

HIGH EFFICIENCY SPS KLYSTRON DESIGN
E. J. Nalos, Boeing Aerospace Company

1. Introduction

Considerable data has now been accumulated on the feasibility of an 80-85% high power klystron design from previous studies. The most likely compact configuration to realize both high efficiency and high gain (~ 40 dB) is a 5-6 cavity design focused by an electromagnet. A refocussing section will probably be required for efficient depressed collector operation. An outline of a potential klystron configuration is given in Figure 1. The selected power output of 70 kW CW resulted from a maximum assumed operating voltage of 40 kV. The basic klystron efficiency cannot be expected to exceed 70-75% without collector depression. Although impressive gains have been achieved in raising the basic efficiency from 50% to 70% or so with a multi-stage collector, the estimated efficiency improvement due to 5-stage collector at the 75% level is only about 8%, resulting in an overall efficiency of about 83%. These estimates need to be verified by experiment, since the velocity distribution of the spent klystron beam entering the collector is not precisely known. It appears that the net benefit of a 5-stage collector over a 2-stage collector is between 1.5 - 3.5 kW per tube. This has the double benefit of less electrical power to be supplied as well as less thermal power in the collector to be dissipated. Table 1 indicates an estimated energy balance in the klystron which leads to the above estimates. A modulating anode is incorporated in the design to enable rapid shutoff of the beam current in case the r.f. drive should be removed. In this case, the collector would become overheated since it would receive the full beam power.

2. Depressed Collector Design

One of the greater uncertainties in the design is the velocity distribution of electrons in the output gap, particularly for a high basic efficiency tube. Experimental verification will be required for the selection of proper depressed voltages at each collecting electrode. Varian has reported that about 10% of the electrons develop twice the d.c. beam voltage in a 50% efficient tube. We estimate that this will be reduced to perhaps 2% for an 80-85% efficient tube. To obtain initial specifications for the collector supply, an estimate was made of the possible voltage ratios required, as indicated in Figure 2.

3. Voltage Regulation

The requirements on the modulating anode and body voltage are dictated primarily by phase fluctuations. At 40 kV, $\phi \approx 3000^\circ$ and at 41 kV, this calculation yields 2972° . Thus, $d\phi/dt = -37^\circ$ per kv. If a 10° phase error were allowable in the klystron, this would translate into a regulation requirement of $\pm 0.67\%$ at 40 kv, provided that klystron-to-klystron phase errors are not correlated. Although it is likely that voltage fluctuations on all klystrons on a given d.c. - d.c. converter will go up and down together, the time delays in distribution, of the order of fractions of microseconds, will make them appear as though they were uncorrelated at a given instant at all klystron terminals. With this in mind, the initial regulation requirement on the modulating anode and body supply was set at 0.5%. Since it is contemplated to include the klystron in a phase compensation loop, it may be possible to relax this requirement when the loop performance is verified.

4. Electron Beam Focusing Design

The focusing options for the klystron include: (1) solenoid ElectroMagnetic (EM) focusing, (2) Multiple-pole electromagnetic focusing with periodic field reversals, introducing the possibility of Permanent Magnet (PM) implementation, (3) Periodic Permanent Magnet (PPM) focusing used successfully on low and medium power tubes (mostly TWT's); and 4) Combined PM/PPM focusing wherein the PM section at the output is used to retain good efficiency and good collimation in the high power r.f. region. The low risk approach of (1) was recommended in order to achieve the highest efficiency, but R&D efforts in a combined PM/PPM approach should be investigated for possible later incorporation.

In order to achieve a conservative design, we have initially selected a capability of achieving 1,000 Gauss in the solenoid when operating at 300°C. Selecting a minimum ID dimension compatible with directly winding the solenoid on the tube involves a trade study of the required solenoid power and weight as a function of solenoid OD. Figure 3 shows the trade of solenoid power and weight with coil OD.

It is anticipated that the solenoid will consist of copper sheet with glass-like insulation between layers, wound directly on the tube body. With factory adjusted cavity tuning, there will be no protruding tuners. It is possible that the solenoid may be used for baking out the tube in space.

As a matter of interest, the performance parameters of a 50 KW PM focused klystron were estimated in Table 2. With the design assumptions postulated, it does not appear to offer any advantages over an efficiently focused solenoid design.

5. Design Approach to Long Life

The objective of SPS is the achievement of 30 year life and since the main component of the MPTS system is the r.f. transmitter, its consideration is of paramount importance. The major transmitter elements which contribute to life are summarized in Table 3. The achievement of uniform tube-to-tube performance will require stringent materials control, well defined construction techniques, and special design features such as temperature compensated cavity frequency control.

An initial risk assessment of the unknowns on the space environment have led us to favor a closed envelope approach as a reference design. Some of the concerns with open envelope operation near the Shuttle vehicle deal with outgassing from non-metallic skin of heavy molecules and absorbed volatile species: cabin leaks (oxygen); fuel cell flash evaporators (water vapor); Vernier control rocket engine exhaust; and main rocket engine outgassing (water vapor). The degree to which such contaminants can be localized, and the pumping speed of space, etc., have yet to be determined.

The NASA objective of 30 year life, in the light of current experience and understanding, thus has to be based on the following phased approach:

- . Conservative Design:
 - Emission; R.F., Thermal and Stress: Derating
- . Determination of Appropriate Manufacturing Procedures
- . Adequate Protective Features
 - Modulating Anode
 - System Monitoring Requirements

5.2 Tube MTBF Considerations

Ideally, a failure model of the transmitter would be desired, in which no failures occurred until wearout mechanisms set in; i.e., avoidance of early mortality. To some degree this can be achieved by a burn-in procedure to identify and remove infant mortality victims. It is anticipated that with the reference design tube, partial or full bakeout in space will be feasible, avoiding the need to perform costly burn-in on the ground. Also, with mass production, automated manufacture, good quality control, and maintenance, infant mortality can be minimized.

With roughly $N = 100,000$ tubes, if a maximum of 2% of all klystrons are allowed to fail at scheduled SPS shutdown, (every 6 months), the required tube MTBF would be approximately

$$\frac{(.02N)}{N} (\text{Tube MTBF}) = 6 \text{ months} - .5 \text{ years; i.e., MTBF} = (50)(.5) = 25 \text{ years.}$$

This is compatible with the reference klystron design; however, a more refined reliability model needs to be developed, of which the exponential failure model is but one case corresponding to a constant failure rate. With proper burn-in procedures, and as better understanding of failure modes is developed, the SPS klystron may require a much lower MTBF to meet the above criteria. With a proper burn-in period, infant mortality failures can be avoided and failures shifted toward cathode wearout limitations. The required burn-in period for current space qualified TWT's is of the order of 1,500 hours. Further understanding of the required tube MTBF under these conditions will evolve with the ground based development program implementation.

6. Klystron Tube Protection

The tube interacts with the subarray through the waveguide feed system. The primary requirement is maintenance of a good r.f. match under all conditions. During initial processing or if mismatched, either external or internal arcing may occur. Commercial waveguide components are available to visually detect arcs and use a trigger signal to disconnect the tube rapidly, in this case by connecting the modulating anode to cathode. This can occur in much less than 1 μ sec, adequate to prevent damage.

With loss of r.f. drive, the entire electron beam power appears at the collector. The conventional klystron is designed to handle this power. In our case, the collector is designed to handle only the spent electron beam after normal r.f. interaction. If the loss of r.f. drive is sensed at the klystron input, the modulation-anode power supply will be used to shut off the electron beam.

The most likely region of dc arcing is between cathode structure and modulation-anode and between the modulating anode and the r.f. circuit. In the event of an arc, the energy stored in the modulation-anode power supply RC circuit is discharged. Ordinarily the arc extinguishes after a brief interval and normal tube performance is restored automatically. Should some unknown fault cause persistent non-clearing arcing, arc logic could be designed to sense repeated loss of r.f. output and to shut down the modulation-anode power supply.

- Adequate Test Program on Ground
 - Failure Mode Identification
 - Infant Mortality Elimination - Burn-in
- Understanding of Space Environment
 - Processing in Space
 - Open Envelope Operation
- Definition of Maintenance Philosophy
 - Allowable Down Time
 - In-place Repair Feasibility
- Development of Improved MTBF Analytical Model
- Space Test Verification

There are promising developments in transmitter life which lend some credibility to the 30 year life objective. For instance, the best ten high power klystrons running on the BMEWS system have seen 9 years of life and are still running. With proper burn-in procedures, current space based TWT's are being qualified for 7 years life. Over 100 such tubes currently in space have been running for well over 2 years. It is our expectation that within the SPS development time-frame, tube MTBF's approaching 30 years with the suggested design approach will be feasible. It is important to recognize that significant life test programs on the ground will be required not only for cathodes, but the entire r.f. envelope.

5.1 Cathode Design

The mechanisms limiting thermionic cathode life are primarily evaporation rate of the cathode material, cathode matrix properties, and impurities. The cathode-tube interaction is paramount in realizing long life, regardless of how good the cathode may be in a diode test. The approach to realize 30 year life must be based on minimizing tube-cathode interactions through conservative design, good beam focusing and proper selection of materials to minimize poisoning gases produced by electron bombardment. The most likely candidates, based on present knowledge, are either a tungsten matrix cathode operating at a temperature of slightly above 1000°C or a nickel matrix cathode operating at about 800°C. The lower temperature would be preferable from the life point of view but factors such as migration and reactivation feasibility tend to favor the higher temperature cathode. Our current assessment, based on discussions with the tube industry suggests that it would probably be unwise to utilize some of the newer cathodes until sufficient life test data has been accumulated. Encouragement with respect to long life in thermionic cathodes can be derived from the work at Bell Telephone Laboratories on the so-called Coated Powder Cathode (CPS), which is in use on long life repeaters, capable of 50,000 hours life at current densities approaching 1 amp/cm², much higher than those proposed for the SPS Klystron (<.2 amps/cm²).

Persistent repeated nonclearing rf arcing in the klystron rf load or output system may result in tube damage. The rf arc logic protection circuit is designed to sense reflected rf power caused by the arcing and to shut down the modulation-anode power supply pending correction of the problem.

7. Operation Under Reduced Voltage

One advantage of the klystron is the fact that efficiency does not deteriorate significantly with voltage. The effect of solar cell voltage degradation on klystron power output is indicated in Figure 4 for the condition that the klystron characteristics remain on the V-I portion of the solar cells corresponding to maximum d.c. output. This condition can only be achieved if the perveance of the tube is slightly changed. If the modulating anode is mounted on a diaphragm, such an adjustment could be made. This feature would also be useful for adjustment of tube-to-tube uniformity. It is seen that if the solar cells are not refurbished, the efficiency remains high, but the power output drops significantly. On this basis, it was decided to refurbish solar cells and not require the transmitter to adjust perveance for solar cell optimal matching.

8. Klystron Power Output Trade Study

The reference klystron represents an initial point design within the given NASA guidelines. It is intended primarily as a vehicle to demonstrate its potential in the SPS application. If the operating voltage at GEO can be increased to a value above 40 kv other klystron power levels become of interest.

One of the advantages of the linear beam amplifier such as a klystron is the fact that the different interaction regions, i.e., beam formation, r.f. interaction, and beam collection are physically separate and hence distribute the thermal stresses over a large area. The most critical portion of the klystron from the thermal point is the output gap. The output gap interception for two typical values of beam transmission (95% and 98%) is indicated in Figure 5. The capability of the output gap to handle this interception is given for two values of heat rejection capability: 0.25 and 0.5 kw/cm² of area. This could be either heat pipe cooling or pumped fluid cooling.

It is seen that for a 4% beam interception and $W = 0.25 \text{ kw/cm}^2$, the maximum beam voltage is about 67 kv, corresponding to a power level in excess of 200 kw. If the perveance were increased from $S = 0.3$ to 0.5×10^{-6} , still within the regime of potentially high efficiency, this power level would correspond to 580 kw. This has encouraged us to investigate two additional point designs, at 250 kw and at 500 kw, respectively, the parameters for which are summarized in Table 4.

The efficiency including solenoid power is somewhat higher than that for the reference design. It is worth noting that even with a longer tube, the efficiency increases by about 2% points due to lower incremental solenoid requirements at higher power. The specific mass decreases from about 0.8 kg/kw at 70 kw to less than 0.4 kg/kw at 500 kw CW. Thus, it appears advantageous to consider a higher power klystron design should the voltage constraints permit it.

The cost of a single klystron tube is estimated from the cost trends in Figure 6. For a 70 kw CW tube, the mass production cost is estimated at \$2800. The acquisition cost of r.f. tubes and 10-year replacement cost of spares, based on a projected transportation cost to space of \$60 per kg, for a system output of 6 GW RF in space, are summarized in Table 5. The transportation costs comprise about 47 to 62% of the total cost. Again, with the assumptions made, it appears advantageous to go to as high power per tube as possible. As the ground-based development program proceeds, the results of these trade studies will be used in updating the present baseline design, not only for the klystron transmitter candidate, but for other transmitters as well.

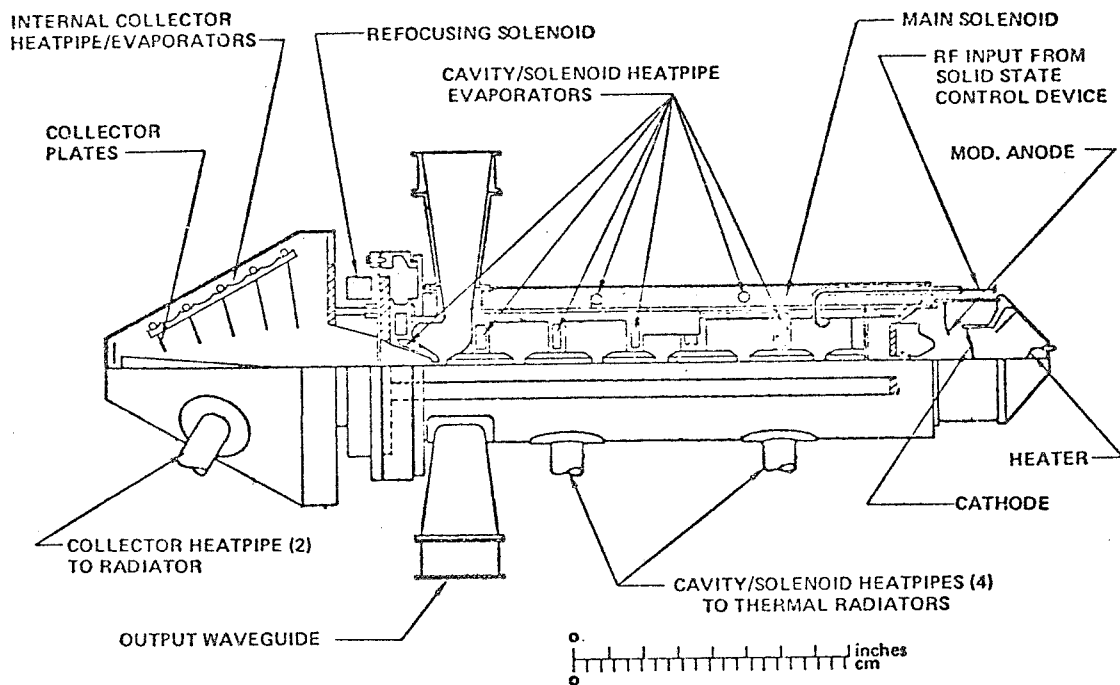
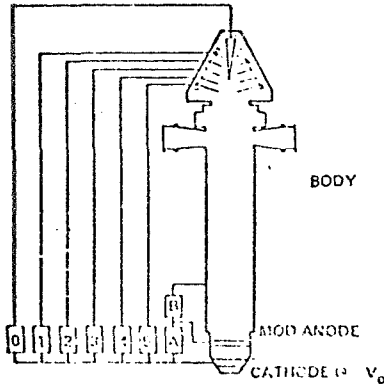


Figure 1 Reference Klystron Configuration

Table 1 Energy Balance in Reference Klystron Design

	2-SEGMENT COLLECTOR	5-SEGMENT COLLECTOR
BEAM POWER	92.62 Kw	92.62 Kw
RF LOSS IN DRIVER CAVITIES	.40 Kw	.40 Kw
RF POWER PUTPUT ¹	70.66 Kw	70.66 Kw
OUTPUT CAVITY RF LOSS	2.19 Kw	2.19 Kw
OUTPUT INTERCEPTION LOSS ²	1.62 Kw	1.62 Kw
POWER ENTERING COLLECTOR	17.75 Kw	17.75 Kw
COLLECTOR RECOVERY	7.10 @ 40%	10.65 @ 60%
THERMAL LOSS IN COLLECTOR	10.65 Kw	7.1 Kw
NET BEAM POWER	85.52 Kw	81.97 Kw
EFFICIENCY EXC. SOLENOID	82.6%	86.2%
NET EFFICIENCY ³	81.2%	84.6%

1. ELECTRONIC EFFIC. (.79) x OUTPUT CIRCUIT EFFICIENCY (.97) x REMAINING POWER (92.22 Kw)
2. BASED ON 4% INTERCEPTION @ $V_{o/3}$ (33%) and 2 $V_{o/3}$ (67%) i.e., .0178 $V_o I_o$
3. INCLUDING 1.5 Kw FOR SOLENOID AND HEATER POWER.



ESTIMATED CURRENT & VOLTAGE DISTRIBUTIONS

COLLECTOR CONFIGURATION	3 SEGMENT			5 SEGMENT		
	V/V ₀	I/I ₀	P/P ₀	V/V ₀	I/I ₀	P/P ₀
MOD. ANODE SUPPLY	.5	.01	.040	.5	.01	.040
BODY SUPPLY ENERGIES	.5	—	—	.5	.01	.040
SPIN ELECTRODE	0	.02	—	0	.02	—
COLLECTOR #1	.6	.02	.017	.5	.02	.017
COLLECTOR #2	.9	.04	.036	.6	.04	.024
COLLECTOR #3	.95	.83	.836	.7	.07	.049
COLLECTOR #4	—	—	—	.9	.15	.125
COLLECTOR #5	—	—	—	.95	.55	.672
TOTAL	1.0	—	.974	1.0	—	.974
EFFICIENCY IMPROVEMENT				1.63		
ESTIM. EFFICIENCY, EXCL. SOLENOID				32.4%		
(76.3% NOMINAL UNDEPRESSED)				36.2%		

Figure 2. Reference Klystron Depressed Collector Design

COPPER SOLENOID 3" ID, 1000 GAUSS, 16.5" LONG

- ASSUMES POWER GENERATION @ 3.5 kg/kw AND PASSIVE HEAT REJECTION @ 6.2 kg/kw @ 125°C.
- AS ABOVE, WITH 3.86 kg/kw FOR 300°C HEAT REJECTION.

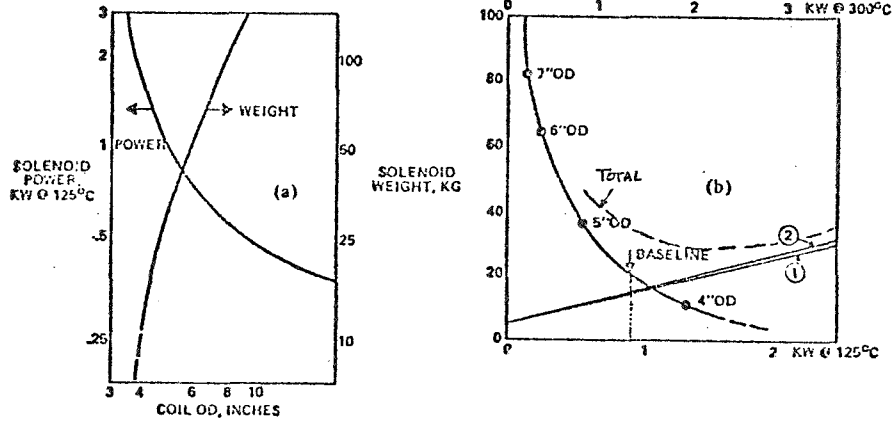


Figure 3 Solenoid Design for High Power Klystron

Table 2 50 KW Permanent Magnet Klystron Design

VOLTAGE/CURRENT	38KV, 1.81 AMPS
PERVEANCE/BEAMPPOWER	S = .244, P ₀ = 69KW
ELECTRONIC EFFICIENCY	0.75
CIRCUIT EFFICIENCY	0.97
RF POWER OUTPUT	50KW
HEATER POWER	.1KW
DRIVER RF LOSSES	.005V ₀ I ₀ = .3KW
OUTPUT INTERCEPTION LOSS	.025V ₀ I ₀ = 1.72KW
RF OUTPUT CAVITY LOSS	.03(50) = 1.50KW
POWER INTO COLLECTOR	15.48KW
COLLECTOR THERMAL INPUT	8.51KW REMOVED @ 500°C

PASSIVE COOLING -
 RADIATOR & HEAT PIPES LIQUID METAL CYCLE @ 2.2/1.5KG/KW FOR 275°C
 @ .94/.43KG/KW FOR 500°C

WEIGHT ESTIMATE

TUBE & POLEPIECES	12.0KG	
COLLECTOR - 5 SEGMENT	6.0	o SPECIFIC WEIGHT = .78 TO .83 KG/KW
MAGNETS	7.5	
RADIATOR DISTANCE	0	1 METER
COOLING @ 275°C	5.4	8.0KG
COOLING @ 500°C	4.2	8.0KG
TOTAL WEIGHT	35.1	41.5KG
		o EFFICIENCY = 80.7%

Table 3. Features Affecting Transmitter Life

BEAM FORMATION

- CATHODE MANUFACTURING MATERIAL PROCESSING
- EMISSION SUPPRESSION FROM SURFACES
- CATHODE BASE MATERIAL PURITY-POISONING MECHANISM
- EVAPORATION RATES FROM IMPREGNATED CATHODES
- HEATER WARMUP
- BURN-IN PERIOD-NO INFANT MORTALITY

BEAM FOCUSING

- SOLENOID DESIGN/MATERIALS-SPACE BAKEOUT FEASIBILITY AND CONTROL
- MAGNETIC CIRCUIT MATERIAL SELECTION SmCo_5 -ALNICO₂-FLUX CONDUCTORS

RF CIRCUIT

- COPPER ALTERNATIVES FOR CAVITIES
- PROPERTIES OF LOSSY INTERNAL CERAMICS
- OUTPUT WINDOW POWER LIMITS BeO , Al_2O_3

BODY AND COLLECTOR

- LEAKAGE OF INSULATORS
- SUPPRESSION OF SECONDARY EMISSION

EXTERNAL

- LEAD AND CONNECTOR COMPATIBILITY

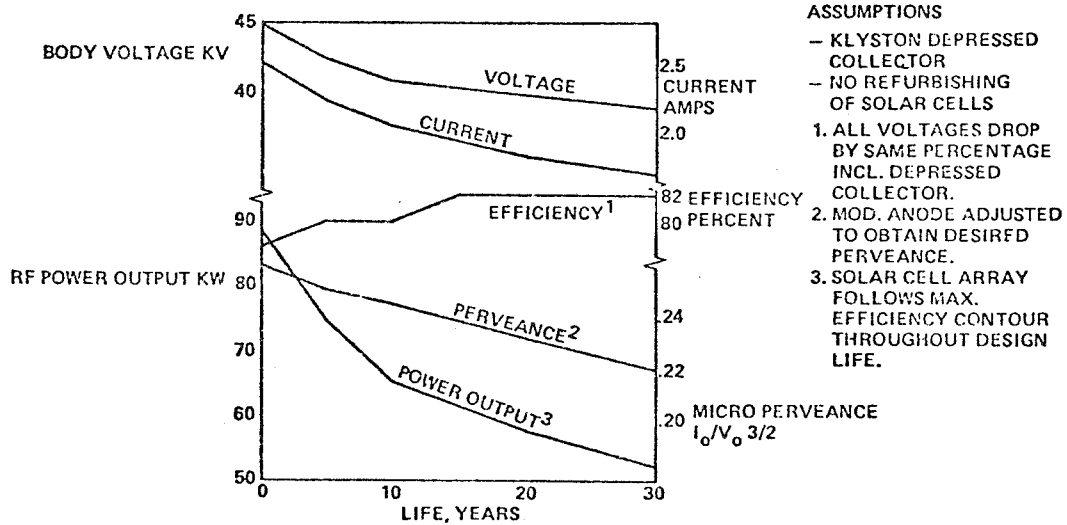


Figure 4 Klystron Performance When Optimally Matched to Spjar Cell Output

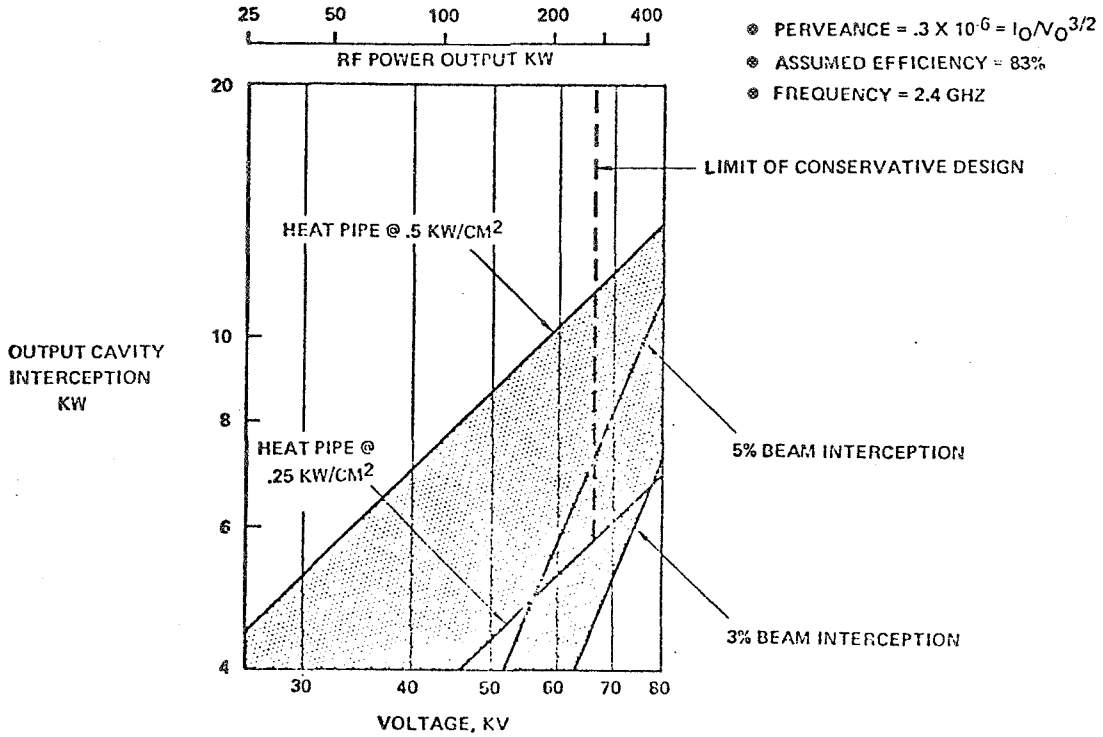


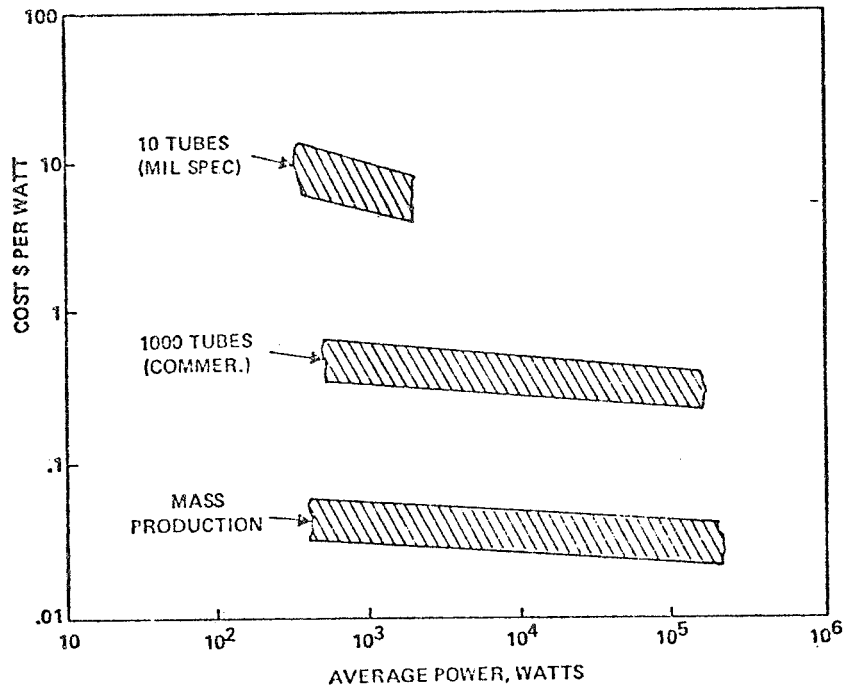
Figure 5. High Power CW Limitations of High Efficiency Klystron

Table 4. Alternate High Power Klystron Designs

POWER VOLTAGE/CURRENT PERVEANCE $K \times 10^{-6}$ RF SECTION LENGTH $\sim \sqrt{V_0}$	70.6kw 42kv/2.2amps .25 16.5in		250kw 65kv/5amps .30 20.5in		500kw 80kv/8.2amps .36 22.8in				
	WEIGHT, kg	POWER, kw	WEIGHT	POWER	WEIGHT	POWER			
TUBE WEIGHT CAVITY, SEALS, BODY ETC. $\sim 1.2 \sqrt{V_0}$	10kg		15kg		16.6kg				
COLLECTOR WEIGHT (EST.) $\sim V_0 I_0$	7.0kg		13.2kg		18.7kg				
SOLENOID (EST.) @ 300°C, 1 KGAUSS, $P \sim B^2 \times L \sim \sqrt{V_0} K$	20kg	2kw	24.8kg	2.98kw	27.9kg	3.98kw			
HEATER AND REFOCUSING COIL		1.0kw		1.50kw		2.0kw			
RF LOSSES		4.2kw		14.7kw		29.8kw			
RADIATOR AND HEAT PIPES	0	1m	0	1m	0	1m			
WEIGHT AND POWER DISSIP'N REQ'D @ 300°C	9.5	14.5	7.2kw	25.3	33.6	19.2kw	47.3	72.0	35.8
WEIGHT AND POWER DISSIP'N REQ'D @ 500°C	4.9	9.3	9.9kw	16.7	32.1	34.1	33.8	64.9	69.0
TOTAL WEIGHT KG	51.4	60.8		95.0	123.7		144	199.8	
SPECIFIC WEIGHT KG PER KW	.727	.860		.380	.495		.268	.400	
EFFICIENCY INC. SOLENOID	80.51%		82.43%		82.67%				

LEGEND:

- SOLENOID FOCUSING, FIVE STAGE COLLECTOR, 45% RECOVERY.
- RF LOSSES AT INPUT, OUTPUT, PLUS 4% INTERCEPTION LOSS TOTAL 4.45% OF $V_0 I_0$
- USEFUL RF OUTPUT = $.7529 V_0 I_0$
- COLLECTOR THERMAL DISSIPATION = $.105 V_0 I_0$
- COLLECTOR POWER RECOVERED = $.0860 V_0 I_0$
- EFFICIENCY = 83.4% EXCLUDING SOLENOID
- HEAT PIPES (I/O METER) + RADIATOR WEIGHT ESTIMATED @ 2.01/1.32kg/kw @ 300°C (BODY AND SOLENOID)
- @ .94/.46kg/kw @ 500°C (COLLECTOR)
- S BAND DESIGN WITH SOLENOID @ 200°C, ID = 3" OD = 4"



(B) COST VARIATION WITH POWER LEVEL AND QUANTITY

Figure 6 Cost Trends in High Power CW Transmitters

Table 5. RF Transmitter Acquisition & 10 Year Replacement Cost

SPS-1546

CANDIDATE	POWER PER UNIT, kw		NUMBER PER SYSTEM	ACQUISITION COST		REPLACEMENTS/MONTH		REPLACEMENT COST		SPECIFIC COST \$/KW		INITIAL ACQ'N		MASS		TRANS-PORT COST	SYSTEM COST
	PER UNIT, kw	PER UNIT, kw		PER UNIT \$K	PER SYSTEM \$M	MTBF, YEARS	REPLACEMENTS/MONTH	REPLACEMENT COST	REPLACEMENT COST	REPLACEMENT COST	REPLACEMENT COST	REPLACEMENT COST	REPLACEMENT COST	REPLACEMENT COST	REPLACEMENT COST		
							SM		K\$/Kw	10 ⁴ Kw		SM	SM				
1	50	120x10 ³	2.7	324	28	357	116	70	.8	4.8	1.7	288	102	830			
2	70	85,000	2.8	238	26	272	91	40	.75	4.76	1.8	266	108	723			
3	250	24,000	7.0	168	24	84	70	28	.4	2.4	1.0	144	60	442			
4	500	12,000	10	120	20	50	60	20	.3	1.8	.9	108	54	342			

LEGEND

CANDIDATE

- 1. PM FOCUSED KLYSTRON 38kv
- 2. EM FOCUSED KLYSTRON 42kv
- 3. EM FOCUSED KLYSTRON 65kv
- 4. EM FOCUSED KLYSTRON 80kv

- TRANSPORT COST AT \$ 60/kg TO ORBIT
- EXPONENTIAL FAILURE RATE
- PASSIVE COOLING
- NO BURN-IN COSTS INCLUDED