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ONE KILOWATT UHF POWER AMPLIFIER STUDY

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TECHNICAL REPORT AFAL—TR—75—56

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FINAL REPORT FOR PERIOD MAY 1974 — JANUARY 1975

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A study effort was conducted to determine the current state-of-the-art in one kilowatt UHF power amplifiers. Studies and investigations culminated in a final technical report containing a detail performance specification and recommended overall design approach for a solid state one kilowatt amplifier. A discussion section is provided which explains the rationale behind the recommended requirements of the detail specification.

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20. ABSTRACT - Contd.

Investigations included research into the characteristics of UHF airborne transmitters, either in existence or under development, which would be used as drivers for a power amplifier. Specific hardware investigations were conducted in the areas of RF power transistors, power combiners and splitters, and certain keying and control circuits. The results of these investigations were used to develop RF block diagram characteristics of a kilowatt power amplifier.

Additional paper studies and analyses investigated cooling requirements, primary power requirements, reliability, packaging and physical characteristics, performance advantages of a reduced bandwidth design, and a comparison of solid state and tube-type kilowatt amplifier characteristics.

FOREWORD

The work covered by this report was accomplished under Air Force Contract F33615-74-C-1157. The effort is documented under Project 1227, Work Unit 12270209, and has been administered under the direction of Mr. William R. Perrigo (AFAL/AAI) of the Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Ohio.

This report covers work performed from 1 May 1974 to 31 January 1975, and was submitted by the author in February, 1975.

This program was conducted by Electronic Communications, Inc., St. Petersburg, Florida, under the direction of Mr. Richard A. Saraydar, Program Manager, and Mr. Paul R. Hoffmann, Project Engineer. Significant contributions to the program were made by Messrs. L. H. Goree, R. I. Bain, F. J. Studenberg, and D. V. Amundson.

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1.0 SCOPE AND OBJECTIVE

The scope of this program was a 9 month detailed study and investigation which would result in a specification for an improved one kilowatt UHF amplifier using present day technology and components. Primary emphasis was to be on solid state technology, investigating transistor amplifier capability, thermal characteristics, RF power combining, broadband noise, size, weight, power dissipation, reliability and trade-offs involving the preceding characteristics. The solid state capability was to be compared with the current capability of vacuum tube one kilowatt designs. The resultant specification was expected to reflect improved capability in the areas of reliability, operation at 50,000 feet, cooling, size and weight.

2.0 PROGRAM SUMMARY

The program began with an investigation into the communications systems currently on command aircrafts. These transmitters would be used as drivers for a kilowatt power amplifier, and their characteristics would in part dictate some of the interface requirements of a high power amplifier. The interfaces between the driving transmitter and the power amplifier were analyzed to determine if an optimum interface existed.

RF power transistor capability was traced over the past several years and projected through 1975. Potential complexity of a kilowatt power amplifier was related to transistor capability over the 1973 - 1975 time frame. Tests were conducted on the highest power RF transistors available today to verify their performance capability in a linear amplifier. The program analyzed potential kilowatt power amplifier configurations to compare such characteristics as size, weight, complexity, primary power, thermal dissipation and reliability. The thermal characteristics of a kilowatt power amplifier were analyzed and extrapolated to high temperature and high altitude performance capabilities. Trade-offs and advantages of a 30 MHz wide satellite band design were investigated. Specific hardware investigations were conducted in the areas of power combiners, linear RF amplifiers and control circuits. The results of these investigations were analyzed and used to project typical performance and characteristics of a solid state kilowatt power amplifier. This amplifier was compared to today's capability in tube-type kilowatt power amplifiers. The final effort in the program was the development of a detailed performance specification for a one kilowatt power amplifier.

3.0 DESIGN INVESTIGATIONS AND ANALYSES

The major investigations into the feasibility and design approach of a solid state one kilowatt power amplifier are discussed in this section. The topics are arranged not necessarily in the order in which they were considered during our study effort, nor in an order of design priority, but hopefully in a sequence which allows for easy understanding of the concept of a high power solid state power amplifier (P. A.). The report begins at the heart of the P. A. with the RF amplifiers, and diverges to the many other design considerations which must be analyzed. Many items discussed early in this section are at least in part affected and modified by later considerations. Presented here is not a step-by-step design approach, but a summary of studies and analyses conducted throughout the program.

3.1 RF Amplifier Analysis.

Performance of an RF power amplifier is dependent upon the capability of the individual RF transistors, the single stage amplifier and the dual amplifier (a quadrature-combined, 2 transistor amplifier assembly).

3.1.1 RF Power Transistor Capability. Constantly improving RF power transistor technology allows predicting more rugged transistors with higher gain and higher output power than are presently available. The trend chart of Figure 1 graphically displays the growth of transistor power capability with time. The chart shows that in the 1972 - 1973 time frame, the state-of-the-art transistor was the 2007 type with a 40 - 45 watt capability. By 1974, the C2M70/JØ2015 transistors were providing 70 - 80 watts at UHF. Extending the curve through 1975 indicates a 100 watt per transistor capability by mid-1975. This extrapolation of our curve is in agreement with transistor manufacturer's projections for 100 watt transistors. In fact, ECI has tested preliminary samples of both TRW (JØ2016) and CTC (C2M100) transistors with a 100 watt capability across the UHF band.

While the 100 watt type transistors have been subjected to preliminary evaluation, it is not possible at this time to project their performance characteristics as accurately as for the C2M70/JØ2015 types. In this report, the detailed discussions are primarily based on the 70 watt transistors. Additional information is then provided to project performance capability of the 100 watt transistors and discuss the impact of using these transistors in a solid state kilowatt design.

3.1.2 Single Transistor Amplifier Capability. The selected power transistor must be analyzed in a single stage amplifier circuit in order to determine its performance capabilities in a dual (two transistor) amplifier. The essential parameters in this analysis are transistor gain in the actual amplifier circuit, transistor efficiency in the circuit,

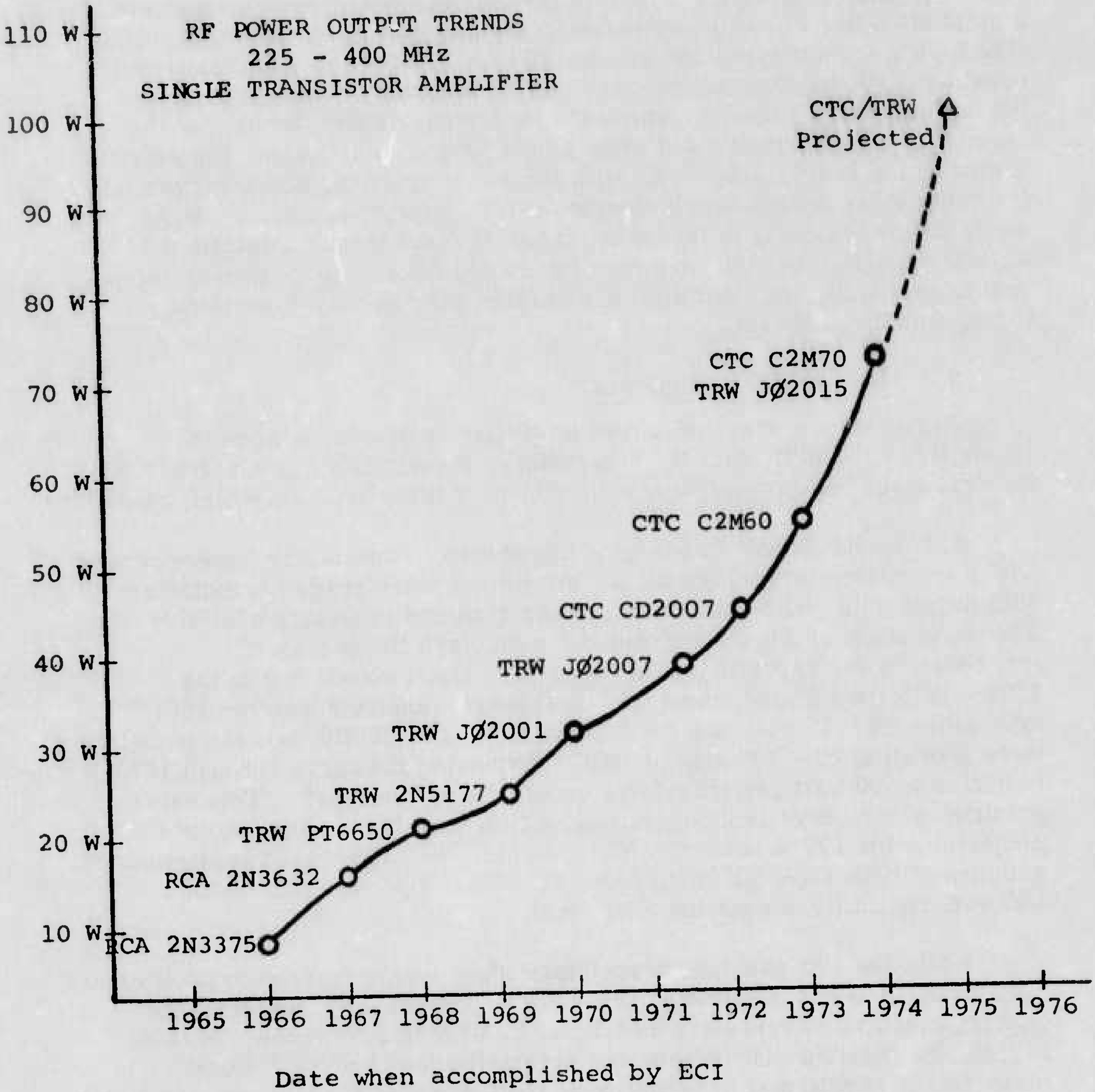

Figure 1. UHF POWER TRANSISTOR TRENDS

thermal resistance from transistor to heatsink and maximum heatsink temperature. Based upon manufacturer's data sheets and the test data obtained at this time on the 70 - 80 watt transistors, the following minimum performance characteristics over the 225 - 400 MHz band appear applicable to production quantities of these transistors.

Amplifier Gain.................................9.0 dB min.
Transistor Efficiency (η_T).....................52% min.
Thermal Resistance Junction-Case (Θ_{j-c})..........1.2°C/W
Thermal Resistance Case-Heatsink (Θ_{c-Hs}).......0.2°C/W

The amplifier gain is the ratio of output power to the amplifier input power. Transistor efficiency is the ratio of output power to DC input power plus RF input power. The sum of Θ_{j-c} and Θ_{c-Hs} is the thermal resistance from junction to heatsink, Θ_{j-Hs}.

It has been demonstrated by transistor manufacturers that today's power transistors are capable of reliable operation at junctions in excess of 180°C. This design analysis will restrict transistor junction temperature to a worst case of 180°C. Typical junction temperatures will be in the 140°C to 160°C range under conditions of typical amplifier efficiency and nominal ambient temperatures. The analysis is also based on a cooling system requirement which limits heatsink temperatures to a maximum of 80°C. This requirement will be analyzed further in Section 3.7 on Thermal Analysis. The following equations are then valid.

$$P_{diss}|_{max} = \frac{(T_{j-max}) - (T_{Hs-max})}{\Theta_{j-Hs}} = \frac{180°C - 80°C}{1.4°C/W} = 71.4\ W$$

and

$$P_{out}|_{max} = \frac{P_{diss}|_{max}}{\frac{1}{\eta_T} - 1} = \frac{71.4\ W}{\frac{1}{0.52} - 1} = 77.3\ W$$

where $P_{diss}|_{max}$ is the maximum allowable power dissipation, $P_{out}|_{max}$ is the dissipation-limited maximum output power available from the amplifier and η_T is the overall transistor efficiency.

The capability of the amplifier with an 80°C heatsink and 52% overall efficiency is therefore 71.4 watts total dissipation and an output power of 77.3 watts. At lower heatsink temperatures the dissipation limited output power capability will increase, to 92.8 watts at 25°C, 110.7 watts at 0°C and so on. The actual output at lower temperatures is limited, however, to the saturated output power capability (P_{sat}) of the amplifier.

For the transistors under consideration, P_{sat} is on the order of 80 watts, and this imposes a practical upper limit on the power available from a single amplifier stage.

By way of summary, an amplifier stage operating on an 80°C heatsink with worst case gain and efficiency is capable of 77.3 watts RF output while operating with a junction temperature of 180°C. At lower temperatures, and/or nominal gain and efficiency, the amplifier can deliver its P_{sat}, or about 80 watts, while operating with junction temperatures much less than 180°C.

3.1.3 Dual Amplifier Capability. The output power capability of a dual amplifier is a rather complex entity. It is essentially dependent upon four items: the output power capability of an individual amplifier stage; the difference in gain between the two amplifier channels in the dual; the insertion loss of the input and output quadrature hybrids; and the coupling imbalance between the hybrid splitter output ports.

The analysis in the preceding section determined that the power capability of a single amplifier was a worst case 77.3 watts at an 80°C heatsink temperature and 80 watts at lower temperatures and/or non-worst case conditions of transistor gain and efficiency. The other three parameters affecting dual amplifier performance all vary significantly with frequency and must be analyzed at various points across the band. The hybrid insertion loss varies from 0.1 dB at 225 MHz to 0.18 dB at 300 MHz and 0.25 dB at 400 MHz. The imbalance of a conventional hybrid is a maximum of 1.0 dB at the band edges and band center. The amplifier gain difference is more difficult to analyze, being a function of variations in transistor characteristics, circuit component value tolerances and alignment techniques. While the gain of the two amplifier channels may be matched closely at certain points in the band, the gains may diverge elsewhere due to different circuit characteristics there. All things considered, a gain difference of 1.0 dB across the band appears to be a fairly reasonable performance which will require careful control of the assembly and test processes, yet will not prove impractical to obtain.

The above dual amplifier parameters are related to dual output power by the following equation:

$$P_{out} = P_l L_H \left[1 + \frac{1}{2\Delta H} (3\Delta G_{21} - 1) \right]$$

where P_l is the maximum output available from the higher power side of the dual, L_H is the insertion loss factor of the input and output hybrids, ΔG_{21} is the gain difference between the two amplifier channels, and ΔH is the hybrid imbalance factor.

For the worst case conditions developed above (that is, P_l = 77.3 watts, L_H = 0.25 dB, ΔH = 1.0 dB and ΔG_{21} = 1.0 dB) the power available from the dual amplifier is found to be 112.9 watts.

Several areas were analyzed in hopes of improving the projected power capability of a dual amplifier. It would be desirable to prevent the worst case L_H, ΔH, ΔG_{21}, and P_l from occurring simultaneously. L_H and ΔH are worst case at 400 MHz. P_l is worst case near 370 MHz which is typically the low efficiency point of the amplifier. It would be desirable to try to minimize ΔG_{21} near the top end of the band where other worst case conditions occur. This could be done by gain-matching the two amplifier channels at 370 MHz. If this is accomplished, the worst case shifts to near 300 MHz where L_H = 0.18 dB, ΔH = 1.0 dB, P_l = 80 watts, and ΔG_{21} = 1.0 dB. The minimum power available from this dual is 118.4 watts.

One further improvement can be made by using a special multiple-coupled quadrature hybrid with a worst case imbalance of 0.4 dB. This hybrid has the disadvantages of larger size (about 1.5 times the size of the conventional hybrids), increased cost (about double) and slightly increased insertion loss (about 0.3 dB at 400 MHz). Nevertheless, using this hybrid in the preceding example increases the dual amplifier power capability to 124.0 watts.

To keep things in proper perspective, it is instructive to consider the dual amplifier power capability under best case conditions. This would occur in the 250 - 275 MHz region when the two dual amplifier channels were matched and the hybrids were balanced there. P_l would be 80 watts, L_H = 0.13 dB, ΔH = 0 dB, and ΔG_{21} = 0 dB. Under these conditions, the dual amplifier will have a power output capability of 155 watts. Of course these conditions will not occur very regularly in real duals, just as is the case with the worst case projections. But both best case and worst case conditions will be approached to a greater or lesser degree in nearly every dual amplifier at some operating frequencies. It is the minimum performance under worst case conditions which ultimately determines the true capability of a power amplifier. This minimum performance capability is on the order of 113 to 124 watts per dual amplifier using 70 watt type transistors.

3.1.4 Capabilities Using 100 Watt Power Transistors. One sample of the TRW JØ2016, and 2 samples of the CTC C2M100 transistors have been supplied for evaluation.

With this limited sampling, it is not possible to project exact performance characteristics of these 100 watt transistors. However, based on these preliminary evaluations, information supplied by the manufacturers, and comparisons with the 70 watt transistors, it is possible to develop preliminary characterizations of these new devices. This will allow a determination of amplifier and dual capabilities similar to those developed for the C2M70/JØ2015 transistors.

The 100 watt transistors should have the following minimum performance characteristics in a broadband amplifier configuration:

Amplifier Gain.......................................9.0 dB min.
Transistor Efficiency (ηT).............................51% min.
Thermal Resistance, Junction-Case (Θj-c)..........0.7°C/W
Thermal Resistance, Case-Heatsink (Θc-Hs)........0.2°C/W

If the maximum heatsink temperature is again restricted to 80°C, the maximum allowable power dissipation for the 100 watt transistors in a broadband amplifier is:

$$P_{diss\ max} = \frac{(T_{j\text{-}max}) - (T_{Hs\text{-}max})}{\Theta_{j\text{-}Hs}} = \frac{180°C - 80°C}{0.9°C/W} = 111.1\ W$$

and the maximum dissipation-limited output power:

$$P_{out}|_{max} = \frac{P_{diss}|_{max}}{\frac{1}{\eta T} - 1} = \frac{111.1\ W}{\frac{1}{0.51} - 1} = 115.6\ W$$

P_{sat} for these transistors is projected to be on the order of 120 watts. Therefore, worst case dissipation-limited output power is 115.6 watts and saturated output power is 120 watts for single amplifiers using the JØ2016/C2M100 type transistors.

Applying the worst case dual amplifier conditions (L_H = 0.25 dB, ΔH = 1.0 dB, ΔG_{21} = 1.0 dB) developed in the 70 watt transistor discussion and substituting P_1 = 115.6 watts for the 100 watt transistors results in a minimum power capability of 169 watts. Gain matching the two sides of the duals, and using the improved hybrid (both as discussed in Section 3.1.3) increases the worst case power capability of these duals to 186 watts. The minimum power capability of dual amplifiers using the C2M100/JØ2016 transistors is therefore in the 169 to 186 watt range.

3.2 Power Combiner/Splitter Investigations.

A 180 degree coaxial combiner/splitter design was built and tested for application in a power amplifier. In theory, the 180 degree design should provide significant reduction of 2nd and other even order harmonics.

Tests conducted indicated that because of phase imbalance between the amplifiers being combined, the 180 degree harmonic cancellation effect across the band was less than expected, and combining efficiency was unacceptably poor. Various phase adjustment techniques were tried, but when the adjustment was made for harmonic cancellation at the low end of the band, combining efficiency degraded elsewhere in the band. Second harmonic reduction up to 15 dB was obtained, but only over a 30 MHz bandwidth. Combining efficiency was similarly bandwidth limited, and degraded more than 3 dB over portions of the 225 - 400 MHz band.

The 15 dB harmonic cancellation at the low end of the band would be a significant improvement in second harmonic performance, but phase tracking problems across the band must be solved before the 180 degree combiner/splitter approach can be practical. At the present time, this approach cannot be considered feasible as a means of obtaining reduced 2nd harmonic content from a wideband UHF power amplifier.

High power combiners using modified stepped-section Wilkinson design techniques exhibited considerably more promise. Low power coaxial and stripline combiner design approaches developed under an IR & D program were modified and tested for suitability as high power combiners. Power handling capability of the coaxial design is increased by increasing the diameter of the coax. The stripline conductor and ground plane thickness can be increased to increase power handling capability of the stripline combiner.

Coaxial designs using 0.141 diameter coax were tested and appear to be usable at the 400 watt level if the coax is thermally bonded to a heatsink. Larger diameter coax would be required for higher power designs, and these would soon become rather bulky.

A stripline 4-way combiner was tested successfully at the 700 watt level. There was less heat concentration in the stripline design than in the coaxial version. The stripline package, measuring approximately 3.7 x 6.1 x 0.7 inches and suspended in free air, handled 700 watts continuously while maintaining surface temperatures below 100°C. Amplitude balance was excellent, on the order of 0.1 dB or better. Insertion loss was measured at less than 0.3 dB, and isolation between ports was on the order of 30 dB. All of these performance characteristics should be maintained or improved as this design is modified for higher power handling capability. It is projected that a kilowatt combiner of this type can be built in a 5.0 x 9.0 x 1.2 inches package or smaller.

3.3 RF Block Diagram Characteristics.

3.3.1 RF Block Diagram Development. The basic block diagram configuration of the RF amplifier section is obtained by combining the dual amplifier capabilities with the output circuit losses and desired output power. A one kilowatt level is assumed at the antenna. The output circuits (Figure 2) include lowpass filter, directional coupler and bypass relay.

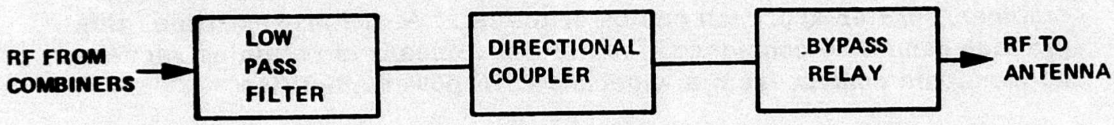

FIGURE 2. OUTPUT CIRCUITS

Tests and research into state-of-the-art components for these functions have determined the following insertion loss numbers for the output circuit components.

Lowpass Filter	0.4 dB
Directional Coupler	0.2 dB
Bypass Relay	0.2 dB
TOTAL	0.8 dB

These insertion losses include connector and interconnect cable losses. The combined output power from the amplifiers must therefore be 0.8 dB above 1 kilowatt, or 1202 watts.

The dual amplifier analysis of Section 3.1.3 yielded minimum power capability per dual of 113 to 124 watts. To overcome the output combiner losses of 0.4 dB and develop 1202 watts into the lowpass filter requires a total of 12 output duals. Let us analyze a 12 dual output amplifier configuration.

The 12 duals could be combined in a single 12-way combiner, six 2-ways and a 6-way, two 6-ways and a 2-way, four 3-ways and a 4-way, or three 4-ways and a 3-way. In general, the combiners with fewer ports can be designed more compactly and located closer to the individual dual amplifiers in a more compact package. The combiner designs themselves are also generally less complex. For these reasons, the combinations of 3-way and 4-way combiners are more attractive. There is little to choose from between four 3-ways and a 4-way and three 4-ways and a 3-way. The choice would be up to the designer, and would be based chiefly on packaging considerations. The approach using the four 3-ways plus a 4-way is the configuration that will be used in these block diagram discussions. The combiner and output circuit losses are shown in Figure 3.

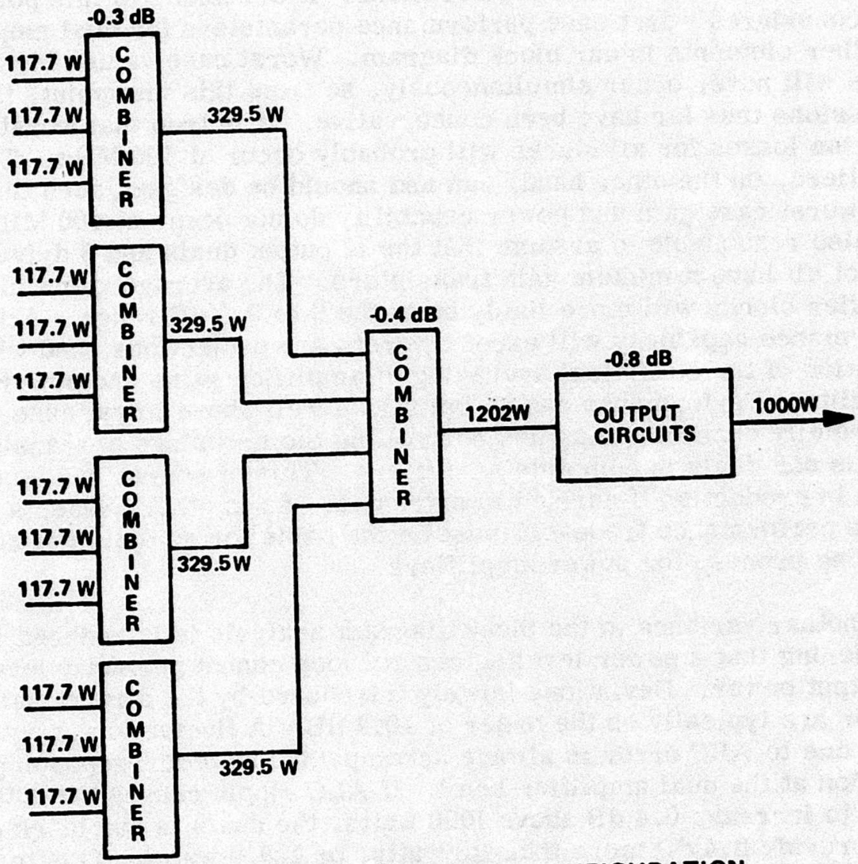

FIGURE 3. POWER COMBINER CONFIGURATION

The 0.3 dB loss assigned to the 3-ways and 0.4 dB assigned to the 4-ways are the worst case type numbers based on our testing and analysis of these types of combiners. The output network described above will require an average dual amplifier output power of 118 watts. This requirement is consistent with the dual amplifier capability developed in Section 3.1.3.

Continuing the block diagram development back to the RF input connector results in the complete RF block diagram shown in Figure 4. Gain and insertion loss numbers assigned to the various blocks are intended to represent worst case performance. Figure 4, therefore represents a feasible kilowatt amplifier RF chain which will function at input drive levels as low as 27 watts (FM) and provide a nominal 1000 watts of RF output.

3.3.2 Practical RF Considerations. Discussions to this point have considered worst case performance parameters for dual amplifiers and other elements in our block diagram. Worst case values for all blocks will never occur simultaneously, so from this viewpoint, the discussions thus far have been conservative. It is true that worst case insertion losses for all blocks will probably occur at 400 MHz. The dual amplifiers, on the other hand, can and should be designed such that their worst case gain and power capability do not occur at 400 MHz. It is also reasonable to assume that the 12 output duals and 3 driver duals will not all have minimum gain transistors. The average gains in the amplifier blocks will more likely be in the 9 to 9.5 dB range. Actual performance capability will exceed worst case projections, and will be a function of the statistical averaging of amplifier gains and power capability. Performance can be optimized well above worst case values by carefully characterizing and controlling the groupings of transistors in duals and duals in complete amplifiers. This of course can be quite costly in production if carried to extremes. As in other areas, a cost versus performance trade-off must be the basis for an optimum manufacturing process for power amplifiers.

Another variance to the block diagram analysis is introduced in considering that a power leveling control loop cannot perfectly level the output power. Deviations largely introduced by the directional coupler are typically on the order of ±0.4 dB. A fluctuation in output power due to ALC error is always accompanied by a corresponding power variation at the dual amplifier level. If ALC ripple causes the output power to increase 0.4 dB above 1000 watts, the duals in our block diagram must provide 0.4 dB more than 118 watts, or 129.0 watts. This may well be beyond the capability of the duals. To remedy this problem, it is necessary to set nominal output power at 0.4 dB below 1000 watts. The

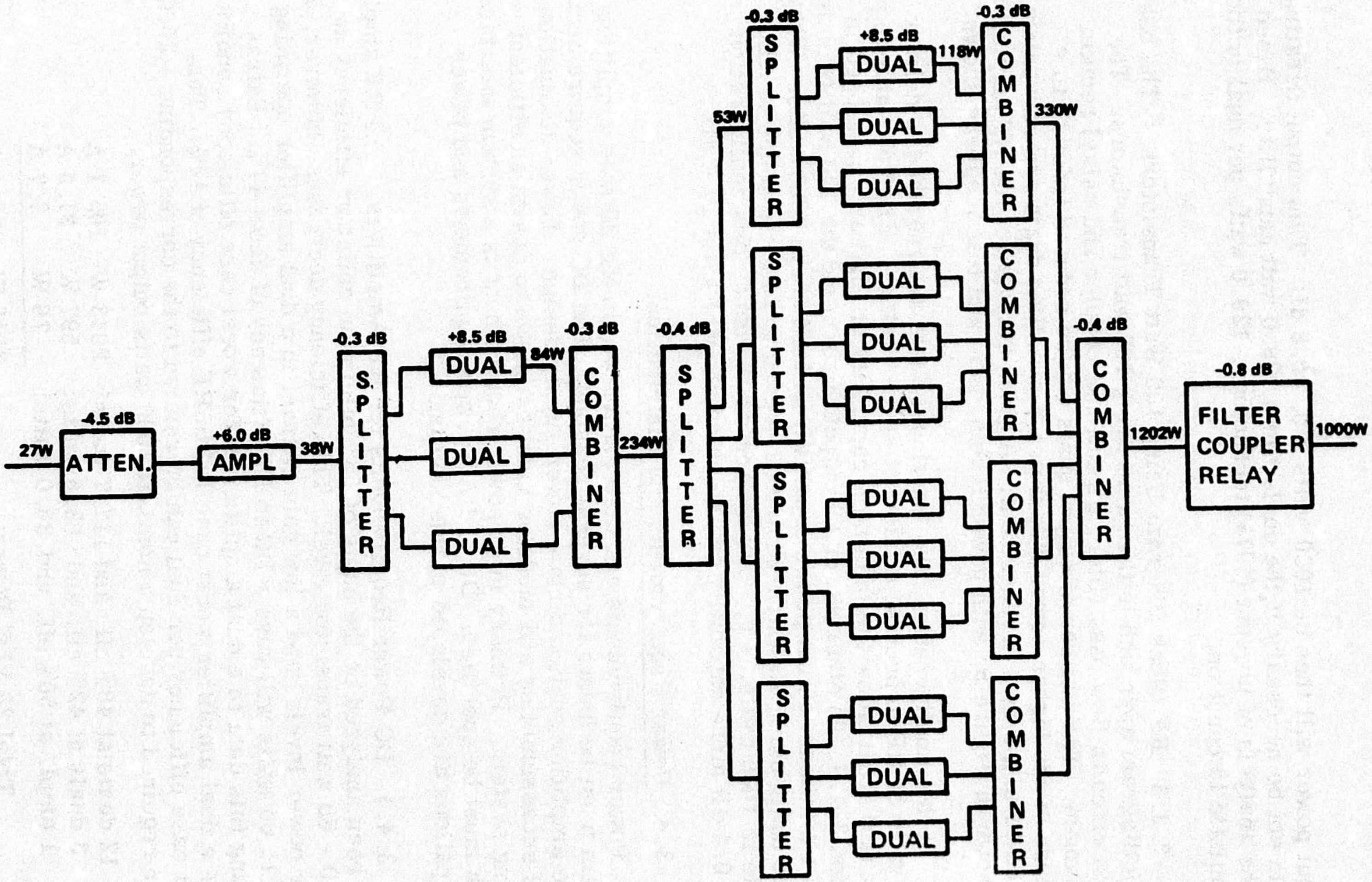

FIGURE 4. AMPLIFIER BLOCK DIAGRAM USING 70 WATT TRANSISTORS

output power will then be 1000 watts + 0, -0.8 dB. This output derating would not be necessary if the duals had a 129.0 watt capability. Based on the analysis of present (1974) technology, 129.0 watts per dual is too optimistic to count on.

3.3.3 RF Block Diagram Using 100 Watt Transistors. The basic block diagram approach is the same using 100 watt transistors. The output circuits (low pass filter, directional coupler and relay) remain unchanged. The number of output duals can be reduced from 12 to 9 because of the higher power output per dual. Nine duals are conveniently combined in a 3 by 3 arrangement. A block diagram of the RF amplifiers is shown in Figure 5, with power levels, gain and loss numbers shown.

In this configuration, the individual duals are required to deliver 153 watts of RF to provide a kilowatt at the antenna. The 153 watts requirement is 0.4 dB below the minimum capability of 169 watts developed in Section 3.1.4. In other words, 9 output duals using the 100 watt transistors have a minimum output power capability 0.4 dB above 1000 watts. Whereas the 12 duals using 70 watt transistors needed to be derated due to ALC ripple to 1000 watts, + 0, -0.8 dB across the band, this configuration with 0.4 dB more capability can be rated at 1000 watts ±0.4 dB.

3.4 <u>Power Requirements and Distribution.</u>

Power requirements and distribution within the kilowatt amplifier system must be known for several reasons. The DC power requirements of the amplifier section dictate power supply design. Power dissipation of all subassemblies and modules must be known to design an efficient cooling system. Primary input power requirement is a system interface which must be specified. DC and AC power requirements and power dissipations are developed in this section.

3.4.1 DC Power Requirements for RF Amplifiers. The RF amplifiers have been analyzed on the basis of 55% minimum collector efficiency at the 70 - 80 watt transistor level. This efficiency decreases, however, at lower power levels, and a low gain channel in a dual amplifier operating at 50 to 60 watts will have a DC to RF efficiency of about 47%. Extrapolating this data to a dual amplifier under worst case efficiency conditions yields a dual amplifier worst case DC to RF efficiency of 48%. This worst case efficiency per dual can be related to the corresponding + 28.0 VDC power required to develop a nominal 1000 watts output power.

12 duals at 48% eff. and 117.7 watts:	2943 W	105.1 A
3 duals at 42% eff. and 83.6 watts:	597 W	21.3 A
1 ampl. at 50% eff. and 38.0 watts:	76 W	2.7 A
Total 28 VDC Power:	3616 W	129.1 A

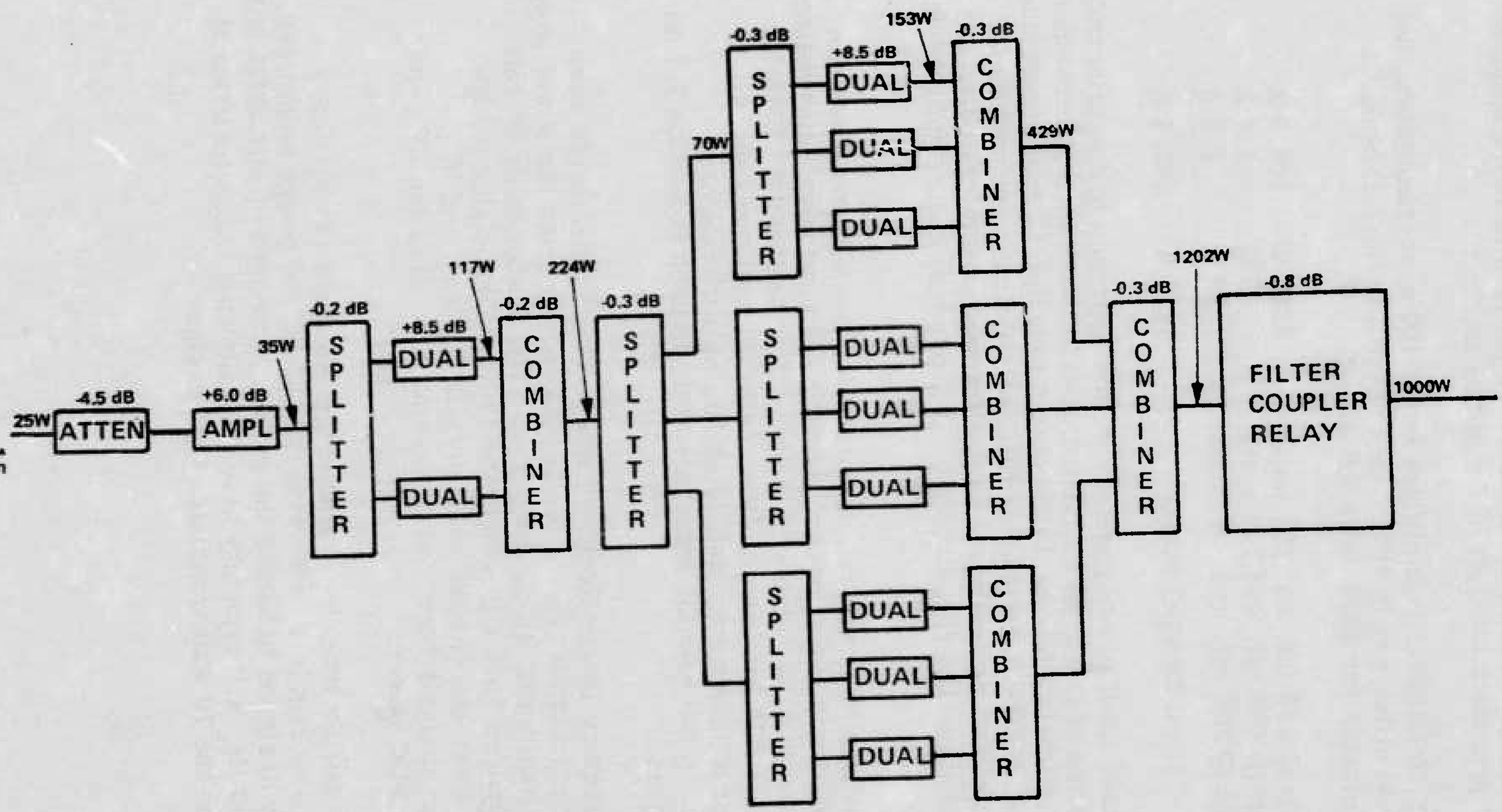

FIGURE 5. AMPLIFIER BLOCK DIAGRAM USING 100 WATT TRANSISTORS

The total input required by these RF amplifiers is 129.1 amps or 3616 watts to provide a kilowatt of RF at the antenna.

Similarly, for the dual amplifiers using 100 watt transistors, the worst case dual efficiency is 48%. This results in the following DC power requirements for 1000 watts RF output.

9 duals @ 48% eff. and 153 watts:	2868 W	102.5 A
2 duals @ 48% eff. and 117 watts:	488 W	17.4 A
1 ampl. @ 50% eff. and 35 watts:	70 W	2.5 A
Total 28 VDC Power:	3426 W	122.4 A

The reduced input power required in this approach is due principally to the elimination of one driver dual and also to the 0.1 dB improvement in combining efficiency for the 9 dual output over the 12 dual arrangement. Again, it is necessary to emphasize that the efficiency projections for the 100 watt transistors are based on preliminary samplings only, and any improvements to the efficiencies used above will reduce input power requirements.

The above data on power requirements for the RF amplifiers can be expanded to provide input power, output power and power dissipation for each module or subassembly in the amplifier assembly. This data is presented in Table I for an amplifier using 70 watt transistors, and Table II for a design approach using 100 watt transistors. Power dissipation information from this table is used in Section 3.7 on Thermal Analysis.

3.4.2 Primary Power Requirements. The requirements were developed in the previous section for 28 VDC power from the power supply for a nominal 1000 watts RF output power. The design using 70 watt transistors required 3645 watts, and the 100 watt transistor design required 3454 watts of DC power as shown in Tables I and II. To simplify our analysis here, let us assume that all of the DC power required is 28 VDC power.

The power supply must be characterized to allow calculation of the primary power required to develop the DC for the power amplifiers. A power supply designed to handle the primary voltages of MIL-STD-704 category B, 400 Hz, will typically have the following characteristics at nominal line for the 70 watt transistor type design.

Table I

POWER REQUIREMENTS USING 70 WATT TRANSISTORS

Item	Max. Input Power DC (Watts)	RF (Watts)	Min. RF Output (Watts)	Max. Dissipation (Watts)
Cplr/Atten/Preamp	78	143	38	183
Control/Protect	20	----	----	20
Driver Ampl.	597	38	234	401
Final P. A. #1	736	54	330	460
Final P. A. #2	736	54	330	460
Final P. A. #3	736	54	330	460
Final P. A. #4	736	54	330	460
Output Cplr/LPF	----	1202	1047	155
4-Way Splitter	----	234	216	18
4-Way Combiner	----	1320	1202	118
Bypass Relays	6	1197	1143	60
Total DC Input:	3645	Total Dissipation:		2795

Table II

POWER REQUIREMENTS USING 100 WATT TRANSISTORS

Item	Max. Input Power DC (Watts)	RF (Watts)	Min. RF Output (Watts)	Max. Dissipation (Watts)
Cplr/Atten/Preamp	72	143	35	180
Control/Protect	20	----	----	20
Driver Ampl.	488	35	210	313
Final P. A. #1	956	70	429	597
Final P. A. #2	956	70	429	597
Final P. A. #3	956	70	429	597
Final P. A. #4	956	70	429	597
Output Cplr/LPF	----	1202	1047	155
3-Way Splitter	----	224	210	14
3-Way Combiner	----	1287	1202	85
Bypass Relays	6	1197	1143	60
Total DC Input:	3454	Total Dissipation:		2618

	Input Power (Watts)	Dissipation (Watts)	Output Power (Watts)
Line Filters	5112	20	5092
Transformer	5092	300	4792
Rectifiers	4792	300	4492
Regulators	4492	755	3737
Filter	3737	92	3645
Total Dissipation:		1467	

A similar supply for an amplifier using the 100 watt transistors would have the following power characteristics:

	Input Power (Watts)	Dissipation (Watts)	Output Power (Watts)
Line Filters	4846	20	4826
Transformer	4826	284	4542
Rectifiers	4542	284	4258
Regulators	4258	716	3542
Filter	3542	88	3454
Total Dissipation:		1392	

The above should be a good approximation to the total primary power requirements of a one kilowatt amplifier system. The above analysis at nominal line allows un-degraded power amplifier performance at low line voltages. At high line the dissipation in the supply and the primary power absorbed by the supply will increase.

The advantage of the higher power 100 watt transistors is a reduction of approximately 270 watts of primary power.

3.5 Packaging Considerations.

Early in the program it was projected that a one kilowatt P.A. using 70 watt power transistors could be packaged in a 2 ATR package size, and that this package could be reduced to 1-1/2 ATR by using the 100 watt transistors. The 2 ATR size still appears realistic, but further analysis suggests that this size cannot be significantly reduced by using the less complex circuitry of the 100 watt transistor design. The limiting item here is the increased thermal densities which result when the package size is reduced. As will be seen in Section 3.7 on Thermal Analysis, the cooling problem is severe enough in the 2 ATR size package, and any reduction in size will increase these thermal problems. The reduced complexity of the 100 watt transistor design does allow more packaging flexibility, but a 2 ATR size is recommended as optimum for a one kilowatt P.A.

The dual RF amplifiers must be packaged in a configuration which can be properly cooled and yet be compatible with desired maintenance concepts of modularity and plug-in modules. A sketch of a 3 dual module which satisfies these requirements is shown in Figure 6. The module could be assembled in the approximate size shown (7.5 x 7.0 x 1.7 inches). These modules could then be packaged along with other RF and control circuits into a 1 ATR RF power amplifier package for the 70 watt transistor design as shown in Figure 7. A similar packaging approach could be used with the 100 watt transistor design.

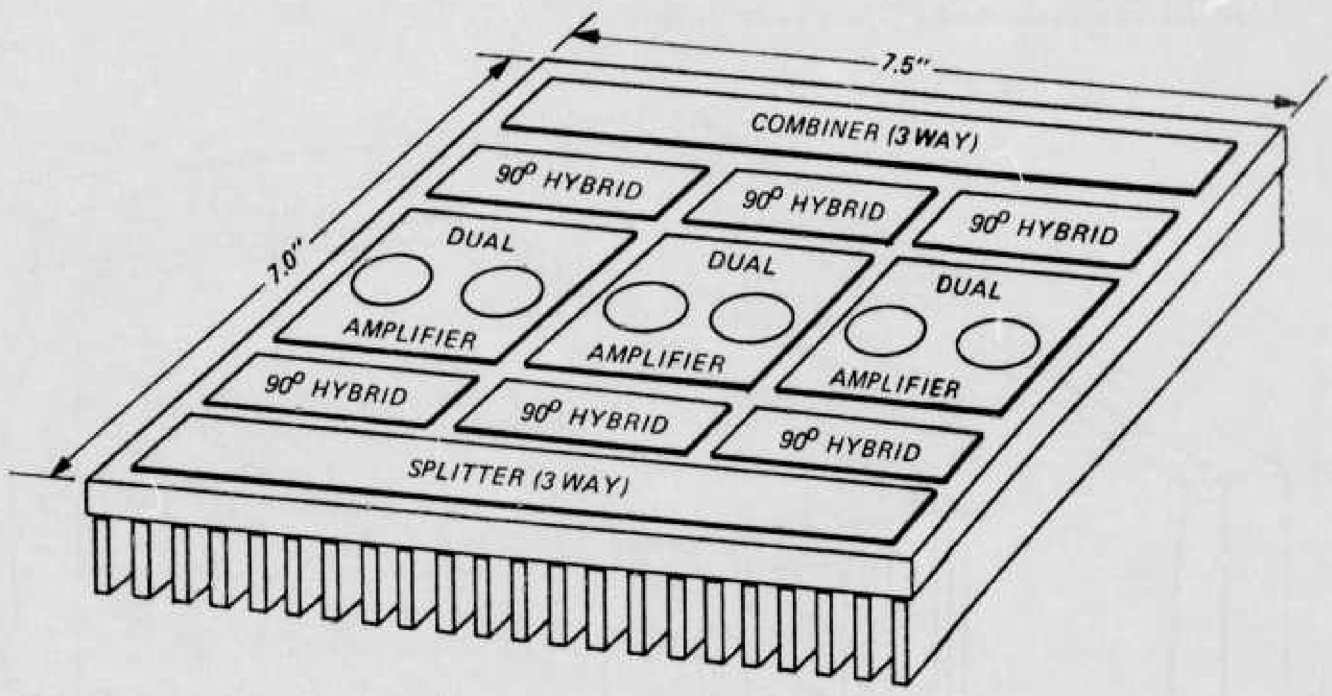

FIGURE 6. 3-DUAL AMPLIFIER ASSEMBLY

At this point, it is necessary to address the choice between one 2 ATR size package (20.25 x 19.56 x 7.62 inches) or two 1 ATR packages (each 10.125 x 19.56 x 7.62 inches). The single box would be excessively bulky and heavy (over 100 lbs.). Two separate boxes are therefore recommended, one for the amplifiers and one for the power supply.

While no detailed packaging concepts were developed for the power supply, certain size estimated were made, based on estimated component sizes and allowable thermal densities on conventional cold plate heatsinks.

28 V Regulators..........	300 cu. in.	(including heatsink)
Rectifiers...............	100 cu. in.	(including heatsink)
Transformer.............	300 cu. in.	(5 x 6 x 10 inch approx. form factor)
Filter Caps..............	150 cu. in.	
Misc. Circuitry	100 cu. in.	(including heatsink)
Blower + Transitions....	100 cu. in.	
Line Filters.............	200 cu. in.	
Subtotal.................	1200 cu. in.	

The above volume estimate does not include interconnect areas, connectors or clearance behind the front panel. The volume requirements in excess of 1200 cubic inches suggests that a 1 ATR size package (1510 cu. in.) will be appropriate for the power supply. The total one kilowatt amplifier will therefore require two 1 ATR size packages, one for the RF amplifiers and one for the power supply.

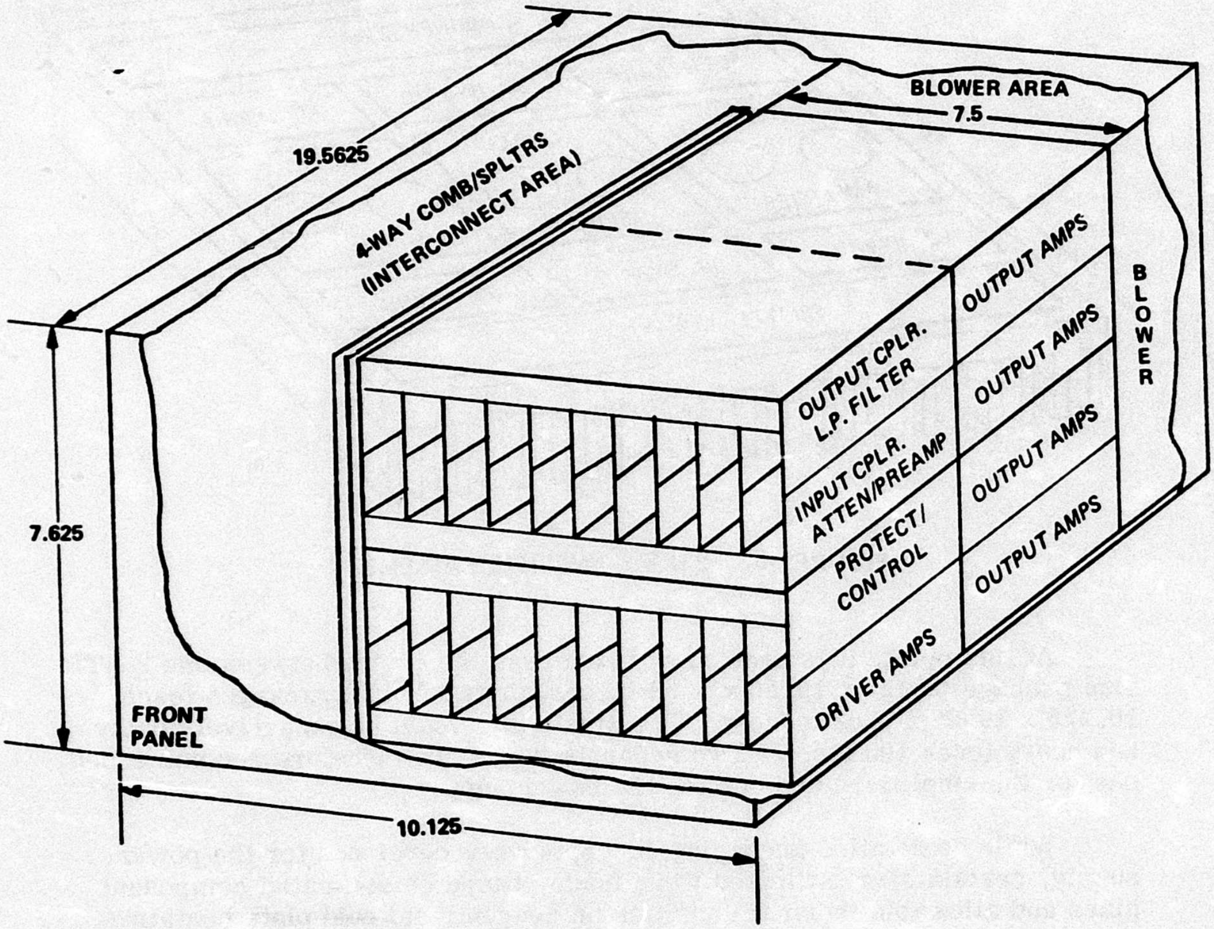

FIGURE 7. ONE ATR P.A. PACKAGE

3.6 Reliability Considerations.

An informal reliability analysis was performed on potential solid state one kilowatt amplifier configurations. The analysis included kilowatt systems designed around the 70 watt and the 100 watt transistors in the RF power amplifiers. In the analysis, failure rates were assigned at the component level. Parts lists were derived from projected schematics for the RF amplifiers, attenuator, power splitters and combiners. For other subassemblies (power supply, regulators, control/protect and directional coupler) parts lists from similar existing ECI circuit designs were used, with parts populations increased or decreased as required to relate to the complexity of a kilowatt system. The analysis was based on 50°C heatsink temperatures and 60°C air temperatures surrounding components. Electrical stress ratios are based on projected usage where possible, and upon equivalent ECI circuits in all other cases. Failure rates generally were obtained from MIL-HDBK-217A with a 10:1 improvement factor for TX rating applied to all semiconductors. Failure rates for the blowers were taken from MIL-HDBK-217A based on representative 400 Hz high speed airborne blowers used on the AWACS HPA program. The appropriate airborne K factors were applied to the base failure rate in accordance with MIL-HDBK-217A.

Results of the analysis on each amplifier design (70 watt transistor design and 100 watt transistor design) are presented under four conditions. First, the amplifier using screened TX rated semiconductors and omitting the blowers; second, the amplifier using standard reliability semiconductors and omitting the blowers; third, the amplifier using TX rated semiconductors and including the blowers.

ONE KILOWATT AMPLIFIER USING 100 WATT TRANSISTORS:

	Estimated MTBF (Hours)
a) TX Semiconductors, No Blowers	3250
b) Std. Semiconductors, No Blowers	1050
c) TX Semiconductors, 2 Blowers	1150
d) Std. Semiconductors, 2 Blowers	670

ONE KILOWATT AMPLIFIER USING 70 WATT TRANSISTORS:

	Estimated MTBF (Hours)
a) TX Semiconductors, No Blowers	2650
b) Std. Semiconductors, No Blowers	900
c) TX Semiconductors, 2 Blowers	1100
d) Std. Semiconductors, 2 Blowers	600

Data is presented in the preceding format to emphasize the following characteristics of high power solid state amplifier reliability.

1. Solid state amplifiers designed with TX screened semiconductors can exhibit relatively high predicted MTBF when the blowers are left out of the picture.

2. A slight but definite improvement in MTBF is obtained with the reduced complexity of the design using 100 watt transistors.

3. There is a significant difference in predicted MTBF when TX rated semiconductors are compared to standard reliability parts; in other words, higher reliabilities are possible for higher costs.

4. The blowers, represented by MIL-HDBK-217A data, are the major item limiting MTBF of a kilowatt system.

Two actions could be taken in this latter area. The first is to investigate the MIL-HDBK-217A blower ratings. Data compiled by ECI from specific blower investigations and field usage indicate that the state-of-the-art blower reliability may be significantly higher than that predicted in the MIL handbook. The second action would be to investigate the availability of higher reliability blowers, and begin specific development of high reliability blowers for kilowatt applications if appropriate designs are not presently available.

The above MTBF numbers are all based on a 100% duty cycle for the entire amplifier system. A high percentage of components in the amplifier and power supply operate at significantly lower stress levels in STAND-BY, or un-keyed modes. Some components are completely unstressed, or in effect, inoperative, except when the amplifier is keyed. In fact, the blowers could be thermally controlled to allow them to be shut off during un-keyed periods when heatsink temperatures drop below some pre-determined level. Applying these considerations to a reliability prediction analysis would generally improve system MTBF numbers and significantly reduce the degrading effect of lower reliability blowers, if these must be used. Actual MTBF improvements are not considered quantitatively here, since they depend to such a degree on the specific mission profile to which the equipment will be subjected.

3.7 Thermal Analysis.

A thermal model of the power amplifier was used to determine forced convection cooling requirements at sea level and various MIL-E-5400 temperature/altitude conditions. A determination of the amount and type of aircraft cooling air required for full power capability at high altitude is presented.

3.7.1 Power Amplifier Cooling at Sea Level. The thermal model of Figure 8 was developed for this analysis. The configuration is based on packaging concepts using the 100 watt transistors, because the more severe thermal densities exist in these high power modules. The power dissipations assigned to each module are taken from Table II. The power dissipating elements in the chassis (splitter, blower, combiner and relay) are not included in this analysis, although in the final design heat must also be removed from these assemblies.

In the thermal model of Figure 8 there are two parallel paths of forced air flow, and thermal loading is slightly different for the two paths. Path A through the two final P. A. modules has slightly higher dissipation and will be the more severe case.

The basic cold plate heatsink design used for all modules is similar to the cold plate shown in Figure 9. Two adjoining modules are arranged with their fins aligned between the two cold plates. The dimensions shown are consistant with the packaging concepts discussed in Section 3. 5.

The thermal system was subjected to analysis using an input air (T_1) of + 55°C at sea level, with the objective of maintaining the heatsink temperature at or below 80°C, a limit imposed in Section 3. 1. 2 on RF amplifier capability. The simplifying assumption was made that the two abutting heatsinks form an isothermal mass. This is not the actual case when the two sinks are unequally loaded thermally, but allows for a first order analysis which must then be adjusted to account for the unequal loading. This first order analysis yields the following characteristics for the system modeled in Figure 8.

Heatsink Dimensions (see Figure 9)	7.5 x 7.5 x 1.8 inches
Fins Per Inch	8
Fin Thickness	0.04 inch
Heatsink Material	Aluminum
T_1 (Input Air Temperature)	+ 55°C
Coolant Flow (Path A)	160 cfm
Coolant Flow (Path B)	120 cfm
T_{2A} (Intermediate Air Temp., Path A)	70°C
T_{2B} (Intermediate Air Temp., Path B)	69°C
T_{3A} (Outlet Air Temp., Path A)	71°C
T_{3B} (Outlet Air Temp., Path B)	75°C

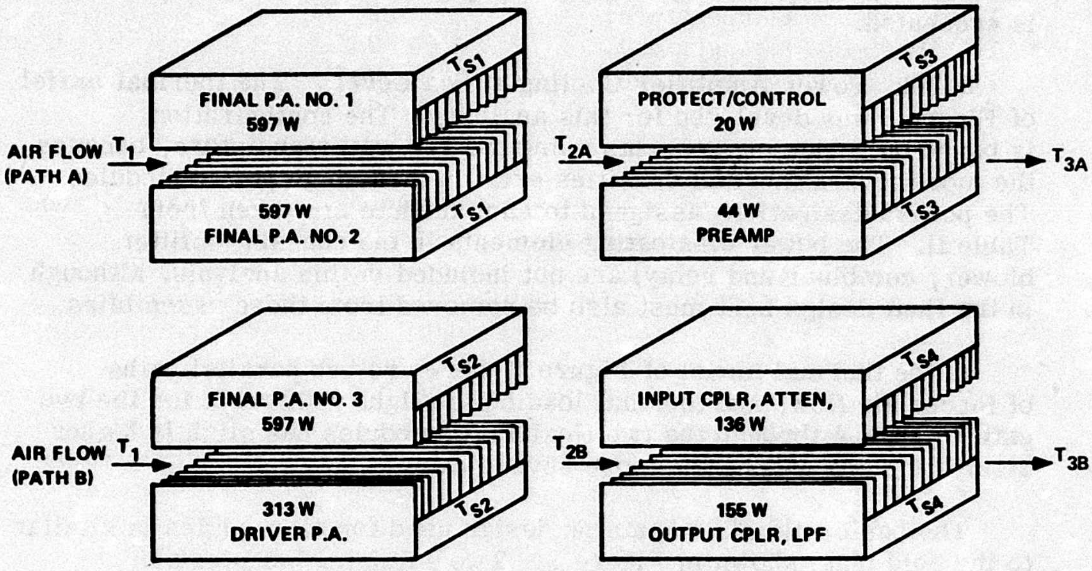

FIGURE 8. THERMAL MODEL OF KILOWATT P.A. MODULES

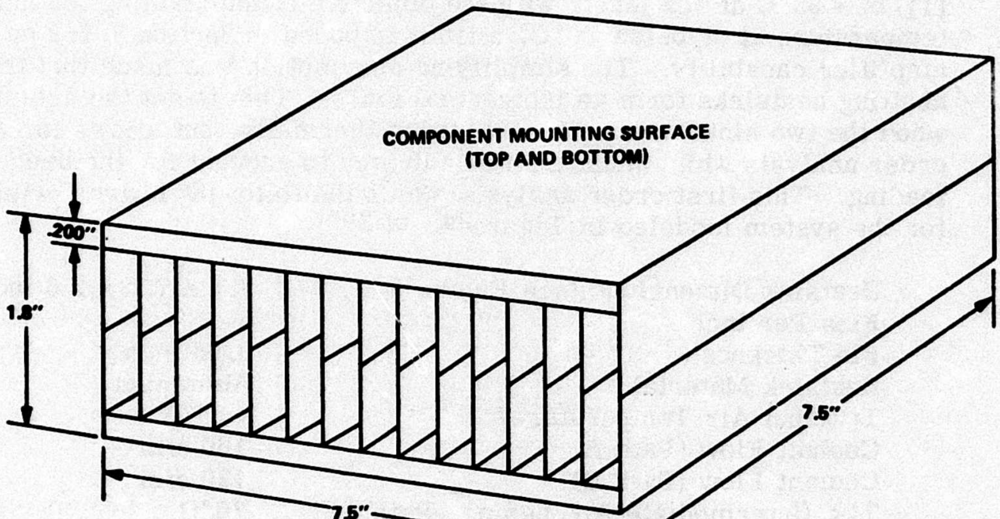

FIGURE 9. COLD PLATE HEAT SINK DESIGN

T_{S1} (Heatsink Temperature)	80°C
T_{S2} (Heatsink Temperature)	79°C
T_{S3} (Heatsink Temperature)	71°C
T_{S4} (Heatsink Temperature)	78°C
Pressure Drop (Parallel Paths)	0.95 inch H_2O

The heatsink described is of reasonable dimensions for casting, and the temperatures are at or below 80°C. An actual thermal design would need to consider the effects of radiation, conduction into the chassis, and the inequal loading of opposite sides of a heatsink pair. Nevertheless, the above analysis is in the right ballpark, and indicates that approximately 280 cfm of air is required at sea level. The blower supplying this air must work into a total pressure greater than the 0.95 inches through the heatsink. Air filter, entrance and exit plenum losses and other fluid dynamic pressure drops will raise the total pressure drop to near 2 inches of water.

This air flow could be obtained with either one large blower or two smaller ones in parallel. The large blower has the disadvantage of being about 5 inches deep, which when added to the 15 inch module length takes up 20 inches of package length. This already exceeds the long ATR length dimension of 19.625 inches. The smaller blowers have depths on the order of 2 inches. This simplifies the length problem and allows a couple inches for the required plenums.

The power supply has less power dissipation, even at high line voltage, than the amplifiers. Power supply dissipation at nominal line voltage is about 1600 watts, which will increase to near 2200 watts at high line (worst case dissipation in the power supply). This is 84% of the 2618 watts dissipated in the amplifiers. A first order approximation to air flow required by the power supply is 84% of 280 cfm, or 235 cfm.

By way of summary, the analysis shows that a one kilowatt P.A. can be cooled at sea level using about 280 cfm air flow through the amplifiers and 235 cfm through the power supply. The packaging approach discussed for the amplifiers may not be optimum for accommodating large blowers. Two smaller blowers in parallel could be used in place of one large blower, or the heatsink/module arrangement could be modified.

3.7.2 Power Amplifier Cooling at Altitude. Cooling becomes more difficult and inefficient at higher altitudes because of the reduced air densities. Even at 10,000 feet, air density is 69% of its density at sea level. At 50,000 feet, air density at a given temperature is 11% of its sea level value. To design a cooling system for full power, continuous operation at maximum temperatures at 50,000 feet would greatly increase the size and complexity of the P.A.

Alternate approaches exist towards solving this problem. These solutions, with one exception, involve a compromise in amplifier performance at altitude. The first compromise is to operate at reduced power levels at higher altitudes. This is a difficult approach, because the RF amplifiers become less efficient at lower power levels, and extreme power reductions are required to reduce power dissipation significantly.

Earlier in this study program, an RF output power crank-back system was proposed to allow continuous operation at high altitudes. In Monthly Progress Report #5 covering the period 6 September to 7 October 1974, a series of 3 graphs was provided to project how this power crank-back would work. These curves were based on a preliminary assumption that a 3 dB power reduction to 500 watts would reduce thermal dissipation sufficiently to allow continuous operation at 50,000 feet. Actual analysis has since indicated that this assumption is not valid. Because of the lower amplifier efficiencies at reduced power levels, a crank-back of about 6 dB would be required to allow continuous operation at 50,000 feet.

Another approach is to limit the duty cycle of operation to prevent excessive heat build-up in the amplifier. Computer analysis indicates that a 5:1 duty cycle (5 minutes OFF, 1 minute ON, ON time not to exceed 1 minute) will allow full power output capability at 50,000 feet and 20°C using the cooling system designed for sea level. Since 50,000 feet and 20°C is the worst case temperature/altitude combination, higher utilization duty cycles can be used at all lower altitudes and/or lower temperatures at 50,000 feet.

A third approach is to consider the maximum temperature at each altitude at which continuous, full-power operation is possible. The constraint must be placed on the equipment to operate within this temperature/altitude contour at full continuous power. This temperature/altitude profile along with the 5:1 duty cycle contour is shown in Figure 10.

Another approach to cooling at altitude is to use aircraft cooling air to cool the equipment. This is discussed in the following section.

3.7.3 Aircraft Cooling Air Requirements. The most desirable approach to the cooling at altitude problem is to have aircraft cooling air

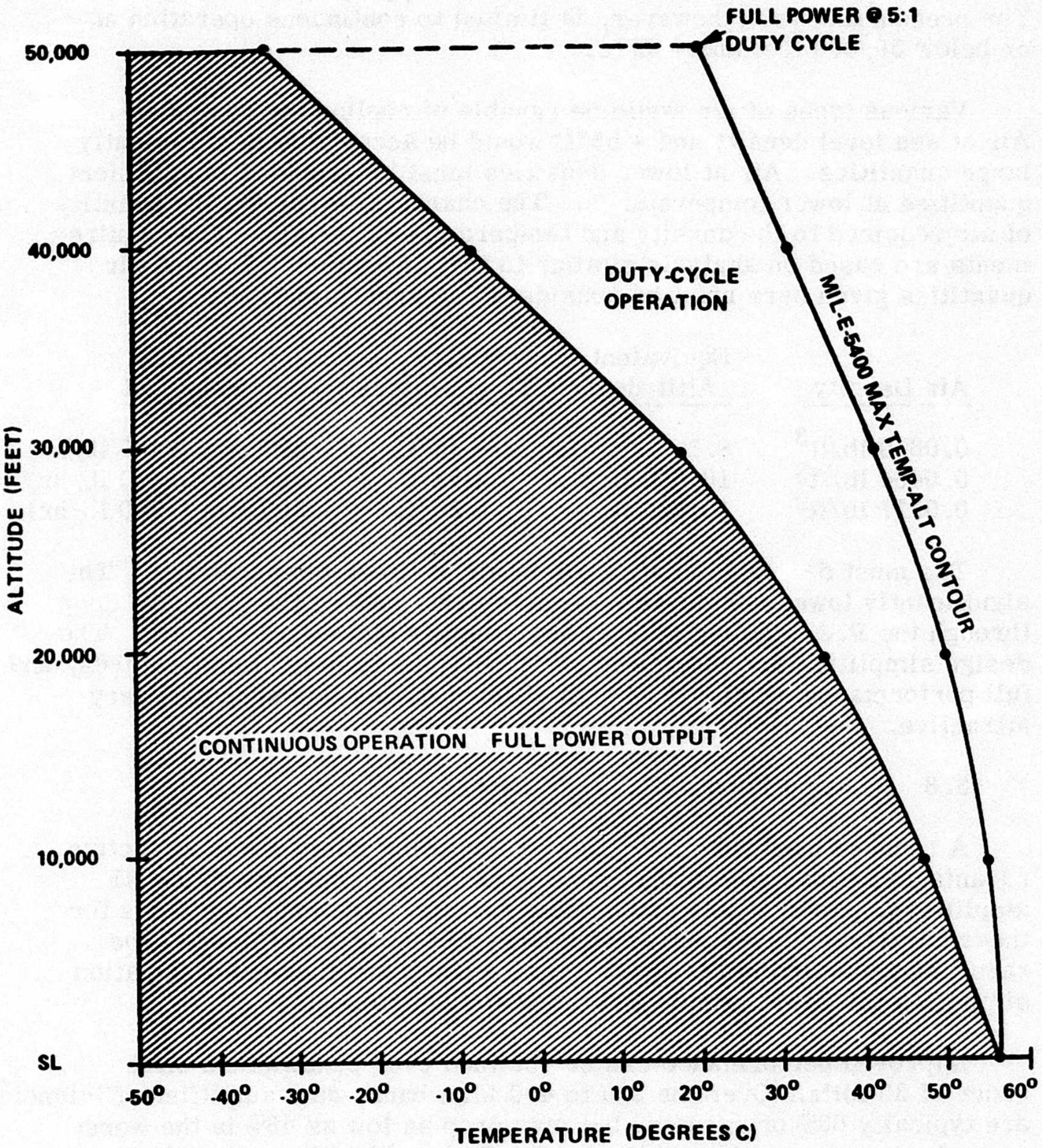

FIGURE 10. TEMPERATURE/ALTITUDE PROFILE

available to the amplifier. If sufficient air is made available, the amplifier can provide continuous full power output at any temperature/ altitude combination required for MIL-E-5400, Class 1 equipment. Subject to additional analysis, this undegraded operation should be available at + 71°C and 70,000 feet with the appropriate cooling air. The present analysis, however, is limited to continuous operation at or below 50,000 feet and + 55°C.

Various types of air would be capable of cooling the equipment. Air at sea level density and + 55°C would be acceptable in sufficiently large quantities. Air at lower densities must be provided in sufficient quantities at lower temperatures. The chart below relates the quantity of air required to the density and temperature of the air. The requirements are based on analysis similar to that of Section 3.7.1 and air quantities given here must be considered as approximations.

Air Density	Equivalent Altitude	Air Temperature	Quantity Required
0.0670 lb/ft^3	S. L.	+ 55°C	597 cfm (2400 lb/hr)
0.0464 lb/ft^3	10,000 ft.	+ 53°C	790 cfm (2200 lb/hr)
0.0517 lb/ft^3	10,000 ft.	+ 20°C	300 cfm (930 lb/hr)

The most desirable cooling air is air at lower temperatures. The significantly lower volume flow requirements reduce the pressure drop through the P.A. cooling system and simplify blower constraints. The design simplification, improved reliability due to lower temperatures, and full performance capability at high altitude makes this approach very attractive.

3.8 Reduced Bandwidth Trade-Offs.

A reduced bandwidth one kilowatt amplifier offers some attractive advantages, especially in the areas of reduced complexity in the RF amplifiers, power supply and cooling system. The principle basis for these advantages is increased efficiency of the RF amplifiers. The resulting reduction in DC power requirements and thermal dissipation simplifies the power supply and thermal requirements.

Improved performance can be obtained over bandwidth's on the order of 30 MHz. Over the 225 to 400 MHz band, dual amplifier efficiencies are typically 60% or greater, but may drop as low as 48% in the worst case at one or two points in the band. Over a 30 MHz band, efficiencies can be optimized greater than 60%. This increase in efficiency results in a dramatic reduction in power supply requirements and thermal dissipation. A power budget showing DC input power and dissipation at the module and subassembly levels is shown in Table III for the 70 watt transistor design. The reduction in power supply output requirements from 3645 watts (130.2 amps) to 2929 watts (104.6 amps) reduces primary power requirements at nominal line from 5112 watts to 4101 watts. The RF amplifier thermal dissipation decrease from 2795 watts to 2021 watts significantly simplifies cooling requirements. These reductions in power supply and cooling requirements would be similarly reflected in the design using 100 watt transistors. This design, in a narrow band, 30 MHz wide kilowatt amplifier, could be packaged in a 1-1/2 ATR box.

Table III

POWER DISTRIBUTION IN REDUCED BANDWIDTH P.A.

	225 - 400 MHz P.A.		290 - 320 MHz P.A.	
	DC Input (Watts)	Max. Dissipation (Watts)	DC Input (Watts)	Max. Dissipation (Watts)
Cplr/Atten/Preamp	78	133	65	170
Control/Protect	20	20	20	20
Driver Ampl.	597	401	482	286
Final P.A. #1	736	460	589	313
Final P.A. #2	736	460	589	313
Final P.A. #3	736	460	589	313
Final P.A. #4	736	460	589	313
Output Cplr/LPF	-----	155	-----	130
4-Way Splitter	-----	18	-----	15
4-Way Combiner	-----	118	-----	88
Bypass Relay	6	60	6	60
Totals:	3645	2795	2929	2021

3.9 Tube Versus Solid State Kilowatt Power Amplifier Comparison.

Following is a comparison of tube and solid state (S.S.) power amplifiers in several key characteristics and performance areas.

a) Output Power: Both capable of 1 KW; tube must be derated above 30,000 feet due to voltage breakdown; S.S. capable of full kilowatt at 50,000 feet with cool air supplied, otherwise full power capability is subject only to duty cycle constraints.

b) Efficiency: Tube requires 3.8 KW input power; S.S. requires 4.9 KW, largely due to wider bandwidth; 30 MHz wide S.S. would require only 3.95 KW.

c) Linearity: Both can be designed to be linear.

d) Bandwidth: ±300 KHz for tube type; full 225 - 400 MHz wideband coverage with S. S.

e) Broadband Noise: Higher in S. S. because of wide RF bandwidths; can be reduced with narrow band filtering.

f) Cooling: Both require cooling air; tube types require higher pressures and S. S. types require higher quantities at lower pressures.

g) Reliability: Typical tube MTBF predictions are 1600 hours excluding blowers and with periodic replacement of tubes; S.S. MTBF predictions are over 3000 hours excluding blowers with no regular maintenance required.

h) Size and Weight: Tube type is slightly over 1-1/2 ATR and 100 lbs. ; S.S. is 2 ATR and 125 lbs.

The solid state advantages in the areas of power capability at 50,000 feet, bandwidth and reliability are impressive. The spread spectrum and frequency hopping communications modes will require solid state amplifiers with their wide instantaneous bandwidths. The improved reliability projections for solid state P. A. 's and reduced maintenance requirements will provide a more favorable cost-of-ownership profile for power amplifiers.

3.10 Conclusions - Overall Design Approach.

The preceding discussions promote the conclusion that a solid state one kilowatt is feasible using either the 70 watt transistors available in quantity now or the 100 watt transistors which will be available later this year. The design approach using higher power transistors offers the potential for lower amplifier complexity, higher efficiency, lower power dissipation, reduced primary power requirements and higher reliability projections. The advantages of the solid state approach over tube kilowatts in the areas of instantaneous bandwidth, higher reliability, and full output power capability at 50,000 feet make the solid state approach very attractive.

The various topics discussed in this report could be integrated into the amplifier system depicted in block diagram form in Figure 11.

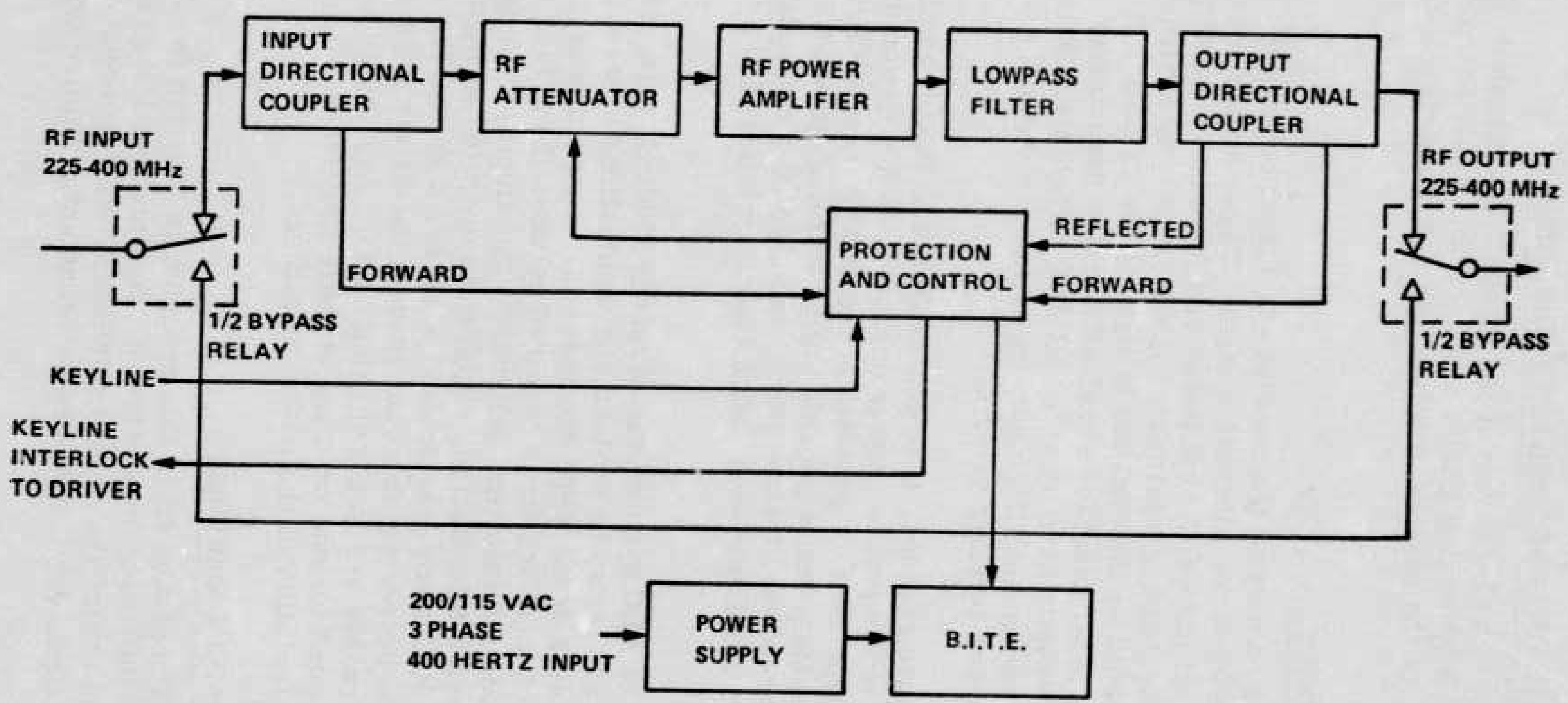

FIGURE 11. OVERALL BLOCK DIAGRAM OF A KILOWATT P. A.

4.0 DETAIL CHARACTERISTICS DISCUSSION

This section is a discussion of the kilowatt specification items, relating them to information gathered during this study program and explaining some of the reasoning behind the recommended specification.

4.1 Interfaces.

There are a variety of transmitters and transceivers which could be used as drivers for a one kilowatt system. These driver transmitters, for the most part, all have different power and modulation control (ALC) circuitry. Designing a one kilowatt system to interface with all of these control loops would be impractical in light of the difficulty of specifying and maintaining ALC interface requirements for each driver, several of which do not presently have an external ALC capability. It is also possible that a power amplifier may be expected to operate with a driver which has no power leveling control.

For the above reasons, it is desirable that a power amplifier intended for general or multi-purpose usage operate with a self-contained control system, as independent as possible of the driver transmitter. This internal ALC system would provide power leveling, protect functions for VSWR, over-power, temperature, and amplifier malfunction, and would preserve amplitude modulation characteristics of the incoming signal.

This type of ALC system was carefully studied, with certain portions breadboarded and tested to modern communications system requirements. No major problem areas were encountered. There appear to be a maximum of three control interface lines required between the driver and power amplifier: mode information, instructing the amplifier to operate either AM or FM; keying information, required to operate the bypass relay in the automatic R/T mode (see Section 4.8); and a key inhibit signal, from the P.A. to the driver which would prevent the driver from keying when the amplifier relays are in a switching mode. Any design which could eliminate the need for one or more of these interfaces would further increase the flexibility of the power amplifier.

4.2 Service Conditions.

The equipment studied in this program is intended for Class 1 or 1X (per MIL-E-5400) airborne operation. Applications for ground-based amplifiers can utilize the same equipments, with appropriate performance or cost advantages due to reduced environmental requirements. Intermittent operation at + 71 °C is not recommended unless cooling air is provided at 20°C in the required quantity.

4.3 Cooling.

The cooling specification is based on the thermal analysis developed in Section 3.7.

4.4 Duty Cycle.

Without auxiliary cooling air, a solid state one kilowatt amplifier cannot provide continuous operation at the high temperature/altitude environments of MIL-E-5400. A preliminary computer analysis of the transient thermal response of a one kilowatt amplifier indicates that operation may be possible at 50,000 feet and 20°C with a 5:1 duty cycle, ON time not to exceed 1 minute. At lower altitudes the allowable duty cycle will increase, until at sea level, continuous operation is possible. The continuous operation at sea level and + 55°C should be a requirement, and the 5:1 duty cycle at 50,000 feet and 20°C a design goal to be met or approached.

4.5 Primary Power.

The analysis of Section 3.4.2 concludes that primary power requirements at nominal line and RF output power will be in the 4846 to 5112 watt range, depending upon the power transistors used in the amplifiers.

In order to minimize the primary power requirements and power supply dissipation at nominal and high line voltages, it is desirable to minimize the voltage drop across the regulators. This can be effected by designing the regulators for saturation at low line voltage. Under certain conditions of load and temperature, this may result in a reduction in power supply output voltage and a corresponding reduction in RF output power. A relaxation in RF output power of 1 dB at low line would encourage design efforts to minimize primary input power requirements.

4.6 Frequency Range.

The basic specification is for a full coverage 225 - 400 MHz power amplifier.

4.7 Emissions.

The kilowatt amplifier should be capable of handling all standard emission types found in line-of-sight and satellite communications systems. These include NBAM and WBAM, FM, FSK and PSK modes. By common agreement with AFAL, the spread spectrum and frequency hopping modes are not addressed at this time, although it can be anticipated that future power amplifiers will eventually require these capabilities when their use and requirements become more well defined.

4.8 Antenna Circuits.

A power amplifier, as an auxiliary piece of equipment to a transmitter, should be designed such that a failure within the power amplifier does not immediately terminate communication capability of the driving transmitter. There should also be a capability of using a driving transceiver in the R/T mode with the single antenna at the output of the P. A. It appears that the best way to satisfy these requirements is with the bypass relay concept. A single pole-double throw RF switch at the input RF connector will direct input power either to the amplifier circuits or directly to a similar switch at the output connector which will connect the driver transmitter directly to the antenna (Figure 12). A received signal at the antenna would be

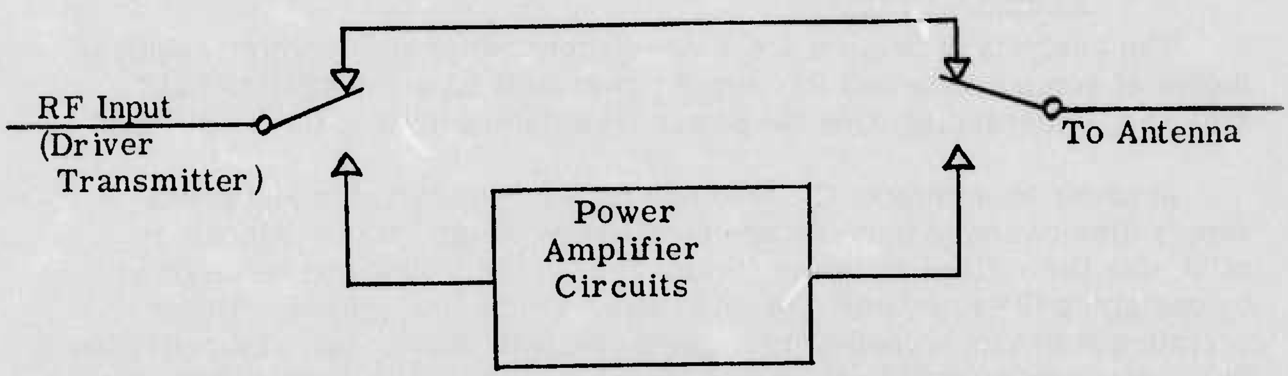

FIGURE 12. BYPASS RELAY CONFIGURATION

similarly connected directly to the driver transceiver for receive operation. The bypass mode can be used for transmission from the driver transmitter in the event of P. A. failure, for R/T operation, or in those cases where a reduced power output is desired. When the P. A. is operating in the R/T mode, it should be compatible with a transceiver operating in an automatic relaying mode.

4.9 Panel Controls/Indicators.

The following controls/indicators as a minimum should be included on the front panel.

a) Primary Power ON/OFF: Located on the power supply panel if separate from the RF amplifier section.

b) Primary power ON indicator.

c) BITE (Built-In Test) meter.

d) BITE Fault Switch: Used to manually step the amplifier through internal tests of each module and function.

e) Mode Control: To select the transmit only mode, T/R relaying mode or straight bypass mode.

f) Elapsed time meter.

g) Power Output Meter: This function could be combined in the BITE meter at the expense of a slight loss of flexibility in the BITE - power monitoring sequence.

h) Malfunction Indicator: To indicate to the operator that the P. A. system is not functioning properly.

i) Blown Fuse Indicators: For both primary and 28 volt lines.

Other controls/indicators may be found desirable.

j) Power Output Level Select: Used to select one or more low power modes.

k) Carrier ON Indicator: A secondary indicator to the RF power meter to provide a highly visible indication of RF power output.

l) Driver ON Indicator: A visual indication that adequate drive is being received from the driving transmitter.

4.10 MTBF.

The discussions of Section 3.5 point out several conditions of design and application which will affect a reliability prediction. Among these are the difference between the 70 and 100 watt transistor approaches, the effect of

TX rated semiconductors, the possible improvements to blower reliability and/or blower failure rate used in the analysis, and the implications of varying mission profile/duty cycle conditions. Depending upon the ground rules applied to the prediction, MTBF's of from 600 hours to well over 3000 hours could be obtained. A fair compromise at this point would seem to be a requirement to predict in excess of 2500 hours MTBF without the blowers, with no duty cycle relief, accompanied by a second requirement for a significant effort to reduce failure rates due to blowers.

4.11 Protect and BITE Circuits.

The amplifier (including power supply) should be protected from various abnormal operating conditions. The power supply should be protected from excessive current drain due to power amplifier failure or malfunction. To avoid the excessive power consumption required for true current limiting, alternate protection such as fuses or circuit breakers may be appropriate in the 28 volt lines. The RF amplifiers should be protected against excessive internal temperature, excessive VSWR, excessive RF drive above rated input levels, over-voltage on the 28 volt lines due to power supply failure, and multiple RF transistor or subassembly failure. The amplifier should indicate a malfunction for any of the above problems, and offer the capability of isolating the failure by means of the BITE sequence. It would be desirable for the amplifier to offer continued operation at reduced power levels in the event of a single RF transistor failure. The specific power derating would depend on several design parameters, but should be in the 2 - 3 dB range for the type of amplifier discussed in this report.

4.12 Physical Characteristics.

Total size requirements of 2 ATR packages were developed in Section 3.5. The total volume requirements are divided almost equally between the power supply and the RF sections. A one ATR size power supply and one ATR size amplifier would allow the one large package to be broken into two smaller units which would be easier to handle, install and maintain.

One additional point should be considered. The optimum packaging for a particular design approach may not lend itself to the specific form factor of an ATR type package. This is especially true in the RF amplifier area where optimum packaging and optimum performance go hand in hand. Certain deviations from standard ATR dimensions should be allowed if these deviations do not result in installation conflicts.

Preliminary weight estimates were made based on the following breakdown by subassembly:

Power Amplifier	No. of Lbs.
8 Modules @ 4 lb. ea.	32
Blower(s)	4
Chassis/Panel	20
	56

Power Supply	
Transformer	35
4 Regulator/Rectifier/Control Modules @ 4 lb. ea.	16
Chassis/Panel	20
Blower(s)	4
	75

4.13 Performance.

The following paragraphs summarize and consolidate studies, investigations, analyses and discussions to arrive at a basis for the corresponding specification performance characteristics.

4.13.1 RF Output Power. The RF amplifier capability analysis (Section 3.1) and block diagram development (Section 3.3) conclude that 12 dual amplifiers can be combined to a kilowatt at the antenna when each dual amplifier is delivering 117.7 watts. Under absolute worst case conditions, the duals may be limited to 113 watts, or 0.2 dB below this level. Also, ALC ripple across the band is responsible for up to ±0.4 dB, or a total delta of 0.8 dB variation in output power. To accomodate these power variations, the kilowatt amplifier discussed herein as being feasible and practical could meet a specification of 1000 watts ±1.0 dB. Under worst case conditions the power could be as much as 1.0 dB below a kilowatt. Under typical conditions, 1000 watts or more would be available.

4.13.2 Output Power Range Selection. The RF drive levels (typically 100 W/30 W for FM/AM operation respectively) are available as reduced output levels by going to the bypass mode. The rated output levels are 1000 W/250 W. Reasonable reduced power select levels for the P.A. might be 500 W/175 W and 250 W/67.5 W. These reduced levels might be used to reduce primary power requirements or to reduce communications range for certain transmissions.

4.13.3 Output Power Meter. The output power meter should provide a constant indication of forward RF output power.

4.13.4 Drive Power. Potential driver transmitters for the kilowatt include 8 watt AM only and 30 watt AM/100 watt FM output levels. The added complexity involved in accommodating the entire input range from 8 watts to 100 watts (plus power variations, tolerances and cable losses) is dependent on several aspects of the specific design approach selected. Satellite communications capability is available only with the 30 W/100 W type systems. Because of this capability and the increased AM power level available with these transmitters, it appears that priority should be given to accommodating the 30 W/ 100 W driver transmitter characteristics in a kilowatt amplifier program. A separate preamplifier can then be specified for those applications where a kilowatt amplifier will be used with an 8 watt AM only driver.

The 30 watt AM/100 watt FM levels are nominal. Typical spec limitations on transmitter output power levels are as wide at ±2.0 dB. Allowance should be made for possible cable loss between the driver and power amplifier. A resulting input power variation of + 2.0 dB, -3.0 dB is consistent both with real life system requirements and with the capabilities of a well designed power amplifier.

4.13.5 Input Impedance. An input impedance of 1.5:1 should be well within the load VSWR capabilities of all driver transmitters. This is also a realistic limit for an amplifier design.

4.13.6 Load VSWR. Extensive testing and analysis has been performed by ECI on UHF power amplifiers and their operation into various VSWR loads. These tests have concluded that a 1 dB power derating is required for operation into a 2.5:1 VSWR in order to ensure safe operation of the power transistors. In applications where this 1 dB derating is unacceptable, it is necessary to "overdesign" the RF amplifier chain for an extra 1 dB of power capability into a nominal 50 ohm load. This "overdesign" would complicate the design of a kilowatt amplifier because of the increased circuit complexity (additional output dual amplifiers), increased power dissipation and increased primary power requirements.

4.13.7 Broadband Noise. Broadband noise measurements were not made specifically for this program. Tests conducted previously have indicated that dual RF amplifiers have noise figures on the order of 25 - 40 dB (±10 MHz and greater removed from the carrier) depending upon operational and test characteristics. It is assumed that these dual amplifiers operating in parallel and combined at the kilowatt level will exhibit the same 25 - 40 dB noise figures.

The worst anticipated noise figure of 40 dB, when applied to each of the amplifiers in the block diagram of Figure 4, and assuming a nominal input power level which results in an attenuator setting of 8 dB, results in the following noise analysis when the amplifier is driven from an ideal source (thermal noise input):

	Noise Level (dBm/Hz)
Input Noise Level	- 174
- 8.0 dB attenuator	- 174
+ 6.0 dB gain ampl., N.F. = 40	- 128
+ 7.9 dB gain dual ampl. assy., N.F. = 40 dB	- 119
- 0.4 dB splitter loss	- 119.4
+ 7.9 dB gain dual ampl. assy., N.F. = 40 dB	- 111
- 1.2 dB output circuit losses	- 112

Some of the above noise levels are approximated to the nearest dB. The analysis is based on the worst expected noise figure in the P.A. Since all amplifier noise figures are assumed to be equal and the analysis begins from a thermal noise source, the resulting output noise assuming an optimistic noise figure of 25 dB for each amplifier is -127 dBm/Hz, or 15 dB better than the 40 dB noise figure analysis. Thus a one kilowatt amplifier operating from a "clean" RF drive will have broadband noise levels of -112 to -127 dBm/Hz at ± 10 MHz and more removed from the carrier.

State-of-the-art driver transmitters have noise levels generally not better than -120 dBm/Hz and typically about -110 dBm/Hz at ±10 MHz and more away from the carrier. The optimistic noise input level of -120 dBm/Hz, when amplified by the same 40 dB noise figure amplifier blocks used above, results in a -106.6 dBm/Hz noise output level as shown below:

	Noise Level (dBm/Hz)
Input Noise Level	- 120
- 8.0 dB attenuator level	- 128
+ 6.0 dB gain ampl., N.F. = 40 dB	- 121
+ 7.9 dB gain dual ampl. assy., N.F. = 40 dB	- 113
- 0.4 dB splitter loss	- 113.4
+ 7.9 dB gain dual ampl. assy., N.F. = 40 dB	- 105.4
- 1.2 dB output circuit losses	- 106.6

This noise level is about 5.4 dB higher than the same amplifier driven from a thermal noise source. It is interesting to repeat the analysis assuming a -120 dBm/Hz noise input as above, but assigning the best case noise figure at 25 dB to the power amplifier stages.

	Noise Level (dBm/Hz)
Input Noise Level	- 120
- 8.0 dB attenuator level	- 128
+ 6.0 dB gain ampl., N. F. = 25 dB	- 122
+ 7.9 dB gain dual ampl., N. F. = 25 dB	- 114
- 0.4 dB splitter loss	- 114.4
+ 7.9 dB gain dual ampl., N. F. = 25 dB	- 106.5
- 1.2 dB output circuit losses	- 107.7

It is significant to note that an improvement in power amplifier noise figure of 15 dB (each amplifier stage) is accompanied by a mere 1.1 dB reduction in output noise. And this is assuming a best expected noise level from the driver transmitter. Assume a more typical -110 dBm/Hz noise source driver, and the effect of a 40 dB noise figure in the power amplifier is almost completely masked out.

The conclusion to be drawn is that while a broadband power amplifier will have a measurable output noise level, the limitation is imposed by the noise characteristics of the driving transmitter. Until transmitters can be designed and built with noise levels better than -120 dBm/Hz, the power amplifier should not be the limiting item in the noise chain.

Based upon an extension of the first noise analysis performed, it would be reasonable to require a power amplifier to have less than -110 dBm/Hz of broadband noise output, ±10 MHz and greater from the carrier, when driven from a noise source with noise levels less than -130 dBm/Hz.

4.13.8 T/R Turn-Around Time. Turn-around time is defined as the time required for the power amplifier to reach 90% of specified output power when switched from bypass to transmit with proper drive applied, and to meet specified bypass insertion loss when switched from transmit to bypass (receive) mode. A major limitation to turn-around time is the switching speed of the bypass coaxial relays. Conventional relays are available with 25 millisecond switching times. Vacuum-sealed relays would allow turn-around times of 10 milliseconds. For applications requiring faster T/R times there are two options. The first is to provide a solid state T/R switch. This would be significantly more expensive than relays at the kilowatt level, and would increase output circuit losses and complexity. The second option is to use separate receive and transmit antennas for the fast turn-around modes. The power amplifier relays would remain in the transmit mode and switching times would be determined by the transmitter keying times. The power amplifier keying times, excluding relays, can be as fast as 100 microseconds in FM/FSK/PSK modes, based upon breadboard investigations conducted during this program.

4.13.9 Harmonics. Broadband 225 - 400 MHz power amplifiers will naturally have a relatively high second harmonic content at the low end of the band. Broadband networks designed to match the amplifiers at 400 MHz cannot be designed using conventional techniques to have significant rejection at 450 MHz, the second harmonic frequency of 225 MHz. Second harmonics of 225 MHz are typically 10 - 15 dB below the carrier.

Lowpass filter technology is currently capable of 45 - 55 dB second harmonic rejection at 450 MHz with low insertion losses (about 0.35 dB). Additional filter rejection could be obtained at the expense of increased insertion loss, but it is best to keep output circuit losses as low as possible in a high power amplifier. It is recommended that the harmonic specification be 60 dB below the carrier, realizing that this limit would be approached only at the low end of the band.

4.13.10 Spurious. There should be no spurious frequency generating circuits in a power amplifier which would result in spurious outputs greater than 80 dB below the carrier. This output characteristic is dependent upon the spectral purity of the drive source, since there are no frequency selective networks in the P.A. to attenuate in-band spurious signals.

4.13.11 Antenna Induced Intermodulation. This characteristic of a power amplifier should not differ significantly from that of a similar lower power transmitter. The power amplifier uses essentially similar output networks with similar but a larger number of RF amplifiers combined to the single output.

4.13.12 Carrier Noise. Carrier noise characteristics should be similar to lower power transmitters, with the exception that P.A. carrier noise is dependent on the driving transmitter carrier noise. Typical transmitter noise limits are 50 dB below the detected output voltage obtained from a carrier 90% modulated. The power amplifier might be expected to contribute a noise level also 50 dB down, which would add to the input noise and result in an output AM carrier noise 47 dB below carrier reference.

4.13.13 Modulation Capability. The power amplifier should be capable of handling 100% modulation. However, when driven by a transmitter modulated 100%, allowable distortion and P. A. nonlinearity may reduce the modulation to 95% under certain conditions of frequency and power level. Since driving transmitters will typically be modulated less than 100%, it is recommended that the specification requirement be for less than a 5% reduction in modulation percentage when the P. A. is driven with a 95% modulated signal.

4.13.14 AM Distortion. Tests conducted during this program indicate that either linearized amplifiers or a modulation correction control loop or a combination of the two can be used to limit added distortion to less than 5% above driver AM distortion.

5.0 DETAIL SPECIFICATION

Following is a detailed specification for the characteristics and performance of a solid state one kilowatt power amplifier referred to herein as "the equipment."

5.1 Interfaces.

The equipment shall be designed with minimum dependence on control signals from the driver transmitter. Three interface lines are allowable as specified below:

a) Mode Information: TTL compatible Logic "0" for AM operation, Logic "1" for FM/FSK/PSK operation. With no control signal connected to this input the amplifier shall operate at the AM carrier level.

b) Key Signal: Logic "1" keys amplifier and bypass relays, Logic "0" unkeys amplifier and switches relays to bypass mode.

c) Key Inhibit: A Logic "0" from the amplifier to the driver transmitter provides a means for preventing transmitter keying while amplifier relays are being switched.

5.2 Service Conditions.

The equipment shall operate under Class 1 or Class 1X conditions as defined in MIL-E-5400, with exceptions as specified herein. Intermittent operation at + 71°C is not required.

5.3 Cooling.

The equipment shall operate continuously and meet the requirements of this specification when provided with cooling air as specified below (or an effective equivalent air supply):

a) Air supplied at a density of 0.0670 lb/ft^3 and + 55°C (sea level) is required in quantities of 597 cfm (2400 lb/hr).

b) Air supplied at a density of 0.0464 lb/ft^3 and + 53°C (10,000 ft.) is required in quantities of 790 cfm (2200 lb/hr).

c) Air supplied at a density of 0.0517 lb/ft^3 and + 20°C (10,000 ft.) is required in quantities of 300 cfm (930 lb/hr).

If auxiliary cooling air is not provided, the equipment shall operate in a MIL-E-5400 Class 1 environment with duty cycle and performance as specified herein.

5.4 Duty Cycle.

With cooling air supplied in accordance with Section 5.3, the equipment shall be capable of continuous operation and satisfy the requirements of this specification.

Operating in a MIL-E-5400 environment with ambient cooling air, the equipment shall be capable of operating at a 5:1 OFF-to-ON duty cycle with the "ON" time not to exceed 1 minute. Output power shall be degraded by not more than 2 dB at the end of the 1 minute "ON" period.

5.5 Primary Power.

The equipment shall meet all applicable requirements of MIL-STD-704 and give specified performance from an AC 400 Hz 3-phase input power source, 115/200 volts, Category B, as defined in MIL-STD-704. At low line voltage a degradation in RF power output not to exceed 1 dB is allowable. Maximum primary input power at nominal line and output power shall be 6600 kVA at a 0.8 maximum power factor.

5.6 Frequency Range.

The equipment shall be capable of operation specified herein on 7000 discrete radio frequency channels spaced, spaced at 25 KHz increments over the frequency range of 225.000 to 399.975 MHz.

5.7 Emissions.

The equipment shall provide transmission of 6A3, 60A3, 16F3, 2.5F1, 0.15F9, 0.6F9, 2.4F9, 4.8F9, 9.6F9, and 19.2F9 types of emissions.

5.8 Antenna Circuits.

The power amplifier shall have a single output antenna port. Operation in the bypass, T/R or Transmit only mode shall be switch selectable from the front panel of the amplifier.

5.8.1 Automatic Power Amplifier Bypass. An indication by the fault monitoring circuit of the loss of primary power shall cause the amplifier to unkey and switch to the bypass mode.

5.8.2 Automatic Relay Compatibility. When in the transmit/receive (T/R) mode, the power amplifier shall be compatible with a transmitter/receiver operating in an automatic relaying mode.

5.9 Panel Controls and Indicators.

The following controls and indicators shall be located on the power supply front panel:

a) Primary power ON/OFF switch
b) Primary power ON indicator
c) Primary power fuses or circuit breakers
d) Blown fuse indicators

The following controls and indicators shall be located on the amplifier front panel:

a) 28 volt ON indicator
b) 28 volt fuse or circuit breaker
c) 28 volt blown fuse indicator
d) BITE (Built-In Test Equipment) meter
e) BITE fault switch
f) RF power output meter
g) Elapsed time meter
h) Mode select switch (transmit only, T/R, bypass)
i) Malfunction indicator
j) Power output level select
k) Carrier ON indicator
l) Driver ON indicator

5.10 MTBF Requirements.

The equipment, excluding blowers, shall have a predicted MTBF of 2500 hours or greater. The prediction shall be in accordance with MIL-HDBK-217 and will assume a 50°C ambient air temperature (unless cooling air will be provided at less than 50°C). The use of contractor field data shall be allowed.

5.11 Protect and BITE Circuits.

Circuitry shall be included to protect the RF amplifiers and power supply from damage caused by excessive VSWR, high RF drive, RF transistor failure, overvoltage on the 28 VDC lines or excessive internal temperature. These fault modes should be indicated by a "malfunction" indicator on the front panel. BITE (Built-In-Test-Equipment) circuits shall be capable of isolating the fault to the module or subassembly level.

5.12 Physical Characteristics.

The equipment shall be housed in the equivalent volume of 2 ATR-size packages, with a total weight not to exceed 135 lbs. The power supply and RF amplifiers shall be in separate packages, each not to exceed 80 lbs. in weight.

5.13 Performance Requirements.

The equipment shall provide electrical performance characteristics in accordance with the following paragraphs.

5.13.1 RF Output Power. The nominal unmodulated RF output power shall be + 30.0 dBW (1000 watts) for FM, FSK or PSK, and + 24.0 dBW (250 watts) for AM into a 50 ohm resistive load (VSWR 1.0:1). When driven with an RF input signal in accordance with 5.13.4, the power amplifier output power will be within ±1.0 dB of nominal under standard ambient conditions.

5.13.2 Output Power Range Selection. The power amplifier RF output power level shall be selectable in all modes to either full rated power, 3 dB below rated power (125 watts AM, 500 watts FM/FSK/PSK) or 6 dB below rated power (67.5 watts AM, 250 watts FM/FSK/PSK) by means of a switch located on the front panel.

5.13.3 Output Power Meter. The output power meter on the front panel shall provide readings of incident and reflected power. The accuracy of the meter readings at a full rated power of 1000 watts shall be within ±1 dB of the actual RF power output from the equipment.

5.13.4 Drive Power. The acceptable input power for nominal performance shall be 100 watts + 2 dB, - 3 dB for FM/FSK/PSK and 30 watts + 2 dB, - 3 dB for AM.

5.13.5 Input Impedance. The power amplifier input impedance shall be 50 ohms nominal. In any non-bypass mode the input VSWR shall be 1.5:1 maximum.

5.13.6 Load VSWR. The equipment shall be protected from damage due to shorts or opens in the interconnecting RF transmission lines from the amplifier or due to a VSWR greater than 4.0:1. When the amplifier is loaded with any impedance producing a VSWR of 2.5:1, the RF carrier output shall be degraded by not more than 1.0 dB. Between 2.5:1 and 4.0:1 the amplifier may operate at reduced power and be protected from damage.

5.13.7 Broadband Noise. The power amplifier output noise power, excluding harmonics and spurious, shall not exceed -110 dBm/Hz exclusive of carrier frequency ±10 MHz, when driven from a source with noise levels less than -130 dBm/Hz.

5.13.8 Transmit/Receive Turn-Around Time. Turn-around time is defined as the time required for the power amplifier to reach 90% of specified output when switched from bypass to transmit with proper drive applied and to meet specified bypass insertion loss when switched from transmit to bypass (receive) mode. Turn-around time shall not exceed 100 milliseconds in the simplex AM mode, and 25 milliseconds in the FM/FSK/PSK modes. (Note: See options, Section 4.13.8).

5.13.9 Bypass Mode Insertion Loss. When the equipment is in the bypass mode, insertion loss shall not exceed 1.0 dB.

5.13.10 Harmonics. All harmonics and subharmonics shall be attenuated at least 60 dB below the full power output when the amplifier is driven from a source with subharmonics at lease 70 dB below the carrier.

5.13.11 Spurious. All spurious signals removed drom the carrier by at least 2 MHz shall be at least 80 dB below the carrier when the amplifier is driven from a source with spurious outputs at least 90 dB below the carrier.

5.13.12 Antenna Induced Intermodulation. The third and higher order intermodulation products caused by an in-band interfering signal of + 26 dBm, or less, coupled into the RF output port of the power amplifier, shall be at least 20 dB below the level of the interfering signal. Measurement shall be made with a + 26 dBm interfering signal at a frequency separation of one percent.

5.13.13 Carrier Noise. At rated AM power output the detected output voltage obtained from an unmodulated carrier shall be at least 36 dB below the detected output voltage obtained from the carrier 85 percent modulated at 1000 Hz. The driving source carrier noise level must be at least 40 dB below the detected output voltage obtained from its carrier 90 percent modulated at 1000 Hz.

5.13.14 Modulation Capability. When driven by a 30 watt ±1 dB RF carrier modulated 90 percent with an audio signal at any frequency between 300 Hz and 3500 Hz, the power amplifier shall be capable of being modulated at least 85 percent.

5.13.15 AM Distortion. At rated output power with 85 percent minimum modulation, the power amplifier shall not add more than 5 percent distortion to a signal from a driving source meeting 5 percent maximum distortion at 90 percent modulation at rated output power.

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