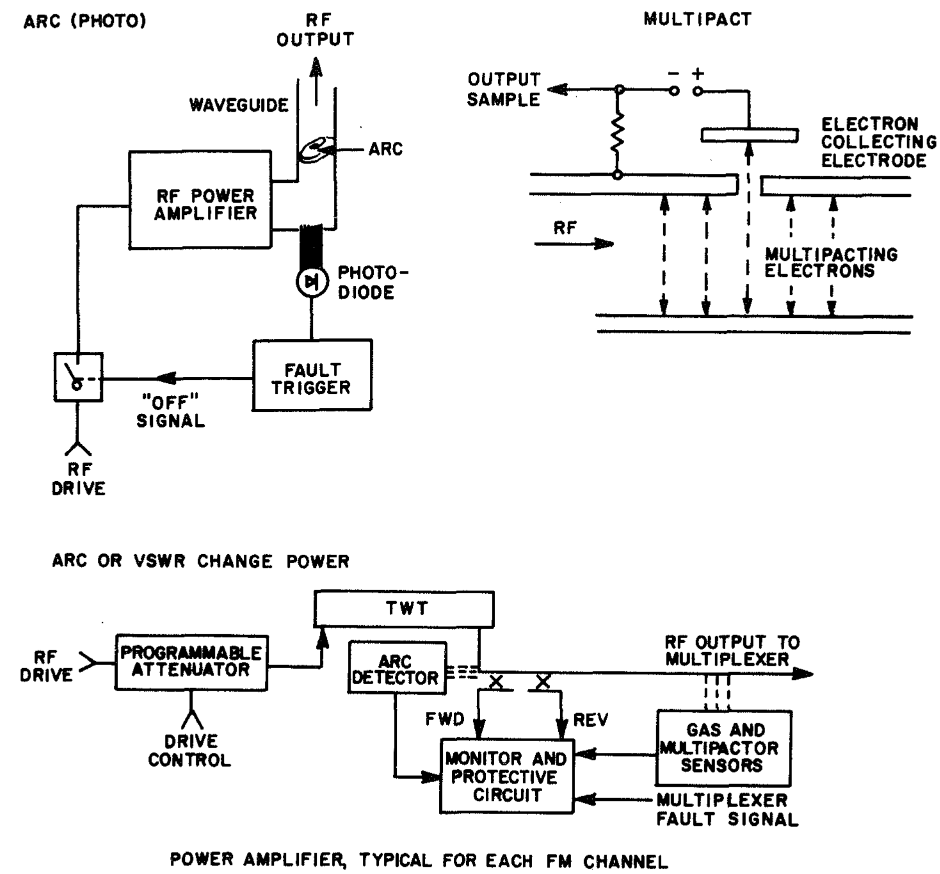


Figure 3-36. RF Monitor Techniques

A third technique involves the rather straightforward concept of measuring forward and reverse power levels, which will be an indication of improper RF operation when the reverse power becomes too large. The high VSWR could be detrimental to the transmitter tube and may appear before arcing or multipactor action is observable. The overall monitor circuit for a typical RF amplifier is shown at the bottom of Figure 3-36. The RF drive is removed in all cases to eliminate the RF breakdown; the drive can then be reapplied to determine whether the breakdown was a temporary situation as with metal whisker burnoff or whether it left a permanent scar necessitating a modified mode of system operation.

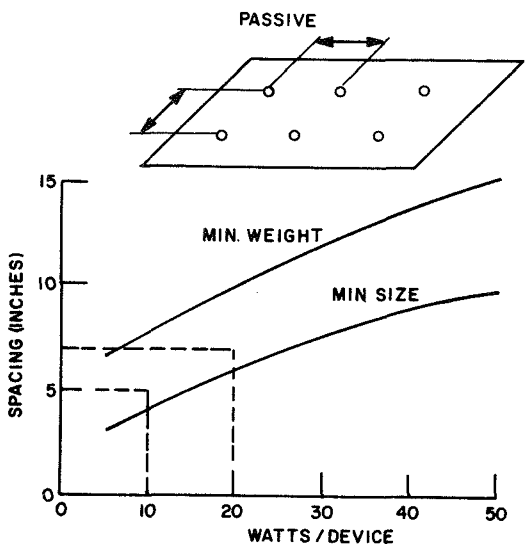
3.3.2 THERMAL CONTROL DESIGN GUIDELINES

All thermal energy generated in the transmitter must be removed by some conducting process and cannot be controlled by convection, as on Earth. The problem was generally addressed to the power conditioner, the tubes used in the high power stages of the transmitter, and the RF circuitry that have losses which depend on RF power level.

3.3.2.1 Dc Power Conditioner Cooling

3.3.2.1.1 Components

The power conditioner components will each require some sort of thermal control. A 3.2 kw power conditioner as considered in Section 3.1.2 will lose about 2 percent of the power in each of the major components, perhaps less in a refined design, but this provides a basis for estimating the thermal control problem. Thus, an initial assumption is that each element of the conditioner absorbs about 70 watts (3.8 kw input required). Heat from solid state devices and other components that can be considered to be essentially concentrated at a point can be distributed on a cold plate (heat sink) with sufficient spacing to keep temperatures within limits. The spacing, however, would be quite large at the 70 watt level, as can be discerned from Figure 3-37. The use of heat pipes to conduct the heat to a more distant point with a less restricting radiating plate should, therefore, receive considerable attention. The method of running a heat pipe by a solid state device is shown in Figure 3-37. The additional temperature drop of 7^{o} per 10 watts would have to be factored into the overall thermal design. The additional flexibility in permissible subsystem design compensates for this factor quite well. Components other than the solid state devices would be handled in the same basic manner, using heat pipes to conduct heat to a more distant radiating plate when the thermal densities and temperature limits do not permit cold plate use.



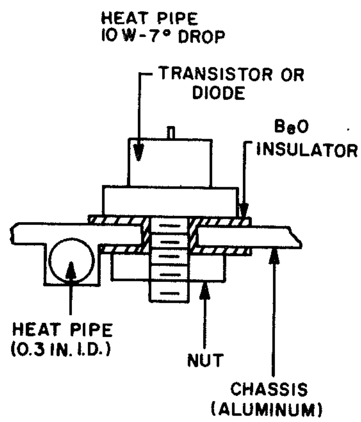


Figure 3-37. Cooling Solid State Devices

3.3.2.1.2 Power Conditioner Subsystem Cooling

There are electrical advantages in having the power conditioner in a moderately small package. This reduces EMC problems, weight and volume, and eases the problem of integration into the overall system. The radiating plate to remove the thermal power for a typical power conditioner would be about 32 by 64 inches, and would use heat pipes to transfer the heat from the conditioner (approximately 14 by 30 inches) across the radiator face. The relative size of the conditioner in a reasonable configuration on the radiating plate is shown in Figure 3-38.

3.3.2.2 High Power Tube Cooling

A considerable amount of effort has previously been expended on tube cooling (References 1, 21, 22, 23, 24, 28, and 30). One example of an experimental 1500 watt radiator plate with four heat pipes to distribute the heat is shown in Figure 3-39. The plate is 42 inches square, and rises to a temperature of about 270°C. The four heat pipes provide some redundancy since the plate will continue to operate at a reduced level with the loss of one or more pipes. At a temperature limit of 270°C, the power handling is:

1. Four Pipes - 1500 watts
2. Three pipes - 1200 watts

3. Two pipes - 900 watts

4. One pipe - 600 watts

The basic approach can be adapted to any of the tubes, and the arrangement of heat pipes on the plate does not have to be symmetrical.

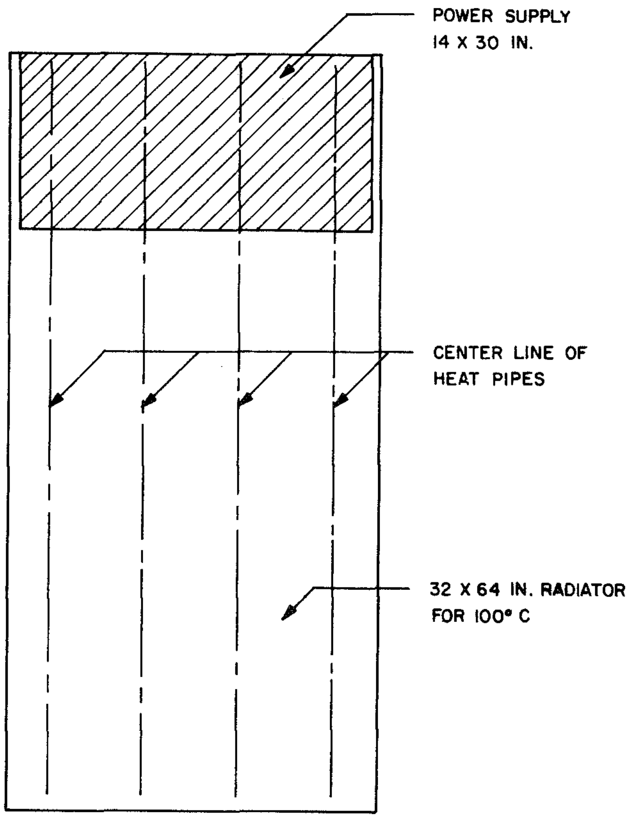


Figure 3-38. Thermal Control Radiator for Power Conditioner

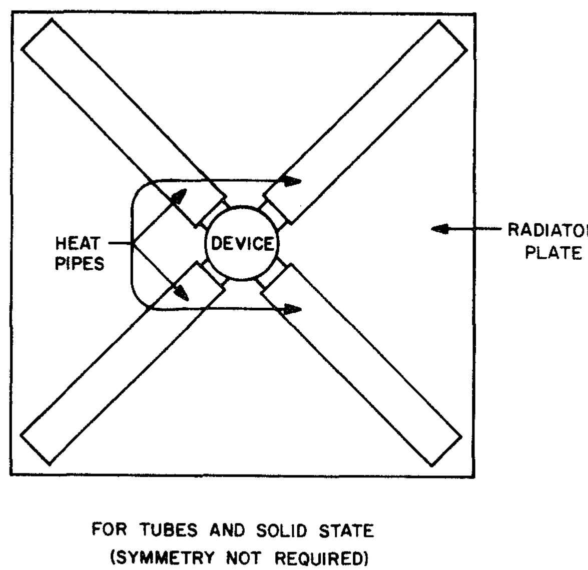


Figure 3-39. Experimental Thermal Control Device for Tubes

3.3.2.3 <u>RF Component Thermal Control</u>

Convection is usually sufficient in the Earth's atmosphere to cool RF components. In space, the heat generated in an RF component must be conducted to a radiating plate to prevent temperature buildup and possible distortion or damage of the RF assembly. The general approach is adaptable to both coaxial lines and waveguide. Either a thermally conducting plate is used for RF components located near a plate and which have relatively small thermal fluxes, or heat pipes are used where thermal power must be distributed because of distance or high flux densities requiring larger radiator plates.

The methods for conducting heat from coaxial and waveguide are shown fundamentally in Figure 3-40. Quarter-wave stubs used with the coaxial components may be either solid conductors or heat pipes, as indicated. Waveguide is normally cooled sufficiently with a cold plate on the broad side of the guide. The walls could also be made into heat pipes for high flux density components, but at a higher development cost for the RF system.

These approaches are applicable to all filters and other RF components, with suitable adaptability. RF loads are used at one termination of each 3 dB hybrid. They can also be approached as wither directly-connected components to radiator plates, or with heat pipes to conduct the heat to a distant or larger radiator plate. Arrangements that might be used, where tapered lines and absorbing coatings are used to convert the unwanted RF into thermal energy are shown in Figure 3-41.

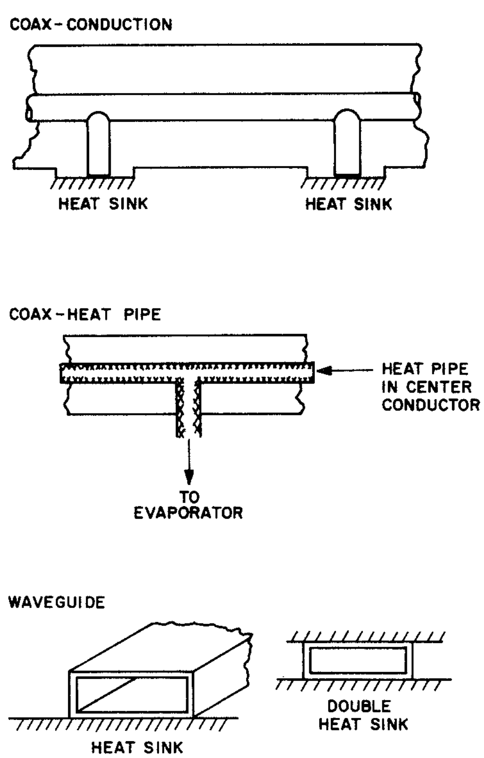


Figure 3-40. Thermal Control in RF Lines

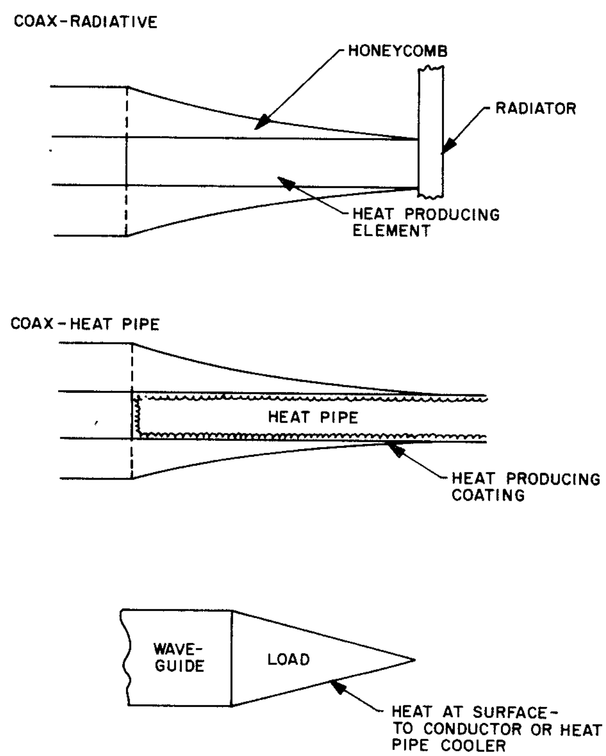


Figure 3-41. Cooling of RF Loads

3.3.3 TUBE QUALIFICATION TESTING

3.3.3.1 Test Plans

Tube qualification testing plans are based on the requirements of the application. For space qualification, the objective is to simulate each phase of the tube's life, including environmental and operational requirements from manufacture to the end of its useful life. These requirements form the basis for establishing a set of test plans. A consideration of the significance of each phase (manufacture, pre-launch, launch and maneuver in space, orbit operation, long life) leads to extracting the more influential factors to formulate the overall plans. These are tentatively selected as follows:

1. Manufacture - basic electrical performance testing and basic mechanical testing
2. Pre-launch - confirm electrical and mechanical requirements
3. Launch and Maneuver - mechanical and high vacuum environmental tests with tubes not operating
4. Orbit Operation - electrical tests in high vacuum environment to meet system requirements and specifications
5. Long Life - tests for performance in vacuum in required mode for designated lifetime

The test plans break down into mechanical, environmental, and electrical tests, with some interfacing to simulate conditions tube will encounter in practice. An added safety factor would normally be included in the test specifications. Electrical tests will be defined by mission requirements, mechanical tests will be determined from the launch vehicle profiles, and environmental conditions will initially be those of the Earth's atmosphere and those of space for longer duration testing. The latter should also include solar radiation effects. Life testing is critical to space qualifying a tube and is considered after establishing the basic one-time tests to simulate all phases of the mission up to long-life operation.

3.3.3.2 Life Testing

Life tests should provide a given level of confidence that the tubes can fulfill their missions. Test duration should eventually be at least as long as the mission duration to ensure that the failure rate follows a predicted law, such as exponential. Someone must then decide on an acceptable confidence level after which the number of tube hours in the life test can be determined. For example, a redundant tube was assumed and the reliability of the two tubes was assumed to be 99 percent. In this case, the tube hours for specified confidence levels and the costs for testing tubes are those listed in Table 3-5. For example, testing eight tubes for two years (140,000 tube hours) would result in a confidence of about 73 percent that two tubes will have a 99 percent reliability over the two-year period, provided no tubes fail in the test. If a tube fails, the tube hours required for 70 percent confidence approximately doubles. For a higher confidence level, additional tube hours of testing are obviously required.

Table 3-5. Life Testing (Two-Year, Two-Tube Redundancy for Reliability)

Confidence Level Based on 99% Reliabiltiy	Tube Hours	
	2-Year	5-Year
70% - No failures	128,000	330,000
80% - No failures	171,000	442,000
70% - One failure of 10 units	260,000	672,000

Life Test Cost - 1 kw, 2 Years

	Linear Beam	L-64S	L-64S with In-Place Facilities
Facilities	$ 80 k	$ 60 k	
Tubes	135 k (10)	11 k (11)	$ 11 k (11)
Power	10 k	10 k	10 k
Personnel	220 k	200 k	70 k
	$ 445 k	$ 281 k	$ 91 k

Life test costs include all test equipment, power, personnel, and the tubes themselves. A vacuum facility would be included for space testing to identify potential problems that may appear but aren't self-evident. Facilities in-place would reduce testing costs by about 25 percent. Costs vary approximately in proportion to the log of the power.

3.3.4 GENERAL CONCLUSIONS

The three supporting areas have no obvious limitations in the studies to date. Monitor and protective circuits are used in most high power transmitters, but the additional problems in a space environment will require further evaluation, particularly by experimental means in a high-vacuum test chamber. The RF monitors are only useful in a high vacuum where RF faults can occur although some testing may be performed at intermediate worst-case pressures to identify the magnitude of the breakdown situations. Test results may then be extrapolated via Paschen's law to more realistic pressures.

Thermal control design will utilize heat pipes for removing heat from the various components to a radiating plate that radiates the unwanted energy off into space. Passive radiators without heat pipes tend to be larger and severely restrict the mechanical configuration of the system. Some heat pipe interface problems will exist, and must be solved, particularly where electrical insulation is also required. Coaxial RF components will have to be further considered since a heat pipe center conductor would require considerable development.

Tube space qualification testing can be planned along the lines of present test plans, but with modifications and additions to simulate the environment to be encountered in the proposed mission. Life testing is a critical part of qualifying a tube for space operations, and should be approached early in a development program to ensure that data is acceptable before a final transmitter is installed in the satellite.

3.4 SCALING EFFECTS

The object of this brief consideration is to indicate the problems in extending experimental and analytical results, which may be at low power or use low power concepts, to the 5 kw power level region. Each of the study tasks may be considered on a subjective basis, and the factors involved identified. The general conclusions on scaling in the various tasks are:

1. Materials effects are generally too poorly known to extrapolate with accuracy to high power operation, particularly in determining the outgassing "atmosphere" which is a major concern in breakdowns. Experimental programs are recommended to determine electrical breakdown data, especially for selected materials in specific configurations at the high voltage considered.

2. Dc to dc power conditioner scaling problems are limited largely to the high voltage transformer. Computations showed disproportionately large size increases for voltage approaching 20 kv; scaling here is not considered simple or reliable. Power scaling with multiple modules is otherwise reasonable.

3. RF components can be scaled to some extent; multipacting and thermal effects don't scale linearly and must be considered as individual problem areas. However, operation of any component that is considered to be linear should be scalable or predictable. Others will require evaluation of factors involved. Problems arise because waveguide components are sized for the frequency involved and generally not to power; coaxial lines can be scaled to power levels in some cases.

4. Doherty amplifier operation is basically scalable since it is expressed as a functional circuit and not as a circuit design. In practice, however, scaling of the experimental breadboard amplifiers outlined in Section 3.2 will encounter problems:

    a. Tube operation cannot be scaled directly in power since higher power tubes have different operating characteristics and specifications, and require different circuitry.

    b. RF circuits cannot be extended directly, due to factors noted in items 1 and 3 above.

    c. Thermal control is complicated by increased heat flux densities (which actually limit gridded tube amplifier power output in space applications).

5. Dc monitor circuitry is generally scalable as long as a spark gap is available that can handle the energy stored in the power supply filter; RF monitor circuits should present no scaling problems.

6. Thermal control can be scaled up as long as the heat pipes, where used, do not approach the critical heat flux level above which it no longer functions. At that point, scaling is not practical.

7. Tube qualification testing requirements are generally scalable, but low power tube performance testing usually can not be scaled up and test programs would be required for each higher-power tube.

Test and experimental programs are necessary in nearly all the high power areas where data is presently available only at lower powers, and where analysis is based on assumptions that do not include space environment effects, which are so uncertain that further experimental evidence is necessary.

3.5 TASK INTEGRATIONS

The purpose of the Integration Task was to develop a logical direction for a continuation of the study toward an eventual flyable transmitter. The output from the task makes up the set of Recommendations in the next Section of this report.

SECTION 4

RECOMMENDATIONS

4.1 PROGRAM RECOMMENDATIONS

The results of the MKTS Phase II study indicate that placing a high-power satellite transmitter in a geostationary orbit is feasible within the bounds of the problem areas that have been identified. No fundamental limitations have been discovered, but numerous new problem areas appear as a result of the space environment. These areas will require further evaluation to determine how best to direct the subsequent development program. Thus, the basic recommendation is that transmitter development be initiated as early as possible and supporting activities be implemented to determine with more accuracy the significance of phenomena peculiar to high-power equipment in space.

The recommendations below are based on the conclusions reached in the tasks, as included in the subsections of Section 3. The items are shown in two general categories: those which should be started now due to the extent of new design problems, and those which may be started at a later time because they do not affect immediate design efforts.

4.2 EARLY TASKS

The early tasks are those recommended for an immediate follow-on program, and include the development of a high-power UHF AM transmitter based on results of the Phase I and II studies. A parallel experimental study of high power RF components in a space environment is also recommended. The transmitter should be a breadboard to determine final operating characteristics for the 5 kw output level, and the related supporting areas should be included in the program. The specific recommendations for the next Phase of the of the MKTS p rogram are the following:

1. Doherty Amplifier Optimization at the 5 kW Output Level. A transmitter should be developed with all the basic elements, including the Doherty amplifier, its driver, the aural channel, and RF components. The components should include a vestigial sideband filter (input type), a color image filter, L-C energy storage for peaks in the AM signal, controlled carrier for maximum utilization of the power conditioner, and the necessary dc monitor and breakdown circuitry.

The final breadboard should then be tested for all but environment effects, which would be the final step in a prototype development.

2. RF Breakdown Tests of Selected RF Components. This is one major critical area in the transmitter which has insufficient data to permit a space transmitter to be fabricated. Several RF components were identified in the just-completed study as subject to electrical breakdown. These should be tested in an environment approaching that of space.

The above represents the minimum items for early implementation. In addition, a number of supporting subsystem problem areas were identified; additional effort should be applied to these areas. However, these are being considered to some extent in a number of related programs and these results can be integrated into the MKTS program. Thus, the major items which will require adaptation and less fundamental investigation are:

1. Tube Life Test Program. The Signal Corps has indicated an interest in life testing a tube of the L-64S type. In addition, the L-64S is a proprietary development and should have a certain amount of life testing in other applications. However, a 2-to-5-year life test may be required in the MKTS program if other sources don't develop.

2. Improved Materials Data. High vacuum tests to date have generally involved only materials measurements, and have not incorporated electrical breakdown measurements. This is expected to be accomplished at some future time.

3. Power Conditioner Module Design. A contract is being provided by the NASA/Lewis Research Center to develop a space qualified power conditioner. The results should be directly applicable.

4. Heat Pipe Development. Work has been continued over about three years in this area, and the results are generally applicable. Additional requirements for the high flux density from the L-64S tubes are being evaluated in a separate program.

Thus, the next phase of the MKTS program should integrate and coordinate these efforts where possible to obtain effective equipment for the final space transmitter.

4.3 FUTURE TASKS

Future tasks deal heavily with environmental data and equipment testing in simulated space environments. Data on electrical breakdowns with dc and RF circuits are necessary to predict breakdown modes in a vacuum environment and to determine methods for avoidance. Then, a determination of the influence of the enclosures and supporting structures is necessary to identify problems in the buildup of outgassing pressure, sublimation, and space plasma. (Ideally, there would be no buildup; practically, there will be some present.) A knowledge of environment as it will exist within the satellite and the performance and life features of equipment in this environment are major considerations in determining system design and techniques. These items cover the principal problems expected from environmental effects:

- Testing for breakdowns caused by outgassing products.
- Further high vacuum breakdown data including vacuum arcs, plasma and RF multipactor effects.
- Analysis of test of outgassing/sublimation pressure buildup in practical system assembly.
- Environment, performance and life testing of equipment.
- RF breakdown monitor and protective circuitry.
- High voltage transformer design above 4 kv.
- Bonded grid tubes - increase life, ruggedness, and reliability.
- Advanced heat pipes - high flux density.

The above investigations will supplement those of the "Early tasks" group in defining the solutions to problems expected in a high power space transmitter. With the data that will evolve, the development of a prototype transmitter can proceed with a high level of expectation for a successful long-life system.

SECTION 5

DETAILED STUDY TECHNICAL RESULTS

This section provides the significant backup information on which the results in Section 3 are based. The technical details are presented in the same sequence as Section 3 to provide a correlation between the two sections. Again, studies are grouped into a high power area with sub-studies on materials, dc technologies, RF technologies, and RF components; the amplifier breadboard study including design information and results on three breadboard amplifiers; a brief discussion on scaling; and the supporting areas of monitor and protective circuits, thermal control design guidelines, and tube qualification test plans. A final section on transmitter systems will form the basis for the recommended future program.

5.1 MATERIALS EVALUATIONS

5.1.1 ENVIRONMENTAL FACTORS TO BE CONSIDERED

Environmental factors and materials effects must be considered for the following four phases of a mission:

1. Prelaunch
2. Launch
3. Orbit maneuver
4. Orbit operation

The data for these various phases have been obtained from similar programs which have considered the problem in detail (Reference 7). The launch phase cannot be specified precisely until the launch vehicle is selected, but assumptions here are sufficient for this study.

5.1.1.1 Prelaunch Environment

The environment to be encountered before launch has the range of conditions on the earth and is summarized as follows:

Temperature: -80° to $+125^{\circ}F$

Pressure: 1.69 to 15.4 psia (includes possible transportation in an unpressurized aircraft)

Humidity: To 100 percent

Acceleration: To 3G

Shock and vibration: Less than 50 percent of flight loads

5.1.1.2 Launch Environment and Orbit Maneuver

The transmitter will not operate during launch or orbit maneuvers. The tube heaters may be turned on if this results in a better ability to tolerate the shock encountered. The launch environment and orbit maneuver is summarized as follows:

Temperature: Expected to be controlled between $20^{\circ}C$ and operating temperatures, which vary between $25^{\circ}C$ and several hundred degrees, depending on specific component operation

Pressure: Atmospheric to minimum of 10^{-12} Torr

Humidity: Drops to essentially zero in space

Acceleration: (Not critical to electrical breakdown; reaches 11.5g in Atlas/Centaur)

Shock: (Not critical to electrical breakdown; typical for Atlas/Centaur is 115G for 1.5 msec with half-sine-wave impulse)

Acoustive Environment: Typically over 140 dB

Orbit maneuver adds nothing to the environment data, except accelerations (especially spin). Temperatures will be influenced by solar radiation, but presumably the thermal system will be capable of operating with this factor.

5.1.1.3 Orbit Operation

Added to the other environmental factors is solar radiation. The basic factors include the following:

Temperature: Controlled by thermal system to stay within component and subsystem tolerances

Pressure: 10^{-12} Torr externally; internal will vary substantially as noted in subsequent discussions on material outgassing

Acceleration and Shock: Small

Radiation:	Particle	Electron Volts	Particles per cm^2 over 2 years
	Electrons	$\geq$ 1.6 x 10^6 ev $\geq$ 4 x 10^4 ev	2 x 10^{11} 2 x 10^3
	Protons	0.1 to 5 x 10^6 ev $\geq$ 30 x 10^6 ev	2 x 10^5 4 x 10^8
	Micrometeoroids	negligible for particles of 0.4 grams or greater	

5.1.1.4 Materials Applicable to Space Transmitters

In addition to identifying and defining the space environment factors, the materials to be used in these environments must be considered. The approach was to identify materials normally used in ground based transmitters and determine the suitability for these same materials in the high vacuum of space. Table 5.1-1 lists typical materials and applications for transmitters and power conditioners, with resulting recommendations.

5.1.2 CORONA AND ARCOVER

Corona breakdown has been studied for many years, but it still presents a rather uncertain physical phenomenon in terms of a precise definition. Corona can be thought of as the formation of an ionized region that is considered to be an extension of the conductor itself. Arcover occurs if the outer perimeter of this ionized layer is changed in such a way that it ultimately comes in contact with a plate or other electrode. Corona has a current level of about one microampere, although it may exist at currents as low as 0.3 microamps.

Table 5.1-1. Typical Materials and Recommendations for Space Systems

A. RF MATERIALS

Material	Comments	TVBS Application
Aluminum alloy	Not 7075 or others which contain sublimable alloying elements. See table.	Antenna
Copper and aluminum	Recommended for use	RF rotary joints; waveguide
Fused quartz	Recommended for use	RF rotary joints; RF insulator
Alumina	Recommended for use	RF rotary joints; RF insulator
Beryllium oxide	Recommended for use - Good thermal conductivity.	RF rotary joints; RF insulator
Stycast (E and C)	Products listed in Appendix A of Ref. 6 Use is temperature limited, which varies with resin type. Not recommended	
Teflon	Recommended for use but has poor corona stability	Coaxial cables
Ceramic and stannous oxide	Requires testing	Harmonic absorber (waveguide)
Nichrome, BeO, and $Al_2 0$	Recommended for use	Harmonic absorber (waveguide)
Fiberglas	Outgassing data needed for final selection. Application will be temperature limited.	Dielectric (antenna)
Steatite	Recommended for use	Coaxial cables
Polyethylene	Teflon better from outgassing standpoint. See table (Ref. 6) for recommended shrinkable materials (temperature limited). Also, polyethylene has poor corona endurance	Coaxial cables
Hardened steel	Recommended for use	Ball bearings
	B. POWER CONDITIONER MATERIALS	
Epoxies	Outgassing problems. See Appendix A of Ref. 6	Potting compounds for transformers
Conformal Coatings (per GE specification)	Not 102 or 125; see Appendix A of Ref. 6	Over power supply parts
Glass-cloth plus melamine, phenolic silicon or epoxy	See Appendix A of Ref. 6; use is temperature limited, which varies with resin type used.	Circuit boards
Teflon	Recommended for use but has poor corona stability	Wire insulation
Mica	Recommended for use; watch water absorption release when put into vacuum	Insulator
Silicone grease	NOT Recommended	Heat transfer medium
Aluminum	See A. RF Materials, above	Heat sink - conductor materials
Copper or silver	Recommended for use	Wire, conductor materials
Nickel or cadmium plating	Nickel recommended for use. NEVER USE CADMIUM	Transistor cases, terminals
Carbon	Recommended for use	Resistors
Nichrome wire	Recommended for use	Resistors
Metallized carbon	Recommended for use	Resistors
Impregnated paper (castor oil, mineral oil, askarels, Halowax)	Not recommended unless used in a hermetically sealed case*	Capacitors
Metallized paper	Not recommended unless used in a hermetically sealed case*	Capacitors
Aluminum or tantalum Foil	Recommended for use	Capacitors
Ceramics	Recommended for use	Capacitors
Plastic films	Not recommended unless used in hermetically sealed case*	Capacitors
Brass	Not Recommended because of sublimation of zinc	Conductors, terminals, connectors, etc.
Silver, Gold or rhodium Plate	Recommended for use	Terminals, etc.
Lead	Not Recommended - sublimes	Solder
Tin	Not Recommended - prone to whisker growth	
Rosin	Not Recommended	Solder flux

*The case must also reduce diffusion to an acceptable level.

In order that corona or an arc be initiated, it is necessary for ions and/or electrons to be present in the gap. The source of the charged particles can be either a cathode or ions resulting from gas molecules. There must be sufficient collisions with gas molecules to produce enough charged particles in the electrode gap to create a self-sustaining conduction path. This condition is the well-known Townsend criterion for breakdown. For a non-uniform electric field it can be expressed as follows:

$$\gamma \left[e^{\left(\int_0^{\Delta} \alpha \, dx \right)} - 1 \right] = 1$$

where:

- γ = Gain by which electrons are removed from the cathode by positive ions
- Δ = Gap length
- α = The Townsend coefficient (the number of ions created through a path of one centimeter in the direction of the electric field)

The electric field strength necessary to initiate a discharge between a given pair of electrodes decreases as the pressure (and density) of the gas is reduced until the mean free path becomes comparable with the electrode spacing. A continuing decrease in pressure will decrease the probability of a collision between each electron and gas molecule, and the breakdown voltage will increase rapidly. Paschen pointed out in 1889 that the breakdown electric field is a unique function of the product of pressure and distance (pd) for a given gas, temperature, and electrode configuration. The minimum breakdown voltage for parallel plate electrodes in air is about 330 volts and occurs at a pd product of about 5 Torr mm. Typical curves for air, oxygen, and hydrogen are shown in Figure 5. 1-1. Note that for values of pd below that for minimum breakdown voltage, an increase in spacing for constant pressure lowers the breakdown voltage. Thus, when the mean free path of electrons is larger than the minimum spacing of conductors, the discharge will originate at some point where the spacing is most favorable (not at minimum spacing) and then spread over a wide region. A discharge will start at higher gas pressures, at the point of minimum spacing, or at a sharp point on a conductor. The elimination of sharp-point (small radius of curvature) conductors will considerably reduce the breakdown possibility, except in the small region between pd products of 2 to 30. Figure 5.1-2 shows breakdown conditions for parallel surfaces and needle points in air.

Operation of high voltage equipment in space will encounter problems in the critical pressure region of 10^{2} to 10^{-2} Torr, which occurs as the spacecraft passes through the 60,000 to 300,000-foot altitude range. High voltages must be turned off to prevent breakdown during this period. In the hard vacuum of space, gas pressures in the critical range may still be encountered from a variety of sources. The primary source is the outgassing products of organic materials used as insulation and coatings; outgas includes adsorbed atmospheric gases (nitrogen, oxygen, and water vapor). Oils, greases, or hydraulic fluids used in the system will most certainly contribute volatile materials. Finally, gases trapped in shaft clearances, sealed bearings, screw threads, and hermetically sealed devices will slowly drift into adjacent areas which my contain high voltage equipment.

Corona and arcover can be minimized or completely eliminated by appropriate design procedures that will negate the conditions which support them. Primary consideration in the design of a high voltage system for space should be given to low outgassing organic materials, which should also exhibit low total weight loss under operating conditions. This can be accomplished by proper selection of materials, stripping of low molecular weight constituents (volatiles) with an initial bakeout period, and using proper geometrical design.

Breakdown at very low pressures (below 10^{-4} Torr) is no longer dependent on the pressure or the nature of the intervening gas. The "vacuum arc" is observed in this

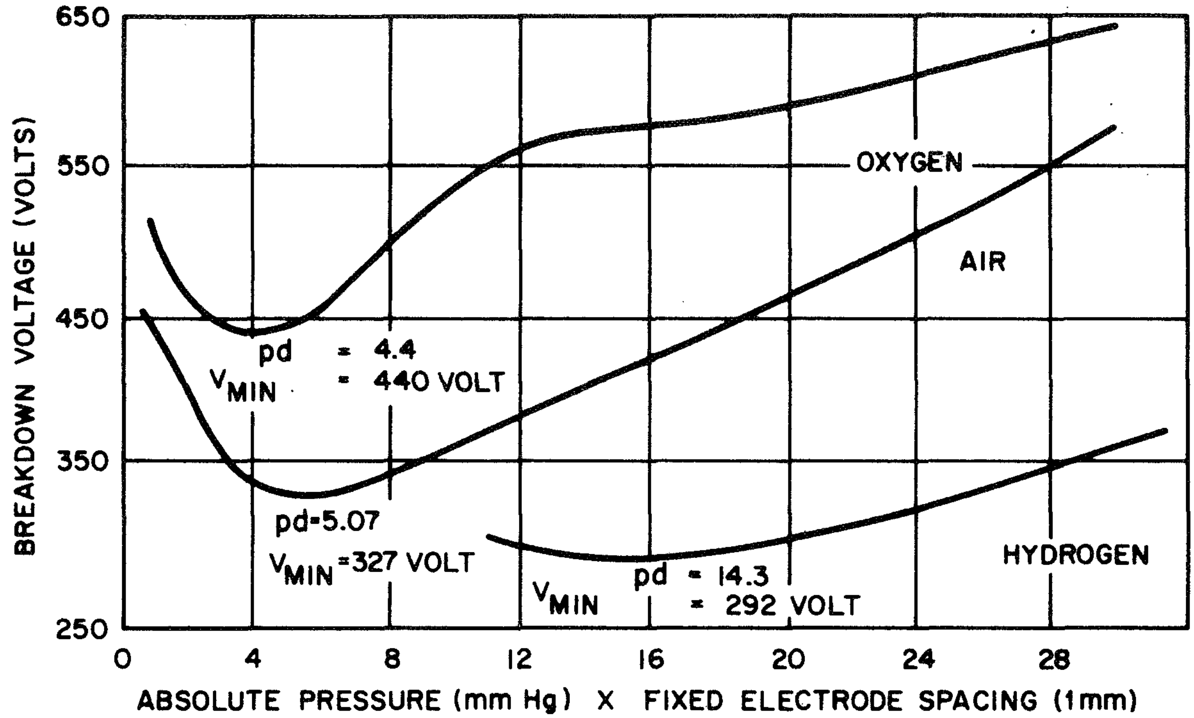


Figure 5. 1-1. Paschen's Law Cruves for Oxygen, Air, and Hydrogen with Electrode Spacing Fixed at 1 Millimeter

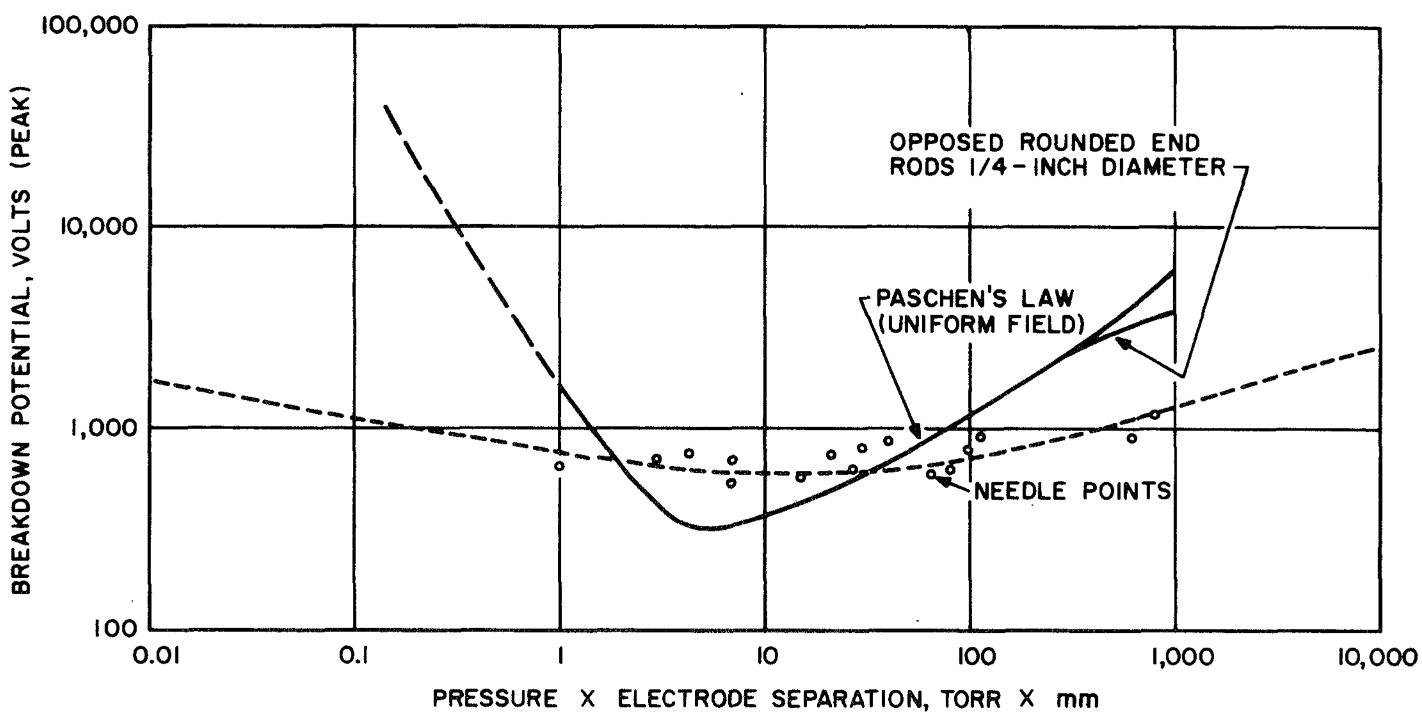


Figure 5. 1-2. Extrapolated Paschen Curve for Uniform and Needle Point Fields

region. The mean free path of the electrons and positive ions at these pressures is large compared with system dimensions; therefore, a charged particle drawn from one electrode to another is unlikely to collide with residual gas molecules. A small ion flow attributable to field emission may begin as the potential increases. The electrons will produce further charged particles at the anode, and these in turn may produce electron emission upon striking the cathode. Whiskering is also likely, which causes a very large localized field intensity to occur. Instability will occur and a heavy current flows when the voltage increases above a critical value; this occurs in paths of vapors released at the electrodes. The current in the arc is limited by the characteristics of the supply circuit.

5.1.3 SUBLIMATION AND OUTGASSING OF MATERIALS

Sublimation and outgassing combined represent the total bulk weight loss of a material. The outgassing is composed of absorbed and adsorbed moisture and gases given off. Sublimation covers all other atoms and molecules released from the material, essentially the base materials.

Outgassing is usually composed of low molecular weight fragments or additives present in most engineering materials, and normally does not include base material. The additives in a material include items such as plasticizers, flame retardants, radiation stabilizers, excess and unreactive catalyst, polymerization byproducts, pigments, dyes, and processing aids.

Particles are continually leaving the surface of all materials, even when they are at standard atmospheric pressures. However, the majority of particles that leave a surface in a high pressure environment are "reflected" back to the surface that they leave. This process can best be understood by considering the mean free path, which is the average distance a particle travels between collisions. Figure 5.1-3 shows that a particle which travels 10 feet (at $p \approx 2 \times 10^{-6}$ Torr) from a surface before interaction will have a far lower probability of returning to that surface than one which travels

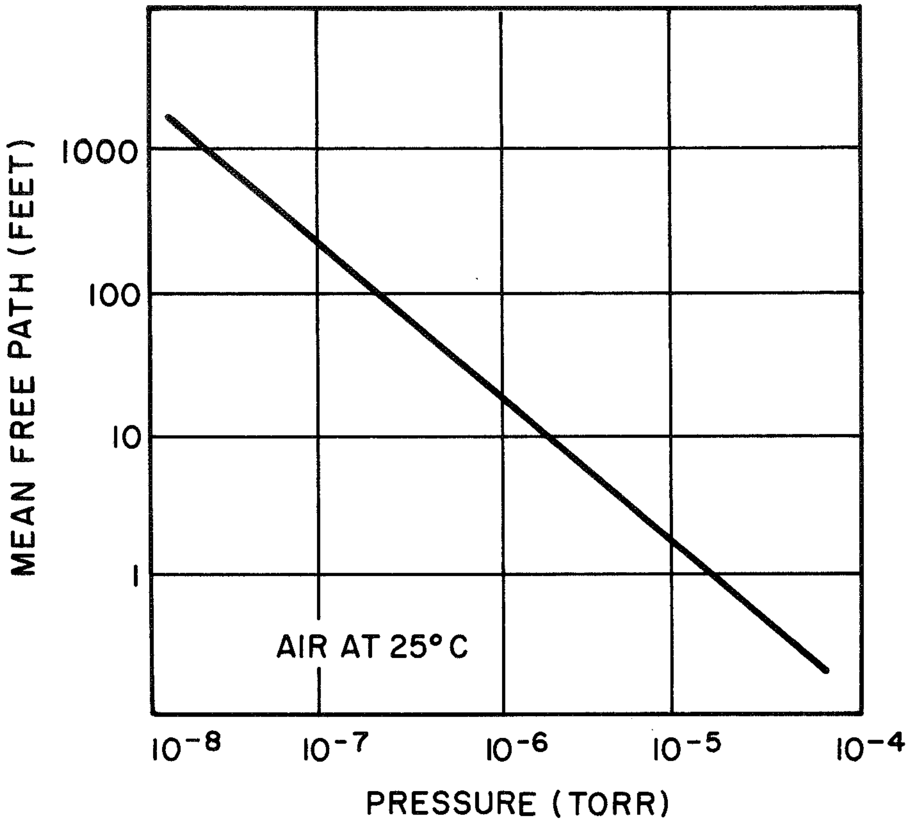


Figure 5.1-3. Mean Free Path Versus Pressure

only 3 x 10^{-6} inches (at p ≈ 760 Torr). Thus, the amount of erosion in a high vacuum becomes an important system factor.

A quantitative systems analysis can be performed if the rate at which particles leave a surface is known; this is usually obtained experimentally. The rate of weight loss per unit area at any time after exposure to vacuum as a function of both material temperature and thickness can be predicted from weight loss data on engineering materials. This rate of weight loss can also be separated into the gas and the bulk weight loss.

Experimental techniques are currently available to obtain required design data. The total weight loss is measured with a continuous weighing vacuum microbalance in a system where the backscatter to the sample of particles sublimed from it is negligible. This measurement produces a continuous total weight loss curve as shown in Figure 5.1-4.

The sample to be tested (as described above) is pre- and post-stabilized in a constant relative humidity and temperature environment. The difference in these weights is the bulk weight loss. The gas weight loss is then the difference between the total weight loss and the bulk weight loss. A good approximation can thus be obtained for both the continuous bulk and gas weight losses. The test technique is repeated for each material at a series of different thicknesses and different temperatures, as shown in Figures 5. 1-5 and 5. 1-6. Each of these curves could also be divided in the manner of Figure 5. 1-4, producing sufficient experimental data to determine the empirical constants and the "equivalent" vapor pressure required. The maximum pressure in any given black box or any given region of the system as a function of time in orbit can then be established, as shown in Figure 5. 1-7. This design data will also produce the information necessary to perform a condensation analysis to determine the destination of the outgassing and sublimation particles.

There is appreciable data in literature on various materials, but there is a definite lack of good consistent information needed to perform a design analysis on a high voltage, high temperature space system. The majority of data included in Appendix A of Reference 6 is actually neither total nor bulk weight loss, as listed; this is because a majority of weight loss data was obtained from before and after measurements rather than from in-situ weighings. The weight loss categories of bulk or total are only the best estimates for the experimental technique utilized. Before and after measurements result in a lower than true value for the total weight loss because some moisture and gases are quickly re-absorbed and re-adsorbed.

Data from various experimenters tends to be inconsistent, even for the same material tested. A generalized set of correlation factors among the test techniques cannot be based on the results of any given material because of the inconsistent differences in the sublimation characteristics of different materials. In addition, variations in temperature, specimen thickness, and time duration cannot be corrected or normalized unless

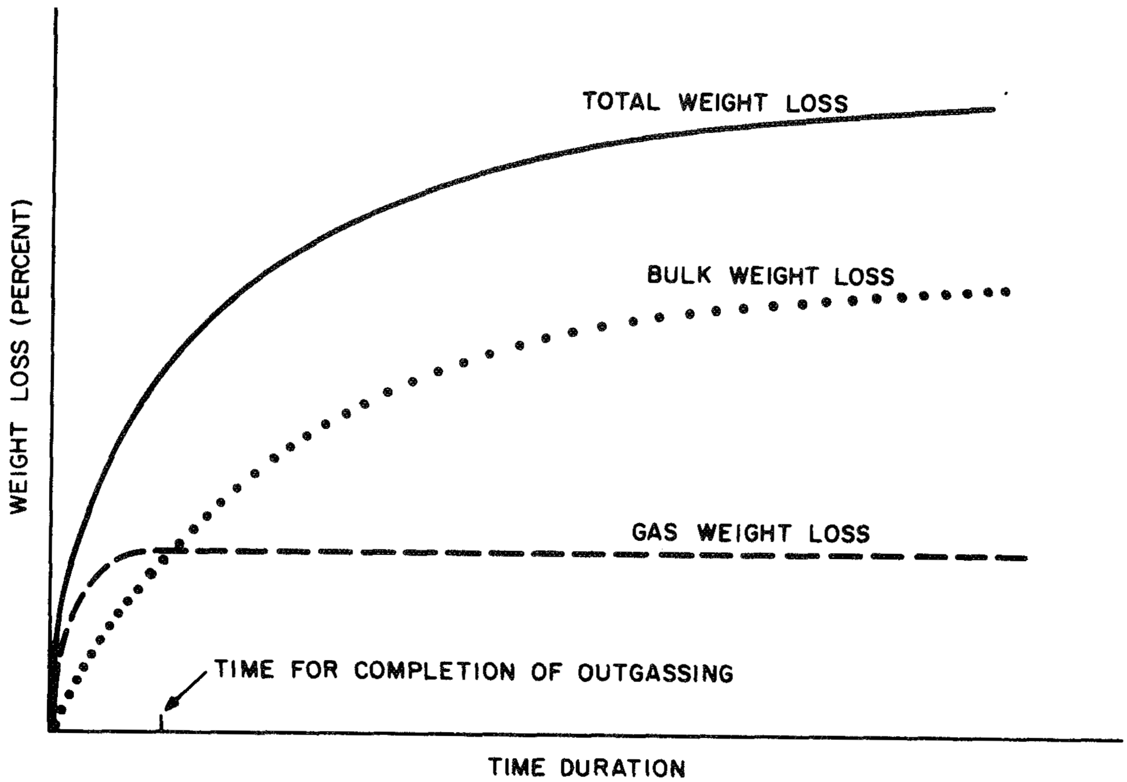


Figure 5.1-4. Typical Continuous Total, Gas, and Bulk Weight Loss Cruves

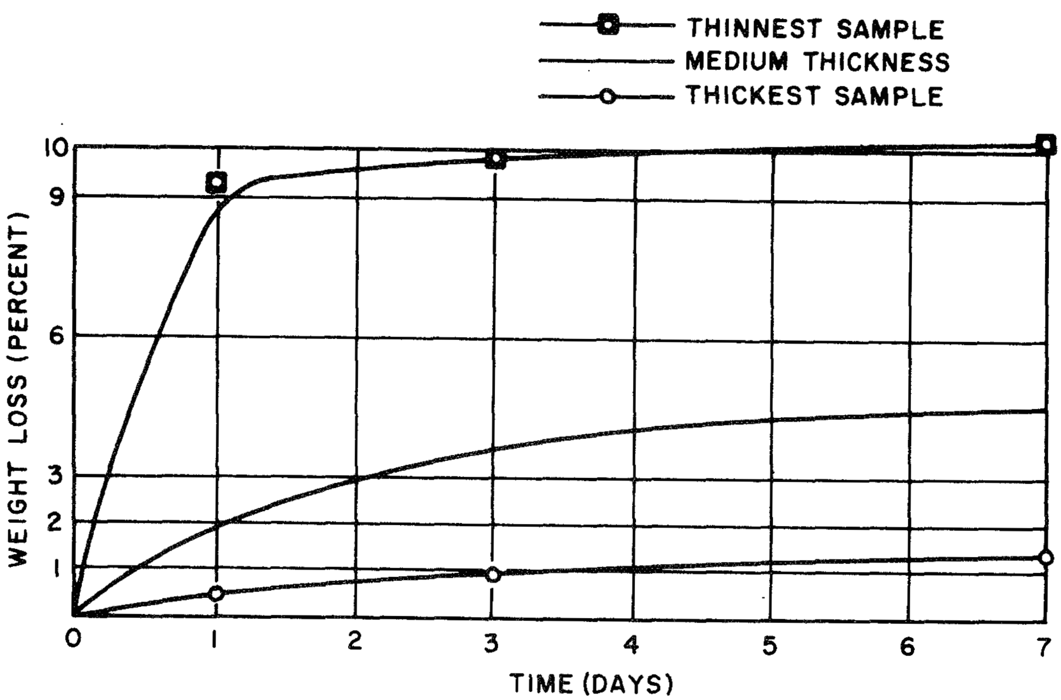


Figure 5.1-5. Typical Continuous Total Weight Loss Dependence on Sample Thickness

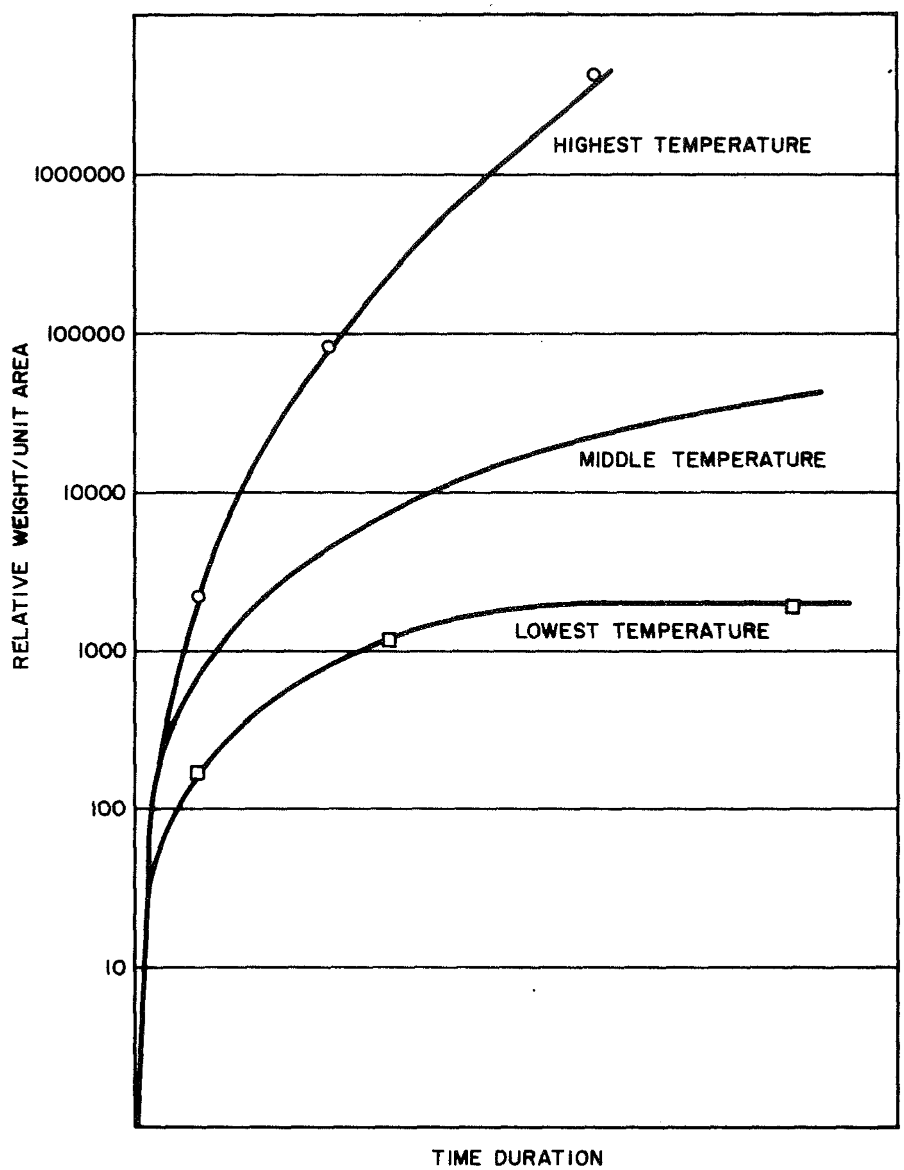


Figure 5. 1-6. Typical Continuous Weight Loss Dependence on Temperature

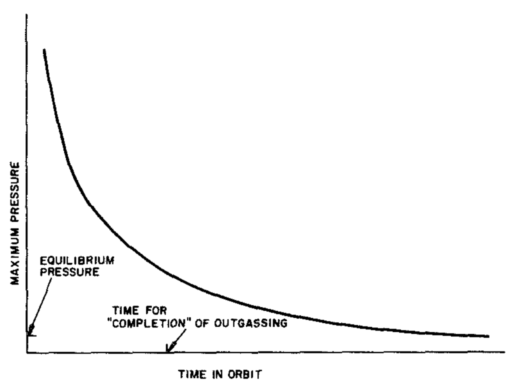


Figure 5. 1-7. Typical Pressure Profile in A Black Box or System After Orbit Acquisition

true design data is available. Finally (and probably most important), is the backscatter --or the amount of sublimed and outgassed material from the sample which returns to the sample at some time during the test--is different for the various test techniques presently employed.

The current literature is virtually void of useful data at high temperatures (over +125°C). There is also a notable lack of data on new materials recently developed, especially those designed for low sublimation in vacuum and for high temperature applications (over 250°C). The application of the literature survey for this program has been directed to a list of candidate materials, with qualitative recommendations from data that could be obtained on those materials selected for hardware use. Table 5.1-1 is the result of this application study.

Models used in determining effects of sublimation and condensation of materials in a system have been described in Reference 6. The application of these models is used in the general technology of materials effects on systems or subsystems in vacuum, but these models were not utilized in this study, except in adapting results from elsewhere and in comprehending the physical processes. The basic approach is to adapt the conventional radiation equation (by developing suitable analogies) to the "radiation" and absorption of particles from materials at elevated temperatures. This, combined with the Langmuir Equation (which provides a measure of sublimation rate) and Frick's Law (which indicates the diffusion rate), provide a basis for a quantitative evaluation of the situation that will develop as a function of time, temperature, materials, and geometry.

5.1.4 THE MULTIPACTOR EFFECT

Secondary emission of electrons by direct bombardment of the walls of an enclosure in a high vacuum can cause an electrical breakdown. The magnitude of the electric field for this to occur and the phase of the electron motion with respect to the field have governing effects. Appropriate conditions will cause the electron motion to be in-phase with the field. Thus, an electron starting across the gap between the walls would collide with the walls and release secondary electrons, just as the electric field reverses and accelerates these new secondary electrons back across the gap. The electric field must be of such a value that the transit time across the gap is equal to 1/2 cycle (or odd multiples thereof) of the ac field. In this way, the secondary electrons released by the initial electron become primary electrons for the next cycle to form another group of secondary electrons. This process is referred to as the multipactor effect (Reference 31 includes a basic description).

The conditions for multipactor discharge are as follows:

1. The mean free path of electrons in the environment under consideration must be long enough to permit them to be accelerated between the emitting surfaces, with a very low collision probability with ambient atoms or molecules

2. The energy of the incident electrons arriving at a surface must produce a net secondary emission ratio greater than one

3. The electron transit time must be in resonance with the applied frequency

4. The applied voltage, the ambient pressure, and the emitting surface for the first three conditions are maintained during the discharge.

A breakdown does not require that the exact optimum conditions occur, and there is a fairly broad region of fields and frequencies over which the phenomenon may be observed. It should be apparent that, for any one frequency, breakdown should be possible in a bounded region between two values of the field, where acceleration of the electrons may be a little greater or less than that for the exact proper phase relations.

This type of breakdown relies for its electron multiplication on the secondary emission of electrons from the walls. The breakdown field is then dependent on the nature of the walls of the vessel in which the discharge takes place. It is relatively independent of gas that is present, as long as the mean free path is sufficient. The behavior of the multipactor effect (obtained from the literature reviewed) indicated the following effects:

1. The multipactor discharge causes a change in the surface condition of electrodes, which, in time, may extinguish an established discharge. The characteristics history of a discharge is fundamentally different when tested in a vacuum chamber with ambient pressure of 10^{-5} Torr and 10^{-7} Torr, the discharge being more stable and less dissipative at the lower pressure

2. The current flow in the discharge has real and reactive components at the fundamental frequency which, under certain circumstances, may be sufficient to load or detune an element by a substantial amount. (This effect has long been known as a nuisance in klystrons, which sometimes cannot achieve their ultimate power output because of a multipactor discharge that occurs during power build-up but could not exist at full power.)

3. Nonlinear effects, including harmonics, are present, and in sensitive portions of the system (e.g., the diplexer or the antenna connections) can result in a possibility of modulation of transmitted signals, and a possible source of electromagnetic harmonic interference

4. Residual gas can be liberated by multipactor discharge and, in some cases, corona and arcover may ensue and cause a destructive effect on some circuit elements.

The following techniques can be employed to eliminate the multipactor effect:

1. Apply a dc bias voltage or magnetic field between electrodes to alter the field present

2. Reduce the mean free path of electrons by pressurization or filling empty spaces of the discharge region with a solid dielectric

3. Spoil the secondary emission ratio of the surfaces by:

    a. use of dielectric coatings (some dielectrics, however, will support multipacting)

    b. selecting materials of low secondary emission ratio

4. Make the electron transit time nonresonant (where frequency is fixed) by:

    a. proper selection of physical dimensions

    b. proper amplitude of the r.f. voltage

Gas amplifier multipactor (GAM) discharge is usually attributed to either outgassing products or multipactor clean-up of adsorbed surface gases. The effects are described as more closely resembling gas discharge breakdown than those of multipactor discharge. However, methods for protecting against this phenomenon are the same as those described for protecting against the multipactor effect.

5.1.5 GUIDELINES AND TECHNIQUES TO ELIMINATE ELECTRICAL FAILURES

A list of design rules or series of design equations that apply in a generalized manner to high voltage breakdown elimination are complicated in that the analysis of a given item in the system is dependent on numerous other parts of the system. The best design approach consists of a series of guidelines combined with a quantitative system analysis on an item-by-item basis. In addition, past experience and application of basic laws of physics describing the relationships between the various design parameters that control electrical breakdown must be included.

Listed below are a number of techniques that will help in the design of a system to prevent catastrophic electrical breakdown. This list is not intended to be a detailed final account of preventing breakdown because each system will have to be evaluated individually; it is presently divided into the following five sections - materials, processes, geometrical configuration, countermeasures, and cut-off circuits:

1. Materials

   a. Select low bulk-weight loss material

   b. Select material with low and/or rapid outgassing characteristics

   c. Foamed encapsulation should be avoided unless tested in detail

   d. Consideration should be given to potting or conformal coating of high voltage terminals. Materials effects must be well known, however, and the overall configuration must be taken into consideration.

   e. The effect of the dielectric loss factor of potting and conformal coating must be considered at RF.

f. The differential coefficient of materials bonded together should be matched as closely as possible. A flexible interface material is frequently considered to compensate for physical shrinkage variations.

g. The corona and multipactor characteristics of various connectors contemplated for use should be established before final selection.

2. Processes

a. An initial bakeout procedure must be included for a system in-orbit prior to high power operation.

b. All materials used for coating and potting should be degassed before use, preferably in a vacuum.

c. Maximum surface wetting and adhesion must be achieved between coatings, potting materials, adhesives, etc., and the surface to which they are applied.

d. Coat electrodes with materials that have a low electron emission ratio.

3. Geometrical Configuration

a. Tracking surfaces and surface conduction distances should be maximized.

b. Venting should be used discriminately to obtain subsystem pressures as far below the critical pressure region as possible.

c. Diffusion paths for outgassing and sublimation products should be minimized.

d. Air pockets must be eliminated.

e. Pointed or sharp edge electrodes should be avoided to minimize electric field stress and corona and arcing tendencies.

f. Where appropriate, conductive plates should be used to minimize the electric field stress.

4. Operation

a. A number of orbits should be completed before high voltage is applied.

b. Initial outgassing in space can be accelerated by heating the system with low voltage heaters.

c. Solar storm sensors should be used to turn the high voltage system off before high density ionizing radiation reaches the spacecraft.

d. Each subsystem should be designed, where possible, to operate in the critical pressure region; this is desirable but not always feasible.

e. Each subsystem should be tested through the critical pressure region to establish limits on operating characteristics and failure modes.

f. Install spark gaps, pressure gauges, ion gauges, and/or test electrodes in various parts of the subsystem or system. These can be used to establish whether a system can be turned on safely. They can also be used to trigger remotely resettable protective circuit breakers or fuses.

5. Cut-off Circuits

a. Utilize circuitry that ensures that the system will not turn on during launch.

b. All subsystems should be designed such that they will not overload or burn out if any subsystem functions as was observed in the critical pressure region test.

5.1.6 ENCLOSURE TECHNIQUES AND COMPARISONS

Four methods of fabricating equipment for operation in the space environment are considered. A summary of some of the pertinent factors was included in Table 3-2.

5.1.6.1 Gas Fill

High-voltage components may be enclosed in a pressure vessel that is filled with a suitable gas for the voltage and temperature levels involved. Pressure levels on the gas fill will be at least several pounds-per-square-inch; thus, a heavy vessel is required.

The advantages are as follows:

1. Positive control of environment is achievable
2. Component spacings can be made small with the use of high pressure and/or high dielectric strength gases
3. The same environment is available during ground test and flight
4. Better shielding possible with a metal vessel
5. Multipacting cannot occur

The disadvantages of this method are as follows:

1. Leaks and/or punctures of the pressure vessel are a probable cause of system failure.

2. Requires use of a heavy pressure vessel with long-life joint seals.

3. Gas fill characteristics may change with time, owing to corona, heating, or other effects which may cause changes in its composition.

4. Development work may be hampered owing to poorer accessability with the use of a pressure vessel.

5. High power feedthrough is required.

5.1.6.2 Dielectric Fill

Spaces between components may be filled with solid, foam, or liquid dielectric as a means of increasing voltage hold-off between elements of the transmitter system. The advantages of this method are as follows:

1. Positive control of environment is achievable.

2. Component spacings can be made small.

3. Multipactor effects cannot exist with solid dielectric fill and can be suppressed by by proper selection of cell size in foams.

4. The same environment is available during ground test and flight.

The disadvantages of this method are as follows:

1. Gas pockets may occur in solid dielectric materials; they are not easily detectable and are difficult to correct once detected.

2. Increased losses because of dielectric power factor (especially at high RF).

3. Weight of dielectric material.

4. Dielectric material is a source of outgassing products, which may result in arcing of nearby vacuum insulated components.

5. Characteristics of the fill may change with time because of outgassing in space or other factors.

6. Breakdown strength may be reduced with time because of treeing or other erosion effects.

7. Sublimation of the material may result in condensation products on nearby components.

8. Accessability may be poor after the component is filled.

5.1.6.3 Vacuum Vessel System

High voltage components may be operated in an evacuated vessel; this simulates space environment after a bakeout period prior to sealing.

The advantages of this method are as follows:

1. Positive control of environment is achievable.

2. Component spacings can be made very small before arcing is a problem.

3. The same environment is available during ground test and flight.

4. Leaks that appear in the vacuum vessel during space flight should not be harmful because a vacuum environment will exist within the spacecraft.

The disadvantages are as follows:

1. Weight of vacuum vessel.

2. Outgassing of components may result in sufficient gas within the vessel to permit arcing and make the equipment inoperative.

3. Multipacting may occur.

4. Development work would be hampered because of poorer accessability of components.

5.1.6.4 Open System

This approach considered the operation of the transmitter as in an open system inside the spacecraft. Vacuum operation would be obtained because of the "pumping action" of the space surrounding the spacecraft. The design would require provision for considerable "openness" within the transmitter and the spacecraft itself so that outgassing products would be rapidly removed from the vicinity of high voltage components. A very desirable situation would be the capability for operation in either the environment of space or in normal earth laboratory conditions.

The advantages of this method are as follows:

1. Minimal enclosure complexity
2. Accessability during development
3. No heavy pressure vessel or fill material required
4. Advantages of vacuum environment during space operation
5. Continuous pumping of outgassing components
6. Interfacing with other spacecraft subsystems is easier because there is no need for penetrations in the pressure vessel (for heat pipes, electrical connections, etc.)

The disadvantages of this method are as follows:

1. Possible contamination during handling and storage
2. Probable need for a "bakeout" period after unit is in space to remove contaminants and adsorbed gases
3. Nearby outgassing component may interfere with operation of transmitter components or vice versa.
4. Adequate provisions must be made to vent components and the interior of the spacecraft in order that low operating pressures may be achieved
5. Subject to multipactor breakdown after unit is in space

5.1.6.5 Preferred Approach

Considerations of the tradeoffs among the above approaches lead to the general conclusion that the open system is the preferred approach for implementation of high power spacecraft broadcast transmitters; this results largely from the rather drastic measures that would be required in the event of a container failure in any of the other approaches. Accordingly, most of this study was directed toward an open mode of space operation. Some exceptions may be found advisable after detailed design efforts are completed and better experimental data is acquired, but the open system is basically preferred.

5.1.7 EQUIVALENT PRESSURE FROM OUTGASSING

The estimate of outgassing equivalent pressure cannot be specified with any certainty unless the enclosure venting can be accurately specified in the analysis; presently, such data is not generally available. In addition, present outgassing data is not very consistent. However, variation in outgassing rate with time can be estimated (again subject to the poor data base), and an estimate of outgassing effects in a completely open system can be considered.

For an example, a 0.1 gram sample of Scotchcast 212 at $100^{o}C$ was selected. Data indicated a 2.3 percent weight loss after 24 hours in a high vacuum, with loss rates of about 1 percent per hour initially; 0.1 percent after 10 hours; and 0.02 percent after 24 hours. The 0.1 percent is also the average loss rate over the 24 hour period.

If the outgassing is mostly water (which is assumed for the purposes of this analysis), one molecule will weigh 3×10^{-23} grams. Then the total loss of 2.3 percent of the 0.1 gram sample in 24 hours is equivalent to about a 7×10^{14} molecules per second average loss. The molecular velocity when leaving the material is required in order to obtain an equivalent molecule density.

The energy relation used to obtain an average velocity is:

$$\frac{1}{2} mv^2 = \frac{3}{2} kT$$

$$\text{or: } v = \left(\frac{3kT}{m}\right)^{\frac{1}{2}}$$

$$\text{with: } T = 373^{o}K\ (100^{o}C)$$

$$m = 3 \times 10^{-23} \text{ grams}$$

$$k = 1.4 \times 10^{-16} \text{ erg } ^{o}K$$

The velocity becomes:

$$v \cong 7 \times 10^{4} \text{ cm/sec.}$$

In the sample, the 7×10^{14} molecules per second were from a total surface area of 1.47 cm^2, so the number of molecules in one cc of space at the surface of the material in a high vacuum is:

$$\text{density} = 7 \times 10^{9} \text{ molecules/cm}^3$$

Molecular density versus pressure data results in a pressure of about:

$$P \text{ avg} = 10^{-7} \text{ Torr}$$

Because this value is for air, the number is only approximate. The initial and 24-hour pressures are:

$$P_0 = 10^{-6} \text{ Torr}$$

$$P_{24} = 2 \times 10^{-8} \text{ Torr}$$

These pressures are obviously lower than necessary for minimal safety. Substantial data from space vehicles have shown that outgassing is a serious threat; therefore, the conclusion is that the enclosure configuration must be a substantial factor and that some materials must have much higher initial outgas rates or lower molecular velocities. (Actually, velocities will extend over a wide range, and instantaneous molecular density will vary about the average.) Thus, further evaluations (including experimental) are in order to provide quantitative data to permit accurate initial designs.

All that can be deduced at this point is that the pressure will build up in a sealed enclosure until it is equal to the vapor pressure of the outgassing (and perhaps sublimation) materials. The pressure buildup for small samples may be limited by the number of molecules of outgassing in the system, and may thus be less than the vapor pressure. Then, as vents are placed in the enclosure, the pressure will drop in the space environment until, with an "open" system, virtually no molecules are held and most escape immediately into space. The intermediate enclosure is the one of concern, and the one with no significant practical data.

5.2 DC HIGH-POWER OPERATION

The dc high-power study was divided into two general areas: components for high efficiency and light weight in a dc-to-dc power conditioner, and power conditioner circuitry using these components in an optimum manner for converting a low-input voltage to a high-output voltage. The components included were largely the switching and rectifying devices, high-voltage transformers, and input/output filters. Control circuits were assumed to follow standard practices. The basic elements constituting the power conditioner circuit and typical efficiencies of each are shown in Figure 5.2-1.

5.2.1 COMPONENTS

5.2.1.1 Power Switching Devices

The power conditioning subsystem for multikilowatt transmitters requires converters to change the voltage supplied by the power source to the level required by the transmitter, and regulators to keep the voltage level constant. Candidate switches for breaking the

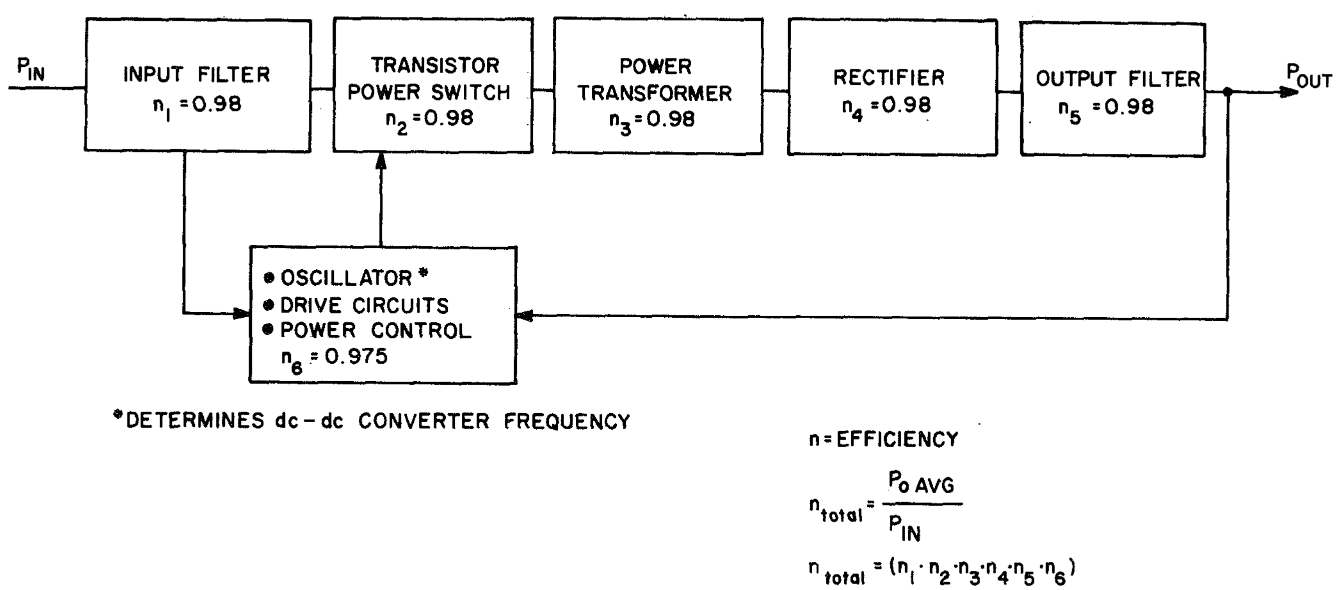


Figure 5.2-1. Power Conditioner Functional Elements

input dc into square waves for these converters and regulators include power transistors, thyristors, and tubes.

Three types of transistors were selected as being representative of the state of the art. The selection included the high voltage-medium current Delco 2N2583; the Westinghouse 1776, which has a high voltage current product; and a very high current transistor, the Westinghouse 1401-1425 (not yet available in production quantities). After consulting with several manufacturers, the GE C158/C159 thyristor (on SCR) was also considered for this study, since this device is representative of the state of the art in high current, high voltage, fast turnoff inverter thyristors.

A typical current waveform for a transistor in a full-wave inverter is presented in Figure 5.2-2. The losses were calculated as the sum of the switching loss during turnon and turnoff (which are the product of the forward collector-to-emitter voltage drop and collector current), and the product of the base-to-emitter voltage drop and the base current during the on-time.

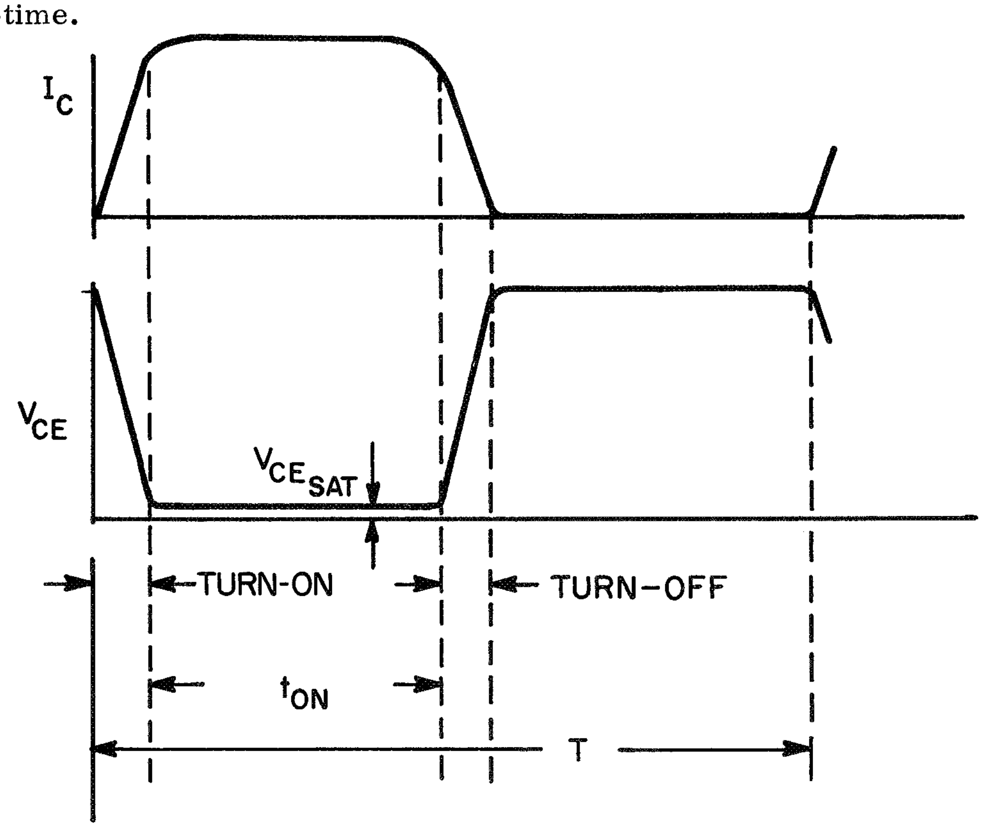


Figure 5.2-2. Transistor Switching Current and Voltage Waveforms

A graph of the calculated loss over a frequency range from 1 kHz to 50 kHz is presented in Figure 5.2-3, and the associated heat sink weights calculated at 50 pounds per kilowatt are presented in Figure 5.2-4. Drive circuit losses have been neglected and are considered separately. Thyristor losses are seen to increase very rapidly with frequency and would be considered only at low frequencies. The magnetic circuit efficiencies are poor at low frequencies (see Figure 3-7) where SCR's would provide a high-efficiency system, and SCR's are not considered further here. *

The 2N2583 transistor has been selected as a preferred device for near-future power conditioners. However, higher current devices may be of interest in larger power conditioners; the Solitron SDT-8655 and 8955 are rated at up to 60 amperes and have a forward collector-to-emitter saturation voltage of 2 volts at 40 amperes. Switching rate data was not well-established, and it is here that much of the efficiency loss occurs. With improved data, the device selection eventually may be revised.

5.2.1.2 Rectifiers

Vacuum tubes are generally too lossy to compete with solid-state switches considered previously, except where very high input voltage might be present, and solid state devices may not be applicable. However, tubes may be used for high-voltage rectification; a 20,000-volt power conditioner might use a single rectifier tube rather than a complex semiconductor rectifier stack. In this case, the tradeoff is one of tube reliability versus complexity of the stack.

Output voltage levels in this study, which are in general above 2,000 volts, do not permit single-cell rectifiers to be used, since the maximum peak inverse voltage rating of a single-cell rectifier is of the order of 2,400 volts. Series rectifier stacks, such as the Amperex Type OSS9110 series might be used. This unit could handle the voltage,

*Recent circuit development show the SCR can operate with high efficiency at a high frequency. This will be evaluated in related programs for the Phase III support program.

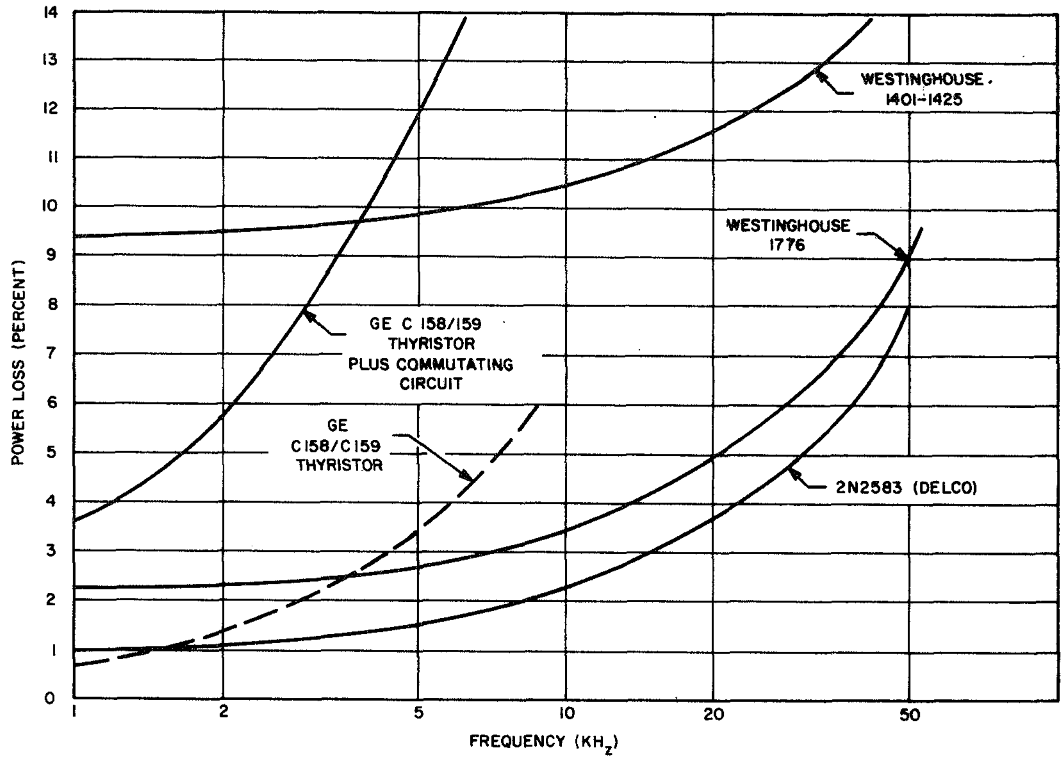


Figure 5.2-3. Percent Power Loss in Switching Devices

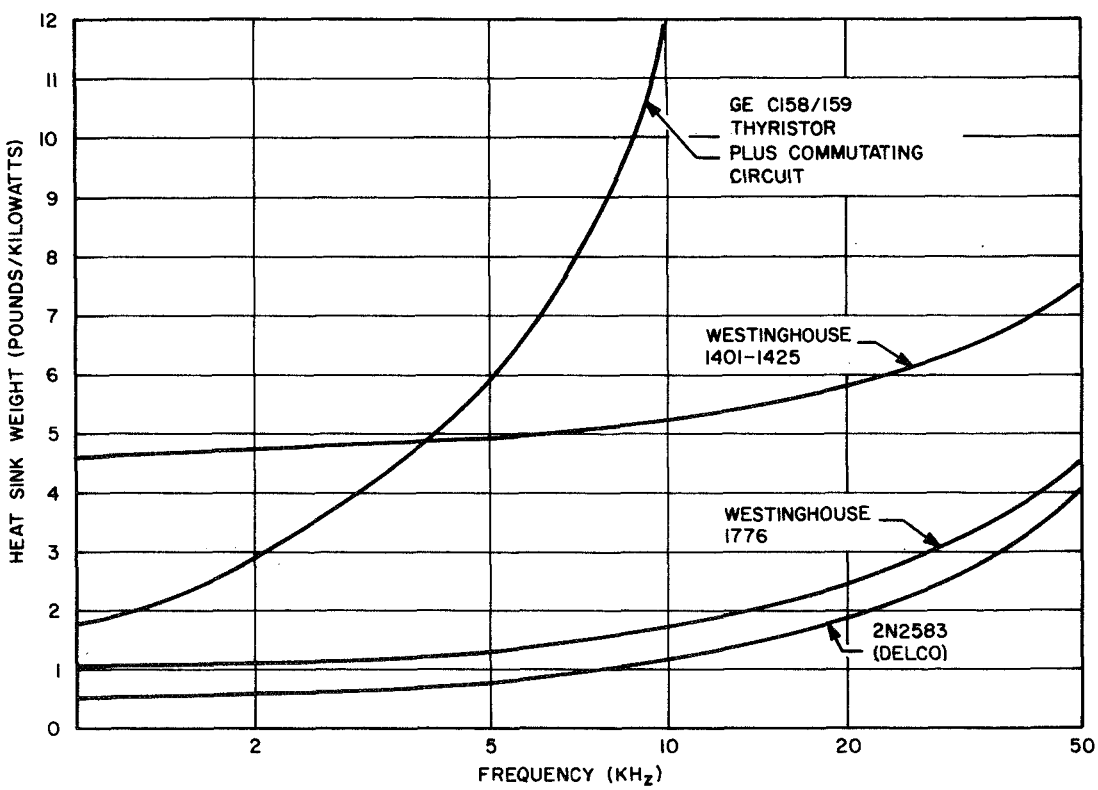


Figure 5.2-4. Heat Sink Weight per Kilowatt versus Frequency

but it probably could not handle the switching speed requirement. High switching speed, in addition to high voltage can be accomplished with a custom-built "stack," using devices similar to the IN3893 as manufactured by Westinghouse, GE, and several other semiconductor manufacturers. The losses in these devices are proportional to the forward voltage drop. As such, this loss is about 1 volt for each 200 volts being rectified (assuming a stack) or 1/2 percent of the input voltage. Switching losses are not the same as in the transistor switch; the voltage across the ON rectifier builds up and (in the case of the IN3893) switches off in 200 nanoseconds. Switching losses for full-wave rectifiers are shown in Figure 5.2-5, which also shows the heat sink weight required. The rectifiers have a power loss approximately equal to 0.04f, where f is the operating frequency of the power conditioner.

5.2.1.3 Transformer Analysis

A power conditioner requires voltage transformation through a transformer; its design contributes substantially to overall system performance. Careful design in terms of efficiency, weight and reliability is required for optimum performance of the power conditioner. The

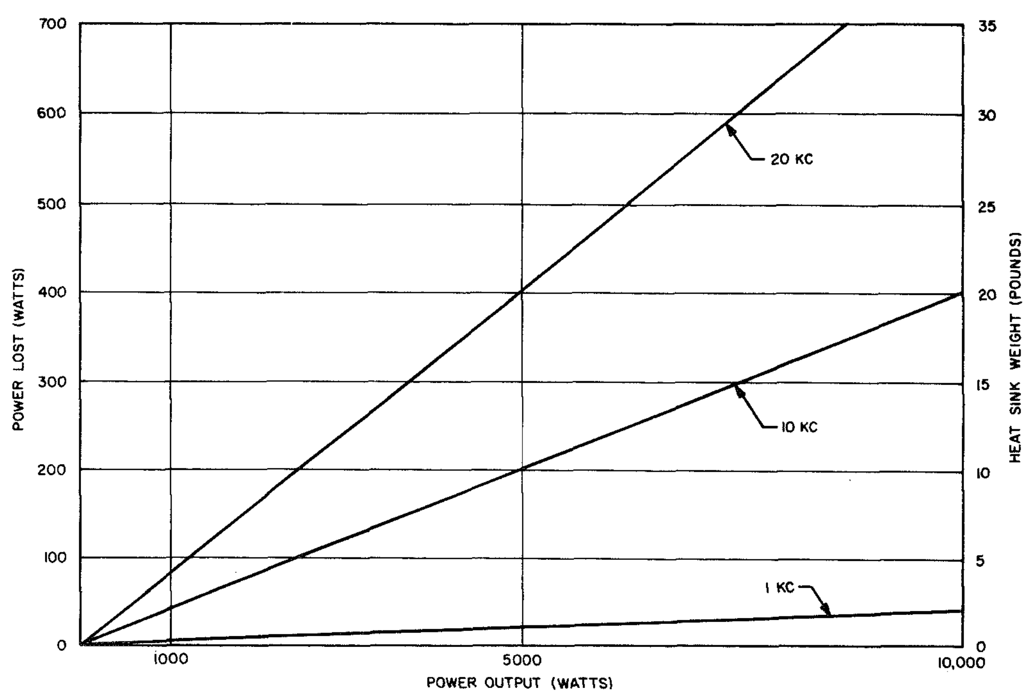


Figure 5.2-5. Rectifier Power Losses and Heat Sink Weight versus Input Power for a Full-Wave Rectifier, 200 Nanoseconds-Turnoff Time (IN3893)

transformer weight increases for an increased efficiency requirement, increased reliability, and a lowered operating frequency. The objective will be to develop tradeoff data to obtain the best compromise among the parameters of weight, efficiency, reliability and frequency, while insuring best compatibility with system requirements.

The primary study inputs were directed toward high-power, high-voltage, dc-to-dc converters. The ranges of performance parameters were:

Input Voltage	100,300, 3,000 volts
Output Voltage	2,000, 6,000, 20,000 volts
Power	500, 1,500, 5,000 watts
Duty	100%
Life	2 years minimum

The additional transformer input parameters related to internal power conditioner constants and variables include:

Efficiency	95 to 99%
Frequency	2,000 to 20,000 Hertz
Hot Spot Temperature	155°C
Internal Temperature Rise	80°C
Voltage Insulation	100 volts per mil
Core Materials	EI laminations, using Permalloy 80 or Alloy 48 from Magnetics, Incorporated
Windings	Primary center-tapped, single-secondary
Losses	Core 60%, copper 40%
Leakage Reactance Maximum	60% total losses

This large variation of input and output requirements was sufficient to warrant using a transformer computer program; the functional block diagram is shown in Figure 5.2-6. The computer provides transformer design for any given set of input conditions. The magnetic

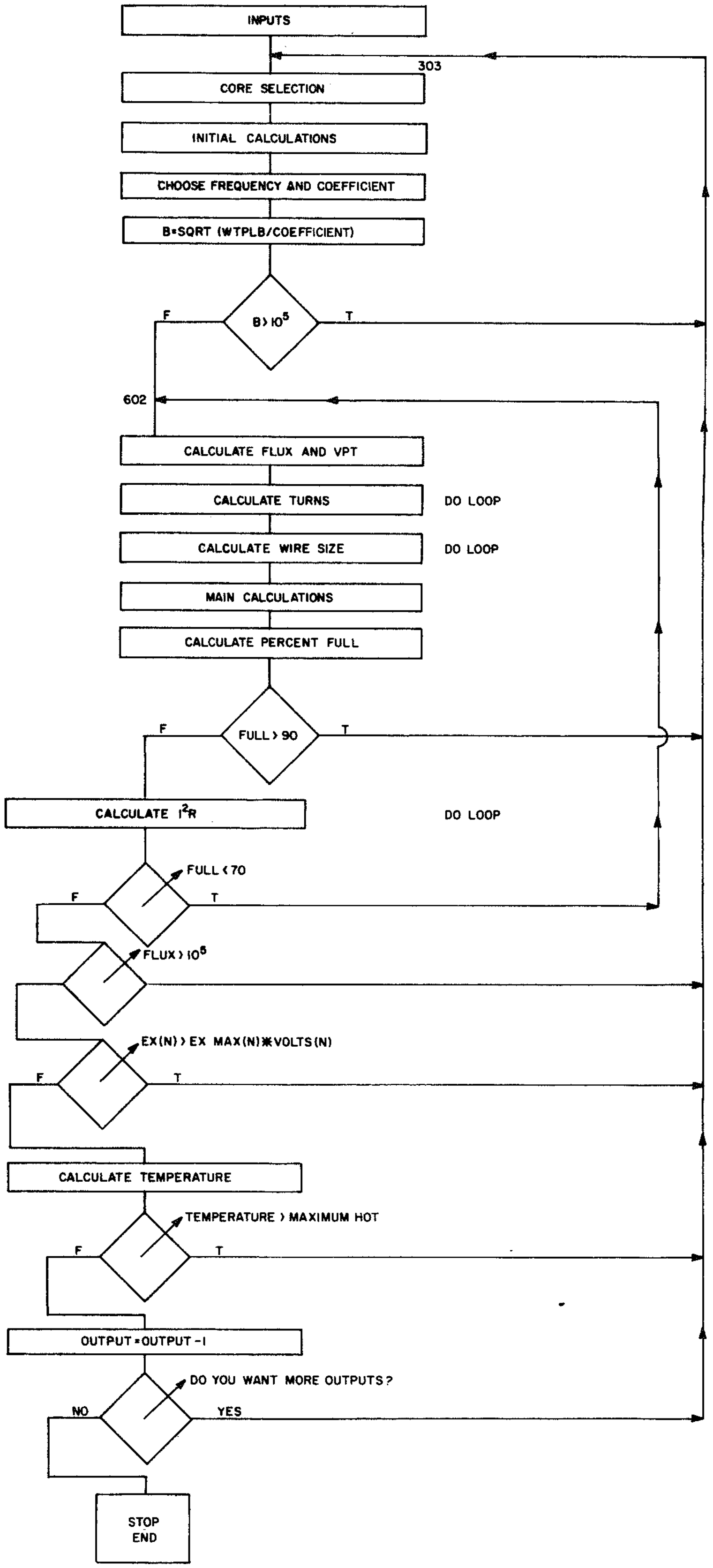


Figure 5.2-6. Transformer Design Computer Program

core size is initialized at some small value and then increased in size by incrementing according to a programmed routine. Per unit resistance, leakage reactance and per unit core loss (based on 60 percent loss in iron, 40 percent in copper) are first calculated, and used to determine core weight, core loss coefficient, and operating flux density. The flux density is compared with the level allowed for the specific core material, and if it is too great, a larger core is chosen and the calculations are repeated. When flux density is satisfactory, the volts per turn, number of turns, and wire size, determined by a maximum amperes per square inch, are calculated. If the wire takes more than 90 percent of the core window, the core size is increased until the required wire can fit into the core.

Copper loss is then calculated. Copper loss less than 40 percent of the total losses suggests that the wire size be changed, and that a new transformer with a larger core be calculated. If the wire size had to be decreased, and the core window was then not sufficiently filled, the flux is decreased by a given increment, and the transformer is recalculated.

Leakage reactance and flux density are calculated; if they are too high, the core size is increased, and all calculations and iterations are repeated. Finally, a high, hot spot temperature, based on thermal resitance and average surface temperatures, requires an increased core size, and all previous calculations are repeated. The transformer data is printed out when all requirements are satisfied, and a new set of input conditions is taken from the matrix to design the next transformer.

The output points do not form ideal curves, since the computer program uses discrete steps in core size and wire size, and stops at the first design that satisfies the established selection criteria. Minor modification to the computer design of a specific transformer can be easily performed manually. Typical curves were selected to satisfy the requirements of a likely power conditioner transformer design. Figure 5.2-7 illustrates a typical set of results; Figures 3.1-5, 3.1-6, and 3.1-7 show the overall smoothed parametric curves.

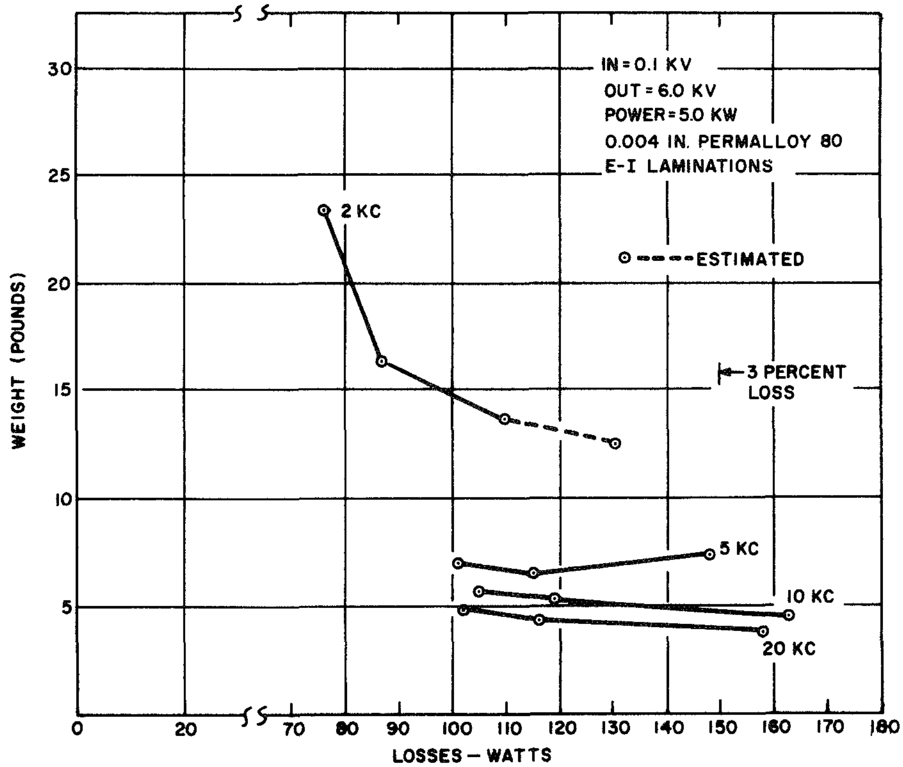


Figure 5.2-7. Typical Results - Transformer Design Computer Program

Comparing core material, the calculations led to the conclusion that Alloy 48 provides a lighter weight transformer at lower frequencies, while Permalloy 80 provides a lighter transformer at higher frequencies. The crossover frequency is in the range of 2 to 4 kilohertz, and a selection will be based on weight only if operated outside this region.

The general effects of the parameters can be summarized:

1. Efficiency. Losses decrease by one-half and weight approximately doubles for a 1 percent change above a nominal 97 percent.

2. Power Output. Increased output power requirement will increase weight by

$$wt_{new} = wt_{old} \left(\frac{Pnew}{Pold}\right)^{0.75}$$

3. Core Material. Selection of core material for minimum weight depends on frequency of operation.

4. Frequency. Increase results in a transformer weight decrease. At frequencies above 5 to 10 kHz, the weight reduction is small.

5.2.1.4 Filter Analysis

The power levels required by an AM TV transmitter were considered to range from 0.15 to 7.7 kilowatts. A primary power and power conditioner size advantage may be realized if the power conditioner were sized to operate at the average load requirement (about 3.5 kw), while satisfying load variations and peak load demands. The average load can be provided by the primary source using a duty cycle controlled regulator with a suitable output LC filter. Power peaks above the average would be provided by the energy storage in this filter. Figure 5.2-8 shows a worst-case TV waveform, which places the most demand on the storage filter.

The filter size is dependent on output ripple voltage, frequency of dc-dc conversion, and switch ripple current in the power transistors and rectifiers, in addition to the load profile. The allowable ripple voltage is 2 percent from the EIA Standard RS-240 (Reference 25). The conversion frequency is assumed to be 4,000 Hertz. The ripple current is the acceptable current change through the power transistor and rectifier switches. High ripple current

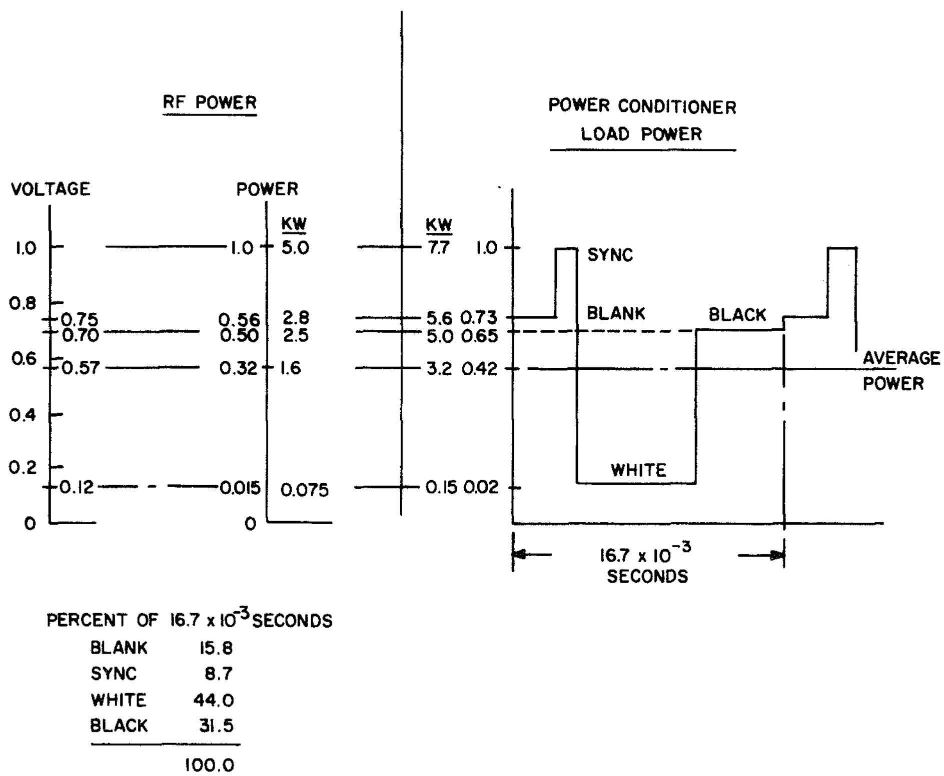


Figure 5.2-8. Power Profiles - RF Power Levels and Worst-Case TV-Field Waveform

causes higher switch losses and an increase of input filter size; therefore, it is desirable to minimize ripple current.

Figure 5.2-9 shows the output filter and the voltage waveform applied to the filter. The load is shown with a switch to show the step load changes of the transmitter power profile. The design criteria for the filter will be to minimize ripple current through the inductive element and to supply step load changes from the output capacitor. The inductor current is considered constant in the provided load profile, and varies only as the switch ripple current varies.

The inductance is selected on the basis of a limiting or specified ripple current. The worst-case condition is a rectified square wave with a 50 percent duty cycle. The current change must be held within ripple specifications for time increments of 0.063 milliseconds (one-fourth of a cycle with a full-wave rectifier and a 4,000-Hz frequency). The voltage applied to the inductance is the output voltage, Eo, when the square wave is

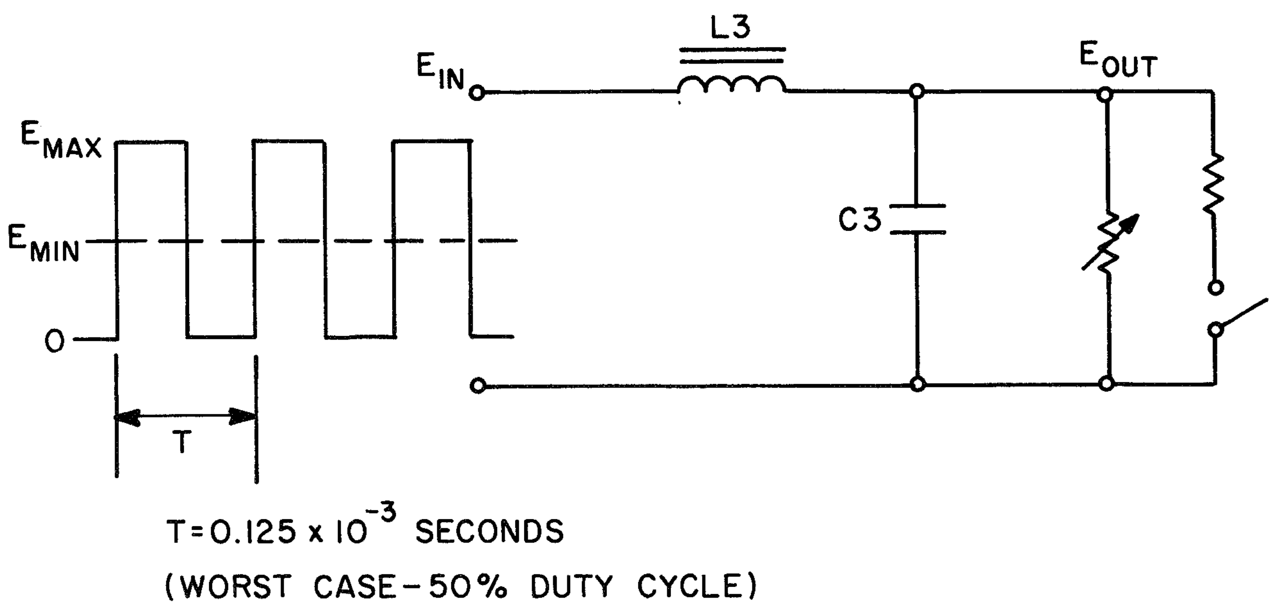


Figure 5.2-9. Output Filter and Load Circuit

at zero, and the current is I_{out} and is equal to E_{out}/R_L. A peak-to-peak current ripple of 14 percent of I_{out} results in:

$$E = L \frac{\Delta I}{\Delta t}$$

$$E_{out} = L \frac{0.14 (E_{out}/R_L)}{0.063 \times 10^{-3}}$$

or

$$L = 0.45 \times 10^{-3} R_L$$

Resulting inductor sizes as a function of allowable ripple for various R_L's and output voltage for the assumed 3.5-kw level are shown in Table 5.2-1.

The capacitors to provide the peak energy storage with less than a 2 percent transient over a TV field (1/60 second) were then determined, using the inductances of Table 5.2-1 with the power demand waveform of Figure 5.2-8. The computation was based on the transient response of the LC filter with an R load. This filter is found to have a damped, low-frequency oscillatory response, but the voltage regulator feedback circuit easily compensates for the oscillatory tendency and provides a stable average voltage. Short duration transients, such as the 7.35-millisecond white picture interval of Figure 5.2-8, require that the capacitors in Table 5.2-1 provide storage for the sync signals but not necessarily the picture variation. Either more capacitance is required for significant picture variation away from the average, or some other control technique is necessary. (See Appendix A on "Controlled Carrier.")

The input filter, also an LC type, presents a low impedance to the power switches and reduces noise transfer back into the source. The ripple current previously discussed is also applied to the input filter through the low impedance power switch. The capacitor used is a tantalum etched foil type.

Table 5.2-1. Filter Weight Summary (0.9 msec Storage, 3.5 kw)

Output Voltage (Kilovolts)	Ripple Current	Inductance Henry	Capacitance Mfd	Inductor Weight (Pounds)	Capacitor Weight (Pounds)	Total Weight (Pounds)
3.5	±0.02	8.6	33	27	44	71
7.5		39.6	6.6	27	37	64
12		101	2.8	27	30	57
3.5	±0.05	3.4	13.2	12	19	31
7.5		15.8	2.6	12	14	26
12	-	40.4	1.1	12	14	26
3.5	±0.1	1.72	6.6	4.0	12	16
7.5		7.91	1.3	4.0	12	16
12		20.2	0.56	4.0	12	16
3.5	±0.2	0.86	3.3	2.2	6.7	8.9
7.5		3.9	0.65	2.2	6.0	8.2
12		10.0	0.28	2.2	5.6	7.8
3.5	±0.3	0.52	2.2	1.4	4.2	5.6
7.5		2.4	0.4	1.4	4.0	5.4
12		6.1	0.2	1.4	4.0	5.4

The ripple current level effect on input filter design is illustrated by an example. A ripple current reduction from 0.1 to 0.05 results in a weight reduction of 3.5 pounds, as shown in Table 5.2-2. The corresponding change in output filter weight, however, is an increase of 10 pounds (15 at 3.5 kv.) for a net system increase of 6.5 pounds. Thus +0.05 ripple current level is recommended for a design of the power conditioner. In addition to less net weight, the switching losses are less than for a higher ripple current.

Table 5.2-2. Input Filter - Switch Ripple Current Effect

Ripple Current	Nominal Current (Amps)	Current Change (Amps)	Capacity Mfd	Capacitor Ripple (Volts, RMS)	Capacitor Units *	Capacitor Weight (lb)
±0.05	40	4	700	1.0	4	0.88
±0.10	40	8	3,500	0.5	20	4.4

Reference General Electric Capacitor Application Note 121EC.

*One unit - 350 mfd. 75 vdc
D3 Case - 0.22 lb.

5.2.2 POWER CONDITIONER DESIGN

5.2.2.1 Requirements

The power conditioner design to transfer the low-source voltage to higher load voltage will be influenced by required specifications. The range of typical requirements are:

Output voltage	2,000 to 20,000 volts
Regulation	±2%
Input voltage	100 to 3,000 volts
Input voltage variation	2:1
Output power	Up to 15 kilowatts
Duty	Continuous
Life objective	2 years in space
Devices	Solid state and tube types

System weight is minimized if the power conditioner is sized for the average power, as mentioned previously. A functional block diagram of a regulated dc-dc converter was shown in Figure 5.2-1. Each block has a power loss, and minimizing the losses of each results in high overall efficiency.

Requirements for a specific application (UHF, AM TV transmitter) illustrate the use of the design data generated in the previous sections. Requirements are:

Output voltage	3,500 volts
Regulation	$\pm 2\%$
Ripple	2%
Input voltage	100 volts nominal
Input voltage variation	1.3 to 1.0
Output power	3.2 kilowatts (average) 7.7 kilowatts (peak sync)
Efficiency	85% minimum
Devices	Solid state
	Ripple current $\pm 5\%$

These requirements may be satisfied by using transistor power switches to generate a square wave voltage that is stepped up by the transformer, then rectified and filtered to provide the desired output voltage. Regulation is provided by duty cycle control of the power switches. The output filter is an LC filter required to limit power switch and rectifier current to safe limits and to provide a low output impedance to the pulsed loads. The input filter is required to reduce source ripple caused by duty cycle operation of power switches.

5.2.2.2 Power Switch Selection

The Delco 2N2583 transistor is selected as the power switch largely on the basis of highest efficiency. Two power switch configurations are applicable: push-pull and bridge. With a source voltage of 100 volts, the transistor would be stressed to 200 volts in a push-pull configuration, but only to 100 volts in a bridge circuit. A source voltage of 130 volts for the push-pull configuration would be usable and would provide adequate derating of the selected transistor, which has a rating of 325 volts.

Both configurations result in equal number of transistors; however, the bridge circuit is less efficient because the two transistors are in series (directly across the input), and switching losses are generally higher. Twice the drive power also would be required. Therefore, the push-pull configuration is preferred.

5.2.2.3 Frequency Selection

The upper frequency of operation is determined by the transistor characteristics, and the lower frequency is determined by the transformer design. A power system analysis which includes prime power weight would be expected to have a relatively constant weight within the frequency range of 3 to 5 kHz. Therefore, 4 kHz was selected for purpose of further design.

5.2.2.4 Power Module Design

The input power requirement for 3.2 kw output at 85 percent efficiency is 3.8 kw, which is the power that must be transferred by the power switch. A source voltage of 100 volts results in an input current of 38 amps. The selected transistor has 10-ampere capability; therefore, four parallel transistors are required. A derating factor may be applied for long-life operation; 50 percent derating would increase the number of parallel transistors to eight. A push-pull switching configuration would require a total of 8 transistors, or 16 with 50 percent derating factor.

Transistors in parallel exhibit some loss problems. The most critical problems are load division equalization, and that the slower opening switches and the faster closing switches are forced to carry full current, several times rating. Thus, certain of the transistors will dissipate nearly all switching losses, which is not desirable for long life; therefore, the power modules should be designed to minimize this unbalance. An approach is to use independent modules for each pair of push-pull transistors, leading to a configuration like that in Figure 5.2-10.

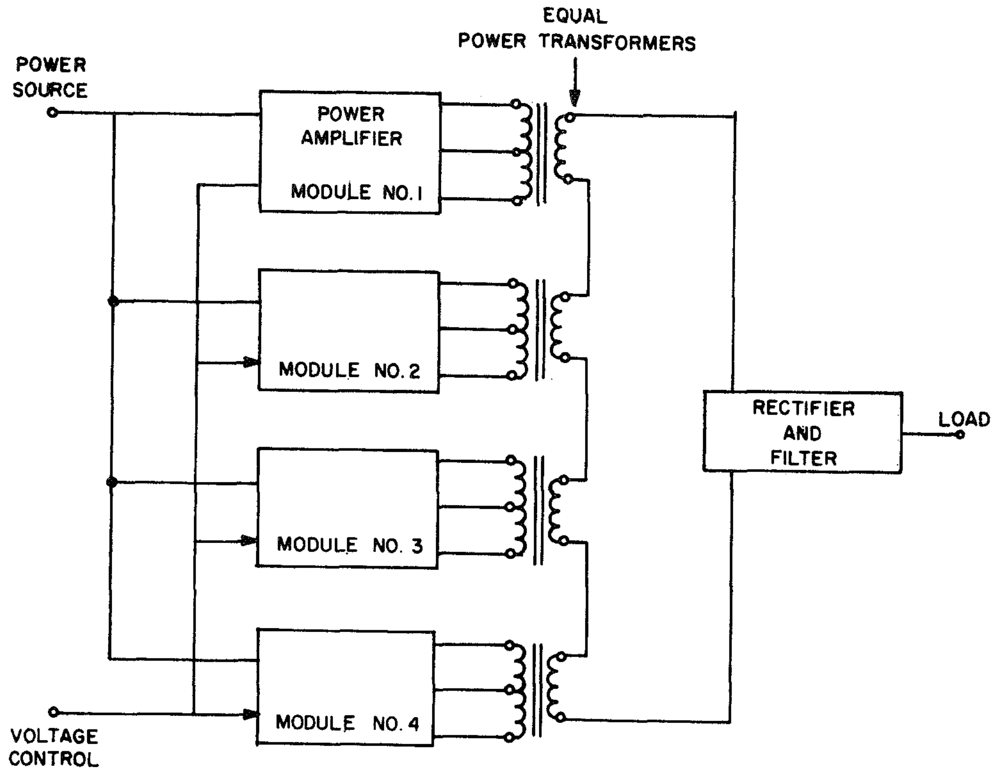


Figure 5.2-10. Power Module Design Configuration

Each power amplifier here is connected directly to the source; control is common; and percent power transfer by each module is based on number of modules. The secondaries of the transformers are series-connected, which forces load-sharing and distributed power dissipation. For example, as a limiting case, power would not be applied to the output if any one of the transistors were not turned on, since the transformer of the OFF transistor looks like a high impedance. Therefore, all of the transistors that are ON have turned ON into a zero load, or high impedance, resulting in zero switching losses to that point in time. The power dissipated when the last transistor turns on is only relative to its percent of the total, because as it turns on, current begins to flow simultaneously through all the ON transistors. The same situation applies to the turnoff period.

Practically, however, all transistors will tend to operate simultaneously, and all transistors will share the switching losses. This loss in a module is proportional to the amount of power from that power module. Therefore, this configuration is proposed as a means to provide long-life operation of power modules operating in parallel.

A detail of the power amplifier and method of control for regulation is shown in Figure 5.2-11. Briefly, the power transistors are turned on by the drive voltage at the start of each cycle. They use duty cycle as a means for output voltage control. When the magnetic amplifier saturates, the SCR fires and applies a reverse voltage to the base of the ON transistor, which turns off and holds off until the base drive voltage reverses. The opposite transistor is then turned on. Parallel duty cycle control is provided by placing all gate windings (isolated from each other) on the same set of cores.

5.2.2.5 Performance

A summation of functional component efficiencies provides a total efficiency estimate.

Functional Component	Efficiency
Transistor	0.98
Transformer	0.98
Rectifier	0.98
Filter Output	0.98
Filter Input	0.98
Drive and Control	0.975
Total	0.885

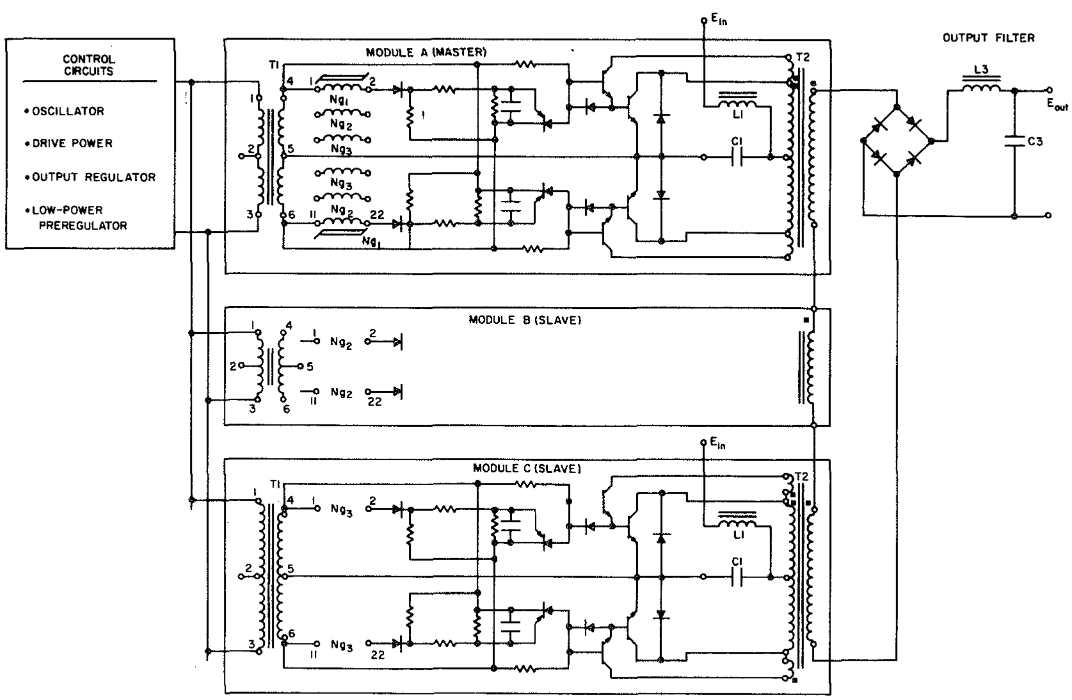


Figure 5.2-11. Power Module, Schematic Diagram

Therefore, the requirement of 85 percent efficiency is satisfied. The expected efficiency range allowing for design and manufacturing tolerances is 85 to 88 percent.

The weight estimate for the power profile of Figure 5.2-8, with energy storage of 8.5 to 9.5 milliseconds, is in Table 5.2-3. A weight estimate for the same power profile, but with the power conditioner having a power capacity equal to the black picture level and energy storage only for power peaks above 5.0 kilowatts, is in Table 5.2-4. The difference shows the effect of energy storage requirement, and may be used for estimating a primary power requirement tradeoff.

The specific weight for a power conditioner providing 8.5 to 9.5 millisecond energy storage is:

3.5 kilovolts	34 lb/kilowatts
6.0 kilovolts	34 lb/kilowatts
20.0 kilovolts	45 lb/kilowatts

A mechanical layout of the power conditioner is shown in Figure 5.2-12. The overall size is 30 by 14 by 6 inches. The largest single-piece part is the output capacitor. The layout size is based on heat pipe cooling rather than area for radiation cooling, and materials insulation rather than distance for high voltage protection (at least in the atmosphere).

5.2.2.6 Electromagnetic Compatibility (EMC)

EMC is a critical system problem, particularly when the power conditioner controls through a pulse width modulation scheme. Pulse width modulation schemes require large output and input filters. These filters are low-pass and generally provide high-frequency attenuation; however, capacitor coupling of the inductors and frequency limitation of capacitors permit transfer of pulse energy at high frequencies to other subsystems. Additional selective filtering may increase the size from the present conceptual design. However, an estimate of size increase can not be attempted without data on EMC requirements and power conditioner noise generation. The recommended procedure is to build the

Table 5.2-3. Weight Summary for RC = 9 Milliseconds

Functional Component	3.5 KV	6 KV	12 KV	20 KV
Power Transistors	1.6	1.6	1.6	1.6
Transformer	9.0	10.0	20.0	44.0
Rectifier	1.6	1.6	3.2	4.8
Filter-Output	72.0	68.0	62.0	57.0
Filter-Input	2.0	2.0	3.0	4.0
Drive Controls	4.0	4.0	4.0	4.0
Harness and Connectors	2.0	2.0	3.0	3.0
Packaging	17.8	17.8	19.2	23.6
Total Weight	110	107	116	142

Notes

1. Ripple current ±0.15
2. Power 3.2 kilowatts average (Continued)
   7.7 kilowatts peak

Table 5.2-4. Weight Summary for RC = 0.9 Milliseconds

Functional Component	3.5 KV	6 KV	12 KV	20 KV
Power Transistors	2.3	2.3	2.3	2.3
Transformer	9.0	10.0	20.0	44.0
Rectifier	2.0	2.0	4.0	6.0
Filter-Output	31	29	26	24
Filter-Input	2.0	2.0	3.0	4.0
Drive Controls	5.7	5.7	5.7	5.7
Harness and Connectors	3.0	3.0	4.0	4.0
Packaging	11	11	13	18.0
Total Weight	66	65	78	108

Notes

1. Ripple current ±0.05
2. Power 5.0 kilowatts average (70 percent duty)
   7.7 kilowatts peak

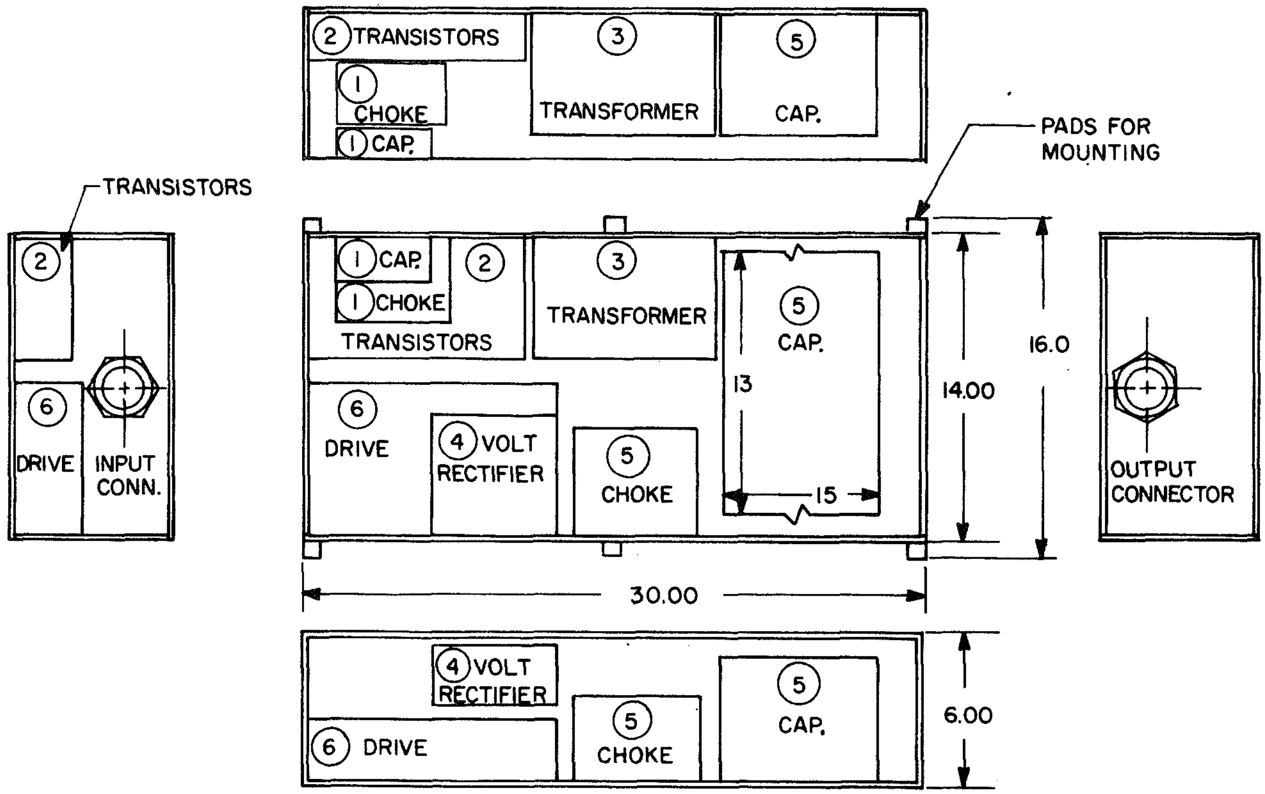


Figure 5.2-12. Power Conditioner Configuration

power conditioner to satisfy the primary requirements, and then to test and evaluate the configuration to determine the additional filter requirements.

5.2.2.7 Space Environment Requirements

A review of materials applicable to high voltage, space environment was performed and is included in Sections 3.1.1 and 5.1. The materials data generated and the design guidelines prepared are consistent with the power conditioner design data presented. However, a detailed design where hardware testing is the end product must make effective use of the materials data to assure good performance.

5.3 RF HIGH POWER OPERATION

5.3.1 REQUIREMENTS

Large spacecraft television broadcast transmitters considered for use in space broadcast service may have one or more transmitters ranging in power rating up to 10 or more kilowatts peak RF output. These levels are two or three orders of magnitude higher than current spacecraft transmitters. Understandably, there is concern about high voltage RF breakdown in the microwave circuitry of these transmitters, especially since breakdown has been experienced at levels as low as a few watts and 20 or 30 volts rms in space or simulated space conditions.

The range of parameters included in the RF area of study include:

1.	RF Power Output	Up to 15 kilowatts FM (cw) or AM sync peak
2.	Frequency	Nominally 800 MHz, 2,500 MHz, 8,000 MHz and 12,000 MHz
3.	Modulation	FM or AM
4.	Instantaneous Bandwidth	30 MHz (maximum) per FM TV channel 6 MHz per AM TV channel
5.	Number of channels combined into a single output terminal	Up to 8
6.	System life	Two years minimum

Basic data was obtained from Reference 10 with adaptations to fit these parameter ranges and to fit the RF circuitry required in a transmitter system.

The initial considerations relate to electrical breakdown modes, including types, circumstances, applicability to various types of RF devices, and means for minimizing breakdown possibilities. This is followed with RF circuit design characteristics for three transmitter systems:

1. S-Band eight-channel FM TV transmitter using TWT's

2. UHF four-channel AM TV transmitter using gridded tubes

3. UHF one-channel AM TV Transmitter using a linear CFA

The electrical breakdown and thermal control problems are assessed for the three systems.

5.3.2 RF ELECTRICAL BREAKDOWNS

5.3.2.1 Types of Breakdowns

There are several identifiable RF breakdown modes to be considered that apply to spacecraft transmitters. In practice, there is often a certain amount of overlap between these modes so that the point of transition from one to another is not always clear. More than one mode can exist simultaneously, and it is possible for the existence of one mode to set off other breakdown modes. Major modes of interest are the following:

Corona. Localized ionization of the gas in the vicinity of an electrode; may result in ultimate failure of a dielectric due to erosion of the dielectric or "treeing," and the gas fill around the electrodes may be chemically changed. Corona current also generates RF noise.

Arcover. A normally disruptive discharge between electrodes due to the ionization of a path between the electrodes; electrodes may be damaged by the arc, and undesirable chemical changes produced in the gas fill surrounding the electrodes. Tracking on dielectric surfaces adjacent to the arc path may occur.

Vacuum arc. Occurs where gas pressure is normally too low to support ionizing discharges. The presence of high fields between electrodes is variously believed to result in field emission and clump or particle exchange. High energy electrons that strike the opposing electrode will vaporize sufficient material at the electrode surface so that localized gas pressure permits an arc to form.

Multipacting. A secondary emission process that occurs in vacuum systems when voltage and frequency are such that the emitted secondary electrons travel between electrodes in an odd number of half-cycles of the applied RF field. The secondary emission coefficient must be greater than 1.0 at the energy level of the impinging electrons in order for multipacting to grow. It results in circuit loading and increased loss effects, and may cause outgassing of electrodes which leads to disruptive arcs. Multipacting surfaces may be either metallic or dielectric.

Bulk Breakdown. An insulation volume failure where arcing occurs within or through the material.

Erosion. May take several physical forms. The surface may be eroded away, causing a crater effect, voids included in the dielectric may be enlarged, or treeing may occur. The net result is a reduction of effective insulation thickness and bulk breakdown becomes more likely.

Flashover of Dielectric/Gas Surface. Where arcing tracks primarily along the surface of a solid or liquid dielectric.

5.3.2.2 Microwave Breakdown Characteristics

A satisfactory theory of high frequency gas discharge breakdown requires only an electron production due to primary ionization of gas molecules by colliding electrons, greater than or equal to the loss of electrons by diffusion to the surrounding walls and attachment to neutral gas molecules. The breakdown voltage due to gas ionization between parallel planes for dc and very low frequencies is expressed by Paschen's law (Figure 5.1-2). A curve for breakdown between needle gaps is also shown. Paschen law curves can be used for rough estimates of air breakdown level, but a number of corrections should be applied. These include component configuration, RF frequency, temperature, pulse length, and gas types.

Temperature is frequently important since it affects gas density for most situations. Temperature can directly affect breakdown in extreme situations where material vaporization or thermionic emission occur. Data is usually given for $20^{\circ}C$. The correction for equivalent pressure at other temperatures (for a given P) is given by the ideal gas law

$$p_o = p \frac{T_o}{T}$$

where temperatures are expressed in absolute units (T_o is 293^{o}K).

Electron energy for low frequencies closely follows the instantaneous value of the RF field, and breakdown will occur approximately at the instantaneous voltage corresponding to the dc breakdown curve of Figure 5.1-2. But as frequency is increased, the effective voltage of the applied RF field E_e is reduced below the rms value in accordance with the correction given graphically in Figure 5.3-1. This is where the frequency is too high for the electron to change its velocity significantly over a half cycle. Another correction, an additive rather than multiplicitive, is required for lower frequencies where the electron motion can follow the RF field (relative to electrode geometry). This correction is given by:

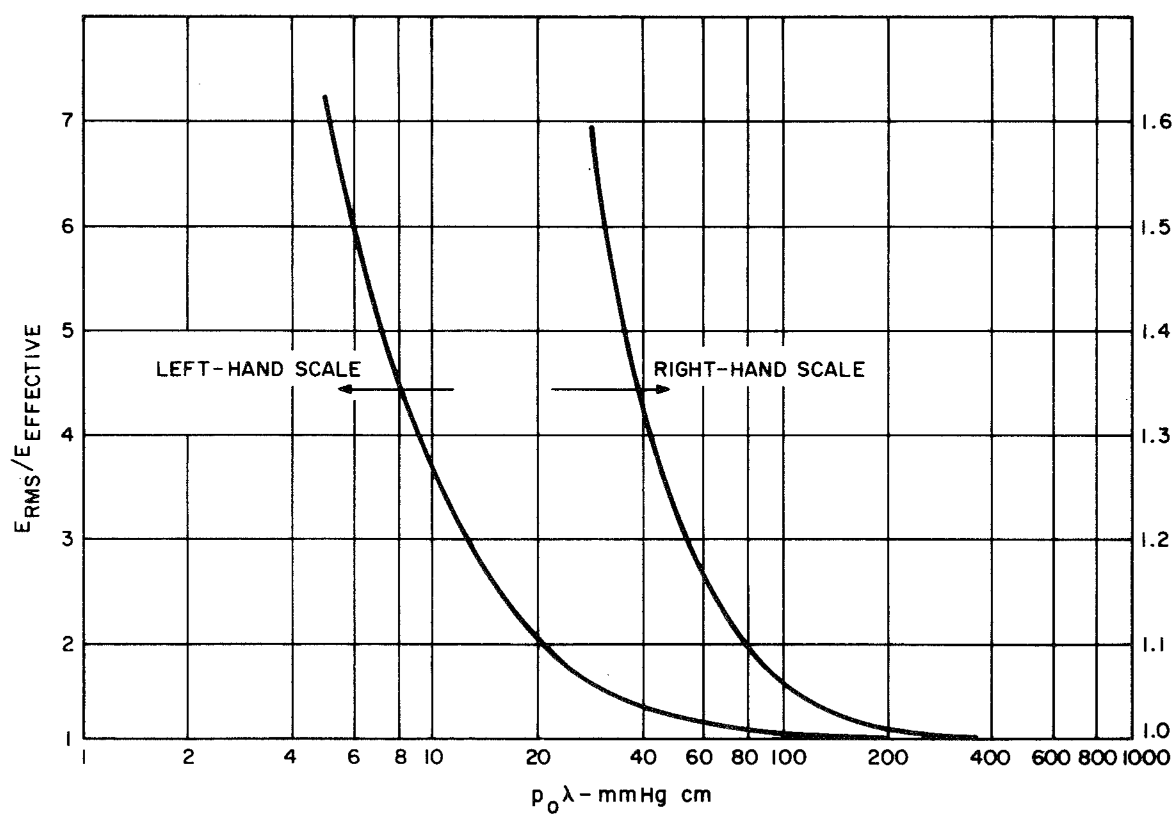


Figure 5.3-1. Ratio of RMS to Effective Value of Electric Field for Air

$$\left(\frac{E_e}{P_o}\right)_{net} = \left(\frac{E_e}{P_o}\right) + \Delta$$

where Δ is plotted in Figure 5.3-2.

5.3.2.3 Rectangular Waveguide and Coaxial Line Breakdown

Several curves useful in computing waveguide breakdown levels are included in Reference 10. Maximum field intensity in rectangular waveguide occurs in the middle of the broad dimension "a" in Figure 5.3-3 which gives the values for (E_e/P_o) net for the above equation. The relation between the power carried by the waveguide and the maximum rms electric field is

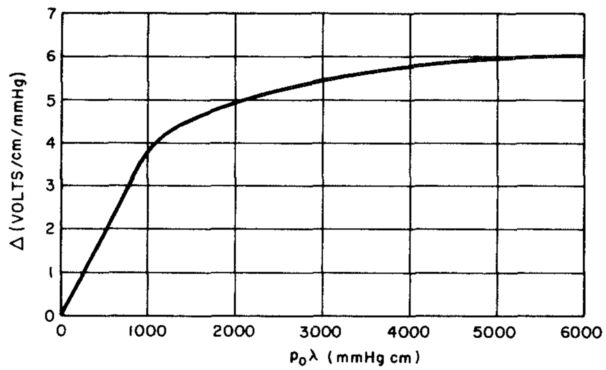


Figure 5.3-2. Additive Term for E_e/P_o in Air as a Function of $P_o\lambda$

$$P = 1.33 \times 10^{-3}\ a\ b\ (\lambda/\lambda_g)\ E_{rms}^2$$

Consistent units of length must be used for electric field strength and in the waveguide dimensions to obtain the power in watts. The parameters for several common waveguides are given in Table 5.3-1. Free space wavelength is λ, while the guide wavelength is:

$$\lambda_g = \frac{\lambda}{[1 - (\lambda/\lambda_c)^2]^{1/2}}$$

where $\lambda_c = 2a$ is the cutoff wavelength of the waveguide. A sample calculation using the above factors is given in Table 5.3-2.

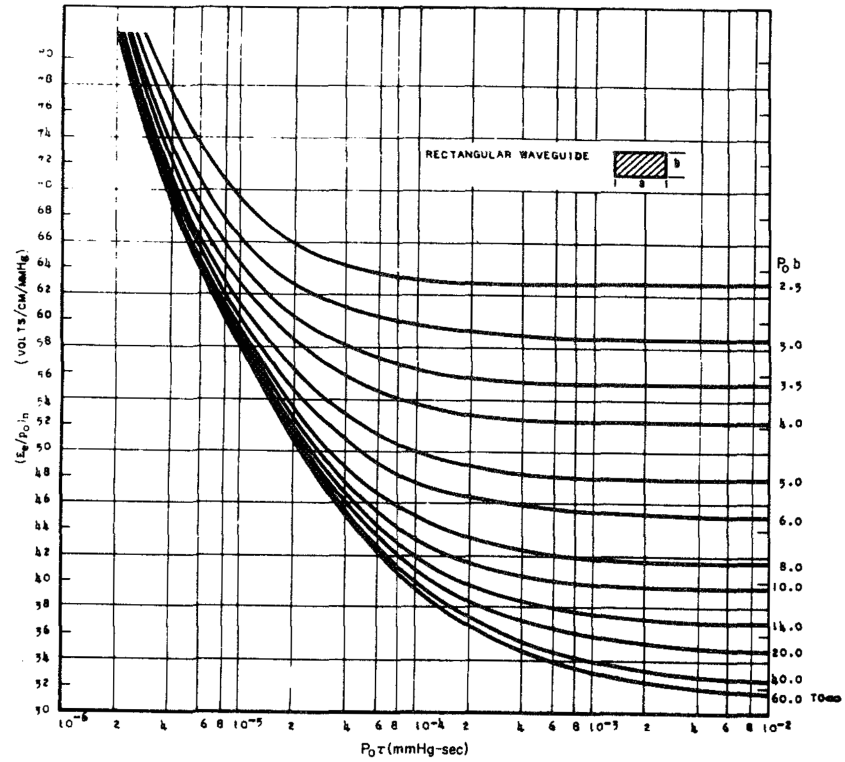


Figure 5.3-3. Ratio of Normalized Single-Pulse Breakdown Field to Pressure as a Function of Pressure Times Pulse Width for Various Values of Pressure Times Waveguide Height and for a/b = 2

The breakdown power for coaxial lines in terms of rms field at the inner conductor is:

$$P = (r_1)^2 [\ell n (r_2/r_1)] (E_{rms})^2/30$$

where r_1 and r_2 are inner and outer conductor radii, respectively. Calculations for breakdown power for 50-ohm lines, where $r_2/r_1 = 2.3$, can be obtained by using the curves of Figure 5.3-4 in the manner of Table 5.3-2.

Power breakdown curves for two typical rectangular waveguides, round waveguide, and a coaxial line are given in Figures 5.3-5 through 5.3-8. Additional data is in Reference 11. Voltage breakdown in RF components usually occurs at a lower level than for the corresponding plain waveguides. Relative peak power capabilities of some typical components are given in Table 5.3-3.

Table 5.3-1. Standard Rectangular Waveguides; TE_{10} Mode Dimensions, Recommended Frequencies and Breakdown Power

RETMA Designation	Frequency Range (kmc/s)		Width (inches)	Height (inches)	Width (centimeters)	Height (centimeters)	Cut-off Wavelength (cm)	CW Breakdown* Power-760mmH (megawatts)	
	f_1	f_2						f_1	f_2
WR1150	0.64	0.96	11.50	5.75	29.21	14.61	58.42	128	180
WR510	1.45	2.20	5.10	2.55	12.9	6.48	25.9	25.3	35.8
WR430	1.70	2.60	4.30	2.15	12.9	6.48	25.9	25.3	35.8
WR340	2.20	3.30	3.40	1.70	8.64	4.32	17.3	11.5	16.0
WR284	2.60	3.95	2.84	1.34	7.21	3.40	14.4	7.30	10.4
WR187	3.95	5.85	1.87	0.872	4.76	2.22	9.51	3.20	4.50
WR112	7.05	10.0	1.12	0.497	2.85	1.26	5.70	1.24	1.64
WR75	10.0	15.0	0.750	0.375	1.91	0.953	3.81	0.600	0.860

* These values are for atmospheric air, but they may be scaled for high dielectric strength gases.

Table 5.3-2. Sample Calculation of Waveguide Breakdown

Compares the cw breakdown power of WR-187 for both full height and 1/8 height at 5000 MHz. The pressure is assumed to be 20 mm Hg at 100°C.

		Full Height	1/8 Height
Normalized pressure for 100°C temperature (Section 5.3.2.2)	p_o	15.7	15.7
Using Table 5.6 compute the following quantities	(ab)	10.5	1.313
	(λ/λ)	0.632	0.632
	$p_o b$	34.8	4.35
	$p_o \lambda$	95	95
Compute	(λ/λ_g)	0.773	0.773
From Figure 5.3.3 determine ($p_o \tau \rightarrow \infty$)	$(E_e/p_o)n$	33	---
From Figure 5.7 in Reference 11		---	44
From Figure 5.3.2 determine	Δ	0.3	0.3
and from section 5.3.2.2	E_e/p_o	32.7	43.7
Multiply by p_o to obtain	E_e	514	686
From Figure 5.3.1 determine	E_{rms}/E_e	1.07	1.07
and compute	E_{rms}	550	735
From the first equation in 5.3.2.3 = Breakdown Power	p	3.24 kw	0.72 kw

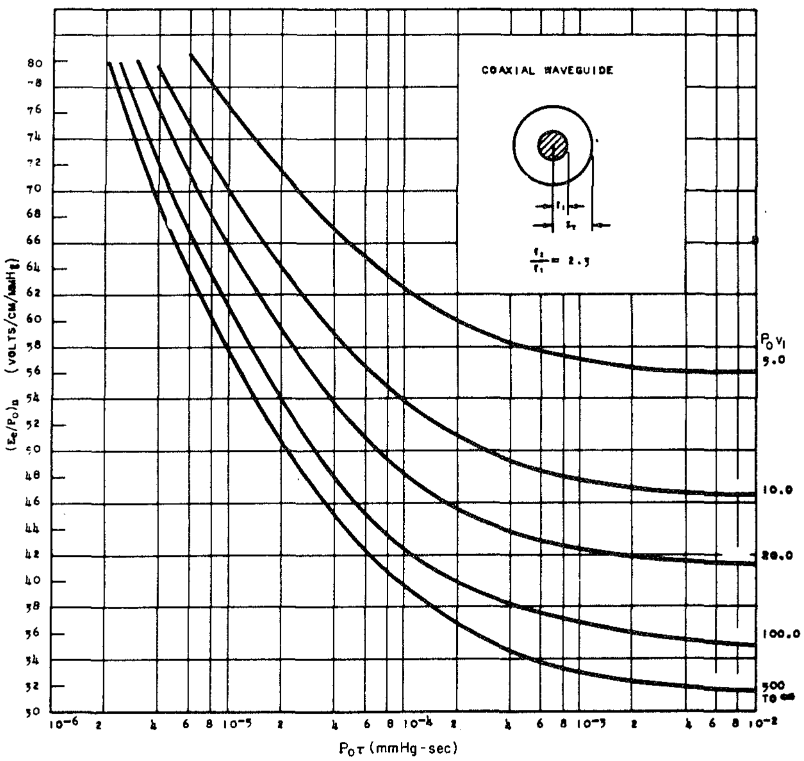


Figure 5.3-4. Ratio of Normalized Single-Pulse Breakdown Field to Pressure as a Function of Pressure Times Pulse Width for Various Values of Pressure Times Inner Conductor Radius

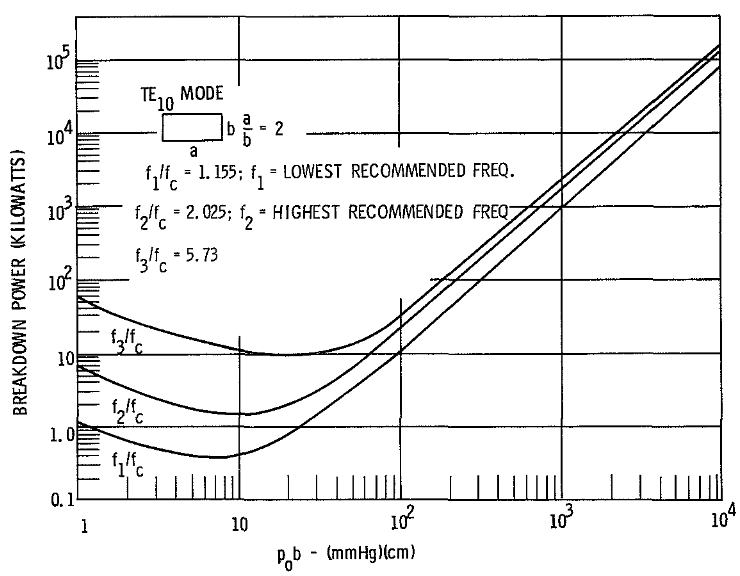


Figure 5.3-5. CW Breakdown Power for Air-Filled Standard Rectangular Waveguides (a/b = 2)

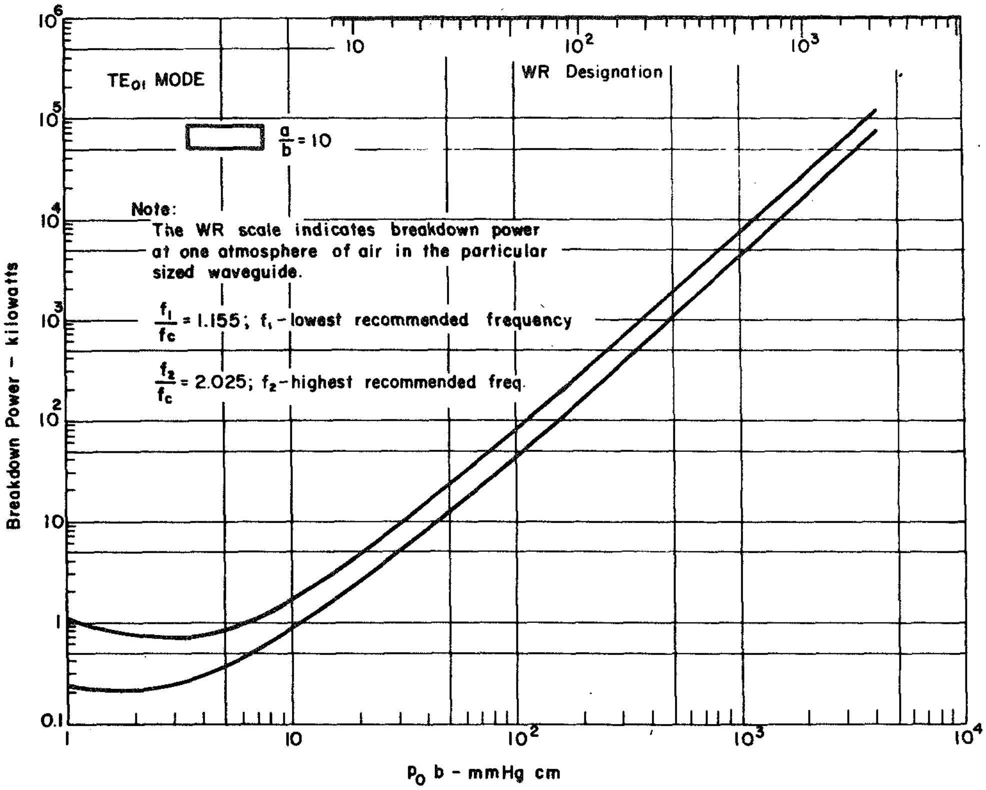


Figure 5.3-6. CW Breakdown Power for Air-Filled Narrow Height Waveguides (a/b = 10)

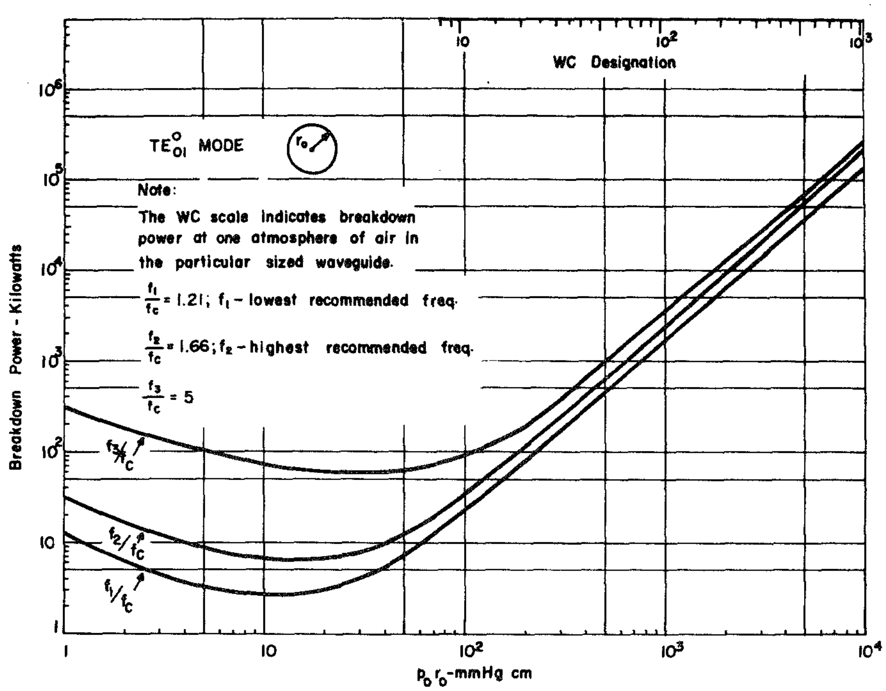


Figure 5.3-7. CW Breakdown Power for Air-Filled Circular Waveguides, TE^{o}_{01} Mode

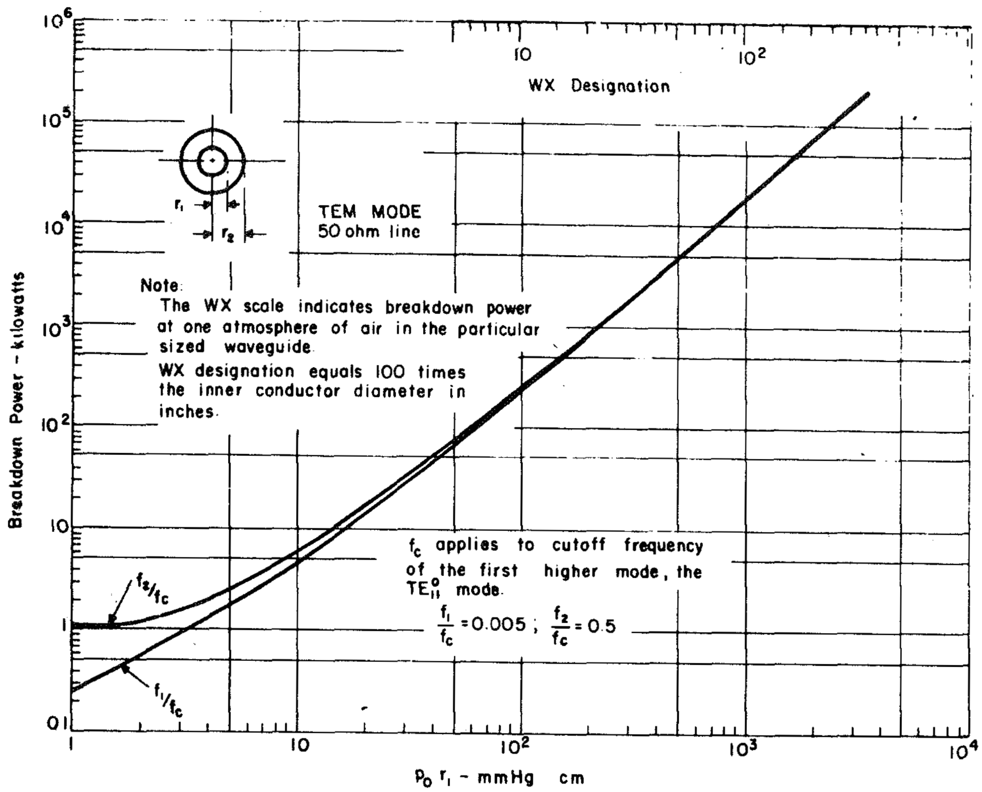


Figure 5.3-8. CW Breakdown Power for Air-Filled Coaxial Lines, TEM Mode

Electric field strength is increased locally by surface roughness and other discontinuities. The increased local field strength, or field enhancement for a number of typical discontinuities is shown in Figure 5.3-9. Tungsten whiskers of 1 to 2 microns and with height-to-diameter ratios of 10:1 result in a field enhancement between 50 and 150. Small, inadvertently-caused deviations from a smooth surface may lead to a vacuum arc, which occurs unexpectedly in what is thought to be an arc-less environment.

Vacuum arc test data is relatively scarce in literature. They occur when very high field strengths are present. Various theories have been proposed. It appears that field emission and clump or particle exchange are mechanisms which initiate the arc process. These mechanisms apparently cause intense localized heating which liberates sufficient gas to permit spark over.

Table 5.3-3. Relative Peak Power Capabilities of High Power Components

Component	Relative Capability	Frequency Evaluated	Pressure Range
H plane bend*	0.6 - 0.9	X-Band	air, 15 psi
E plane bend*	0.97	X-Band	air, 15 psi
H plane tee*	0.80	X-Band	air, 15 psi
90° twist*	0.80 - 0.90	X-Band	air, 15 psi
Magic tee*	0.80	X-Band	air, 15 psi
E plane tee*	0.06	X-Band	air, 15 psi
Cross guide coupler*	0.21	X-Band	air, 15 psi
Rotary Joints* - TM_{01}	0.14	X-Band	air, 15 psi
- Coax	0.15	X-Band	air, 15 psi
Twists**	0.25	S-Band	air, 15-35 psi
Folded Hybrid**			
Symmetric arm	0.63	S-Band	air, 15-35 psi
Asymmetric arm	0.37	S-Band	air, 15-35 psi
Short slot 3 db** Hybrid	0.26	S-Band	air, 15-35 psi

* The X-Band measurements were taken where a 1.2 microsecond pulse length was used.

** Straight-section achieved only 50 percent of theoretical power; 12 microsecond pulse length was used.

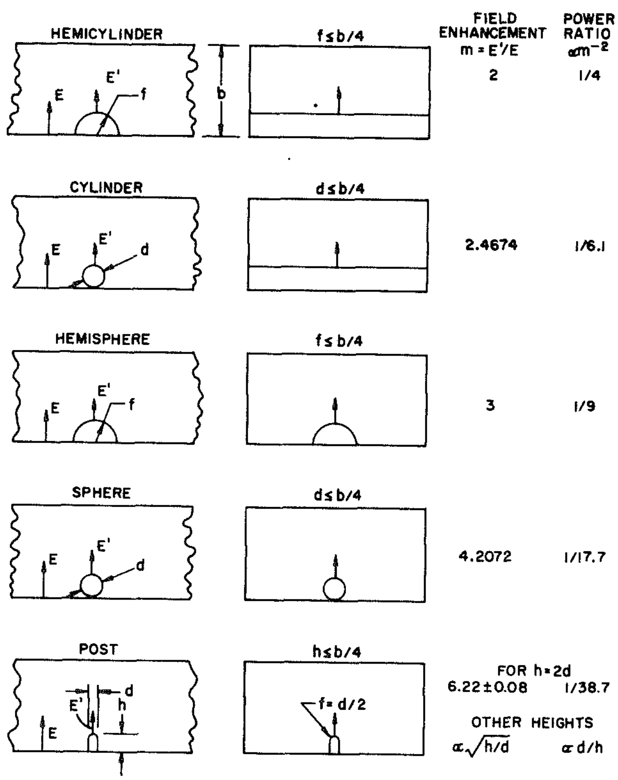


Figure 5.3-9. Electric Field Enhancement Factors and Power-Handling Degradation for Various Obstacles in Rectangular Waveguides

Field emission occurs around 10^6 v/cm. Pre-breakdown currents have been measured in the range of 10^4 to 10^5 v/cm, indicating field enhancement. Notes on field enhancement in previous paragraphs apply in the area of vacuum arcs. One experiment reported operation of a 0.0625 inch gap at 33 kv, corresponding to at least 2×10^5 v/cm holdoff. Vacuum-insulated systems designs should carefully consider the problem of metal whisker growth in the RF components, particularly in systems with a planned long life.

5.3.2.4 Multipactor Effects

Multipacting is a secondary emission breakdown phenomena which only occurs under certain RF field conditions in vacuum insulated systems. Three basic conditions, as mentioned in Section 5.1.4, must exist for multipacting to occur:

1. Sufficiently high vacuum (less than 10^{-1} mm Hg pressure).
2. Secondary emission ratio of electrodes in the RF field must be 1.0 or greater.
3. The operating frequency and voltage applied to the electrodes must be such that transit time of emitted electrons between electrodes is roughly the period of odd multiples of half-cycles of RF.

Peak RF voltage necessary for a multipacting discharge between parallel plates with a uniform applied electric field is given by an approximation expression (Reference 33)

$$V_o = \frac{\omega^2 md^2}{e} \cdot \frac{1}{\frac{k-1}{k+1}(\pi \cos \phi) + 2 \sin \phi}$$

where ω is radian frequency of the applied voltage, m is electron mass, d is plate spacing, k is the ratio of electron arrival speed to secondary electron emission speed, and ϕ is the electrical phase angle at which the average electron is emitted. Good agreement of test data with the above relation is obtained with k = 3. The resulting values of breakdown voltage are conveniently plotted as a function of the product of operating frequency and electrode spacing in Figure 5.3-10. The right and left boundaries are set by phase considerations: -58 and +18 degrees for the 1/2 cycle mode. Upper and lower voltage limits for the theoretical multipacting zones are set by the electron impact energy where secondary emission coefficient δ of the electrode materials ≥ 1.0. Existence regions for the higher order modes through the 9/2 are also included in Figure 5.3-10.

Typical curves of secondary emission coefficient δ for several materials are given in Figure 5.3-11. Thus, multipacting can be avoided at both low and high field intensities, except that the high intensities are reached only by traversing the entire multipacting region. This is usually possible if the electric field buildup is rapid enough that the multipacting electron cloud does not have time to build up significantly.

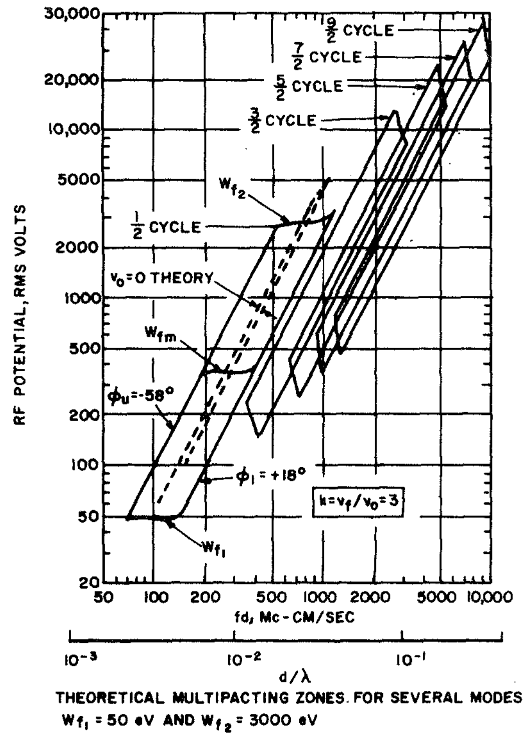


Figure 5.3-10. Illustration of Multipactor Prediction by Method of Hatch

The multipacting region for parallel electrodes, shown in Figure 5.3-12, is based on experimental measurements. Note particularly the change in region outline after two minutes of outgassing (resulting from operation of the multipactor discharge for that interval of time). Evidently, higher order modes of multipacting existed initially, and a reduction of secondary emission coefficient of the surfaces with outgassing precluded this existence after cleanup. The existence of multipacting then follows closely the boundary for the 1/2 mode in Figure 5.3-10. Similar measurements shown in

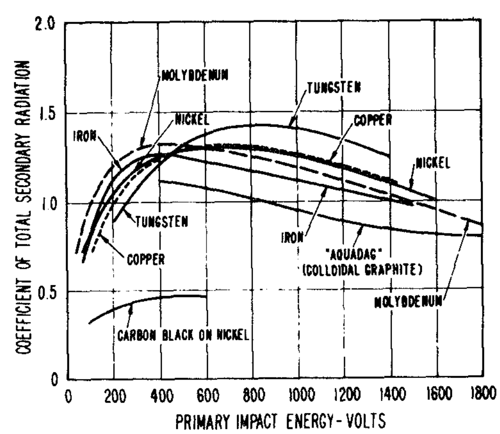


Figure 5.3-11. Secondary Emission Characteristics of Several Materials as a Function of Primary Impact Energy

Figure 5.3-13 demonstrate differences in parallel plate multipacting regions for several materials.

Typical data for a coaxial line is given in Figure 5.3-14. Curves for the three sizes should have been coincident according to the earlier mentioned scaling principle; however, they do not coincide at the lowest operating voltages. Investigators have suggested that: (1) the shortcoming of the thin sheet assumption at the minimum energy boundary, and (2) the increased electron loss to the sides for larger electrode separations, are possible causes for the discrepancies. Agreement with theory is good at the higher voltages. The effect of a dc bias on multipacting in a coaxial line is shown in Figure 5.3-15.

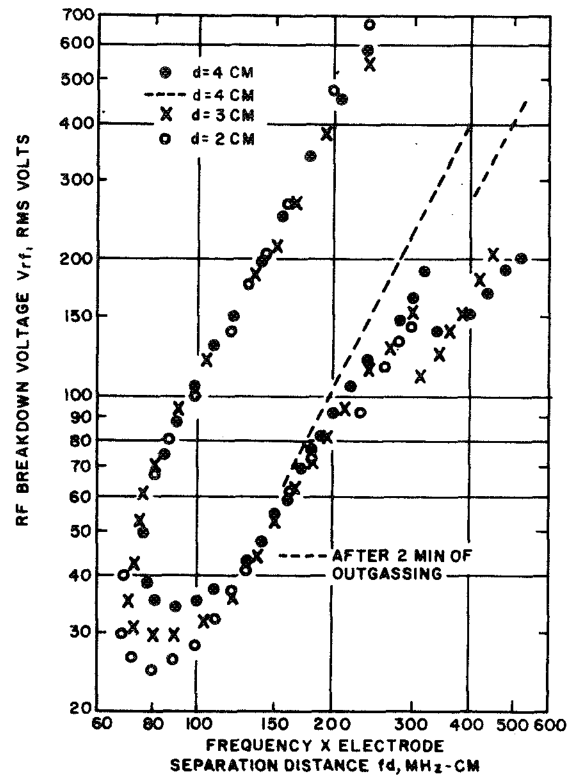


Figure 5.3-12. Multipacting Region for Parallel Plate Electrodes

Multipacting tests have been conducted on coupling slots in the broad wall of an X-band waveguide. A test fixture shown in Figure 5.3-16 was used, and test data for several slot widths and wall thicknesses are shown. Circuits with very non-uniform fields (such as the thin wall slots) do not multipact as readily as configurations with uniform fields, usually explained by a greater loss of electrons from the multipacting zone and a reduced effective δ for the thin multipacting surfaces.

5.3.3 SUPPRESSION OF BREAKDOWNS

5.3.3.1 Arcing and Corona

Arcing and corona suppression techniques are generally covered in Section 5.1.5. These will require the inclusion of frequency effects on Paschen's law. The basic approaches involve:

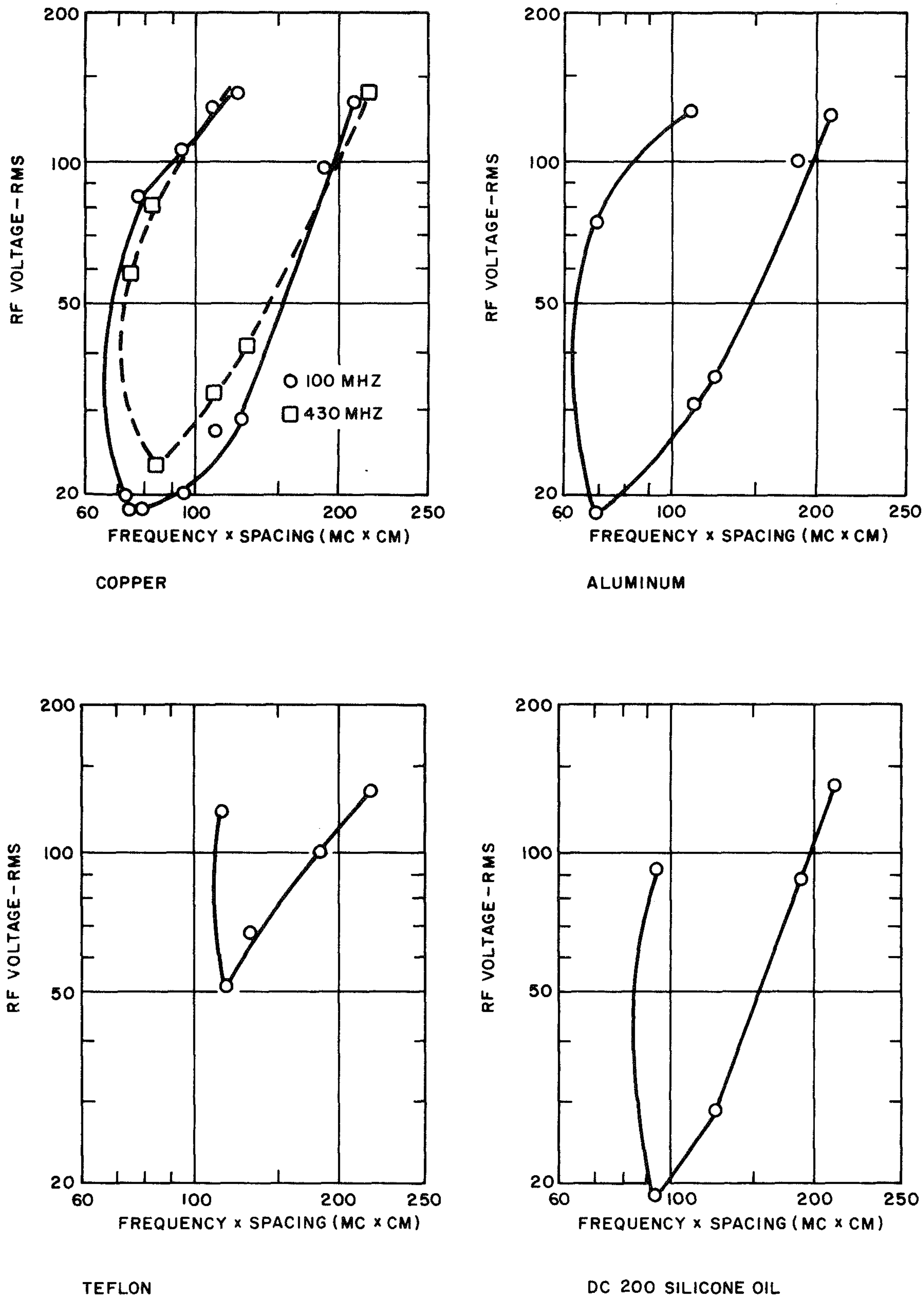


Figure 5.3-13. Multipacting Regions for Several Materials

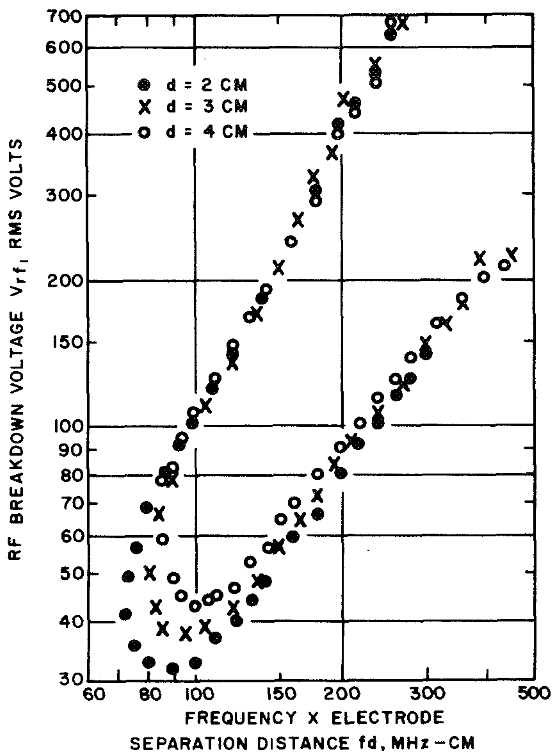


Figure 5.3-14. Multipacting Region for Coaxial Electrodes with $r_2/r_1 = 2.3$

1. Appropriate materials selection.

2. Venting of guide and coaxial line.

3. Providing bakeout heaters and gas sensors in system.

4. Avoiding all sharp points and edges where electric fields exist.

5. Adding local insulation on terminals.

The latter sometimes presents problems, which are considered separately later.

5.3.3.2 Partial Insulation

There are instances when a designer will seek to prevent arc-over between conductors by placing an insulating barrier between them. Extreme caution is necessary lest he actually cause the

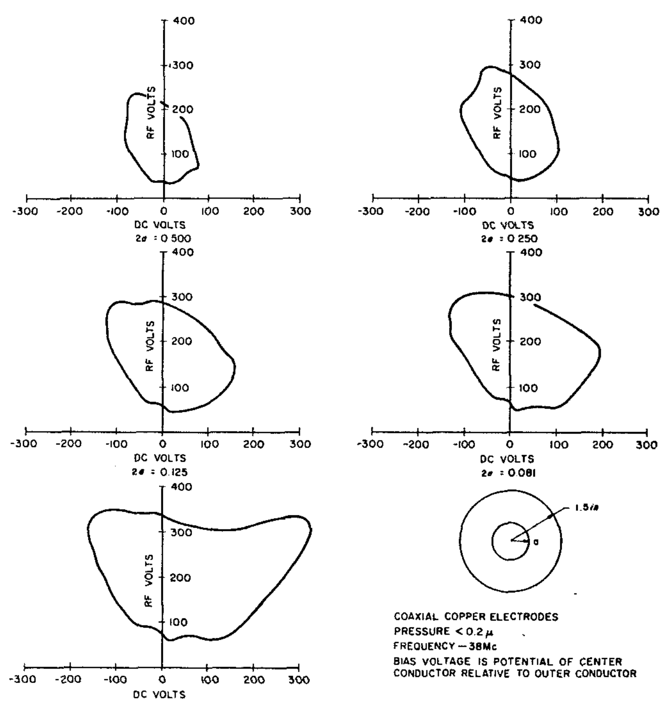


Figure 5.3-15. Regions of Multipactor Discharge in a Coaxial Geometry

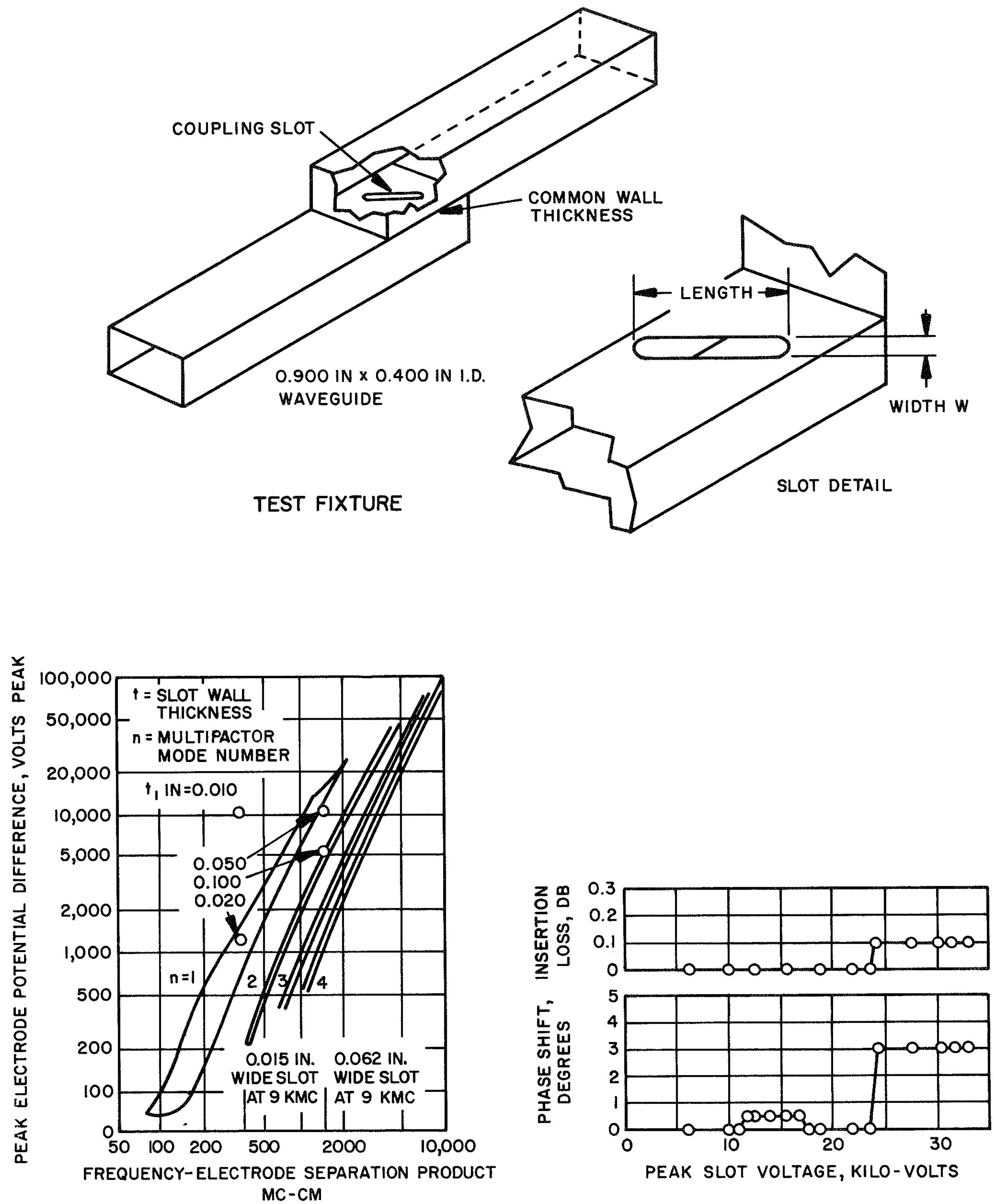


Figure 5.3-16. Multipacting in an X-Band Slot (Reference 11)

onset of corona by introducing a high dielectric constant in series with the air gap, thereby overstressing the air. The ratio of dielectric constants, the resultant air gap, and the insulation thickness must be considered to ensure that the voltage across the air gap does not exceed the values indicated in Figure 5.1-2 with dc voltages applied to the electrodes.

A high ratio of air to insulation thickness is desirable in the prevention of corona or sparkover where insulation is used and the space between electrodes cannot be completely filled. The use of insulating barriers is of dubious value except to increase the air strike distance. The barrier may prevent arc-over but may cause corona to form if the air gap is overstressed. Corona discharge causes the air to become a conductor, and the full voltage is then induced across the insulating barrier. Therefore, barriers, when used, should be capable of withstanding full voltage to prevent sparkover.

5.3.3.3 Multipactor Suppression

Several methods of avoiding multipacting are apparent from the preceding material:

1. Avoid voltage ranges where multipacting might occur for a particular fd product.
2. Operation at a voltage above the multipacting region requires a turn-on of the RF source at a sufficiently high rate that the multipactor effect does not have time to build up.
3. Control electrode configuration and spacings to avoid the multipactor existence region.
4. Place a large dc bias across the gap.
5. Change the existence region by means of a dc magnetic field.
6. Fill the region with some material (solid, liquid or gas).
7. Keep $\delta < 1.0$ over the operating voltage range.
8. Apply a coating of material having $\delta < 1.0$.

The selection of one or more of these techniques must consider the system effects and application feasibility. The final item listed includes four refractory materials (information from MIT Lincoln Laboratory), all capable of high temperature operation and having $\delta < 1.0$. The four materials are:

1. Tungsten Carbide
2. Titanium Carbide
3. Vanadium Boride
4. Titanium Boride

The major disadvantage of these materials seems to be increased RF loss and the application problems in some component configurations.

5.3.3.4 Insulation Breakdown

Electrical breakdown of insulation material occurs when for some reason it becomes conductive. Electrons under very high stress are detached from the atoms of the insulation and are then able to carry current. The current can increase without limit at some critical level of stress, and the structure of the insulator is disintegrated and breakdown occurs. Typical breakdown strengths, including frequency effects, are listed in Table 5.3-4.

Breakdown level is also reduced drastically with operating time. One example is the case for Teflon in air which will fail at a stress of 1600 v/mil in 0.1 hour whereas it will fail at 400 v/mil in 100 hours. Another example is paper phenolic laminate; at room temperature breakdown voltage is reduced with time, but at elevated temperatures an initial improvement is obtained during the first month of operation. Evidently this is due to a reduction of moisture content. A slow dropoff of breakdown voltage for the remainder of the test period is then observed.

Table 5.3-4. Initial Values of Materials Electric Strength

	Thickness (Mils)	rms (volts/mil)	
		60 Hz	100 MHz
Asbestos-fabric, phenolic molding compound	32	68	U
Asbestos-filled phenolic molding compound	32	110	U
Asbestos-filled diallyl phthalate molding compound	60	836	U
Diallyl phthalate molding compound, unfilled	20	2900	30*
Mica-filled phenolic molding compound	30	624	23*
Cellulose-filled melamine molding compound	60	808	U
Silica-filled epoxy casting compound	45	815	U
Glass cloth, silicone-base laminate, Grade G-7	60	450	56
Glass cloth, melamine-base laminate	60	394	15*
Glass cloth, epoxy-base laminate	45	774	U
Glass cloth, polytetrafluoroethylene-base laminate	60	623	119
Paper phenolic laminate, Grade XXX	60	940	U
Paper phenolic laminate, Grade XX	32	1206	20*
Linen phenolic laminate, Grade LE	32	654	U
Canvas phenolic laminate, Grade CE	32	574	U
Canvas Phenolic laminate, Grade C	32	522	U
Polystyrene, unpigmented	30	3174	220
Polystyrene, experimental resin	45	a2500	111
Polyethylene, unpigmented	30	1091	132
Polytetrafluoroethylene (Teflon)	30	850	143
Monochlorotrifluoroethylene (Kel-F)	20	2007	29#
Isocyanate gas-expanded foam (Density 13.8 lbs. per cu. ft.)	100	123	U
Syntactic foal (Phenolic microbaloons, epoxy resin) (Density 13.8 lbs. per cu. ft.)	100	55	U
Glass bonded mica	32	712	76
Ordinary glass	32	1532	20#
Forsterite, Alsimag-243	65	499	74
Alumina, Alsimag-576	55	298	69
Steatite	32	523	56#
Dry process porcelain	32	232	60#

\# - Puncture with attendant volume heating effect
* - Volume type failure due to excessive heating
U - Unstable condition due to excessive heating at very low stress
a - 20 mils at 60 Hz

Another correction must be applied for material thicknesses that differ from a test sample. A conservative estimate of the safe operating stress E is given by $E = F E_o$, where E_o is the electric strength taken from the breakdown tables and F is an empirical safety factor. The safety factor that is recommended is:

$$F = \frac{1}{2\left[1 + \left(\frac{d}{\sqrt{d_o^2 + 0.002d^2}} \log_{10} f\right)\right]}$$

where d_o is the thickness at which E was measured, d is the proposed thickness for application, and f is the frequency of the applied voltage in Hz. F will vary from 0.050 to 0.333 over normal frequency and thickness ranges.

5.3.4 TRANSMITTER RF SYSTEMS

The three transmitter configurations noted in Section 2.1 were used in determining typical RF circuitry configurations. These three RF circuits are outlined here; the separate RF assemblies and components are considered in subsequent sections.

5.3.4.1 Microwave Subsystem for an S-Band, Eight-Channel, FM TV Transmitter

This microwave subsystem is part of a multi-channel TV Satellite Transmitter consisting of eight amplifier chains, each capable of 2.5 kw output to the antenna in FM TV service in the 2.0 to 3.0 GHz frequency range. Provision will be made in the microwave subsystem for multiplexing the eight signal channel outputs into one to two antenna-feed terminals with negligible interaction between signal channels. Other functions will include harmonic and spurious signal suppression, power output and fault sensors, and necessary protection for the power amplifiers from excessive signal reflections to antenna or microwave subsystem component degradation. The RF subsystem must be capable of reliable operation over a two- to five-year period of near-continuous operation.

Specifications for this transmitter configuration include the following:

1. 36 MHz bandwidth per channel
2. 12 MHz guard band between channels
3. 30 db channel isolation
4. VSWR: Source = 1.67:1 max.

   Antanna = 1.2:1

   Input to RF circuit = 1.5:1
5. Insertion Loss: 0.7 dB max.

The resulting RF configuration is shown in Figure 5.3-17. The original specification required that all eight transmitter outputs be delivered to a single antenna terminal, but this is not a realistic requirement due to the close channel spacing that was specified. However, multiplexing the channels into two groups of alternate channels that are fed to separate antennas is feasible and results in 60 MHz guard bands within each multiplexer.

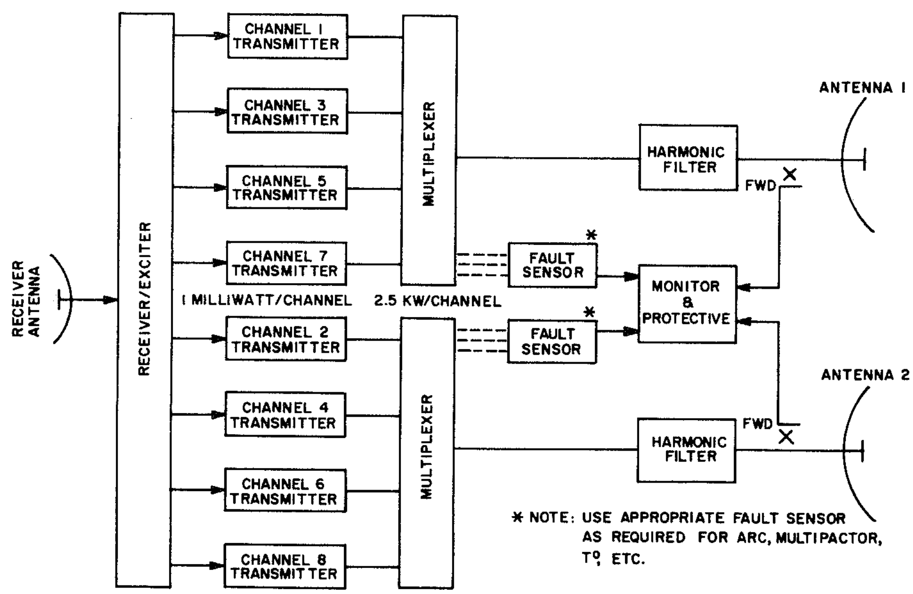


Figure 5.3-17. Eight-Channel FM Multiplexer Using Separate Antennas

A filter action is required for harmonic and spurious signal rejection. Harmoic VSWR control is inherent in the proposed multiplexer circuit. The 3 dB coupler/bandpass filter circuit is the same form as a family of harmonic filters used in high power situations. A sufficiently low harmonic VSWR should be achievable by selection of the type of hybrid used in the circuit. Also, some harmonic attenuation will be obtained from the multiplexer filters, though they will probably not be optimized for harmonic rejection. A single harmonic filter is then used after the multiplexer output and before the antenna for required harmonic injection.

An isolator is not required for control of gain and phase ripple of the TWT output if the assumption of 1.67:1 TWT output VSWR for normal operation is achieved in practice. This value is typical for power tubes. Exact values would depend on tube design. Use of an isolator located near the tube would provide tube protection in the event of a waveguide arc, although other protective functions could give sufficiently rapid protection by cutting off RF drive and crowbarring the tube power supply. Other components required in the system are directional couplers and detectors for power, VSWR, and fault monitoring; arc detectors; and miscellaneous items such as waveguide elbows. Expected performance, Table 5.3-5, shows the worst case loss is 0.48 dB (12 percent); the goal was less than 0.7 dB. The highest VSWR gives a deviation from linear phase of 2.1 degrees with 1.67 VSWR, compared with the 3 degree specification. The weights are based on conventional components but could be reduced substantially by emphasizing light-weight fabrication. The data is for the dual four-channel multiplexer configuration requiring two antennas.

Table 5.3-5. Summary of S-Band Circuit Characteristics

	2.6 to 3.0 GHz			2.0 to 2.6 GHz		
		WR340			WR430	
	(minimum)		(maximum)	(minimum)		(maximum)
Insertion Loss - (dB)	0.34		0.48	0.32		0.45
Total Power Dissipation, 6 Channels - (KW)		1.5			1.4	
Input VSWR-1.0 Antenna VSWR	1.17		1.27	1.17		1.27
-1.2 Antenna VSWR	1.28		1.35	1.28		1.35
Weight (pounds)		105			176	
Net Volume of Components (ft^3)		2.6			4.7	

Satisfactory operation of all components of the S-band system in the atmosphere is expected. The waffle-iron harmonic filter is the only component likely to multipact under high vacuum conditions. Suppression techniques suggested previously could be used to eliminate multipacting, or the waffle-iron filter could be replaced by a leaky wall filter. However, this substitution would increase weight by at least 27 pounds, volume by 1.2 or more cubic feet, and loss by about 0.05 dB.

Thermal requirements are reasonable. Cooling requirements are met by attaching one surface of the components to a "cold-plate" surface. The hot spot temperature rise in the microwave circuit would not exceed about 23°C.

5.3.4.2 Microwave Subsystem for a UHF, Four Channel, AM/VSB TV Satellite Transmitter

This four-channel TV transmitter consists of eight amplifier chains, four visual RF channels capable of 5 kw peak output to the antenna and four accompanying aural channel amplifiers at 500 watts FM. A multiplexer will combine these eight channels into a single antenna-feed terminal with negligible interaction between signal channels. Other subsystem functions include vestigial sideband filtering, harmonic and spurious signal suppression, power output and fault sensors, and necessary protection for the power amplifiers from excessive signal reflections due to antenna or microwave subsystem component degradation. The subsystem must be capable of reliable operation over a two to five year period of near-continuous operation.

Some of the more pertinent specifications for the system were:

1.	Power:	visual channel - 5 kw sync peak
		aural channel - 500 w FM
2.	Bandwidth:	visual plus aural - 6 MHz
3.	Separation:	5 UHF TV channels (30 MHz)
4.	Isolation:	30 dB between channels

5.	VSWR:	Source - 8:1 (gridded tube)
		Antenna - 1.2:1
		RF Circuit Input - 1.15:1
6.	Phase Linearity:	3^o
7.	Insertion Loss:	0.7 dB maximum average
8.	Vestigial Sideboard Shaping:	per RF-240 (Reference 25)
9.	Color Subcarrier Image:	-42 dB

Selection of transmission line type for the UHF application poses a more difficult choice than at S-band. Coaxial transmission lines may appear to be a better choice since they are much smaller in cross-section for the 5 kw power level (3-1/8 inches versus a 12-inch maximum dimension for waveguide). Closer examination, however, determined that coaxial cavities and filters with reasonable insertion loss are considerably larger than comparable waveguide units. This is due to the very narrow bandpass characteristics required for aural/visual signal diplexing and for multiplexing the four television channels. Multipacting also occurs at a much higher level (exceeding 30 times higher power when comparing 3-1/8 inch coax with WR1150 waveguide), and peak power handling capacity of waveguide in air is comparably higher also. Cooling of waveguide in space applications tends to be much simpler since power is dissipated on the walls of the waveguide which provide good heat conduction paths to a heat sink. In contrast, coaxial lines have inner conductors which are normally thermally and electrically insulated from the outer conductor, thus requiring special design and fabrication for heat removal. A consideration of the waveguide circuit over a coaxial line configuration led to recommending half-weight WR1150 waveguide for UHF.

Multiplexing of the four visual and four aural channels into a single antenna terminal requires rather bulky components in order to realize reasonably low losses. The selected circuit is shown in Figure 5.3-18. It uses combinations of filters and hybrids which offer "constant impedance" at all frequencies within the broad passband of the hybrids. Aural channel bandpass, and TV channel bandpass filters are used in the diplexers and multiplexers, respectively, as was shown in Figure 3-17.

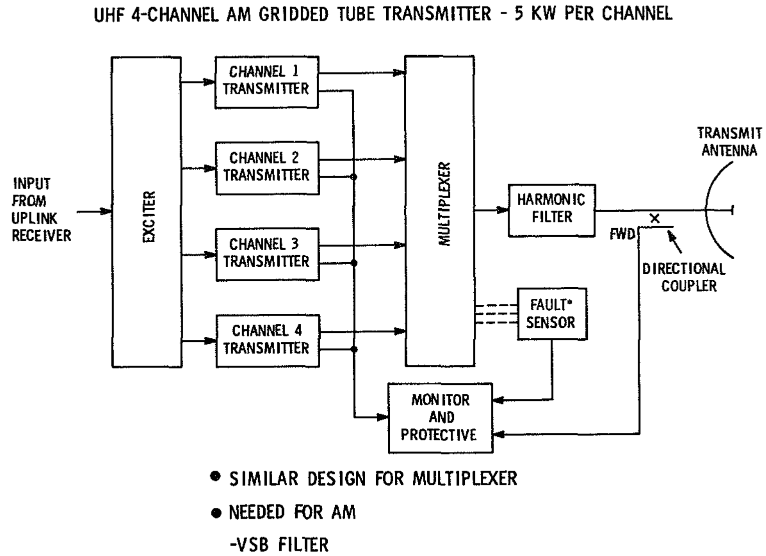


Figure 5.3-18. Basic 4-Channel Transmitter Block Diagram

Vestigial sideband filtering is accomplished prior to the power applifier stage where the RF power level is 50 to 100 watts peak. Intermodulation products will be produced in the power amplifier, but by maintaining adequate power amplifier linearity they will be below the required -20 dB level. Achieving the -42 dB level for the color subcarrier image, however, is unlikely in the VSB filter. A color image notch filter to suppress this component, located 3.58 MHz below the video carrier, will be necessary. A cavity that shunt loads the output transmission line of each power amplifier at its color image frequency will be used.

Harmonic attenuation will be provided primarily by a waffle-iron, reactive-type filter similar to the S-band transmitter unit. Only one filter is required, located prior to the antenna. Past experience has shown that gridded tube amplifiers are not noticeably affected by the use of reactive type harmonic filters. Further reduction of harmonic VSWR, if necessary (perhaps to reduce voltage breakdown problems), can be obtained with added filters of the leaky wall type.

Phase and amplitude fluctuations in excess of allowable values are likely unless special precautions are taken. Gridded tube amplifiers may have source impedance VSWR's of around 8:1. The product of amplifier reflection coefficient Γg and combined antenna/ microwave circuit reflection coefficient Γa should be:

$\Gamma a \ \Gamma g \leqq 0.09$

for acceptable gain/phase performance if no other source of ripple is present. This places a limit on antenna/microwave circuit VSWR of about 1.3 over the TV channel bandwidth. However, an input VSWR of 1.15 or less should be attained to allow for other sources of gain and phase ripple. This will be very difficult to achieve with a broadband antenna, multiplexer, and other components contributing to circuit VSWR.

Two alternatives can be considered if sufficient improvement cannot be achieved by matching techniques. A ferrite isolator (or isolator connected circulator) can be employed at each power amplifier. Insertion loss, cooling, and/or size and weight problems must be considered in the use of such devices. Another approach is to use two half-power amplifiers combined with a 3 dB coupler type of hybrid (see Reference 15, Appendixes A and B) which can also provide substantial isolation. Other required components such as directional couplers for power, VSWR, and fault monitoring were also shown in Figure 5.3-18.

Performance of the UHF microwave circuit described meets requirements of the specification with the exceptions discussed below. Overall performance data, summarized in Table 5.3-6 shows the worst case loss is 0.60 dB (15 percent), compared with the specified 0.7 dB maximum.

Table 5.3-6. Summary of UHF, 4-Channel Circuit Characteristics (Waveguide Components)

	AURAL		VISUAL	
	minimum	maximum	minimum	maximum
Insertion Loss -(dB)	0.42	0.56	0.46	0.60
Input VSWR (6 MHz channel)				
1.0 Antenna VSWR				
not tuned	1.21	1.30	1.21	1.30
with tuning	1.11	1.15	1.11	1.15
1.2 Antenna VSWR				
not tuned	1.30	1.38	1.30	1.38
with tuning	1.15	1.20	1.15	1.20
Total Power dissipation (kw)	2.9			
Total Weight of Components (pounds)	784*			
Net Volume of Components (ft^3)	45.9			

*Using off-the-shelf components; about 470 pounds with special design effort for low weight.

Satisfactory operation of all UHF components at atmospheric pressure is expected. Multipacting in space is likely in the waffle-iron harmonic filter, and there is a slight chance of occurrence in the half-height, side-wall hybrid. The waffle-iron filter may be eliminated if harmonic output levels are sufficiently low, a saving 0.08 dB loss, 72 pounds weight, and 1.4 cubic feed of volume. Then, multipacting in the system would not be likely.

Thermal requirements are reasonable. Cooling by conduction is attained by attaching one surface of the waveguide components to a "cold plate" surface. Under this condition the hot spot temperature rise in the microwave circuit would be about 13°C.

5.3.4.3 Microwave Subsystem for a High Power, Single Channel, UHF, AM/VSB TV Satellite Transmitter

The microwave subsystem described here is for a UHF single channel AM TV transmitter using a crossed-field amplifier tube. The transmitter has two amplifiers, one capable of 15 kw peak output for AM/VSB visual channel operation in the 700 to 890 MHz frequency range, and the other with the 1500 watt FM aural signal associated with the visual signal. The microwave subsystem will diplex the two signals into a single antenna-feed terminal with negligible interaction between signals. Other subsystem functions will include vestigial sideband filtering, harmonic and spurious signal suppression, power output and fault sensors, and necessary protection from excessive signal reflections due to antenna or microwave subsystem component degradation. The subsystem should be capable of reliable operation over a two- to five-year period of near-continuous operation.

Some of the pertinent specifications are:

1.	Power:	visual - 15 kw sync peak
		aural - 1.5 kw FM
2.	Bandwidth:	6 MHz
3.	Isolation:	30 dB (between visual and aural channels)
4.	VSWR:	Source - 1.1:1
		Antenna - 1.1:1
		RF Circuit Input - 1.2:1
5.	Amplitude Distortion:	less than 0.5 dB
6.	Phase Linearity:	3° maximum
7.	Insertion Loss:	0.4 dB maximum
8.	Vestigial Sideband	per RF-240 (Reference 25)

The use of coaxial line components results in a smaller microwave subsystem (since a multiplexer is not required). The tube manufacturer will probably use a coaxial output and the basic problems of using this type of line must be solved whether or not waveguide is used elsewhere. With these considerations in mind, a coaxial system is recommended.

The circuit for the 15 kw CFA transmitter is shown in Figure 5.3-19. A balanced diplexer with aural reflection notch filters is used for aural/visual signal diplexing. Harmonic rejection is supplied by a low-pass coaxial filter of the stepped inner conductor variety. A leaky wall harmonic filter can be used between amplifier tube and diplexer in the event that harmonic padding (in addition to that provided by the diplexer) is required. Vestigial sideband filtering is accomplished at the input to the CFA. Suppression of the color subcarrier image is accomplished with two notch filters in the diplexing assembly.

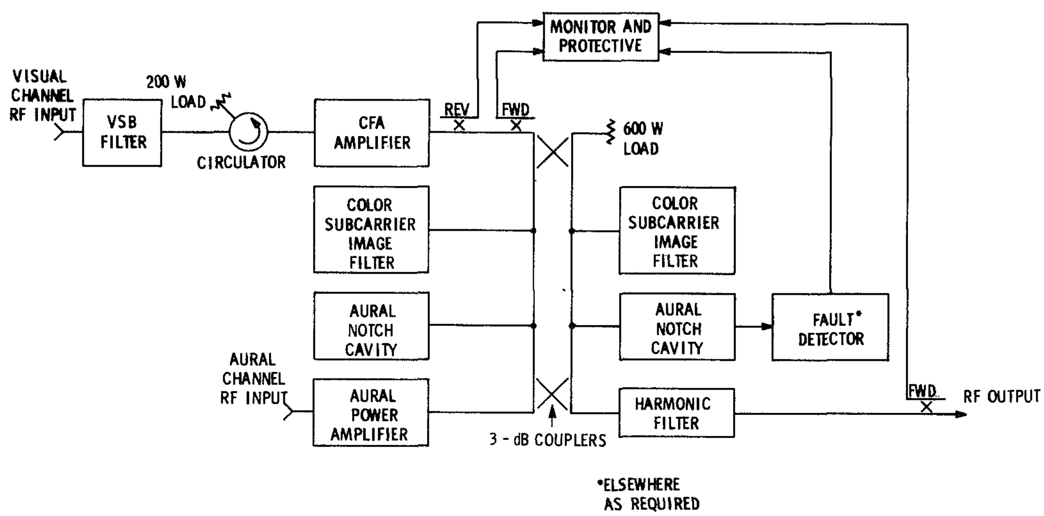


Figure 5.3-19. UHF Single-Channel AM Transmitter 15 kw Sync Peak

A circulator, connected as an isolator (by using a load on the third port) is at the input of the CFA to terminate relflections from the tube, microwave circuit and antenna. The CFA is nearly transparent in the reverse direction, and reflections in the RF circuit will appear back at the driver stage output with perhaps a 0.5 dB loss. A part of this signal, unless attenuated, will be reflected by the driver stage back into the CFA input and will be amplified, thereby creating large CFA output distortions. Use of the circulator/isolator plus achieval of low microwave circuit/antenna VSWR should give the required gain and phase ripple characteristics. The circulator and load should have a power rating of 200 watts.

System and component designs are such that operation either at atmospheric pressure or in the vacuum of space is possible. Electrical performance of the described circuit is expected to meet specifications, with the exception of the likely occurrence of multipactor breakdown, discussed in subsequent sections. Cooling of coaxial components appears more complex than cooling of the waveguide circuit components as mentioned previously.

Major performance parameters for this transmitter are listed in Table 5.3-7. The weight is slightly higher, about 13 percent, than for a waveguide configuration, but both types could be reduced with lightweight design efforts. The waveguide configuration, however, would occupy about three times the volume of the coaxial configuration.

Table 5.3-7. Summary of UHF One-Channel Circuit Characteristics (Coaxial Components)

	Aural	Visual
Insertion Loss (dB)	0.45	0.40
Input VSWR		
with 1.0 Antenna VSWR	1.15	1.15
with 1.1 Antenna VSWR	1.19	1.19
Total Power Dissipation (kw)	1.62	
Total Weight of Component (pounds)	123.5 *	
Net Volume of Components (ft^3)	3.4	

*Based on conventional components; may reduce to 75 pounds for special lightweight designs.

Multipactor breakdown may be major problem in operation of the coaxial circuit in space. Both the hybrid and harmonic filters are likely to multipact since fundamental (1/2) mode operation is indicated at the operating voltage. The possibility of high order multipacting modes in the aural notch filter and even in the 3-1/8 inch coaxial line exists. Substitution of a leaky wall harmonic filter for the waffle-iron version in the waveguide approach would make multipacting unlikely. A considerable increase in bulk would result from the use of these components, which would have to be evaluated on a system basis.

Thermal requirements are more stringent and cooling means more difficult to implement than for previously described waveguide circuits. The use of heat-pipe center conductor cooling techniques are indicated to be the most reasonable way of removing the 1.6 kw of dissipation (the bulk of which is dissipated in center conductors of the coaxial components). Heat pipe designs should readily handle the heat loads of these conductors. The hot spot temperature rise will be about 25^{o}C with heat pipe cooling.

5.3.5 RF ASSEMBLIES

The functional RF assemblies included in the previous systems descriptions are considered in terms of components used and overall operation. Specific components are considered in the subsequent section.

5.3.5.1 Multiplexers

There are several approaches to implementation of transmitter multiplexing, the function of which is to permit the several transmitters in a system to radiate into a common space with negligible interaction between transmitters. The two extremes are filter multiplexing, which combines all signals onto a single line, and separate antennas for each transmitter channel. The system resulting in the fewest antennas with reasonable loss will usually be used in the microwave circuit designs, but a re-evaluation should be made before a particular design is selected for a given system to determine overall system tradeoffs.

Preference was given to balanced filter configurations in the selections of multiplexer designs. Thus, reflections from the filter as frequency approaches cutoff are directed to a load on the input hybrid of the filter and the transmitter "sees" a constant, matched impedance regardless of whether or not it is operated within the bandpass of the filter. The use of this type of filter generally reduces re-reflection amplitudes in the system and results in more predictable transmitter performance with better gain and phase ripple characteristics.

5.3.5.1.1 S-Band Multiplexer, Eight-Channel

Waveguide was selected for the S-band as a result of low insertion loss and good power handling characteristics. An investigation of filter performance revealed that 12 MHz separation and 30 dB isolation of adjacent FM TV channels would result in excessive losses for reasonable filter configurations as well as excessively close tolerances and sensitivity to thermal effects. Accordingly, the transmitter outputs were multiplexed into two groups of four alternate channels each, as shown in Figure 5.3-20. Filters for each diplexing section of the multiplexer pass the signal of the transmitter connected to the left-hand terminal of the diplexer and reject signals of all other transmitters. The output to each antenna therefore includes the four input RF signals, and no interactions of channels in the transmitters occur.

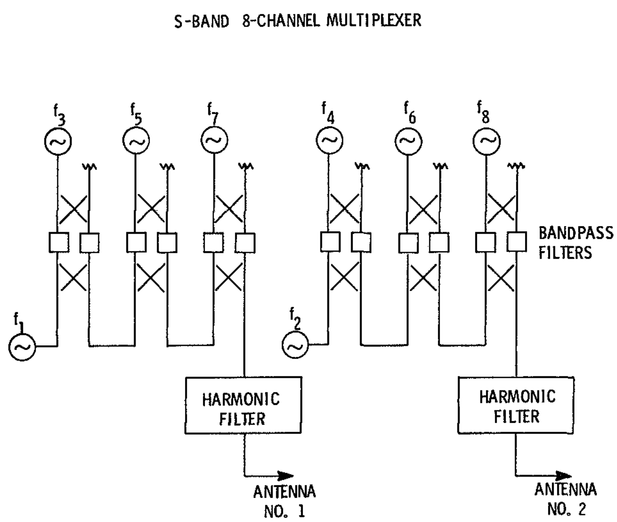


Figure 5.3-20. S-Band Multiplexer Configuration for Two-Antenna System Employing Hybrid Diplexers

Conventional inductive-iris, direct-coupled cavity filters were selected for the bandpass filter design. A description of this filter is included in Section 5.3.6. Estimates of multiplexer performances are summarized in Table 5.3-8. The loss figures include both dissipation due to signal transmission through the components and worst-case loss in the balance loads due to deviation from 3 dB coupling, VSWR of components, and non-infinite isolations. VSWR's were calculated using the estimation method of taking the square root of the sums of each reflection coefficient squared. (Worst case reflection coefficients of each component were used in these VSWR calculations.) Insertion loss for the four signal channels averages about 0.21 dB for the WR 430 unit and 0.23 dB for the WR 340 multiplexer.

5.3.5.1.2 UHF Multiplexer, Four TV Channel

Waveguide was selected for use for the four channel UHF multiplexer as discussed in Section 5.3.4.2. The multiplexer design consists of four aural/visual channel diplexers, plus a multiplexer for each of the four composite TV channels as shown in Figure 5.3-21.

The four-channel multiplexing circuit is identical in nature with one of the S-band four-channel group multiplexers. Hybrids and bandpass filters are scaled versions of the S-band components, using 1/2 height waveguide to conserve space and weight. Descriptions of these components are given in Section 5.3.6. The aural/visual signal diplexer for each television channel is similar to the TV channel multiplexer except that single-cavity aural-reject filters are employed. Performance of the aural/visual diplexer sections above is given in Table 5.3-9 and the overall multiplexer performance is in Table 5.3-10. RF power losses

Table 5.3-8. Waveguide Multiplexer Electrical Performance Summary

	WR 340 (2.7 GHz)	WR 430 (2.3 GHz)	1/2 Height WR1150 (0.800 GHz)
Loss - dB			
Channel 1	0.145	0.133	0.133
Channel 2	0.223	0.199	0.206
Channel 3	0.253	0.229	0.236
Channel 4	0.283	0.259	0.266
Loss - Watts*			
Channel 1	87	80	176
Channel 2	136	120	264
Channel 3	153	137	302
Channel 4	171	155	341
TOTAL (watts)	547	392	1083
VSWR			
Channel 1	1.10	1.10	1.10
Channel 2	1.15	1.14	1.15
Channel 3	1.19	1.19	1.19
Channel 4	1.22	1.22	1.22

*Note: Loss power calculated for 2.5 kw output and S-band; 5.5 kw TV channel output at UHF.

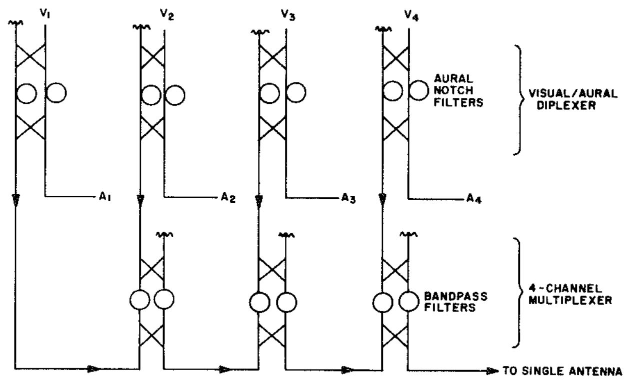


Figure 5.3-21. Four-Channel UHF Multiplexer Configuration Employing Single Antenna with Single Polarization

Table 5.3-9. Waveguide Aural/Visual Diplexer for 5 kw UHF Transmitter System

Visual Insertion Loss (dB)	0.22
(watts)	300
Aural Insertion Loss (dB)	0.20
(watts)	28
Input VSWR (aural and visual)	1.10
Aural Passband (MHz)	0.1
Visual Passband (MHz)	6

Table 5.3-10. Performance of Waveguide Multiplexer for Four-Channel UHF TV Transmitter System

		Aural Channel	Visual Channel
Loss			
TV Channel 1	(dB)	0.33	0.32
	(watts)	40	380
TV Channel 2	(dB)	0.41	0.40
	(watts)	50	490
TV Channel 3	(dB)	0.44	0.43
	(watts)	54	525
TV Channel 4	(dB)	0.47	0.46
	(watts)	57	560
VSWR			
TV Channel 1		1.15	1.15
TV Channel 2		1.19	1.19
TV Channel 3		1.22	1.22
TV Channel 4		1.26	1.26

average about 10 percent of the total RF power input. The loss for feeding aural and visual channels into separate antennas is about half this value (5 percent). A tradeoff study should be performed on a one antenna versus a two antenna arrangement, including all system parameters after a system and mission are defined.

5.3.5.1.3 UHF Diplexer, Single TV Channel

The basic transmission line used for the 15 kw single channel transmitter is 3-1/8 inch, 50-ohm, rigid coaxial line. Components that are compatible with this transmission medium were selected for the aural/visual diplexer.

A circuit diagram of the diplexer, which uses the same basic circuit as the waveguide diplexers used in the 5 kw, four-channel UHF transmitter is shown in Figure 5.3-19 (repeated here). Electrical performance of the diplexer is as follows:

Loss			
	Aural	(dB)	0.35
		(watts)	127
	Visual	(dB)	0.25
		(watts)	900
VSWR			
	Aural		1.1
	Visual		1.1

5.3.5.2 Spectrum Shaping in AM-VSB Transmitters

5.3.5.2.1 VSB Filter

Two basic approaches to shaping the required spectral response of AM/VSB television broadcast transmitters are considered. Frequency-selective circuits may follow the transmitter to eliminate undesired lower sideband components and other out-of-band spectral components, or precede the final stage input in the driver amplifier stage of the transmitter. The power amplifier for the latter approach must then be sufficiently linear so that appreciable out-of-band components are not generated. A small amount of supplementary filtering for suppression of the color subcarrier image frequency is usually necessary in practice. Block diagrams of these two approaches are given in Figure 5.3-22, and comparative performance is presented in Table 5.3-11. The improvement in microwave circuit efficiency is readily apparent from the data. On the other hand, efforts to linearize the power amplifier stage might cause some reduction in its efficiency, but lack of adequate information on the new high efficiency tube types precludes an accurate evaluation of the situation at this time. The recommended location for the VSB filter is prior to the power amplifier. Note that this recommended approach is used extensively in current ground-type TV transmitter designs. Specifications and the circuit diagram of a commercial vestigial sideband filter that would be suitable for either of the UHF transmitters considered in this report were given in Figure 3-18. This unit weighs 54 pounds (ground version - space version about 30 pounds) and occupies one cubic foot.

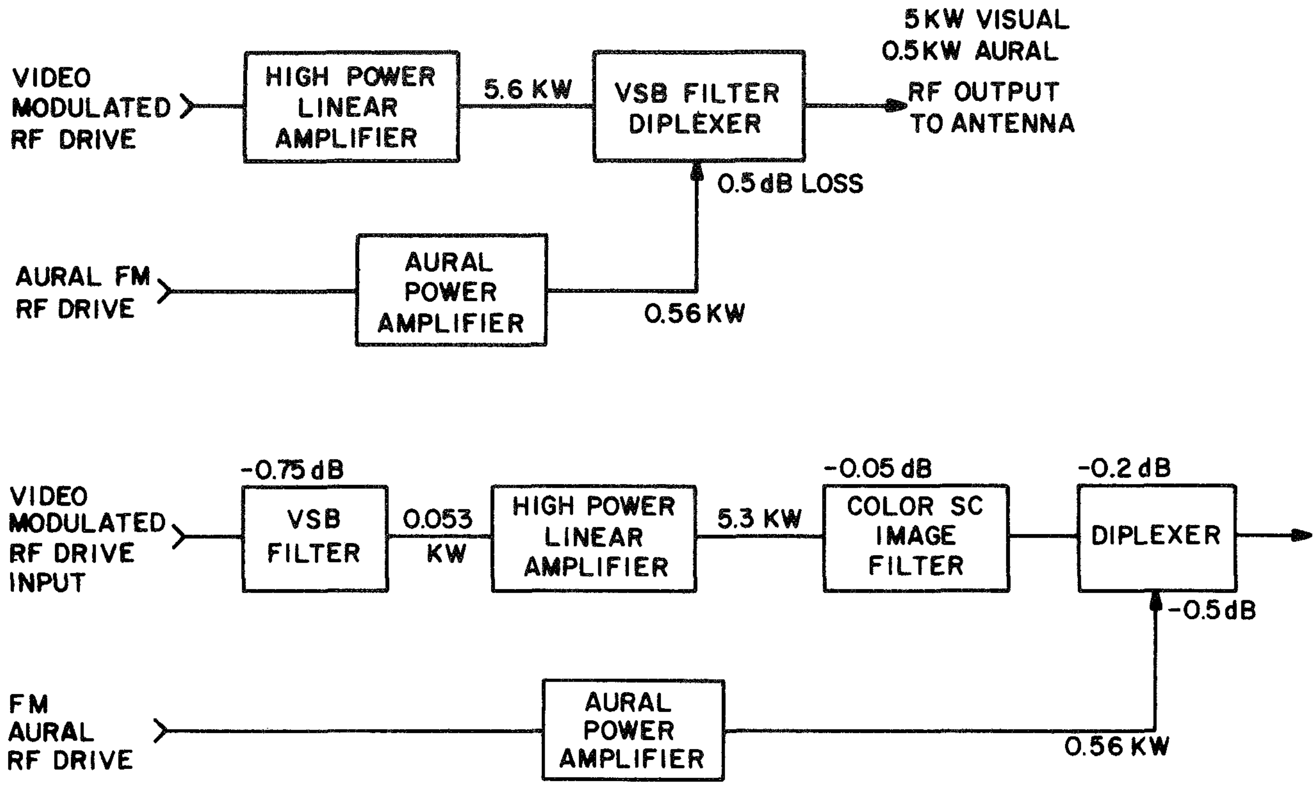


Figure 5.3-22. Circuit Diagrams for Two Approaches to VSB Filters

Table 5.3-11. Comparison of Approaches to VSB Filtering (Shown for 15 kw-peak-CFA Transmitter)

	VSB Filter in Output	VSB Filter in Input
Electrical Characteristics*	(kw)	(kw)
Power output required for antenna	5.00	5.00
VSB Filter/Diplexer Loss (Visual)	0.60	----
Diplexer Loss (Visual)	----	0.24
Color SC image filter loss (Visual)	----	0.06
Aural output required to antenna	0.50	0.50
Diplexer loss (Aural)	0.06	0.06
TOTAL RF OUTPUT REQUIRED FOR TV CHANNEL	6.16	5.86
VISUAL DRIVE REQUIRED	0.056	0.063
Mechanical Characteristics* (Weight)	(Pounds)	(Pounds)
VSB Filter/Diplexer wieght	694	---
Dixplexer weight	---	124
Color SC image filter weight	---	54
VSB filter weight	---	54
TOTAL	694	232

*Comparisons based on ground transmitter component performance and weights.

5.3.5.2.2 Color Image Filter

The color image filter is required to reduce the level of the lower sideband of the color subcarrier, which is manifested largely in the third order intermodulation product 2fo - (fo + 3.58) MHz, where fo is the carrier frequency and fo + 3.58 is the upper color subcarrier frequency. The FCC requirement is for the lower sideband component to be 42 dB below the +200 KHz component of the transmission output spectrum (Reference 25). This component will probably be more than 20 dB below the reference at the transmitter output. A single cavity stub-type notch filter at the power amplifier output is adequate for the added suppression of this component in the gridded tube transmitter. The CFA re-reflection gain, however, requires that stubs be added to the diplexing filter in the manner shown previously in Figure 5.3-19, so that a low VSWR is obtained at the color subcarrier image frequency.

5.3.6 MICROWAVE COMPONENTS

5.3.6.1 Transmission Line

Recommended transmission lines were included in Section 3.1.5.3.1. In summary, those selected were:

S-band: WR340 guide (2.6 - 3.0 GHz)
WR430 guide (2.0 - 2.6 GHz)

UHF: WR1150 half height guide
3 1/8 inch coaxial line

For low power circuits:

S-band: 1-5/8 inch air core coax
7/8 inch teflon core coax

UHF: 1-5/8 inch air core coax

Waveguide would be aluminum for low weight.

Coaxial line is usable at both S-band and UHF for at least some power levels used in the three transmitters considered. Teflon insulated, 7/8-inch line is the smallest standard line recommended for use at 2.5 GHz. A rather high loss of 3.5 dB per 100 feet precludes its use in long lengths. High inner conductor operating temperatures at higher RF power levels may also cause excessive outgassing of the teflon insulation. One and five-eighths inch air insulated line with attenuation of 1.04 dB per 100 feet could be used up to the 2.5 kw power level at S-band if the losses were tolerable; however, some thermal safety margin is desirable and only lower-powered circuits should use this line.

5.3.6.2 Harmonic Filters

A typical requirement in transmitting systems is that harmonic output be reduced to a level considerably below that of normal high-power amplifier harmonic output levels. This may be accomplished by a reactive-type filter that reflects harmonic energy back at the amplifier. High voltages may develop, however, at the harmonic frequencies due to circuit resonances that could exist between power amplifiers and filter.

Another class of filters presents a dissipative impedance to harmonic frequencies, and can be designed to give a moderately good impedance match for the lower order harmonics (at least 2nd, 3rd, and 4th). These absorptive filters are normally located close to the power amplifier so that the likelihood of high Q harmonic resonances existing between filter and power amplifier is small. Absorptive filters tend to be much larger than reflective filters, so a scheme frequently used is to cascade an absorptive filter of moderate harmonic attenuation with a reflective filter of high attenuation as was shown in Figure 3-19. The absorptive filter acts as a "pad," limiting harmonic filter input terminal VSWR to a reasonable value regardless of the reflective filter VSWR. For example, harmonic VSWR's will be 3.0 or less if the absorptive filter has an insertion loss of at least 6 dB (at the harmonics).

Suppression of harmonics in waveguide systems over a very wide range (about 10 to 1) is obtained with waffle-iron filters of the type that were shown in Figure 3-20. This type of reflective filter requires about 30 inches length in WR430 guide. Performance is excellent, with 55 or more dB harmonic insertion loss. VSWR in the passband (372 MHz) averages 1.13. Dissipative loss in the WR430 filter is about 0.14 dB. No problem is expected with breakdown in air, but multipactor breakdown is a likely possibility in space. These filters are applicable at both UHF and S-band. Typical performance data for waffle-iron and several other filters are listed in Table 5.3-12.

Coaxial filters, using the same basic technique of conductor separation steps as the waffle-iron filter, are applicable at UHF. A cross-section view of a typical filter was included in Figure 3-20. A 3-1/8 inch coax filter would typically offer 50 to 35 dB of harmonic attenuation (decreasing as frequency increases) for 2nd through 4th harmonic, 0.07 dB insertion loss, 1.1 VSWR, and would weigh about five pounds. It is rated for about 25 kw cw power in air. Multipacting in the 1/2 mode is likely for the 5 to 15 kw power range. Supplemental heat pipe cooling will probably be required for the inner conductor structure.

Table 5.3-12. Summary of Harmonic Filter Characteristics

Description	Nominal Operating Frequency (GHz)	Harmonic Insertion Loss (dB)	Passband Insertion Loss (dB)	Passband VSWR	Stop Band VSWR (maximum)	Dimensions (inches)	Weight (lb)
WR340 Waffle Iron	2.8	>55 (thru 10th)	0.16	1.13	---	4 x 2 x 24L	10
WR340 Leaky Wall Pad	2.8	>6 (thru 4th)	0.02	1.05	1.5	10 x 10 x 12L	5
WR340 Leaky Wall	2.8	>45 @ 2nd, 20 @ 4th	0.20	1.15	1.5	11 x 12 x 44L	37
WR430 Waffle Iron	2.3	>55 (thru 10th)	0.14	1.13	---	5 x 2.5 x 30L	23
WR430 Leaky Wall Pad	2.3	>6 (thru 4th)	0.02	1.05	1.5	13 x 13 x 15L	12
WR430 Leaky Wall	2.3	>45 @ 2nd, 20 @ 4th	0.18	1.15	1.5	13 x 15 x 56L	76
UHF Waffle Iron	0.8	>55 (thru 10th)	0.085	1.13	---	12 x 3 x 69L	72
3-1/8 Coax, UHF	0.8	50-35 (thru 4th)	0.07	1.10	---	4 D x 10L	5

Dissipative type harmonic filters are often of the "leaky-wall" type like that shown in Figure 3-21. An array of iris couplings to terminated auxiliary waveguides are used to direct the harmonic energy from the main waveguide into the harmonic terminations. These irises are resonant at the harmonics (usually the 2nd, 3rd, and 4th) so that coupling to the fundamental frequency energy is quite low. The iris slots are typically placed on all walls of the waveguide so that coupling exists for the various modes of propagation that can exist at the harmonic frequencies. The slot arrays are normally tapered in long iris dimension at either end of the filter for low VSWR at the fundamental frequency. Performance of a leaky wall filter type of harmonic pad is summarized in Table 5.3-12. No problem with voltage breakdown or heating is expected. Load materials that have low outgassing properties must be selected, however. Ceramic "spears" that are coated with a metallic film are promising candidates for these terminations; their drawbacks appear to be their weight and fragile nature.

Similar leaky wall filter designs are also used in coaxial line configurations. Coaxial line center conductor cooling requirements are substantially the same as for standard coax of the same size, and power handling ability should also be about the same if reasonable precautions are taken in iris design and fabrication. No additional multipacting problems are expected from the addition of irises and auxiliary waveguides to the basic filter structure.

5.3.6.3 Hybrids

Waveguide hybrids of the short-slot, 3 dB coupler type appear to be the optimum choice for the waveguide systems. They have good electrical performance over a wide bandwidth, can handle nearly the power of uniform waveguide line, fit the requirements of both multiplexers and power combiners for wide bandwidth with good input VSWR, are mechanically suitable for use in multiplexer and combiner networks, lend themselves to conduction cooling, and are readily fabricated. The mechanical arrangement and performance of these hybrids were indicated in Figure 3-22. These hybrids are available in sidewall and top wall coupled versions. The hybrid versions used in circuits described in this report have a -3 dB coupling ratio from the primary to the secondary guide. Phase angle between the outputs is very close to 90 degrees over the frequency range of the hybrid. Power handling capabilities range from 40 to 70 percent of the breakdown rating of uniform waveguide. The sidewall coupler is realizable in reduced height versions, an important space saving feature at UHF frequencies where maximum power handling capability is not required. Multipactor and power breakdown levels in the hybrids are expected to be 40 to 80 percent of the corresponding level for uniform waveguide.

Coaxial hybrids of roughly comparable performance characteristics are obtained with the construction given in Figure 3-23. The coupling length can be as little as one-quarter wavelength at the center frequency. Several cascaded quarter wavelength sections of various coupling ratios are used in more elaborate versions to achieve bandwidths of several octaves.

The branch-line type of hybrid can also serve in coaxial systems. The simplest two branch version was shown in Figure 3-23; however, multiple branches may be used if broader band performance is desired. Power handling levels approach that of uniform coaxial line of the same outer conductor size. One of the main drawbacks of the branchline hybrid is the likelihood of poorer VSWR at harmonic frequencies, which makes the likelihood of the need for an absorptive harmonic filter greater than if the coupled line hybrid were used.

5.3.6.4 Multiplexer Filters

Conventional direct-coupled cavity filters were selected for application in S-band waveguide systems. The inductive iris filter, shown in Figure 3-24, was chosen because it does not suffer reductions of height along the length of the cavity; voltage breakdown levels are therefore a function only of standing waves within the cavities. A computer program was used to evaluate bandpass characteristics, power reduction factor, and dissipation loss. These factors for 4, 5, and 6 cavities with WR 430 and WR 340 waveguide sizes are shown in Figures 5.3-23 through 5.3-28. All filters were designed to have approximately 26 dB reflection loss, 78 MHz from band center. The four cavity filter was chosen on the basis of minimum bandpass power loss.

A filter approach for application to UHF coaxial multiplexer uses uniform 70-ohm coaxial line with inductive pin-coupling for the one to two wavelengths long cavity sections. In this case, also, the four-cavity filter shown in Figure 3-24 gave the lowest insertion loss. Bandpass characteristics, power reduction factor, and dissipation loss curves for 3-, 4-, and 5-cavity filters, are given in Figures 5.3-29 through 5.3-31. Bandpass dissipation loss can be reduced by increasing cross-sectional dimensions of the cavities since loss is inversely proportional to cavity diameter.

Diplexing aural and visual channels in an AM-VSB transmitter can be accomplished with narrow bandpass or band-reject filters. A single-cavity bandpass filter in waveguide or a single-cavity, coaxial aural reflecting filter would be adequate for this requirement. Performance of both channel multiplexing and aural/visual diplexing filters is given in Table 5.3-13. None of the filters are expected to multipact.

5.3.6.5 RF Loads

Loads capable of dissipating moderate amounts of power are required as terminations on hybrids used in multiplexers, power combiners, or in circuits employing circulators. Several approaches appear feasible.

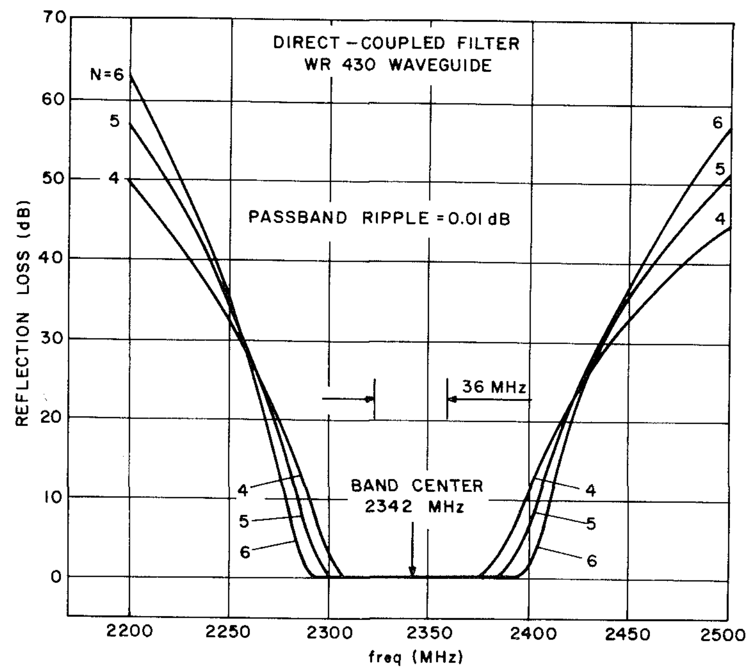


Figure 5.3-23. Bandpass of Direct-Coupled Filter; WR430 Waveguide

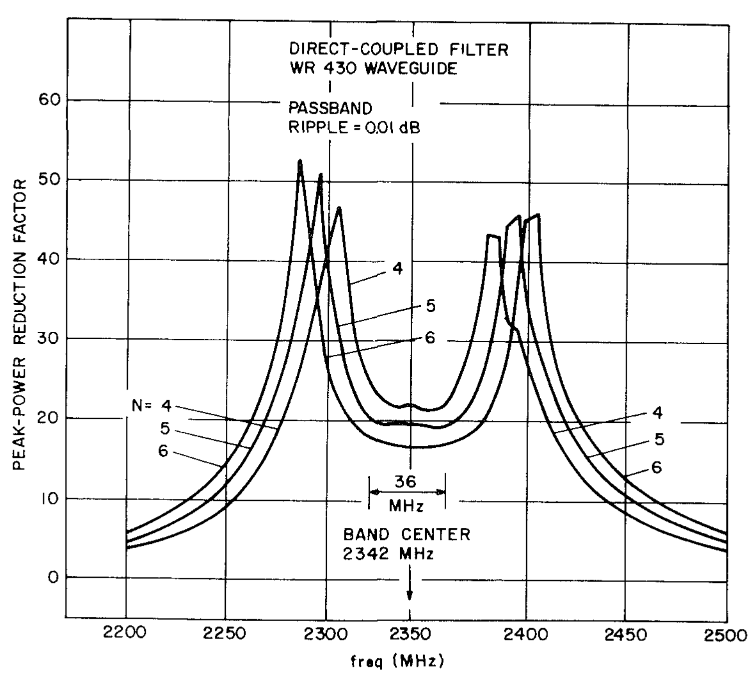


Figure 5.3-24. Peak-Power Reduction Factor Direct-Coupled Filter; WR430 Waveguide

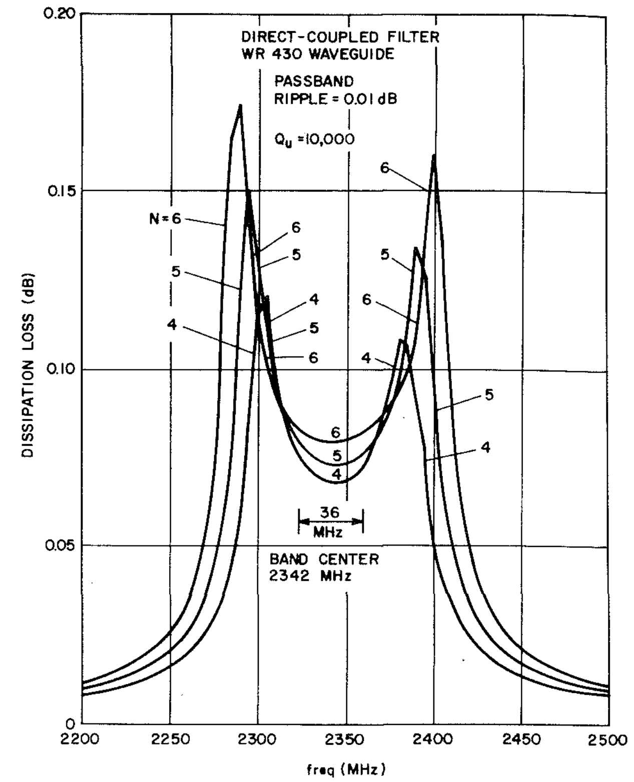


Figure 5.3-25. Dissipation Loss, Direct-Coupled Filter, WR430 Waveguide

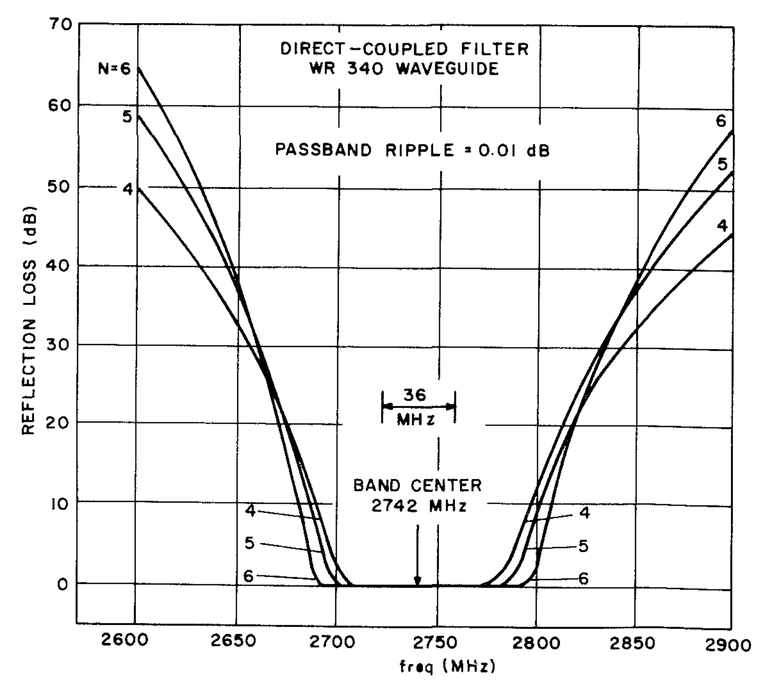


Figure 5.3-26. Bandpass of Direct-Coupled Filter; WR340 Waveguide

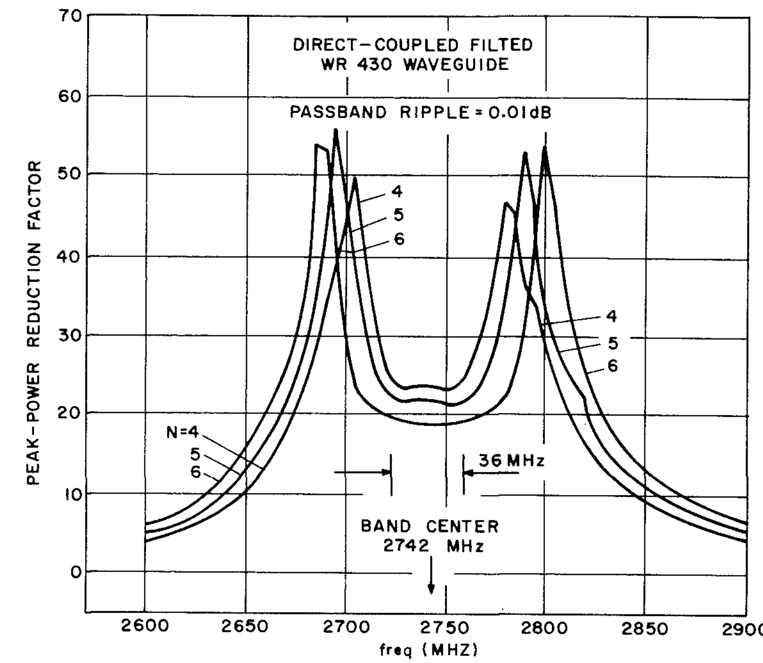


Figure 5.3-27. Peak-Power Reduction Factor, Direct-Coupled Filter; WR340 Waveguide

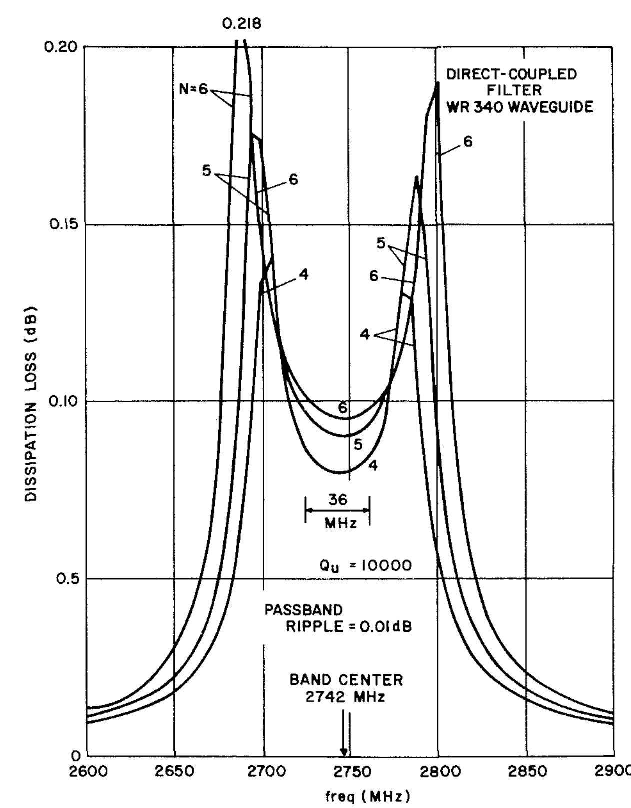


Figure 5.3-28. Dissipation Loss, Direct-Coupled Filter; WR340 Waveguide

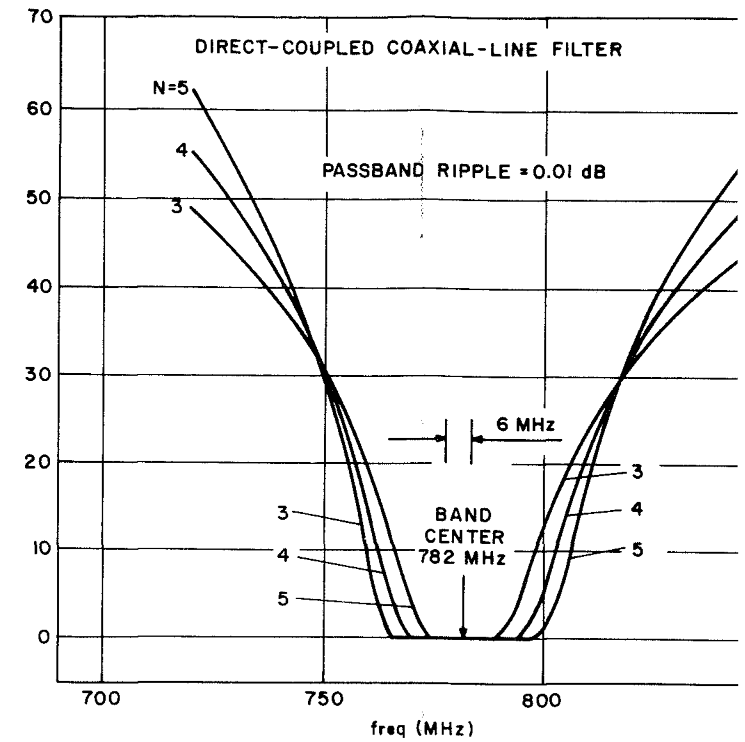


Figure 5.3-29. Bandpass of Direct-Coupled Coaxial Line Filter

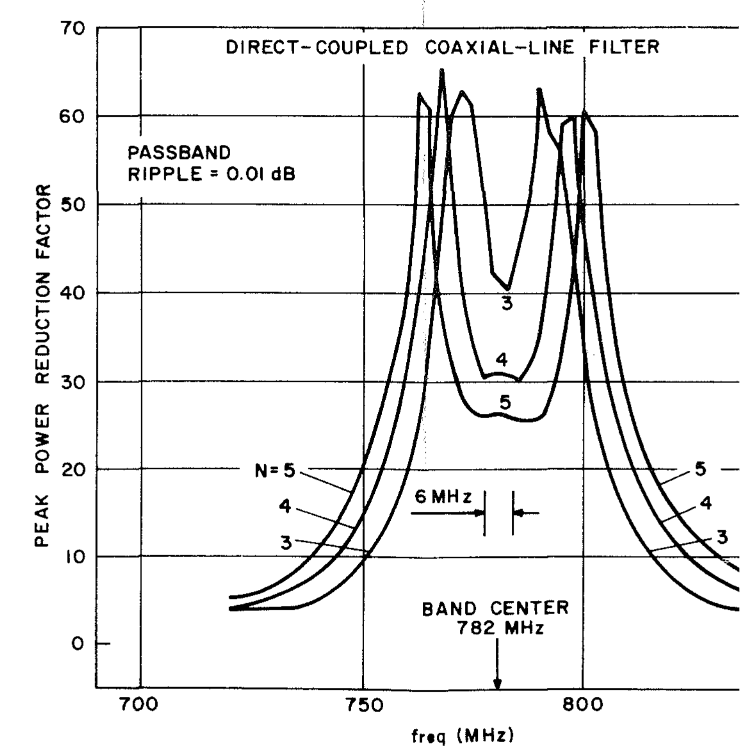
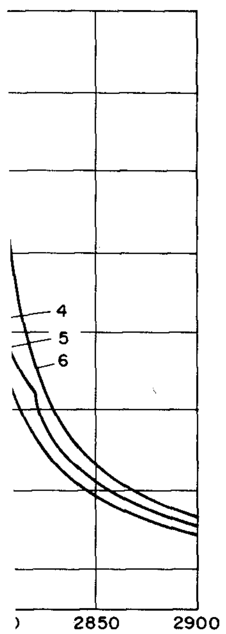


Figure 5.3-30. Peak Power Reduction Factor, Direct-Coupled Coaxial Line Filter



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Waveguide

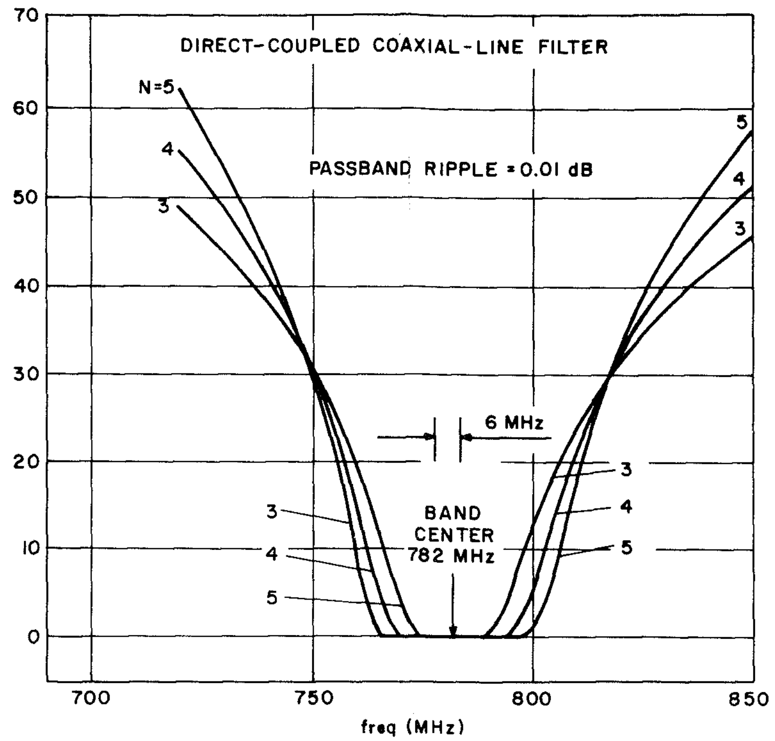


Figure 5.3-29. Bandpass of Direct-Coupled Coaxial Line Filter

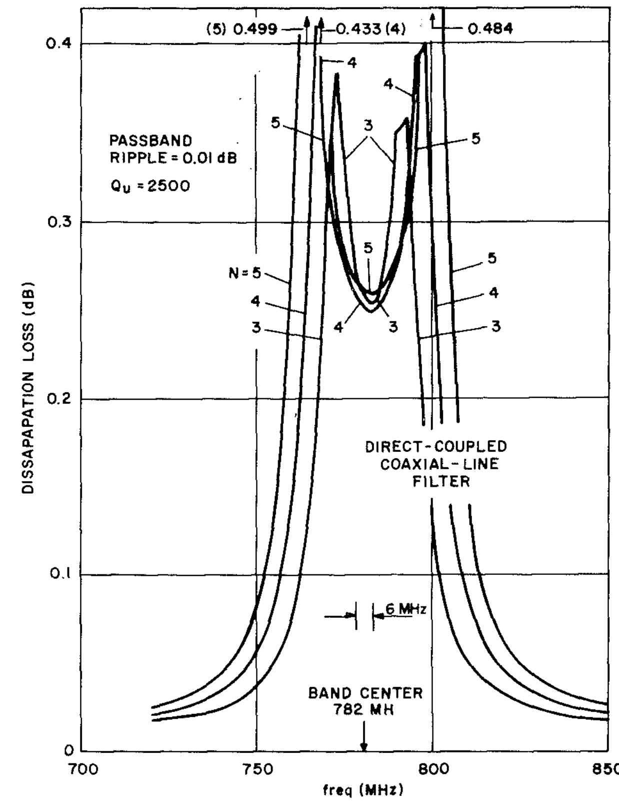
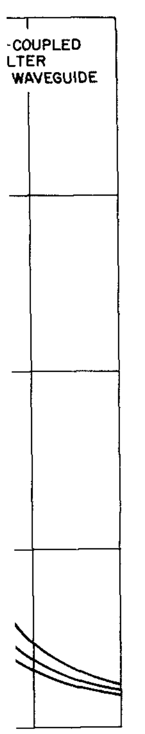


Figure 5.3-31. Dissipation Loss, Direct Coupled Coaxial Line Filter



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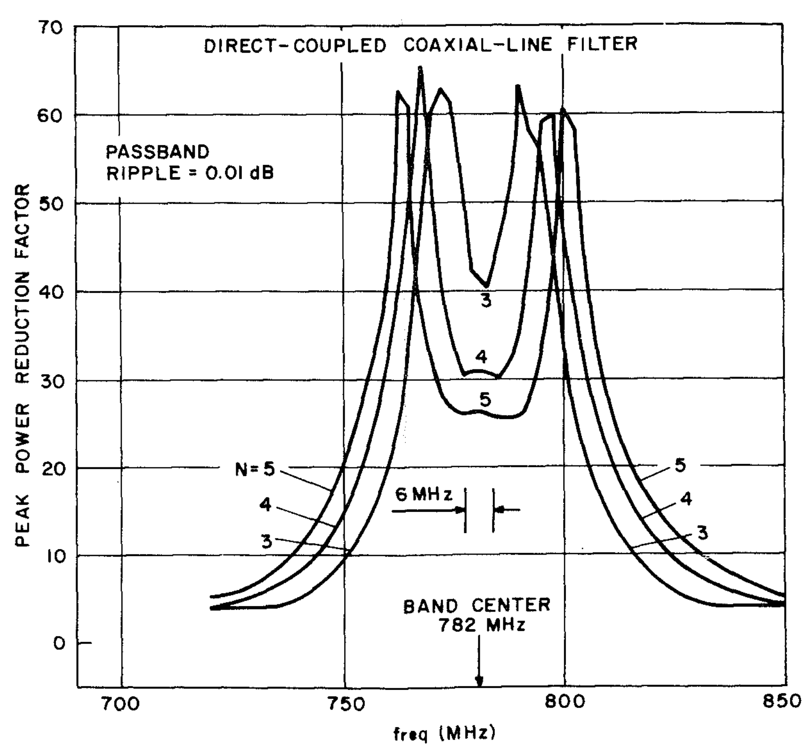

Figure 5.3-30. Peak Power Reduction Factor, Direct-Coupled Coaxial Line Filter

Table 5.3-13. Summary of Multiplexing Filter Characteristics

Component	f_o Frequency (GHz)	Power at f_o (kw)	Adjacent* Channel Power (kw)	Loss at f_o (dB)	Loss at* Adj. Ch. Freq. (dB)	Total Loss (watts)	Pass-band VWSR	Dimensions (inches)
WR340 Multiplexing Filter	2.7	2.5	2@ 2.4	0.08	0.05	110	1.10	WR340 x 13 L
WR430 Multiplexing Filter	2.3	2.5	2@ 2.5	0.07	0.05	100	1.10	WR430 x 14 L
WR1150 (Half-Height) Multiplexing Filter	0.8	5.5**	2@ 5.5**	0.08	0.03	190	1.10	Half-Ht. WR1150 x 49 L
3-1/8 Coax. Multiplexing Filter, 10 inch Cavity Diameter	0.8	5.5**	2@ 5.5**	0.08	0.015	150	1.10	10 D x 78 L
Waveguide Aural Pass Filter	0.8	1.5	---	0.15	---	55	1.2	Half-Ht. WR1150 x 49 L
Coaxial Aural Notch Filter	0.8	1.5	---	0.3	---	100	---	8 D x 28 L

* Assume one adjacent channel each side of passband
** Total AM-VSB channel power (aural + visual)

Coaxial loads are currently available which use a short cylindrical resistor as the center conductor of a short-circuited section of coaxial line, as was shown in Figure 3-26. A beryllium oxide substrate, coated with a conductive film, is a typical construction for the resistor. Cooling may be by a combination of readiation and conduction, or heat pipe cooling might be used for higher power dissipations. Some development of techniques for thermal bonding of beryllia to the coaxial shorting plate, development of insulating fluid heat pipes, plus tests of resistive coating compatibility with berylia would be required. Estimates of typical load characteristics for the three transmitter systems are listed in Table 5.3-14.

Waveguide loads would employ a fill or partial fill of lossy material plus various impedance matching techniques to achieve a good input VSWR. Many present load designs use a coating of lossy materials on a shorted section of tapered waveguide, as in Figure 3-27. Cooling is accomplished by conduction of heat through the lossy material into the waveguide walls. The load may be attached to a cold plate or a heat pipe arrangement might be used. Another arrangement uses a block of beryllium, or other material with high thermal conductivity, which is coated on one surface with a resistive film. The general developmental needs relate to materials selection and fabrication techniques that will give the desired loss characteristics, freedom from outgassing, thermal conductivity, and have acceptable thermal stress characteristics. Estimates of performance of these loads are also given in Table 5.3-14.

Table 5.3-14. Load Characteristics

Component	Frequency (GHz)	Power Input (watts)	VSWR (maximum)	Cooling Means
3-1/8 inch coaxial, 50-ohm	0.7 - 0.9	220	1.10	Radiation and conduction at either end of resistor
3-1/8 inch coaxial, 50-ohm	0.7 - 0.9	600	1.10	Heat pipe
WR340 - bulk loss material	2.6 - 3.0	25	1.05	Conduction
WR340 - resistive film	2.6 - 3.0	25	1.05	Conduction
WR430 - bulk loss material	2.0 - 2.6	25	1.05	Conduction
WR 430 - resistive film	2.0 - 2.6	25	1.05	Conduction
WR1150 (half-height) - bulk loss material	0.7 - 0.9	220	1.05	Conduction
WR1150 (half-height) - resistive film	0.7 - 0.9	600	1.05	Conduction

5.3.6.6 Isolators and Circulators

A coaxial circulator, in an isolator connection, will be required in the UHF, 15 kw, CFA transmitter. The circulator would probably be located in the input line of the CFA. A 150- to 200-watt, 3-port circulator with a load of corresponding power rating could be used. Adequate conduction-cooled circulator designs are available for this power level for air operation. Suitability for space operation involves the question of materials use and fabrication techniques that are compatible with operation in a vacuum. Insulating materials and bonding materials must not outgas excessively and must be otherwise suitable for the application. Shielding of magnetic fields must be accomplished in accordance with requirements of the spacecraft systems. Insertion loss of such a circulator is typically 0.4 dB.

5.3.7 HIGH VOLTAGE RF BREAKDOWN

Both ionizing and multipactor characteristics of most of the components previously described in this report were estimated. A summary of these results and notes on the procedure used in making the estimates are noted below. The most susceptible components are listed in Table 3.5.

5.3.7.1 Transmission Lines

The maximum electric field in uniform waveguide, where energy is propagating in the TE_{10} mode (the usual case), occurs between the center lines of the guide's broad walls. All electric field components of the TE_{10} mode are perpendicular to the broad walls. Maximum voltage in uniform waveguide is given by the expression

$$(bE_m) = \sqrt{0.75 \times 10^3 \left(\frac{b}{a}\right) \left(\frac{\lambda g}{\lambda}\right) P}$$

where:

E_m - Maximum electric field volts rms/unit length

P - Power carried by the waveguide

a - Width of the waveguide

b - Height of the waveguide

λ - Free space wavelength at the operating frequency

λg - Guide wavelength at the operating frequency

The maximum voltages in the waveguide assemblies were computed with this equation and compared with the minimum voltage required for multipacting to occur. The results, showing multipacting in either S-band or UHF waveguide systems is not likely, are summarized in Table 5.3-15. The minimum voltage is considered to be at the 9/2 mode. Test data found in the literature indicates that the occurrence of multipactor action in such higher-order modes is a poorly defined situation. Quite often higher order multipacting modes exist for only a brief time while components are outgassing, then extinguish, leaving only the lower order mode(s) which occur at higher voltages. From the above information, the peak rms values of the voltages in uniform waveguide, with the specified multiple signals, appear to be below that required for high-order mode multipacting.

Table 5.3-15. Multipacting Conditions for Transmission Lines

Component	Power (kw)	Voltage* (maximum kv)	fd (MHz-cm)	Voltage Range (kv)	Comments
S-Band Waveguide WR340 and WR430	2.5	1.1	> 10,000	> 30	Not expected to multipact
	4 @ 2.5 each	4.4	> 10,000	> 30	Not expected to multipact
Half-height UHF Waveguide	5	1.1	5,000	7.5 - 30	Not expected to multipact
	4 @ 5 each + 4 @ 0.5 each	5.8	5,000	7.5 - 30	Not expected to multipact
	15	1.9		0.75 - 9	Not expected to multipact
1-5/8 inch coax (2 GHz)	2.5	0.36	2,250	0.75 - 9	Not expected to multipact
3-1/8 inch coax (700 MHz)	15	0.87	1,575	0.55 - 5	May multipact in high order modes

*Voltages are for unity VSWR. Multiply by VSWR for actual operating voltage and check multipacting range.

The rms voltage applied to a coaxial line is given by the relation

$$V = \sqrt{PZ_o}$$

For P = 15 kw and characteristic impedance Zo = 50 ohms, V = 865 volts rms, and peak rms voltage of 1140 volts will occur when aural and visual signals are diplexed in the 15 kw CFA transmitter. The multipacting level ranges from 550 volts for the higher order modes to 5 kv for the 3/2 mode with fd = 1575 and UHF 3-1/8 inch coax. (The 1/2 mode is not likely due to electron energy level considerations.) A definite possibility for higher order mode multipacting is indicated in Table 5.3-15 data, but experimental verification is required due to the uncertainties existing in the higher order modes.

5.3.7.2 Filters

Breakdown voltage between teeth in the WR340 waffle iron filter section has been calculated to be 3300 volts rms from breakdown tests on a WR650 filter under standard atmospheric conditions. The voltage at 2.5 kw is about 400 volts rms, so no breakdown problems in air are expected in any of the waveguide sizes.

Multipactor breakdown is a possiblilty in a high vacuum for waffle iron filters, as shown in Table 5.3-16. Multipacting can occur in the 5/2 mode at about 250 volts, and at 1300 volts for the 1/2 mode, when the fd product is 700 MHz cm.

A definite possibility for higher-order mode multipacting in coaxial lines exists, as noted in Table 5.3-15, but experimental verification is required due to the uncertainties existing in the higher order modes. Multipacting in high order modes often appears to cease after the initial period of operation, so there is a possibility that multipactor effects will not be a problem after the initial turn-on period. The coax line and related components should be included in a multipactor test program.

A stepped inner conductor coaxial harmonic filter in the UHF band would be rated for 25 kw CW power in air. It has an estimated fd ratio of 500. An operating voltage of 865 volts rms (at 15 kw) would be in the multipacting range, and is likely since this is in the fundamental (1/2) multipactor mode. The need for development of multipactor suppression techniques should first be confirmed by tests on development components. A comparison of multipacting conditions with circuit voltages is included in Table 5.3-16.

Table 5.3-16. Multipacting Conditions for Filters

Component	Power (kw)	Voltage* (maximum kv)	fd (MHz-cm)	Multipacting Voltage Range (kv)	Comments
Waffle-Iron (S-band) filter	2.5	0.4	700	0.25-1.3	Multipacting likely
	4 @ 2.5	1.6	700	0.25-1.3	Multipacting likely
Waffle-Iron (UHF) filter	5.0	0.57	700	0.25-1.3	Multipacting likely
	4 @ 5 ea. + 4 @ 0.5 ea.	3.0	700	0.25-1.3	Multipacting likely
	15	0.99	700	0.25-1.3	Multipacting likely
Coaxial, Stepped Inner Conductor (UHF)	15	0.87	500	0.18-2.4	Probably will multipact
Waveguide Leak-Wall Iris (S-band)	2.5	100	1875	0.75-7.5	Not expected to multipact
(UHF)	15	250	1875	0.75-7.5	Not expected to multipact
Coax, Leaky-Wall Iris (UHF)	15	450	1875	0.75-7.5	Not expected to multipact
Waveguide Multiplexing Filter (S-band)	2.5	5.5	> 10,000	> 30	Not expected to multipact
(UHF)	5.0	5.5	5000	7.5-30	Not expected to multipact
Coacial Multiplexing Filter (UHF)	15	5.2	6600	12-30	Not expected to multipact
Coaxial Aural Notch Diplexing Filter (UHF)	1.5	14.5	6700	13-30	May multipact in high order mode
Waveguide Aural Pass Diplexing Filter (UHF)	1.5	5.9	5000	7.5-25	Not expected to multipact

*Voltages are for unity VSWR. Multiply by VSWR for actual operating voltage and recheck multipacting range.

Leaky wall waveguide filters should handle nearly the power of full height waveguide, except possibly for iris slots in the filter walls. An expression for fundamental slot voltage is:

$$E_m W = \left(\frac{\sqrt{P\,\pi^2\,K\,1^2\,(Z_{10})}^{1/2}}{\lambda_g \sqrt{ab}} \right) \sin \frac{\pi X}{a}$$

where terms not previously defined are:

E_m - maximum rms voltage across the slot

w - width of slot

k - polarizability factor (=0.105 for w/1 = 0.25)

1 - length of slot

Z_{10} - wave impedance = 377 $\lambda g/\lambda$ ohms

This equation was used to determine that the fd product is about 1875 for a second harmonic coupling slot in any of the waveguide sizes. Multipacting in the 9/2 mode, with a starting voltage of 750 volts, is not expected. A similar situation exists for the coaxial leaky wall filter, when the slot voltage for 15 kw at 800 MHz is 450 volts, slightly below the 9/2 mode multipactor starting level. Multipacting, therefore, is not likely but confirming tests should be performed. Also, multipacting is not likely except perhaps in the coaxial notch filter in a high order mode.

The four-cavity waveguide filter is subjected to greater internal voltages than uniform waveguide due to standing-waves in the structure. Referring to Figures 5.3-23 through 5.3-28, it is seen that the power reduction factor is 23 times (WR340). The filter height and cross-section configurations are the same as for uniform waveguide where voltage breakdown is equal to $\sqrt{23}$ x 1100 = 5300 volts for S-band. Added to this must be the effects of adjacent channel transmitters, which will approximately double this voltage at peaks of the composite voltage from these transmitters. This voltage (about 11 kv) is still below the multipacting zone for S-band full height waveguide and UHF half-height waveguide. The inductive irises used as coupling elements between filter sections were chosen because they have the same fd (=fb) product and do not reduce the multipacting level.

Coaxial multiplexing filters have a power reduction factor for a four-cavity filter of 30 to 1 due to resonant buildup of fields, per Figures 5.3-24 through 5.3-31. The corresponding voltage for a filter line impedance of 70 ohms and a 15 kw transmitter is 5610 volts rms. The filter has a rather narrow multipacting range of 12 to 30 kv, which is above the operating voltage for the filter, and multipacting is not expected.

Maximum voltage in the coaxial aural notch cavity for a 15 kw TV system at a power output of 1.5 kv will be 14.5 kv rms. An fd product of 6700 gives a multipactor starting voltage of around 13 kv for the 9/2 mode, so multipacting may occur as indicated in Table 5.3-16. However, as discussed previously for other components, the 9/2 mode may appear a transient phenomena, occurring only during the initial operation of the transmitter.

The final filter considered, the waveguide aural bandpass diplexing filter, has a power multiplying factor of about 96 for a 3/2 wavelength cavity whose Q is 2×10^3. The voltage in uniform half-length waveguide is 350 volts for 0.5 kw and 605 volts for 1.5 kw. Thus, operating voltages would be 96 x 350 = 3420 volts rms for the 0.5 kw aural channel transmitter (5 kw UHF TV system), and 5920 volts rms for 1.5 kw aural power (15 kw UHF TV system). Multipacting should not be experienced since the starting level is 7.5 kv for the 9/2 mode.

5.3.7.3 Hybrids

Voltages and spacings in the short-slot waveguide hybrids are such that multipactor starting levels are not greatly different than in uniform waveguide. Substantial safety factors exist in uniform waveguide so detailed calculations were not made. Sidewall hybrids have been tested to breakdown at 40 to 70 percent of uniform guide power breakdown level while top wall hybrids can be expected to breakdown at 40 percent of uniform guide power level. Multipacting conditions for the various hybrids are shown in Table 5.3-17.

Table 5.3-17. Multipacting Conditions for Hybrids

Component	Power (kw)	Voltage* (maximum kv)	fd (MHz-cm)	Multipacting Voltage Range (kv)	Comments
Waveguide Hybrid Sidewall (UHF)**	4 @ 5 ea. + 4 @ 0.5 ea.	7.98	5000	7.5-30	Slight chance of multipacting in high-order modes
(S-Band)**	4 @ 2.5	6.3	10,000	> 30	Not expected to multipact
Waveguide Hybrid Topwall (S-band)**	4 @ 2.5	6.3	20,000	> 120	Not expected to multipact
Coaxial Hybrid, slab Line (UHF)**	15	0.78	500	0.18-2.4	Probably will multipact
Coaxial Hybrid,** branch line (UHF)	15	0.71 to 0.87	1210 & 1575	0.4-3.0	May multipact in high order modes

*Voltages are for unity VSWR. Multiply by VSWR for actual operating voltage and check multipacting range.

**Voltages are calculated for multiplexer service.

A coaxial slab-line hybrid with a quarter wavelength transmission line coupling section (per Figure 3-23a) has a maximum voltage between conductors that falls within the multipacting region for a typical odd mode impedance of 40 ohms, where P_{in} is input power. Spacing fd is about 500 MHz-cm and the operating voltages at 5 and 15 kw are within the 1/2 mode multipacting range. Thus, multipactor suppression techniques will be necessary with this type of hybrid.

The branch line coaxial hybrid (per Figure 3-23b) will have the same multipacting level as the $Z_o/\sqrt{2}$ lines. Multipacting levels will range from 450 to 2000 volts rms at 800 MHz for a Z_o = 50 ohm, 3-1/8 inch, hybrid. Voltages in the lines vary from full applied transmitter output voltage (865 volts for a 15 kw transmitter) down to near zero volts. Therefore, multipactor breakdown is a possibility for one of the higher order modes of operation.

5.3.7.4 Other Components

Loads

Multipacting conditions at the input to the loads are the same as for uniform line. Power levels, however, will be on the order of 1 percent or less of rated transmitter power, so no problem is expected in this area. The two load types considered are included in Table 5.3-18.

Table 5.3-18. Multipacting Conditions for Loads and Circulators

Component	Power (kw)	Voltage (Max. kv*)	fd (MHz - cm)	Multipacting Voltage Range (kv)	Comments
Load, Coaxial (UHF)	0.2 - 0.6	0.1- 0.17	1575	0.55 - 5	Not expected to multipact
Load, Waveguide (S-band)	4 @ 0.025	0.44	>7500	>15	Not expected to multipact
Circulator, 7/8 in. Coax (UHF)	0.2	0.2**	390	0.15 - 1.5	May multipact in 3/2 mode

*Voltages are for unity VSWR. Multiply by VSWR for actual operating voltage and recheck multipacting range.

**Voltage includes reflection from a short-circuited port to simulate worst-case condition.

Circulators

Multipacting is likely in a typical 200-watt, UHF circulator using 7/8-inch coaxial connectors. Internal fd products of around 100 to 200 indicate the occurrence of multipacting in the fundamental (1/2) mode. Inclusion of this unit in a development test program is necessary, and multipactor suppression is probably required.

5.4 UHF POWER AMPLIFIER BREADBOARD

5.4.1 SELECTION OF DOHERTY AMPLIFIER

The initial part of the UHF Power Amplifier Breadboard study was to determine the relative merits and demerits of the Chireix Outphasing and the Doherty high-efficiency circuits. The result of this was to be the selection of one of the two for breadboarding at a low power level to show efficiency capability. Comparisons were made on the basis of efficiencies, sensitivities to phase and amplitude aberrations, linearities, and complexities, with considerations of the problems that might be encountered at UHF. The results of the investigation were included in Figure 3-28 of Section 3.2.1; details will be expanded upon here.

5.4.1.1 Chireix Outphasing Circuit

5.4.1.1.1 Circuit

The Chireix Outphasing circuit operation involves a low-level RF drive signal, two phase modulators which convert the TV video signal into oppositely phase modulated signals with phase angle proportional to modulation amplitude, two high-power RF amplifier chains, and a combining circuit at the output. The basic block diagram of the Outphasing circuit is shown in Figure 5.4-1. The combiner converts the two phase modulated, constant amplitude, vectors into a single amplitude-varying output signal. The phase modulator may be low or medium level, but the main amplifier chain will almost certainly require two stages each, and probably three (depending on output power required).

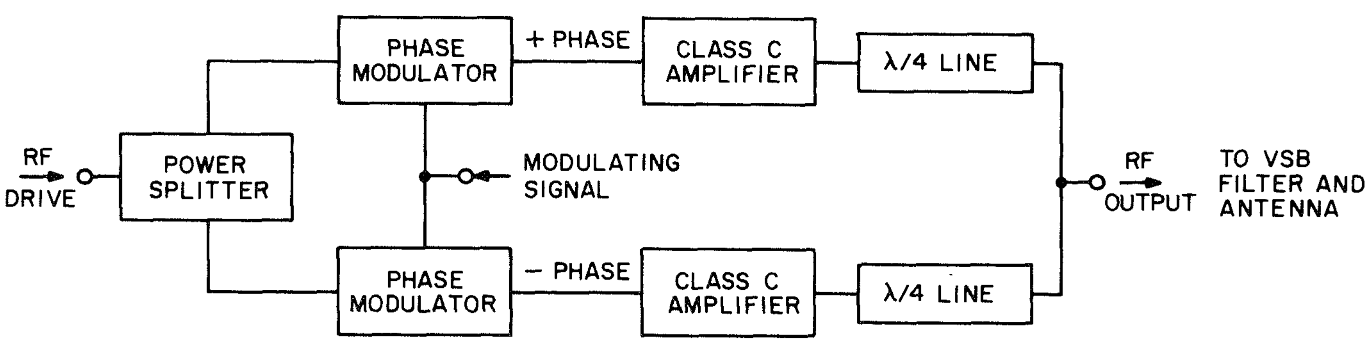

Figure 5.4-1. Chireix Outphasing Circuit

5.4.1.1.2 Efficiency

The general operation of the Chireix Outphasing circuit can be developed from the output circuitry of Figure 5.4-2 and the vector diagram of currents in Figure 5.4-3. The average efficiency has been estimated at 55 percent for an average signal (Reference 1 and its sub-references). The relatively low efficiency is due to the reactive components of plate current that arise as a function of varying load impedance effects arising from the interaction of the two output tubes. The two amplifiers operate Class C with efficiencies approaching perhaps 75 percent peak, but the transmitter will only realize about a 60 percent peak efficiency (when tuned to optimize the efficiency at the average output level rather than the maximum output level). The variation of the ratio of actual power to the voltage-current product (fundamental components of RF) is shown in Figure 5.4-4, where the 140-degree phase angle between the two voltage vectors is the selected initializing level. Thus the efficiency drops rapidly at larger phase angles, the result of which corresponds to small signal levels (white picture), and deviates nearly 9 percent for the picture black levels. This could be improved only if an isolator could combine the two channel signals, but no such practical device is

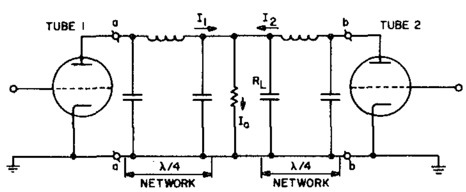

Figure 5.4-2. Outphasing Combiner Output Circuit

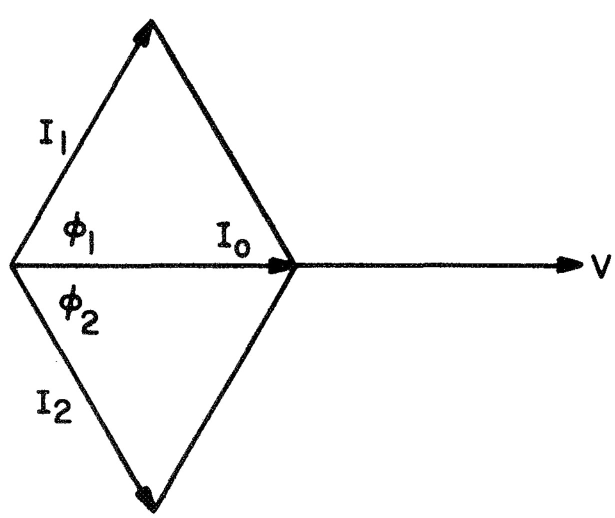

Figure 5.4-3. Vector Signals in Outphasing Amplifier

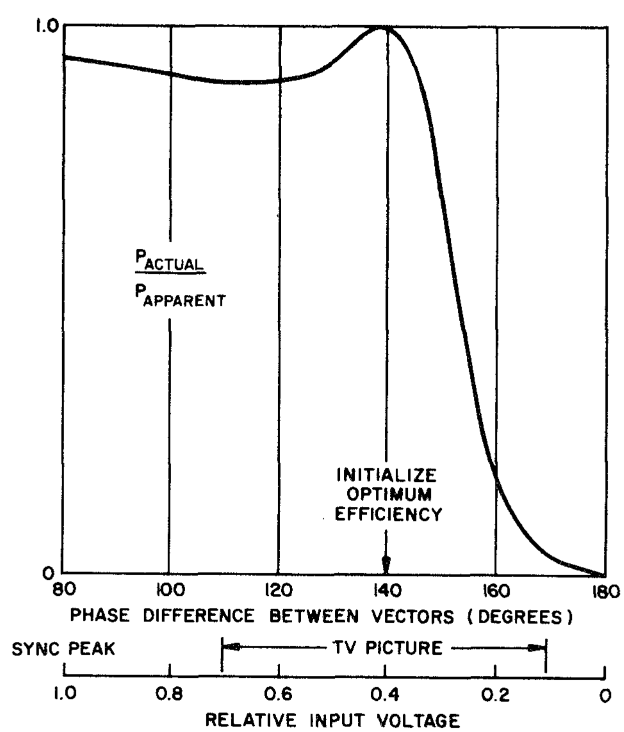

Figure 5.4-4. Ratio of Actual to Apparent (Voltage x Current) Outphasing System; Phase = 140 Degrees

available. The curve of Figure 5. 4-4 is not efficiency as such, but is indicative of the variation of efficiency; that is, large reactive currents cause large I^2R losses in the tube and circuitry without providing useful output. Thus, the 55 percent figure will be assumed to be realizable; it would be computed in more detail if other circumstances were not pessimistic in nature. Further details on the circuit operation are in References 2 and 4.

5. 4. 1. 1. 3 Sensitivities to Phase and Amplitude

A basis for comparison of the Outphasing circuit with the Doherty can use two specifications points for TV picture accuracy (from Reference 25). Circumstances may show these to be restrictive in practice for space TV, but the conclusions will only be influenced in terms of magnitudes of differences between amplifiers.

One comparison point can be the blanking level accuracy, assumed to be within 2. 5 percent of the peak sync amplitude reference. Blanking is at the 75 percent voltage point, so the output voltage at the blanking level should be held within 3. 33 percent. Then the differences in either phase or amplitude that would produce the 3. 33 percent error in resultant output vector can be computed. The initial phase difference between vectors is set at 140 degrees ($\phi_1 + \phi_2$ in Figure 5. 4-3) and the blanking level to a 105-degree difference (for 75 percent voltage input in Figure 5. 4-4). Note that errors can result from differential operation of the two amplifiers or from both channels being off equally. A 3. 33 percent error permits the following individual errors (if both phase and amplitude errors exist which is quite likely, each would necessarily be smaller):

1. One-channel amplitude: 6. 8 percent
2. One-channel phase: 3. 0 degree
3. Two-channel amplitude: 3. 34 percent
4. Two-channel phase: 1. 5 degrees

These are computed from the simple geometrical arrangement of the two output vectors. Thus, the Outphasing circuit is sensitive to both amplitude and phase, which should be expected, since the information is expressed in both amplitude and phase at different times within the amplifier system.

5.4.1.1.4 Linearity

The Chireix Outphasing circuit is fundamentally a nonlinear circuit. That is, the output is the sum of two vectors, from Figure 5.4-3, is:

$$E_o = 2V \cos \phi$$

where each voltage vector is V. Operating over any reasonable angular interval then results in a cosine output function. However, the actual circuit isn't quite that simple since the load impedance becomes reactive as the phase angle approaches high and low values relative to the design-center. This complicates the actual expression for the output function, but the nonlinearity is still present and would have to be accounted for, probably by feedback. The circuit is sensitive to both amplitude and phase, so two separate feedback loops will almost certainly be necessary to get both accuracy and linearity.

5.4.1.1.5 Complexity

Complexity will be considered in terms of number and uniqueness of circuits. The following elements for the outphasing amplifier are required:

1. Two matched phase modulators (low to medium level)
2. Two Class C RF amplifier chains, at least two stages each, with one stage being a limiter (amplitude feedback if used would be included after the limiter stage)
3. Output combiner with two 90-degree lines
4. Output high-power vestigial sideband filter required (refer to Table 5.3-11 in Section 5.3.5.2.1).

The limitation of requiring an output rather than an input VSB filter places a substantial weight disadvantage on this amplifier relative to that of a linear RF amplifier.

5.4.1.2 Doherty Circuit

5.4.1.2.1 Circuit

The elementary Doherty circuit operation has been described several times in the various documents published (References 1, 2, 3, and 5). Fundamentally, the Class B input stage in the circuit of Figure 5.4-5 operates with a high load impedance for small input levels and thus reaches maximum RF plate voltage swing and maximum efficiency for a relatively low input (usually adjusted to 1/2 peak voltage, or 1/4 peak power). A further increase in drive signal causes the second, or peak, tube to conduct, which serves to reduce the effective plate impedance of the first stage as well as contributing output power. Thus, the first stage operates near maximum possible efficiency over the upper 3/4 of the power range, raising the effective efficiency for a TV amplifier from 40 percent for a straight Class B linear amplifier to about 60 percent. The 90-degree phase shifter provides the necessary coupling to give the proper impedance change between the peak tube and the input tube. The peak tube is heavily biased and operates as an efficient Class C stage.

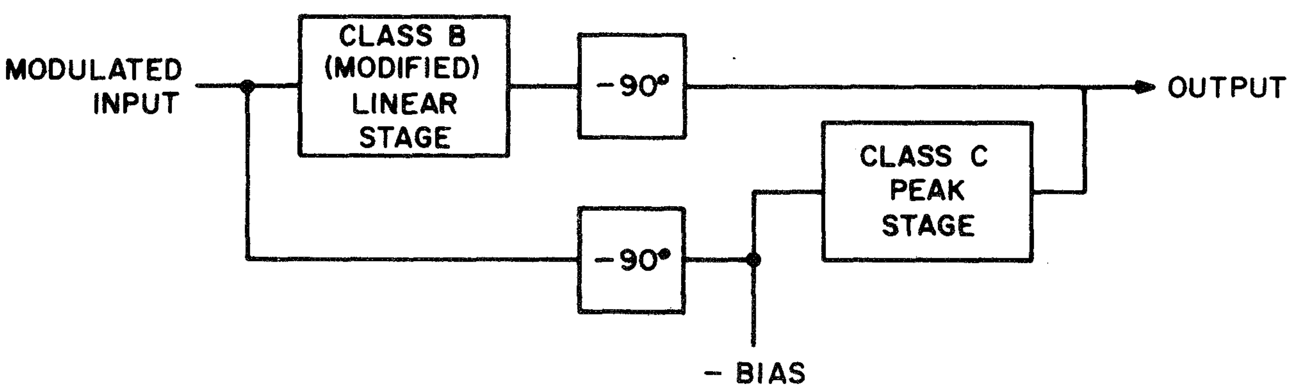

Figure 5.4-5. Doherty Block Diagram

The voltage and current relations in the input and peak tubes in an ideal situation are shown in Figure 5.4-6. The circuit operation does depend on tube characteristics to some extent, and thus the output voltage which should be linear may have some variations in practice. In

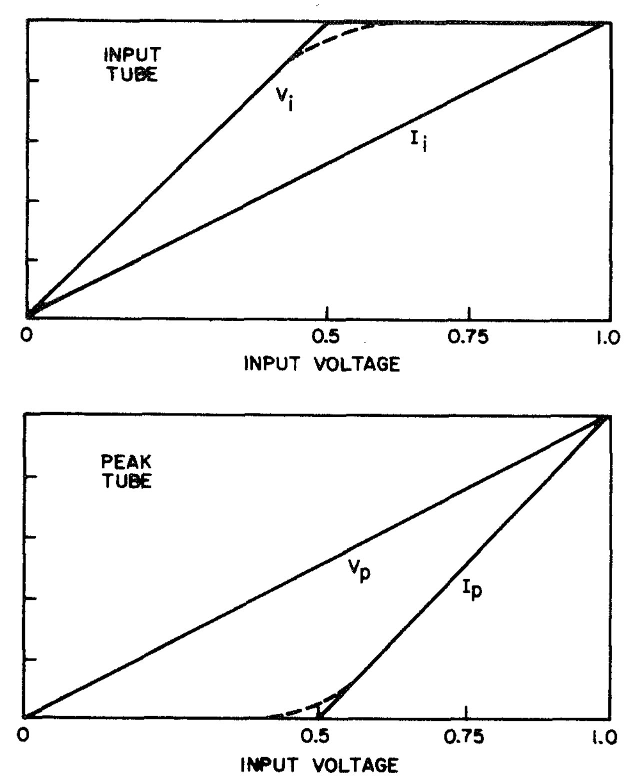

Figure 5.4-6. Voltage and Current Relations in a Doherty Amplifier

addition, a preliminary look from a small signal viewpoint indicated a linear output is unlikely, although a more rigorous evaluation should be performed, preferably experimentally. (Actually, the simulator approach being pursued should indicate how linearity is influenced by adjusting for maximum efficiency. See Section 5.4.4.)

5.4.1.2.2 Efficiency

For typical TV picture cases, including distributed picture signals, a Class B amplifier would provide about 40 percent efficiency in a practical case, while the Doherty circuit would provide 57 percent under the same circumstances. With a small modification to the Doherty in which the input stage is a self-biased Class C stage that becomes more efficient as signal increases, a 60 percent efficiency is possible. The efficiency of a Doherty circuit was computed in Appendix 5 of Reference 20. Thus, a small improvement over the Outphasing circuit is expected.

5.4.1.2.3 Sensitivity to Phase and Amplitude

The approach is to assume a perfect Doherty operation and compute the variations permitted in amplitude and phase to satisfy the requirements at the blanking level, where a 3.33 percent amplitude error is permitted. Stray nonlinearities may appear as in the Outphasing circuit, but a relative comparison is still reasonable between the two amplifiers. An additional requirement, not needed in specifying the Outphasing circuit, is a phase accuracy of 7 degrees for the color subcarrier at 3.58 MHz; this is at the blanking level amplitude, so the calculations will all be made for that point.

The approach used for this calculation assumes that one stage is the reference and the allowable deviation in the other stage is computed for the 75 percent input blanking voltage. The voltage on the peak tube plate is the same as the output voltage, and the contributions from the two tubes are assumed to be proportional to their currents. (The voltage itself is a composite and cannot be easily divided between the two tubes.) Thus, the input tube contributes 75 percent of its peak current and the output tube 50 percent of its peak current, or a ratio of 3:2. To stay within the 3.33 percent error allowed, the accuracies would have to be less than:

1. Peak tube (input tube as reference); 8.3 percent
2. Input tube (peak tube as reference); 5.5 percent

Actually, both tubes might have variations, and if proportionally divided, the worst-case maximum would be 3.33 percent each, which is the number included in Figure 3-28 that compares this circuit with the Outphasing. In practice, simultaneous worst-case errors in both tubes would probably not occur.

Phase sensitivity is based on assuming the input and peak tubes as references, and then assuming both are equally poor. This leads to

1. Peak tube (input tube as reference); 17 degrees
2. Input tube (peak tube as reference): 11.7 degrees

However, the worst case occurs where both vectors deviate from a reference (per RS-240 of Reference 25), and the restriction becomes the 7-degree limit. This worst case is not very likely, and some compensation can probably be applied. The phase stability of 10 degrees required for all other parts of the spectrum is a more likely figure. The data in Figure 3-28, however, reflects both figures.

5.4.1.2.4 Linearity

The Doherty circuit should be linear on a strictly theoretical basis. However, it does depend on tube characteristics in causing the change in load impedance of the input stage, and some nonlinearity in the overall characteristic is expected. The specific characteristic is not predictable with present analysis approaches, but a rough consideration of end points (Appendix A of Reference 3) indicates that an S curve is likely to result. A feedback loop is anticipated to compensate for the amplitude variation; a feedback loop for phase correction is not likely if phase predistortion is included to remove the major variations. The phase stability requirement, determined above, results in a significantly lower criticality relative to the Outphasing circuit.

5.4.1.2.5 Complexity

This circuit is simpler than the Outphasing in that only two tubes are involved. The complexity arising is the analog nature of the impedance change in the output circuit of the input stage, which requires a 90-degree phase shifter with the correct characteristic impedance (twice the antenna load impedance). The impedance matching and loading adjustments at UHF present new design problems, but they are little different from those likely to be encountered in any other circuits beyond the simple Class B amplifier. Thus, the Doherty circuit is much simpler in terms of number of stages, probably has less complexity per stage, and has the final significant advantage of using an input type VSB filter which saves very substantially on system weight.

5.4.1.3 Selection

The above considerations indicate that the Doherty circuit would be the simpler of the two in terms of design and fabrication effort, and should provide a little better performance. However, the level of analysis involved is not really sufficient to ensure that the Doherty will operate significantly better than the Outphasing circuit. Both circuits have been used commercially at low frequencies for voice transmission, and either would probably serve for this program. However, the UHF TV problems may be substantially different, and low-frequency conclusions are not necessarily directly scalable to high frequencies. The Doherty appears to be preferable, though, on the basis of adequacy, good efficiency, and probable simplicity in design, fabrication, and implementation.

5.4.2 INTERDIGITAL DOHERTY CIRCUIT

5.4.2.1 Circuit

The interdigital Doherty amplifier circuit utilizes the properties of an interdigital filter line to provide the tuning and coupling required. The interdigital filter is comprised of a section of transmission line which operates through a coupling process between tuned posts spaced along alternate sides of the line. The line used in this amplifier was 1/8 wavelength in height and less than 1/4 wavelength in width. A sketch of the amplifier, which was shown photographically in Figure 3-29 is shown in Figure 5.4-7, while the electrical circuit is shown in Figure 5.4-8.

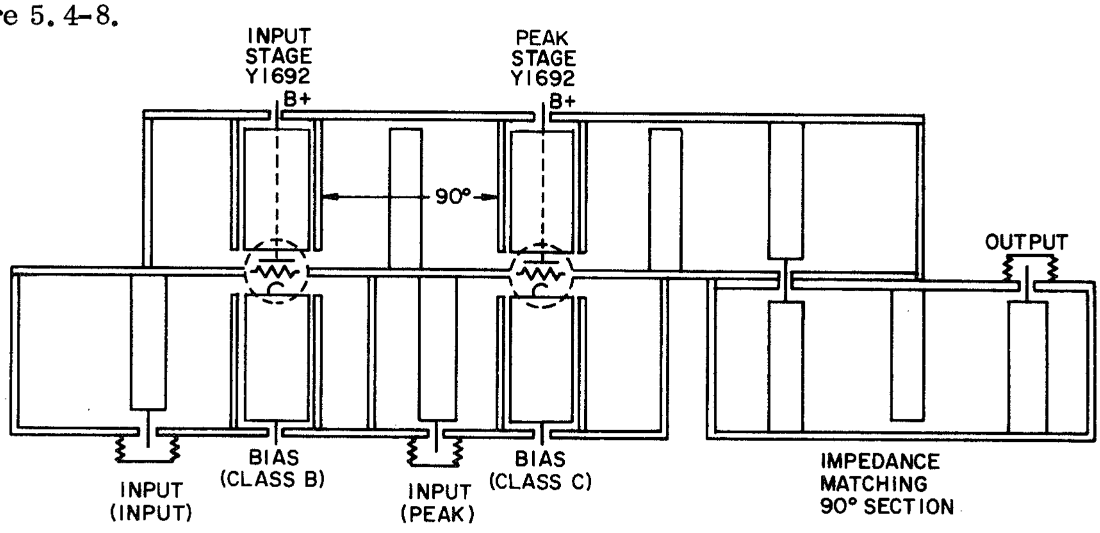

Figure 5.4-7. Interdigital Cavity Doherty Amplifier (Not to Scale)

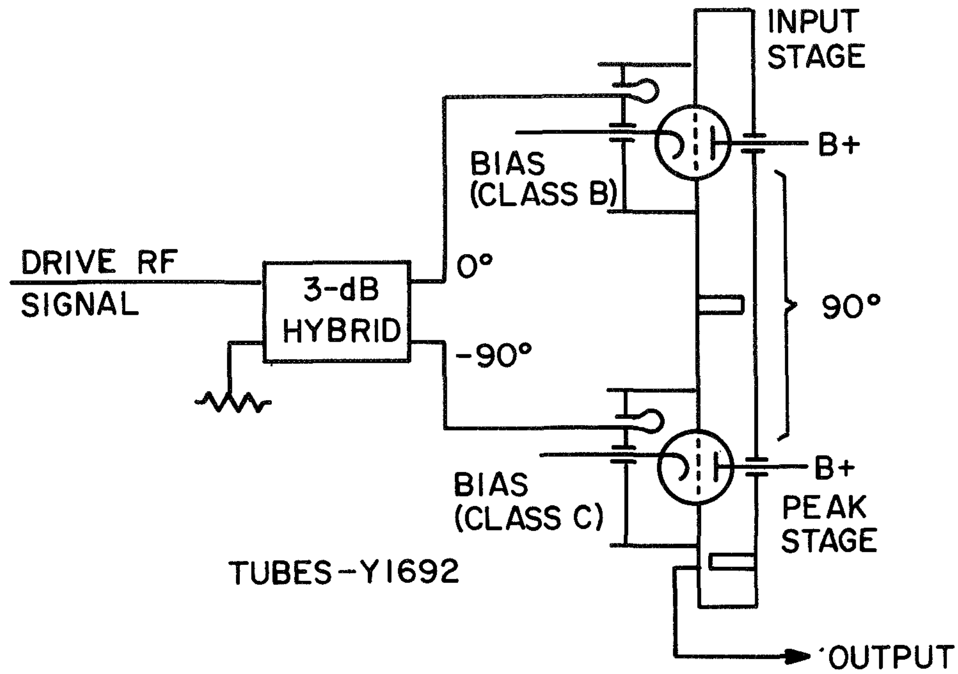

Figure 5. 4-8. Interdigital Doherty Circuit

An external 3-dB hybrid is used to split the input signal between the two tubes. At the same time, this hybrid provides the -90 degree phase shift required to balance the -90 degree coupling between plates in the output circuit. The tubes used are Y1692's which are a low-power developmental planar triode with good efficiency and gain characteristics. An impedance matching section was added to the amplifier output to provide an intermediate step between the high impedance load required at the tube plates and the 50-ohm output line.

The plate voltages were 300 volts, and power at Class C peak was about 22 watts with an efficiency of 65 percent, a little less than would be expected at a lower frequency. The tube was originally rated at 25 watts plate dissipation with 500 volts on the anode, but the tube could not maintain this level for long durations without developing internal shorts. Biases were varied during the tests but generally were about -4 volts on the input Class B stage and -16 volts on the peak Class C stage.

5.4.2.2 Doherty Performance

A major difficulty was encountered with the interdigital circuit in that is was designed on the basis of manufacturer's tube data. Considerable testing was performed but proper Doherty operation could not be achieved. The discovery was then made that the available tubes varied considerably from specifications, particularly in the grid-plate capacity, which was nearly twice the specification. The amplifier had a limited tuning range and a complete redesign would have been necessary to adapt to the Y1692 tubes in their present manufactured configuration.

The results of a typical run as a Doherty amplifier when tuned as well as possible under the limitation of the resulting incorrect impedances and couplings tended to follow a simple Class B function, as was shown in Figure 3-30. Peak efficiency was of the order of 50 percent, which is also considerably less than expected, again indicating improper operation. The output-versus-input power levels and efficiency at selected points are shown in Figure 5.4-9. The effect that caused the difficulty was an apparent overcoupling of the output stage, resulting in a double-peak response curve with a large dip in the center; this is indicated in Figure 5.4-10. Efficiency and gain data were usually taken near the 780-MHz peak to obtain best gain and highest output power.

Continuation of this amplifier would require a redesign of the circuit. Basically, the circuit is sound in principle but must be adapted to the specific tube and its characteristics. Thus, one recommendation would be adapt to a production type tube rather than a developmental tube and to rebuild with the new dimensions required.

5.4.2.3 Characteristic of 90-degree Interdigital Section

An impedance matching section was fabricated to provide independent confirmation of the impedance inverting performance of the interdigital 90-degree line. In addition, it was designed to reduce the large range of different between the tube load impedance (designed for 2500 ohms) and the output impedance (50 ohms). The circuit is a three-post interdigital filter, as shown in Figure 5.4-11 and is the output section of the interdigital amplifier in Figure 3-29.

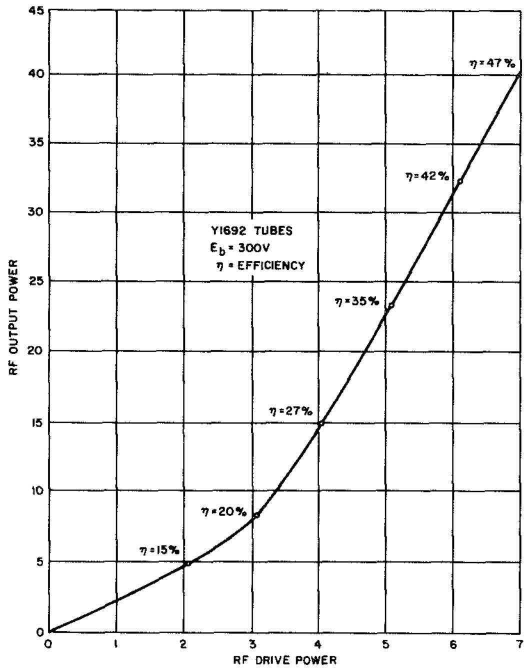

Figure 5. 4-9. Typical Response of Interdigital Doherty Amplifier with Incorrect Coupling of Circuits

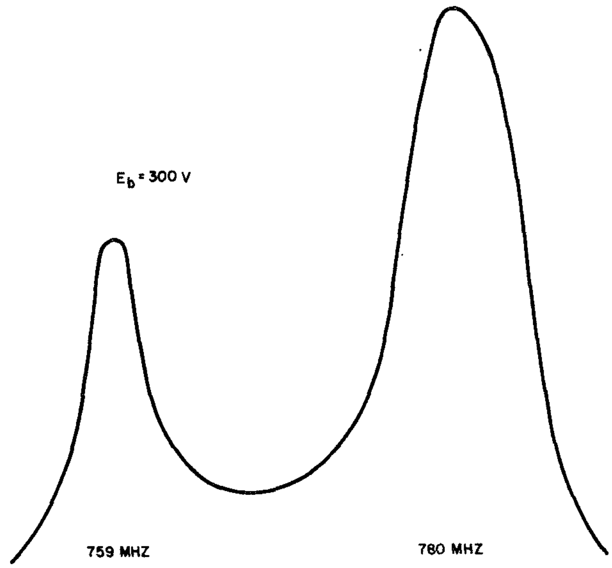

Figure 5. 4-10. Overcoupled Effect in Output Circuit of Interdigital Doherty Amplifier Configuration

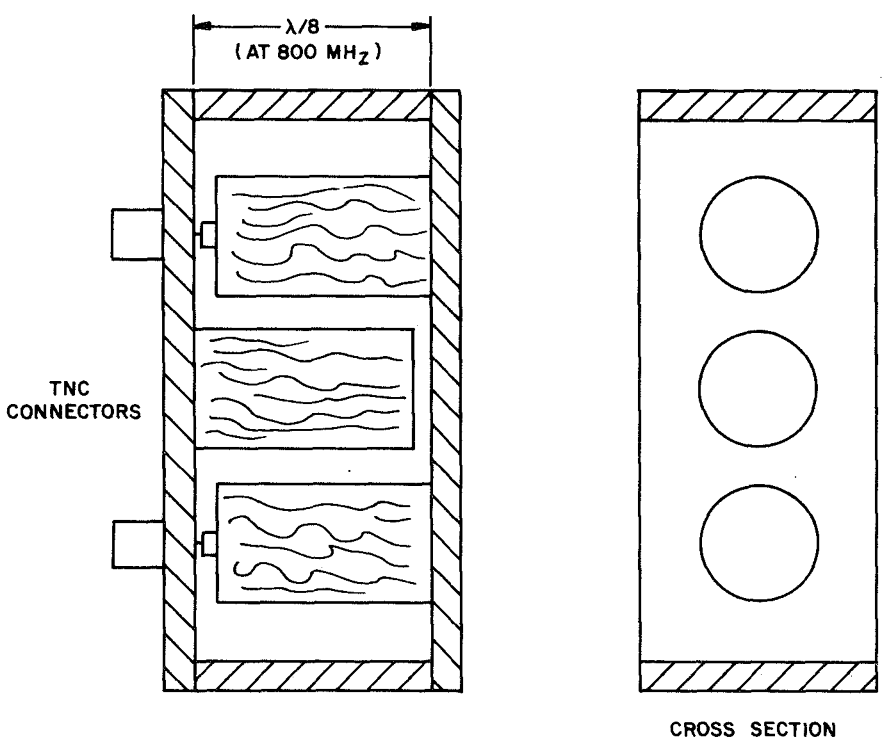

Figure 5. 4-11. UHF Impedance Inverting Line (90-degree Phase Length)

In testing this line at 800 MHz, the following data resulted:

Output Load Z (ohms)	Input Measured (ohms)	Computed Characteristic Z (ohms)
50	345	133
135	135	135

The characteristic impedance if the line is a true 90-degree line at the 800-MHz test frequency is $Z_c = (Z_{load} \cdot Z_{in})^{\frac{1}{2}}$. The two loads and measured input impedances indicated the same (essentially) characteristic impedance, so the line did provide the 90-degree shift as intended.

This line would result in a 345-ohm impedance rather than a 50-ohm impedance at the output of the main interdigital line, so the coupling requirements in the final stage could be relaxed somewhat. This did not eliminate the overcoupling effect, however.

5.4.2.4 The Y1692 Tube

The expected performance of the Doherty amplifier was based on an initial run made with individual tubes in the output circuit only, blocking off the first stage plate circuit. Two cases were measured under typical conditions that were used in the Doherty configuration; output-versus-input power and efficiencies are shown in Figure 5.4-12. The data indicates a gain of less than 10 dB, which is attributed in part to the output coupling problems. Efficiency was also slightly less than had been expected.

5.4.3 THE TWO-CAVITY DOHERTY AMPLIFIER

5.4.3.1 Circuit

The two-cavity Doherty amplifier described previously in Section 3.2.3 was developed and tested on a related program, but is included here in support of the assertion that a Doherty amplifier is feasible for the UHF region. In addition, this circuit is considerably more flexible than the interdigital, and could be tuned to the proper frequency while couplings are adjusted to provide the required impedance relations.

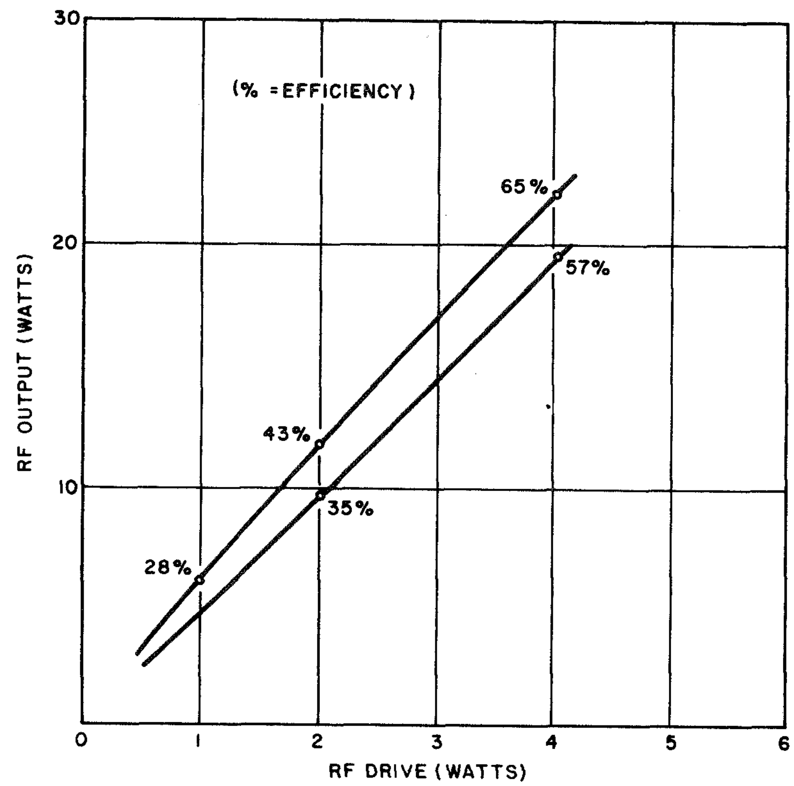

Figure 5.4-12. Y1692 Characteristics in Class C Amplifier with E_b = 300 Volts (Two-Tube Samples)

The circuit, which is similar to that of the previously described amplifier in principle, uses two separate cavities for the two stages and a 1/4 wave 50-ohm coaxial cable for the 90-degree phase shift between plate cavities. Commercial cavities were used, which had cathode tuning cavities as an integral part of the units. The 2C39 tubes are less efficient that the more recent tubes, but they did provide an indication of Doherty operation. The basic circuit diagram, indicating the tuned input cavities as well as the output cavities with interconnecting phase shifter, is shown in Figure 5.4-13. Again an external 3-dB hybrid serves to split the input signal between the two stages, and also has the -90 degree phase shift required.

The 2C39's were operated with 500 plate volts and an output of about 30 watts maximum per tube. Individual stage efficiencies were measured to be about 55 percent at an output power of 26 watts. This applied both the Class C stage and the self-biased Class B stage, where the B stage has a constant bias potential until the second stage picks up, and thereafter develops additional bias proportional to drive signal.

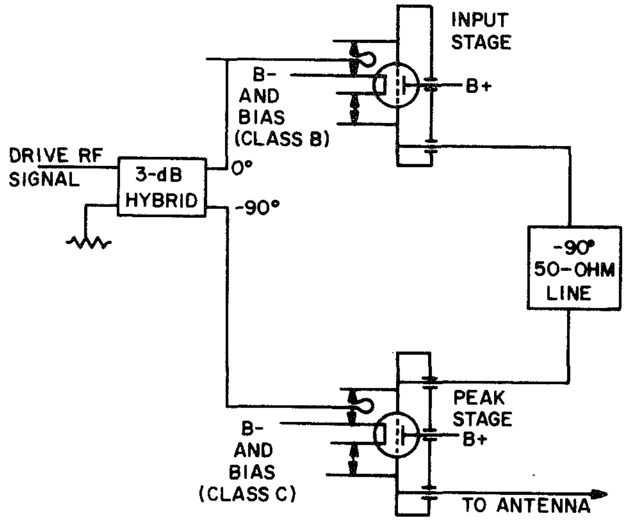

Figure 5. 4-13. Two-Cavity Doherty Amplifier Circuit

5.4.3.2 Doherty Performance

The two-cavity Doherty amplifier showed a definite improvement in performance over the standard Class B linear, but fell short of the expected efficiency improvement. However, this particular project was limited in extent and was carried to the point of showing operation with the characteristics of the classical Doherty operation and with better than Class B linear efficiency; results are shown in Figure 3-32. The data indicates the Doherty attained about 40 percent of the improvement that would ultimately be expected.

The efficiency should be improved by further refinement of adjustments. For example, the load impedance of the input stage should have about a 2:1 variation between operation at low signals, where the peak tube is cut off, and where there is maximum output operation. A smaller variation was obtained in the actual circuit indicating that Doherty operation was being obtained but that the couplings between the cavities through the 50 ohm -90 degree phase shifter and of the 50-ohm output line were not optimized. However, there is no fundamental reason that the expected improvement cannot be obtained.

The maximum efficiency of this amplifier was not as high as expected, largely due to the lack of optimality. However, the 2C39 tubes and the cavities tended to be somewhat lower in efficiency than more recent tubes using improved cavity fabrication. A typical curve of output-versus-input power for the Doherty configuration as well as the measured performance of a Class B stage modified to achieve Class C operation near maximum input levels are shown in Figure 5.4-14.

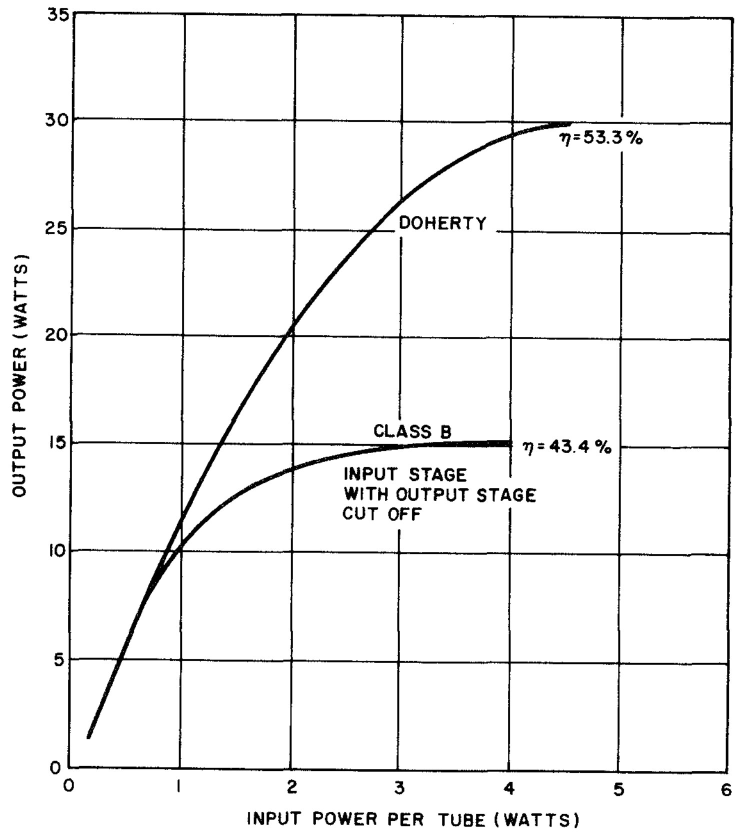

Figure 5.4-14. Power Output of Two-Cavity Doherty Amplifier with 2C39 Tubes

Two other factors enter in reducing the efficiency below the ideal case and must be considered in estimating eventual capability. The first tube operates as a Class B amplifier at low signal levels while the peak tube is biased off. The latter appears to be a capacitor to the circuit (grid/plate) but will be a lossy type, thereby reducing small signal efficiency. Both tubes operate at large signal inputs and a "paralleling" loss appears. These factors might reduce efficiency by 5 percent to possibly 10 percent of normal (3 percent to 6 percent overall for the amplifier) but the situation is not well determined in available data, particularly at UHF. Thus, the peak Doherty efficiency of 54 percent for the 2C39 amplifier was probably not far below the best attainable with these tubes.

5.4.4 SIMULATOR AT 30 MHz

The analytical and experimental efforts, and the realization of the interplay of biasing, impedances, and drive levels (which ideally would be different for the two stages), suggested a computer program is a necessity for optimizing the operation of the Doherty amplifier in a UHF configuration. This is especially the case for the grounded grid, low-plate resistance triodes available at the frequencies of interest. However, a simulator approach was selected in which lumped circuit constants would be used, but the simulator would be perhaps more realistic in determining operating characteristics since it could include some factors which are not well defined and could not be included appropriately in the computer program.

Another independent program involved the development and testing of a Doherty simulator operating at 30 MHz. The tests indicated that even at this frequency, the interrelations of drive, bias, and impedances were not simple to adjust for best operation. Continuation of experimental efforts with this simulator are anticipated in the near future.

The simulator has about 4 watts of output, using two 7913 tubes. The circuit simulates the two-cavity grounded grid configuration in that the 90-degree line between the plate circuits is a low impedance line, 100 ohms in this case. The amplifier's signal is split; the part going to the "input" stage has a 90-degree phase lead network, shown in Figure 5.4-15. Grids are grounded, and biases are supplied through the grid-cathode loop, while the negative terminal of the high-voltage plate supply returns directly to the cathode. Separate bias supplies are shown with the input stage biased to -3 volts and the peak stage to -7.15 volts. The 90-degree line is set at 100 ohms to match directly into the 50-ohm load, since the delay line impedance is twice the actual load impedance under normal operating conditions. A match for the 100-ohm line is simulated by tapping the delay line down on the tank circuit inductances.

The amplifier photograph was in Figure 3-33 and performance of the circuit was shown in Figure 3-34. Further efforts on the Doherty high-power amplifier circuits will be based on operational characteristics derived from this simulator. Variations and techniques for improvement, linearization methods, and other important performance improving techniques can be evaluated easily and quickly before incorporation in the less versatile UHF amplifiers.

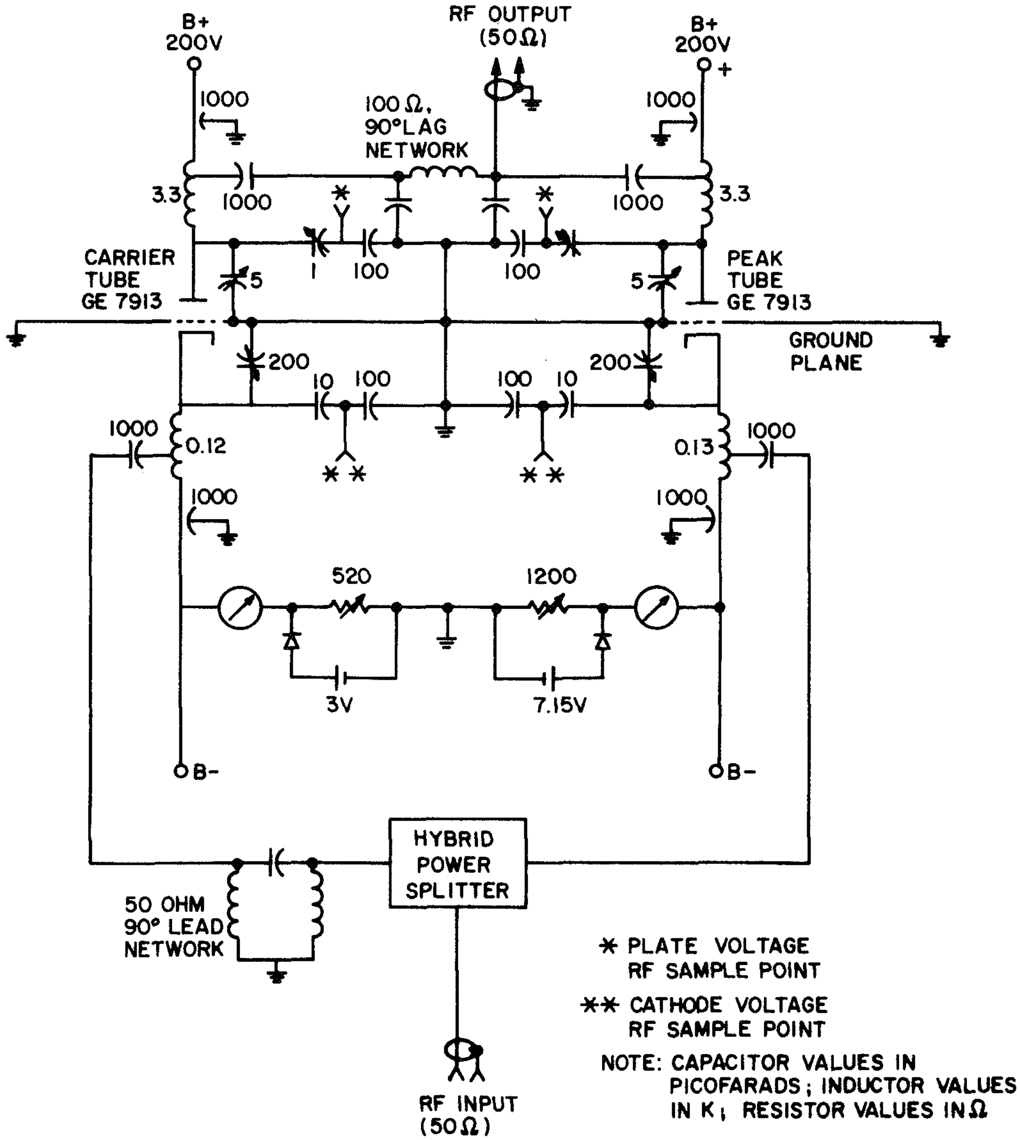

Figure 5.4-15. 30-MHz Doherty Amplifier Breadboard

5.5 SCALING EFFECTS

The purpose of this effort was to determine the validity of directly scaling low power tests to the 5 kW transmitter level, the objective power output for a possible future AM-TV transmitter. The validity of extrapolating the analytical results where tests were not included in the program is also of interest; where extrapolation is not considered valid, the contributing factors are indicated.

5.5.1 MATERIALS EFFECTS

The major concern in materials selection is the area of electrical breakdowns. The effects of higher voltages can be deduced from considering each of the factors involved. In general, electrical breakdowns in gasses can be extrapolated by using Paschen's Law curves (such as shown in Figures 3-1, 3-2, 3-9, and several in Section 5.3), and reasonable confidence can be placed on obtaining consistent results for certain cases. Uncertainties, however, suggest that experimental methods be employed where data is not yet well established.

For example, the outgassing products and particularly the sublimation for complex materials can be quite variable, since each different type of material given off has a different Paschen's law curve. In addition, the rate of material leaving the surface depends on the material thickness, shape, and temperature, and is not well determined from present experimental work. Thus, electrical breakdowns can be extrapolated on a gross basis for materials with known characteristics in a vacuum environment but, in general, straight extrapolation is not considered accurate.

Electrical breakdown within insulating materials is a definite problem area in space. The application of high voltage in an improperly designed system will sometimes release additional outgassing in an insulator, thus resulting in surface arcing. Tree effects within insulators also create breakdown paths through the material. Neither insulation effect is considered scalable in terms of voltage or power levels, but further experimental data may improve this situation.

Enclosure dimensions can be scaled to some extent with Paschen's Law, but this has the problem of enclosure confinement effects which have not been well evaluated. Thus, simple size changes may not necessarily give a proportionate change in voltage level tolerance; but, if the assembly's surface open area is maintained proportional to size change, then scaling between voltage and spacings should be reasonable.

Scaling is generally limited in the RF area where waveguide is used, since waveguide sizing is largely a function of frequency and not power or voltage. An exception might be where the height of waveguide is varied; however, this is a minor factor which might be considered if difficulties are predicted in outgassing breakdown. Multipacting, the other major breakdown type in RF circuitry, might be predicted from data similar to that in Figure 5.3-12 through 5.3-16 with some confidence. The approach was to determine whether operation fell within the anticipated bounds of multipacting, and scaling will not necessarily induce or eliminate multipacting if it exists under initial conditions. However, the presence of outgassing or surface contamination will change the multipacting (probably in an unpredictable manner) until clean vacuum and surfaces are attained.

Vacuum arcs are less well defined but are of concern. These appear in a high vacuum system when metal whiskering results in very high field intensity at the whisker and current through the whisker becomes great enough to vaporize it. Vacuum arcs depend on voltage, metal, time, and mechanical configuration. They are not well defined and not easily scalable, although initial estimates might be made on the basis of available data. However, the effect is always reduced by using large spacings and low-whiskering metals.

5.5.2 DC CIRCUITS - POWER CONDITIONER

5.5.2.1 Voltage Effects

Higher output voltages will require the use of larger transformers, larger (physically) filter capacitors, higher voltage rectifiers, and better insulation in the output circuitry. Larger input voltages will normally only require better insulation. High voltage transformer weights for a 5 kW supply were determined to be (Reference 10):

2 kV and 97% efficiency:	2.8 pounds
6 kV and 97% efficiency:	4.8 pounds
20 kV and 97% efficiency:	32 pounds

The non-linearity in transformer weight is indicated in Figure 5.5-1. The rapid increase in weight is due to insulation requirements and their consequent effects on the whole transformer. However, the 20 kV case was computed with conventional techniques; if this voltage were to be used, the transformer should be studied in more detail in terms of design techniques and insulation materials. Thus, the scaling used here seems to be somewhat out of line, and a modified approach for higher power transformers should be investigated.

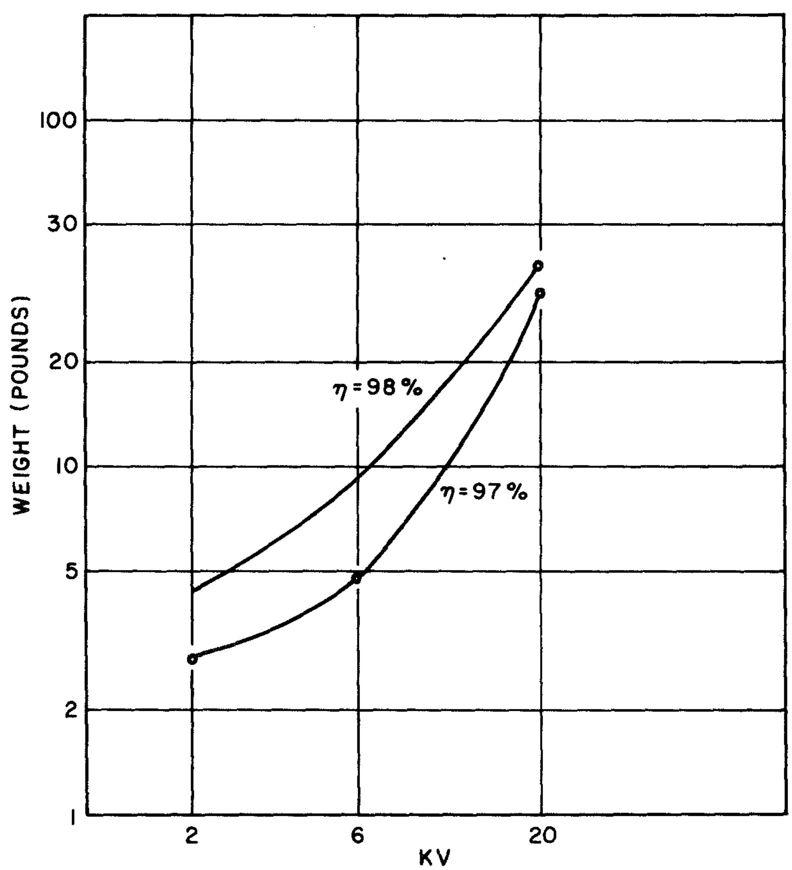

Figure 5.5-1 Transformer Weight Versus Output Voltage

The input and output filters depend strongly on ripple current tolerable inside the power conditioner; L-C filters are assumed for both input and output. The ripple is determined largely by the inductance for a constant output average power, and sufficient capacitance must be included for the energy storage in the output filter, particularly for the AM transmitter. Some of the components determined in an earlier study (Reference 10) are shown in terms of weight in Figure 5.5-2, all for a 98% efficiency in the overall filter. Some of the variations noted are due to differences in fabrication techniques rather than to proportionate changes due to the voltage changes. Thus, these data are representative of the state-of-the-art off-the-shelf components and can be used for voltage scaling for initial design considerations, but interpolation might not be precise for a specific design requirement.

Output rectifiers must be stacked for high voltages, since each device has a limited voltage rating. The losses in the rectifiers depend on the switching speed, which may be

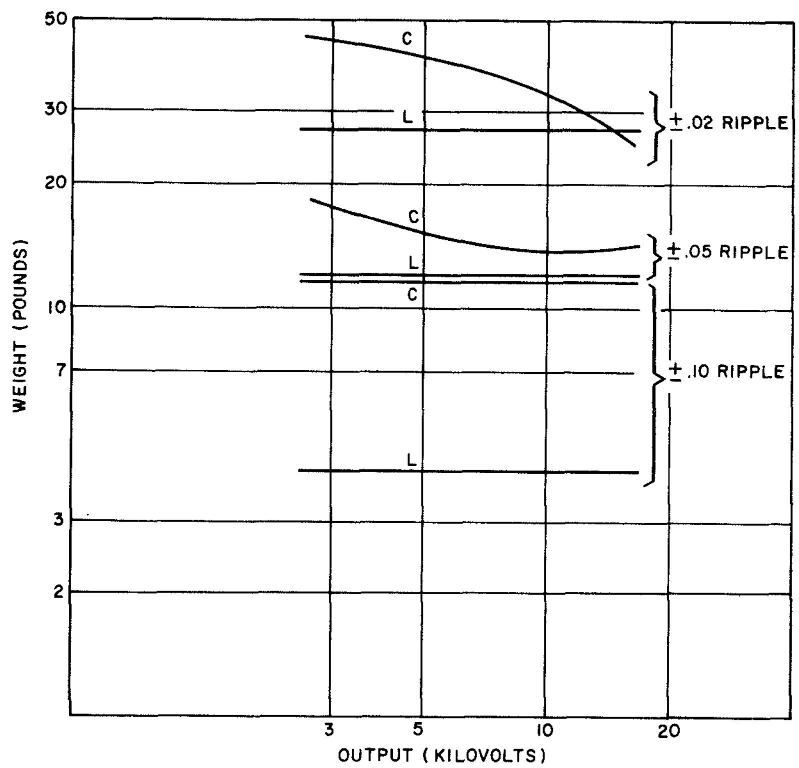

Figure 5.5-2 Filter Component Weights for 3.2 KW

lower (and more lossy) as additional devices are added to the stack. That is, equalization will be required due to variations among the serial stacked rectifier units, which would slow the overall response and increase losses. The alternative is vacuum rectifiers which generally can be obtained at 20 kV and up. The scaling, here then, is not obvious or straight-forward, but will depend on design preferences and on the tradeoffs between solid state and vacuum rectifiers as a function of voltage level. The difference is probably not a critical matter, except that reliability, which has not been assessed, may suggest a preferred component.

Insulation is always a problem, and particularly so in space where the effects of the space vacuum must be factored into the design. Insulation thickness varies with voltage and its properties may vary in characteristics with time, temperature, and thickness. Thus long term properties may not be scalable unless experimental confirmation is obtainable.

5.5.2.2 Module Effects

The power conditioner configuration recommended in this study was composed of four modules, each operating with a maximum current of 10 amperes. Thus, the power per module is dependent on the input voltage, since the transistors performing the switching operating in the power conditioner are operated as isolated units rather than paralleled in order to achieve maximum switching efficiency. The number of modules is generally given by:

$$N \geq \frac{\text{Total Power Output Requirements}}{\text{Input Voltage x 10 Amperes x Efficiency}}$$

A 3.2 kW output power conditioner, as considered in Section 5.2, uses four modules, with 100 volts input. The 88% efficiency assumed results in an input of about 3.7 kW. Thus, the number of modules will step up one for each additional 10 amperes of primary current necessary to provide the required input power. Scaling becomes more complex in power conditioners beyond this simple module-number relation, especially in regard to transformer design and interconnections per above.

5.5.3 RF SCALING

RF breakdown from gaseous products in the gap between two electrodes can be predicted to some extent from Paschen's Law, such as included in Figures 5.3-5 through 5.3-8. However, the usual problem of having a mixed "atmosphere" from the outgassing prevents an accurate indication of breakdown conditions. Heavier gas elements might permit a higher voltage (for instance, Figure 5.1-1 indicates oxygen will sustain a higher voltage than hydrogen), but the effect is not directly scalable with presently available data. An acceptable approximation could probably be obtained for arcing and corona since a safety factor should be included anyway. Corrections for frequency effects are necessary, as outlined in Section 5.3.2, but these are generally straightforward. The use of Paschen Law curves adapted to waveguide and coaxial line RF components would be required for any scaling, however, even for only approximations.

5.5.3.2 Multipacting Effects

Multipacting, as mentioned in Section 5.5.1 above, is generally scalable within limits of available data. Limitations in using this data appear when surface contamination and outgassing appear. Design efforts can be based on data available as long as the data covers the material, temperature, configuration, frequency, and voltage range required. Scaling as such is not complex, but each case must be considered as an isolated situation, and prediction for a major change in signal levels is only as good as the data.

5.5.3.3 RF Systems and Assemblies

Scaling factors in the three RF subsystems of Sections 5.3.4 through 5.3.6 must be considered for each situation. The conclusions on circuit designs are valid and would not be changed solely as a consequence of power changes until the breakdown region is approached. However, the space breakdown regions are variable in the multipacting region; present data can be used for estimates with some degree of confidence; but, again, the unknown factors such as gas effects and contaminants may alter the phenomena.

Scaling of outgassing effects are of greatest concern where the highest voltages exist, which is generally in the filters in the RF system. Thus, these should be considered first in determining possible breakdown modes. In addition, materials should not be changed without considering the resulting effects, and venting should be provided at the same level as previously.

Insulation is a different problem, since higher voltages require more or different insulation, resulting in at least a change in insulator dimensions and possibly a small change in circuit configuration. Insulation breakdown is not clearly defined in terms of scaling; the procedure would be to assume scaling is valid, taking into account any changes in design, and perform a confirmation test in a vacuum environment.

Multipacting scaling is accomplished only through analysis (for a first estimate) and utilization of appropriate experimental data curves where such exist. The major problem elements for the power levels considered in this study were the waffle iron waveguide filter and most of the UHF coaxial components. However, different components are susceptible to multipacting at different power levels, and the scaling problem becomes one of individual component analysis. The effects of standing waves in filters is always of concern since the voltages are normally quite a bit larger than in plain waveguide.

The RF system configurations otherwise are essentially not affected by power. That is, the same components will be used with the same interconnections. Frequency responses would remain the same so complications in design are not required as power levels change.

5.5.4 UHF AMPLIFIER EFFECTS

5.5.4.1 Circuitry

The basic functioning of the Doherty circuit is described on a completely general basis, and is not related to specific power levels. No power limit is implied by the general operational characteristics; for example, a one-megawatt LF Doherty transmitter is described in Reference 4. There is no specific power limit at which Doherty operation is not feasible, but the elements within the amplifier circuit will vary in a number of respects.

The most important variation is in the tubes themselves. Gridded tubes are not scalable in all respects to higher power operation. Usually the nominal tube characteristics (μ, g_m, r_p) are different, and the interelectrode capacitances become larger with higher power levels. Thus, the specific circuit design must be performed specifically for each tube type considered.

Usually the load impedance will be specified, and the output impedance determined from the type of transmission line used. This results in different circuitry for impedance matching, both in the output circuitry and in the coupling to the -90^{o} phase shifter between tube anodes. In addition, input circuitry will change considerably as the grid-cathode capacitance increases, as it usually does in larger tubes. Power scaling may influence performance also at high power levels if the tube becomes too large physically for the cavities normally used (quarter wave long) and the circuit is forced to go to the lower efficiency three-quarter wave cavities. (This point is discussed in Reference 35.)

Thus, there is no concern about scaling the Doherty circuit to the 5 kW level where the L-64S tube is quite capable of performing. Sufficient circuit work has been performed to assure that circuits should not be a limiting area. Efficiency scaling is limited somewhat by the effect of the peak tube as a lossy capacitor when only the first tube is operating, at the lower input levels. Thus, a lower efficiency will almost certainly result when the tube's capacities are major elements in a cavity's L-C makeup. The scaling required to incorporate this efficiency loss has not been determined explicitly, but is still not a critical factor.

5.5.4.2 Other Amplifier Types

Use of other than gridded tubes at UHF and microwave tubes at S-band and higher introduce new scaling problems. However, the tubes themselves in these cases are the final amplifiers, and external circuitry is scalable to the extent discussed under RF scaling in Section 5.5.3. Thus, such scaling must consider the tube design; more accurately perhaps is that the tube designer will take care of most scaling problems in his design.

5.5.5 SUPPORTING AREAS

5.5.5.1 Monitor and Protective Circuits

This area is quite well developed for ground based equipment, and power limitations are based on the energy that the spark gap can absorb when a crowbar action is required. Voltage problems are the same as for the power conditioner as far as dc is concerned, and the requirements for scaling should have problems essentially the same as those outlined in Sections 5.5.1 and 5.5.2.

Some design changes are required when going to a higher power microwave type tube (a CFA may be of concern here) since multiple collector rings are generally predicted, and these may require multiple crowbar circuits. The scaling of protective circuits to higher powers is not considered a problem.

RF monitoring is also not considered a scaling problem. Basically, the monitoring measures the presence of breakdown effects, which are not scaled directly in power as was noted previously. The three detection techniques outlined in Section 3.4.1 can be used at all levels since the evidence of breakdown existence is largely independent of specific voltages in the transmission line and RF components.

5.5.5.2 Thermal Control Design Guidelines

Thermal control designs are scalable with a reasonable degree of confidence, using previously derived parametric data (Reference 1 and others). The radiating plate will vary with power level in both weight and size, but predictably. The only difficult area is that of operation approaching "burn out" where the temperature becomes too high and the fluid no longer returns to the evaporator surface.

The thermal system in that case is unstable and temperature rises rapidly, overheating the system. Thus, a higher power system would require that the heat pipe capacity and radiator plate area be increased proportionately.

5.5.5.3 Tube Qualification Testing

The study included consideration for higher power tubes and this is not a problem in terms of validity of scaling. The more significant problems are in availability of test facilities for the high power tubes, and in being certain that the tests include all pertinent environmental and operational factors.

5.6 MONITORING AND PROTECTIVE REQUIREMENTS IN HIGH POWER TRANSMITTER SYSTEMS

5.6.1 GENERAL REQUIREMENTS

The transmitter system is defined to have the following basic elements:

1. Power Conditioner
2. Low Power RF Amplifier Group
3. High-power Amplifier Stage
4. Microwave Circuit
5. Thermal Control
6. Control, Monitoring, and Protective (CM&P) Circuitry

These are interconnected as indicated by Figure 5.6-1. It is often difficult to separate the functions of control, monitoring, and protecting; thus, it is convenient to consider this as one subsystem. The CM&P subsystem design will be unique for each system, since mission requirements, as well as requirements of the various subsystems listed above, can influence its design. Functionally, the control portion of the CM&P subsystem can be considered as the "nervous system" of the transmitter which is associated with various command, sensor, regulative, and data output functions. These functions of the CM&P subsystem can be seen from an examination of the simplified diagram for a TWT high-power amplifier, Figure 5.6-2.

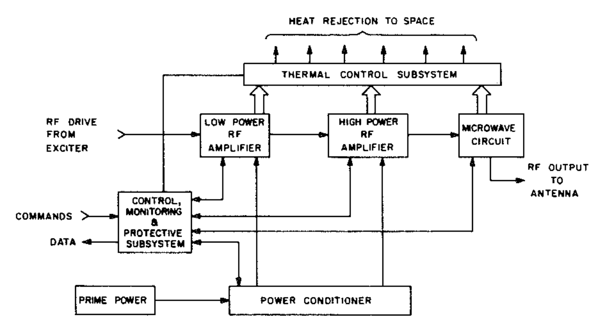

Figure 5.6-1. Elements of a High Power Transmitter System

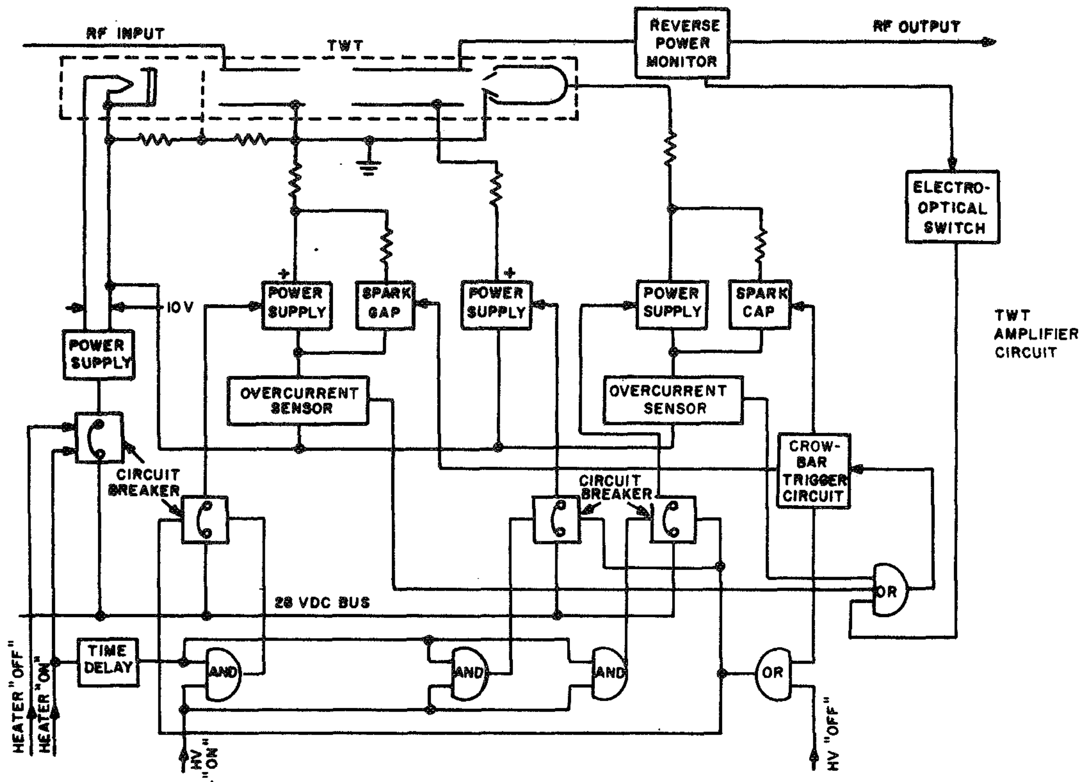

Figure 5. 6-2. Simplified TWT High Power Amplifier Schematic

Equipment and techniques for implementing the Command, Control Logic, and Data Readout functions are conventional and are not detailed here. Solid state rather than relay logic would almost certainly be preferred for the spacecraft transmitters. Advances are being made in these areas, so current literature or practicioners should be consulted further for the latest methods that can be used in a transmitter design. Sensors and power switching devices will be considered in the following sections after a consideration of the requirements of the various subsystems.

5. 6. 2 HIGH POWER AMPLIFIER PROTECTIVE REQUIREMENTS

The tube is practically the entire high-power amplifier where microwave tubes are used since the RF circuitry is a part of the tube. Three microwave tube types will be considered, based on three Lewis Research Center tube studies (References 21, 24, and 30) all of which require more complex power supply arrangements (numerous element voltages required) than present conventional tube designs. The monitoring and protective circuitry will be correspondingly more complex. Gridded tubes are incorporated into an amplifier cavity to form a high-power RF amplifier. Monitoring and protective requirements for this class of transmitter closely parallel those used in present ground station units of similar circuit design. The operational requirements of each amplifier type are briefly reviewed below.

5.6.2.1 Crossed-Field Amplifier Transmitter

The concept used differs from most circular format, re-entrant beam CFA's in two major respects: 1) a beam injection gun is used, and 2) depressed collector rings are employed to attain low noise and high efficiency in linear amplifier service. A cross-section of the CFA is shown in Figure 5.6-3 (from Reference 30). The inner connections of this tube with the power supply and other transmitter elements are indicated in Figure 5.6-4. This figure shows eleven collector voltages although this may vary in a final tube design. The turn-on sequence for the transmitter is:

1. Turn on gun heater (and vacuum pump if used).
2. Time delay of 3 to 5 minutes for heater warming.
3. Turn on sole.
4. Turn on cathode and collector supplies.
5. Turn on accelerator supply to start beam current.
6. Apply RF.

A reverse of the above sequence (no delays required) is used for normal turn off.

A tube arc would require a crowbar on the cathode/collector supplies to minimize internal tube damage due to dissipation of power supply energy in the tube. A typical value of tube arc dissipation allowed (for no damage) is of the order of 10 Joules. The crowbar trigger circuit would be activated from samples of current output of the power supplies. The other supplies do not need to be crowbarred since they are low capacity units. The accelerator power supply should be turned off simultaneously with crowbarring on a fault as an added precaution (this would tend to block current flow from the cathode).

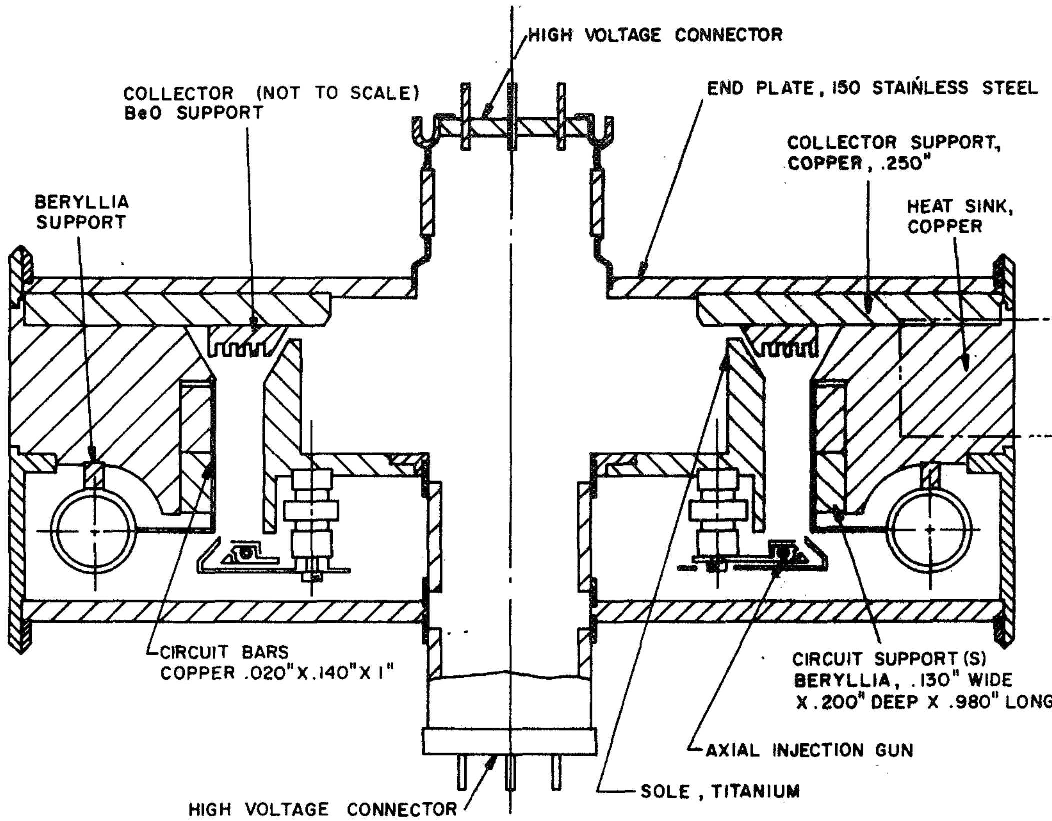

Figure 5.6-3. Cross-Section of CFA Amplifier Tube

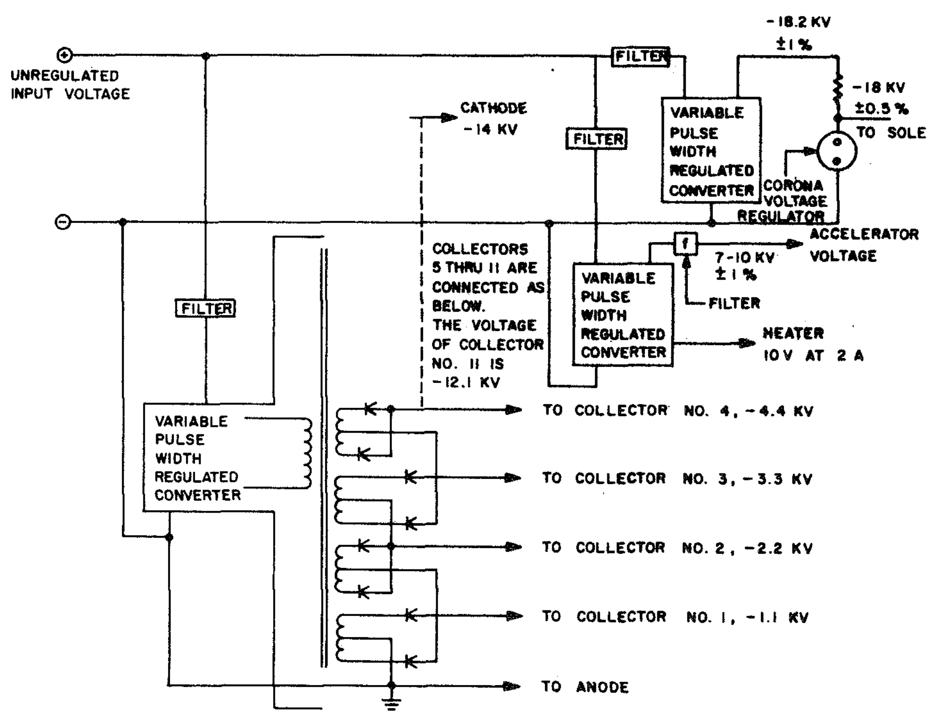

Figure 5.6-4. Power Supply for Crossed-Field Amplifier Tube

Arcs in the output RF circuitry would be suppressed by turning off RF drive to the CFA and/or turning off the accelerator supply. A similar procedure would be used for high VSWR conditions that may occur as a result of arcs or other conditions. An automatic means for controlling RF drive to the CFA should be provided.

5.6.2.2 Klystron Transmitter

A major improvement in klystron efficiency is expected with the multi-potential reflex collector illustrated in the klystron cross-section of Figure 5.6-5 (from Reference 24). Typical interconnections between klystron, power supplies, and other circuit elements

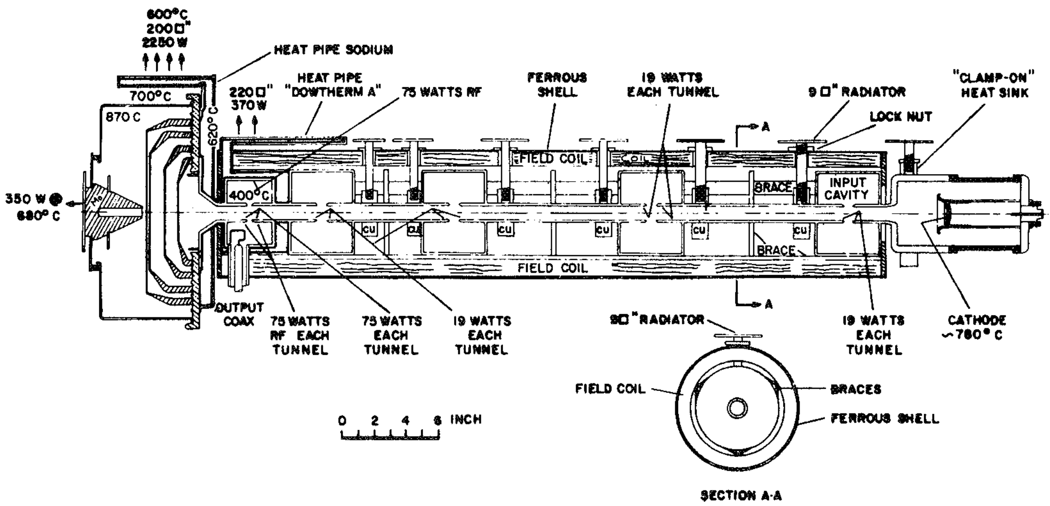

Figure 5.6-5. Layout Sketch of 850 MHz AM Klystron

are shown in Figure 5.6-6. Start-up and shutdown for ground test under normal conditions would utilize the following procedure:

1. The klystron is installed in the magnetic field coil and socket environment.
2. Apply and adjust magnetic field supplies, enabling the tube to approach the ambient temperature experienced during operation.
3. Apply ion pump supply voltage.
4. Apply heater voltage.
5. Apply and adjust beam and collector voltages. Both body current and ion pump current should be monitored to assure normal operation.

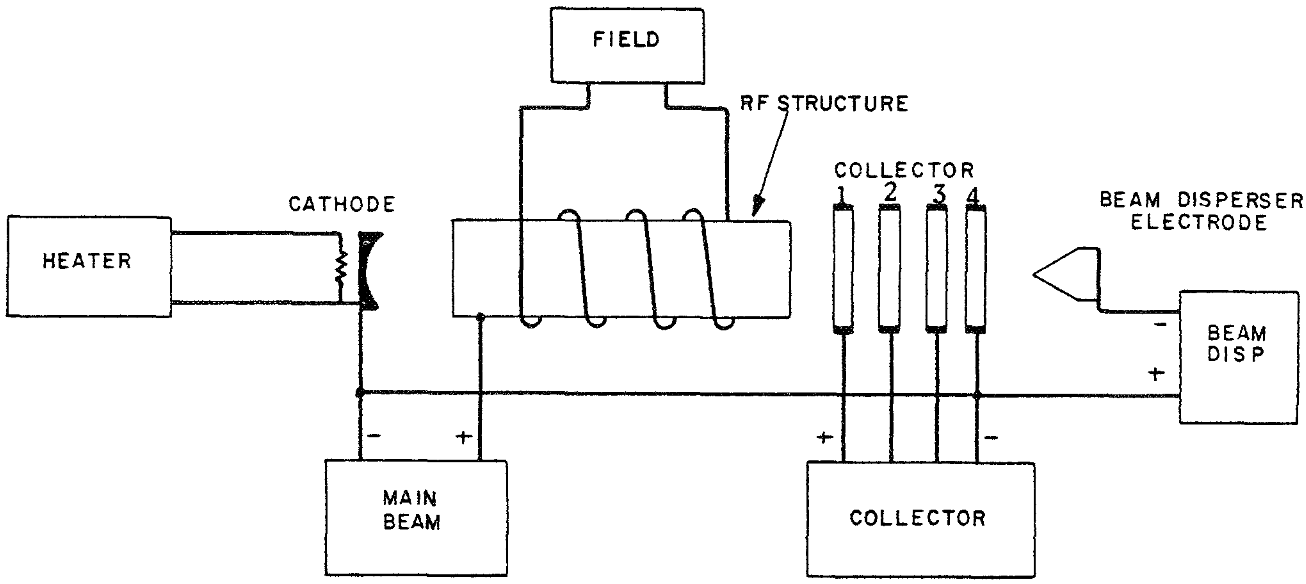

Figure 5.6-6. Schematic Diagram of Power Supplies Required for Operation of Magnetically-Focused Klystrons with Solenoid and Reflex Collector

6. Apply and adjust RF drive power; both drive and output powers should be monitored. RF drive should be applied simultaneously with magnet power in cases where collector depression is not employed and then the beam power should be applied. This avoids the high collector dissipation which would ordinarily take place at zero drive.

The shutdown procedure for the klystron is essentially the reverse of the startup procedure, with the exception that the beam voltage and RF drive can be removed simultaneously.

1. Remove beam voltage, collector voltages, and RF drive voltage.
2. Remove heater voltage.
3. Remove ion pump supply voltage.
4. Remove magnetic field coil supply voltages.

The Lewis Research Center klystron study proposed that two power supply sections be used. One would be a well-regulated supply that would supply electromagnet, heater, and beam voltages while the other would supply voltages for the collectors. The latter should be crow-barred under tube arc conditions and the beam supply turned off. RF arcs in the output section or waveguide would be extinguised by removal of RF drive to the klystron. Means of controlling drive should be provided as in the case of the CFA.

5.6.2.3 TWT Transmitter

The new TWT design (Reference 21) utilizes a multiple voltage jump resynchronization scheme in the slow wave structure region and a multiple-stage depressed collector. Both tube and associated power supply are illustrated in Figure 5.6-7. A typical turn-on and turn-off procedure is:

Turn on

1. Heater supply.
2. Anode supply.
3. Circuit supply
4. Collector supply
5. Solenoid supply (8 and 11 GHz only).
6. Five minutes after Step 1, turn on cathode supply.

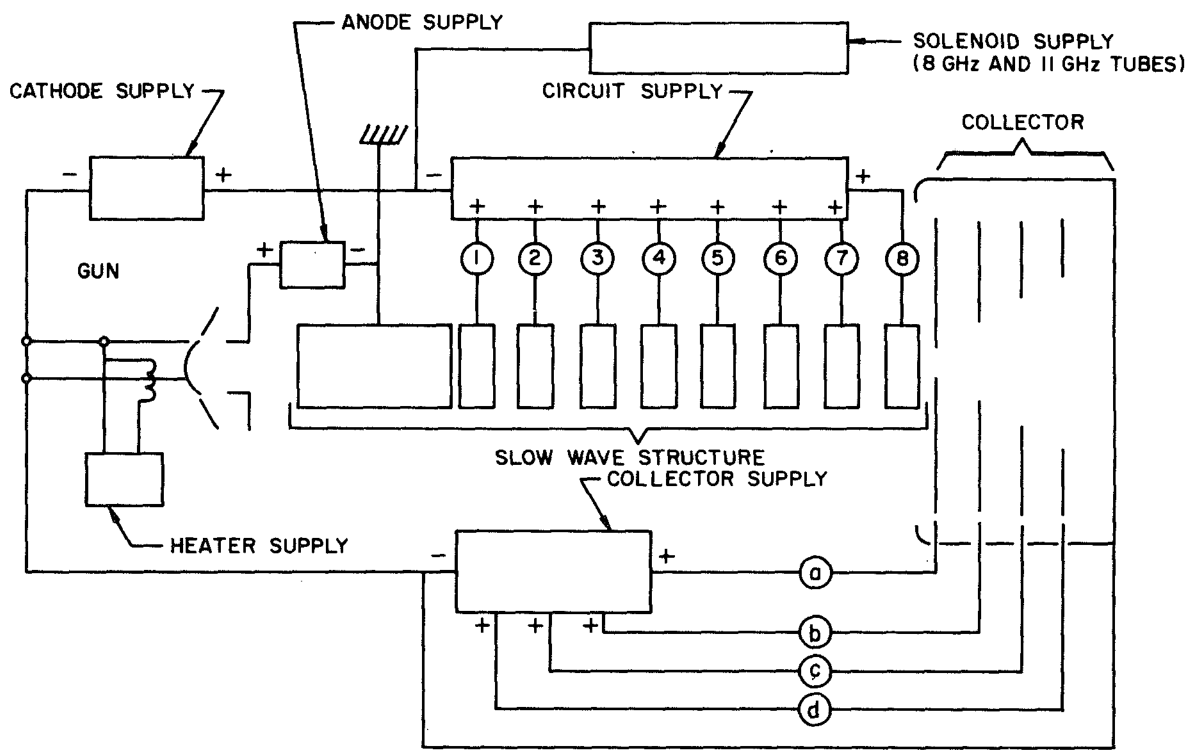

Figure 5.6-7. Power Supply Schematic Diagram for Multi-Voltage Jump Taper Tubes with Four-Stage Collector

Turn off

1. Turn off cathode supply
2. Ten msec after this, turn-off:
   a. Anode supply
   b. Circuit supply
   c. Collector supply
   d. Heater supply
   e. Solenoid supply (8 and 11 GHz only).

Some coupled cavity tubes tend to break into transient oscillations during the switching periods for the cathode supply voltage. An alternate procedure can be used in this case, which eliminates such transient oscillations. (See Reference 14). Comments relating to tube protection and drive control for the previous tube types generally apply to the TWT also.

5.6.2.4 Gridded-tube Transmitter

A possible space mission using gridded tubes is a UHF television satellite using the Doherty high efficiency linear amplifier for AM, or a Class C single tube amplifier for FM. These tubes will likely be used in a grounded-grid configuration. A typical simplified circuit for the Doherty is given in Figure 5.6-8. Turn-on sequence for the transmitter is:

1. Turn on heater and bias supplies.
2. Heater warm up time delay.
3. Apply plate voltage.
4. Apply screen voltage (if tetrode or pentrode).
5. Apply RF drive.

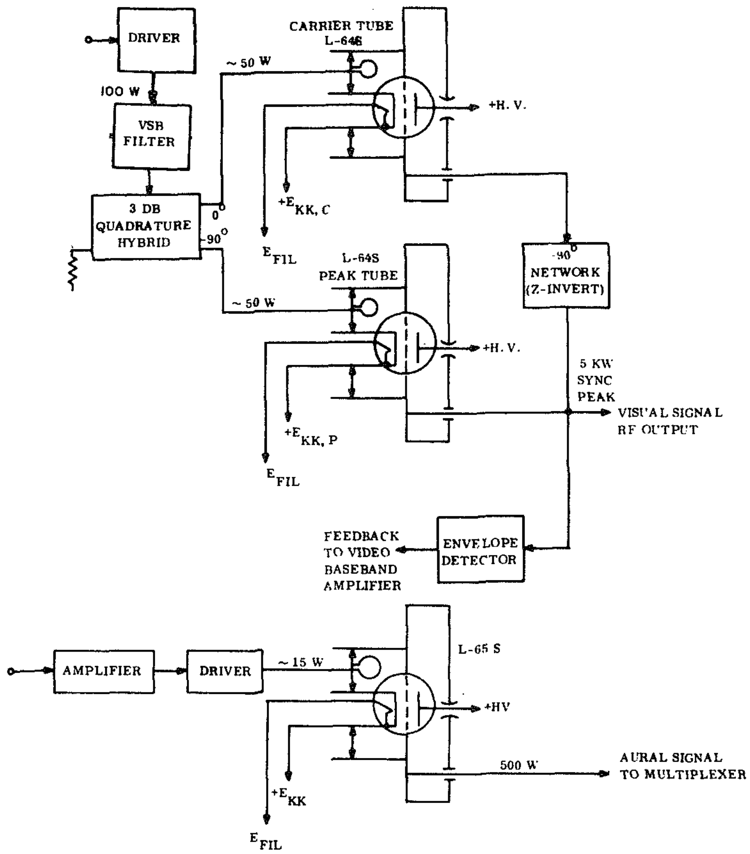

Figure 5. 6-8. Gridded Tubes Used in a Doherty Amplifier

A reverse sequence, without time delay, is used for transmitter turn-off. Protective requirements are:

1. Remove plate (and screen) voltage and RF drive if grid bias is lost or upon plate overcurrent.

2. Remove RF drive (and screen voltage) upon plate voltage RF load loss, or grid overcurrent.

3. Remove RF drive if output arc occurs.

The plate supply should be crowbarred with the occurence of a tube arc. Operation of the Doherty at reduced power can be obtained in the event of a failure of the peak amplifier stage. In this case, the carrier tube could be operated at one-fourth rated transmitter output. As in the case of the other transmitters, provision for RF drive control should be made.

5.6.3 POWER CONDITIONER SUBSYSTEM MONITORING AND PROTECTIVE REQUIREMENTS

Protection will be required in the event of a short or overcurrent in the output circuit of the power conditioner dc-to-dc inverter(s). It will be required to turn off the inverter by removing drive in the case of a pulse-width regulating system, or by opening the primary bus with a circuit breaker or relay. Similar action will have to be taken in the event of an internal switching transistor fault. A crowbarred power supply for high-power amplifier tubes should have a rapid disconnect of its input power bus to keep dissipation in power conditioner components to a tolerable level. Currents and voltages in the power conditioner may be monitored with sensors as described in Section 5.6.6.

5.6.4 MICROWAVE SUBSYSTEM MONITORING AND PROTECTIVE REQUIREMENTS

5.6.4.1 Data and Fault Sensing

Sensors are required for RF power level, operating temperatures, and RF breakdown. Gas pressure due to outgassing within or around the microwave components should also be monitored to anticipate breakdowns. Directional couplers are used to isolate forward and reflected RF wave components. VSWR changes from these measurements often indicate occurrence of RF breakdown between the location of the coupler and the RF output load.

The likelihood of ionizing breakdown occurring can be assessed from data derived from ion gauges placed adjacent to the RF component or perhaps even sampling pressure within the item. The occurrence of multipacting is evidenced by the presence of free electrons (and ions, where residual gas is present). Sampling holes, placed where incident electron paths are normal to the opening, allow a small sample of the multipactor electron flow to be collected on a biased electrode. (This was shown in Figure 3-36.) It may be possible in some cases to clean up multipacting without destroying the component by programming a variable duty cycle type of operation during the clean up operation. Occurence of multipacting would cause the transmitter to go to a pulse mode of operation (or signal the need for such). Initial operation would be at a small duty factor to prevent excessive buildup of gas-augmented multipactor discharge (see Reference 11). The duty cycle can be increased as the multipacting surfaces are cleaned up until multipacting ceases or its level becomes tolerable. Normal operation would be achieved at this point.

5.6.5 THERMAL CONTROL SUBSYSTEM MONITORING AND PROTECTIVE REQUIREMENTS

Operation of heat pipes, shutters, and other components of the Thermal Control Subsystem may be monitored for diagnostic and protective purposes. Heat pipes may be subjected to burnout due to excessive heat input or degradation of characteristics with life. Monitor of evaporator surface temperature will probably be sufficient. The heat source should be turned off in the event of excess temperature and then slowly brought back toward normal power level (if such is possible). Normal operating temperatures can be monitored with thermistors, thermal resistors, or thermocouples, the latter being the most commonly used.

5.6.6 SENSORS

5.6.6.1 Dc Power

Currents and voltages are usually monitored separately as a measure of circuit power flow. Current monitoring is accomplished with "dc-dc" transformers (a saturable core device) or metering resistors. Either unit gives a readout in voltage. The former approach is usually preferred for two reasons, although it is the more complex method: the usual 5-volt high level telemetry signal would result in excessive circuit loss, and "hard-wiring" of the telemetry system to the monitored point results in an increased likelihood of inducing ground loop voltages in the telemetry system. Voltages are read with a voltage divider or multiplier resistor and dc-dc transformer. The same preference for the multiplier exists in this case. These voltage samples of system currents and voltages can also be used as inputs to the control system logic if suitable interface equipment is incorporated.

5.6.6.2 Microwave

Directional couplers are used to sample forward and reflected wave RF levels in waveguide and coaxial transmission lines. A typical loop-type of coupler that will find use at UHF and possibly S-band is shown in Figure 5.6-9; the multiple-coupling aperture waveguide coupler is in common use at higher frequencies.

The RF sample outputs of these couplers are converted to analog outputs, as in Figure 5.6-10, or by a microwave power meter if high accuracy (1 percent) is required. A typical approach that would be adapted to spacecraft use is a thermistor head with associated electronics which gives a dc output proportional to RF power level with a convenient 0-10 mw or 0-100 mw RF sample level range.

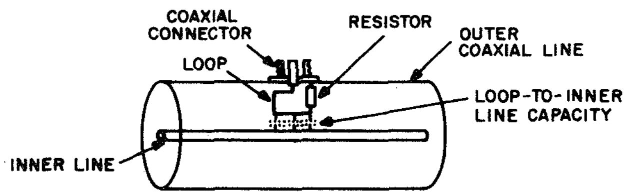

Figure 5.6-9. Loop-Type RF Power Monitoring Directional Coupler

5.6.6.3 Gas Pressure

Measuring gas pressure in the high vacuum environment within the spacecraft or within spacecraft components may be very useful. The device frequently used for this purpose is the triode ionization gauge. Typically, this gauge contains a hot tungsten filament (O volt potential) as a source of electrons, a grid at 150 volt, and a collector at -20 volts. The pressure in a system (as measured by an ionization gauge) can be expressed as

$$P = \frac{1}{S} \quad \frac{i_c}{i_g}$$

where S is the sensitivity of the gauge for the particular gas, i_c is the collector or positive ion current, and i_g is the grid or electron current. For ionization gauges, S ≅13 for nitrogen. Construction of the

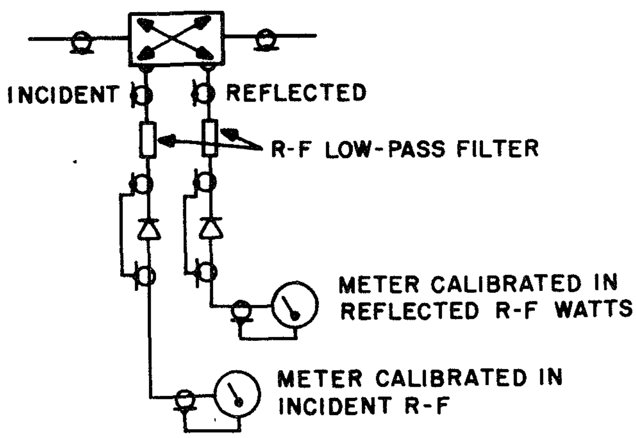

Figure 5.6-10. Metering Current Low-Pass Filters Used With Directional Couplers For RF Monitoring Power

gauge and the basic measuring circuit are illustrated in Figure 5.6-11. Another possibly useful gauge is the cold cathode ionization gauge (Penning); the construction of such a gauge is shown in Figure 5.6-12.

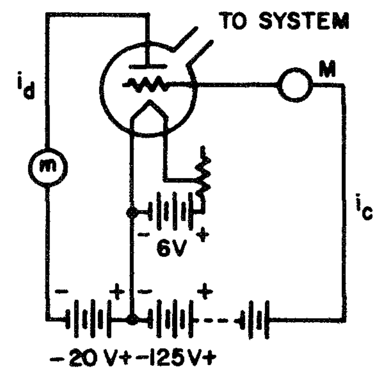

Figure 5.6-11. Triode Ionization Gauge

5.6.6.4 RF Breakdown

RF arcs in the microwave system can be detected with photo-diodes which act as light sensitive variable RF resistors with very fast (100 nsec) responses. Light from the arc will trigger the associated electronics unit to turn off the RF in one of the low level stages of the transmitter, such as was shown in Figure 3-36.

The existence of multipacting breakdown is detected by measuring free electron density at selected points along the microwave subsubsystem. A typical detector arrangement was shown in Figure 3-36. Holes are placed in the walls of RF components between which the multipacting electrons flow. Electrons passing through these holes are collected on a biased electrode, and the resulting current is measured in a dc-dc transformer arrangement or as a voltage drop across a metering resistor.

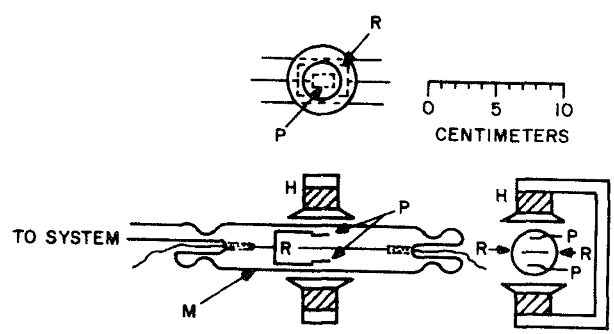

Figure 5.6-12. Cold-Cathod Ionization Gauge (Penning)

5.6.7 POWER SWITCHING AND PROECTIVE DEVICES

5.6.7.1 Prime Power

Adaptation of aircraft circuit breakers and relays is a likely approach to the power switching problem. Completely solid-state power switching systems have been proposed for aircraft power systems (Reference 32). Work is continuing in this area but is not generally available since it is associated with classified programs. However, it is not likely to be used in high power circuits due to the high voltage drop of 0.5 to 1.0 volt through the semiconductor switch plus the high drive requirement (10 percent of output current) for transistors which are used as dc circuit switches. Of course, semiconductor switches will be used in low power applications such as logic circuits.

5.6.7.2 Crowbarring

Triggered gas tubes and spark gaps are used as current shunts across power supply outputs for protection of high power vacuum tubes from internal arc damage. A basic crowbar circuit was shown in Figure 3-35. An arc in the high power transmitter tube results in greatly increased current drain in the power supply output. This current increase is sensed and used to trigger the crowbar device. The triggered crowbar device presents a much lower impedance across the power supply than the supply's output impedance, so most of the stored energy in the power supply output filter will be diverted through the spark gap. Normally, activation of the crowbar is in a microsecond or less, and results in arc energy dissipation in the high power tube of less than 10 Joules. Arcs of this energy level may actually "clean up" the tube in most cases, rather than causing damage, where the tube arc is due to whiskering on a tube electrode.

Both hydrogen thyratrons and triggered spark gaps are applicable in this service. The thyratron requires less trigger energy but is more complex. The triggered gap device lends itself well to multiple gap arrangements which could simultaneously discharge the multiple power supplies used in the new multiple-collector tube designs in the event of an arc in any part of the tube. Some available ceramic hydrogen thyratrons and spark gaps may meet or nearly meet spacecraft requirements.

5.6.7.3 RF Switching

Low and medium RF levels, such as in the drive circuits, can be switched conveniently with semiconductor or ferrite switching devices. Probably the best approach to high power switching, however, is to use electromechanically driven waveguide or coaxial switches. The former uses moving vanes or rotors to direct the energy flow while coaxial devices use a movable center conductor contact to accomplish the switching action. Devices for accomplishing these tasks are well developed for ground and/or airborne applications at the power levels under consideration in the study, but some may require adaptation for the space environment.

5.7 THERMAL CONTROL DESIGN GUIDELINES

5.7.1 APPROACHES

The choice of a thermal control technique will be restricted to passive radiators and heat pipe radiators. Active heat transfer loops, using pumps to move a fluid past the heat producing elements and through the radiators, are not considered. Note, however, that active loops and heat pipe systems have similar characteristics and requirements.

5.7.1.1 Radiator Requirements

Radiators are required to remove heat from any heat dissipating component in a long term spacecraft. Techniques are considered in two categories: passive radiators and heat pipe radiators. Where a relatively small area of a component is attached to a passive radiator, heat must be conducted along the radiator plate and radiated from its surface. The surface temperature decreases with increasing distance from the source, and less heat is radiated than if the entire radiator were isothermal. A heat pipe in the surface of the radiating plate, however, is a nearly constant temperature device throughout its length, and tends to keep the plate temperature almost constant, thereby increasing its radiating effectiveness.

5.7.2 COMPONENT INTERFACES

5.7.2.1 Solid State Devices

Solid state devices, such as transistors and diodes, are small concentrated heat sources. Several of these devices used in a circuit would require care in spacing to avoid overheating. The minimum spacing between heat sources as a function of power dissipation is shown in Figure 3-37. The curves shown represent two size extremes, offering advantages of minimum area or minimum weight for a $70^{o}C$ source temperature.

The radiator thickness and component spacing were juggled until the lightest radiator was defined for each power. The minimize size radiator was for an isothermal radiator, which can only be obtained at the expense of increased weight.

The spacing requirement sometimes proves to be impractical, and the alternative solution is to use heat pipes, which allow complete freedom in packaging. A possible arrangement where the heat pipes are integral with the transistors or diode support is also shown in Figure 3-37. The only limitation on the configuration is the evaporator surface area, but this can easily be allowed for in the design and presents no problems unless there is a drastic increase in the power levels in solid state devices.

5.7.2.2 Transformer and Chokes

Heat is generated in the windings and in the core of a transformer or choke. Sufficient conductance must be provided to transport the heat to a radiator without exceeding the temperature limits of the component.

A temperature of 70°C must not be exceeded at the mechanical interface to prevent damage to the windings. Passive temperature control of this type of component can be accomplished by spacing the transormer or choke from other components, as with solid state devices, or heat pipes can be used to allow compact packaging.

5.7.2.3 Vacuum Tubes

Vacuum tubes to be used in a high power transmitter in a spacecraft require special consideration. Detailed treatment of temperature control of tubes that are suitable for space applications is given in References 21, 22, 23, 24, 28, and 30; see Figure 3-39 for an example.

5.7.2.4 Waveguides

The primary thermal considerations for a waveguide are the thickness of the wall required to keep temperature differentials to an acceptable level and the location of the heat sink. The two are interrelated to some extent since positioning of the sink will affect the temperature distribution.

Temperature limits are based on thermal distortion, the limit being taken as 0.6 percent dimension change. Aluminum has a coefficient of thermal expansion of 2.36×10^{-5} per $^{\circ}$C.

Thus, the average temperature can rise 254°C above the reference temperature before the expansion exceeds 0.6 percent. Distortions caused by differences in heating between waveguides and other elements, such as filters, hybrids, etc., are not accounted for in this limit and should be evaluated to establish a more realistic limit.

The heat distribution in the waveguide is assumed to be evenly distributed, and the waveguide is assumed to be of constant thickness. The temperature at steady state can be determined from the Poisson Equation which, with the appropriate constants, yields a maximum at the farthest point from the heat sink:

$$T_{max} - T_0 = \frac{L^2 Q}{8KAt}$$

$\frac{Q}{At}$ = W/in.^{3} absorbed

K = thermal conductivity

L = total length of thermal path

The results of this equation for an aluminum waveguide are plotted on Figure 5.7-1.

Waveguides can be spaced on the radiator surface to prevent overheating, as is shown for the power supply components; or they can be grouped, and heat pipes can be used if required to prevent excessive temperatures. Typical hot spot temperatures of the various waveguide components on a 100°C sink are listed in Table 5.7-1.

5.7.2.5 Coaxial Transmission Lines

The primary problem encountered with coaxial lines is cooling of the inner conductor. The outer element can be treated, thermally, in the same manner as a waveguide.

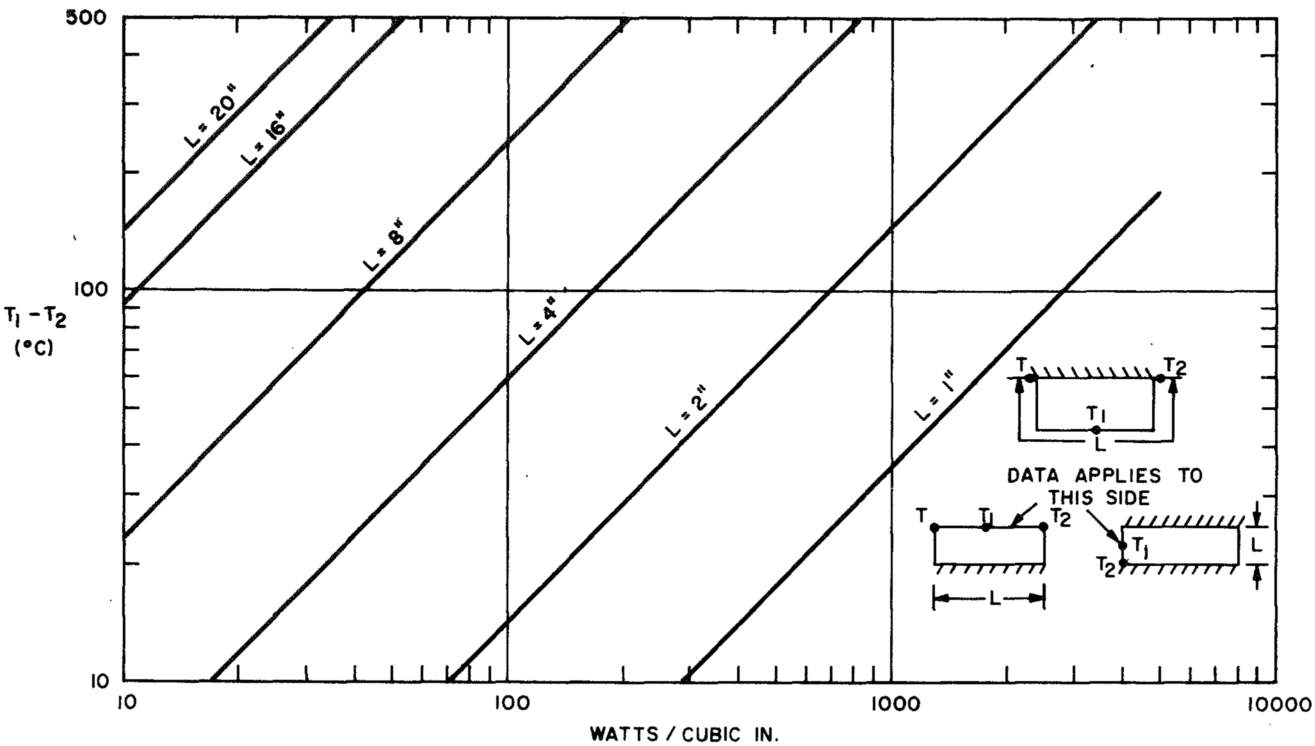

Figure 5.7-1. Temperature Rise in an Aluminum Waveguide

Table 5.7-1. Waveguide Component Thermal Characteristics

Component	Total Loss (watts)	Loss per Foot Length (watts)	Hot Spot* Temperature (°C)	Comments
WR 340 Waveguide	---	12.2	103	
WR 340 Sidewall Hybrid	50	48	105	
WR 340 Multiplexing Filter	110	101	123	
WR 340 Multiplexer Load	25	25	106	Temperature at waveguide surface
WR 1150 (half-height) Waveguide	---	5	101.3	
WR 1150 Aural Pass Cavity	55	13.5	103.5	
*100°C heat sink attached to one broad wall; hot spot is center of opposite broad wall.				

Heat generated in the inner conductor must be radiated, conducted, or convected to or through the outer conductor so that is can be radiated to space. A possible arrangement using the inner conductor supports to remove heat from the inner conductor is shown in Figure 3-40. The temperature rise using conduction cooling can be determined from Figure 5.7-1 by applying suitable conversions to coaxial lines.

An alternative arrangement where the heat generated in the inner conductor of the coaxial line is too high for conduction cooling is also shown in Figure 3-40, where the inside surface of the hollow center conductor forms a heat pipe evaporator. The support is also hollow and lined with a dielectric wick; the fluid used is also dielectric. The heat flow capacity of the heat pipe evaporator in this configuration is far higher than will normally be generated by the conductor. The heat pipe center conductor, after penetrating the outer conductor through the support, attaches to a suitable radiating plate. Some of the likely hot spot temperatures for the RF coaxial components considered in this study are listed in Table 5.7-2.

Table 5.7-2. Coaxial Component Thermal Characteristics

Component	Total Loss (watts)	Loss per Foot Length (watts)	Hot Spot Temperature 100° Sink (°C)	Comments
7/8-inch Coaxial Line (S-band)		19.5	173	Copper inner conductor
1-5/8-inch Coaxial Line (S-band)	---			
Radiation cooling		8*	140	0.6 surface emissivity
Stub supported		8*	147	One stub per foot; 0.08 wall Al inner conductor
3-1/8-inch Coaxial Line (UHF)	---			
Radiation cooling		15.1*	140	0.6 surface emissivity
Stub supported		15.1*	128	One stub/foot; 0.08-inch wall Al inner conductor
3-1/8-inch Slab Line Hybrid (UHF) Conductive cooling	160**	-----	210	Solid Al slab; coax stub near each connector
3-1/8-inch Aural Notch Cavity (UHF)	100	50***	232	Stub cooled at junction with coax line
3-1/8-inch Harmonic Filter (UHF) Conductive cooling	240	-----	325	Coax stub near either end of filter
3-1/8-inch Coaxial Load				
Radiation cooling	200	200	400	0.6 emissivity
Conduction cooling	600	600	475	Solid B_eO substrate; coax stub near either end of load resistor
Heat Pipe cooling	600	600	125	Dielectric heat pipe (requires development)

*70 percent of loss is in inner conductor
**91 percent of loss is in slab lines
***See Figure for dimensions of cavity; 90 percent of total loss assumed to be concentrated in center conductor.

5.7.2.6 Microwave Loads

The microwave output power that is not radiated by an antenna must be dissipated in a dummy load. The load configuration depends on the type of transmission lines used -- coaxial or waveguide.

5.7.2.6.1 Coaxial Load

A coaxial load is more difficult to cool than a waveguide type because the heat is generated on an internal surface. Load configurations are shown in Figure 3-41. A coolant can be used to remove heat from the inside surface, but it must be a dielectric fluid, and the cylinder supporting the resistive film must be a nonconductor, probably a ceramic. Cooling of the load can be accomplished by using the cooling surface as a heat pipe evaporator or by direct radiation. The heat pipe would be difficult to use because the walls, wick, and fluid must be dielectric, although thermal efficiency is better. Requirements for direct radiation are also shown in Figure 3-41.

5.7.2.6.2 Waveguide Load

A typical waveguide load is also shown in Figure 3-41. Heat is generated along the surfaces of the wedge and is removed by conduction, radiation, or a heat pipe. The capability of direct radiation cooling from the surface of the load is shown in Figure 5.7-2. Fins attached to the load permit the capacity figures to be multiplied by approximately three or more.

5.7.2.7 Other Microwave Components

Several components have not been included in the above discussion. Many of these are close to the configurations discussed, and the discussion is directly applicable, while others need specific consideration. Components should be investigated in more detail as more specific designs are generated. Furthermore, the system as a whole must be analyzed to determine the overall interaction of the components in a flight configuration.

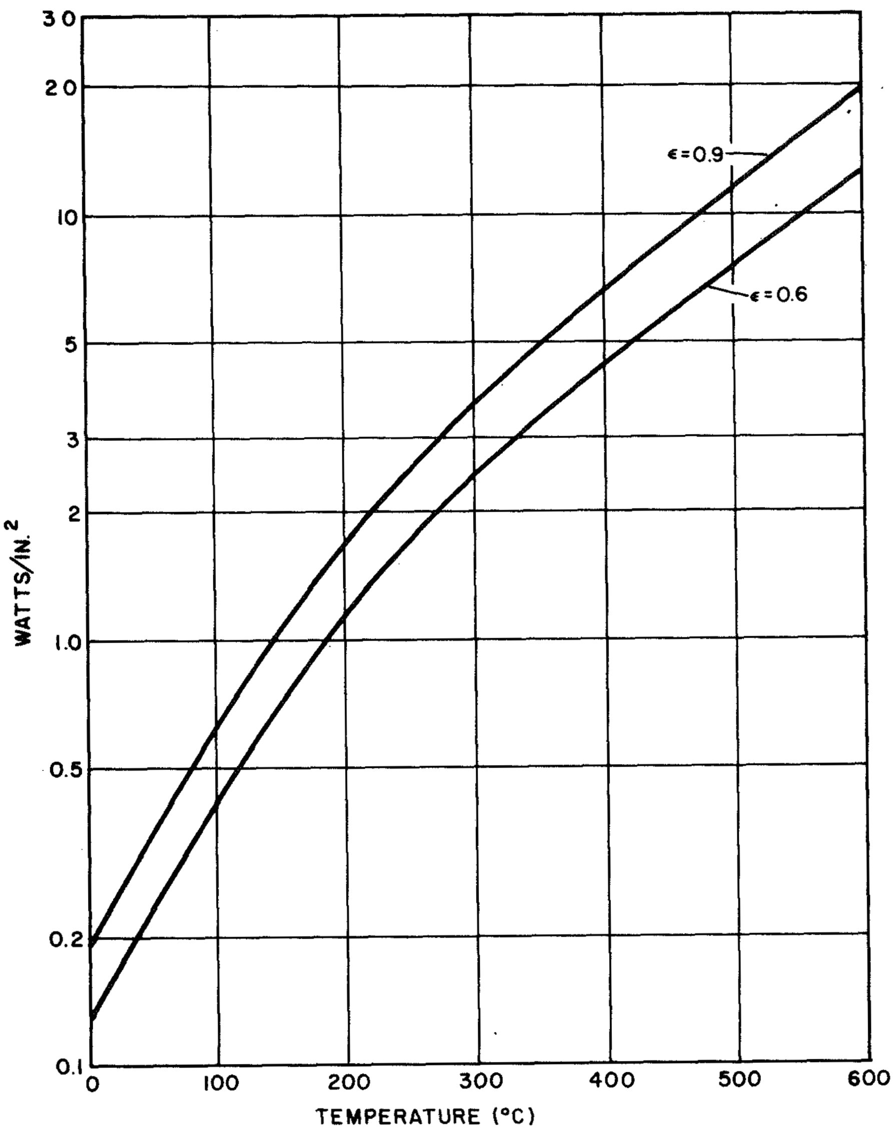

Figure 5.7-2. Waveguide Load Direct Radiation Cooling

5.8 TUBE QUALIFICATION TESTING

5.8.1 REQUIREMENTS FOR SPACE SYSTEMS

The requirements for qualification testing of tubes for space applications must be based on the environmental factors to be considered. Overall test plans must include the environmental, mechanical, and electrical effects on the tube operation, and the differences between space and ground based equipment. A very large number of parameters must be considered in determining the suitability of a tube, including severe mechanical requirements (from launch), as well as a continuing operation over a long time period (2 to 5 years continuous) in a severe high vacuum environment.

Some of the mechanical and environmental factors for a space transmitter are listed in Section 5.1. Tube testing will include: (1) mechanical tests simulating the launch and maneuver operations and (2) electrical operation under conditions simulating ground operation and orbit operation.

Present specifications vary widely for tubes and will vary for different types of tubes in space applications. Thus, each tube type is expected to have a unique set of test specifications, but all will encounter the same basic mechanical/environmental specification Electrical differences will lie largely in the requirements imposed as a result of the space vacuum or the partial-vacuum when outgassing or sublimation of materials is significant. The latter may make additional tests necessary to determine environment monitoring required to minimize electrical breakdowns.

Space qualification has been performed on a number of tubes, although mostly low power tubes. These form a general basis for developing further test plan formats. In addition, some consideration is given to sample lots to use in life tests.

5.8.2 TUBE TESTING STATE OF THE ART

Widely varying test standards have been used in tube qualification testing. For example, each military tube type has its own set of specifications, usually a subset of MIL-E-1. A few typical ones are as follow:

	Type	
Gridded tubes:	6166A	MIL-E-1/1543
	7650	MIL-E-1/1552
	8172	MIL-E-1/302K
Klystrons:	6994	MIL-E-1/1088A
	8493	MIL-E-1/1112D
TWT:	8128	MIL-E-1/1605

These documents are supplemented by numerous test reports on the testing of specific tubes for life and environmental qualification. These test reports normally include the parameters tested for the application of interest. For example:

Type	Application	Report Number
VA 531A Klystron	Phoenix	301.60.00.00-R4-01
BLM 102 Magnetron	CF (?)	301.60.00.50-A1-07
EE59Y Gridded (Mach.)	QRC-160-8	301.60.30.00-R2-01

The tests in these cases are listed with resulting data and conclusions.

Specific tube documents often reference general testing documents which form the basis for the specific test procedures. The following are typical documents relating to tube testing:

MIL-E-1F: Covers the general requirements and ratings for electron tubes. There are a large number of sub-specifications covering the various tubes used by the military.

MIL-STD-202C: Establishes uniform methods for testing electronic and electrical component parts. The testing is generally applicable to tubes, but does not detail tube specifications.

MIL-STD-1311: Covers test methods for electronic tubes; it has six test categories, with three types of tests for each.

Some of the details on these documents are in Reference 17.

5.8.3 SPACE QUALIFIED TUBES AND TESTING

Relatively little information has been available on space qualification testing methods, and only smaller tubes have been so qualified. For example, the Hughes 394H TWT operates to 20 watts, while the Watkins-Johnson WJ-395-2 is rated at 100 watts (the highest at the present time). Most such tubes are in or near S-band, although the WJ-350 is a 35-watt X-band tube. Some aspects of tube qualification have been discussed with various companies to ascertain their approaches and opinions.

5.8.3.1 Watkins-Johnson

Watkins-Johnson has a number of space-qualified tubes, although specific techniques used in the space qualification were not available in the information channels investigated. Life testing has been considered, and costs for 200-and 600-watt TWT's are noted as $234K and $256K respectively, plus $20K for two years of operation.

5.8.3.2 Mark 12 Re-entry Nose Cone

This classified program could not disclose any details of the space qualification program. However, tests included a 3-kv Hipot at a pressure of 10^{-1} Torr., other tests relate to environment (usually non-operating conditions).

5.8.3.3 Hughes

Three documents by Hughes' Electron Dynamics Division provided inputs on practical space qualification testing for two of their traveling wave tubes. The following documents were covered:

241H Acceptance Testing
1164 Acceptance Testing
1164 Qualification Testing

These tubes are both low power TWT's, with dc inputs of the order of 60 watts. The procedures for the Accpetance Testing generally took the following sequence:

- Pre-Environmental Functional Tests
  - Visual and Mechanical
  - Power Commands (operation with "pulser")
  - Polarity Protection
  - Power In/Out
  - Input VSWR Test
- Random Vibration
- Limited Functional Tests
- Thermal Vacuum
- Burn-In
- Final Functional Test

A diagram of the test setup for each test and a list of required test equipment are included. The descriptions of the tests indicate applied power, time sequence, and expected results.

The Qualification Test included the Acceptance Test to be performed before considering space qualification testing. These tests are more extensive than those above and include the following:

- Acceptance Tests
- Electromagnetic Compatibility
- Functional Test
- Acceleration Test
- Functional Test (repeated after each major step in test program)
- Shock Test

Functional Test
Random Vibration Test
Functional Test
Sinusoidal Vibration Test
Functional Test
Thermal Vacuum Test
Final Functional Test

Specifications are provided for each of these tests. For example, most of the vibration and shock specifications cover the three axes in both directions and have varying amplitudes versus frequencies in the case of vibration. Figure 5.8-1 indicates a typical test block diagram, and Table 5.8-1 lists corresponding test equipment. The specifications also include waveforms or timing of sequences in chart form where data were sufficiently different.

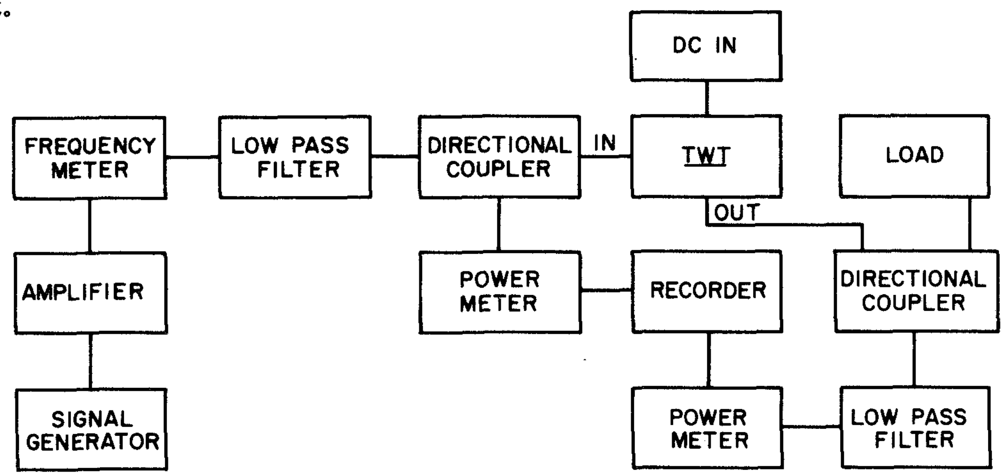

Figure 5.8-1. Block Diagram for RF Tests on TWT

Table 5.8-1. Typical Test Equipment List for RF Tests

Signal Generator	:	HP 616B
Amplifier	:	HP 491A
Frequency Meter	:	FXR N401A
Low Pass Filter (2)	:	Microlab LA-40N
Directional Coupler (2)	:	Narda 3043-10
Power Meter (2)	:	HP 431B
Recorder	:	Moseley 135
Load	:	Microlab TD-5MN

A paper published by Hughes (Reference 36) emphasized life testing, providing data on five tubes used in space programs. An appendix listed the failure modes for TWT's, although no rates were given because tubes passing the infant-mortality stage had too few failures to provide any reasonable data. One item of interest was the potting of the high voltage terminals with flexible polyurethane containing aluminum powder for the required thermal conductivity. Other information included the following:

Most prevalent cause of failures: heater open or short

Use proven materials, processes, and techniques with good mechanical design.

Long life cathodes desirable: used oxide type at 700^{o} to 750^{o}; life is 10^{5} hours with 0.1 amp/cm^{2}.

Pre-age tubes for 100 to 200 hours, bake-out at $500^{o}C$ with helix raised to $1000^{o}C$; follow with 200 to 2000 hours aging.

Total life tests covered 761,000 tube hours using 41 samples, total involving five tube types; no failures.

No specific testing procedures were included.

A pertinent report, Spacetube Life Tests and Spacecraft Data, indicated the results of life testing 62 tubes for a total of 1,571,000 tube hours, plus 63 tubes for a total of 314,000 hours of actual service. The Chi-Square test was used, and the estimated failure time (MTBF) was 820,000 hours with a confidence factor of 90 percent and 2,058,000 hours with a 60 percent confidence level. The only faults encountered in all the testing were due to other than tube performance factors. The test procedures included a 4-1/2 year shelf life check, which indicated no deterioration. For redundant systems in space, the redundant element was switched on at 3-month intervals to check its status.

5.8.3.4 Eimac

Eimac provided data on TWT acceptance tests for two tube types and design requirements for two others. Total testing hours reported were 250,000. The testing tube-hours were provided to establish confidence limits for a 40,000 hour MTBF. (This is about 1/3 the

MTBF assumed to be desirable for a 99 percent 2-year life with a redundant tube, and more than an order of magnitude less than in the Hughes report mentioned above.) Testing procedures were listed in the following categories:

1. Marking and Mechanical (Inspection)
2. Nominal Performance - Acceptance Tests Specifications
3. Environmental Acceptance Testing
4. Final Performance (Repeat "Nominal")

The items included were:

1. Nominal Acceptance Test Specifications
    a. Prime power
    b. Telemetry outputs
    c. Power output
    d. Stability
    e. Gain
    f. Spurious signals
    g. Reflected ripple
    h. Noise figure
    i. Input VSWR
    j. Telemetry output impedance
    k. Warmup time
    l. Phase linearity
    m. AM-PM conversion

n. Converter control

o. "On" indication

The "Environmental Acceptance Tests" added the following:

1. Vibration (non-operating)
2. Post-vibration electrical tests
3. Low T^{o} turn-on (-40°C to +25°C)
4. Vacuum tests to 10^{-5} Torr
5. Vacuum (non-operating) to 10^{-10} Torr
6. Stabilization (recheck operation).

A second report by Eimac covered a 50-watt S-Band TWT (X1249/X1250). Tests on these tubes (as of 24 May 1967) included temperatures from -30° to +100°C; vibration at 20 G's in the 20-2000 Hz range; and shock at 200 G's for 1 $\pm$0.5 microseconds, with five shocks in each of six directions.

5.8.3.5 Jet Propulsion Laboratory

JPL has an extensive life testing program. Tubes are first tested in a "qualification" program, which involves vibration, shock and thermal/vacuum testing, and using specifications devised specifically for spacecraft tubes. The status of life testing was indicated (verbally) as follows for typical tubes:

1. Gridded Tube:
   Siemens RH7C 10 watt: 8000-hour life
2. CFA
   20 Watt: 3000-hour life

3. Klystron

Eimac 20 to 100 watt:	Testing about to start

4. TWT's

Hughes 10 watt:	At 35,000 hours and still going
Watkins-Johnson 20 watt:	At 10,000 hrs. and going
W-J 100 watts:	About to start

All tubes were S-band tubes. Some of the 20-watt TWT's are being tested in a vacuum, and some of the 100-watt tubes will also be in vacuum.

5.8.3.6 Others

Other space qualification of tubes has been accomplished elsewhere, although specific data was not obtained. The following are two additional sources for future consideration:

BTL - Involved a 5-watt C-Band TWT. Included a cathode life test and life test in equipment (50,000 hours).

RCA - S-band TWT for Relay Project; no data obtained.

5.8.4 TEST PLANS REQUIRED FOR SPACE-QUALIFIED TUBES

5.8.4.1 Present Status and Opinions

A general evaluation of tube testing was discussed with several tube manufacturers and knowledgeable personnel. Dr. H.G. Kosmahl of the NASA Lewis Research Center indicated that the most important aspect of space qualification is life testing, and life testing is primarily concerned with cathode life. Cathodes have finite lives, depending on type, temperature, and the removal of impurities by getters or the equivalent within the tubes. Published information has indicated little of problems in meeting other environmental conditions to be encountered, although the potting of high voltage terminals by Hughes suggests that problems may be encountered (and will, without proper precautions).

However, plans should incorporate the requirements for the environmental conditions and the general requirements covering vibration, shock, temperature, pressure, radiation, acoustics, and accelerations that will be encountered during the entire mission. The life testing will require the major amount of attention to ascertain the testing that must be performed under non-earth conditions to provide reliability data for space qualification.

5.8.4.2 Acceptance Testing

Acceptance testing is considered a preliminary test which should be included in the program for space tubes. A list of items and suggested specifications generally follow that indicated in the previous section; additional details are in Reference 17.

5.8.4.3 Space Qualification Testing

The problem, as above becomes one of adapting a test program to the program requirements and to the tube characteristics. The qualification testing is intended to determine the ability of the tube to survive all the rigors of application to a space high power transmitter, except extended life tests. Some of the parameters, which include repeats of parts of the acceptance testing, should be as listed. Tests can generally be subdivided into three categories: (1) ground checkout, (2) launch and manuever (non-operating), and (3) orbital operation.

5.8.4.3.1 Ground Testing (prelaunch)

Functional Testing

This is essentially a repeat of the acceptance testing except that operation sequencing to be used in space is implied; i.e., operation is checked for typical performance as a TV amplifier, including start up procedures, temporary fault removals with the shutdown and start up again procedures, and terminus of operation for eclipse shutdown or substitution of a redundant unit.

This procedure is especially of concern with an AM transmitter where "carrier control" will effectively reduce the output power during the high average power demands of dark TV pictures. Thus, the testing should include actual TV signals (or simulated to represent worst-case waveforms) as well as discrete measurements of amplitude and phase variations over the TV band. Tests programs should be based on the following (at room ambient conditions):

1. Functional Tests

   a. Protective circuit functioning - check with tube cold and hot, RF, and dc protection

   b. Telemetry sensors - output under normal and abnormal operating conditions

   c. Harmonic and other spurious output levels

   d. EMC under TV modulation conditions

   e. Insertion losses, circuit losses, and others as appropriate in circuit to be used in space

   f. 200-hour aging test to identify drift tendencies, for near-future operation.

A shelf life test should be included as a part of the life test to be considered to verify operation of redundant units.

5.8.4.3.2 Environmental Testing

The environment tests for ground simulated conditions are operating tests using the following:

1. Environment: Atmospheric pressure and ground ambient temperature with heat pipe or other space thermal control device in place. Humidity may be controlled if necessary; ambient temperature should vary from about zero to 50^{o}C.

2. Mechanical: Non-operating vibration, shock, and acoustics as used in initial "Acceptance Testing"

5.8.4.3.3 Launch and Manuever Phase Testing

No operation is expected during these stages of the mission. Thus, the tube is expected only to survive the trip, meeting certain environmental requirements without deterioration of characteristics. These tests should be performed after the Ground Testing considered above and should be followed by "Orbit Simulation Testing." Tests should include the following:

1. Acceleration: utilize values above those expected from the normal launch vehicle operation. Include longitudinal and angular acceleration, and other accelerations as approproate to maneuvering expected.

2. Shock: determined by the launch vehicle characteristics; several shocks in each dimension as well as at angles relative to the tube axes should be included.

3. Temperature: tube should be cycled in temperature through that expected during launch.

4. Acoustic: 141 dB suggested for the Atlas/Centaur launch vehicle, which would be adjusted for other vehicles as required with duration and spectrum to simulate vehicle acoustic noise.

5. Vibration: types of vibration that should be applied include: sinusoidal (using a spectrum as normally encountered in a launch vehicle); random (which is similar but uses a continuous spectral density; torsional (in radians/sec^2); fatigue effects; spin; and simultaneous combinations of these vibrations.

5.8.4.3.4 Orbital Operation Testing

These tests will essentially be the same as the ground based functional tests but with environmental conditions applied simultaneously.

Functional Testing

Refer to "Functional Testing" above. The tests should be performed in a vacuum to simulate space conditions. Tests should verify unchanged operation following the "launch" tests described above, covering all the factors listed in the "acceptance" and "ground" functional tests.

Environmental/Functional Testing

The following should be performed:

1. Pressure: reduce from atmospheric at twice the rate expected within the launch vehicle; operate at 10^{-3} and 10^{-5} Torr.

2. Operate pressure sensors used to determine level of outgassing which will permit transmitter operation.

3. Check telemetry and decision circuitry.

Temperature

The above tests should be performed with heat pipes in place, this will require a cold plate (or equivalent) in the vacuum chamber to simulate the space sink. Temperature should be cycled from maximum during the tests to a non-operating temperature to be determined by the "eclipse" and energy storage conditions, generally not determined at this time. Thermocouples will be used to measure strategic points over the 200-hour test to ensure acceptable cooling system performance.

5.8.4.4 Life Testing

The number of tubes for testing can be selected and the duration of the test can be determined from Section 5.8.5. Then the method of conduction of the life test would include the following:

1. Cycling. The tube will probably be shut down during eclipse period, so that the test cycle should turn the tube off about every 23 hours, for a period of one hour. Breakdown faults also should be induced once per month (or at some other specified interval) to determine the status of the protective circuitry.

2. Environment. The economic practicality of testing all tubes for extended periods in a high vacuum is open to question. However, several tubes should be tested under these circumstances, preferably by being sealed in an evacuated chamber that is periodically checked for level of vacuum. At least one tube should also be subjected to the radiation environment of space. Presumably, these tests would verify cathode life as well as other aspects of tube integrity.

The life test fixtures should be capable of handling RF operation since this is the desirable mode throughout the test period. A 2-year life test should be planned as a minimum. The use of one tube to drive the other tubes permits a minimum signal generator size and also eliminates a load for that particular tube. Facilities to handle electrical faults should be included in each tube circuit, and means for switching the "driver" tube must be included to minimize the possibility of having the entire test shut down because of its failure. Finally, the methods used in other tube testing, particularly as in Hughes, Eimac, and Watkins-Johnson TWT tests, should be examined in further detail for preferred techniques.

5.8.4.5 Test Formats

Each test should have a TSS (Test Specification Sheet) with the following information:

1. Objective of Test
2. Test Configuration
    a. Tube and Circuit
    b. Test Equipment
3. Measurements Required
4. Expected Results
5. Data Format
6. Interpretation of Results

These will have to be prepared on the basis of the specific tube and its application.

5.8.5 SAMPLE SIZE AND TEST DURATION

5.8.5.1 Failure Rate

A very important question arises as to how many tubes must be used in qualification and life tests. The number, as can be suspected, will be directly related to the degree of confidence desired. Certainly, the more tubes used, the higher the confidence that the data obtained is representative of the expected tube performance. Test results are statistical in nature; this data can be utilized for incorporating redundancy and can be assumed to be the basis for predicting transmitter life.

The assumption on redundancy is that the second tube will be started after the first fails, and the probability of success for two tubes is:

$$P(S)_2 = (1 + \lambda T)\, e^{-\lambda T}$$

where λ is the failure rate. The failure rate for 2 and 5 years, based on the equation for the success for two tubes and a 99 percent probability (85.6 percent for each tube), would have to be:

$$\lambda_2 \text{ years} = 9.2 \times 10^{-6}$$

$$\lambda_5 \text{ years} = 3.56 \times 10^{-6}$$

These numbers assume an exponential failure rate. The experiment to determine life tests would have to ascertain this to be a reasonable assumption. Qualification tests will determine how well a tube will perform in space; life tests will determine how long a qualified tube will function.

5.8.5.2 Sample Size - Qualification Tests

Qualification tests can be considered as go/no-go types where time is not a factor and the success probability would be based on a binomial distribution with $\underline{n}$=tubes "operating" independently. Sample size for a required confidence level that the tubes will have a given probability of survival must be determined. Further, reliability requirements are expressed as overall requirements, and the qualification reliability should be substantially higher to permit a larger part of the permitted failure rate to apply to life testing; a binomial distribution is assumed. The confidence interval must be determined for a relatively small sample, which involves the use of Pearson's Incomplete beta function; however, a good approximation can be obtained by interpolation in a table of the binomial distribution function. Tables used (Reference 17) showed probability intervals versus number of samples for a 95 percent confidence level. Thus, the reliability is suspected to be near 90 percent if 90 percent of the samples survive. However, the range of reliabilities which could have led to this result if a 95 percent confidence is desired are as follows:

Number of Samples	Probability Range for a 95-Percent Confidence of Obtaining 90-Percent Successes
10 (9 successful)	55 to 100 percent
20 (18 successful)	69 to 99 percent
50 (45 successful)	78 to 97 percent

Actually, a 95-percent confidence level may be high for these tests; for a 70-percent confidence range:

Number of Samples	Probability Range for a 70-Percent Confidence of Obtaining 90-Percent Successes
10 (9 successful)	70 to 99 percent
20 (18 successful)	77 to 97 percent
50 (45 successful)	82 to 96 percent

Thus, it appears that the non-life tests might involve 20 or more samples, or at least as many as possible. The range of confidence probabilities decreases as the number of success improves; for example:

Number of Samples	95-Percent Confidence Range	70-Percent Confidence Range
10 (10 successful)	69 to 100 percent reliability	82 to 100 percent reliability

Initially, a sample of 10 would be recommended; if one or more failed, the number should be increased to narrow the range of reliability possibilities. Large, expensive, small-production tubes may require some compromise in establishing a set of limits for the non-life tests.

5.8.5.3 Sample Size-Life Tests

An estimate of λ, the failure rate in a life test, can be obtained by using the chi-square estimator. From this, the number of samples can be determined to provide the 99-percent reliability with the desired values of λ for a given confidence level. The actual value of λ is less than the chi-square estimator:

$$\lambda \leq \lambda_{est.} = \frac{\chi^2(C, df)}{2T}$$

where

C = confidence level of estimator

df = degrees of freedom = 2 ($\underline{n}$ + 1)

$\underline{n}$ = number of failure in test

T = total operating time on all units under test

χ^2 = tabulated values

The confidence level is the probability that the estimated value of λ is greater than (or equal to) the "true" value of λ.

The value of C can be assumed as 70 percent, 80 percent, and 90 percent. Then the values of χ^2 for 0, 1, and 2 failures during the test are:

	n = 0 df = 2	n = 1 df = 4	n = 2 df = 6
C = 70%	2.41	4.88	7.23
C = 80%	3.22	5.99	8.50
C = 90%	4.61	7.78	10.6

These values of χ^2 are then placed into the equation for λ, and the following total numbers of tube hours (number of tubes times operating period) are required, assuming a 2-year operation with $\lambda = 9.2 \times 10^{-6}$.

Confidence	Total Operating Time (Tube Hours)
No failures occur	
70%	T = 128, 000
80%	T = 171, 000
90%	T = 245, 000
One failure occurs	
70%	T = 260, 000
80%	T = 319, 000
90%	T = 414, 000
Two failures occur	
70%	T = 385, 000
80%	T = 452, 000
90%	T = 564, 000

A practical test duration of two years requires the following number of tubes (rounded off to next high digit) for a 2-year mission:

Confidence	No Tube Failure	One Tube Failure	Two Tube Failures
70%	8	15	22
80%	10	19	26
90%	14	24	33

These numbers would be considered for the initial tests on tubes. The tests would probably be continued until at least one tube failed, to determine at least one identifiable failure mode for the tube. The following tube hours would be required for a 5-year reliability:

Confidence	No Failures	One Failure	Two Failures
70%	330,000	672,000	995,000
80%	442,000	824,000	1,167,000
90%	633,000	1,070,000	1,454,000

A sample of 10 tubes with one failure would require an extended test time to attain a desired level of confidence; i.e., an 80-percent confidence that the failure rate is no worse than 9.2×10^{-6} per hour (2-year requirement as computed previously) requires the times for testing to be:

No failures: 17,500 hours

One failure: 31,900 hours

Two failures: 45,200 hours

Additional failures within these times would reduce the willingness to accept the failure rate of 9.2×10^{-6} as the "true" failure rate for the tubes under test (within the 80-percent range).

5.8.6 TEST COSTS

5.8.6.1 Cost of Qualification Tests

Qualification testing is assumed to be accomplished only after the life test setup is established. Thus, the costs are largely for the use of special test equipment (shake tables, vacuum chambers with environmental control, radiation, acoustic shock, and others) and the time for operating the tests. The costs are relatively independent of tube type and are assumed to be only a function of tube power level, which influences the magnitude and complexity of the tests. Cost data used previously and considered to be applicable here are (Reference 1):

Tube Power Level	Qualification Costs ($ K)
1 watt	5
10 watts	7.2
100 watts	8.4
1 kw	8.7
10 kw	10
100 kw	12.3

The tests generally include those outlined in Section 5.8.4.

5.8.6.2 Costs of Life Tests

The costs for testing tubes to meet space requirements will be considered in terms of facilities, operating costs, manpower, and tube costs. Three estimates are indicated below, covering 1-watt, 1000-watt and 100-kw tubes. A minimum of 10 tubes for an 80-percent confidence in the 2-year failure rate will be assumed.

1-watt Tubes

Test Facility (power supplies, RF sources, recorders, RF components, and other components and test devices not covered by overhead)		$ 10,000
Tubes (10)		20,000
Power - 2 kw at 2¢/kwh x 16,000 hours (assume 90 + % duty cycle)		640
Engineers (1/2-man years)		20,000
Technicians (1-man year)		20,000
	Total	$ 70,640

1-kw Tubes

Power supplies (assumed)		$ 30,000
Tube mounting hardware, test fixtures		20,000
Protective "crowbar" circuits		10,000
RF sources, performance recorders		10,000
RF components		10,000
Power - 30 kw at 2¢ x 16,000 hours		9,600
Tubes (10) - linear beam Tube costs may vary considerably with type and production status.		135,000
Engineers (1-man year)		40,000
Technicians (9-man years)		180,000
	Total	444,600

100-kw Tubes

Power supplies (10) 200 kw each	$350,000
Tube sockets, mounting hardware	40,000
Protective "crowbar" circuits	50,000
RF sources, performance recorders	10,000
Cooling systems	50,000
Microwave components	50,000
Power - 2 mw @ 2¢/kwh x 16,000 hours	640,000
Tubes (10) ten at $43,000	430,000
Engineers (2-man years)	80,000
Technicians (16-man years)	320,000
Driver Equipment (1-kw case, less 1/2-man year engineering and 7-1/2 man years technicians)	274,600
	2,294,600

5.8.7 RISK FACTOR

This study could not place quantitative values on risk factors in tube qualification testing. Risk is generally based on the willingness to accept a certain level of performance, based on the profit if the venture is successful versus the loss if not successful. A TV broadcast satellite is relatively expensive, and the loss factor could become too high if a tube acceptance level were set low.

The risk from tube failure is reduced by including redundancy and performing a suitable battery of tests that will identify tube weaknesses which could abort the mission. A high confidence level would be established if no failures occurred in extensive testing of a number of tubes, and the inclusion of some redundancy should reduce the risk factor from tubes to an acceptably low value.

Tube testing that results in a number of faults would indicate the risk factor is much too high, but the accuracy (confidence) could be better established by expanding the number of tubes under test. Practical difficulties include the larger amount of monitoring circuitry and the potential failures of tube switching equipment. The lowest risk in the satellite would probably result from a favorable test program, combined with a small amount of redundant equipment. This concept will require further evaluation on a quantitative basis for specific tubes and missions.

5.9 TRANSMITTER SYSTEMS

5.9.1 GENERAL RECOMMENDED APPROACH

The MKTS II Program has indicated a number of problem areas that should be investigated further to better define performance expectations in a space TV transmitter having a multiple kilowatt output. These areas generally follow the conclusions of the present study and can be summarized as indicated in Table 5.9-1. The first part covers the high power in space situation, the Doherty amplifier development, supporting circuitry, and the integration into a basic transmitter configuration. This program will provide sufficient information to reasonably ensure success in the development of a space transmitter

Table 5.9-1. Recommended Areas for Program Continuation

CRITICAL ITEMS FOR NEAR FUTURE CONSIDERATION		FUTURE ITEMS REQUIRED FOR ULTIMATE TRANSMITTER	
High Power:	Improved Materials Outgassing Data Power Conditioner - below 4 kv - Module Design for High Efficiency - L-C Energy Storage Filter RF Breakdown Data in Selected Components in Vacuum	High Power:	Outgas Pressure Buildup in Typical Mechanical Enclosures and Support Configurations Data on Vacuum Arcs, Plasma, and Multipacting Electrical Breakdown Data on Outgas Products High Voltage Transformer Design (above 6 kv)
High Efficiency Transmitter:	Optimize 5 kw Doherty Amplifier Tube Life Test Initiation System Testing - Include all elements plus supporting subsystems	Transmitter:	Additional RF Components for Specified Mission Diplexers and Multiplexers Bonded Grid Tubes Environment, Performance, and Life Testing
Supporting Subsystems:	Dc Breakdown Monitor and Protective Circuitry Heat Pipe Thermal Control Development Controlled Carrier Circuitry	Supporting Technologies:	RF Breakdown Monitor and Protective Circuitry Advanced Heat Pipes for Thermal Control
		Application of Techniques to Other Missions, Particularly in the Microwave Frequency Region and for FM TV Systems	

The second group of future items covers additional details on each of the above areas, and places more emphasis on the breakdown area and environmental testing. This listing would be accomplished to some extent in the near future in related programs by other interests in high voltage space problems. The balance may be involved in future MKTS-type programs.

5.9.2 PROGRAM RECOMMENDED

The recommended program revolves around the development of a high power breadboard Doherty transmitter. The program should include experimental materials evaluations, vacuum breakdown tests including RF components, development of high power RF circuitry components for an AM TV transmitter, and developments of vital supporting areas. A program to include these items is implied in the block diagram of Figure 5.9-1, which shows the MKTS transmitter development within the boxed-in area and a number of related supporting programs that would normally be of interest to other high voltage space programs. The following is a brief summary of the areas in Table 5.9-1 and their relations to Figure 5.9-1.

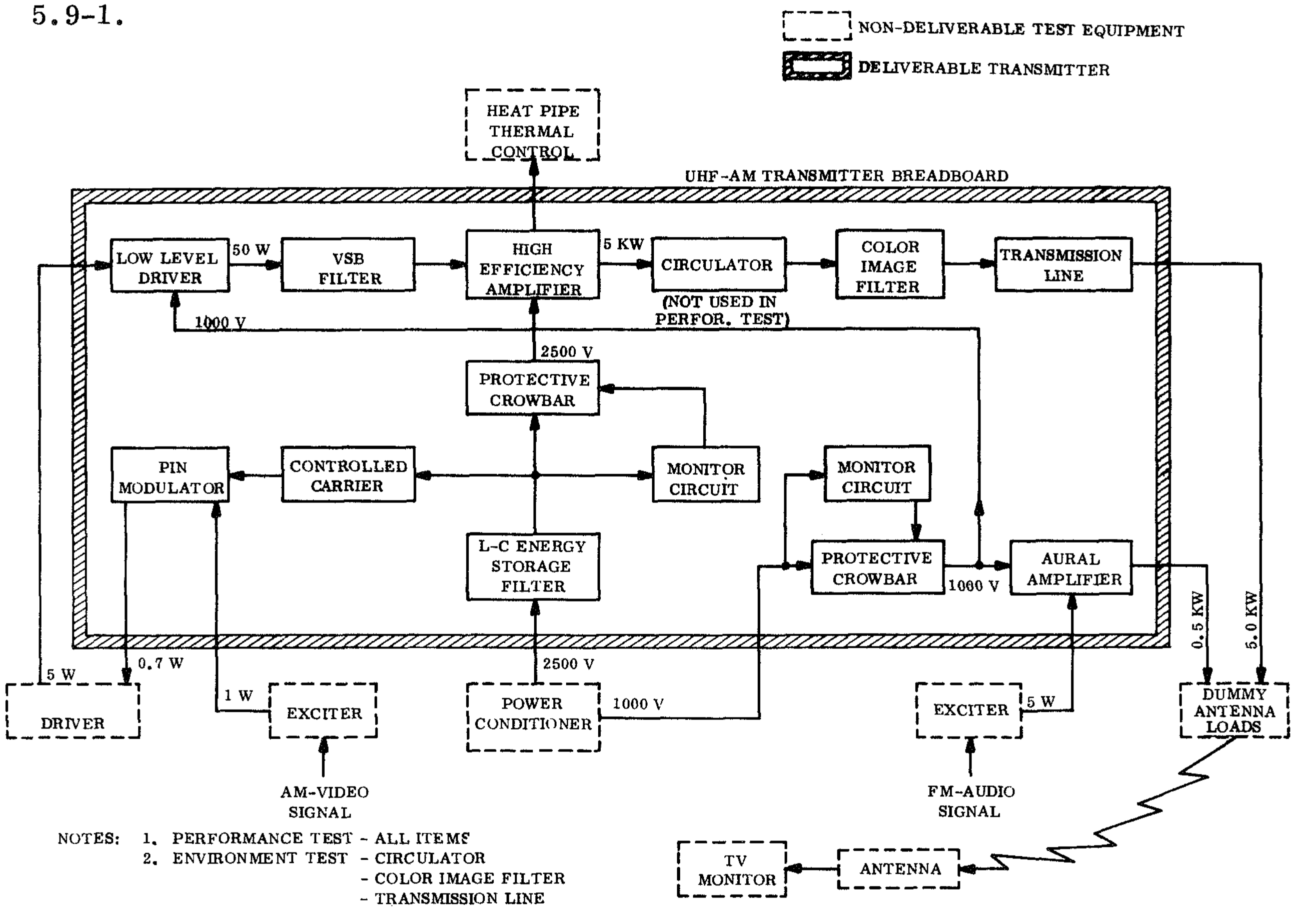

Figure 5.9-1. Block Diagram of Transmitter and Test Equipment

High Power in Space

1. Materials Evaluation - High voltages are of interest in a number of areas (the SERT II Program, for example, involves ion propulsion with high voltages); related programs will be surveyed and results applied to this program. Early efforts will be on insulators for power conditioners, and will include insulators such as polythermaleze, GE Micamat No. 77863, and Textolite 11617B. Tests will be on outgassing and sublimation; results will later be related to electrical breakdowns and bakeout requirements.

2. Dc Power Conditioners - A power conditioner is scheduled to be developed in another program. That study will include the L-C energy storage filters for AM TV transmitters in addition to determining the best circuits for high efficiency and minimum breakdown likelihood. The L-C filter will be a part of the proposed transmitter proper and an addendum to the power conditioner effort.

3. RF High Power Technology and Components - This area covers two critical regions: experimental evaluation of high vacuum breakdown and the design of special RF components. Some RF breakdowns are expected with the coaxial RF components, particularly in bandpass and harmonic filter areas. Some initial RF tests in a vacuum chamber should be performed in any follow-on program. The tests would primarily be to determine multipacting effects at UHF for the initial phases; later tests could consider the effects of other breakdown modes. RF component studies should include the vestigial sideband filter and the color subcarrier image filter, which are of primary concern and should receive early attention with emphasis on a space-type configuration. A circulator, required especially for a CFA amplifier and possibly for the Doherty amplifier, will also be considered.

High Efficiency Transmitter

1. Doherty Amplifier - The results of the present study indicate that a Doherty amplifier will operate at UHF but an optimized configuration was not achieved. Thus, this effort should be concerned first with optimization analysis using the 30 MHz Doherty simulator (Section 5.4.4), and apply results to the low power UHF Doherty test amplifier circuitry (as in Section 5.4.3). This effort would be performed on related studies since the Doherty amplifier is also of interest in other space programs. A 5 kw high efficiency amplifier should be developed, using production type L-64S triodes (See Appendix B).

2. Testing of the high power Doherty amplifier requires a low power driver circuit. This stage should have about 100 watts available for test purposes and be capable of gain control for use with controlled carrier equipment (see below) and with RF protective circuitry (a more future item, per Table 5.9-1).

3. Complete TV testing will require that an aural channel amplifier at 500 watts output (FM voice) be included. A diplexer to combine the visual and aural RF signals is not proposed for the immediate program but would be an early item once the other elements of the transmitter are proven.

4. System Testing - After completing all development tasks and component testing, the system should be assembled per Figure 5.9-1 and tested for operation at rated specifications. Only atmospheric environment tests would be performed at this time, and environmental (vacuum) tests should be deferred until complete electrical and thermal operation is established.

Supporting Subsystems

1. Dc breakdown monitoring and protective circuitry is required to operate the high power Doherty amplifier considered above, and should also be available to protect the other two stages recommended for early development. Conventional crowbar

techniques are anticipated. RF protective circuits are not required for operating at the power levels considered in a standard atmosphere environment, and are deferred for a future phase of the program.

2. Heat pipe development has been progressing for space systems, and considerable analytical and experimental work has been accomplished. Specific heat pipes for the Doherty amplifier would be considered here, but would largely involve adapting presently available designs to the amplifier configuration that evolves. Thus the proposal program includes essentially an interfacing task to permit final system testing with heat pipe cooling included.

3. Controlled carrier is a technique that varies the transmitter output so that the dc input power required is held essentially constant in an AM TV transmitter. The picture level determines the power required, and substantially more power is required for a dark picture than for a light one. Appendix A describes a test that confirms the basic validity of the technique for varying carrier level to match picture conditions. Reducing the carrier power for the darker pictures permits the power supply to be keyed to an average power requirement rather than to a maximum or some other compromise point. The techniques for accomplishing this and the effects on transmitter performance should be examined and followed with a development for use in final transmitter tests.

5.9.3 APPLICABILITY OF PROGRAM TO OTHER MISSIONS

Emphasis has been placed on UHF-AM TV as an early mission requirement but the program is also cognizant of possible missions at other frequencies. A major factor leading to the UHF approach is the anticipated early availability of a high efficiency tube (the L-64S per Appendix B). However, the newer microwave type tubes will be available in a few years and will be the devices considered for use at the higher frequencies. The linear CFA is also a good candidate for the UHF region and has been included in the present study. The applicability of the various tasks to other bands and modulation types is indicated in Table 5.9-2. Thus the MKTS program should have wide applicability in many areas and lead to a general level of confidence in developing high power space transmitters of all types.

Table 5.9-2. Applicability of UHF/AM Gridded Tube Transmitter Development to Other Transmitters

	UHF BAND				S-BAND	S & X-BAND	
	GRIDDED TUBE		CFA		CFA	KLYSTRON	TWT
TRANSMITTER COMPONENT	AM	FM	AM	FM	AM	FM	FM
HIGH EFFICIENCY AMPLIFIER	100%	75%	-	-	-	-	-
CONTROLLED CARRIER	100%	-	100%	-	100%	-	-
L-C ENERGY STORAGE FILTER	100%	-	100%	-	100%	-	-
VSB INPUT FILTER	100%	-	100%	-	100%	-	-
COLOR-IMAGE FILTER	100%	-	100%	-	100%	-	-
LOW LEVEL DRIVER	100%	90%	100%	90%	-	-	-
AURAL AMPLIFIER	100%	-	100%	-	10%	-	-
MONITOR & PROTECTIVE CIRCUITS	100%	100%	50%	50%	50%	50%	50%
HEAT PIPE	100%	100%	50%	50%	50%	50%	50%
CIRCULATOR, RF	100%	100%	100%	100%	50%	50%	50%
OUTPUT TRANSMISSION LINE	100%	100%	100%	100%	30%	10%	10%
POWER CONDITIONER	100%	100%	50%	50%	50%	50%	50%
MATERIAL & COMPONENT TESTS (VOLTAGE BREAKDOWN, OUTGASSING AND MULTIPACTING)	100%	100%	50%	50%	50%	50%	50%

SECTION 6

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APPENDIX A

CONTROLLED CARRIER PERFORMANCE

A.1 OBJECTIVE

The objective of a controlled carrier is to permit a power supply average output to be keyed to an "average" transmitter power requirement for an AM-TV system. The instantaneous power required by the transmitter varies from white picture level at about 1.5 percent of sync peak power to the black picture level at 50 percent of the sync peak power; it reaches blanking level at 56 percent of sync peak about 16 percent of the time and peak sync itself about 8 percent of the time. The latter two are fixed, but the picture may have widely varying average requirements: a movie composed of snow scenes has a lower than average requirement, while a movie of all night scenes will require well above average power. Neither of these conditions are normal, and there is no way of determining beforehand which will occur and for how long. The proposed solution is to vary the transmitter power output (actually the carrier output) such that the total power required at any time matches or is less than the power capability of the dc-to-dc converter and primary solar array power source. The power supply then does not have to be oversize to meet the infrequent high power demands from dark pictures, which would add substantially to weight and cost.

The feasibility of controlled carrier can be assessed by the effect of varying received power on a typical TV receiver, using viewers to determine the resulting effects. Some experimental data has been derived to determine the effect of small changes in received power and the effect of rate of change of power as picture content varies. The results of this testing, applied to the transmitter end of the chain, will influence the requirements for the L-C storage filter, which was found to be a major item of weight in Sections 3.1.3.1 and 5.2.1.3.

A.2 TEST APPROACH

Tests were performed using a gain-controlled amplifier in the antenna line prior to the TV test receiver. An instrument TV set generated an error signal which was used to maintain the antenna line signal at a constant RF average power level. The controlled signal was then applied to a number of different TV receivers to determine when the effect was detectable.

Response times were altered for the various tests, and the test receivers, as well as a reference receiver without controlled carrier, were observed by a number of viewers; a local station was the signal source. Time constants were varied from 0.22 ms (about 7 line periods) to 18 ms (roughly a field period).

A.3 GENERAL RESULTS

Very short time constants resulted in disturbing the sync pulses because the receiver AGC could not accommodate the rapid signal level variation; thus, 0.22 ms was not acceptable. Increasing the time constant to 1.8 ms resulted in reasonable operation, although the variation in sync peak height was still three times that permitted by the FCC. Consequently, a 6-ms time constant in the controlled carrier was considered a satisfactory value for a system, because viewers were unable to distinguish any differences between the test and reference receiver performances. The L-C storage filter for the transmitter with the 6-ms time constant in the controlled carrier circuit could be reduced considerably from that of Section 3.1.3 and 5.2.1.3.

A.4 CONCLUSIONS

The concept of a controlled carrier for reducing energy storage in an AM TV transmitter power supply is a major advancement for a space TV system, where weight and prime power should be conserved. An objective in a future study will be to evaluate techniques for incorporating C-C into an AM transmitter, particularly the Doherty type as considered in this study.

APPENDIX B

L-64S TUBE DATA

A major reason for promoting the gridded tube transmitter at UHF is the development of the high efficiency UHF L-64S planar triode. The tube was originally an L-band wide-bandwidth tube with special application in a Signal Corps application. It was subsequently modified to include a Philips cathode to obtain a long life at high current levels. This cathode will supply a higher CW current than the conventional oxide cathodes and can result in long life if the cathode is derated. Thus, it can operate as well for CW purposes as the oxide cathode, but at a much lower temperature. Maximum current in the L-64S is 15 amperes, while the MKTS application may require only one ampere.

A second cathode improvement was the bi-potential cathode, in which the cathode surface immediately under the grid wires has low emission while the area between grid wires emits heavily. Thus, the grid current is reduced dramatically during positive swings of the grid voltage; this resulted in simple conduction cooling of the grid, while liquid cooling might otherwise be required, at least at higher power levels.

The tubes were initially tested at about 700 MHz in a circuit having a 22-MHz bandwidth. More extensive testing is in progress, but the data has indicated efficiencies of over 70 percent in a Class C mode and gains of the order of 16 dB at the 22 MHz bandwidth. Calculations show that several additional dB gain should be realized in a circuit having a 6-MHz bandwidth, as in conventional AM TV. Typical operation, covering four of the tubes fabricated last year, is indicated in Figures B-1 through B-4.

These tubes are now being engineered for production. The oxide cathode tube, the Y1498, has been produced for other customers. The Philips cathode has been fabricated and is being tested. The bi-potential cathode is yet to be fabricated as a production item, but it is expected to be in the near future.

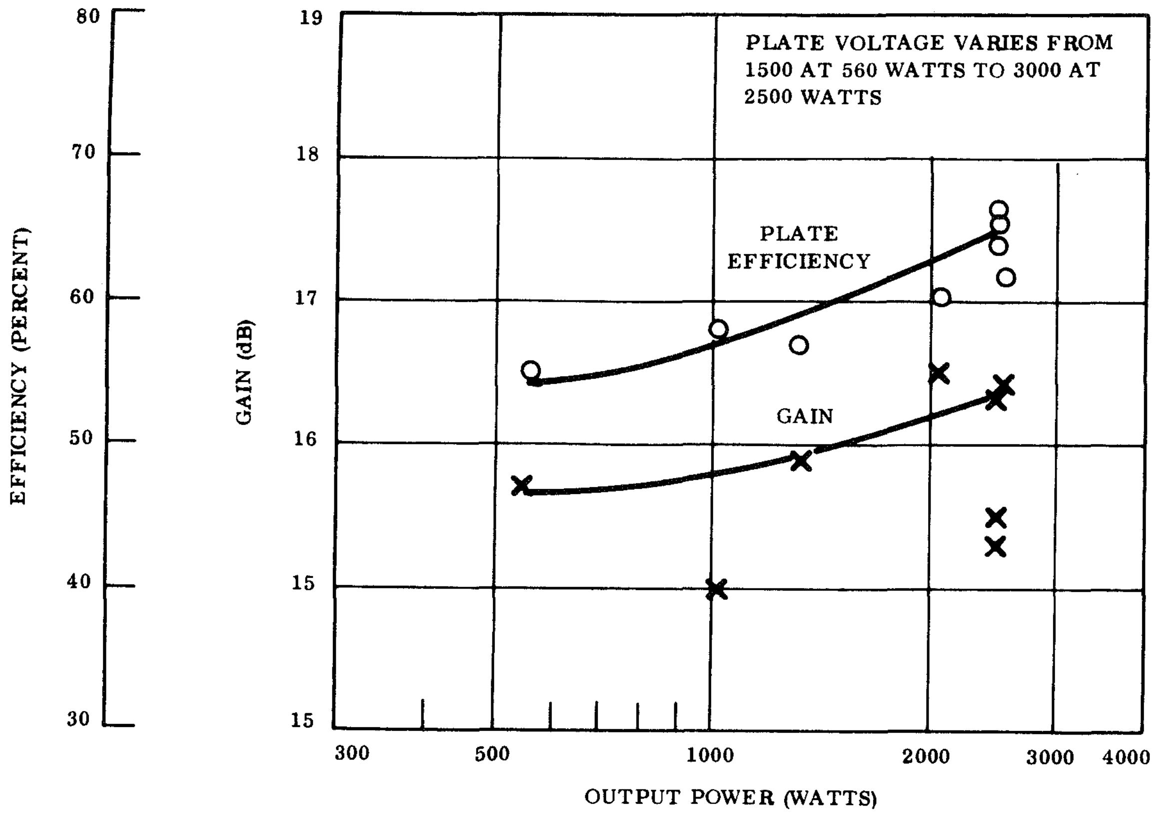

Figure B-1. L-64S Tube No. 27 Efficiency and Gain

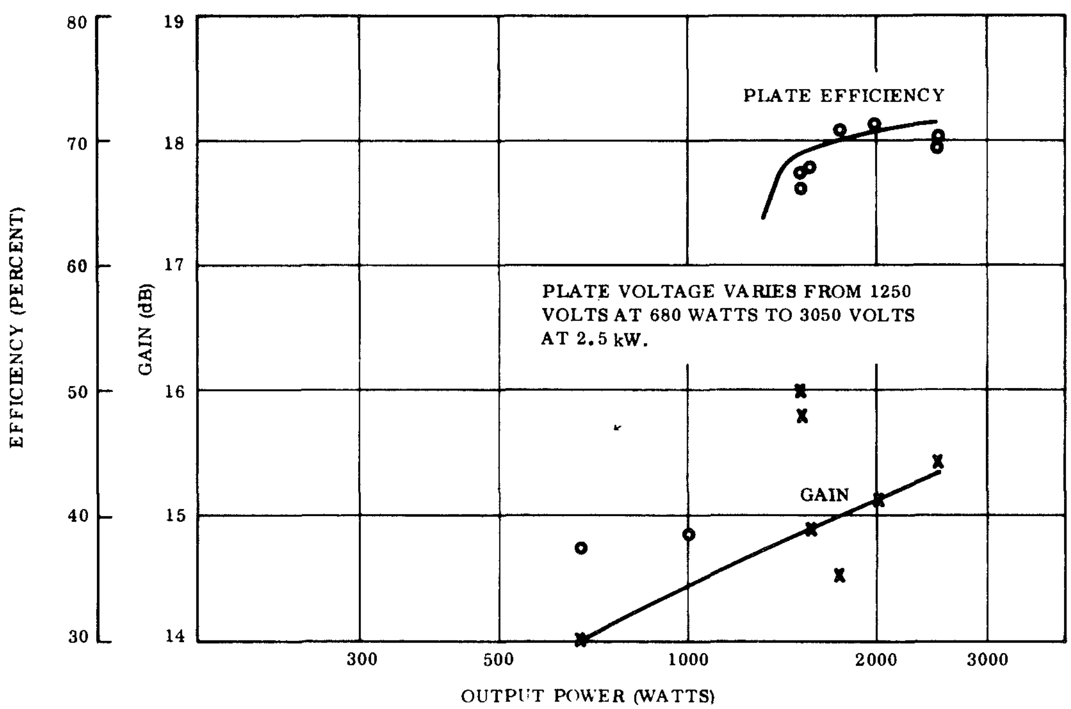

Figure B-2. L-64S Tube No. 28 Efficiency and Gain

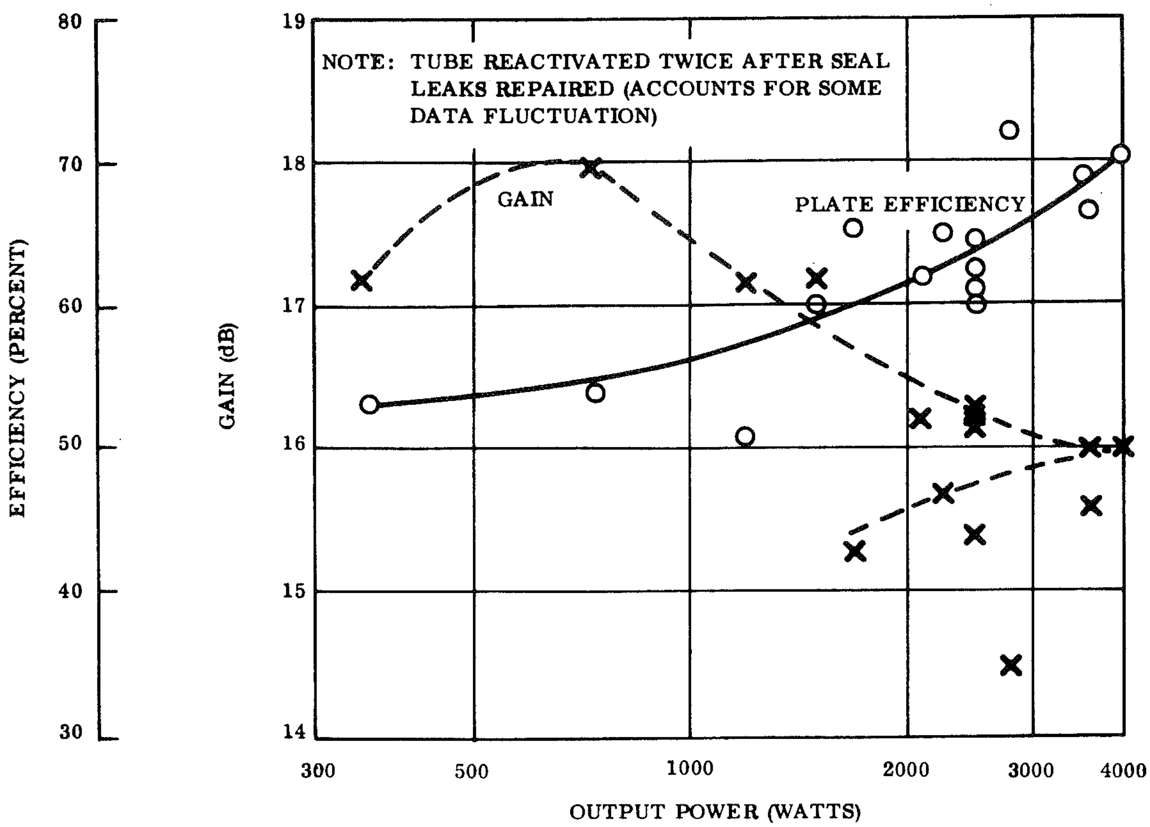

Figure B-3. L-64S Tube No. 29 Efficiency and Gain

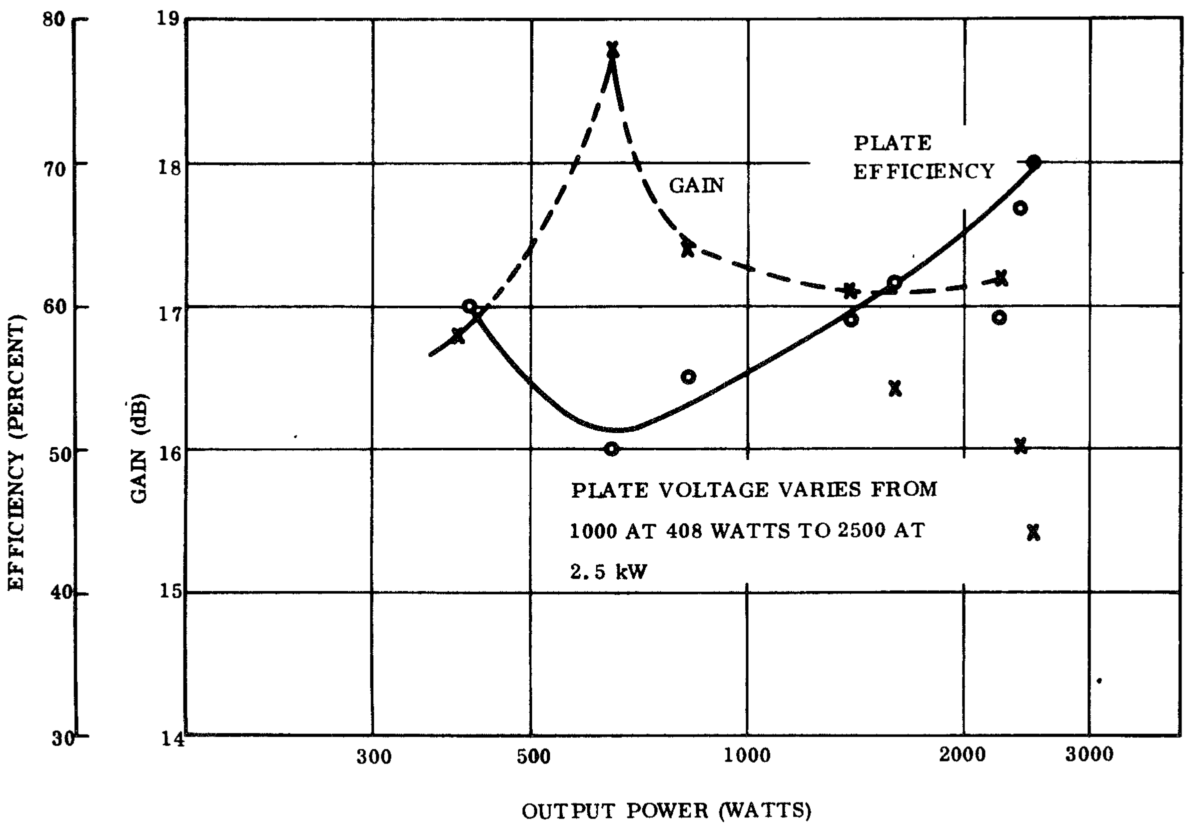

Figure B-4. L-64S Tube No. 30 Efficiency and Gain

A more distant tube, the L-69S, is presently being developed to provide highly ruggedized construction as well as improved performance. This tube will have the grid wires rigidly fastened to the cathode surface with an insulating material. Thus, the grid/cathode spacing can be reduced to increase gain and efficiency, and the grid current will be greatly reduced because the grid wires will be electrically insulated from the electron stream. The latter effect has been confirmed in a breadboard tube. The L-69S will be an eventual replacement for the L-64S at some later date when production tubes are available.

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