[redacted]

018

DRF-07249

SPACE
SYSTEMS

MULTIKILOWATT TRANSMITTER STUDY FOR SPACE COMMUNICATIONS SATELLITES

VOLUME 1
SUMMARY REPORT
PHASE 1

FACILITY FORM 602

N70-27440 (ACCESSION NUMBER)	(THRU)
27 (PAGES)	1 (CODE)
CR-109651 (NASA CR OR TMX OR AD NUMBER)	07 (CATEGORY)

GENERAL
ELECTRIC

FOLDOUT FRAME

DOCUMENT NO. 68SD4268
10 JUNE 1968

MULTIKILOWATT TRANSMITTER STUDY
FOR
SPACE COMMUNICATIONS SATELLITES

VOLUME 1
SUMMARY REPORT
PHASE 1

PREPARED FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA

UNDER

CONTRACT NAS8-21886

GENERAL ELECTRIC
SPACE SYSTEMS ORGANIZATION
Valley Forge Space Center
P. O. Box 8555 • Philadelphia, Penna. 19101

PRECEDING PAGE BLANK NOT FILMED.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION 1

INTRODUCTION & SUMMARY

1.1 OBJECTIVES

The results of NASA system studies have verified that cost-effective boradcast satellite systems require the use of high-powered satellite transmitters. This is due to the necessity of broadcasting from synchronous orbit to large coverage areas containing low cost ground receiving equipment. High powered (multikilowatt) space transmitters will enhance the performance of other satellite systems such as deep space probes requiring high data rates, spacecraft-to-spacecraft communications, and satellite-to-aircraft and ship communications and navigation.

The general objective of this study was to define and analyze techniques of high power TV transmission from a long life (minimum of 2 year) satellite. The specific objectives of the study were:

- Transponders were to be parametrically analyzed to achieve high efficiency, low weight and low cost. Transmitters were to be selected for design based primarily on transponder performance which was to include the effects of thermal control, power conditioning and uplink receivers.

- Three representative transmitter conceptual designs were to be accomplished for the transmitters selected upon the basis of parametric analysis. These designs were to include electrical, thermal, and mechanical considerations.

- Key technology problem areas were to be identified from data obtained from the parametric analysis and the transmitter conceptual designs.

1.2 APPROACH

The initial phase of the program involved parametric analyses of transmitters, supporting subsystems, and their combinations in transponder configurations. The first three items of the Program Approach shown in Figure 1 include these analyses. The analyses resulted in sets of data showing efficiency, weight and cost parameters as a function of transmitter output power; these three parameters were considered the most significant for defining a satellite TV transmitter.

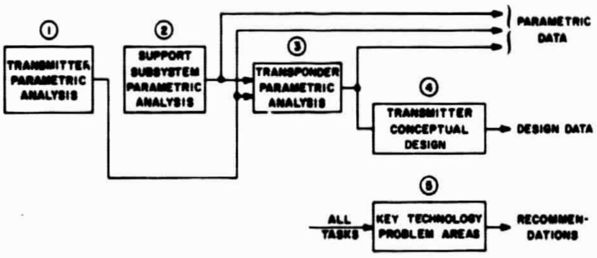


FIGURE 1. PROGRAM APPROACH

In the analyses, subsystems and components were limited to extrapolations to the 1970 state-of-the-art; however, the results of current NASA studies involving advanced klystrons, traveling wave tubes (TWT) and crossed field amplifiers (CFA) were included. Both AM and FM modulation techniques were analyzed. Frequencies from 700 MHz to 12.7 GHz were considered, with four representative bands actually being selected to be compatible with existing TV channels, channels allocated for satellite test, and channels under consideration for future allocations. Transmitters were evaluated for RF output powers from 50 watts to 20 kilowatts, which are adequate for most applications involving TV. A minimum satellite operating life of two years was specified.

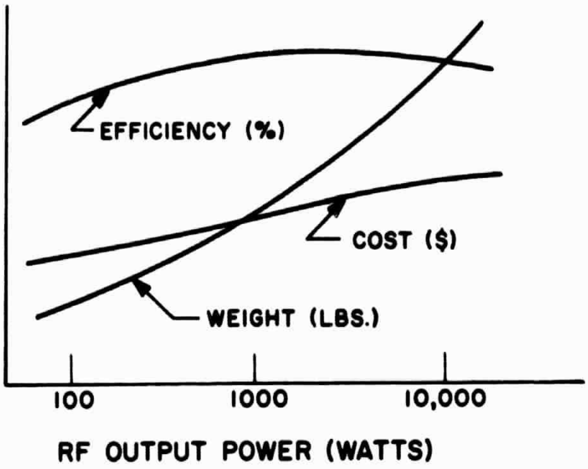


FIGURE 2. PARAMETRIC DATA PRESENTATION FORMAT

Parametric tradeoffs were to result in sets of data in the format shown in Figure 2. Separate curves were to be presented for each frequency band and modulation type considered for the transmitter, and for the supporting subsystems. The ranges of inputs used are shown in Figure 3.

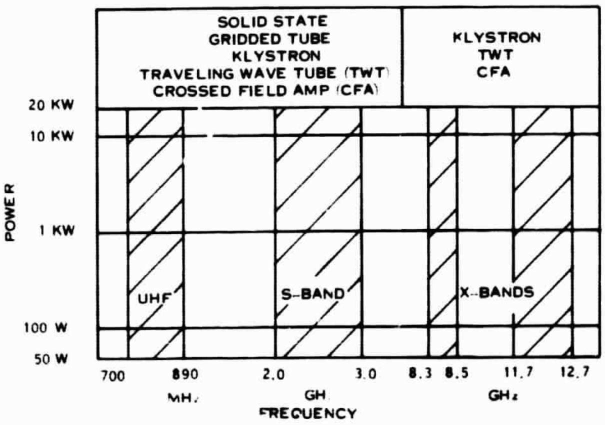


FIGURE 3. STUDY PARAMETERS

The parametric data of the transmitters were to be combined with those data from the supporting subsystems to permit a determination of the best overall transponder configuration. From this, the best transmitter configuration could be derived from a system viewpoint.

1.3 SUMMARY

The analysis of parameters affecting efficiency, weight and cost resulted in the following high power transmitter types being selected as the best candidates for specific frequencies and modulations: (See Section 2)

- UHF/AM - CFA and gridded tube (in Doherty circuit).
- UHF/FM - CFA
- S- and X-band/AM - CFA
- S- and X-band/FM - TWT and klystron

Conceptual designs were accomplished for the CFA UHF/AM, the gridded tube UHF/AM, and the TWT S-band/FM as representative of the above candidates. The conceptual designs delineated electrical, thermal, and mechanical configurations for each of the three transmitters. (See Section 3)

The parametric analysis and conceptual designs identified several key technology areas which are recommended for investigation prior to the initiation of development of any specific multikilowatt transmitters. These technology areas are: (See Section 4)

- Components
  - Tubes and their qualification test requirements
  - Hybrids
  - Multiplexers
  - VSB Filters
- Design Techniques
  - Materials compatible with the space environment
  - High Power DC and RF Problems
  - High efficiency AM amplifiers
- System Interface Problems
  - Power Conditioners
  - Thermal Control
  - Monitor and Protective Circuits

SECTION 2

PARAMETRIC ANALYSIS

The parametric analysis study compares the many possible transmitter configurations for the frequency bands, power levels, and modulation modes representing a wide spectrum of broadcast missions. The study is divided into two general areas; (1) the transmitter parametric analysis with inputs from an amplifier device survey, and (2) a supporting technology parametric analysis including the power conditioner, uplink receiver, and thermal control devices. Figure 4 indicates the interfacing of these areas within the overall transponder. Since the overall transponder provides the basis for decisions on subsystem selections, this will be presented first, followed by an evaluation of each of the subsystems.

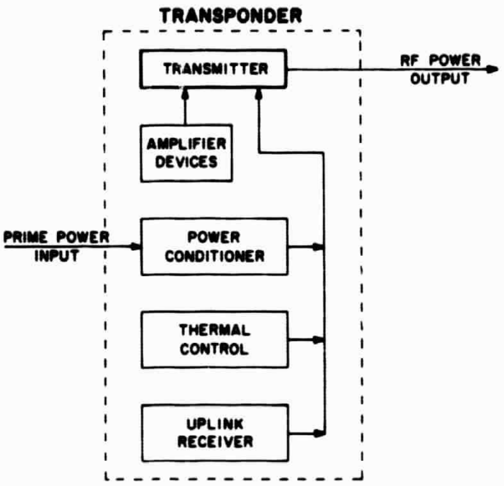


FIGURE 4. TRANSPONDER ELEMENTS

The parametric analysis was intended to provide trade-off curves showing the efficiency, weight, and cost of various configurations as a function of RF output power. (For AM, this is peak sync power; for FM, average power). Efficiency is considered the most significant parameter. If the transmitter efficiency is high, less DC input power is converted to unwanted heat, less prime power is required, and a smaller power conditioner is sufficient. Where no significant differences in efficiencies for alternate configurations of subsystems were apparent, cost and weight were used as a selection criteria.

The parametric data was obtained for at least three nominal power levels from .2KW to 20 KW. Smooth curves were drawn through the points. Each of the subsystems in Figure 4 were analyzed and efficiency, weight, and cost curves determined as a function of RF output power. The subsystem parameters were combined appropriately to determine the overall parameters for the transponder. The basic elements of the analysis are those indicated in Table 1, which combines the requirements specified by Figure 3 with other requirements which relate to practical TV systems.

TABLE 1. REQUIREMENTS AND CONSTRAINTS ON TRANSMITTER PARAMETRIC ANALYSIS

RANGES OF PARAMETERS FROM FIGURE 3

MULTICHANNEL: 1, 4, 7, AND 12 CHANNELS
POWER COMBINING/DIVIDING: 1, 8, 128 TERMINALS
BANDWIDTHS: AM = 10 MHz (U.S. AND EUROPEAN BASEBANDS)

FM_1 = 36 MHz (6 MHz BASEBAND; m = 2)
FM_2 = 60 MHz (6 MHz BASEBAND; m = 4; X-BAND ONLY)
UPLINK AND DOWNLINK HAVE SAME BASEBAND.

2.1 TRANSPONDER PARAMETRIC ANALYSIS

The transponder is assumed to include a transmitter, uplink receiver, power conditioner, and thermal control equipment. The overall efficiency is defined as the ratio of output RF visual channel power to the total DC input power required by the subsystems. The resulting transponder efficiencies permit a selection of the most efficient transponders, which permit the selection of preferred transmitter configurations. By comparing these data with data shown later for the transmitter alone, the dominating effect of the transmitter on the overall transponder efficiency can be observed.

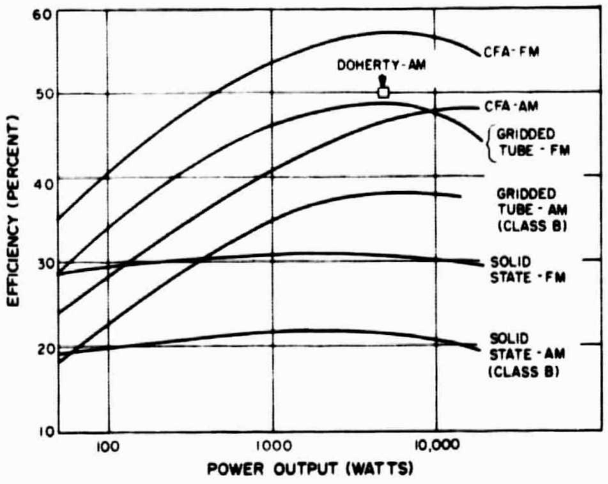


FIGURE 5. TYPICAL UHF TRANSPONDER EFFICIENCIES

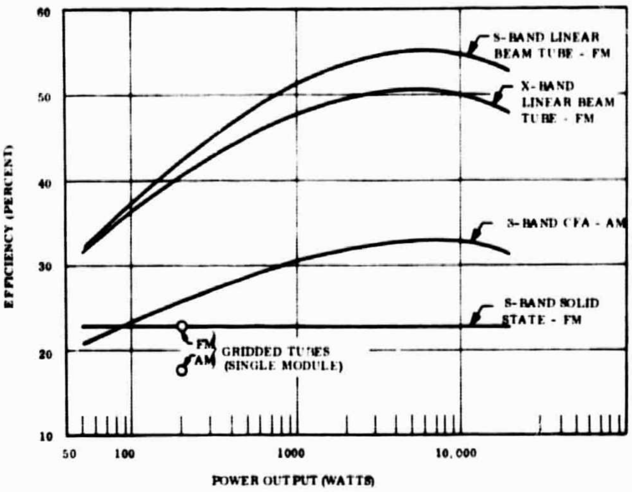


FIGURE 6. S-BAND AND X-BAND TRANSPONDER EFFICIENCIES

The UHF transponder efficiencies shown in Figure 5 compare the AM and FM transponders using the linear CFA (crossed-field amplifier), the gridded tube, and transistors (solid state). The Doherty circuit, a high efficiency configuration for a gridded tube AM-TV amplifier, is shown for a 5 KW output; the power level from the best tube expected in the time frame considered. The Doherty circuit is substantially superior in efficiency to the Class B linear amplifier used in the other gridded tube calculations. Solid state transponders have low efficiencies, largely due to the low gains of the devices and the resulting large driving power required which does not contribute to the output signal but is dissipated as heat. The CFA is a preferred tube for UHF/FM systems; for UHF/AM systems, gridded tubes in a Doherty circuit and linear CFA's are candidates.

At S- and X-bands, linear beam tube transponders (using TWT's or Klystrons) provide best operation on the basis of efficiency for FM operation; the linear CFA is preferred for all AM service. CFA's for FM were eliminated, based upon lower device efficiencies. Both gridded tubes and solid state devices result in low efficiencies and are not recommended within the state-of-the-art expected for the 1970 period. Figure 6 indicates the comparison of the transponders considered. These data are derived on the basis of 1970 devices and single channel operation. The curves indicate lower efficiencies at high and low powers, with a maximum somewhere in the center. This generally results from combining the transmitter and power conditioner data, both of which tend to have better efficiencies at the middle of the region shown.

Weights and costs of transponders can be important in certain cases, but are not likely to be major criteria in selecting optimum transmitters due to the small differences among systems. Solid state transponder weight shown in Figure 7 tends to be

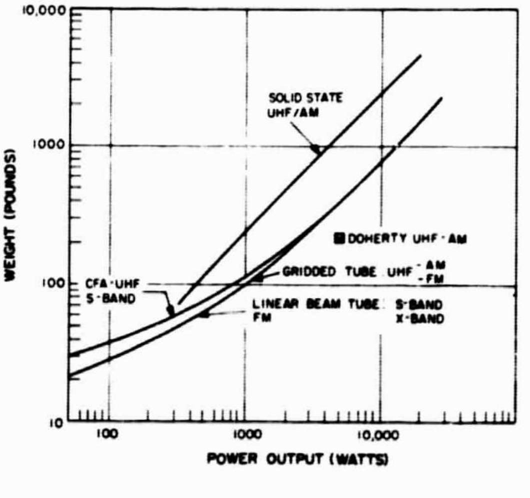


FIGURE 7. TYPICAL TRANSPONDER WEIGHTS

greater than for the other types as a result of the modular construction, the large number of separate modules, and the required increased size of the power conditioner and thermal subsystems. For the gridded and microwave tubes, little significant difference is noted except the CFA transponder tends to be slightly heavier at low powers (under a kilowatt) largely due to higher voltage power conditioner weight. Operating frequency effects tend to be small, and are not of consequence.

Transponder costs are important from a system viewpoint. The low costs of the solid state transponders at low power levels stand out. High power solid state transponders, however, are more expensive due to the large number of modules involved, and to the required large power conditioner and thermal control equipment. The linear CFA tends to cost somewhat more than the gridded tube and linear beam transponders as shown in Figure 8.

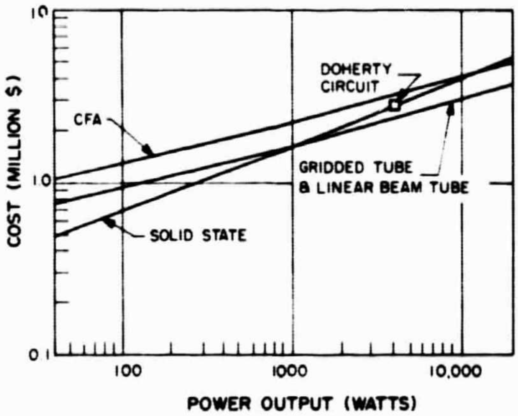


FIGURE 8. TRANSPONDER COST (ENGINEERING PLUS FABRICATION OF ONE UNIT)

2.2 TRANSMITTER PARAMETRIC ANALYSIS

The transmitter parametric analysis includes a survey of all feasible RF amplifier output devices followed by a parametric evaluation of transmitter configurations using the best amplifier devices expected by 1970. Auxiliary microwave components, particularly power combiners and multiplexers, are also considered parametrically. The output of the device survey is a list of characteristics for the best devices expected by 1970. The transmitter study output is a series of parametric curves of efficiency, weight, and cost for the various configurations as a function of output power, covering all frequency and modulation ranges of interest. The plan for the transmitter parametric analysis is shown in Figure 9, which includes as an input the contract constraints and requirements. The output parametric data was used in generating the transponder parametric curves given in Section 2.1.

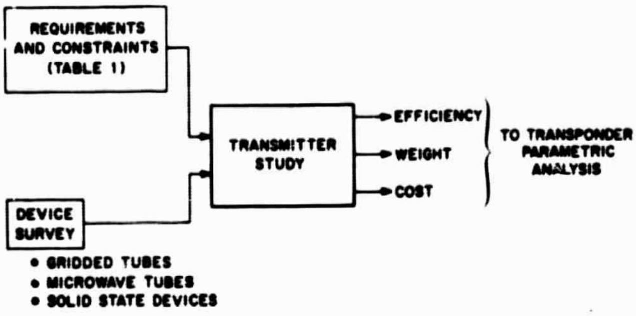


FIGURE 9. TRANSMITTER PARAMETRIC ANALYSIS

2.2.1 DEVICE SURVEY

The device survey considered expected performances, by 1970, of gridded tubes, traveling wave tubes (TWT), klystrons, crossed-field amplifiers (CFA), and solid state devices which can provide RF power outputs from 50 watts to 20 KW. This task consisted of discussions with various manufacturers of devices, literature searches, evaluating known developments, and extrapolating where data was otherwise not available.

2.2.1.1 GRIDDED TUBES

Little advanced tube development was uncovered in the survey, due to the limited demand for tubes in the UHF region and to the competitive klystrons which have been widely used in UHF TV stations. A typical gridded tube is the RCA A2882, which can supply 30 KW peak sync power for TV but has low circuit efficiency above 700 MHz. A recommended tube is the GE L-64S developmental type with 2.5 KW output which is capable of high efficiency UHF performance and is applicalbe for all high power requirements. Figure 10 indicates the efficiency expected from gridded tubes. The 5 KW limit for high efficiency types is based on a reasonable extension of techniques used in the L-64S type of tube. The lower power level efficiencies tend to be a consequence of the utilization of conventional fabrication and design methods, and probably to the small demand for very high efficiencies.

A number of lower power tubes, up to a few hundred watts, were identified but data was often inadequate, and analysis was used to estimate the performance shown in Figure 10. Gridded tubes are not recommended for S-band operation since efficiencies are usually below 30%, which is substantially less than for microwave type tubes. The low efficiencies are largely attributed to transit-time effects and limitations imposed by practical circuits.

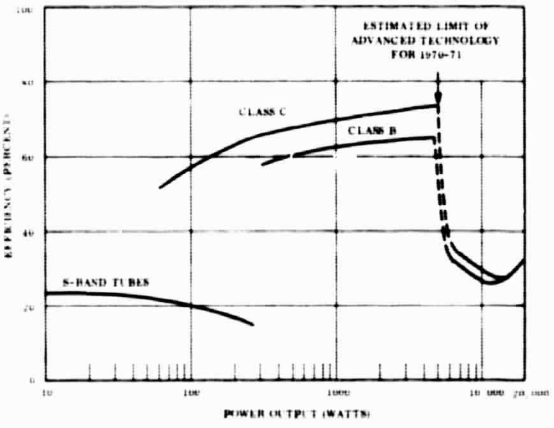


FIGURE 10. GRIDDED TUBE EFFICIENCY - UHF AND S-BAND

2.2.1.2 SOLID STATE DEVICES

Solid state devices, which largely include transistors, varactors, and bulk effect devices, were considered because of their long life capabilities as well as their moderately high efficiency. Their limitation when used in a transmitter lies in the low gains for transistors, usually 5 to 6 dB for the frequencies and power levels of interest. Problems with the other devices include the large driver requirements for the passive varactor diodes, and limited CW power from bulk effect devices. Figure 11 includes efficiencies for transistors and varactors. Predictions for 1970 were not obtainable from manufacturers who were reluctant to indicate expected performances either for competitive reasons or because of unpredictable breakthrough potentials now in progress. The predictions shown in Figure 11 were based on estimates by the Electronics Laboratory of GE.

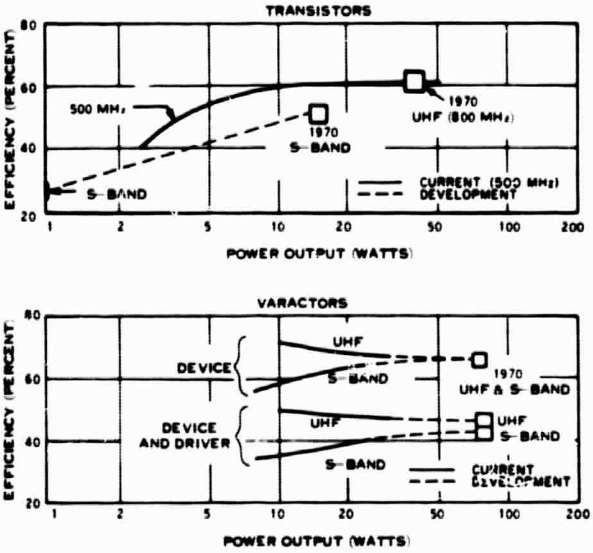


FIGURE 11. EFFICIENCY VS POWER OUTPUT FOR TRANSISTORS AND VARACTORS

2.2.1.3 MICROWAVE TUBES

This survey considered three types of tubes: TWT's, Klystrons, and CFA's. The survey data resulted in a set of curves indicating that the linear CFA was more efficient than klystrons or TWT's for AM TV at all frequencies (other tubes cannot provide good efficiency over the wide dynamic range involved). For FM TV transmission, the CFA was also preferred at UHF due to size and efficiency; but, the TWT's and klystrons were preferred at the higher frequency bands. Efficiencies of the tubes tend to decrease at low power levels due to nonoptimum element configurations required by the relation of frequency and tube geome-

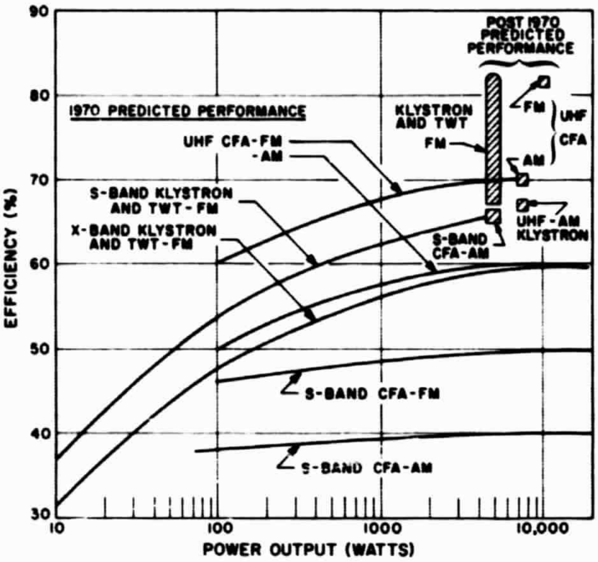


FIGURE 12. TYPICAL MICROWAVE TUBE EFFICIENCIES

try. Figure 12 shows the efficiency as a function of power level for the linear CFA at UHF and S-bands, and klystrons and TWT's at S- and X-bands. Since the initial survey, some advancements in performance of post-1970 state of the art tubes have been predicted as a result of several tube study contracts from NASA's Lewis Research Center. These points are shown on Figure 12. The overall efficiencies are significantly higher. If the requirement for a 1970 state-of-the-art is extended several years, then the MKTS results would be altered to increase the efficiency curves of CFA's, TWT's and klystrons. Klystrons would then become contenders for UHF/AM applications. The basic advancement is the depressed collector configuration which avoids the erratic performance formerly caused by reflected and secondary electrons drifting back up the beam.

2.2.1.4 PREFERRED DEVICES

Gridded tube efficiencies are only high enough for practical satellite transmitters in the UHF band. Tubes at higher frequencies are inherently very low in efficiency, and, therefore, were eliminated from further consideration. Solid state devices have good efficiencies at both UHF and S-bands. Of the microwave type tubes, the CFA provides the greatest efficiency at UHF, AM, and FM, and is the only practical tube for S-band AM. However, S-band and X-band FM efficiency is greatest for the TWT and klystron. The low efficiency tubes are eliminated from further consideration since the ultimate transmitter efficiencies will be very close to these tube efficiencies. Table 2 summarizes the results and lists the devices evaluated in the transmitter parametric analysis.

TABLE 2. APPLICABLE DEVICE TYPES FOR 1970 STATE-OF-THE-ART

TYPE	MODE
GRIDDED TUBE	UHF AM & FM
TWT	S-AND X-BAND FM
KLYSTRON *	S-AND X-BAND FM
CFA	UHF AM & FM S-BAND AM
SOLID STATE	UHF AND S-BAND AM & FM

* [FOR A POST-1970 STATE-OF-THE-ART. THE KLYSTRON MAY ALSO APPLY TO UHF AND S-BAND AM.]

2.2.2 TRANSMITTER PARAMETRIC DATA

The transmitter parametric analysis involved assuming typical transmitter configurations, using devices selected from the Device Survey, and determining efficiencies, weights, and costs. For this task, single channel transmitters were assumed. Multiple output stages were paralleled when power requirements exceeded the device upper limit. Also included are parametric data on power combiners and dividers, and on frequency multiplexers. The multiplexers would permit more than one TV transmitter to utilize the same antenna.

The basic transmitter configuration for AM visual signals (such as used in standard TV broadcasting) consists of an RF chain for the visual signal, and a separate low power chain for the accompanying aural RF signal. The audio RF is considered to be FM for most applications, although AM was included to provide a complete system coverage. A level 10 dB below the visual peak signal was assumed. Figure 13 is block diagram of the transmitters. The second circuit shown is for FM TV operation. From a brief analysis, the effect of combining the aural and visual signals into a single channel in the AM TV case leads to a substantial reduction in visual RF output, to about 50% of the separate channel configuration. Efficiency is also lower since the picture signal must operate at a level where the tube efficiency is usually poorer. For FM, this is not the case, provided the aural signal is on an FM subcarrier; then, the visual signal is merely reduced by about the 10% power assigned for the aural signal, and efficiency is essentially unchanged.

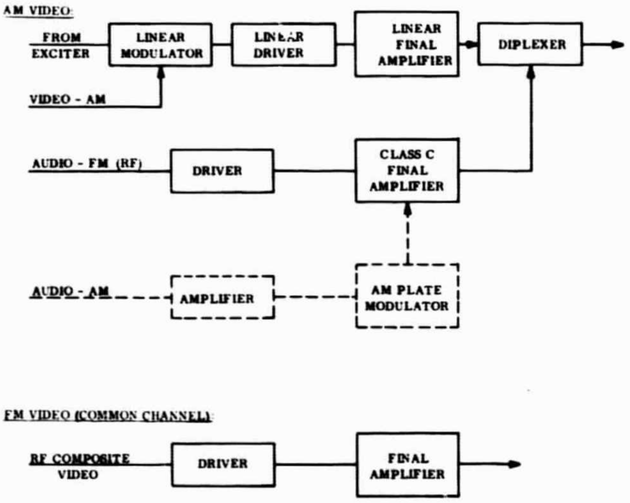


FIGURE 13. TRANSMITTER CIRCUITS

2.2.2.1 GRIDDED TUBE TRANSMITTER EFFICIENCY

The transmitter circuits of Figure 13 were used at different power levels for both AM and FM visual signals. The L-64S and L-65S tubes, were used to plot the efficiency curves of Figure 14. Reduced efficiency at lower power levels was generally due to the combination of less tube efficiency and a greater percentage of loss in driver circuits. For the AM visual case, efficiencies are for peak signal levels. This is somewhat unrealistic since the average TV signal is at a much lower power level when considered over a frame. One average case is shown in Figure 14, corresponding to about a 32% average amplitude relative to the peak sync pulse. Also shown is a typical efficiency for S-band transmitters.

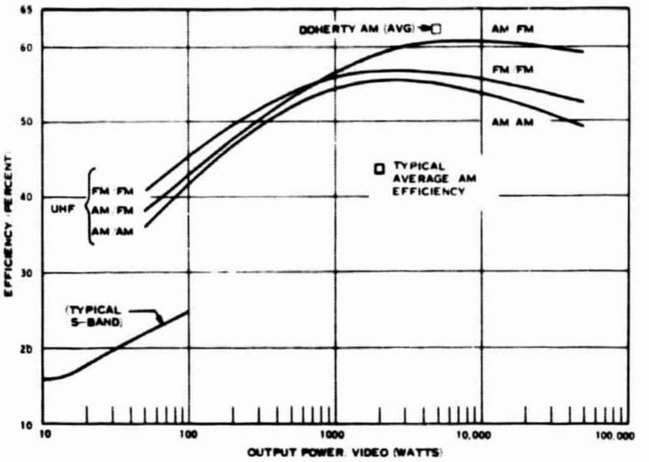


FIGURE 14. EFFICIENCY OF GRIDDED TUBE TRANSMITTERS

Maximum power level is a little over 100 watts, and efficiencies may approach about 25% peak (which is far below that of the microwave type tubes). Thus, gridded tube recommendations are confined to UHF.

2.2.2.2 GRIDDED TUBE HIGH EFFICIENCY CIRCUITS

The AM transmitters described in the previous paragraph assumed a Class B linear final transmitter stage, but the average efficiency of such a stage is relatively low. An alternative is to employ one of several high-efficiency output stages; the average efficiency for a Doherty type circuit is shown in Figure 14. Because of the stress on efficiency for space transmitters, gridded tube recommendations include the development of the Doherty (or similar) circuit.

TABLE 3. HIGH EFFICIENCY UHF/AM AMPLIFIERS

Circuit	Approximate Efficiencies	
	Peak Sync (percent)	Average (percent)
Class B Linear	60	40
Linear CFA	70	60
Dome "Class C" Linear*	75	53
Class C Plate Modulated* (1970 potential)	75	60
Terman-Woodward (Needs Heavy VSB Filter)	73	72
Doherty (Preferred)	65	62
Dome (Transmitter)	60	57
Chireix Outphasing	60	55
Fisher (varies with design)	60	55

*Not considered practical for TV

Table 3 lists a number of AM TV circuits, including the linear CFA which will be discussed below. The Doherty was selected on the basis of good efficiency and operability with a small vestigial sideband filter.

2.2.2.3 SOLID STATE TRANSMITTER EFFICIENCY

High powered transistor transmitters are, of necessity, made up of a large number of low power modules in parallel. There is a small loss in the output power combiners, but the larger loss is a consequence of the device low gain, which necessitates a large number of driver stages that absorb DC power but do not contribute to the RF output. Since all modules have the same efficiency, the transmitter efficiency should be nearly constant regardless of transmitter output power above a one-module size. Figure 15 shows that the efficiencies are nearly constant with power level, and the overall efficiencies are low. Thus, this type of transmitter is recommended largely for low power operation or as drivers, where the efficiencies of the various tubes become small and the solid state becomes advantageous for other reasons such as reliability.

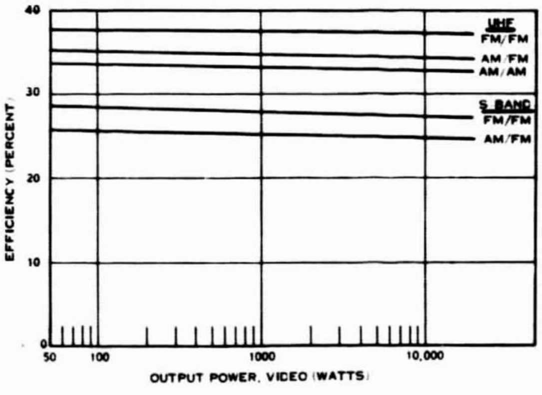


FIGURE 15. TRANSISTOR TRANSMITTER EFFICIENCY

2.2.2.4 MICROWAVE TUBE TRANSMITTER PARAMETRIC ANALYSIS

Transmitters for microwave type tubes were considered for all bands. The linear CFA can provide AM visual signal transmission at all bands, although only UHF and S-band were considered as having merit. For FM transmission, the CFA was included at UHF and the linear beam tubes (TWT or klystron) for S- and X-bands. In Figure 16, single tubes were assumed for all cases; the data assumed were the 1970 state-of-the-art survey data which were shown on the device efficiency curves, Figure 12. In general, the curves tend to follow the device efficiency curves since the devices make up a major part of the transmitter. Lower tube efficiency and proportionately more drive circuitry tends to reduce low power efficiencies somewhat. If the newer (post-1970 state-of-the-art) tubes shown in Figure 12 were considered, higher efficiencies would result.

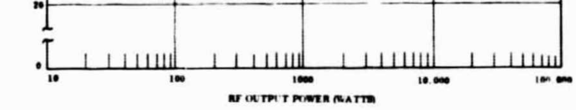


FIGURE 16. MICROWAVE TUBE TRANSMITTER EFFICIENCIES (1970 TECHNOLOGY)

2.2.2.5 TRANSMITTER WEIGHTS

Transmitter weights, to provide a common comparison basis, were assumed to include one channel of audio and video. The redundancy question, which relates to tube life, could change the overall picture, but insufficient data was available for determining comparable configurations for the different tubes and solid state devices. The data shown in Figure 17 generally indicates the expected results. Gridded tube transmitters are slightly lighter than microwave tube types (except at highest powers) because of the low tube weight, but the difference is not critical. Solid state transmitters become quite heavy due to the modular construction; this might be reduced by a research effort to reduce module weight, but present techniques result in large weights relative to the other devices.

The higher weights for high power gridded tube transmitters are a result of paralleling modules. If higher power single tubes are manufactured, the weight would be reduced because of the smaller quantity of circuitry and because no power combiner is required.

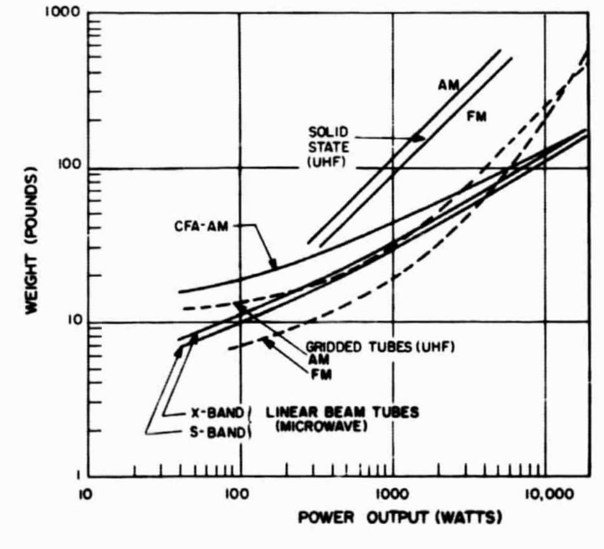


FIGURE 17. TYPICAL TRANSMITTER WEIGHTS (ONE CHANNEL)

2.2.2.6 TRANSMITTER COST

The cost of transmitter configurations was a third parameter used in comparing the various possible cases. The costs were divided into engineering cost to obtain a flight qualified unit, and fabrication costs required for each unit produced after the engineering model is completed. The engineering costs include the transmitter development plus the tube life and qualification testing, but not R&D for the transmitter circuit development or for tube development.

In general, the costs for any particular transmitter is dependent largely on tube (device) type and varies little with frequency. Figure 18 shows the engineering and fabrication costs for the gridded tube transmitter, solid state transmitter, and the microwave tube types (Klystron, CFA, and TWT). The CFA and linear beam tube transmitters are one-tube configurations, resulting in costs which are proportional to power level. Solid state and gridded tubes are assumed to be incorporated into modular transmitters, with module powers of 50 watts and 2.5 KW, respectively. Fabrication costs rise somewhat with power until the one-module level is attained; then, the cost goes up approximately in proportion to the number of modules involved. The power combiner cost is assumed to be included in the cost curves of Figure 18 where multi-modules are used.

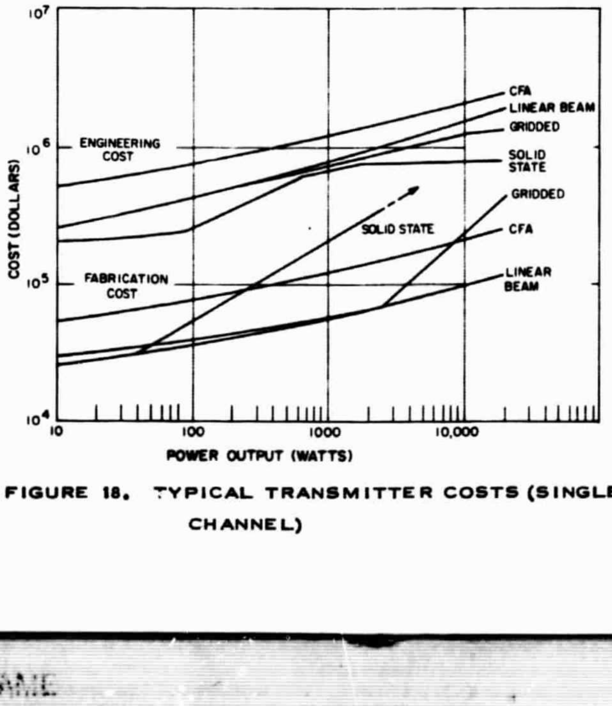


FIGURE 18. TYPICAL TRANSMITTER COSTS (SINGLE CHANNEL)

Again, the curves of Figure 18 do not include redundancy, which is not well defined yet. However, the gridded tube transmitter has a slightly lower engineering plus fabrication cost compared with the solid state transmitter cost, which is competitive at very low powers. The gridded tube transmitter has a much lower cost compared to the CFA which, however, may be competitive on a system basis due to its higher efficiency and lower power supply requirements for a given output power.

2.2.3 AUXILIARY RF COMPONENT PARAMETRIC ANALYSIS

2.2.3.1 POWER COMBINER/DIVIDER PARAMETRIC ANALYSIS

Power combiners are required where multiple output tubes (devices) are required, such as for solid state transmitters and for gridded tubes above a single tube capability. The same type of equipment can be used for power dividing to feed array antennas by a single tube transmitter. Efficiency was important in the transmitter evaluation. Figure 19 indicates efficiencies for various frequencies and transmission line types. Strip-line is very lossy and is recommended only for low powers, under 100 watts. Coaxial transmission line is of value at UHF to reduce volume, while straight waveguide configurations are recommended for all high power operations and for all X-band configurations.

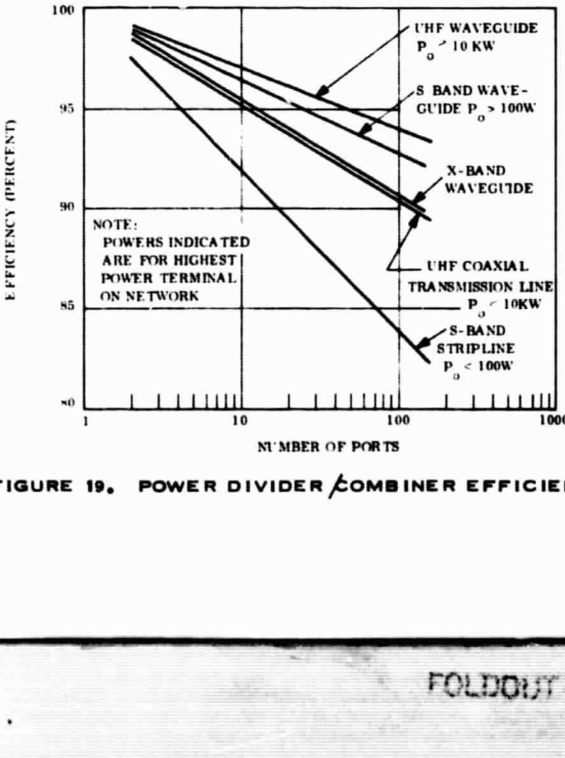


FIGURE 19. POWER DIVIDER/COMBINER EFFICIENCY

2.2.3.2 MULTIPLEXER PARAMETRIC ANALYSIS

Frequency multiplexers are required when more than one channel is to be transmitted simultaneously by a single antenna feed. For AM visual transmitters, separate transmitters are required, and outputs must be combined without mutual interference. Thus, the multiplexer must be a filter arrangement which permits certain frequencies to pass to the antenna, but prevents other frequencies from entering the output terminal of the final stage. The efficiencies for such devices depend on the type, number of channels, and separation. For the efficiency data of Figure 20, a nominal frequency separation was chosen such that further separation would not greatly influence the evaluation parameters. As before, the waveguide type is least lossy, coaxial line is next, and stripline, which is the lossiest, is recommended only for low power levels. Waveguide tends to be heaviest, stripline lightest; cost of stripline is also much less than waveguide and coaxial line, which tend to be about equally expensive.

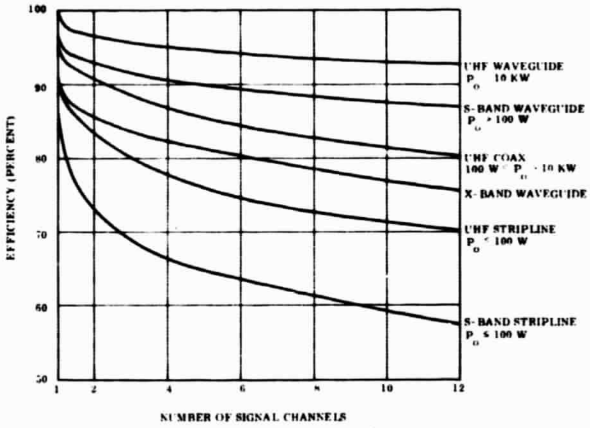


FIGURE 20. EFFICIENCY OF MULTIPLEXER

2.2.3.3 VSB FILTERS

Vestigial sideband filters (VSB) will probably be required for UHF-AM transmission since satellite TV transmitters will be competing with ground transmitters for spectrum space. In such situations, double sideband operation is not likely to be tolerated. Conventional VSB filters have good efficiencies, but are heavy and voluminous; these are undesirable characteristics for satellite applications. One solution to weight reduction, which will also reduce power loss, is to use low level input-type VSB filters with linear final amplifiers rather than the large high-level output-type filters. This subject will require additional evaluation, but results will apply to all UHF-AM transmitters.

2.3 SUPPORT TECHNOLOGY PARAMETRIC ANALYSIS

Three supporting subsystems were considered in the parametric analysis of the transponder: the power conditioner, the uplink receiver, and the thermal control equipment. These were combined with the transmitter parametric data to produce overall transponder parametric data presented in Section 2. Figure 21 indicates these relationships as included in the study.

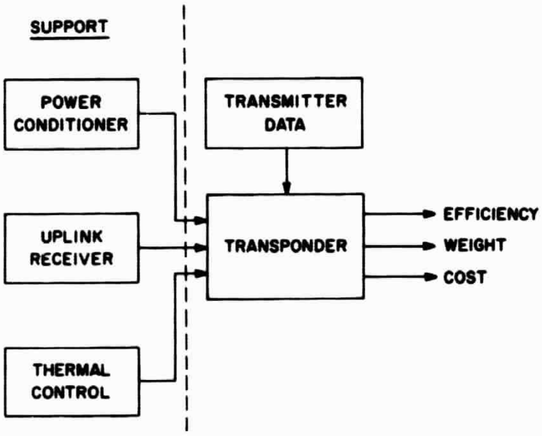


FIGURE 21. SUPPORT TECHNOLOGIES PARAMETRIC ANALYSIS

2.3.1 POWER CONDITIONER

The power conditioner accepts a DC input voltage from a prime power source, regulates it, and converts it to the voltages required by the transmitter and associated equipment. Nominal input voltages for the parametric analysis were assumed to be 45, 300, and 2000 volts. Efficiency of the conditioner tends to rise with power output due to more efficient use of the components in the circuitry. Figure 22 indicates that the efficiency for a 300 volt input reaches 90% at about the 5 KW level, which was assumed to be the one-module limit based on thermal considerations for the transformers. For a 45 volt input, the larger conductors required offset the efficiency improvement and about 85% is realized. For higher power levels, parallel conditioners are used; this decreases efficiency by the loss in the power combining device. The 2000 volt input case is not likely to be available from a solar array by 1970, but should have an efficiency close to that for 300 volts. Output voltage is not a major efficiency factor; the 300 volt input is assumed for all tube-type transmitters.

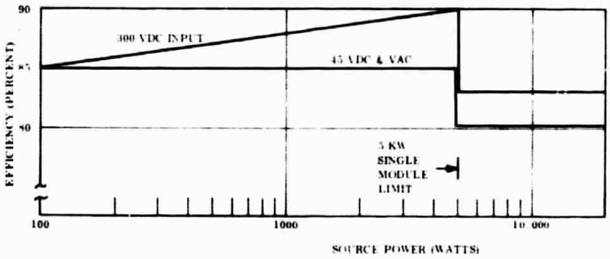


FIGURE 22. CONVERTER/REGULATOR EFFICIENCY

Weight is slightly less for the 300 volt input approach, while cost is closely related to power requirements. Figures 23 and 24 show the specific weights and costs for the conditioner. The specific weight (that is, pounds per kilowatt) is not significantly affected by the total power level since the heavy components are scaled closely to the power level. Costs were generally a function of power, and output voltage did not contribute significantly to the curves shown.

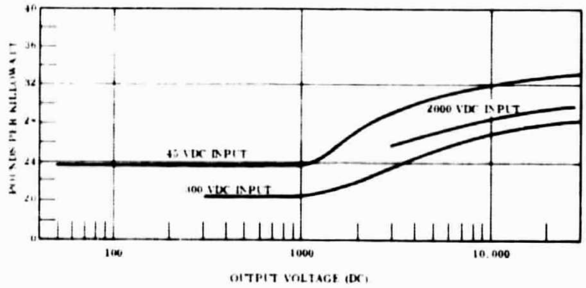


FIGURE 23. POWER CONDITIONER WEIGHT

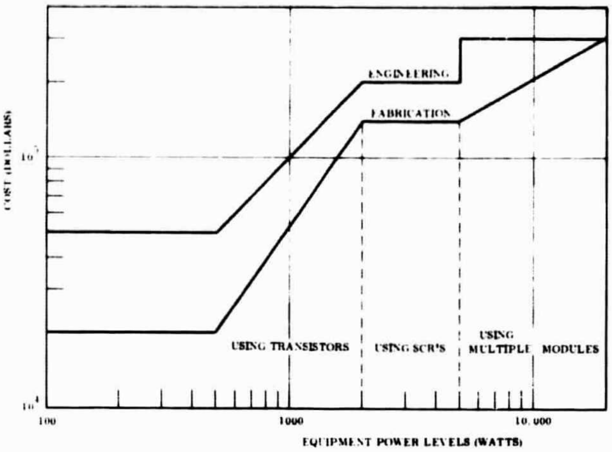


FIGURE 24. POWER CONDITIONER COSTS

2.3.2 THERMAL CONTROL

Active cooling systems were not recommended due to the inherent low reliability of the pumps, plumbing and components for a minimum two year satellite mission. Experimental heat pipes have been constructed and substantial success achieved with a configuration in which heat pipes in the surface of the radiating plate distribute the heat across the plate at the highest (and most effective) temperature. The thermal control method selected was based on using passive heat pipes, combining these with radiation plates to dissipate the heat into space. Weight and cost were nominal, and were included in the transponder parametric analysis.

The major concern was the required amplifier temperature which directly determined the area of the radiating plate and the equipment weight. In Figure 25, solid state devices which must operate near 100°C are heaviest, microwave tubes at 200° to 300°C will require less radiation area and are lighter, while the L-64S tube with an anode temperature near 500°C requires the least area and weight.

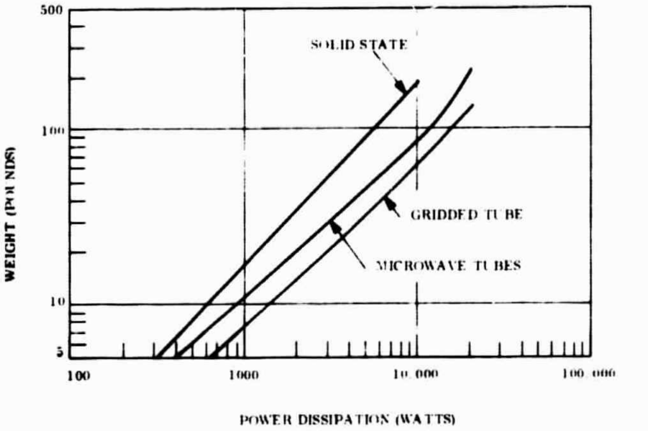


FIGURE 25. WEIGHTS OF THERMAL CONTROL DEVICES

Costs had a reverse trend, with the lowest temperature being the easiest to engineer and construct and, therefore, the lowest in cost, as indicated in Figure 26. Organic fluids would be used in high temperature heat pipes; water would be used for solid state equipment and lower temperature tubes.

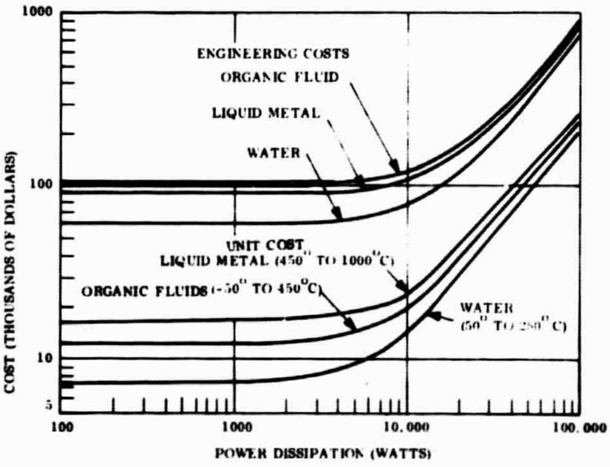


FIGURE 26. EXPECTED COSTS FOR RADIATOR PLATE WITH HEAT-PIPE FINS

Another heat pipe constraint concerns affixing the pipe to the transmitter tube, particularly where the interface is at a high voltage. Current experimental data indicated the problem not to be critical. A brazed insulator results in only slightly more temperature differential across the interface than a copper spacer, where boron nitride is used as the insulator. A clamped junction on the other hand, has a considerable resistance to heat flow, creating a substantial temperature drop. Table 4 lists typical temperature differentials for a heat flux density of 100 watts per sq cm, about the practical limit. Since large temperature differentials mean the tube will operate at a higher temperature, there must be some concern on where to place the insulation and clamped junctions in the system.

TABLE 4. INTERFACES WITH HEAT PIPES

TYPE OF INTERFACE	TEMPERATURE DIFFERENTIAL (°C)
	100 W/CM^2
BRAZED	0.5
COPPER SPACER BRAZED	8
CLAMPED	45
BRAZED WITH BORON NITRIDE INSULATION (6 KV OPERATION)	10
BRAZED WITH BERYLLIUM OXIDE INSULATION (3 KV OPER)	5

2.3.3 UPLINK RECEIVER

The state-of-the-art was found to be currently adequate for developing a suitable uplink receiver, although future developments in parametric amplifiers would improve the performance over current tunnel diode amplifiers. The cost, weight, and power of receivers were insignificant with respect to overall satellite cost, weight, and power. Therefore, a representative receiver was employed in developing the parametric data presented earlier. Figure 27 is a block diagram of the typical multichannel receiver used in the parametric analysis. The uplink channels were assumed to be FM which would give a better S/N than AM. The receiver in the satellite would convert to AM for an AM transmitter, or retain the FM for an FM transmitter. The receiver is shown with a capacity for 12 simultaneous channels at an uplink frequency of about 8 GHz. Each of the three receiver chains can handle up to four FM signals; the output TWT bandwidth limits the number of FM channels per chain. In the parametric analysis, only the number of channels used by the transmitter was assumed.

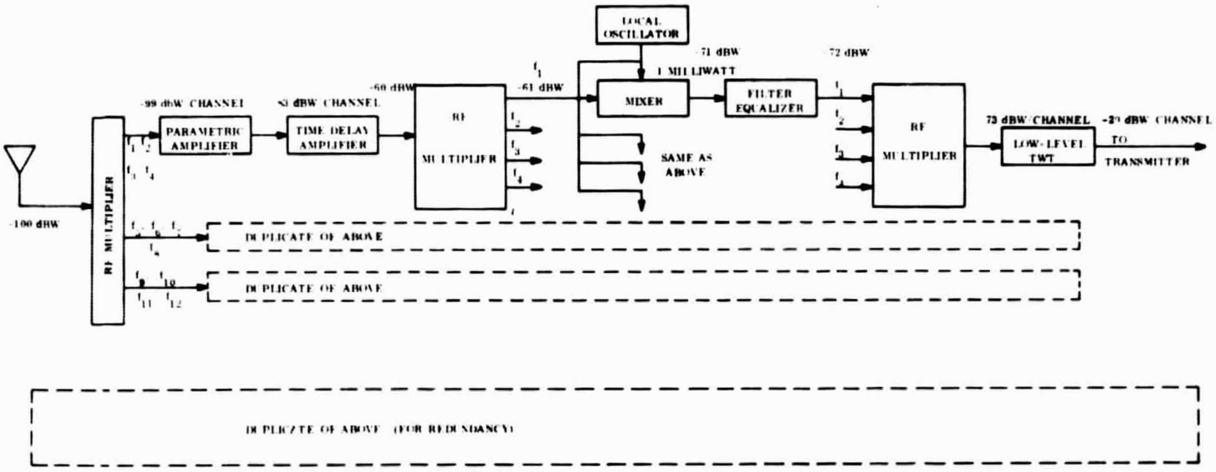


FIGURE 27. TYPICAL SATELLITE RECEIVER BLOCK DIAGRAM—12 CHANNELS

SECTION 3
DESIGN STUDY

3.1 TRANSMITTER STUDY

From the parametric analysis and assumed system operating requirements, three representative transmitter types were selected for a conceptual design study. The three selected were: UHF-AM Gridded Tube Transmitter (Doherty high efficiency circuit), S-band FM TWT Transmitter (adaptable to X-band), and UHF-AM CFA Transmitter.

One possible mission is direct TV broadcasting to conventional home receivers which are designed for AM operation. Two of the three representative transmitter designs are adaptable to this particular type of mission. Broadcasting is considered a feasible mission at the higher frequencies for use by heavily populated areas using a community antenna with converter and cable distribution, by conventional home receivers with converters, and by special receiving installation in schools, community viewing centers, etc.

Table 5 lists the three transmitters with the numbers of channels, power, efficiency, weight, and cost for each. The design study delineated the electrical, thermal, and mechanical configurations for these three transmitters.

TABLE 5. THREE TRANSMITTER CONCEPTUAL DESIGNS

1. UHF-AM GRIDDED TUBE TRANSMITTER
   - TOTAL RF OUTPUT POWER = 20 KILOWATTS
   - 4 CHANNELS – 5 KILOWATTS PER CHANNEL
   - TRANSPONDER EFFICIENCY = 43.5%
   - TRANSPONDER WEIGHT = 40.5 POUNDS/KILOWATT
   - TRANSPONDER COST = $210,000/KILOWATT
2. S-BAND FM TWT TRANSMITTER
   - TOTAL RF OUTPUT POWER = 20 KILOWATTS
   - 8 CHANNELS – 2.5 KILOWATTS PER CHANNEL
   - TRANSPONDER EFFICIENCY = 47.9%
   - TRANSPONDER WEIGHT = 101 POUNDS/KILOWATT
   - TRANSPONDER COST = $200,000 KILOWATT
3. UHF-AM CFA TRANSMITTER
   - TOTAL RF OUTPUT POWER = 15 KILOWATTS
   - 1 CHANNEL
   - TRANSPONDER EFFICIENCY = 44.2%
   - TRANSPONDER WEIGHT = 42.2 POUNDS/KILOWATT
   - TRANSPONDER COST = $270,000/KILOWATT

3.2 UHF–AM GRIDDED TUBE TRANSMITTER

This 4-channel transmitter uses four Doherty circuits, each with two L-64S tubes. The output from each transmitter channel is fed into a multiplexer, and the composite RF signal is transmitted.

To obtain a high efficiency level for an overall TV signal, a Doherty type circuit is employed. This circuit uses two L-64S tubes in the visual channel to provide a 5 KW peak sync signal, and one L-65S tube to provide 500 watts FM audio required. Figure 28 shows a circuit diagram of such a transmitter. This circuit has not been used in the UHF region and has received little (known) attention for a TV application. Thus, the techniques required to implement this circuit will require analysis and breadboarding to demonstrate feasibility.

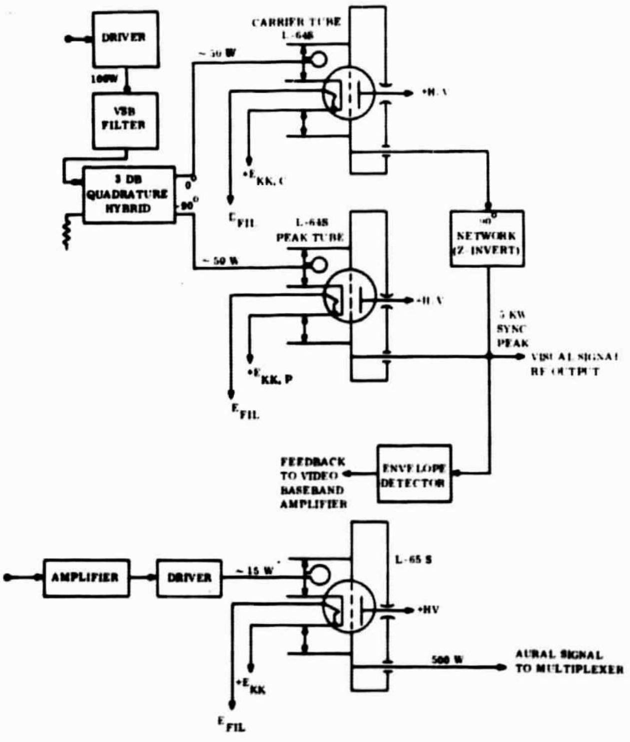


FIGURE 28. FIVE KW UHF TV TRANSMITTER CHANNEL

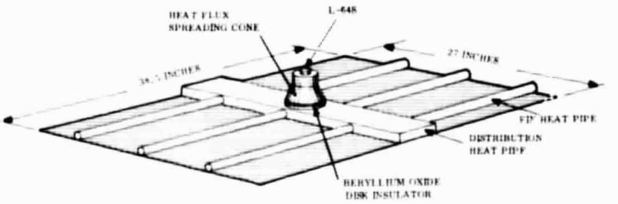
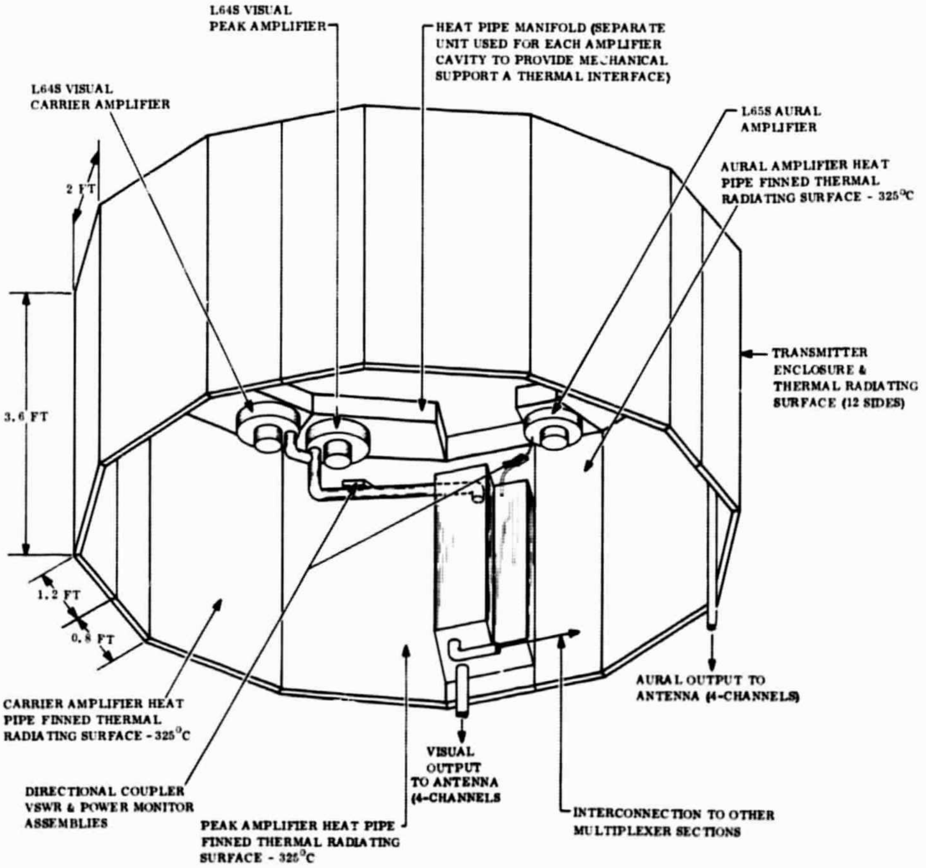


FIGURE 29. THERMAL CONTROL SYSTEM FOR A GRIDDED TUBE TRANSMITTER

Thermal control of the L-64S tube is also a problem due to the relatively high voltage on the anode and the high heat flux density. The L-64S will operate with an anode internal temperature of 500°C. This is an advantage in that a smaller radiator plate can be used to dissipate the heat than if a lower temperature were used. Figure 29 shows the recommended design technique of using a solid copper cone to spread the heat flux density and using a boron nitride insulator. Attached is a "finned radiator" using several heat pipe "fins" set into the radiator plate. The mechanical requirements imposed by the circuitry are shown in Figure 30. Here a 16-panel cylindrical enclosure provides heat radiating plates for the four transmitters and the output waveguide assembly. The configuration is intended to show some of the factors involved in integrating the mechanical and thermal requirements into a common enclosure design.

3.3 S–BAND FM TWT TRANSMITTER

The second transmitter selection was based on providing FM service at



NOTE:
HIGH-POWER STAGES SHOWN FOR
ONE TV CHANNEL ARE TYPICAL
OF THE OTHER THREE CHANNELS

FIGURE 30. MECHANICAL ARRANGEMENT OF A FOUR-CHANNEL GRIDDED TUBE TRANSMITTER

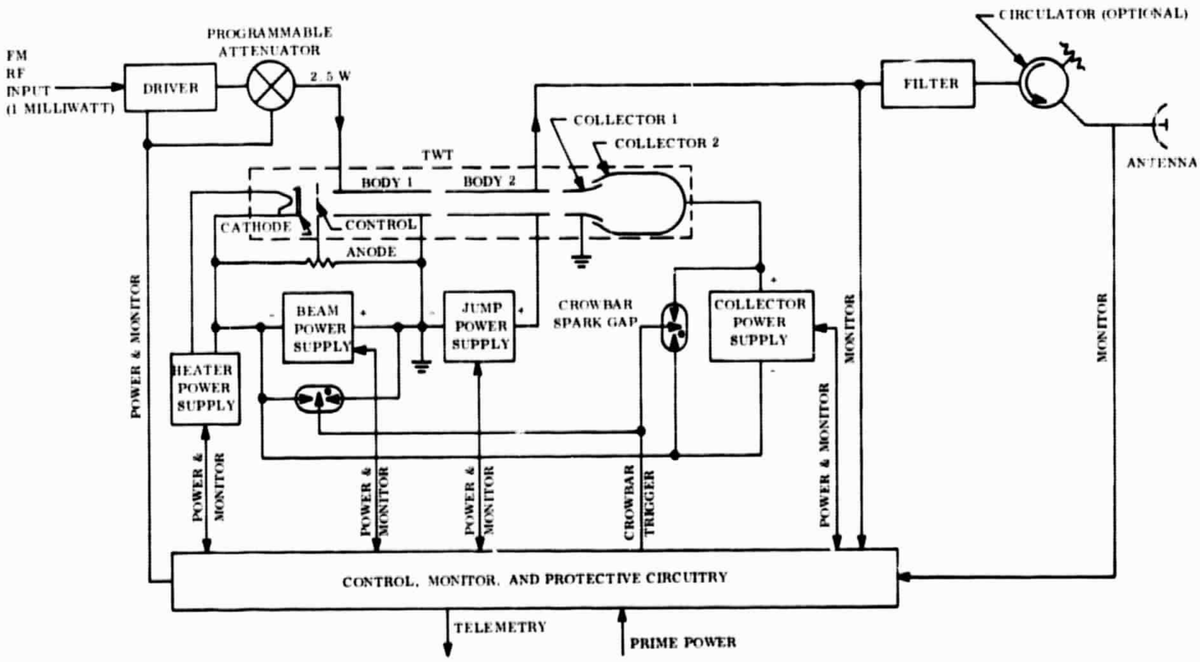


FIGURE 31. CIRCUIT FOR FM TWT TRANSMITTER

S-band or X-band. FM transmission can provide a better S/N than AM with a given transmitter power, but imposes a corresponding requirement for an FM/AM conversion on the ground. The transmitter is assumed to have eight available channels, with six operating at any one time and two on standby. One configuration for combining the several channels involves an eight channel multiplexer using isolation filters. Other configurations could utilize separate antennas for each channel or pair of transmitters, or could employ antenna polarization isolation in which four channels use right hand circular polarization and the other four left-hand. (The system implications of polarization isolation have not been assessed, however.)

The transmitter is relatively straightforward, since the tube is the major part of the transmitter. The high gain of 40 dB or more permits the use of a lower power driver, and the single channel output waveguide would only include a harmonic filter and the connection to the multiplexer. Since the aural channel is on an FM subcarrier, no separate aural RF amplifier is required. The circuit shown in Figure 31 includes power supplies and protective circuits, which will be required for all satellite transmitters.

Thermal control is a persistent problem; it differs from that of the gridded tube in that the TWT collector may operate at about 300°C while the body should be kept at about 200°C. For greatest thermal system effectiveness, the two tube sections should have separate "finned radiators", somewhat as shown in Figure 32. Here the collector with its higher thermal power and higher temperature uses

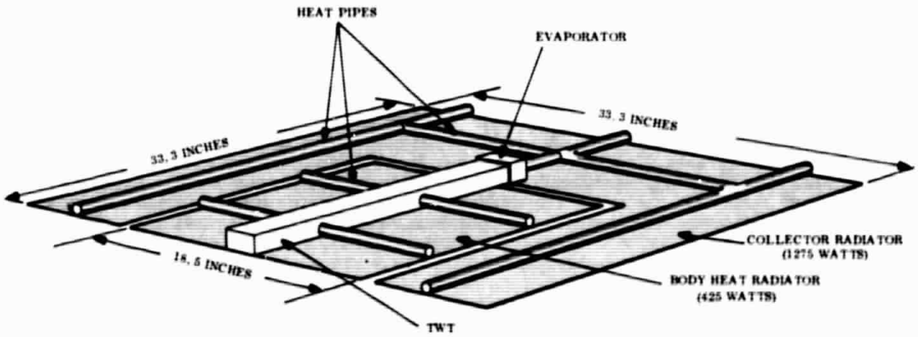


FIGURE 32. THERMAL CONTROL SYSTEM FOR TWT TRANSMITTER

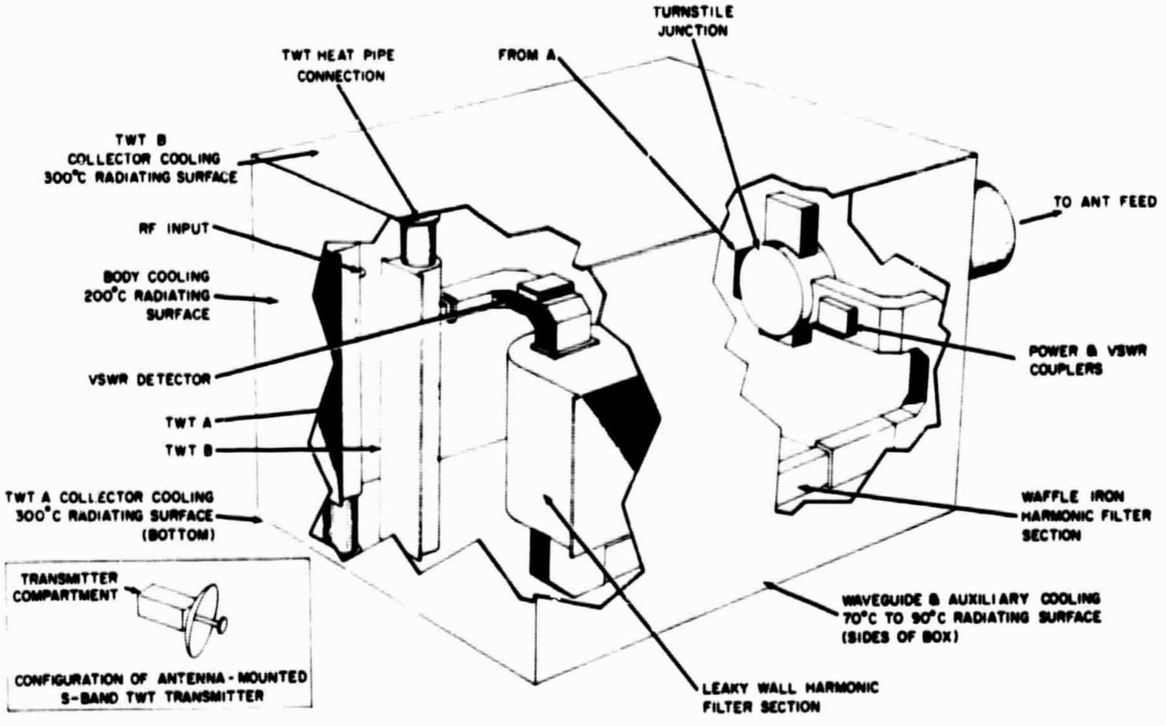


FIGURE 33. MECHANICAL ARRANGEMENT OF TWO CHANNELS OF S-BAND TWT TRANSMITTER

the outside part of the radiator plate, while the body with a lower temperature and thermal power used the inside section.

One suggested mechanical enclosure for the TWT transmitter is such that the outside surfaces serve as heat radiator plates. This configuration has two TWT transmitters in each of four volumes. As shown in Figure 33, the surfaces are used for cooling the waveguide assembly as well as the tubes with the two different temperature requirements on each.

3.4 UHF–AM CFA TRANSMITTER

The third transmitter considered was a high power, one tube, UHF-AM CFA transmitter with 15 KW peak sync output power. The circuit is fundamentally like the TWT just described, since most of the final amplifier stage is integral with the tube. For the linear CFA, a number of collector plates at different potentials are required. This complicates the power supply subsystems as can be deduced from Figure 34. Several collector rings will be used, although a firm number has not been determined. Again, the power supplies and protective circuits are shown. Since this is an AM visual channel transmitter, a separate aural FM channel is shown, and a diplexer must be included for combining the two RF signals. An L-64S gridded tube can provide the 1.5 KW aural power required.

The thermal problem is somewhat more difficult in the CFA since the slow wave circuit tends to have a very high heat flux density. An approach involving several connecting heat pipes has been considered but will require additional evaluation for the dissi-

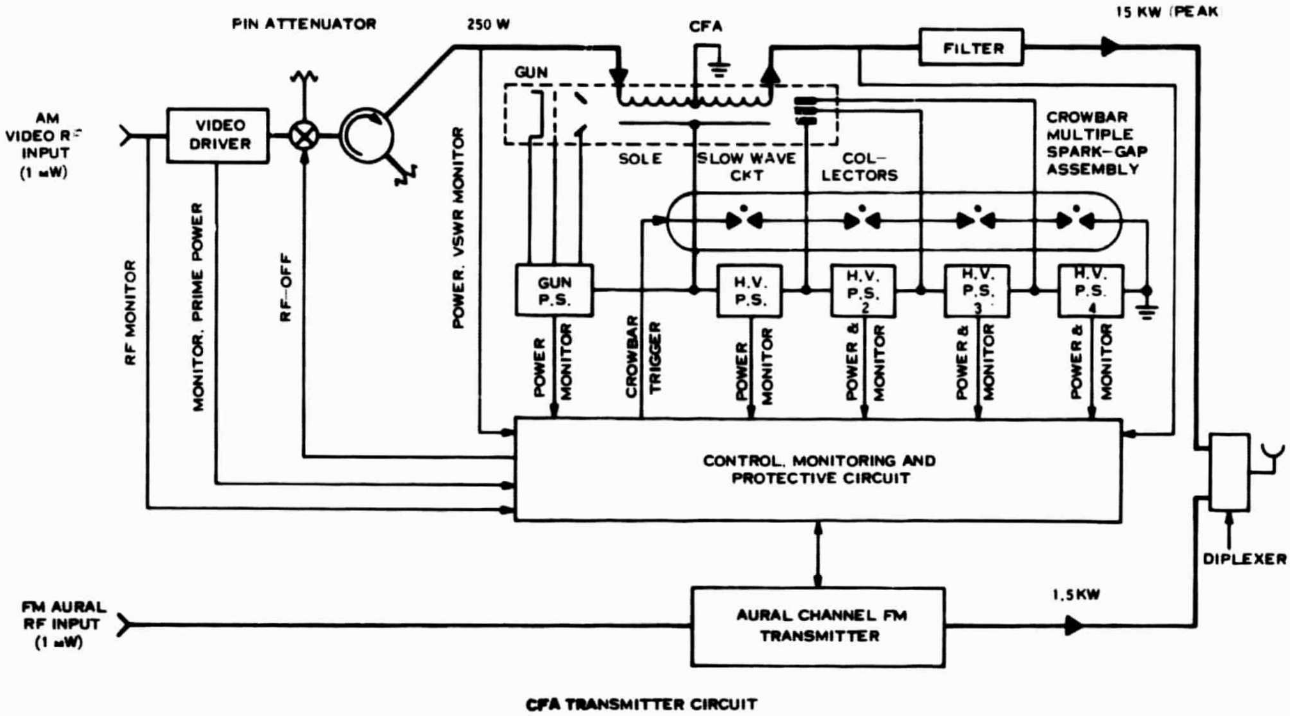


FIGURE 34. CFA TRANSMITTER CIRCUIT

pation power levels involved. Figure 35 shows a technique for attaching several heat pipes from the slow wave structure to a common condenser which is also used by the collector and sole heat pipes. Fortunately, the three cooled regions of the tube can operate at the same temperature.

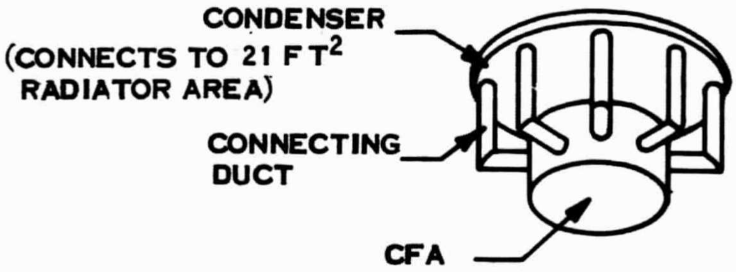


FIGURE 35. CROSSED FIELD AMPLIFIER THERMAL CONTROL SYSTEM

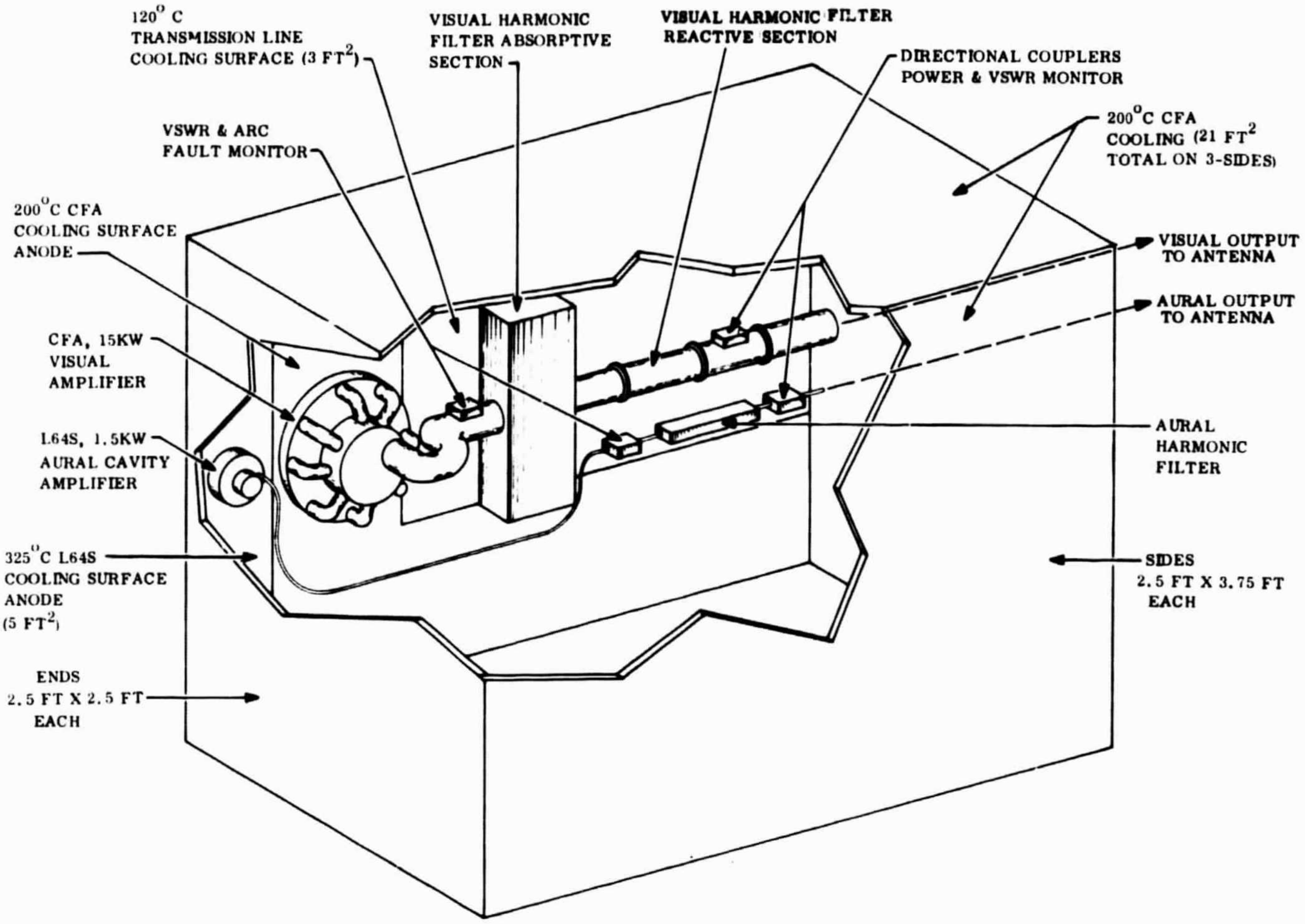


FIGURE 36. DIAGRAM OF CFA TRANSMITTER
THERMAL CONTROL SURFACES

A typical mechanical configuration was devised for the single CFA transmitter. The circuit, being basically high power in nature, has a significant heat loss in the waveguide system. Thus, the enclosure's heat radiating plates must handle this dissipation adequately as well as the tube's heat dissipation. The sketch shown in Figure 36 includes both the visual and aural RF channels, and all circuitry except the diplexer.

SECTION 4

KEY TECHNOLOGY AREAS

The results of the parametric analysis and design problems associated with the three conceptual designs identified key technology areas which should be investigated prior to initiating a development program on specific high power transmitters or transponders. Table 6 lists these technology problem areas which include investigation of components and techniques as yet unproven for high power, long life operation in the space environment, and unique system interface problems associated with high power transmitters.

Tubes used in the power amplification stage of high power, long life space transmitters represent the basic key problem since no proven device exists and since the development and qualification test cycle for tubes has historically run from four to six years. The technology problems associated with klystrons, traveling wave tubes and crossed field amplifiers for multikilowatt space transmitters are currently being investigated under separate NASA studies. Multikilowatt gridded tubes are further along in the development cycle because of DOD and industrial programs; however, these need modifications to make them suitable for long life operation in space. All tubes will require prototype design and long life qualification testing prior to the start of a satellite program to lower the schedule and cost risks associated with a total satellite program.

TABLE 6. KEY TECHNOLOGY AREAS

COMPONENTS

- TUBES - QUALIFICATION AND LIFE TESTS
- HYBRID & TERMINATIONS
- MULTIPLEXERS
- VSB FILTERS

TECHNIQUES

- MATERIALS EFFECTS
- DC HIGH POWER
- RF HIGH POWER
- HIGH EFFICIENCY AM AMPLIFIERS

SYSTEM/INTERFACE PROBLEMS

- POWER CONDITIONERS
- THERMAL CONTROL
- MONITOR & PROTECTION CIRCUITS

Other components not yet proven for high power operation in space relate to the need for power combining and dividing (with terminations to remove unbalance in power inputs), multi-channel multiplexing for both FM and AM transmitters, and the vestigial sideband filtering for AM.

Techniques requiring early evaluation relate to high voltage, high power operation in the space environment. Experience has indicated that certain materials create a small atmosphere as a result of outgassing which can cause electrical breakdown in the space equipment. An evaluation must be accomplished of material effects in high vacuum, of high voltage and current effects in DC circuits (particularly the power conditioner), and of RF circuits where additional phenomena such as multipacting causes a cloud of electrons in a waveguide to disrupt RF flow.

Design techniques employing high efficiency AM circuitry for UHF-AM gridded tube transmitters need to be evaluated to exploit the favorable efficiency and the advanced development status of the gridded tube. These circuits should be breadboarded for performance feasibility testing.

Interference problems between the ransmitter and the satellite were identiied to be serious for several auxiliary subsystems. The multiple voltages, currents, temperatures, and heat fluxes of the various transmitter tube elements present a complex mechanical and electrical interface situation for both the power conditioning and thermal control subsystems. Design techniques must be nvestigated which are compatible with he material and high power limitations of space operation previously described. Efficient and low weight power conditioners will be necessary. Thermal control techniques compatible with the unique geometries of the transmitter tubes and their location in the satellite must be analyzed.

Monitor and control circuitry is a critical problem for an unattended, high power transmitter where faults must be isolated and corrected by internal decision circuitry or from ground commands based upon diagnostic telemetry data. Sensors, disconnection and isolation devices, logic circuitry, and correction techniques must be identified and evaluated for compatibility with all the technology areas previously discussed.

SECTION 5

RECOMMENDATIONS

It is recommended that the Multikilowatt Transmitter Study for Space Communication Satellites be continued into phase 2 to evaluate the technology problems discussed in Section 4. Figure 37 shows an eight month program which will analyze these technologies in proper time sequence.

Near the conclusion of Phase 2, the results of the MKTS studies can be compared with the results of the advanced klystron, TWT and CFA studies by NASA to determine the best routes for development of prototype multikilowatt spaceborne transmitters.

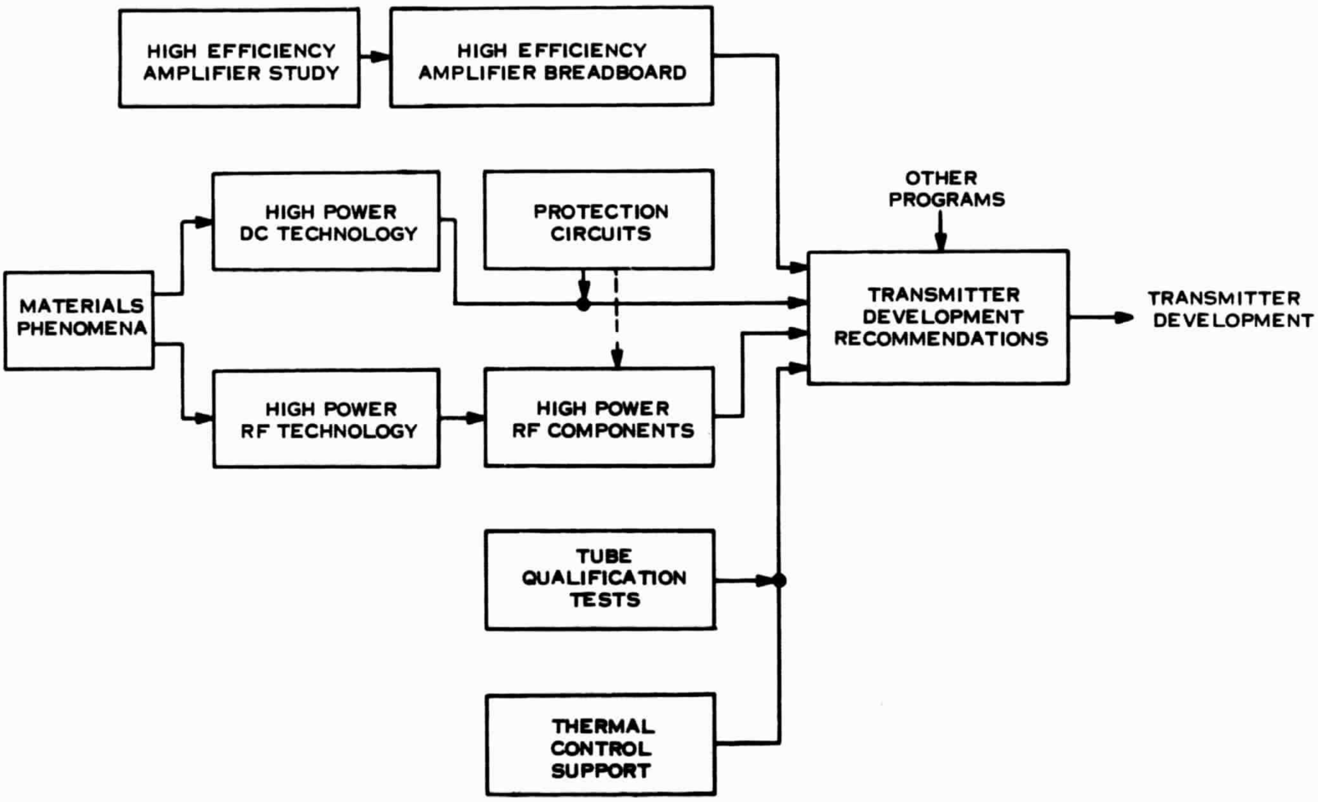


FIGURE 37. PROGRAM CONTINUATION

END

DATE

FILMED

JUL 21 1970