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by

prepared for

Contract No. NAS3-11515



LITTON INDUSTRIES
ELECTRON TUBE DIVISION
960 INDUSTRIAL ROAD • SAN CARLOS, CALIFORNIA



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FINAL REPORT

ANALYTICAL STUDY PROGRAM TO DEVELOP THE
THEORETICAL DESIGN OF SPACE BORNE
ELECTROSTATICALLY FOCUSED KLYSTRON AMPLIFIERS

[19-3]

by

W. R. Day and T. H. Luchsinger

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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LIST OF SYMBOLS

a	drift tube radius
A	surface area
b	electron beam radius
B	magnetic flux density
d	resonator gap spacing, particle diameter
D	depth of penetration
e	electron charge
G_o	dc beam conductance
G_e	electronic conductance
k	microperveance
K	thermal conductivity
L	lens spacing (period)
m	electron mass
N	number of penetrating particles/meter ² -sec
P_o	probability
q	heat flux
Q	resonator quality factor
Q_o	internal resonator quality factor
Q_L	loaded resonator quality factor
R_{sh}	resonator shunt resistance
r_o	electron beam radius
S	lens-to-body spacing
Δt	temperature drop

LIST OF SYMBOLS (Cont.)

T	mission time
v_m	velocity of meteoroid
v_t	velocity of sound in target material
V	voltage
V_b	beam voltage
V_c	collector voltage
W_o	beam power
ΔX	wick thickness/heat pipe diameter
γ	propagation constant
ϵ	emissivity
η_c	circuit efficiency
λ	wavelength
ρ_m	meteoroid density
ρ_t	target density
ω	angular frequency
ω_q	reduced plasma frequency

ANALYTICAL STUDY PROGRAM TO DEVELOP THE
THEORETICAL DESIGN OF SPACE BORNE
ELECTROSTATICALLY FOCUSED KLYSTRON AMPLIFIERS

by W. R. Day and T. H. Luchsinger

Litton Industries Electron Tube Division

SUMMARY

The object of this investigation was to extend the electrostatically focused klystron art to permit the design of considerably higher efficiency amplifiers for operation in a space environment. Primary emphasis was placed on the critical problems of obtaining higher efficiency and adequate heat transfer while maintaining long operating life, small size and light weight. Voltage jumps, extended interaction output resonators, low pervance electron beams and multistage depressed collectors were found to afford a solution to the problem of efficiency enhancement in ESFK's. A transverse-field depressed collector was conceived which promises to permit high efficiency amplification of AM signals as well as FM signals. The problem of heat transfer associated with space borne ESFK's was solved by using a liquid potassium heat pipe radiator operating at 500°C.

Electrical and mechanical designs were made for ESFK's intended for TV satellite applications at 0.85, 2.0, 8.0 and 11.0 GHz.

1.0 INTRODUCTION

This report contains the results of an analytical study program to develop the theoretical design of space borne electrostatically focused klystron amplifiers, conducted by the Research Department of Litton Industries Electron Tube Division for NASA Lewis Research Center on Contract No. NAS3-11515. At the inception of this contract the state of the electrostatically focused klystron art, from an efficiency viewpoint, was represented by two Litton ESFK's. The L-5101 provides 1 kW CW at 2.3 GHz with an efficiency of 49 percent and the L-5182 provides 1.2 kW CW at 4.4 GHz with an efficiency of 44 percent. These klystrons operate without depressed collectors.

The purpose of this investigation was to extend the electrostatically focused klystron art to permit the design of considerably higher efficiency amplifiers for operation in a space environment. During this study program primary emphasis was placed on the critical problems of obtaining higher efficiency and adequate heat transfer while maintaining long operating life, small size and light weight. Voltage jumps, extended interaction output resonators, low perveance electron beams and multistage depressed collectors were found to afford a solution to the problem of efficiency enhancement in ESFK's. A transverse-field depressed collector for the ESFK has been conceived during this program which promises to permit high efficiency amplification of AM signals as well as FM signals.

The problem of heat transfer associated with space borne ESFK's has been solved by the use of liquid potassium heat pipe radiators operating at 500°C. These radiators are small,

light weight, economical and have a high reliability in a micrometeoroid environment.

The influence of a particular television modulation system (VSB-AM or FM) on the klystron design was also examined. Critical design areas have been identified and suitable tests and experiments have been recommended to verify critical ESFK parameters.

Electrical and mechanical designs of electrostatically focused klystrons for TV satellite applications at 0.85, 2.0, 8.0 and 11.0 GHz are presented in this report. These designs are intended to yield the highest overall efficiency consistent with the specifications set forth in Exhibit "A" of the contract (see Appendix I).

The significant result of this study program is the potential advancement achieved in the state of the art of high efficiency, electrostatically focused klystron design.

2.0 ELECTRICAL DESIGN

2.1 MODULATION SYSTEM INFLUENCE ON KLYSTRON DESIGN

Before detail design of klystron amplifiers for TV satellite application could begin, it was necessary to consider the consequences of the type of modulation system to be employed. The problems of amplitude modulation of a signal in a nonlinear system, such as a microwave amplifier at saturation, are well known. Severe intermodulation problems will result which can seriously degrade picture quality. This problem must be circumvented by operating the amplifier in a linear region of its drive characteristic which is approximately 3 dB below saturation. The nature of the amplitude modulated NTSC television signal also results in very inefficient amplifier operation since the average picture power is approximately equal to 0.319 peak synch power. An intolerable reduction in efficiency results from the use of amplitude modulation with a conventional microwave amplifier.

The possibility of combining the output of two phase modulated klystron amplifiers to produce a resultant amplitude modulated signal was investigated. Such a system would have the advantage of high efficiency since the klystrons could operate at saturation. Chireix¹ developed such a system of outphasing modulation using triodes in Class C amplifiers. A microwave equivalent could be constructed using PIN diode phase shifters and klystrons; however, for the composite NTSC television signal composed of a vestigial sideband AM video carrier and an FM audio carrier, there are practical problems. The AM and FM signals would have to be separated and amplified in individual systems. This would require three klystrons (two for the AM outphasing system and one for the FM signal) and the efficiency advantage would be

lost. A further difficulty would be the need for a vestigial sideband filter in the output circuit since phase modulators will produce a double sideband signal from the video input voltage. Because of the difficulties associated with employing outphasing modulation to the VSB-TV signal it was not considered further.

Another possible method for obtaining high efficiency amplification of an AM signal is to vary the input power to the amplifier in accordance with the level of the input signal. By so doing, the amplifier would always operate at or near saturation. This could be done by incorporating a control grid into the electron gun of a klystron amplifier and applying the video signal to the grid. Such a system would produce a double sideband output and a VSB filter would be required. A separate amplifier would be required for the FM audio signal. The grid modulator would have to have a nonlinear output characteristic to match the klystron grid control characteristic. Unfortunately, there are more serious problems associated with grid modulated klystrons such as gain, phase and bandwidth variations which result from beam current variations. At low signal levels (low beam current) the bandwidth will be severely reduced and the gain and phase shift will have changed greatly from their high signal level (high beam current) values. For these reasons, the grid modulated klystron must be rejected as a means for obtaining high efficiency AM TV signal amplification.

Another version of the grid controlled klystron amplifier was investigated which promises to give a limited increase in efficiency (~20%). The klystron is designed to operate saturated at the blanking pulse level and a positive grid pulse is applied to the control grid in synchronism

with synch pulse. This has the effect of adding input power to the klystron beam only during the synch pulse period. This power is not present and, therefore, not wasted in the interpulse period. A separate FM audio amplifier will be required for this system although a VSB filter will not be required.

It may be concluded at this point that an efficient AM amplification system is probably not one which varies the input power with the signal level but one which recovers the unused input power. At low signal levels most of the beam power in a klystron is delivered to the electron beam collector where it is dissipated as heat. By suitable depressed collector design a large portion of this power can be saved by reducing the velocity of the electrons before they are collected. Since the velocities in the spent electron beam vary with the modulation level, each velocity class must be collected separately for optimum efficiency. This is possible only to a limited degree in a conventional O-type, multistage depressed collector because there is no automatic velocity sorting mechanism present. This limitation has been overcome by the design of a transverse-field depressed collector for electrostatically focused klystrons. Details of this collector are given in Section 2.4.

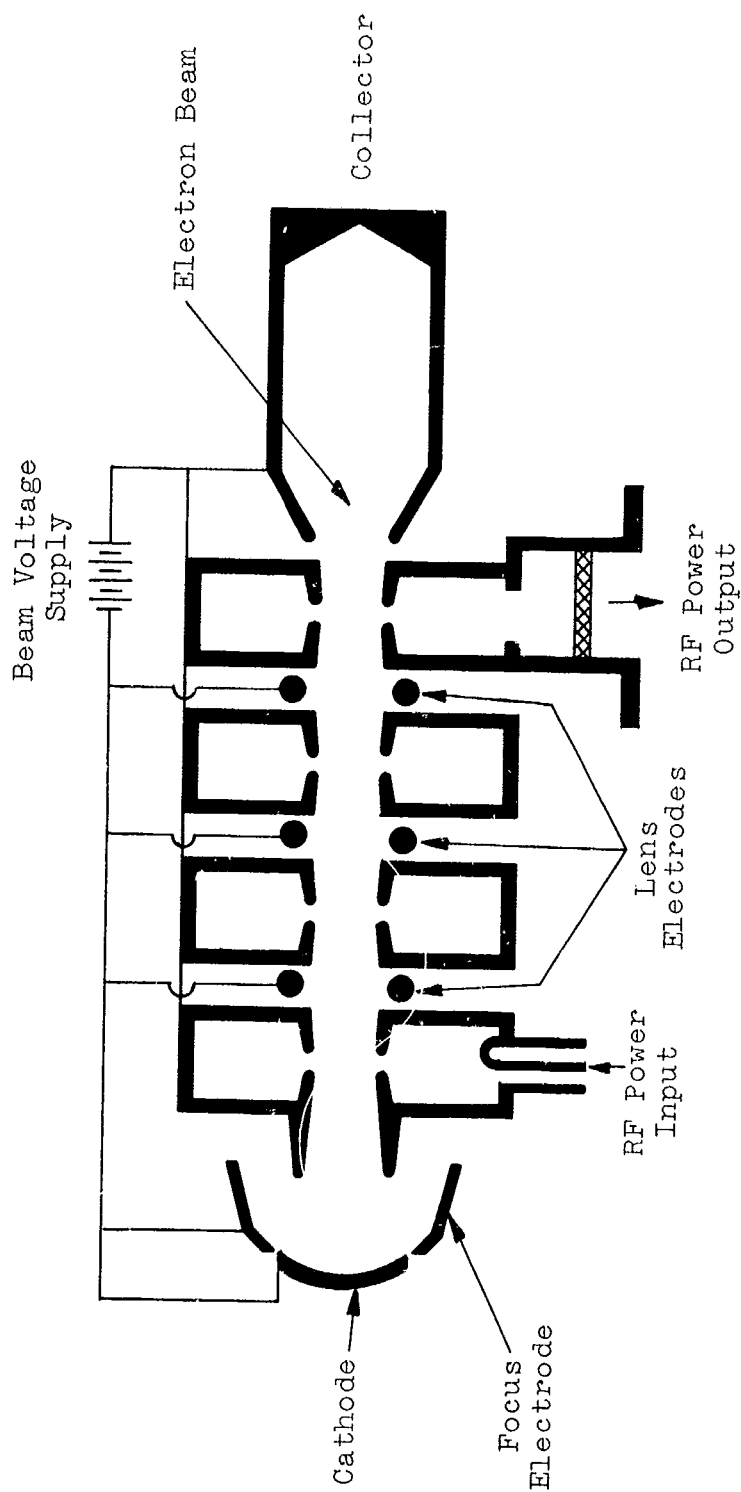
The transverse-field collector will provide high efficiency AM operation of ESFK's because its automatic velocity sorting feature permits all electrons to be collected at a potential near the potential to which they have been accelerated, regardless of the modulating signal level. In addition, this collector provides higher efficiency for frequency modulated ESFK's because the amount of collector depression can be greater without returning secondary and reflected primary electrons to the interaction circuit.

2.2 EFFICIENCY ENHANCEMENT STUDIES

2.2.1 Electrostatically Focused Klystron Efficiency

Figure 1 shows a diagrammatic sketch of an electrostatically focused klystron. It is seen to consist of a Pierce type electron gun to provide an electron beam, a number of cavity resonators to rf modulate the electron beam, a set of electrostatic lenses to focus the beam in the drift spaces between cavities, input and output connections for the rf signal and a collector for the spent beam. The efficiency of this device depends on the perveance of the electron beam, the percentage transmission of the beam through the circuit and on the velocity distribution within the modulated beam. The efficiency of an ESFK has a unique dependence on the mechanism of electrostatic focusing. Slow electrons, which result from rf modulation of the electron beam, are unable to penetrate the retarding electrostatic fields of the focusing lenses and are returned to the body where they are collected at low energy. The elimination of slow primary electrons from the electron beam reduces the effective beam loading and increases the interaction efficiency. Slow secondary electrons which may result from beam interception are similarly eliminated from the lens cells; however, if they are formed in the interaction gaps they will contribute to beam loading. This built-in velocity sorting mechanism of the focusing lens system accounts for the high efficiency exhibited by ESFK's.

From a circuit viewpoint, the efficiency depends on the cavity R_{sh}/Q , Q_o , the gap coupling coefficient, and the electronic loading. For enhanced efficiency, the spent beam must be collected at the lowest possible value of kinetic energy consistent with a minimum number of returned secondary and reflected primary electrons.



DIAGRAMMATIC SKETCH OF ELECTROSTATICALLY FOCUSED KLYSTRON

Fig. 1

With a knowledge of the design factors which limit efficiency, an investigation aimed at improving efficiency was conducted. Electrostatic focusing imposes some special requirements on the design of klystrons which bear on the efficiency. For instance, the optimization of the R_{sh}/Q of a cavity is made by designing the cavity to have a height approximately equal to the cavity radius minus the post radius. This can seldom be done in an ESFK design because of the finite lens period (spacing) required for stable beam focusing. The space between lenses must provide adequate voltage hold-off for the lens and sufficient wall thickness for the cavity to permit adequate heat transfer. The remaining space determines the resonator height. It has been shown by Luchsinger and Day² that the maximum normalized lens spacing in an ESFK is:

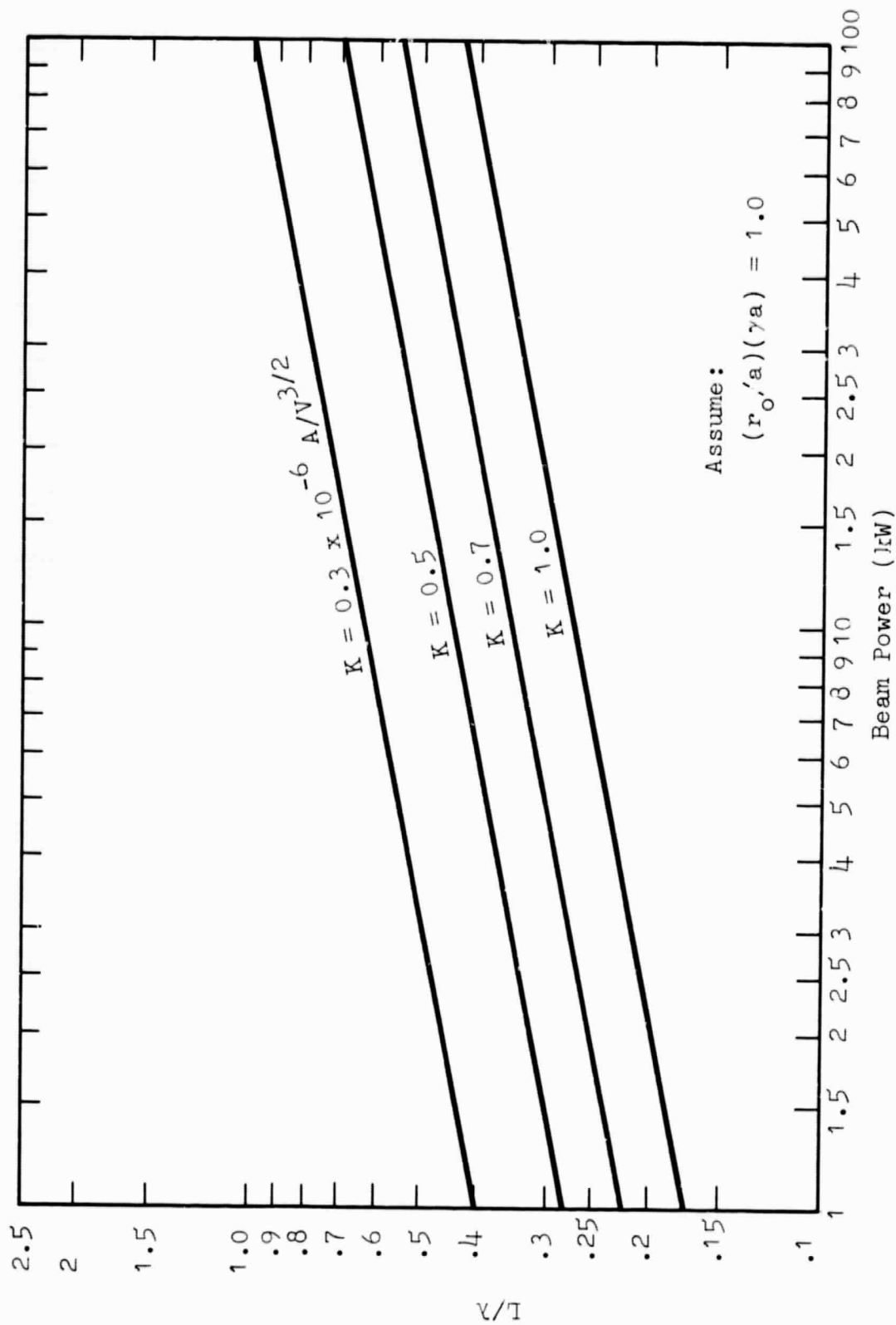
$$L/\lambda = (.171) \frac{W_o^{.2}}{k^{.7}} \frac{r_o}{a} (\gamma a)$$

where W_o = beam power in kilowatts

k = microperveance of electron beam

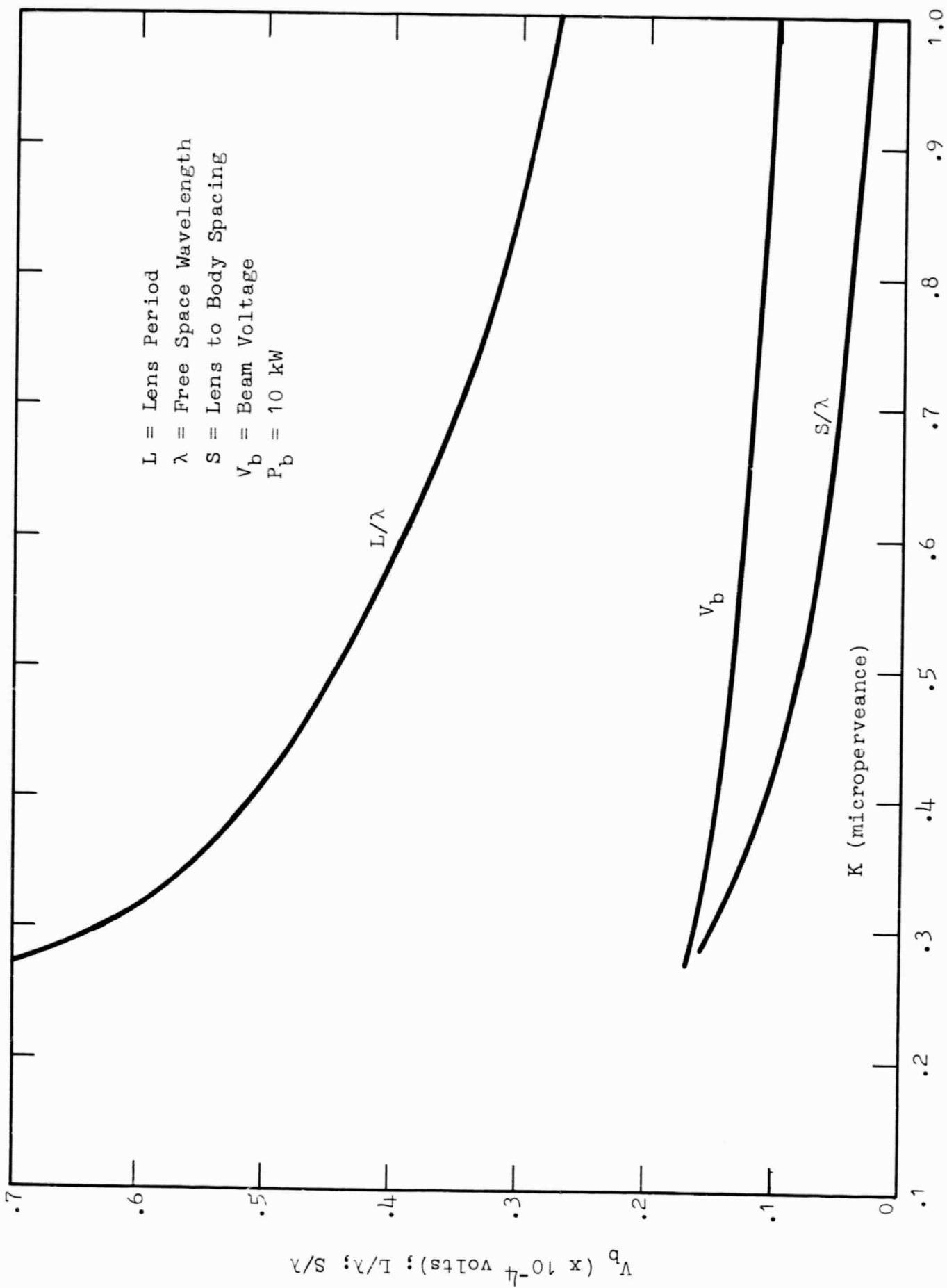
Figure 2 shows the normalized lens spacing vs beam power, with perveance as a parameter, for ESFK's. Low perveance designs permit the design of better resonators because of the greater distance between lens cells.

Figure 3 shows how the selection of beam microperveance affects the lens period, the beam voltage and the lens-to-body spacing, for a beam power input of 10 kw. It is interesting to observe that lower lens-to-body voltage gradients result from higher voltage (lower perveance) designs.



MAXIMUM NORMALIZED LENS SPACING VS BEAM POWER
 FOR ELECTROSTATICALLY FOCUSED KLYSTRONS

Fig. 2



ESK FOCUSING PARAMETERS VS BEAM MICROPERVEANCE FOR BEAM POWER = 10 kW

Low perveance electron beams are desirable because they do not defocus badly under rf bunching. Their lower space charge forces reduce the internal velocity spread which leads to more efficient interaction.

Voltage jumping, extended interaction output resonators and depressed collectors have been investigated for efficiency enhancement in ESFK's. The results of these studies are given in the following subsections.

2.2.2 Voltage Jumps

Klystron output power and efficiency are basically limited by the extent of rf velocity spread in the electron beam at the output cavity gap. In most high efficiency klystrons the amplitude of the rf voltage at the output gap is such that the slowest electrons are stopped or possibly turned back. It has been shown that if the dc beam voltage is increased before the electron beam transits the output gap, the efficiency can be increased.^{3,4} A reduction in the velocity spread arises from the fact that the increased potential at the jump raises the velocity of the slow electrons more than the fast ones.⁵ Significant efficiency improvement has been obtained by Hefni³ and at Cornell⁴. Efficiencies in excess of 70 percent have been reported for magnetically focused klystrons. From this past work it appears that a voltage increase of approximately 40 percent is sufficient to obtain most of the inherent efficiency enhancement in a magnetically focused klystron.

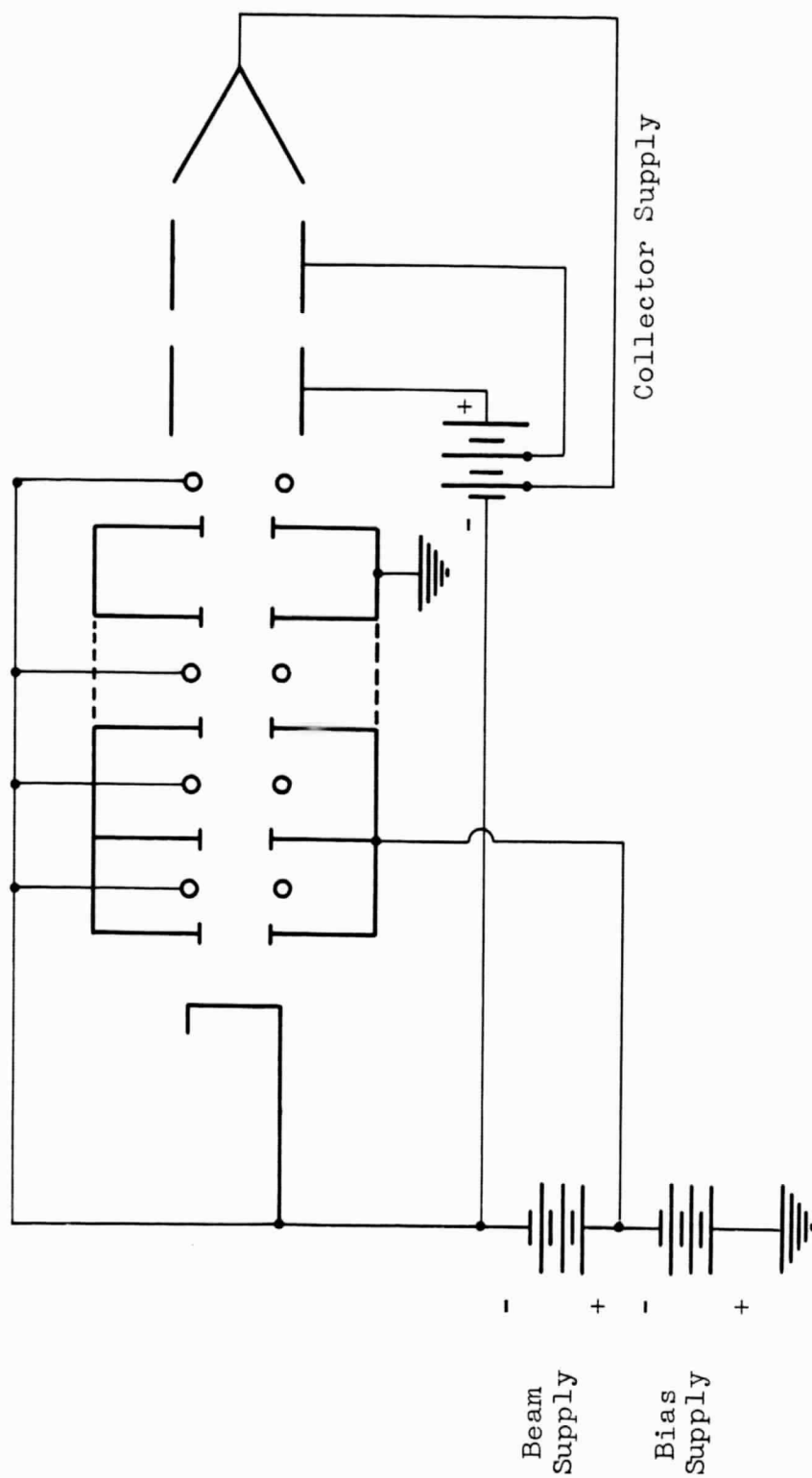
It is desirable to use the smallest possible voltage jump in order to minimize the structural problems which result from the incorporation of a jump in the klystron. Cornell workers⁴ have found that applying the bias voltage across the penultimate cavity gap gave greater efficiency enhancement than biasing any

other gap. Furthermore, they show that the best place for bias to be applied is not the penultimate gap but in the final drift tube immediately before the output gap. In the electrostatically focused klystron (ESFK) the voltage jump can be accomplished in the focusing lens cell between the penultimate cavity and the output cavity. A velocity jump across the penultimate gap would require an rf choke in the cavity which may degrade the efficiency and present quite a structural problem.

In the ESFK it would be desirable to operate the output cavity and waveguide structure at ground potential in order to facilitate heat conduction and eliminate the need for dc isolation in the output circuit. Figure 4 shows a power supply connection diagram for an ESFK incorporating a voltage jump and a three-stage depressed collector. The reduction in velocity spread in the beam, which results from the voltage jump, makes the collector depression problem somewhat easier because there are fewer slow electrons.

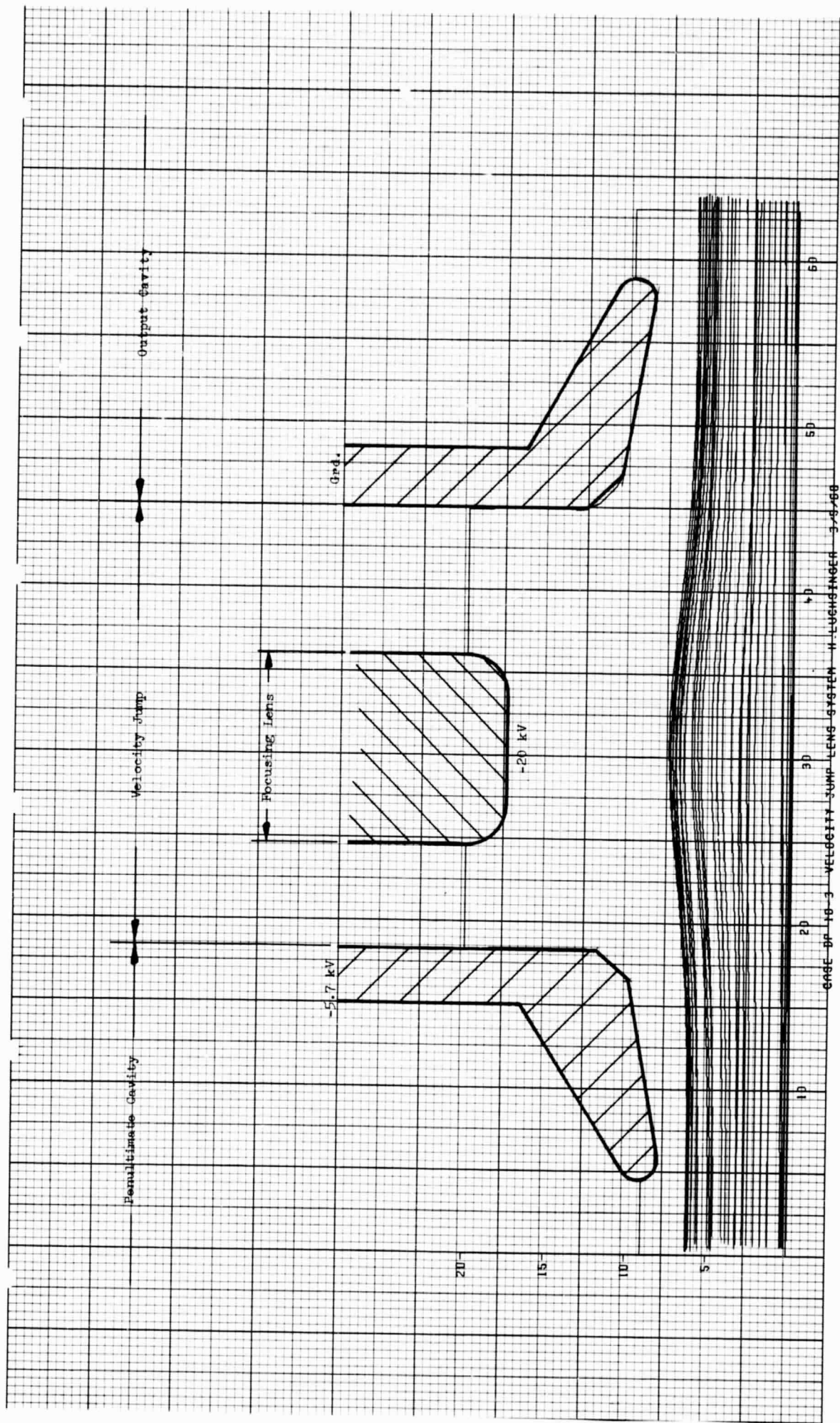
Figure 5 shows the computed electron optics for the dc beam which result from a 40 percent voltage jump in the lens between the penultimate and output cavity of an ESFK. The lens is asymmetrically placed in the lens housing which serves two purposes:

- a) The voltage gradient does not increase due to the higher voltage since the distance between lens and cavity wall is increased on the higher voltage side.
- b) The beam does not become overfocused due to electron acceleration because the focusing force is reduced and the beam diameter at the entrance and exit of the lens system stays constant.



POWER SUPPLY CONNECTION DIAGRAM FOR ELECTROSTATICALLY FOCUSED KLYSTRON
WITH VOLTAGE JUMP AND DEPRESSED COLLECTOR

Fig. 4



BASE DR 10-3 VELOCITY JUMP LENS SYSTEM - H. LUCHSINGER 3-8-68

Fig. 5

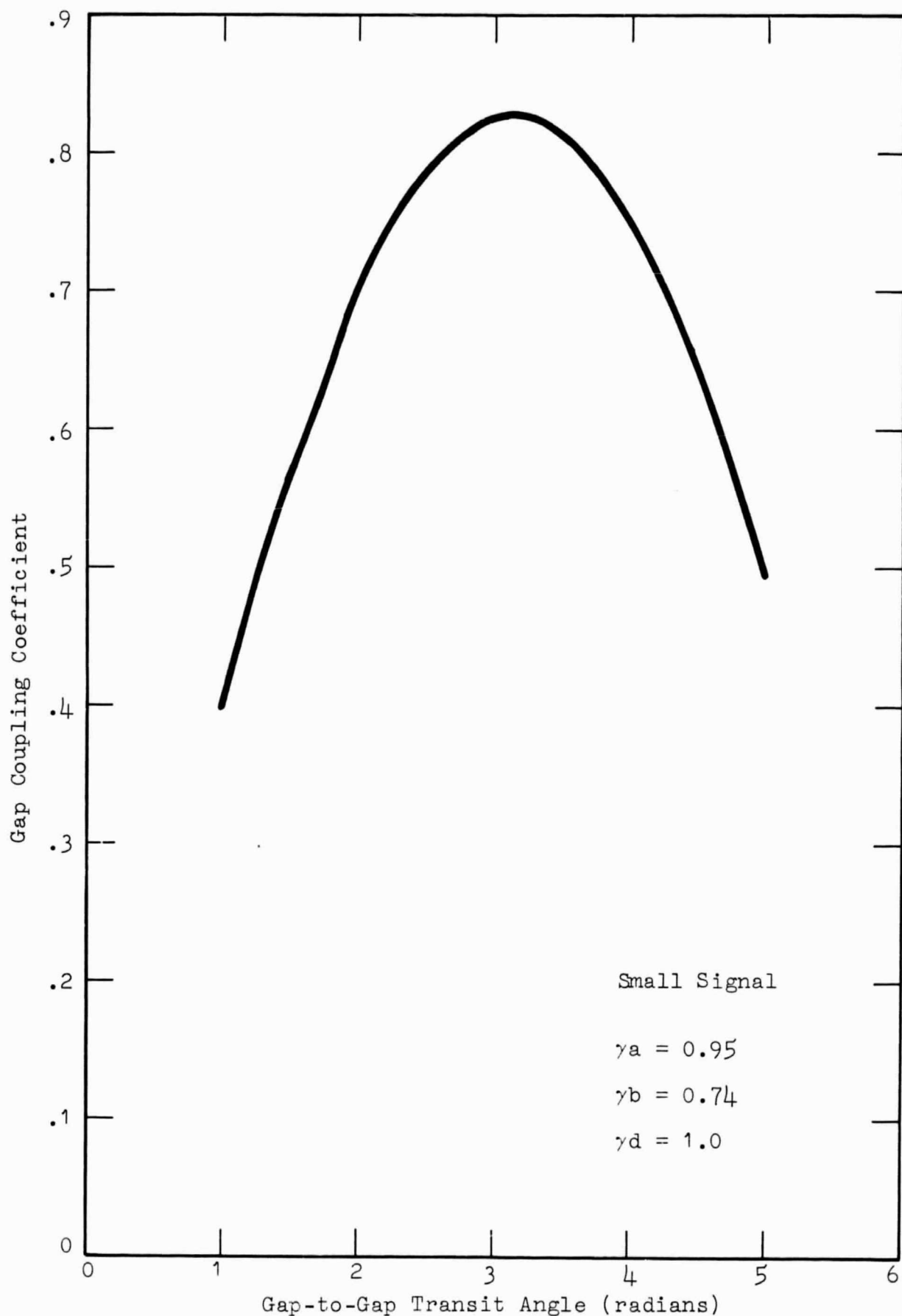
Note that the electron trajectories are shown under dc conditions. The plot clearly shows that the current density is highest at the edge of the beam which enhances the rf coupling to the fields in the cavity gaps. It is expected that the beam diameter will be increased slightly under rf drive due to increased space charge forces.

2.2.3 Extended Interaction Output Cavity

Litton Electron Tube Division has employed extended interaction resonators to increase the efficiency of electrostatically focused klystrons. Higher values of R_{sh}/Q are obtained with these resonators which enhances efficiency and bandwidth. Because of the finite distance between lens cells in the ESFK, it is not possible to use more than two cavities in the extended interaction resonators. The pi-mode, two-section resonator has been found to be the most practical for use in the ESFK.⁶ This type of circuit has been investigated extensively by the use of a BASIC language time-sharing computer program. The program was written to compute the gap coupling coefficient and normalized beam loading conductance vs transit angle between gaps with beam filling factor, gap transit angle, synchronous voltage/beam voltage and ω_q/ω as parameters. A listing of this program appears in Appendix II.

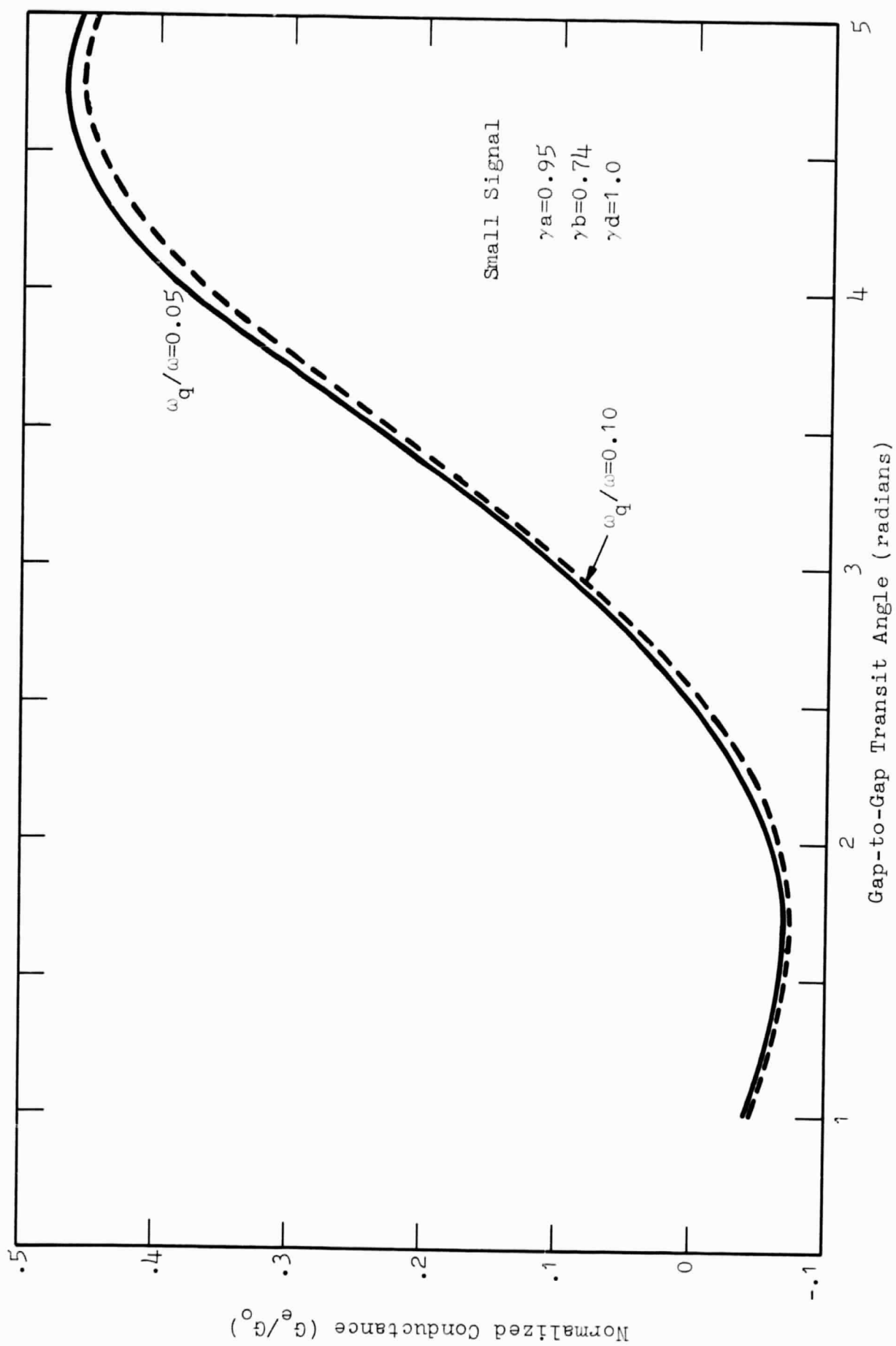
Figure 6 is a plot of gap coupling coefficient vs gap-to-gap transit angle and Fig. 7 is a plot of normalized beam loading conductance vs the same variable. Data for these curves were calculated by means of the aforementioned computer program.

Collector depression in a conventional linear beam tube is more effective when it is operated in such a manner that the velocity spread in the spent beam is small.⁷ The most



TWO-CAVITY PI-MODE RESONATOR GAP COUPLING COEFFICIENT

Fig. 6



TWO-CAVITY PI-MODE RESONATOR BEAM LOADING CONDUCTANCE

Fig. 7

effective means for reducing the velocity spread in the spent beam of a klystron is to reduce the magnitude of the peak rf voltage with respect to the beam voltage across the output cavity gap. In a klystron with a matched load across the output cavity, the peak rf voltage at saturation becomes approximately equal to the dc beam voltage. When the rf voltage swings negative, electrons are retarded and some are reduced to near zero velocity. These very slow electrons will be reflected by a depressed collector and may be returned to the interaction circuit where they cause undesirable heating, beam loading and oscillations.

By using a heavily loaded output cavity, the peak value of the rf voltage across the output gap can be reduced to a value considerably less than the dc beam voltage. The spent electron beam will have no very slow (or very fast) electrons which permits a more effective depressed, O-type, collector operation. The heavily loaded output circuit design results in a lower electronic efficiency for the klystron because the rf gap voltage is reduced; however, it will be shown that the overall efficiency of such a design will be higher than a conventional matched load klystron because of the increased depressed collector efficiency. More will be said about depressed collectors in the following subsection.

The use of a heavily loaded extended interaction resonator for the ESFK output circuit is advantageous for other reasons. Because of the heavy loading, the resonator may be designed to have a negative beam loading conductance without danger of oscillation. Figure 7 shows that a negative beam loading conductance can be obtained by making the drift distance between gaps sufficiently short. The negative beam loading obtainable with the extended interaction output cavity will result in a higher electronic efficiency than is available with conventional single-gap cavities.

Another benefit derived from heavy loading of the output circuit is the reduction of rf circuit losses because the circuit efficiency, η_c , will be high.

$$\eta_c = 1 - Q_L/Q_o$$

High circuit efficiency is not only important from the standpoint of obtaining a high overall efficiency, but also from a thermal dissipation aspect. This is particularly important in the 8.0 and 11.0 GHz klystrons where the small size of the output circuit causes the power density to be high. The two-cavity extended interaction resonator has an inherently higher power handling capability because it has approximately twice the surface area of a conventional single gap resonator.

2.2.4 Conventional Depressed Collector

O-type depressed collectors have been used with considerable success for a number of years in traveling-wave tubes. They have not found wide acceptance in klystrons primarily because the klystron interaction is so efficient that (a) the cost and complexity is not justified for most applications, and (b) the velocity distribution in the spent beam is so great that the amount of depression obtainable (without electron reflection) is too small.⁸ For the klystrons under consideration in this program the depressed collector is essential. The efficiency of these klystrons without collector depression would be intolerably low for operation in a space environment.

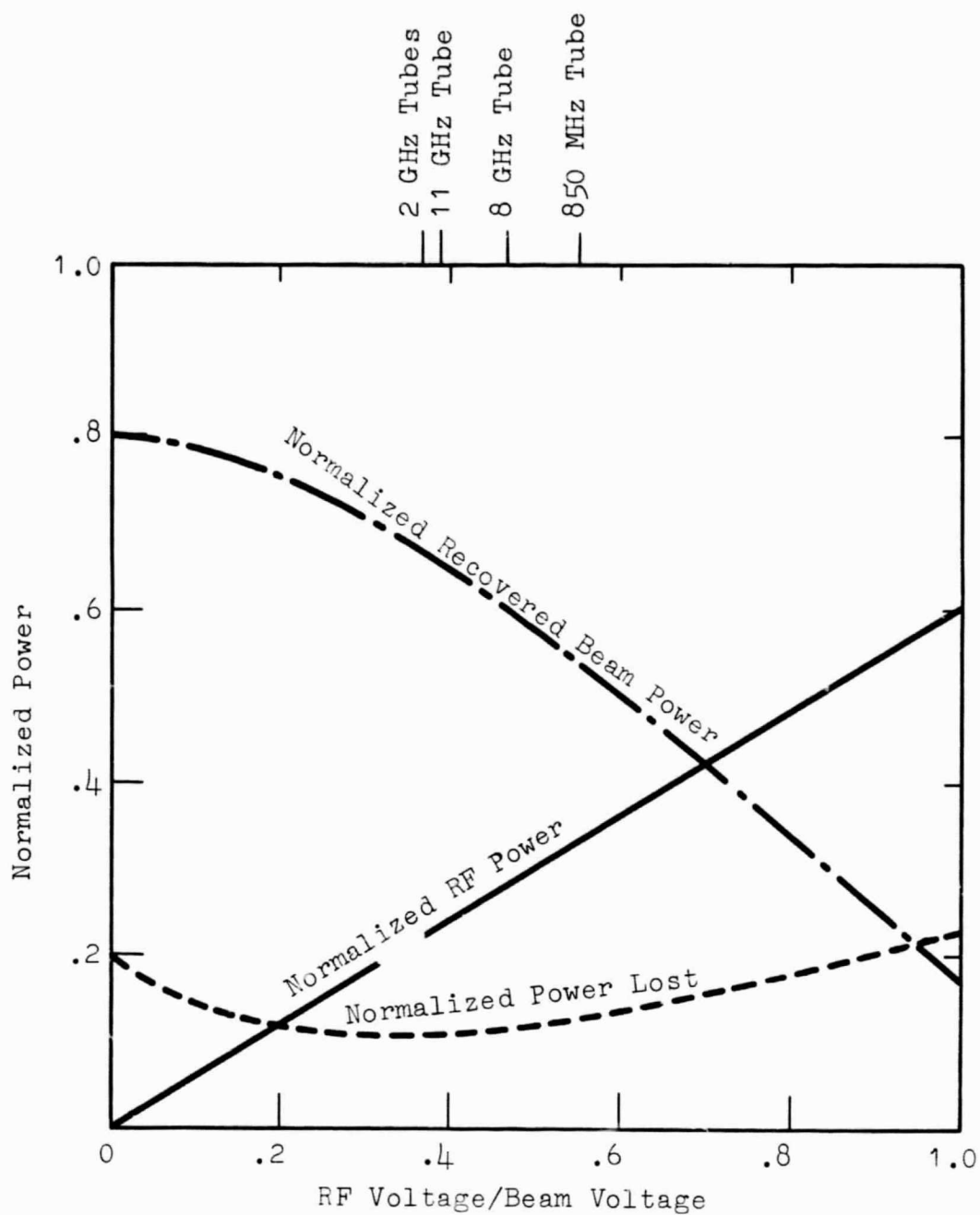
Conventional depressed collectors suffer from several shortcomings which limit their effectiveness in recovering power from a spent electron beam. The velocity sorting mechanism, which causes various velocity electrons to be collected

on electrodes which will reduce their kinetic energy to the lowest possible value, is not highly efficient since it depends on electric fields and space charge spreading in the beam. Since space charge spreading is an influential factor, the collector efficiency will vary with the modulation level of the beam. The amount of depression is limited by space charge blocking of the collector due to a heavy concentration of low velocity electrons. If the concentration of electrons is large enough a virtual cathode may form and return electrons to the interaction structure. Secondary electrons liberated from the collector surfaces are accelerated by the electric fields between the collector segments and by the field between the tube body and the collector. These returned electrons will cause a reduction in efficiency and can cause undesirable heating, beam loading and oscillations if they enter the interaction circuit.

Sterzer⁹ has shown that a conventional, O-type, multi-stage depressed collector with more than three segments is not profitable for increasing efficiency. This is a direct result of the fact that most of the electrons in the spent beam have energies corresponding to a voltage which is equal to the dc beam voltage times one minus the electronic efficiency. Of the remaining electrons, the majority are even slower. The most productive parameter in depressed collector design appears to be the reduction of the velocity spread in the electron beam. In the AM klystrons, linear operation will produce a much lower velocity spread; however, it is not anticipated that this will be sufficient for high efficiency. Two-section, pi-mode, extended interaction resonators will be used for the output cavities, as discussed in the preceding subsection. These resonators will be operated in a region of negative beam loading conductance and heavily coupled to the load.

By this technique, the output cavity gap voltages will be considerably reduced and therefore the velocity distribution in the spent beam will be reduced, thereby allowing increased single stage collector depression. A similar output circuit will be used with the FM klystrons which will operate at saturation.

An analysis of the distribution of output power, power recovered and power lost in an ESFK was made in order to determine the optimum loading (rf voltage/beam voltage) which should be employed for the highest possible efficiency. The areas of power loss are beam interception, rf losses in the output circuit (circuit efficiency), and dissipation losses in the collector. Experimental data taken on a 1 kW S-band ESFK (Litton L-5101) with a single stage, conventional O-type depressed collector was used as a basis for this study. Figure 8 shows the normalized output power, power lost and beam power recovered by collector depression vs rf voltage/beam voltage. As the rf voltage to beam voltage ratio is decreased from unity (matched load design) by overcoupling the output resonator, the output power is reduced. However, the beam power which can be recovered with the depressed collector is now increased since the velocity distribution in the electron beam is reduced. Furthermore, the beam transmission will be increased because of the reduced space charge forces in the electron bunches which will permit more current to reach the collector. The circuit efficiency will be increased (reduced rf losses) as a result of the decreased output cavity Q_L . In other words, the decreased conversion efficiency resulting from a reduction in the rf voltage by loading will be more than offset by the increased beam power recovery and the lower rf losses. This is the case until the required collector depression becomes excessive for a conventional depressed collector for reasons previously stated in this section.



Normalized Power Lost - - - - -
 Normalized RF Power - - - - -
 Normalized Recovered Beam Power - . - . -

POWER DISTRIBUTION VS NORMALIZED RF VOLTAGE

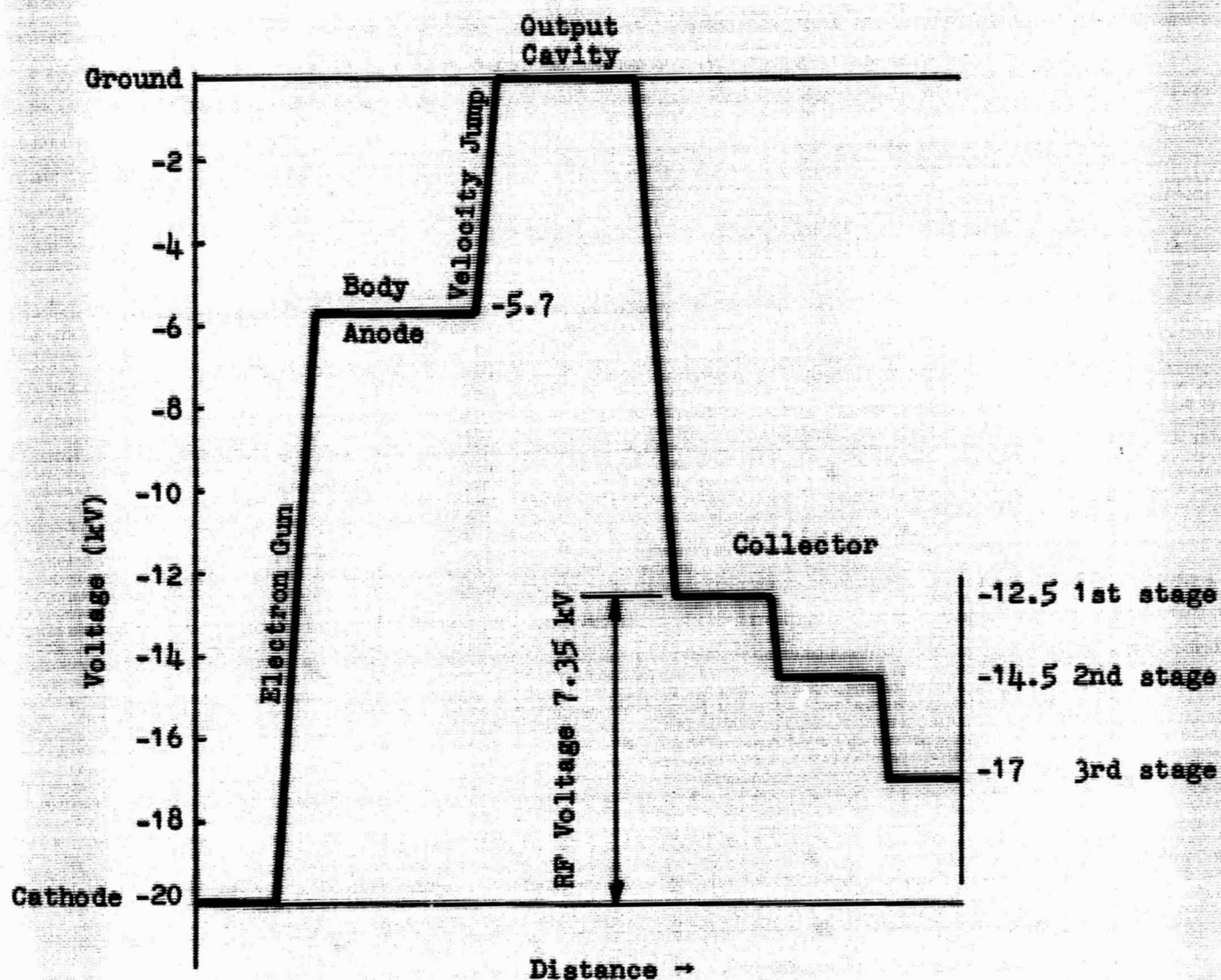
Fig. 8

The approximate design points for the ESFK's under study are shown at the top of Fig. 8. These points were determined by balancing the reduction in conversion efficiency against the power recoverable with a conventional depressed collector and the reduced output circuit losses. In the case of the 2.0 GHz FM klystron, the amount of output circuit loading was also dictated by the 30 MHz instantaneous bandwidth requirement.

A voltage distribution diagram for the 2.0 GHz ESFK is shown in Fig. 9. The first stage of the collector is depressed to a level corresponding to the peak rf voltage in the output cavity, with respect to the cathode. The third stage is depressed to about 85 percent of the beam voltage. This is a conservative value which has been verified experimentally on the Litton L-5101 without returning electrons to the circuit. The second stage is depressed to a potential in between the first and third stages. In actual practice all voltages should be adjustable in order to permit optimization of the collector efficiency.

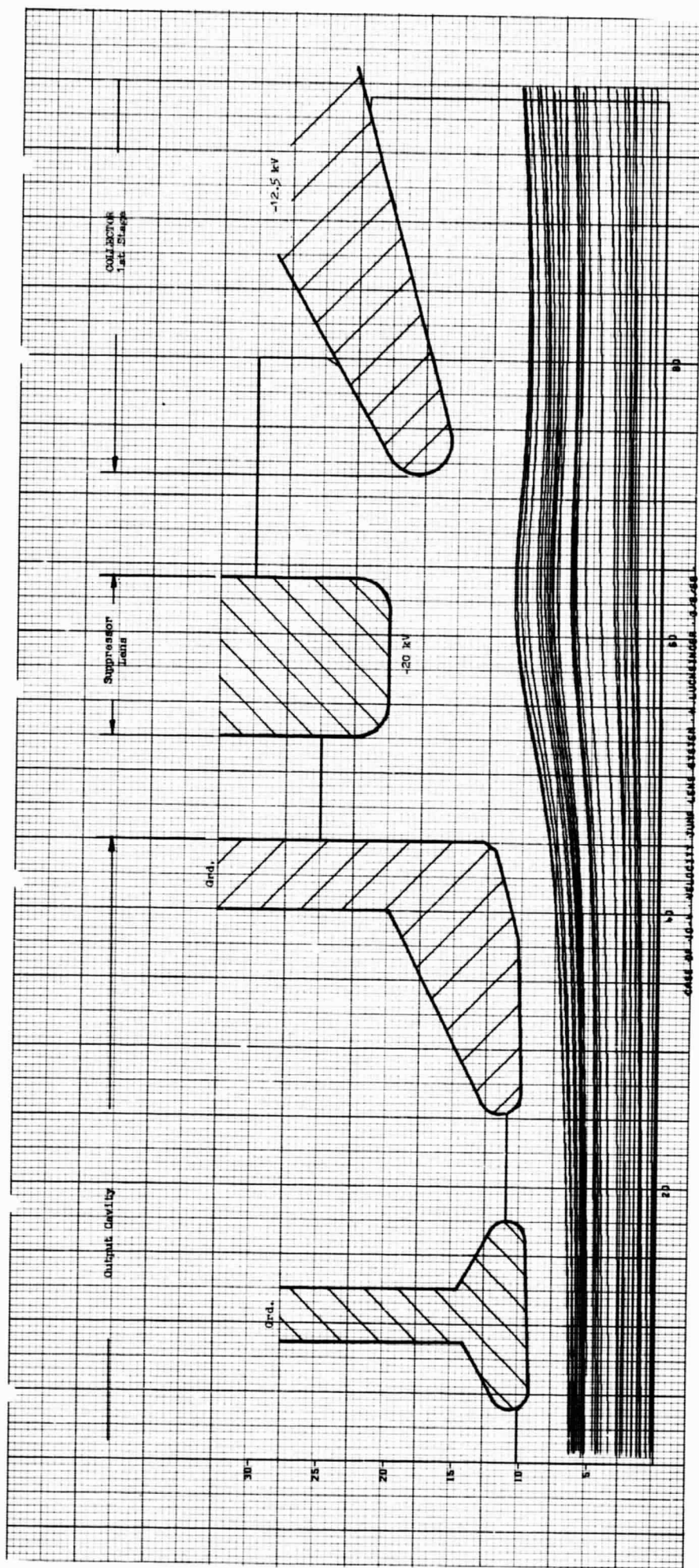
A digital computer design study of the electron optics associated with the output cavity and three-stage depressed collector, based on the work of Sterzer⁹, was made. The resulting dc electron trajectories and electrode shapes are shown in Figs. 10 and 11. The dc electron beam can be seen passing through the double-gap extended interaction cavity, the suppressor lens, and into the collector. All the dc beam is collected on the most depressed stage of the collector and therefore the maximum beam power will be recovered.

The problem of returned secondary electrons from the depressed collector will be minimized by (a) grooving and carbon coating the internal collector surfaces in order to lower the secondary emission coefficient and (b) by placing



VOLTAGE DIAGRAM FOR 2 GHz FM ESFK

Fig. 9



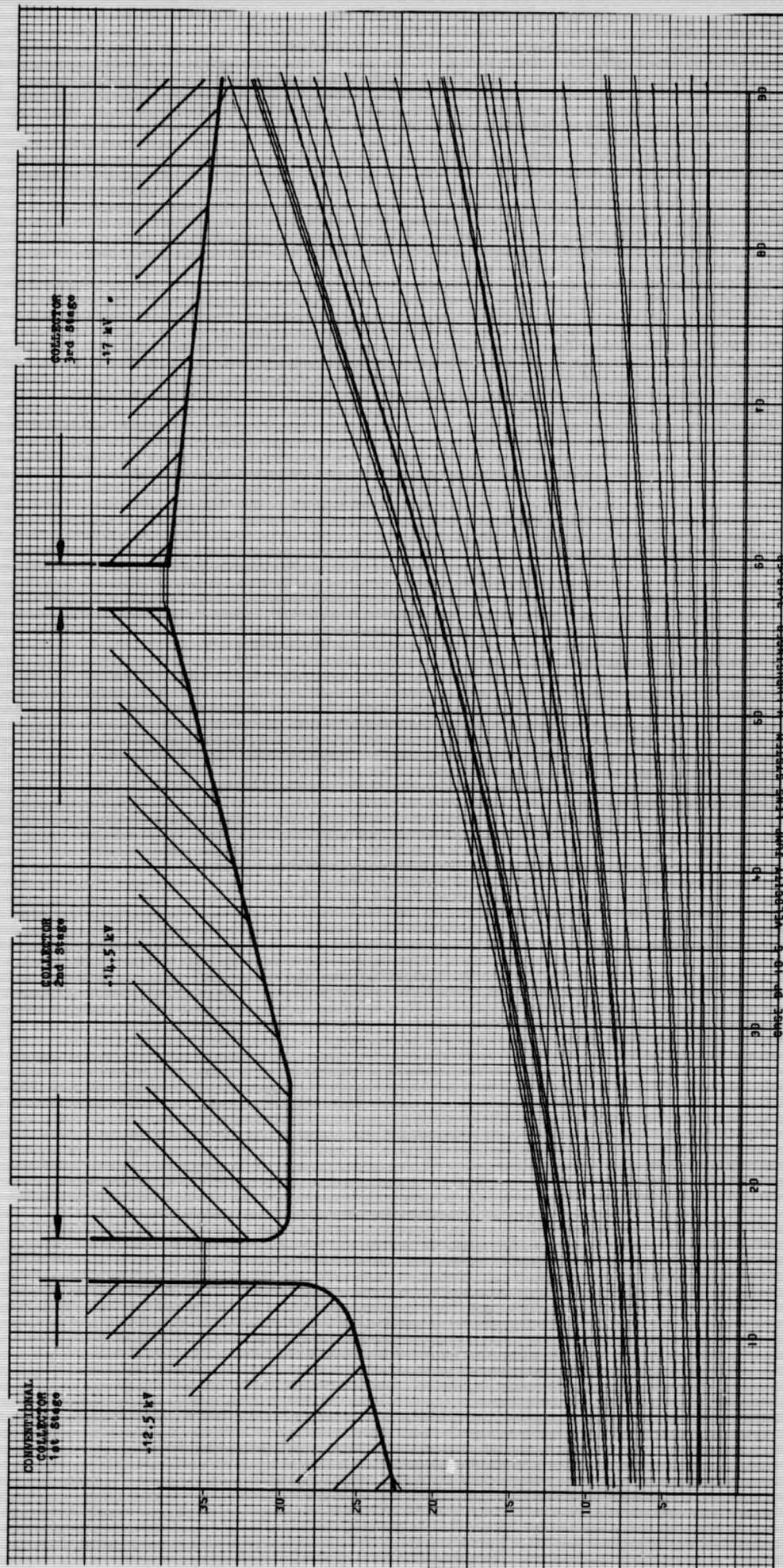


FIG. 11

a negative lens ring between the output cavity and the collector entrance to form a potential barrier sufficient to stop most secondaries. The potential barrier varies from the cathode potential at the suppressor lens ring to approximately one-half of the cathode potential at the center of the beam. This is sufficient to stop most secondary electrons which originate in the collector since most of these electrons will not have been accelerated to a potential greater than one-half the cathode potential by passing through the fields of the collector segments. This suppressor lens will also act as an ion drain for the collector.

Even with the best available materials and techniques, it is not possible to suppress all secondary electron emission from the collector surfaces. Some of the secondary electrons emitted from the most negative collector surface will be accelerated by the electric field between collector segments and will impact on the more positive segments. This secondary electron current causes a loss in power and therefore efficiency. An even more serious problem, previously discussed, is presented by the secondary and reflected primary electrons which find their way back to the interaction circuit and cause heating, beam loading and oscillations.

An ingenious depressed collector design has been found in the literature¹⁰ which minimizes the returned electron problem. This design used tilted collector segments which are not axially symmetric and an axial magnetic field. Secondary electrons see a crossed E and B field and cannot return along the axis to the interaction structure. This collector was studied and was found to be impractical for a high power electron beam because of the requirement for a large magnetic field and the problem of injecting the spent beam

of an ESFK into the axial field. The thin plates which form the collector surfaces would also be very difficult to cool.

2.3 ELECTROSTATICALLY FOCUSED KLYSTRON DESIGNS

The electrical design of the 0.85, 2.0, 8.0 and 11.0 GHz electrostatically focused klystrons was made to incorporate the results of the efficiency enhancement studies previously described. Low perveance electron beams were employed in order to enhance efficiency (Webber¹¹ has shown that the highest klystron efficiencies result from low beam perveance, $k \approx 0.4 \times 10^{-6}$, and high voltage), to obtain the greatest possible distance between lenses, to reduce velocity distribution in the beam and to reduce cathode current densities. Low cathode current densities are mandatory for the long lifetimes required of space borne tubes.

A 40 percent voltage jump has been incorporated in the focusing lens between the penultimate cavity and the output cavity of each ESFK.

Each ESFK utilizes a double-gap pi-mode, extended interaction output resonator. The transit angle between gaps is 0.7π and the gap transit angle, γd , is 0.8. These output circuits are heavily coupled to the load in order to reduce the output gap voltage and consequently the velocity distribution in the spent beam.

A three-stage, O-type depressed collector has been incorporated in these designs because the transverse-field depressed collector was not conceived early enough in the program. The effect on the ESFK performance to be expected by using the transverse-field depressed collector will be discussed in a later section.

The electron guns and focusing lens systems were designed using the Litton all-digital electron optics program. Higher convergence electron guns, than have previously been used in ESFK's, were designed for the 8.0 and 11.0 GHz klystrons in order to obtain a value of cathode current density compatible with long life. Oxide coated cathodes are satisfactory for the 0.85 GHz and 2.0 GHz ESFK's; however, dispenser cathodes will be required for the 8.0 and 11.0 GHz ESFK's since their cathode current densities exceed one ampere per square centimeter.

Voltage gradients in the focusing lens cells were designed to be less than 118 kV/cm (300 volts/mil.) for all ESFK's. The lens gradients are less than 79 kV/cm (200 volts/mil.) in the 0.85 and 2.0 GHz ESFK's. These values have proven to be very conservative in operating ESFK's built by Litton and will provide the high reliability required for a klystron operated in space.

All ESFK's, with the exception of the 2.0 GHz FM klystron, will be four-cavity devices. The 30 MHz, 3 dB bandwidth requirement of the 2.0 GHz FM klystron necessitates the addition of a fifth cavity. Electrical design parameters for all klystrons are given in Table I.

The overall efficiency given in Table I for each ESFK was calculated by dividing the saturated output power by the total input power. The total input power is the sum of the heater power, output power, rf power loss in the output circuit and unrecovered beam power. The rf power dissipated in the output circuit was determined from the circuit efficiency which is dependent upon the loaded Q of the output resonator. Unrecovered beam power is that power dissipated in the depressed collector plus power lost in the body due to beam

TABLE I
ESFK DESIGN PARAMETERS

Frequency	MHz	850	2000	2000	8000	11,000
Modulation		AM	FM	AM	FM	FM
RF power (sat.)	kW	7.5	5	5	5	5
Cathode voltage	kV	-20	-20	-20	-20	-25
Body voltage	kV	-5.7	-5.7	-5.7	-5.7	-7
Output cavity voltage	kV	Grd.	Grd.	Grd.	Grd.	Grd.
Voltage jump	%	40	40	40	40	40
Cathode current	Amp	1.13	1.13	1.13	.89	.85
Perveance k_1	$10^{-6} \text{A/V}^{3/2}$	.66	.66	.66	.52	.37
Perveance k_2	$10^{-6} \text{A/V}^{3/2}$	.4	.4	.4	.315	.215
Gain	dB	40	40	40	40	40
Cavities (incl. output)		4	5	4	4	4
Type of output cavity		Double gap	Double gap	Double gap	Double gap	Double gap
Q_L output cavity		98	65	65	132	144
Q_1		300	130	800	500	700
Q_2		2500	500	2000	2000	2800
Q_3		4000	2000	3500	3200	3000
Q_4		-	3500	-	-	-
Q_o output cavity		5200	5000	5000	4000	3800
R_{sh}/Q output cavity		125	125	125	100	100
R_{sh}/Q buncher cavities		80	80	80	75	65
RF voltage saturation	kV	11.1	7.35	7.35	9.4	9.8
3 dB bandwidth (output cavity)	MHz	8.7	31	31	60	76
Circuit efficiency η_c	%	98.1	98.7	98.7	96.7	96.2
Expected overall efficiency η_t *	%	71.5	69.5	69.5	68	65
γ_1		.753	1.77	1.77	7.1	8.7
γ_2		.637	1.5	1.5	6.0	7.4
a	cm	1.49	.635	.635	.175	.143
b	cm	1.17	.495	.495	.136	.111
d	cm	1.33	.565	.565	.141	.117

* With conventional O-type depressed collector

TABLE I (Cont.)

Frequency	MHz	850	2000	2000	8000	11,000
Modulation		AM	FM	AM	FM	FM
γ_{1a}		1.175	1.12	1.12	1.24	1.24
γ_{2a}		1.0	.95	.95	1.05	1.05
γ_{1d}		1.0	1.0	1.0	1.0	1.02
Buncher drift angle	degrees	27.9	27.3	27.3	28.1	28.4
b/a		.78	.78	.78	.78	.78
Cathode diameter	cm	6.37	2.71	2.71	1.05	.86
Cathode area	cm ²	31.9	5.75	5.75	.88	.595
Beam area $b^2\pi$	cm ²	4.3	.77	.77	.058	.0387
Convergence		7:1	7.5:1	7.5:1	15:1	16:1
Cathode loading	A/cm ²	.035	.197	.197	1.01	1.34
Type of cathode		Oxide	Oxide	Oxide	Dispenser	Dispenser
Depressed collector		Triple stage	Triple stage	Triple stage	Triple stage	Triple stage
Collector power w/o rf	kW	5.0	3.4	3.4	3.6	3.8
Collector power w rf	kW	3.0	2.1	2.1	2.1	2.4
RF output coupling		3-1/8 coax	WR 430	WR 430	WR 112	WR 90

interception. The amount of collector depression, which determines the unrecovered power in the collector, was estimated from the velocity and current distribution in the spent electron beam. Collector voltages were specified in such a manner that they would be greater than the lowest voltage electron in the spent beam (i.e. no returned electrons).

Because electrostatic focusing system requirement determine the maximum drift distance between resonators, there are not as many possible trade-offs between design parameters as may exist in a magnetically focused klystron. For instance, it is not possible to use a three-cavity, extended interaction output circuit because the electrostatically focused beam will diverge excessively over this distance. The design parameters were optimized to yield the highest overall efficiency consistent with the focusing system constraints and the bandwidth requirements. This optimization consisted of varying the conversion efficiency by various loadings of the output circuit and calculating the resulting change in circuit efficiency, beam perveance, beam voltage, velocity distribution, beam current interception and recovered beam power as discussed in Section 2.2.4.

These ESFK designs incorporate all the known techniques for efficiency enhancement such as low perveance electron beams, voltage pumps, extended interaction output resonators and multistage depressed collectors.

2.4 TRANSVERSE-FIELD DEPRESSED COLLECTOR

A new approach has been taken to eliminate the shortcomings of the conventional O-type depressed collector which were discussed in Section 2.2.4. These shortcomings are:

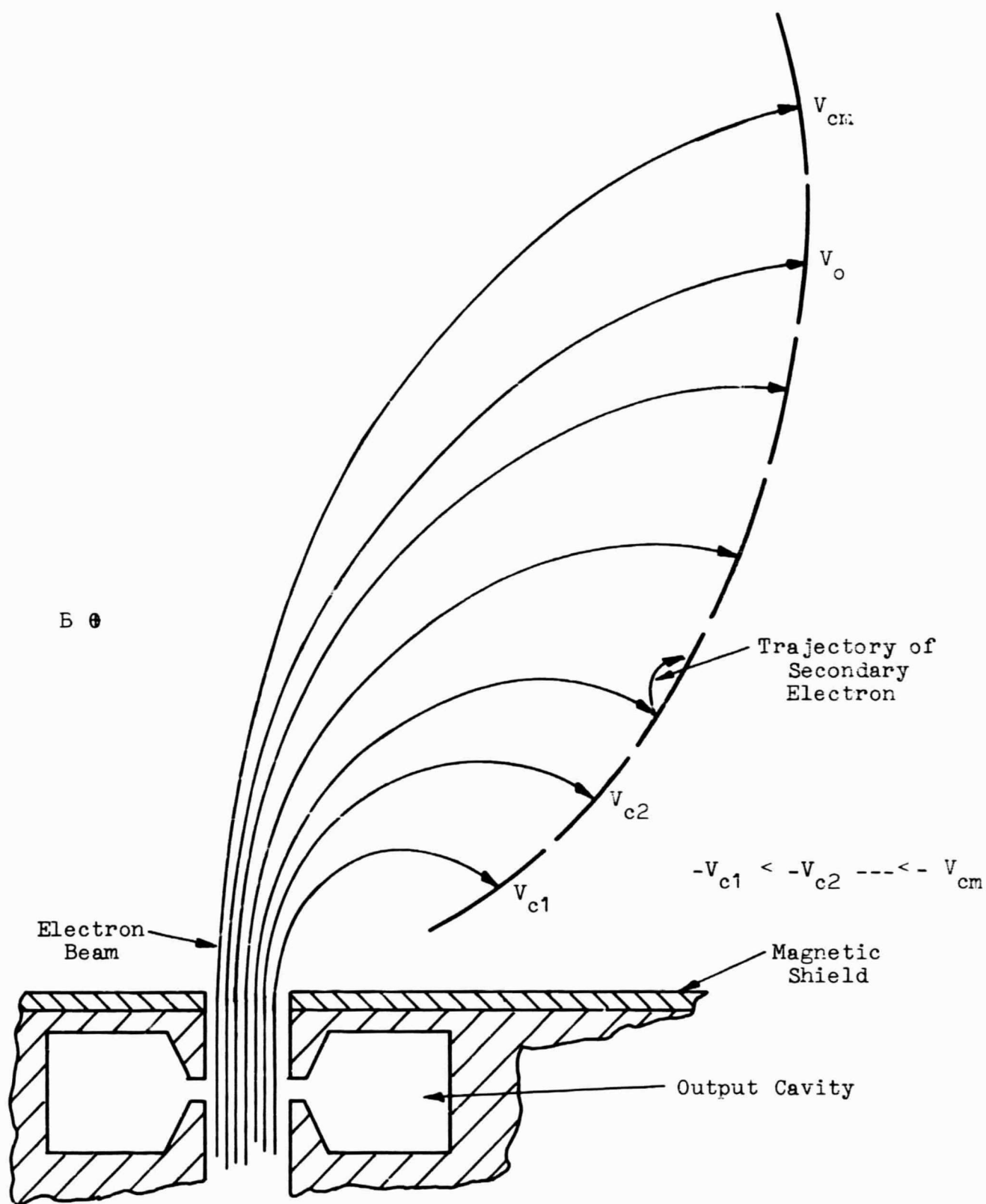
- a. Inefficient velocity sorting
- b. Dependence on space charge
- c. Space-charge blocking
- d. Returned secondary and primary electrons.

The new approach utilizes a transverse magnetic field to:

- a. Perform automatic velocity sorting and to
- b. Prevent the return of secondary and reflected primary electrons to the interaction circuit of the klystron.

Space charge blocking due to virtual cathode formation will not be a problem in the transverse-field collector since the electrons will not see retarding electric fields until they have spread over a relatively large area as a result of the magnetic field deflection. In other words, the space-charge forces in the collection regions of this collector will be greatly reduced over those in a conventional depressed collector.

Figure 12 is a schematic drawing of the transverse-field depressed collector. The velocity modulated electron beam exits the output cavity of the electrostatically focused klystron and enters the transverse magnetic field of the collector. The entering electrons will be deflected in a plane perpendicular to the magnetic field. The electrons will move in a circular path (ignoring space charge for the purpose of



SCHEMATIC DRAWING OF TRANSVERSE-FIELD COLLECTOR FOR ESFK

Fig. 12

illustration) having a radius r_m given by:

$$r_m = \frac{1}{B} \sqrt{\frac{2mV}{e}} \quad (\text{meters})$$

where: B = magnetic flux density (weber/sq. meter)

m = electron mass (kilograms)

e = electron charge (coulombs)

V = voltage (volts)

The initial forces on the entering electrons will be primarily due to the magnetic field because the electric field gradients due to the collector segments will be small at this point. Low velocity electrons will experience a small radius deflection whereas high velocity electrons will be deflected along a much larger radius. Intermediate velocity electrons will be distributed along intervening collector segments. As the amplitude modulation on the beam varies, the current distribution on the collector segments will vary; however, the majority of the electrons will impact on collector segments biased to collect them with a minimum energy loss. This is the automatic velocity sorting feature of the transverse-field depressed collector which makes it superior to the conventional, 0-type depressed collector.

The exact effect of the collector segment electric fields and space charge on the electron motion must be studied; however, this requires the use of digital computational techniques. A recommendation to undertake such a study has been made in Section 5.0.

It is of interest to predict the magnitude of the magnetic field required for a transverse-field collector for the ESFK's being studied. Consider an electron accelerated to 35 kV, which is a worst case for these ESFK's. This electron will have a radius of 4.22 cm with a transverse magnetic field of only $0.015 \text{ weber/meter}^2$ (150 gauss). This demonstrates that very modest values of magnetic field are required for the transverse-field collector. These magnetic fields may be obtained from light weight, permanent magnets.

Referring to Fig. 12, it may be seen that the interaction region of the ESFK is shielded from the magnetic field of the collector to prevent any disturbance of the electrostatic focusing. This magnetic shield can be relatively thin and consequently lightweight since the collector field strength is low. The collector segments are located in such a manner that the electrons impact normal to the surface in order to minimize the secondary electron yield. In addition, low secondary electron yield materials will be employed for the collector surfaces. Some secondary electrons will, nevertheless, be liberated as a result of the collection process. A secondary electron leaving the collector surface sees a transverse magnetic field and will be deflected as shown in Fig. 12. The adjacent collector segment, toward which the electron is deflected, is more negative than the segment from which it originated. The secondary electron is retarded rather than accelerated as is the case in an O-type depressed collector. There is virtually no possibility of a secondary or reflected primary electron finding its way back to the klystron drift tube.

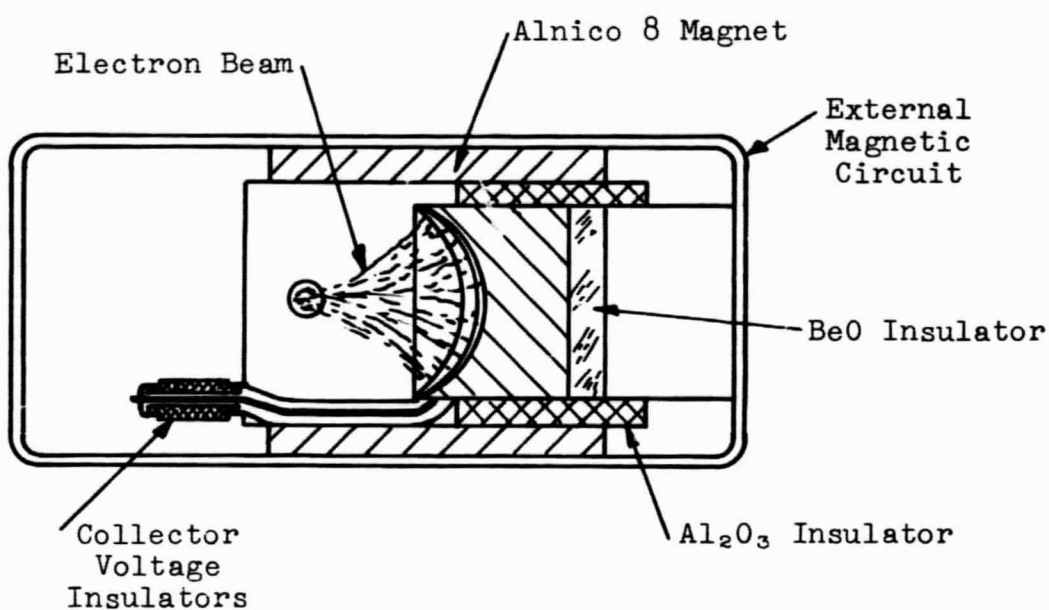
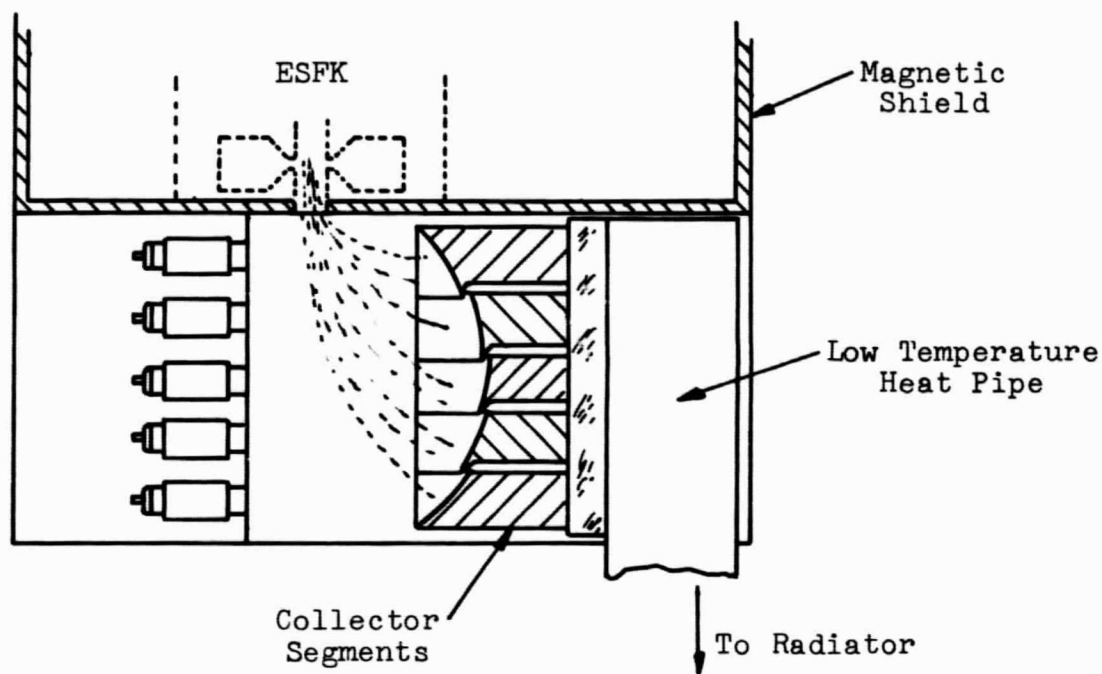
In a plane perpendicular to the plane of Fig. 12 the electron beam will spread due to its space charge. The collector segments must have sufficient height to collect all the electrons in this plane. Space charge effects on the beam spread in the plane perpendicular to the magnetic field are expected to be small compared to the transverse-field forces because of the low perveance beams employed in these klystrons.

Since the transverse magnetic field cannot begin abruptly at the magnetic shield, field measurements were made on an appropriate magnet and shield structure to determine the shape of the entrance field. This realistic magnetic field shape was used in the computer calculations.

Figure 13 shows a possible mechanical configuration for a transverse-field depressed collector employing heat pipe cooling. The collector segments are mounted on a BeO insulator inside a vacuum tight enclosure. Heat is conducted from the segments through the BeO ceramic to a low temperature ($\sim 200^{\circ}\text{C}$) heat pipe. Al_2O_3 ceramics are used to support the top and bottom of the collector segment assembly and to prevent heat flow in these directions.

The magnetic circuit configuration shown was selected because it has the minimum leakage flux. Minimum leakage flux is desirable in order to minimize shielding requirements and reduce magnet weight. Alnico 8 has been selected for the magnet material because of its high coercive force and stability with temperature variations.

Size and weight calculations have been made for the magnetic circuits for the various ESFK's. The magnets are Alnico 8 and the flux return paths are Armco iron. Table II lists the overall sizes and weights.



CONFIGURATION OF A HEAT PIPE COOLED
TRANSVERSE-FIELD COLLECTOR

Fig. 13

TABLE II

SIZE AND WEIGHT OF MAGNETIC CIRCUIT
FOR ESFK TRANSVERSE-FIELD COLLECTOR

Frequency (GHz)	.85	2.0	8.0	11.0
Overall Dimen- sions (cm)	30.5x20.3 x20.3	20.3x11.4 x11.4	16.5x8.9 x8.9	16.5x8.9 x8.9
(in)	12x8x8	8x4.5x4.5	6.5x3.5 x3.5	6.5x3.5 x3.5
Weight (kg)	9.85	2.27	1.32	1.32
(lbs)	21.7	5.0	2.9	2.9
B (weber/m ²)	.015	.015	.015	.015

The ultimate efficiency of the transverse-field depressed collector will be determined by the number of collector segments and the efficiency of the power supplies employed as well as the residual velocity at which the electrons are collected. Unfortunately, the transverse-field collector was conceived late in the program and time did not permit an optimum design to be determined by computing the electron trajectories with various velocity distributions present.

3.0 MECHANICAL DESIGN

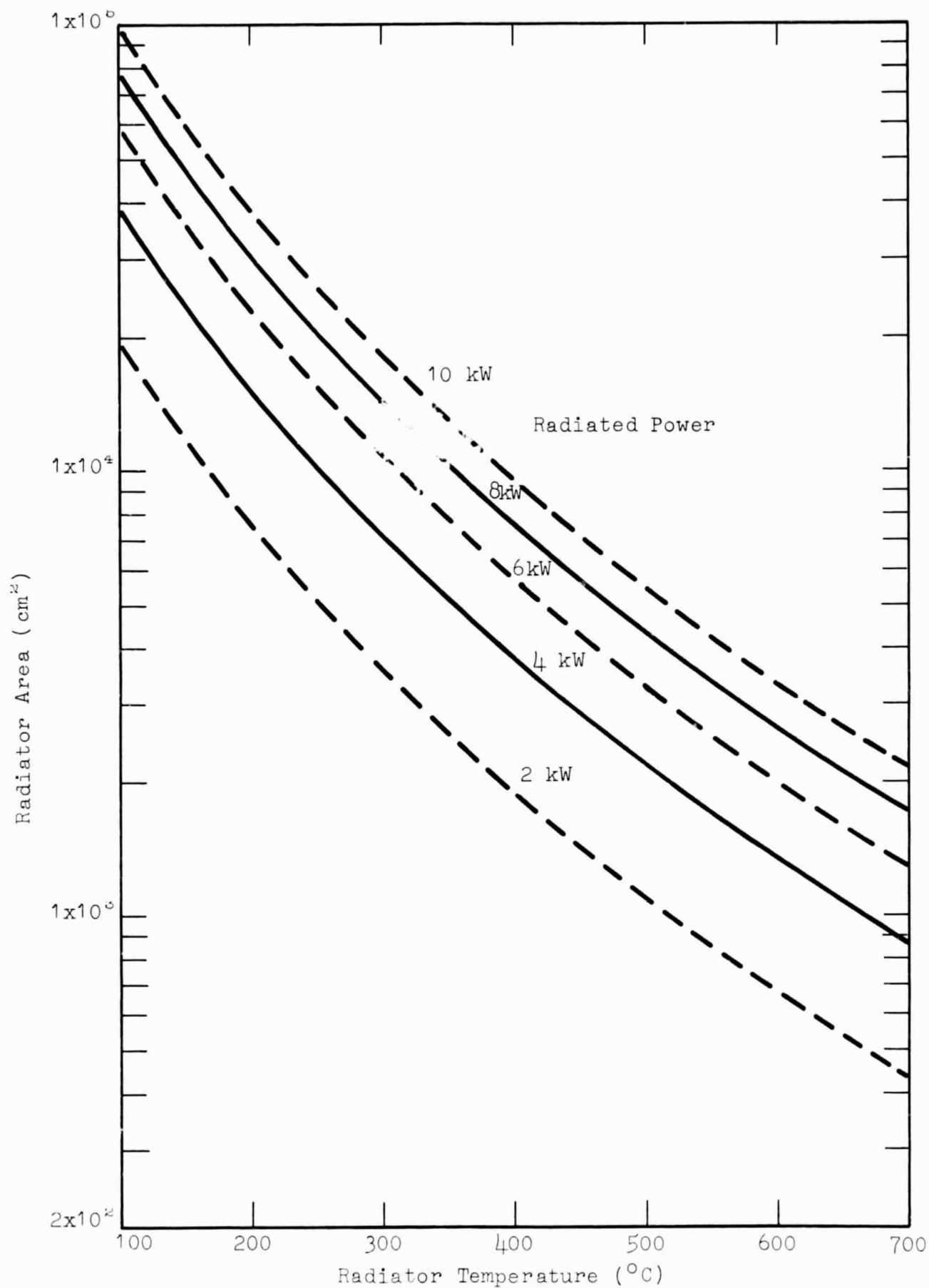
3.1 THERMAL DESIGN

3.1.1 Collector Cooling

An investigation of "heat pipe" heat transfer systems^{12,13,14} was made as a part of this study program with the assistance of Dr. K. T. Feldman of the University of New Mexico's Mechanical Engineering Department and Mr. R. W. Werner of the University of California's Lawrence Radiation Laboratory. Heat pipes are of special interest for space applications since they provide a nearly isothermal transfer of heat in a zero gravitational environment. Isothermal heat transfer is highly desirable since the heat must be removed from a relatively small collector area and radiated from a much larger area to the space background.

Basic to any radiation heat transfer system is the trade-off between radiating surface temperature and surface area. Figure 14 shows the radiating surface area required vs temperature, with collector power as a parameter. The emissivity is assumed to be 0.90 which is a realistic value for oxides on stainless steel or molybdenum.

One may see from Fig. 14 that heat pipes operating with water or organic fluids at low temperatures will require very large radiators, whereas radiators fed by liquid metal heat pipes operating at higher temperatures require considerably less radiator area. High operating temperatures create a potential ground checkout problem because of gas permeation of the vacuum envelope of the microwave tube. Most metals become quite porous to gas atoms at elevated temperatures. Kohl¹⁵ gives a figure which shows the diffusion rates of certain gas-metal combinations. Gold is the only metal which



RADIATOR AREA VS RADIATOR TEMPERATURE

$\epsilon=0.90$

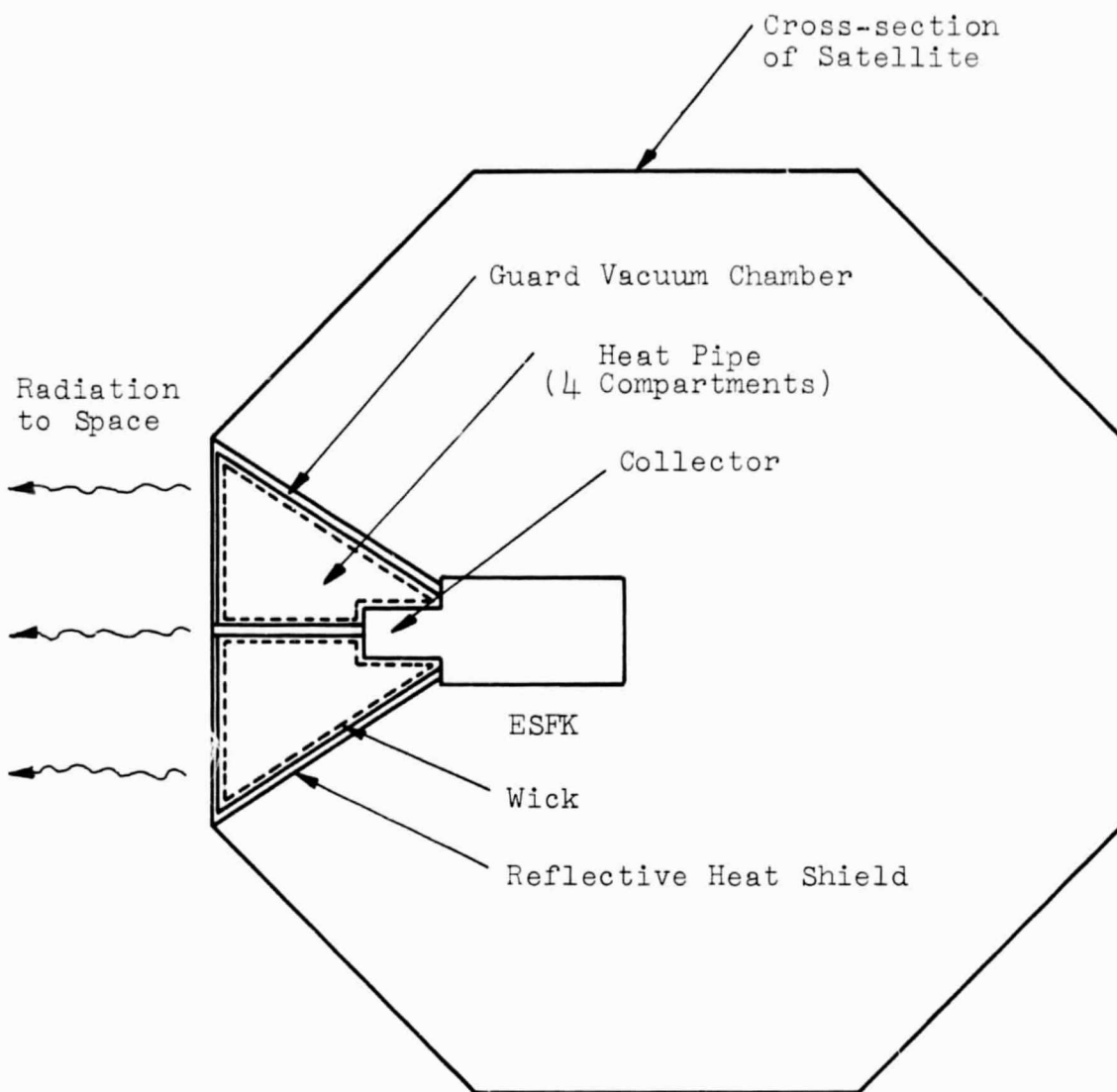
Fig. 14

resists gas permeation at high temperatures. Gold plating can be used to prevent gas permeation at temperatures up to $\sim 500^{\circ}\text{C}$; however, at higher temperatures gold diffuses rapidly into other metals which is undesirable from a structural viewpoint. An appendage ion pump may be used to maintain the vacuum in the microwave tube operating with a high temperature heat pipe - radiator system during processing and testing at the factory. This pump can be punched off from the klystron after terrestrial testing has been completed. There will be no gas permeation problem when the klystron is operated in the space environment. In fact, the klystron may be opened to the space vacuum provided there is no significant outgassing of other spacecraft components which might contaminate the klystron.

Low temperature operation is most desirable from the standpoint of microwave tube reliability; however, the temperature must be selected by a trade-off between reliability and satellite size and weight.

3.1.1.1 Conical Heat Pipe Radiator

Figure 15 shows the high-temperature, conical heat pipe. The radiator surface can be placed in one side wall of the satellite and the heat need not be radiated to the solar cell panels or to the antenna. This configuration requires the side walls of the heat pipe to be insulated in order to prevent thermal radiation to the interior of the satellite. The proposed solution to this problem is an outer vacuum vessel with a reflective coating which, when evacuated, forms a "thermos bottle" around the heat pipe. The guard vacuum surrounding the heat pipe will prevent gas permeation through the side walls during ground checkout. The heat pipe interior is divided into four separate vessels in order to provide



CONICAL HEAT PIPE

Fig. 15

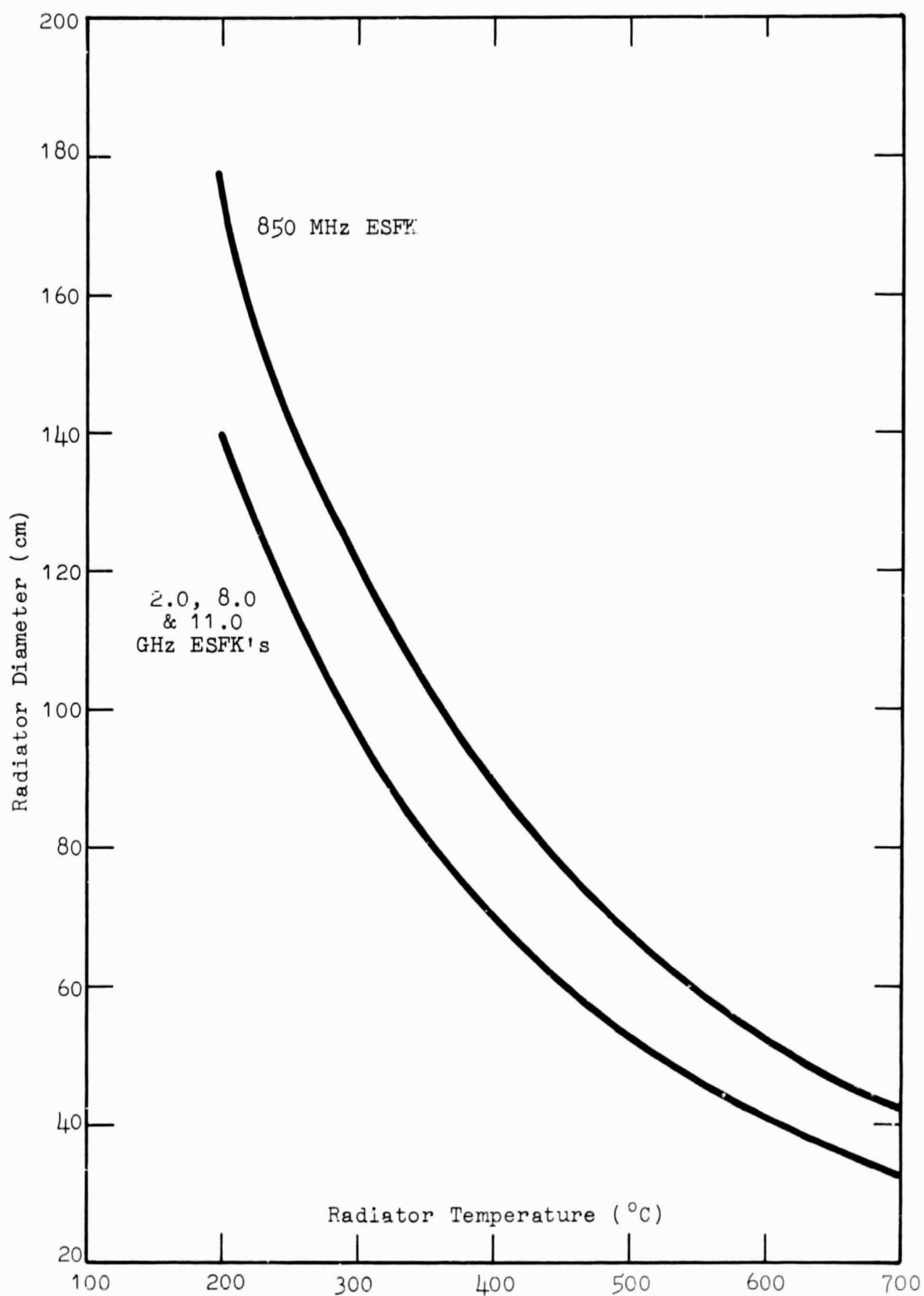
redundancy in the event of a micrometeoroid puncture. With a conservatively designed liquid metal system the loss of two out of the four sections of the heat pipe could be tolerated because liquid metal systems are capable of operating over a wider temperature range (500-900°C) than water systems. Water or organic fluid systems must be limited to smaller temperature ranges because of their high vapor pressures at high temperatures.

The working fluid for a heat pipe of this design would be a liquid metal. Sodium, potassium, lead, lithium and cesium are possibilities. The heat pipe wick would be two layers of 200 - 400 mesh screen wire with flow channels beneath.

Figure 16 shows the radiator diameter vs temperature required for a conical heat pipe. The radiated power is assumed to be 4 kW for the 2.0, 8.0 and 11.0 GHz ESFK's and 6 kW for the 0.85 GHz ESFK. An emissivity of 0.90 was assumed.

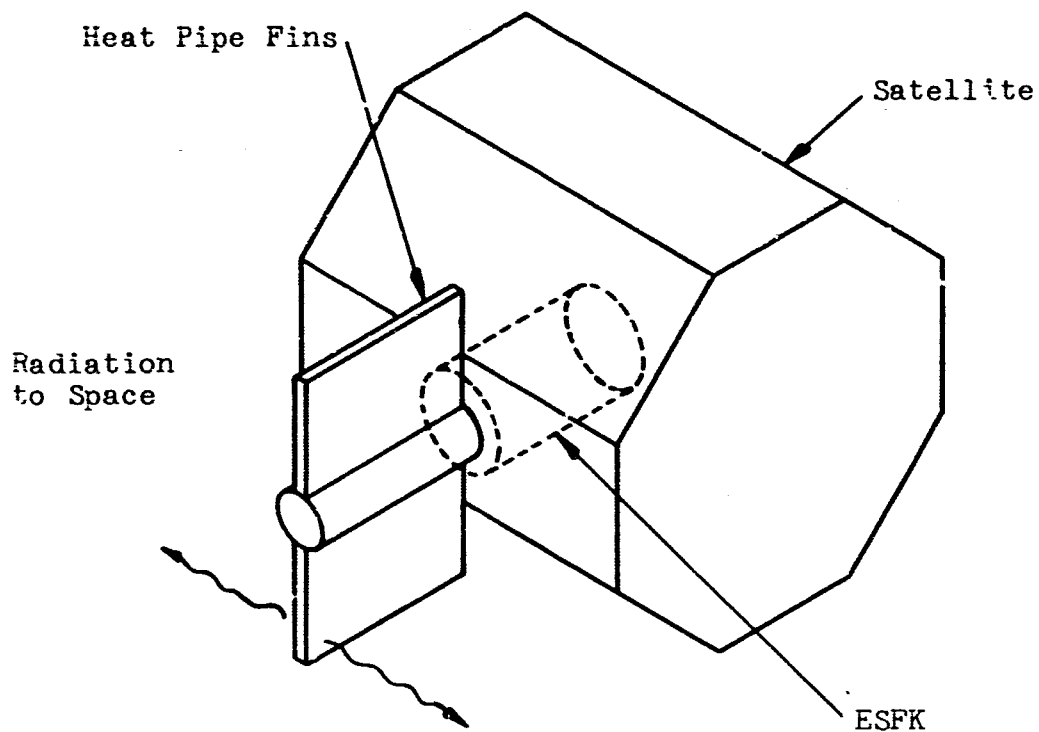
3.1.1.2 Two-Fin Heat Pipe Radiator

Figure 17 shows the two-fin heat pipe radiator which has some definite advantages over the conical heat pipe radiator. The primary advantage is a larger radiating surface since both sides of the fins can radiate. This advantage results in a smaller and lighter weight heat exchanger. In the conical heat pipe radiator only one side of the radiator surface is effective in transferring heat to space by radiation. A high reliability in a micrometeoroid environment can be easily realized by making the radiating fins from many small cylindrical heat pipes with relatively thin walls. Another advantage is that the entire radiator is external to the satellite body. This minimizes the problem of thermal radiation to the internal components of the satellite.



CONICAL HEAT PIPE RADIATOR DIAMETER VS TEMPERATURE

Fig. 16



TWO-FIN RADIATOR HEAT PIPE COOLING SYSTEM

Fig. 17

Figure 18 shows the relative two-fin radiator panel sizes vs temperature for the 2.0, 8.0 and 11.0 GHz ESFK's.

Before the weights of the various heat pipe cooling systems could be predicted, it was necessary to study the influence of micrometeoroid puncture protection. Using the meteoroid data of Whipple¹⁶, and the penetration equation of Charters and Summers¹⁷, it was possible to determine the depth of meteoroid penetration in various materials. The depth of penetration is given by:

$$D = 2.78d \left(\rho_m / \rho_t \right)^{2/3} \left(v_m / v_t \right)^{2/3}$$

where: d = particle diameter

ρ_m = density of meteoroid

ρ_t = density of target

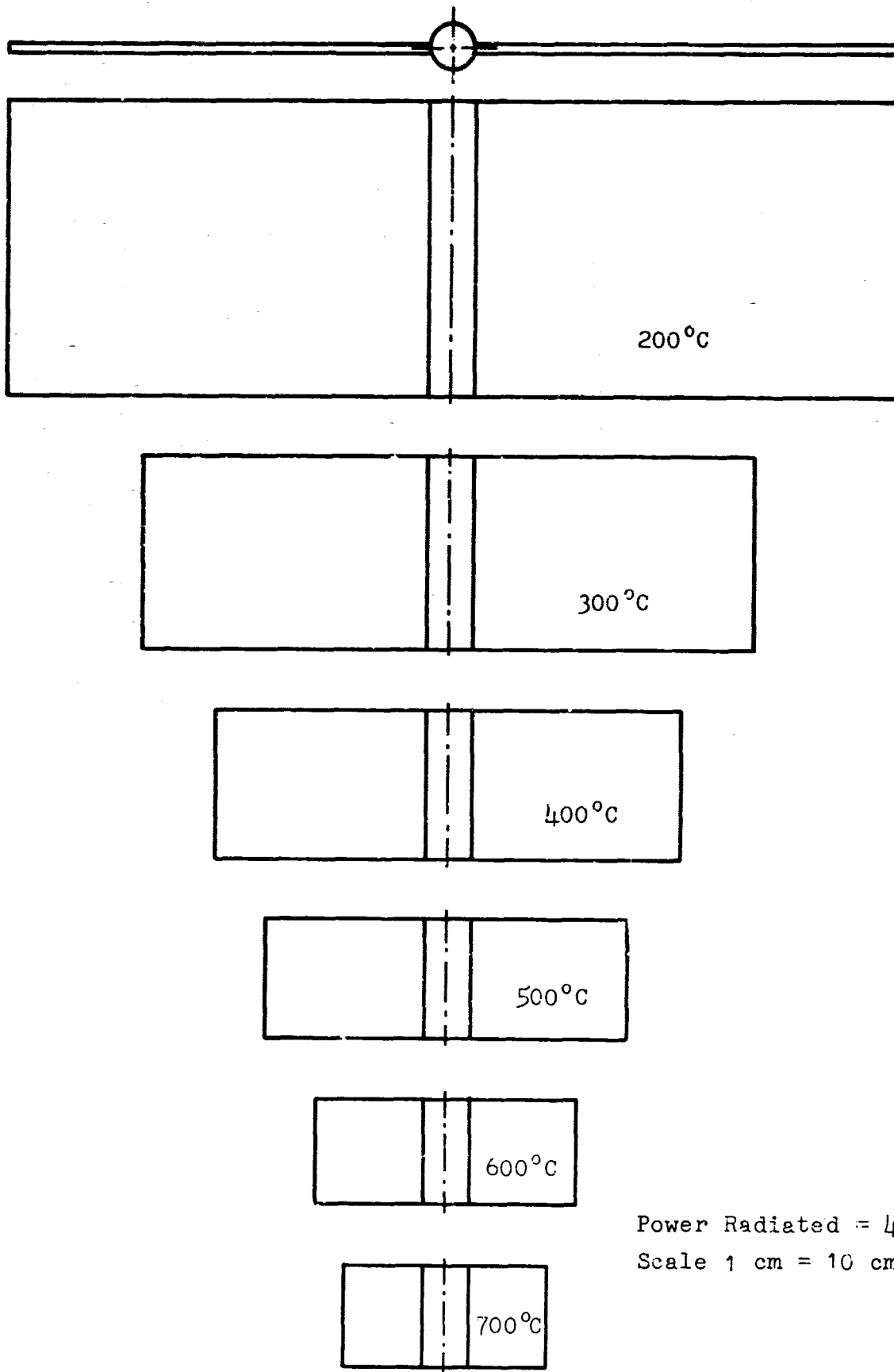
v_m = velocity of meteoroid

v_t = velocity of sound in target material

By assuming the particle velocity to be 30 km/sec and the particle density to be 0.44 gm/cm³, it was possible to calculate the depth of penetration in such materials as stainless steel and molybdenum.^{18,19} Figure 19 shows the number of micrometeoroid impacts per square meter and the depth of penetration in stainless steel vs the particle mass, for a 30,000 hour mission time.

The probability P_o of no puncture is

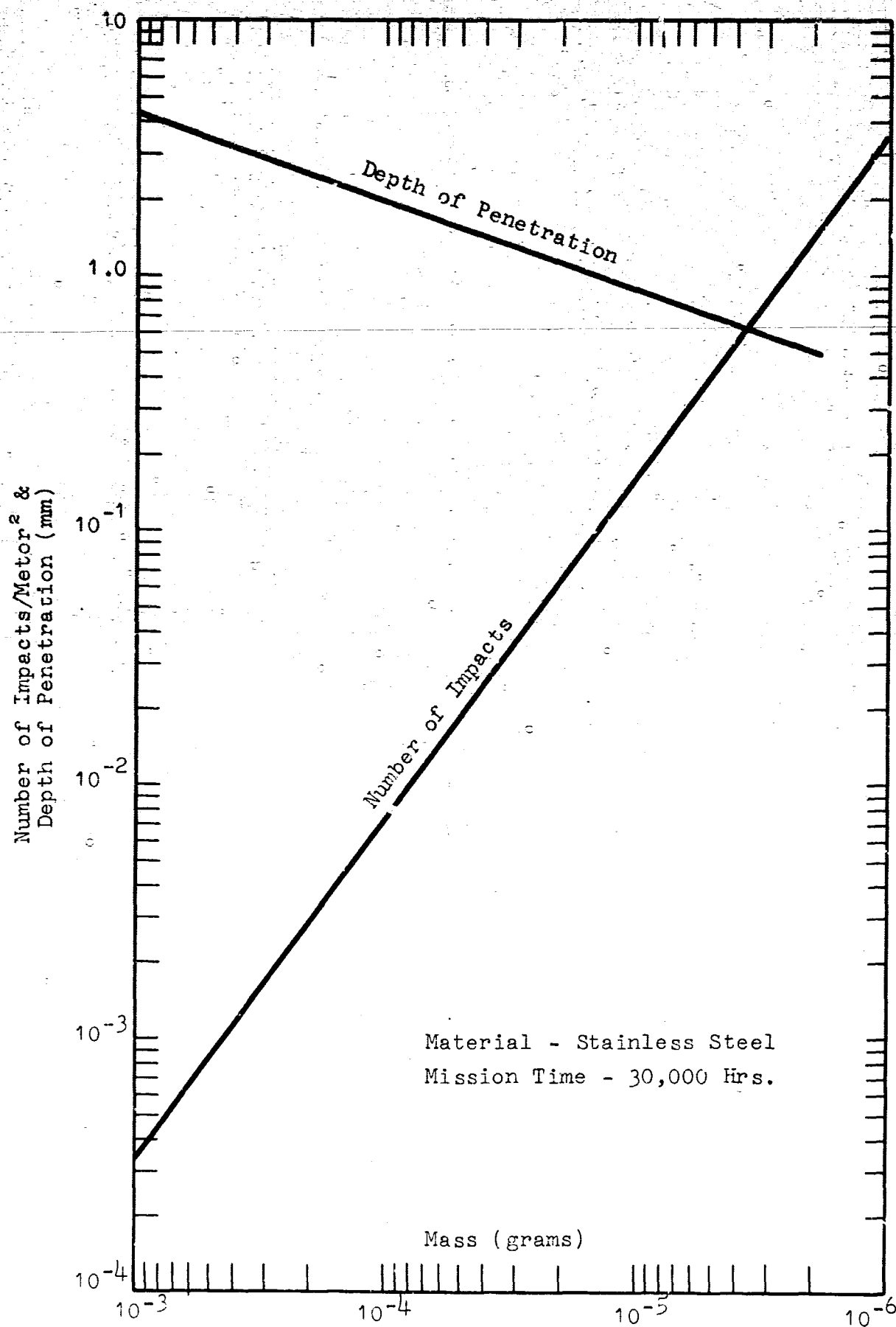
$$P \approx 1 - NAT$$



Power Radiated = 4.0 kW
Scale 1 cm = 10 cm

TWO-FIN RADIATOR
FOR 2, 8 & 11 GHz ESK

Fig. 18



MICROMETEOROID IMPACTS AND DEPTH OF PENETRATION

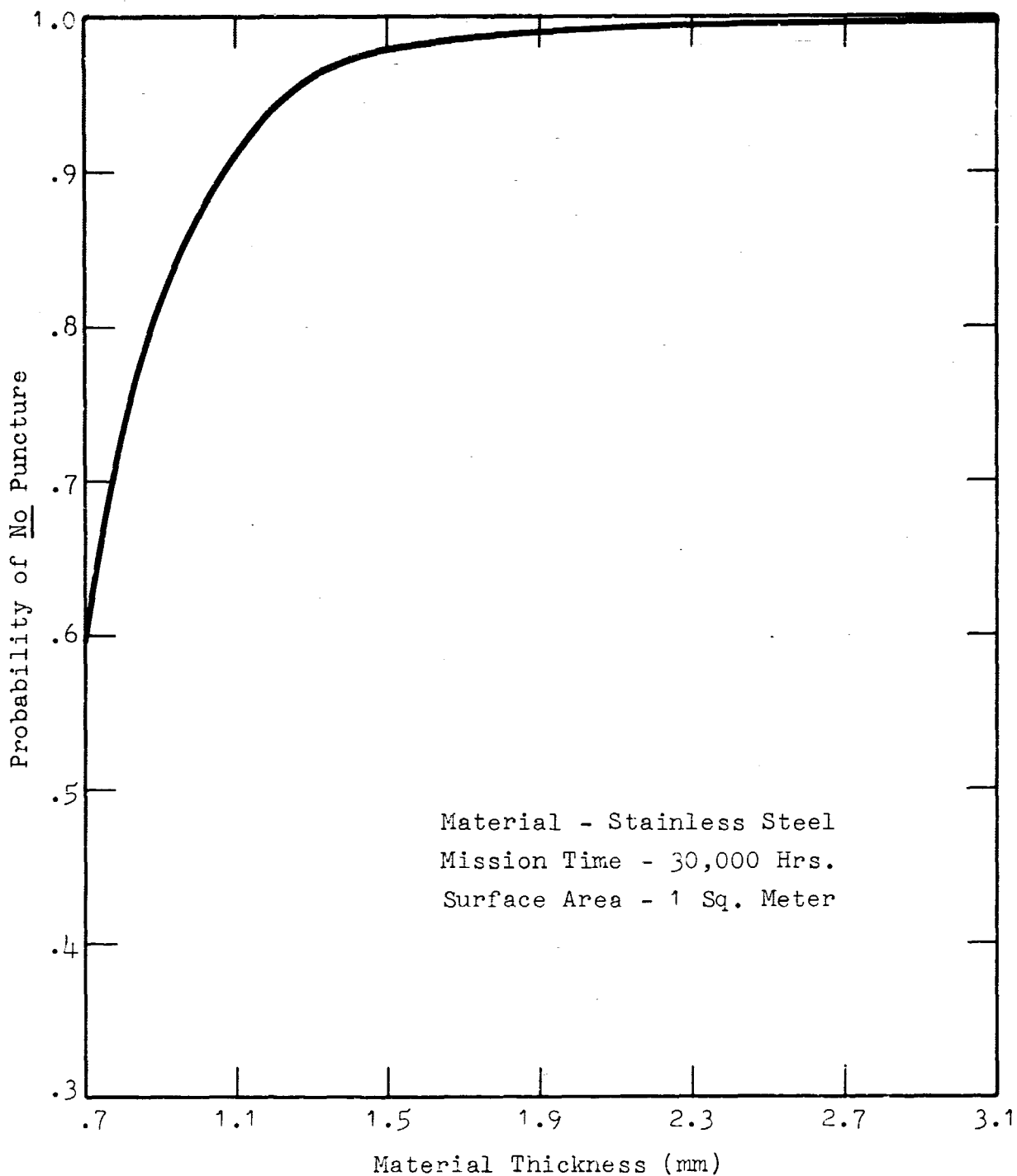
Fig. 19

with a Poisson distribution and P_0 close to unity,¹⁷
where: N = number of particles capable of penetration/ m^2 sec
 A = surface area (M^2)
 T = mission time (sec.)

Figure 20 shows the probability of no puncture vs material thickness for one square meter of stainless steel in 30,000 hours. It can be seen that one pays a severe weight penalty for probabilities greater than ~0.995.

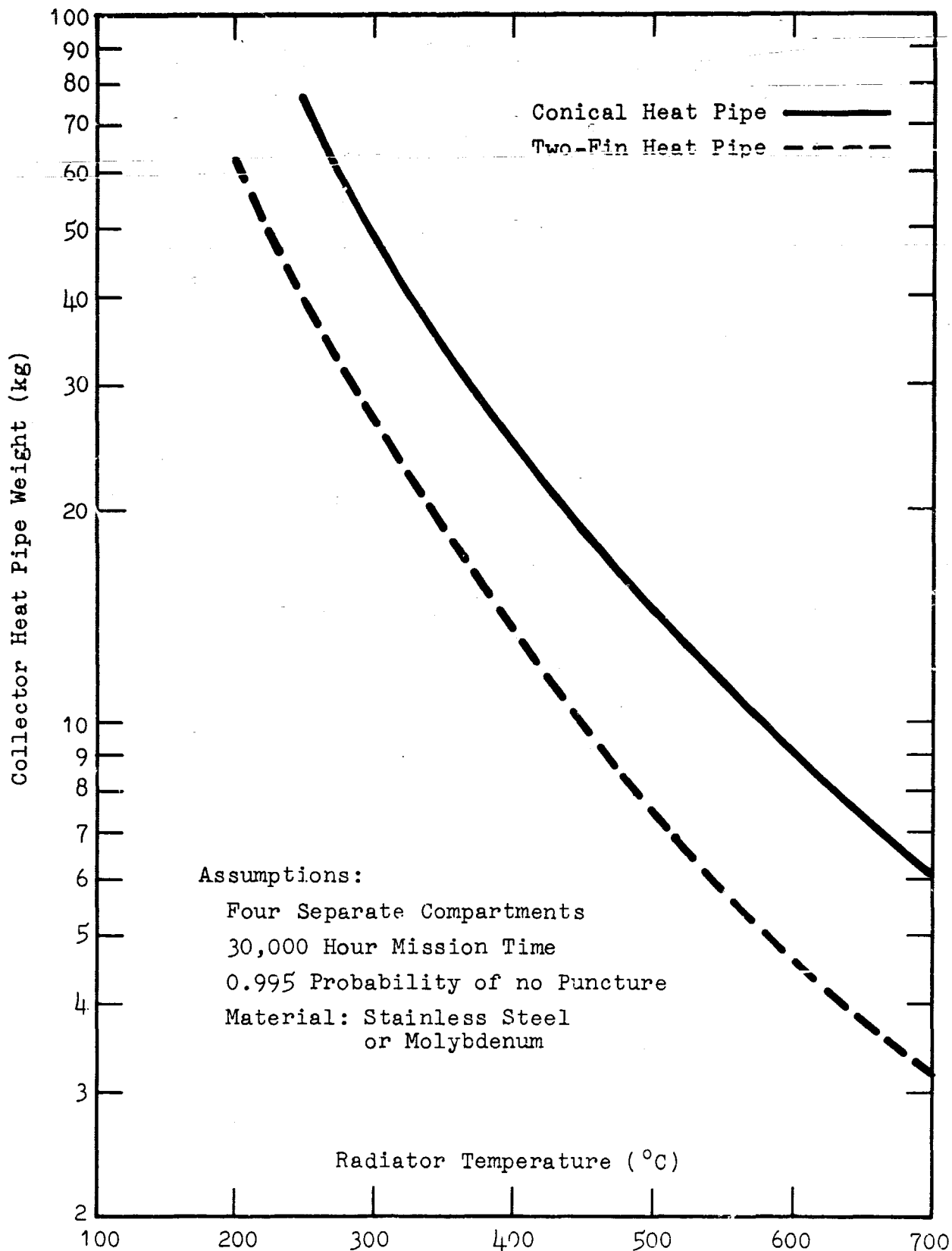
The weights of the conical heat pipe radiator and the two-fin radiator were calculated vs temperature by assuming a 30,000 hour mission time and a 0.995 probability of no puncture. The calculations apply for either stainless steel or molybdenum since their strengths and densities compensate for each other in the penetration equations. Figure 21 shows the collector heat pipe weight vs temperature for the 0.85 GHz E3FK. The same information is shown for the 2.0, 8.0 and 11.0 GHz ESFK's in Fig. 22. Clearly, the two-fin heat pipe radiator offers a significant weight advantage over the conical heat pipe radiator at any operating temperature.

A study was made to determine the weight savings which might be realized in the collector heat exchanger if the beam power was applied only when rf drive was present (i.e. beam power supply interlocked to the rf drive). In this mode of operation the collector would not have to dissipate the unrecovered dc power in the unmodulated beam. The weight savings possible with the FM klystrons operating at saturated rf drive is about 30 percent. Unfortunately, there is no weight savings with the AM klystrons because the average rf level of the typical television signal is so low. Realistically, the heat exchanger would have to be designed for the full no-rf-drive collector power.



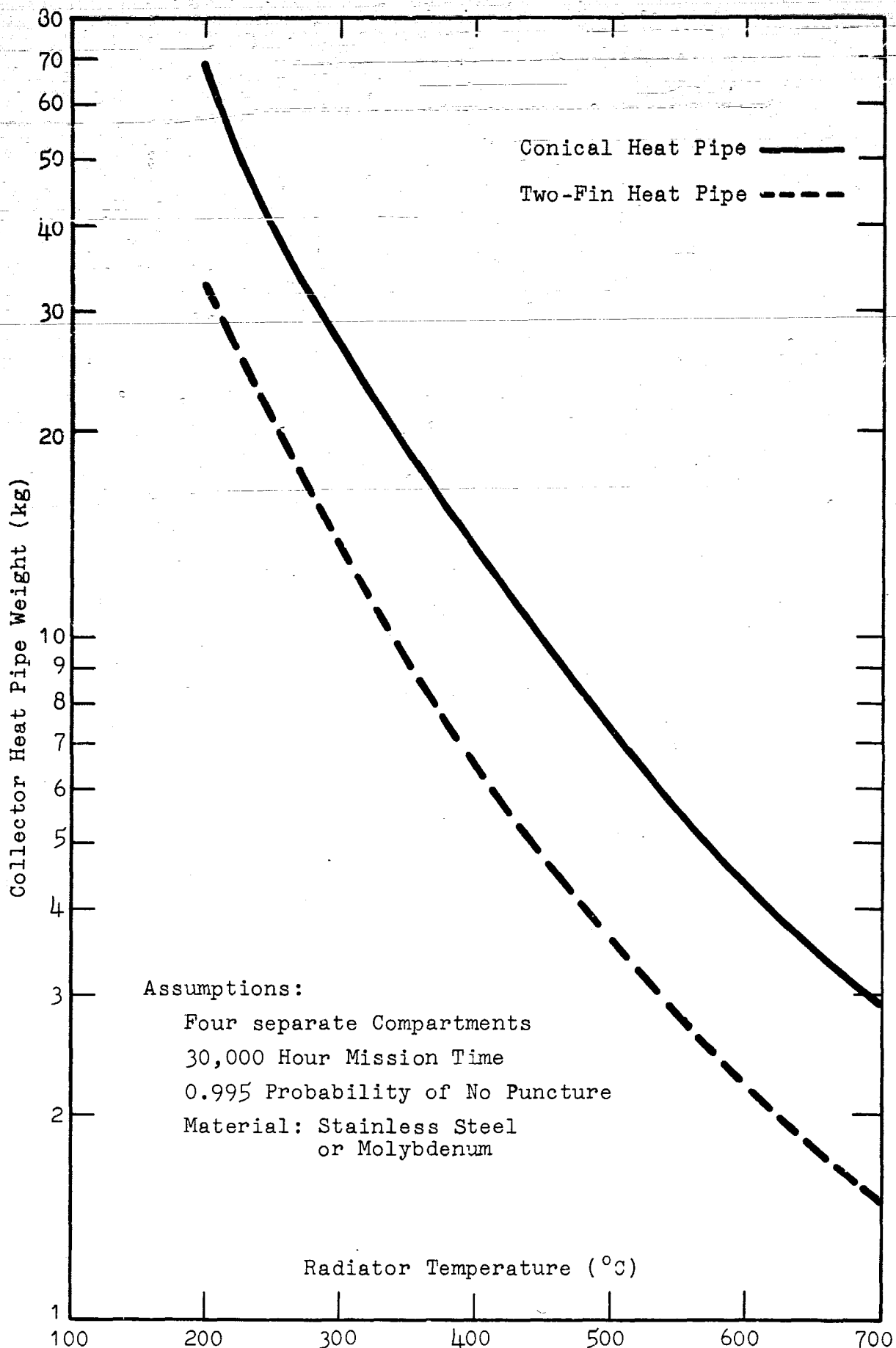
PROBABILITY OF NO MICROMETEOROID PUNCTURE
VS MATERIAL THICKNESS

Fig. 20



COLLECTOR HEAT PIPE WEIGHT VS TEMPERATURE FOR 850 MHz ESFK

Fig. 21



COLLECTOR HEAT PIPE WEIGHT VS TEMPERATURE FOR 2.0, 8.0
 & 11.0 GHz ELECTROSTATICALLY FOCUSED KLYSTRONS

The added system complexity and loss of flexibility would have to be weighed against the relatively small weight reduction to be gained in the case of the FM ESFK's.

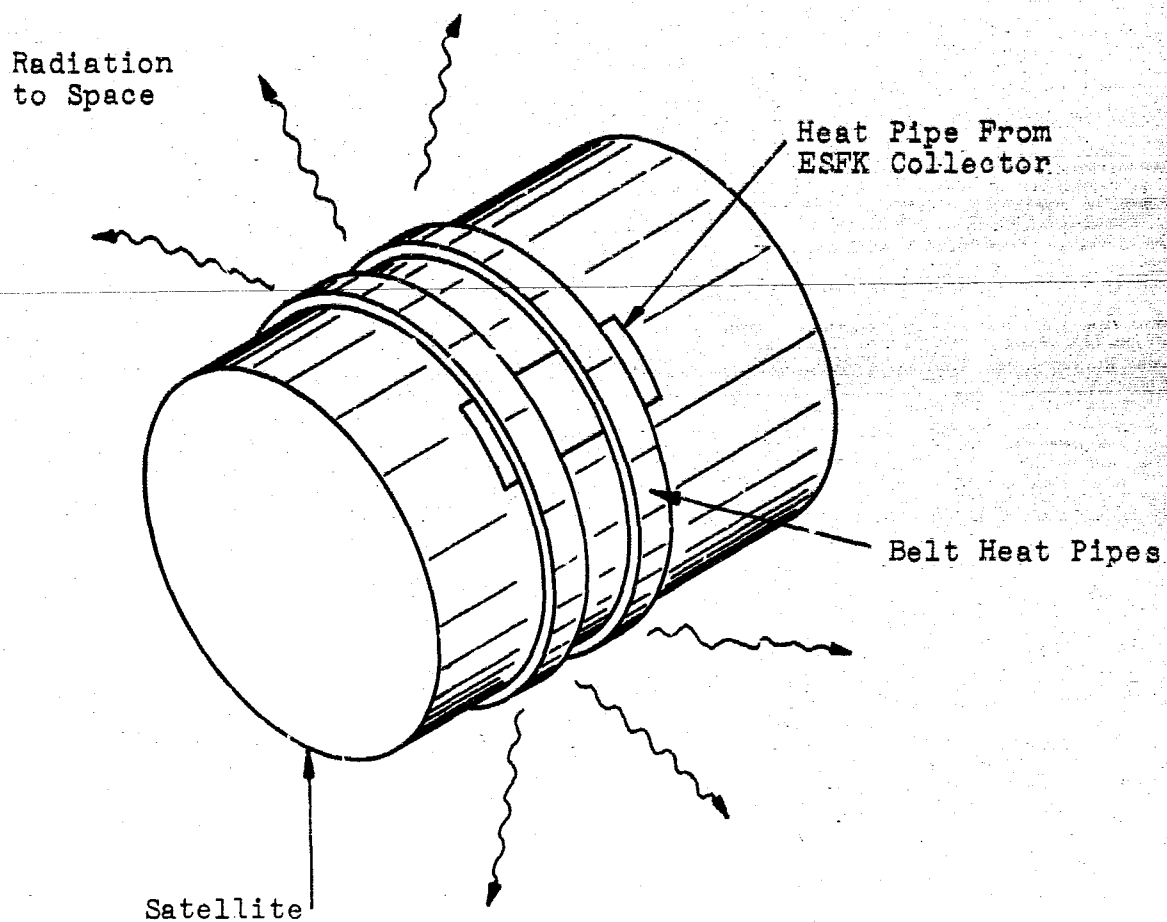
3.1.1.3 Low-Temperature Belt Heat Pipe Radiator

Figure 23 shows the concept of the belt heat pipe which encircles the satellite body. This type of heat radiating system can have a very large surface area and operate at a low temperature ($\sim 100^{\circ}\text{C}$) using water or an organic fluid. Two disadvantages accrue from the fact that the heat pipe radiator is part of the satellite rather than part of the microwave amplifier. An interface problem exists between the tube builder and the satellite builder in the matter of mating the tube to the cooling system. Also, the belted cooling system will tend to heat the satellite body which may cause internal temperatures to be excessive.

Solar radiation will heat the areas of the belt which are directed toward the sun which will render these areas ineffective for heat transfer. It was felt that the inherent disadvantages of the low-temperature belt radiator far outweighed its advantage of low temperature and it was not considered in greater detail.

3.1.2 Detail Heat Pipe Design for Two-Fin Radiator

The superiority of the two-fin heat pipe radiator for collector cooling of the ESFK's was established by the previously described study. This configuration, operating in the 400°C to 600°C range, provides the lowest weight and highest reliability heat radiator. Internal satellite heating problems are minimized since the radiator is completely external.



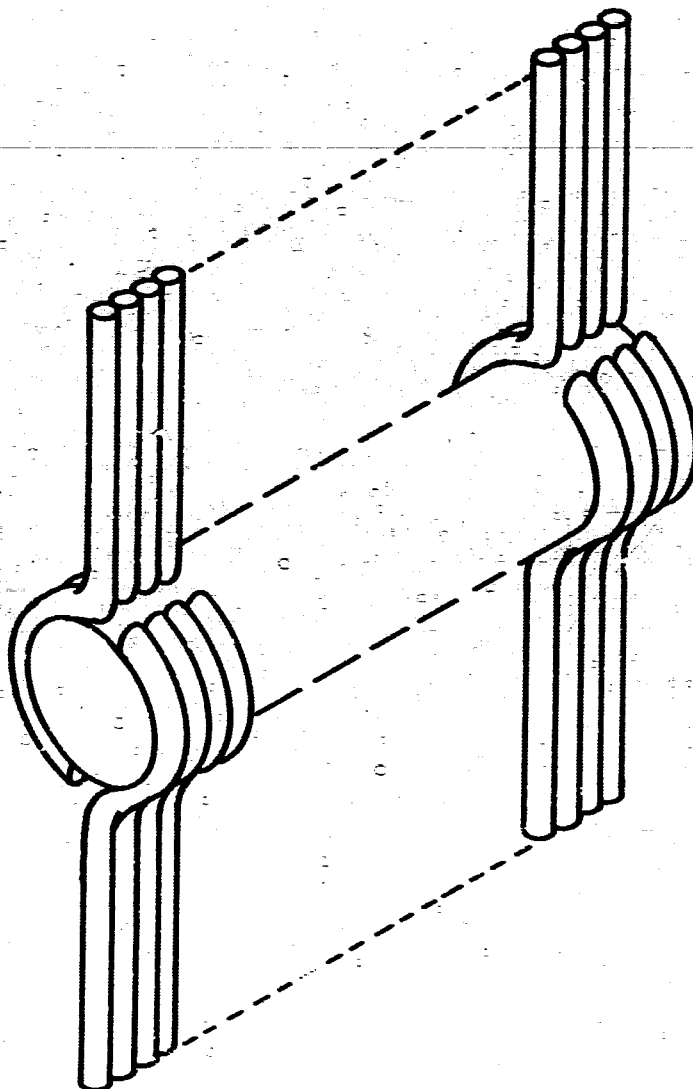
LOW TEMPERATURE BELT HEAT PIPE
COOLING SYSTEM

Fig. 23

As a consequence of the initial study, it was decided to concentrate on the detail design of a two-fin heat radiator composed of many individual heat pipes for high reliability in a micrometeoroid environment. Figure 24 shows the configuration of the heat radiator composed of individual heat pipes brazed to the electron beam collector of the klystron. Each heat pipe will half-wrap the cylindrical collector body. The internal construction of the collector will avoid the use of copper as a collector material or as a brazing material since its vapor pressure becomes marginal in the 500°C to 600°C temperature range.

The remaining question in the design of such a heat exchanger is what operating temperature should be selected. Clearly the higher the operating temperature, the smaller and lighter weight will be the heat radiator. However, for reliability reasons the maximum operating temperature should be restricted to 400°C to 500°C. Since these temperatures exceed the critical point for water and organic fluids, a liquid metal must be used as the heat transfer medium in the heat pipe. Sodium and potassium are metals which have the desirable properties required for heat pipe applications. Computer computations have been made for 1 cm diameter heat pipes using both metals to transport powers appropriate to the design of two-fin heat radiators for the various ESK's.

Assuming a power dissipation of 4000 watts, the length of the heat pipes will be 71 cm at 400°C and 47 cm at 500°C. A total of 36 1 cm diameter heat pipes will be used for both cases. The surface flux at the collector is $\leq 10 \text{ w/cm}^2$. This is a sufficiently low number so that problems of nucleate boiling in the wick structure will not occur. Heat pipe fluids such as potassium can sustain superheats across the



TWO-FIN HEAT PIPE RADIATOR CONFIGURATION

Fig. 24

wick of at least 20°C before nucleate boiling will be initiated. In terms of surface flux for potassium this can be estimated as follows:

$$q_{\text{surface}} = k \frac{\Delta t}{\Delta x} = (.35)(20)/\Delta x$$

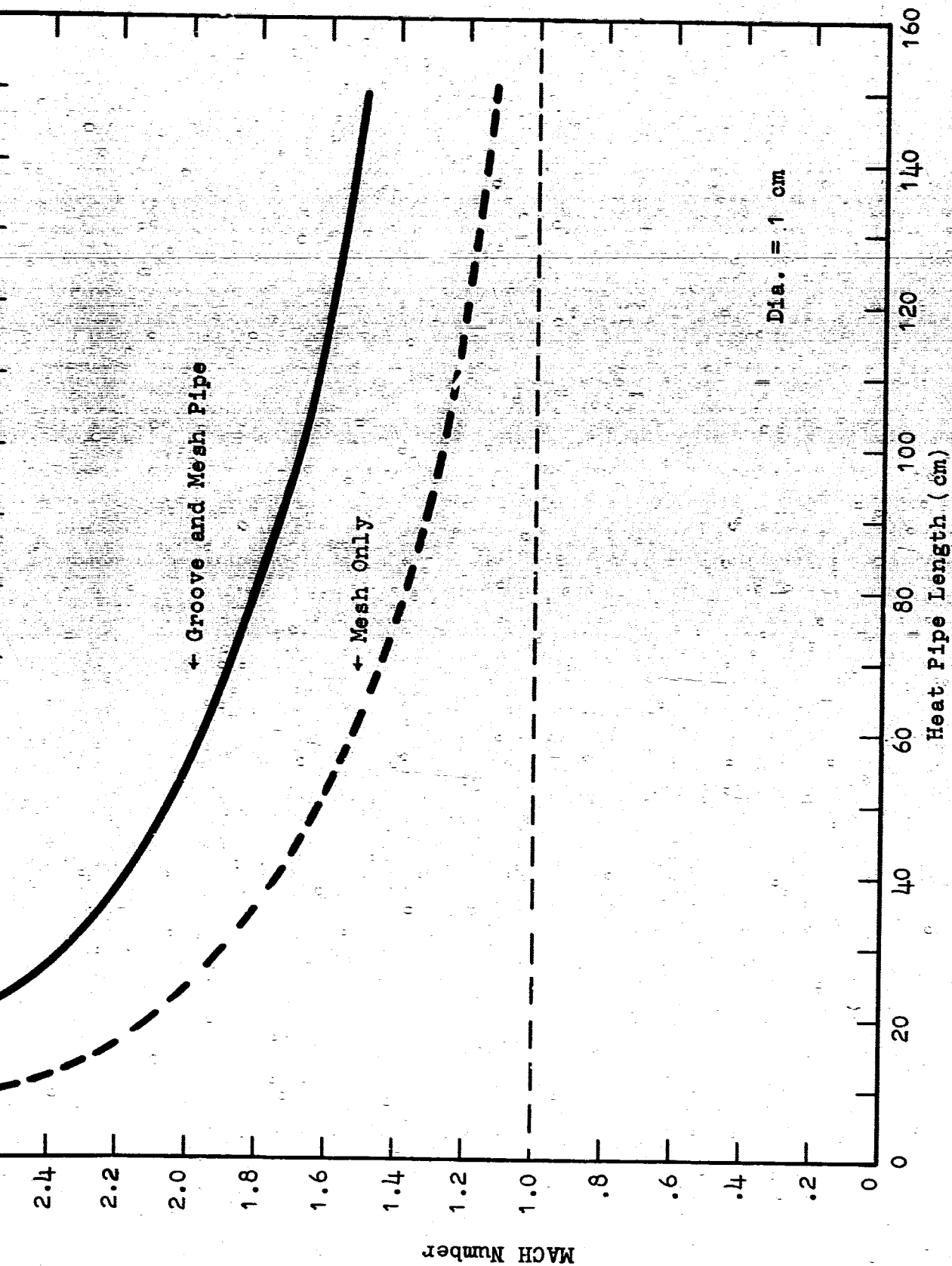
where k = thermal conductivity of K. It can be shown that Δx approaches (0.2) (heat pipe radius) as a limit. Thus, for the 1 cm diameter pipe:

$$q_{\text{max}} = (.35)(20)/(.2)(.5) = 70 \text{ watts/cm}^2$$

The 1 cm diameter heat pipe affords a safety factor of 7.

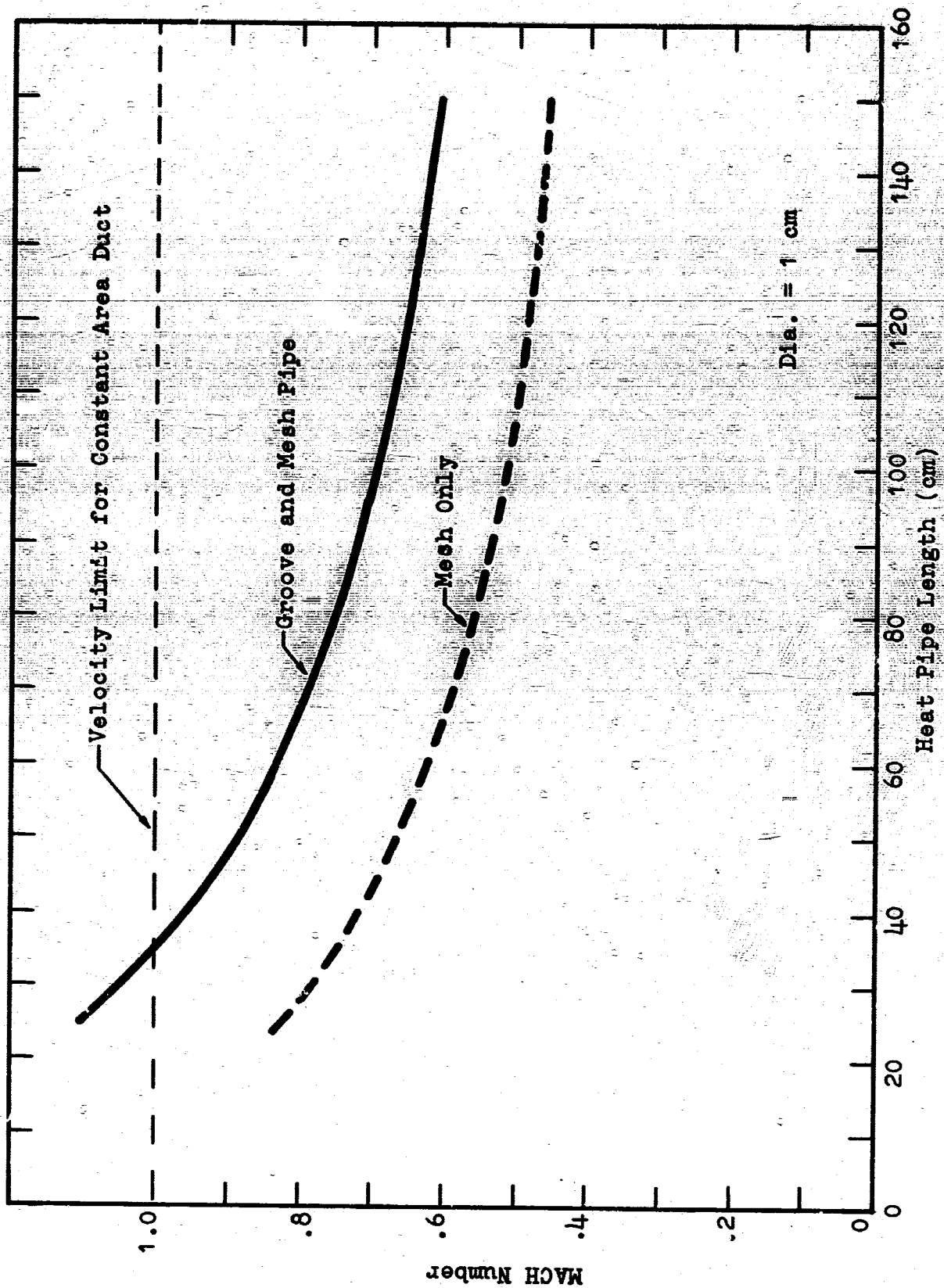
Various heat pipe properties were computed for temperatures of 427°C and 500°C using potassium as a working fluid. Figure 25 is a plot of the Mach number of the vapor in a potassium filled heat pipe at an operating temperature of 427°C. Since the velocity in a constant area duct, when the starting velocity is subsonic, cannot exceed Mach 1, it is evident that this heat pipe will not function at this temperature. The Mach number decreases with increasing length because the capillary size increases to compensate for the increasing liquid flow impedance and the mass flow is therefore less.

Figure 26 shows the same Mach number plot for a temperature of 500°C. This heat pipe will function since the vapor velocity is subsonic.



MACH NUMBER OF POTASSIUM VAPOR AT 427°C VS HEAT PIPE LENGTH

Fig. 25



MACH NUMBER OF POTASSIUM VAPOR AT 500°C VS HEAT PIPE LENGTH

Fig. 26

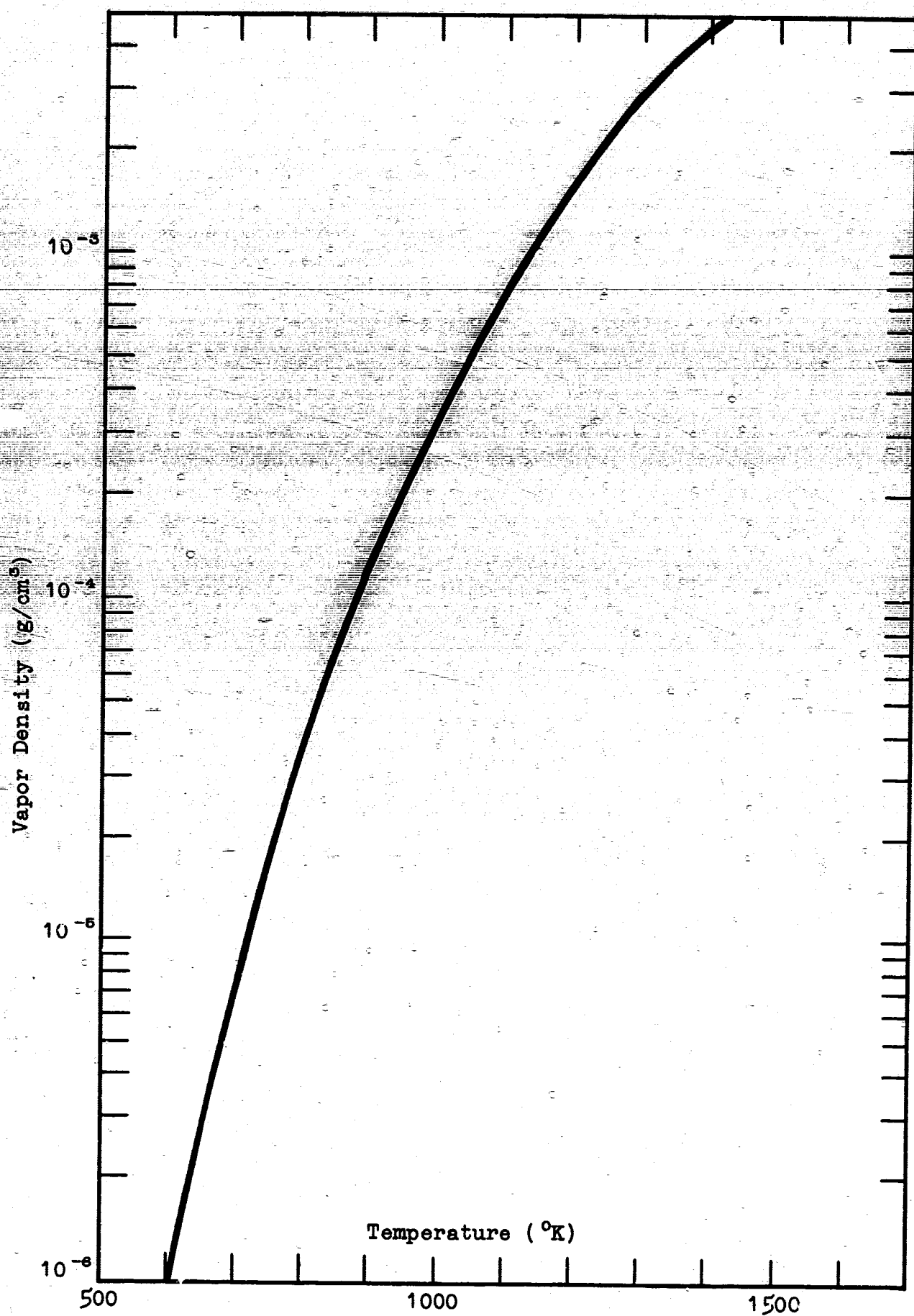
The sensitivity of the lower temperature limit of heat pipe operation to sonic velocity is evident in Figs. 27 and 28. These figures show the density of the saturated vapor as a function of temperature. The density changes about four orders of magnitude in 1000 degrees. It may also be observed that potassium is superior to sodium from the standpoint of having a lower operating temperature. The lower temperature limit of heat pipes has been observed experimentally by nonisothermal, erratic behavior at temperatures which indicate greater than sonic vapor velocities.

Figure 29 shows the axial power capability of the potassium heat pipe operating at 500°C. For a 47 cm heat pipe length the axial power capability of ~700 watts exceeds the requirement of $4000/36 = 110$ watts by a safety factor of 7. Figure 30 shows the calculated optimum capillary radius as a function of heat pipe length. For the 47 cm heat pipe length the optimum capillary radius can be obtained by using a stainless steel screen having a mesh size of 50 x 50 wires to the cm with 0.0127 cm diameter wires. This is a readily available material.

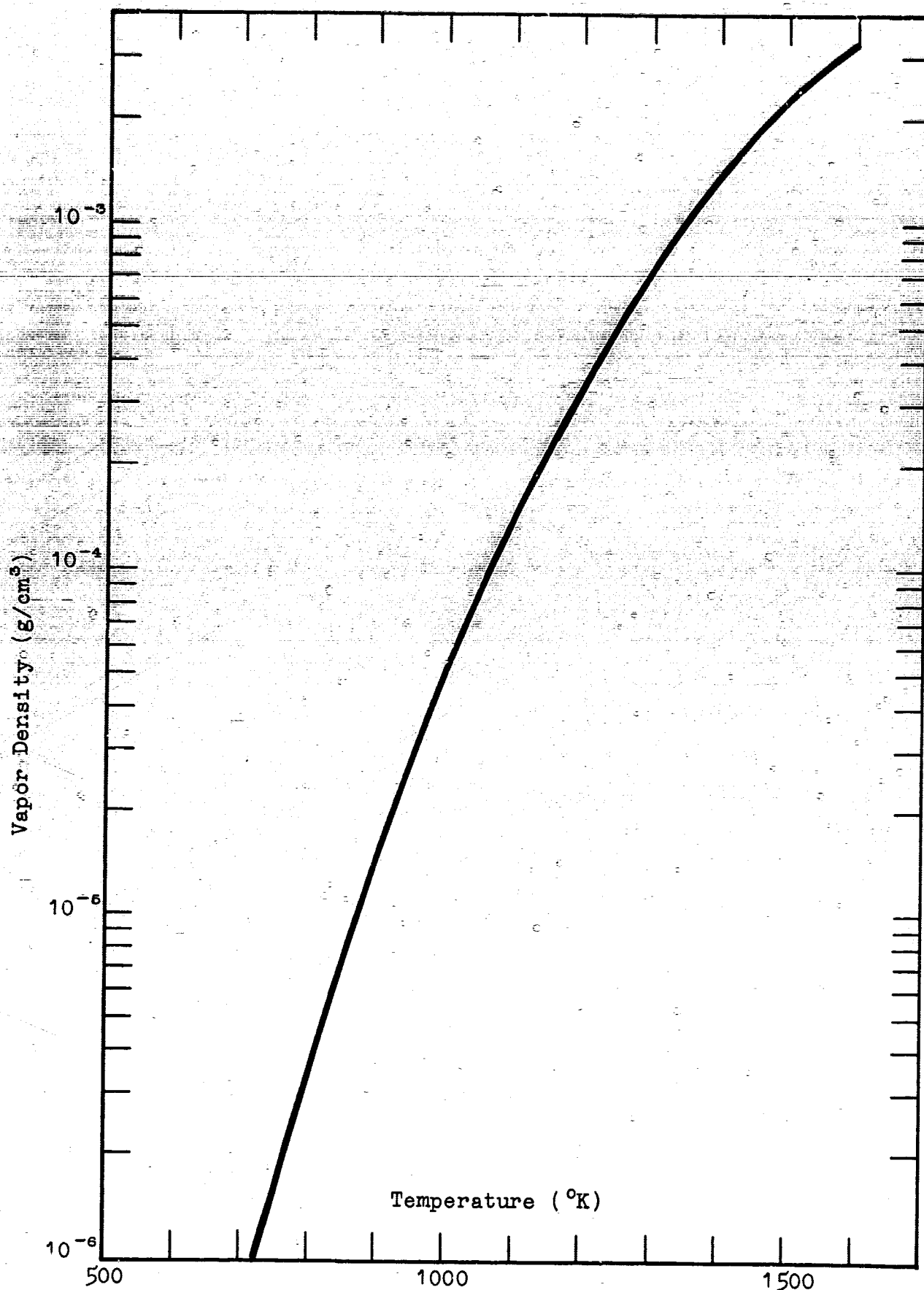
It can be shown that the thickness of the wick should be (0.2) (heat pipe radius) or 0.10 cm. Since the screen thickness is .025 cm, four complete wraps of the screen will be required to provide adequate flow area.

The vapor pressure of potassium at 500°C is approximately 0.075 psi. The allowable creep stress for 304 stainless steel is 10,000 psi for 1 percent in 20,000 hours. Obviously there is no stress problem.

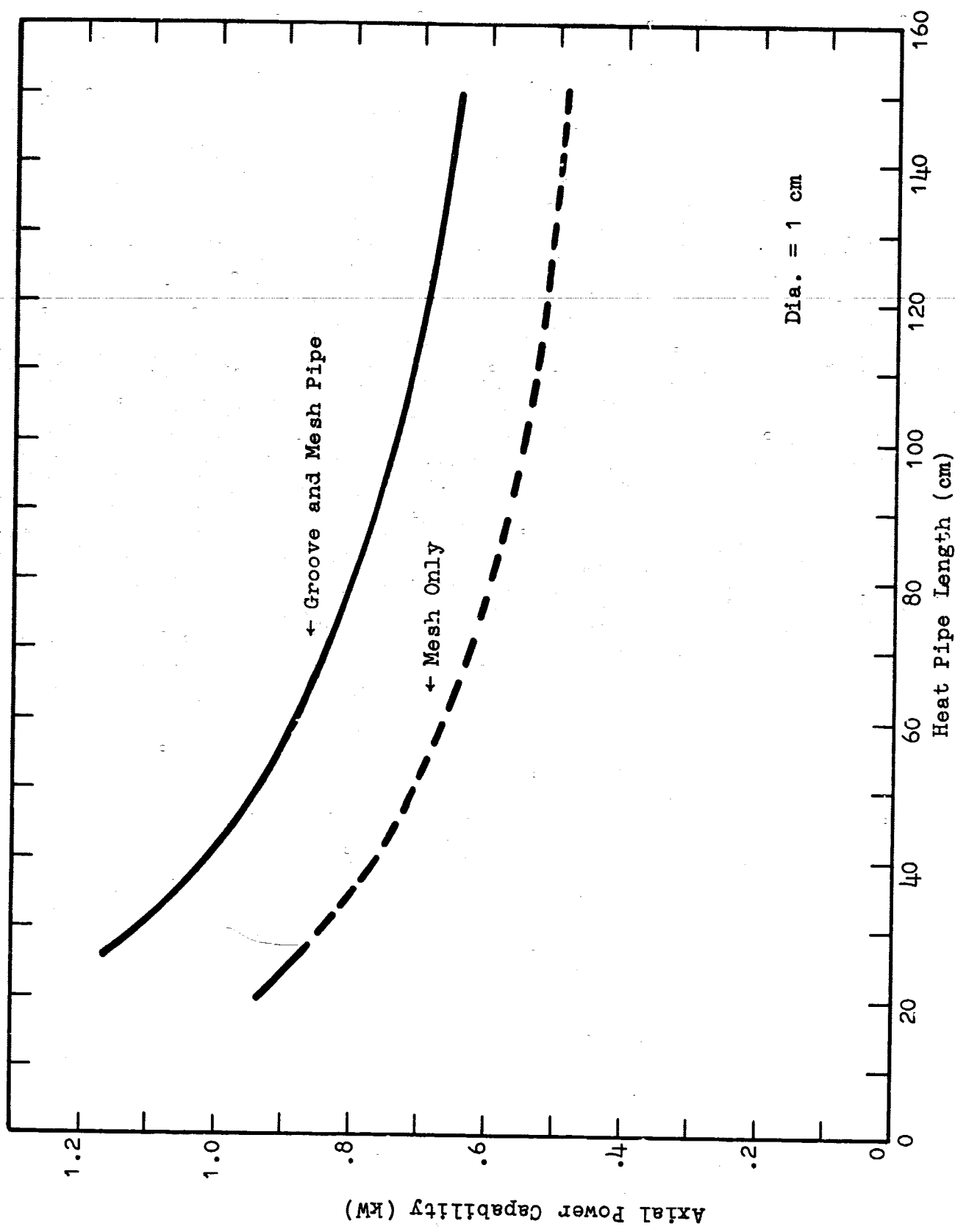
Table III lists the design parameters for the two-fin heat pipe radiator for the 2.0, 8.0, and 11.0 GHz ESFK's. Table IV gives the same information for the 850 MHz ESFK.



DENSITY OF SATURATED POTASSIUM VAPOR VS TEMPERATURE

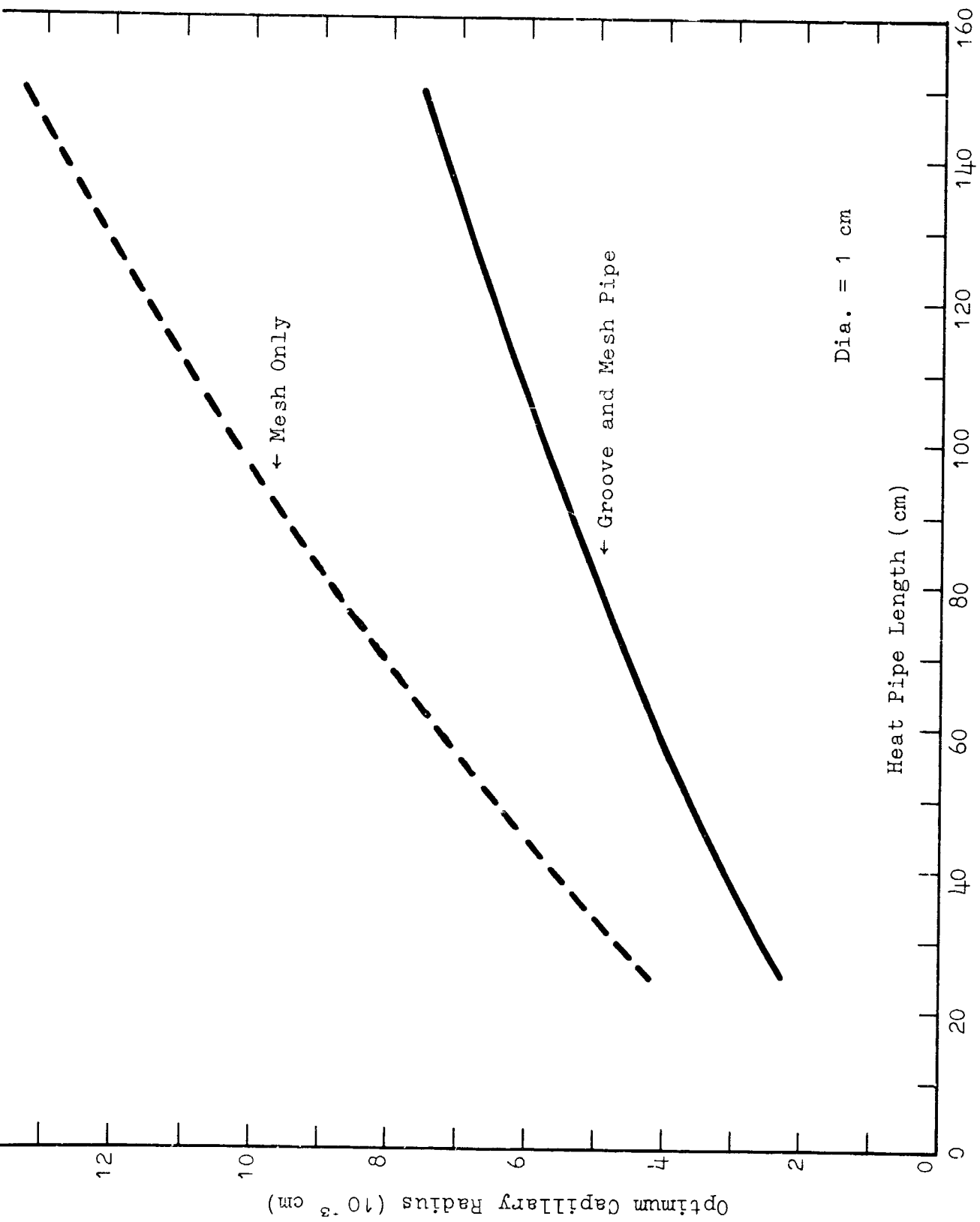


DENSITY OF SATURATED SODIUM VAPOR VS TEMPERATURE



AXIAL POWER CAPABILITY VS LENGTH FOR A POTASSIUM FILLED HEAT PIPE AT 500°C

Fig. 29



OPTIMUM CAPILLARY RADIUS VS LENGTH FOR A POTASSIUM FILLED HEAT PIPE AT 500°C

Fig. 30

TABLE III

TWO-FIN HEAT PIPE RADIATOR PARAMETERS
FOR 2.0, 8.0 and 11.0 GHz ESFK's

Power dissipation	4000 watts
Operating temperature	500°C
Number of pipes	36
Fluid	Liquid potassium
Diameter of pipe	1.0 cm (.400")
Length of pipe	47 cm (18.5")
Wall thickness	.05 cm (.020")
Material	304 Stainless Steel
Surface emissivity	0.8
Probability of no puncture (each pipe)	0.985
Collector diameter	7.6 cm (3.0")
Weight of radiator	2.18 kg (4.8 lbs)
Overall dimensions	
Length	18 cm (7.1")
Width	77.5 cm (30.5")

TABLE IV
TWO-FIN HEAT PIPE RADIATOR PARAMETERS
FOR 850 MHz ESRF

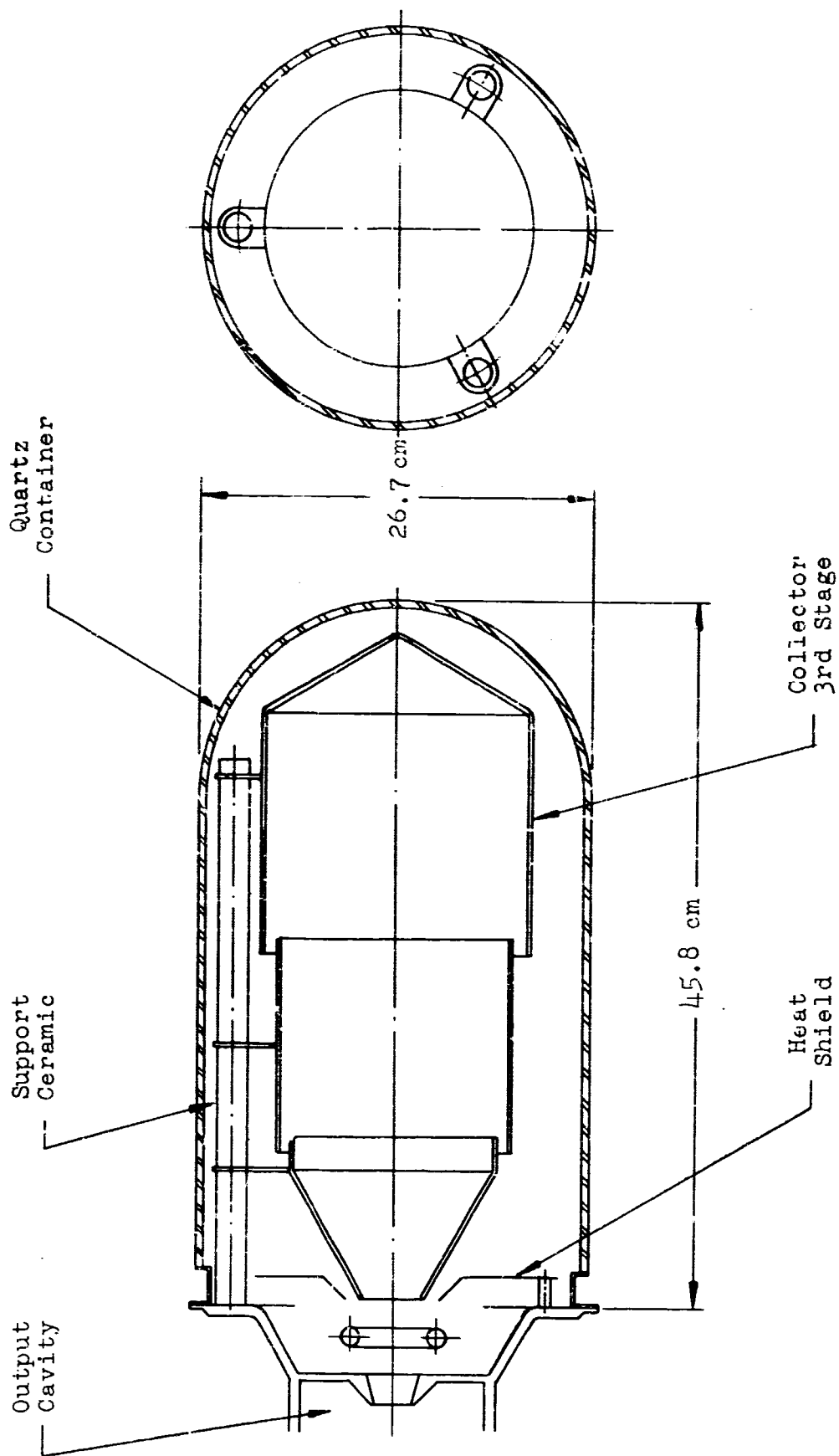
Power dissipation	6000 watts
Operating temperature	500°C
Number of pipes	76
Fluid	Liquid potassium
Diameter of pipe	1.0 cm (.400")
Length of pipe	47 cm (18.5")
Wall thickness	.05 cm (.020")
Material	304 Stainless Steel
Surface emissivity	0.8
Probability of no puncture (each pipe)	0.985
Collector diameter	14 cm (5.5")
Weight of radiator	4.54 kg (10.0 lbs)
Overall dimensions	
Length	38 cm (15")
Width	64 cm (25.2")

3.1.3 Direct Radiation Cooled Collector

The possibility of using a collector which radiates directly to space, as illustrated in Fig. 31, rather than a heat-pipe cooled collector was investigated. Such a collector must utilize a high melting point material with good strength properties and a high emissivity. These characteristics are found in the refractory metals.

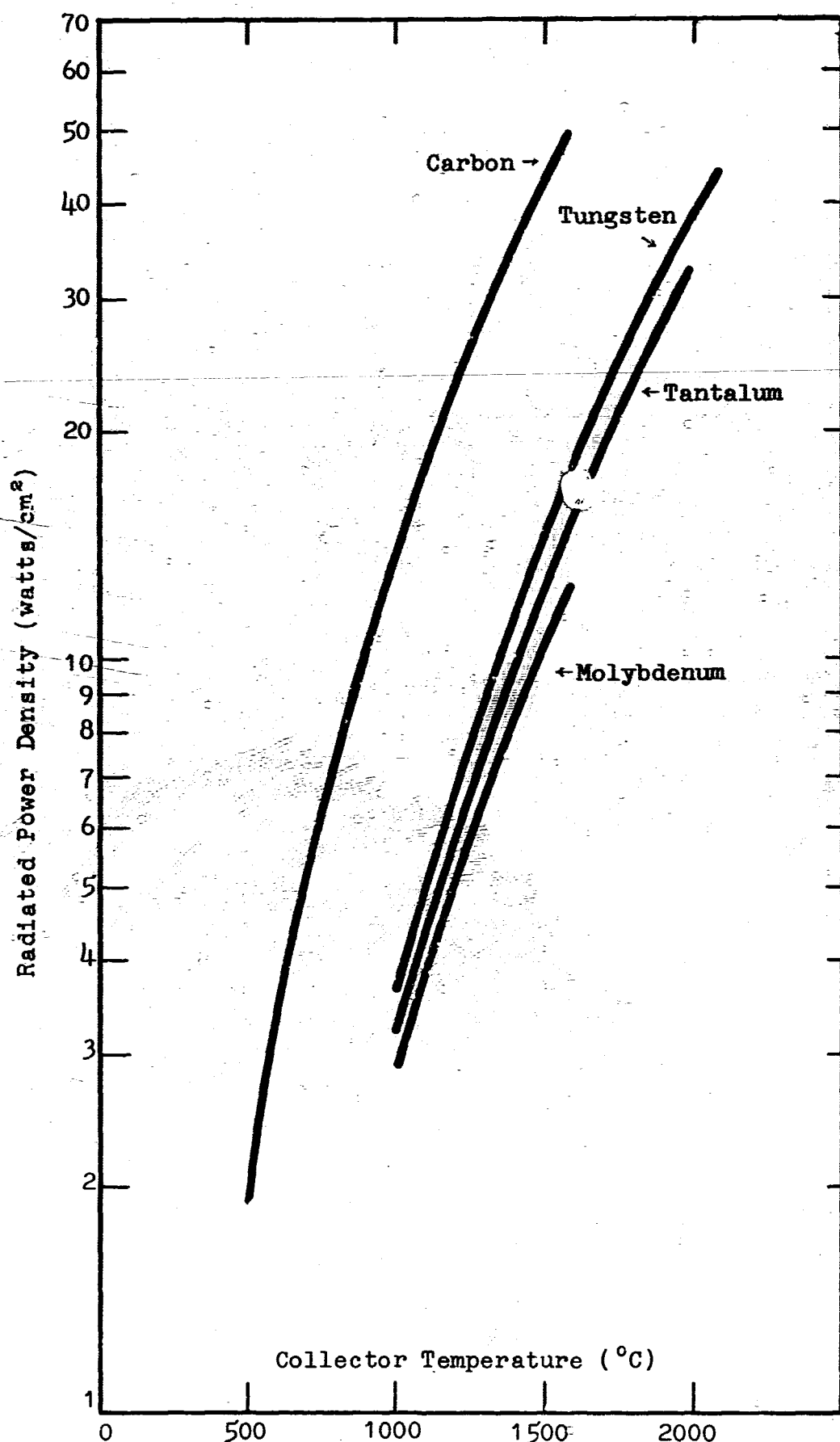
Figure 32 shows the radiated power density (watts/cm²) vs temperature for a direct radiation collector using carbon, tungsten, tantalum and molybdenum as collector materials. Titanium is an interesting material because of its low secondary electron emission coefficient; however, its relatively low melting point of 1800°C is undesirable. The power density on the collector surfaces will vary with rf drive and some hot spots may be unavoidable. It appears that only high melting point materials should be considered for direct radiation collectors, at least until some experimental insight has been established.

Tungsten has been selected as a collector material for this investigation because its characteristics are well documented. Certainly other materials may prove to be equally, or possibly more, suitable. Figure 33 shows the evaporation rate and the electron emission characteristics of tungsten vs temperature. These parameters determine the practical operating temperature of a direct radiation collector rather than the melting point of the material. Primary electron emission is particularly important in the case of a multi-stage depressed collector since an emitted electron will be accelerated through one or more electric fields between the stages. The electron will very probably find its way back down the klystron drift tube and cause reduced efficiency



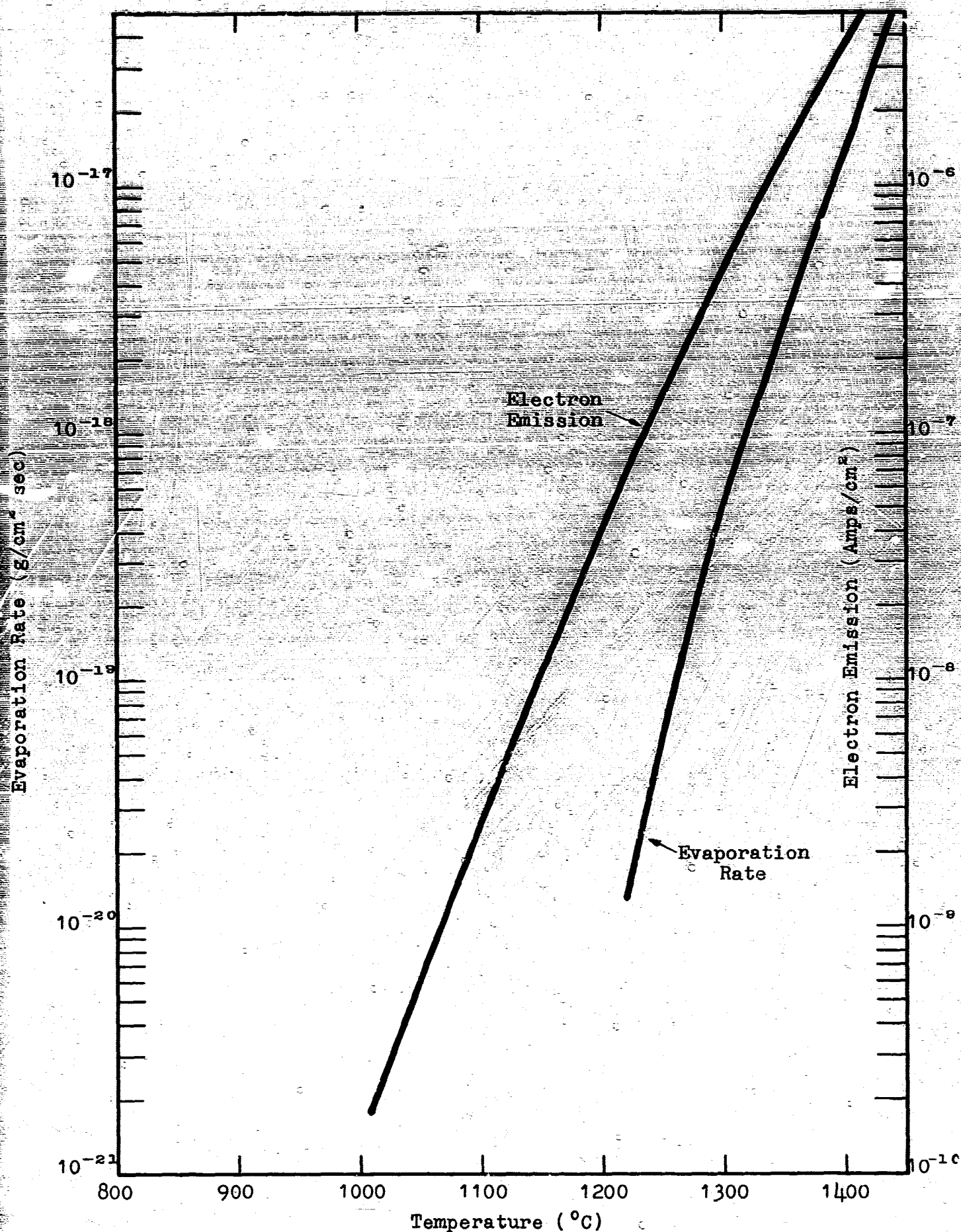
DIRECT RADIATION COOLED COLLECTOR

Fig. 31



POWER DENSITY VS OPERATING TEMPERATURE FOR A RADIATION COOLED COLLECTOR WITH COLLECTOR MATERIAL AS A PARAMETER

Fig. 32



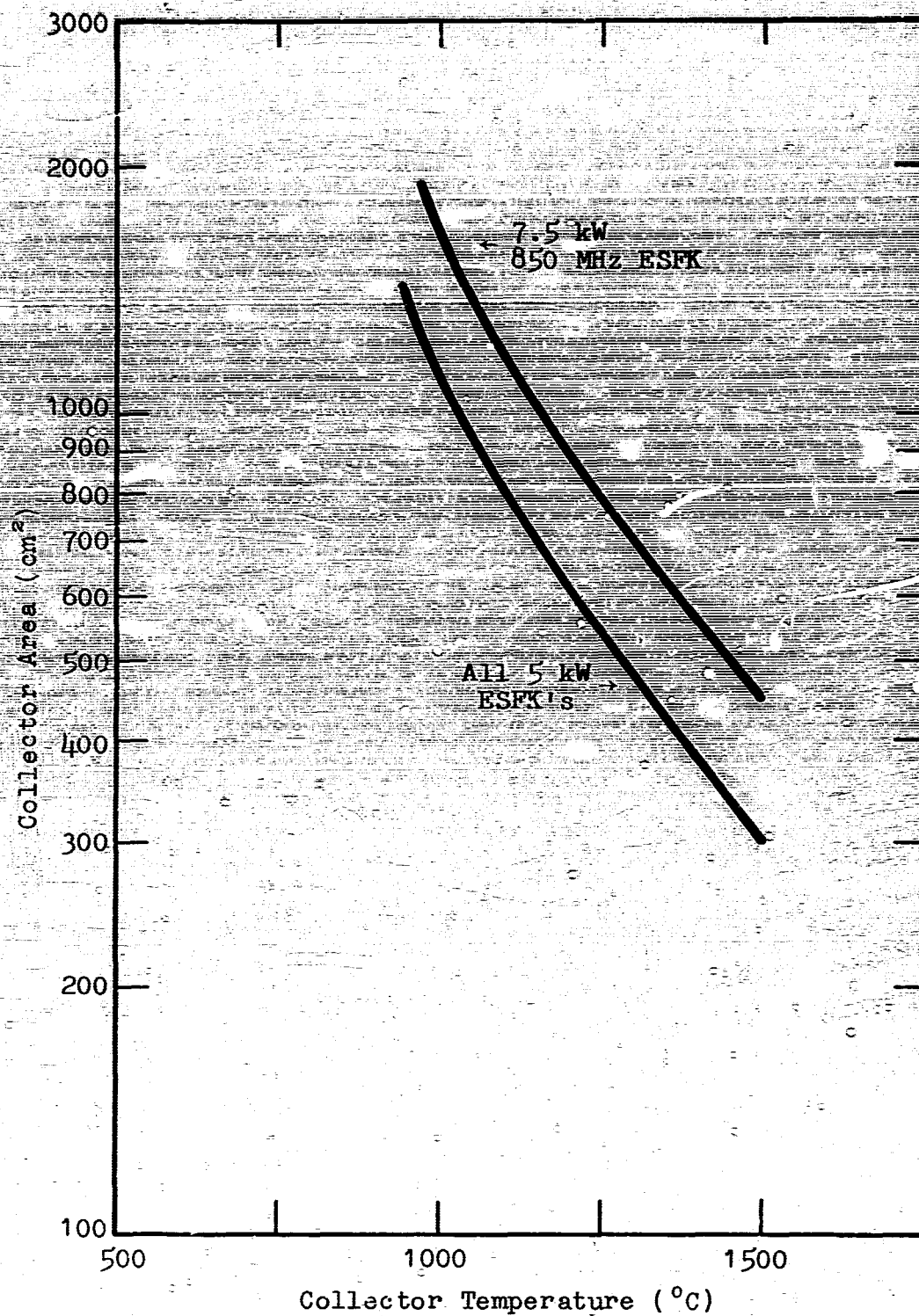
EVAPORATION RATE AND ELECTRON EMISSION OF TUNGSTEN VS TEMPERATURE

Fig. 33

or oscillation. Electron emission is still detrimental to efficiency even if the electron does not find its way back to the drift cube. Any acceleration received by the electron represents a loss in energy in the depressed collector.

Examination of Fig. 33 shows the electron emission reaches 1.0 microampere per cm^2 at approximately 1330°C . This is about as high an emission as could be tolerated for a collector which has a surface area approaching 1000 cm^2 . Equally important from a practical standpoint is the evaporation rate of tungsten as a function of temperature. Evaporation causes the deposition of tungsten on the ceramic insulators which electrically isolate the collector segments. Even though the insulators are carefully designed with grooves and shadowed areas, a high evaporation rate does present a reliability problem for a 20,000 hour mission. It appears that direct radiation collectors should not be designed to operate at temperatures in excess of 1300°C for high reliability and efficiency. Figure 34 shows the collector area required vs temperature for the ESFK's under investigation.

The direct radiation collector presents new problems to the tube manufacturer and to the user if there is no vacuum envelope. The manufacturer must exhaust, bake out, process and test the tube in a special vacuum chamber which also must act as a heat sink for the radiation cooled collector. Such a chamber is certainly feasible but will require development. After testing is completed, the user's problems begin. The tube would be shipped in an evacuated canister to maintain cleanliness. This canister must be removed prior to installation of the tube in the satellite. At this time the tube will become contaminated, by high power tube standards, and will so remain until it is placed in



COLLECTOR AREA VS TEMPERATURE FOR A TUNGSTEN
RADIATION COOLED COLLECTOR

Fig. 34

space. At this time a "space cathode conversion and vacuum processing procedure" must take place. For this procedure to be carried out, the heater power and beam power supplies should be variable and programmable. In other words, it becomes impractical to open the tube to air prior to launch.

As an alternate procedure, it would be possible to utilize a vacuum tight "window" structure around the collector during processing, testing and shipping. The heat could be radiated through a sapphire or quartz window which forms a part of the vacuum envelope while the tube is in a terrestrial environment. After the tube is in space, the window could be jettisoned and the tube could be operated in the space vacuum. The window should be removed to prevent evaporation deposits from building up on its surface and reducing its transmission properties.

The following conclusions can be drawn concerning the direct radiation cooled collector as compared to the heat pipe cooled collector:

- a. The direct radiation collector is probably less expensive to fabricate (depends on cost of large quartz or sapphire windows).
- b. The direct radiation collector is smaller in size and may be lighter weight.* (For 5 kW ESFK's approximately 26.7 cm diameter by 45.8 cm long structure weighing 4.6 kg.)
- c. There is no micrometeoroid puncture problem.

*This statement must be qualified because the quartz window weight may exceed that of the heat pipe cooled collector.

- d. The necessarily "flimsy" support structure of the direct radiation collector poses potential shock and vibration problems.
- e. The returned electron problem is much greater with the direct radiation collector.
- f. The reliability of a direct radiation collector operating at 1000°C to 1300°C is considered to be less than that of a multi-heat-pipe cooled collector operating at $\sim 500^{\circ}\text{C}$ because of the material evaporation problem (see Fig. 33).

It is Litton's recommendation that the two-fin heat pipe cooled collector be used for the ESEK's under consideration, rather than a direct radiation cooled collector, because of its higher reliability.

3.1.4 Body Cooling

Cooling of the body section of the electrostatically focused klystrons will be by conduction to the mounting deck which will serve as a heat sink. The ESEK body sections which operate at a potential higher than ground will conduct their excess heat through a beryllia (BeO) ceramic insulator to the mounting deck. The ESEK's are so designed that the output cavity section, where most of the body heat will be generated due to rf losses, operates at ground potential and may be bolted directly to the mounting deck for maximum heat transfer.

The 8.0 GHz and 11.0 GHz tubes have special heat transfer problems in their output cavities because of their small dimensions. The use of a heat pipe, with water or an organic liquid as the working fluid, was considered for improving the

heat transfer from the output cavity to the mounting surface. Heat transfer calculations indicated the output cavity gap temperature would not exceed 300°C with two percent beam power interception and the rf losses present. This temperature is not unreasonable and does not justify the added complication of incorporating a heat pipe in this area.

3.2 ELECTROSTATICALLY FOCUSED KLYSTRON STRUCTURE DESIGNS

3.2.1 Common Design Features

All five electrostatically focused klystron designs include the following common features:

- a. Pierce type electron guns
- b. Doubly reentrant buncher cavities
- c. Double-gap extended interaction output cavity
- d. Voltage jump in penultimate lens
- e. Heat sink body cooling
- f. Two-fin heat pipe radiator for collector cooling
- g. Three-stage conventional depressed collector
- h. All metal-ceramic construction
- i. Heat choke between body and collector

All klystrons have been designed to operate in a space environment and to survive the shock and vibration of the launch. Only low vapor pressure materials such as copper, molybdenum, stainless steel and ceramics (no organics) will be used in the klystron structures. These materials are not sensitive to the radiation environment of space.

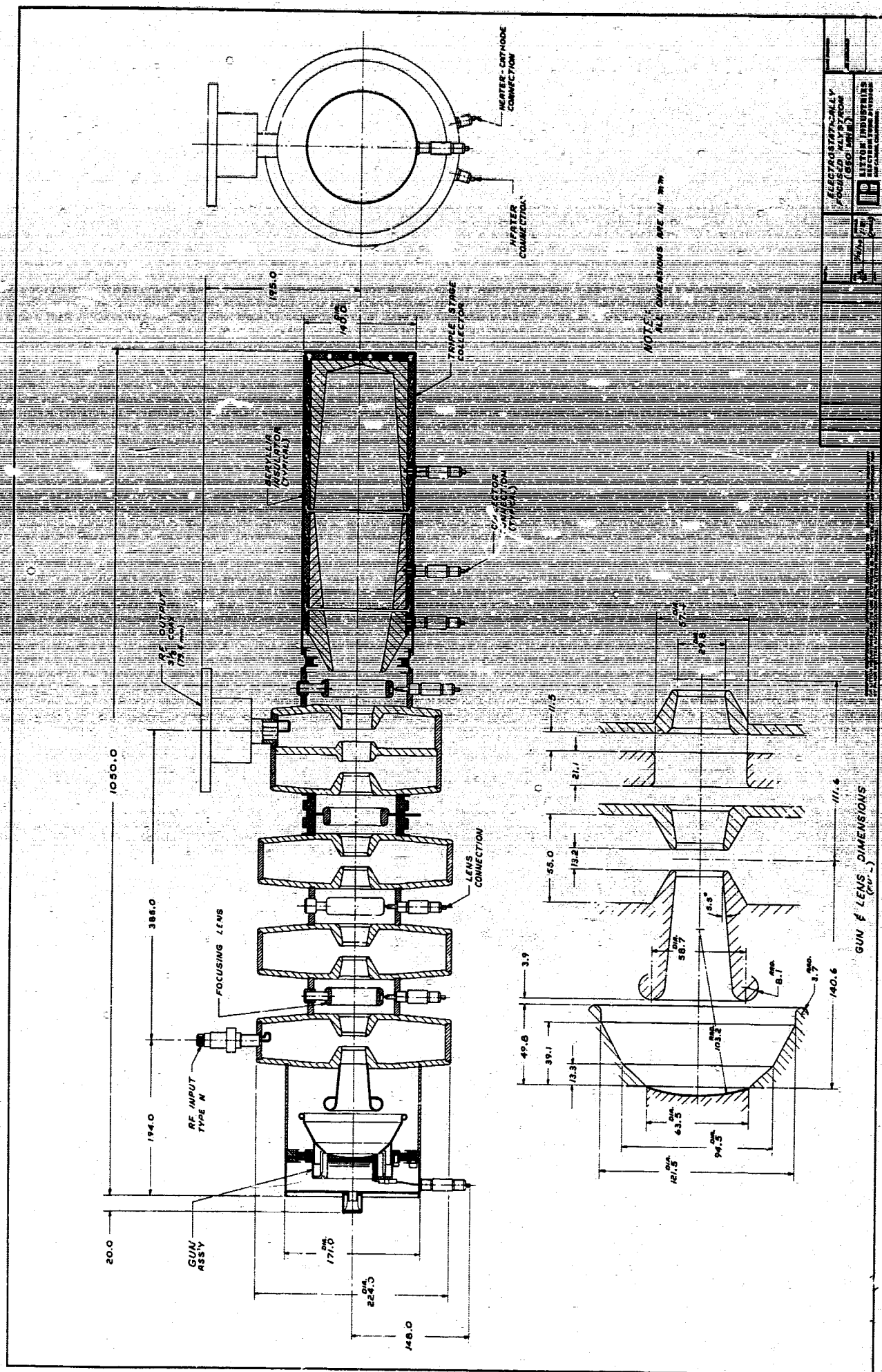
Body brazes will be made with gold-copper alloys (no silver) which will permit the high temperature bakeout ($\sim 650^{\circ}\text{C}$) which has been employed by Litton for years to produce long lifetime microwave tubes. Nickel-molybdenum alloy brazes (1320°C) will be employed to braze the molybdenum collector segments to the beryllia (BeO) ceramic insulators in the collector. It is advisable to eliminate all copper from the collector since its internal operating temperature will be about 550°C . The vapor pressure of copper becomes marginal for high reliability tubes at this temperature.

Cold test cavities were constructed and measured in order to accurately determine the ESFK cavity dimensions.

The heat pipe fins of the heat exchanger system, shown in Fig. 24, are demountable and would be bolted to the ESFK collector after the bakeout. This technique permits the klystron to be baked in a normal size oven and also permits the heat pipes to be sealed-off and tested prior to installation.

3.2.2 850 MHz ESFK

Figure 35 shows the layout of the 850 MHz ESFK. The body structure is made from molybdenum for high strength and minimum weight. Molybdenum also has excellent thermal conductivity and a low expansion coefficient which are desirable properties. The inside surfaces of the unloaded resonators will be copper plated to minimize rf losses. Three alumina (Al_2O_3) ceramic rods are used to support the focusing lenses. Lens voltage is applied through a feed-through insulator. This is a standard ESFK lens design used by Litton in several other klystrons. The penultimate lens assembly is different since it must serve as an insulator for the voltage jump between the buncher cavity section and the output cavity.



	ELECTRONICALLY FOCUSING (ESF) GUN
LITHIUM INDUSTRIES, INC. 10000 W. 10TH AVE. DENVER, CO. 80202	FIG. 35

A heat choke insulator is provided between the collector and the body section of the ESFK to minimize the conduction of heat from the collector. The collector assembly is made by brazing molybdenum collector segments to BeO ceramic insulators which are, in turn, brazed inside a molybdenum housing. Nickel-moly eutectic brazing material with a melting point of 1320°C will be used to eliminate copper from this assembly. Beryllia and moly have very similar expansion coefficients which make such a brazed assembly possible. The beryllia ceramic insulators are stepped in order to lengthen the voltage breakdown path along their edges.

RF input and output connectors are coaxial type N and 3-1/8 inch (7.94 cm) rigid line, respectively.

All critical dimensions are given on the layout drawing (Fig. 35) for the electron gun, cavities and focusing lens system.

3.2.3 2.0 GHz ESFK's

Two ESFK designs are required at 2.0 GHz. The AM klystron is a four-cavity device while the FM klystron is a five-cavity device. Figure 36 shows the five-cavity FM klystron and lists dimensions for both devices. Structurally, this ESFK is very similar to the 850 MHz klystron described in Section 3.2.2.

The rf input is a type TNC coaxial connector and the output is a WR(430) rectangular waveguide.

3.2.4 8.0 GHz ESFK

The mechanical design of the 8.0 GHz ESFK differs considerably from the previously described klystrons, as Fig. 37 indicates. The smaller physical size of the resonators and the reduced spacing between resonators necessitated a departure from the design concepts employed in the lower frequency klystrons.

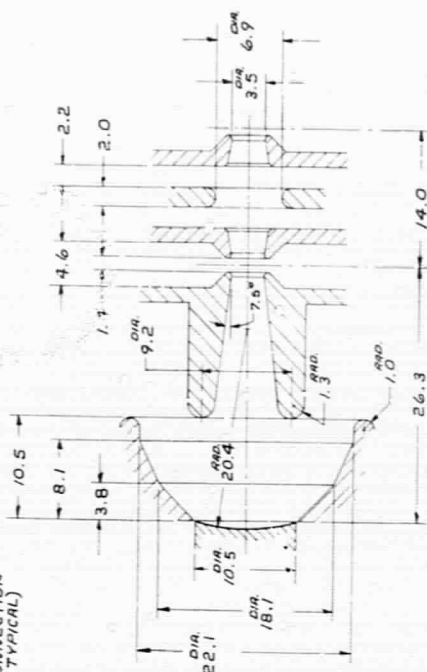
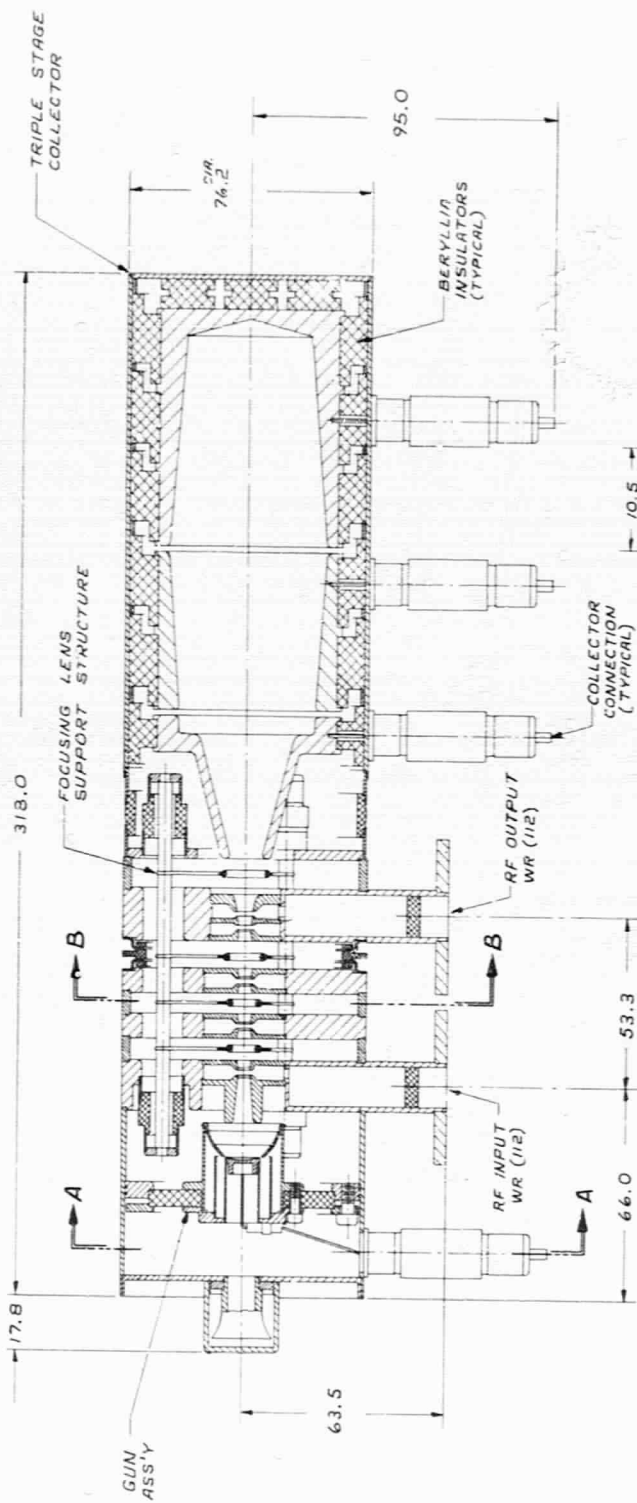
All focusing lenses are supported by three internal rods as shown in Section B-B of Fig. 37. This technique eliminates the need for feedthrough insulators in the space between cavities which would be difficult to fabricate in the allowable space and would have unreliably high voltage gradients. Since the lenses are designed to operate at cathode potential, they will be tied to the cathode lead inside the vacuum envelope.

Thermal analyses of this structure indicates that molybdenum cannot be used for the cavity top and bottom walls because it does not have a sufficiently high thermal conductivity. Copper will be used for these portions of the klystron.

RF input and output connections are made by means of WR(112) rectangular waveguide.

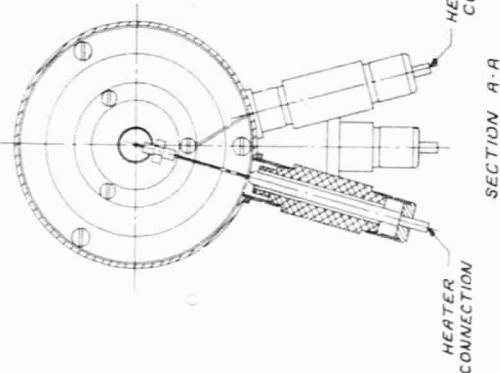
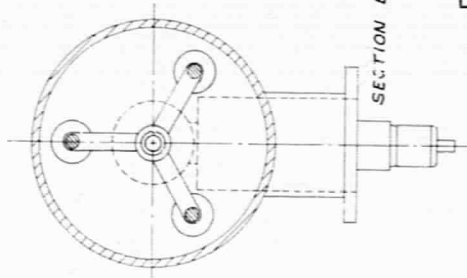
3.2.5 11.0 GHz ESFK

The mechanical design of the 11.0 GHz ESFK, shown in Fig. 38, is essentially identical to that of the 8.0 GHz ESFK. RF input and output connections are provided by means of WR(90) rectangular waveguides.



GUN & LENS DIMENSIONS (3x)

NOTE: ALL DIMENSIONS ARE IN mm



DATE PRINTED		SEE ASSEMBLY	
ELECTROSTATICALLY FOCUSED KLYSTRON (B GHz)		LITTON INDUSTRIES ELECTRON TUBE DIVISION SAN CARLOS, CALIFORNIA	
SCALE		FULL (3x)	
1/2" = 1"		1/4" = 1"	

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4.0 SUMMARY OF ELECTROSTATICALLY FOCUSED KLYSTRON PERFORMANCE CHARACTERISTICS

4.1 ELECTRICAL PERFORMANCE

A summary of ESFK performance characteristics is presented in Table V along with the power supply requirements. The reader is referred to the technical requirements for the ESFK's given in Appendix I and to the power supply connection diagram shown in Fig. 4 of this report.

Table V shows that the output power, gain, bandwidth, linear dynamic range, deviation of small signal gain from linearity, signal-to-noise ratio, and phase requirements of the contract (Appendix I) can be met with the electrostatically focused klystron. Computer calculations, using the Litton multicavity klystron program, indicate the phase linearity and deviation from linearity specifications can be met; however, this program cannot take into account the effects of the voltage jump or the extended interaction output cavity conductance.

The overall efficiency given in Table V for each ESFK was calculated by dividing the saturated output power by the total input power. The total input power is the sum of the heater power, output power, rf power loss in the output circuit and unrecovered beam power. The rf power dissipated in the output circuit was determined from the circuit efficiency which is dependent upon the loaded Q of the output resonator. Unrecovered beam power is that power dissipated in the depressed collector plus power lost in the body due to beam interception. The amount of collector depression, which determines the unrecovered power in the collector, was estimated from the velocity and current distribution in the spent electron beam. Collector voltages were specified in such a manner

TABLE V

ESFK PERFORMANCE CHARACTERISTICS

Frequency	MHz	850	2000	2000	8000	11,000
Modulation		VSB-AM	VSB-AM	FM	FM	FM
Peak synch power	kW	7.5	5.0	-	-	-
Peak picture power	kW	3.5	2.3	-	-	-
Average picture power	kW	2.6-3.0	1.75-2.0	-	-	-
Min. picture power	kW	1.3	0.9	-	-	-
Sound power	kW	0.75	0.5	-	-	-
Saturated output power	kW	-	-	5.0	5.0	5.0
Gain (min.)	dB	40	40	40	40	40
3 dB bandwidth (min.)	MHz	6	6	30	30	30
Linear dynamic range (min.)	dB	20	20	-	-	-
Deviation of S.S. gain from linearity, 3 dB below saturation (max.)	dB	0.5	0.5	-	-	-
Signal to noise ratio	dB	78	75	62	69	68
Phase linearity and deviation from linearity over BW (max.)	$\Delta\phi(\omega)$ degrees	1.2	1.2	-	-	-
$\frac{\delta^2\phi(\omega)}{\delta\omega^2}$	deg/(MHz) ²	-	-	0.05	0.05	0.05
Expected overall saturated efficiency % (with conventional depressed collector)		71.5	69.5	69.5	68.0	65.0
Expected overall average*efficiency % (with conventional depressed collector)		26.7	26.0	69.5	68.0	65.0

*Based on average picture power of .32 peak synch.

TABLE V (Cont.)

Frequency Modulation	MHz	850 VSB-AM	2000 VSB-AM	2000 FM	8000 FM	11,000 FM
<u>Power Supply Requirements</u>						
Beam supply						
Voltage	kV	14.3	14.3	14.3	14.3	18.0
Current	A	.32	.2	.2	.2	.2
Bias supply						
Voltage	kV	5.7	5.7	5.7	5.7	7.0
Current	A	.05	.05	.05	.05	.05
Collector Supply #1						
Voltage	kV	4.0 $\pm$ 1	3.5 $\pm$ 1	3.5 $\pm$ 1	4.0 $\pm$ 1	4.5 $\pm$ 1
Current	A	1.13	1.13	1.13	.89	.85
Collector Supply #2						
Voltage	kV	2.5 $\pm$ 1	2.5 $\pm$ 1	2.5 $\pm$ 1	3.0 $\pm$ 1	3.0 $\pm$ 1
Current	A	0.7	0.5	0.5	0.4	.3
Collector Supply #3						
Voltage	kV	4.5 $\pm$.5	2.0 $\pm$ 1	2.0 $\pm$ 1	2.5 $\pm$ 1	2.5 $\pm$ 1
Current	A	0.3	0.2	0.2	0.1	0.1
DC heater supply						
Voltage	V	12.6	12.6	12.6	6.3	6.3
Current	A	12	3.2	3.2	3.0	2.3

that they would be greater than the lowest voltage electron in the spent beam (i.e. no returned electrons).

The power supply requirements listed in Table 7 are the best estimates possible until experimental results are obtained. Once experimental tubes have been tested it will be possible to relax the adjustability requirements for the collector supplies from ± 1000 volts to ± 200 volts. Some tube-to-tube variations are inescapable and variable collector voltages will always be required in order to obtain optimum efficiency.

All high voltage supplies should have a regulation of ± 1.0 percent and a ripple not exceeding ± 0.1 percent in order to minimize spurious amplitude and phase modulation of the signal being amplified. The heater voltage supply should have a regulation of ± 3.0 percent and a ripple not exceeding ± 5 percent.

A new type of transverse-field depressed collector for ESFK's was conceived late in this study program which promises to drastically improve the efficiency. A description of this collector was given in Section 2.4. The most important application of the transverse-field depressed collector is in the amplitude modulated ESFK's where the efficiency is unacceptable with a conventional depressed collector. Table VI lists the expected ESFK efficiencies using the two collector types. The transverse-field collector efficiencies were computed in a manner similar to that described for the conventional collector except for the larger degree of depression. The transverse-field collector was assumed to have five segments biased to collect electrons at voltages ranging from the slowest electrons to the dc potential electrons. Estimates of the electron velocity and current distribution were made to determine

TABLE VI
ESFK EFFICIENCY COMPARISONS

Frequency	MHz	850	2000	2000	8000	11,000
Modulation		VSB-AM	VSB-AM	FM	FM	FM
Expected overall average* efficiency:						
Conventional collector	%	26.7	26.0	69.5	68.0	65.0
Transverse-field collector	%	81.0	77.5	79.0	77.5	74.0

*Based on average picture power of .32 peak synch.

the amount of power dissipated in each collector segment. No claims of high accuracy can be made for these calculations because a computer analysis of the electron motion in this collector has yet to be made.

4.2 MECHANICAL PERFORMANCE

The electrostatically focused klystrons have all been designed to operate in the environment of space and to survive the shock, vibration and acceleration of the launch (ref. Appendix I). The ESFK's were designed to be cooled by conduction and radiation to space. Details of their cooling systems were discussed in Section 3.1. A summary of the sizes and weights of the klystrons and their heat radiators is given in Table VII.

It should be observed that the ESFK lends itself well to a high packaging density, such as that of a satellite, since it has no stray magnetic fields to affect other components. The space normally occupied by solenoids or permanent magnets, on magnetically focused devices, is available for use by other components.

4.3 OPERATING SEQUENCE

All of the electrostatically focused klystrons will operate in an identical manner. There will be no further operation after acceptance testing has been performed until the satellite has been placed into orbit. The operating sequence will then be as follows:

- a. Apply rated heater voltage (some surge current limitation may be required).
- b. After a five-minute warmup time, apply collector voltage, bias voltage and beam voltage either in this order or simultaneously.

TABLE VII
ESFK SIZE AND WEIGHT SUMMARY

Frequency	MHz	850	2000	2000	8000	11,000
Modulation		VSB-AM	VSB-AM	FM	FM	FM
Total length	cm	107.0	49.5	54.3	33.6	32.8
	in	42.2	19.5	21.4	13.2	12.9
Max. ESFK radius	cm	19.5	17.5	17.5	9.5	9.5
	in	7.7	6.9	6.9	3.7	3.7
Radiator width	cm	64.0	77.5	77.5	77.5	77.5
	in	25.2	30.5	30.5	30.5	30.5
ESFK weight	kg	52.2	11.1	12.0	5.46	5.0
	lbs	115.0	24.5	26.5	12.0	11.0
Radiator weight	kg	4.54	2.18	2.18	2.18	2.18
	lbs	10.0	4.8	4.8	4.8	4.8
Total weight	kg	56.7	13.3	14.2	7.6	7.2
	lbs	125.0	29.3	31.3	16.8	15.8

c. Apply rf drive power.

The shutdown sequence should be the exact reverse of the startup procedure.

All power supplies should contain protective circuits to remove all high voltage in the event of an arc or the loss of voltage. For instance, the loss of collector voltage could result in destruction of the klystron due to excess power dissipation in the collector.

5.0 RECOMMENDED VERIFYING EXPERIMENTS

5.1 GENERAL REQUIREMENTS

As a result of the analytical study program to develop the design of space borne electrostatically focused klystron amplifiers, new design concepts have been originated which require verification. Of greatest concern are those concepts which relate to the attainment of high efficiency. Specifically, these are voltage jumping, extended interaction output resonators and collector depression. The most potentially promising new concept is the transverse-field depressed collector which not only permits higher collector efficiency but also affords a solution to the problem of obtaining high efficiency with amplitude modulated carriers.

The area of electron beam collector cooling by means of heat pipe radiators must also be experimentally verified. Fabrication techniques need to be developed and life testing must be performed.

5.2 DESCRIPTION OF VERIFYING EXPERIMENTS

The recommended verifying experiments are listed below in a decreasing order of importance.

5.2.1 Transverse-Field Depressed Collector Investigation

The purpose of this investigation is to experimentally verify electrostatically focused klystron efficiency enhancement by the use of a transverse-field depressed collector which was described in Section 2.4. It is recommended that this investigation be pursued in two phases. Phase I should be an analytical study of the collector design using an all digital electron optics computer program which allows the

use of a transverse magnetic field. Phase II should be an experimental verification of the collector using an existing ESFK, which has been modified to incorporate magnetic shielding, to provide the modulated electron beam.

Phase I should employ a transverse-field electron optics computer program, similar to a recently developed, proprietary, Litton program, to calculate the spent electron beam trajectories. This program permits a variable field strength, transverse magnetic field to be specified along with arbitrary electrode shapes and potentials. Up to 27 electron rays may be specified to enter the collector region with any specified axial or radial velocity. The current density across the beam may also be specified. A five-point method is used by the program to solve Poisson's equation throughout the collector space by successive iterations until convergence is obtained. Electron trajectories are computed and plotted by a Cal-Comp plotter. A Lagrangian formulation is used by this program.

Calculations should be made to determine the effect on the electron motions due to all forces present which include space charge, the electric fields associated with the collector segments and the transverse magnetic field. Various collector segment shapes and potential distributions should be examined along with variations in the entering beam velocity and current distributions.

At the conclusion of Phase I it will be possible to construct a transverse-field depressed collector suitable for experimental evaluation.

Phase II should consist of experimental verification of the most promising transverse-field depressed collector design produced in Phase I. For reasons of economy it is recommended that an existing ESFK such as the Litton L-5101 (1 kW CW, 2.3

GHz) be modified by incorporating a magnetically shielded body and a transverse-field depressed collector. Tests should be conducted to determine the collector voltage distribution required for optimum efficiency at various rf drive levels and magnetic field strengths. The rf signal should be amplitude modulated and the AM efficiency improvement should be determined. Knowledge gained from this investigation will enable the design of transverse-field depressed collectors for space borne ESFK's.

5.2.2 Investigation of Voltage Jumps in Electrostatically Focused Klystrons

The purpose of this investigation is to experimentally verify efficiency enhancement by voltage jumping in electrostatically focused klystrons (see Subsection 2.2.2). Voltage jumping has been shown to be an effective means for enhancing efficiency in a magnetically focused klystron; however, voltage jumping has never been done in electrostatically focused klystrons. It is recommended that an existing ESFK be modified by incorporating a voltage jump in the focusing lens cell between the penultimate and output cavities. The proper lens configuration should be determined by an electron optics computer program.

Tests should be conducted to determine the optimum value of the voltage jump for maximum efficiency. Knowledge gained from this investigation will aid in the design of high efficiency ESFK's for space borne applications.

5.2.3 Investigation of Heat Pipe Radiator Cooling of Electron Beam Collectors

The purpose of this investigation is to experimentally verify the practicality of cooling electron beam collectors by means of heat pipe radiators. It is recommended that an existing electron gun be employed to provide heating of a suitable collector structure. The power input to the collector should be variable from zero to 4000 watts, depending on the applied cathode voltage. The heat pipe radiator should be composed of 1 cm diameter stainless steel tubes with stainless steel mesh wicks as described in Subsection 3.1.2. The heat pipes should be charged with potassium under vacuum and the open ends should be sealed by electron beam welding.

Tests should be conducted to determine the transient behavior of the heat pipes during turn-on as well as their steady-state operation. Various oxide coatings should be evaluated for increasing the surface emissivity of the radiator.

It is recommended that most of the testing and possible life testing be conducted at NASA Lewis Research Center because of the availability of large vacuum chambers with cold walls.

6.0 CONCLUSIONS

This study program has shown that the overall efficiency of electrostatically focused klystron amplifiers can be greatly enhanced over the present state of the art. Specific improvements in the design of ESFK's include the use of low perveance electron beams, voltage jumps, extended interaction output resonators and multistage depressed collectors. The problem of obtaining high efficiency amplification of AM carriers was examined and it was concluded that grid modulation schemes were impractical for ESFK's and would degrade system performance and reliability. A transverse-field depressed collector was conceptually devised which promises a potential solution to the AM efficiency problem by recovering a very large portion of the unused beam power at all modulation levels.

The critical area of heat transfer in space borne klystrons was studied. It was concluded that a two-fin liquid potassium filled heat pipe radiator, operating at approximately 500°C, resulted in the optimum heat exchanger design from the viewpoint of minimum size and weight and maximum reliability. This design utilizes many individual heat pipes for high reliability in a micrometeoroid environment. It has also concluded that adequate body cooling could be provided for the klystrons by direct conduction to their mounting deck.

Complete electrical and mechanical designs were made for ESFK's at 0.85, 2.0, 8.0 and 11.0 GHz, which incorporate the results of the efficiency enhancement and thermal studies. Conventional, three-stage, depressed collectors are incorporated in these designs because they were made prior to the conception of the transverse-field depressed collector.

These designs are an extension of proven design and construction practices which have demonstrated high reliability in the past. Operating lifetimes in excess of two years can be expected from these klystrons.

Verifying experiments have been recommended for certain critical areas of the space borne electrostatically focused klystron design. These experiments should be conducted prior to a full scale ESFK development program.

In summary, the electrostatically focused klystrons designed for TV satellite application as part of this study program offer the advantages of high overall efficiency, light weight and small size. The performance requirements can be met by the use of only one amplifier and no filters.

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8.0 ABSTRACT

ANALYTICAL STUDY PROGRAM TO DEVELOP THE THEORETICAL DESIGN OF SPACE BORNE ELECTROSTATICALLY FOCUSED KLYSTRON AMPLIFIERS

by

W. R. Day and T. H. Luchsinger

ABSTRACT

The design of high efficiency electrostatically focused klystrons was studied with primary emphasis on efficiency enhancement and heat transfer in a space environment. Voltage jumps, extended interaction resonators, low perveance electron beams and multistage depressed collectors were found to enhance ESFK efficiency. A transverse-field depressed collector was conceived which promises to permit high efficiency amplification of both AM and FM signals. Liquid potassium heat pipe radiators operating at 500°C were designed for collector cooling.

Electrical and mechanical designs were made for ESFK's intended for TV satellite applications at 0.85, 2.0, 8.0 and 11.0 GHz.

APPENDIX I

EXHIBIT "A"

CONTRACT #NAS3-11515

EXHIBIT "A"

1.0 SCOPE OF WORK

The Contractor shall perform the following tasks:

- 1.1 Conduct an analytical study program to develop the theoretical design of space borne electrostatically focused klystron amplifiers which satisfy the requirements of paragraph 2.0 and 4.0.
- 1.2 Identify critical design areas.
- 1.3 Define and recommend suitable tests and experiments required to verify the critical design parameters of the tubes.
- 1.4 Present to the Government the results of the preliminary studies three (3) months after the award of the contract for review and narrowing down the possible alternatives. The presentation shall be implemented as specified in paragraph 5.0.
- 1.5 Furnish Monthly Progress Reports in accordance with the clause "Reports of Work".
- 1.6 Furnish a Final Technical Report in accordance with the clause "Reports of Work". In the Final Technical Report, the critical design areas shall be identified and suitable tests and experiments shall be defined and recommended to verify the critical design parameters of the tubes in accordance with the requirements of paragraph 3.0.

2.0 DESIGN

Each design shall be the result of trade off analyses and engineering evaluations which shall include but not necessarily be limited to the following parameters.

2.1 Parameters

- 2.1.1 Efficiency
- 2.1.2 Gain, bandwidth, S/N, Phase linearity
- 2.1.3 Life

- 2.1.4 Power supply requirements
- 2.1.5 Mechanical design, including structures and materials
- 2.1.6 Thermal design and tube cooling, including components and structures
- 2.1.7 Vacuum environment, gravitational environment and background temperature
- 2.1.8 Operation, if any, and conditioning of the tube prior to the launch and in ultimate orbit

2.2 Trade off and Design Criteria

The design tasks shall be based on the following technical criteria:

- 2.2.1 Expected life of 2 years or more.
- 2.2.2 Maximum overall efficiency, including power supply's and driver stages' efficiencies.
- 2.2.3 Available driver power: 1 watt.
- 2.2.4 Minimum weight, including focusing, driver stages, filters, if any.
- 2.2.5 The estimated time of launch is 1975. The factor relating weight and efficiency shall be 100 lb/kW.

Two (2) spacecraft configurations as shown in figures 1 and 2 shall be used as a basis for the integration of the tube with the satellite structure.

2.3 Design Results

The results of the design analysis shall include, but not necessarily be limited to the following:

- 2.3.1 Electronic tube design and analysis of tube performance.
- 2.3.2 Mechanical tube design, materials and analysis of performance (behavior).
- 2.3.3 Thermal design and analysis of thermal behavior.

- 2.3.4 Sequence of tube operation, including start up and shut down.
- 2.3.5 Description of operation during pre-launch, launch and orbital phases.
- 2.3.6 Development schedule and costs.

3.0 VERIFYING EXPERIMENTS

Based on the results obtained in paragraph 2.0 the Contractor shall define and propose experiments which are sufficient to demonstrate the electronic performance and the mechanical and thermal characteristics of the klystron amplifiers predicted therein.

The description of such experiments shall include but not necessarily be limited to the following:

- 3.1 Required tube and all associated components.
- 3.2 Required power supply and driver stage(s).
- 3.3 Development cost.
- 3.4 Development schedule.
- 3.5 Test objectives and test instrumentation.

4.0 TECHNICAL REQUIREMENTS AND OPERATIONAL CONDITIONS

The klystron amplifiers shall possess the following operational and environmental characteristics.

4.1 Electrical Operational Characteristics

4.1.1 Power Output

- 4.1.1.1 The power output under vestigial sideband modulation only shall be:

Frequency	850 MHz - AM	2 GHz - AM
Peak Synch. Power	7.5 kW	5.0 kW
Peak Picture Power	3.5 kW	2.3 kW
Average Picture Power	2.6 - 3.0 kW	1.75 - 2.0 kW
Minimum Picture Power	1.3 kW	.9 kW
Sound Power	.75 kW	.5 kW

4.1.1.2 The power output under FM modulation shall be:

Frequency	Power
2 GHz	5 kW
8 GHz	5 kW
11 GHz	5 kW

4.1.3 Modulation Type

<u>Frequency</u>	<u>Modulation Type</u>
850 MHz	AM Vestigial Sideband Only
2 GHz	AM Vestigial Sideband FM
8 GHz	FM only
11 GHz	FM only

4.1.4 Linear dynamic range for AM: 20 dB, min.

4.1.5 Deviation of small signal gain from linearity,
3 dB below saturation (for AM only) 0.5 dB, max.

- 4.1.6 Signal to noise ratio, S/N, over bandwidth for
 AM: 42 dB, min.
 55 dB, desirable

and 32 dB min. or 45 dB desirable for FM.

- 4.1.7 Phase linearity and phase deviation from linearity.

AM System: Deviation $\Delta\phi(\omega)$ from linear phase
 anywhere over bandwidth, 1.2° max.

FM System: $\frac{\delta^2\phi(\omega)}{\delta\omega^2} =$ - $0.05^\circ/(\text{MHz})^2$ max.
 - $0.015^\circ/(\text{MHz})^2$ desired

- 4.1.8 Bandwidth; 3 dB points: 6 MHz for all AM-VSB
 applications and 30 MHz for all FM applications.

- 4.1.9 Tube Efficiency

The term, "tube efficiency" is defined as the ratio

$$\eta = \frac{P_{\text{rf out}}}{P_{\text{DC}} + P_{\text{F}} + P_{\text{in}}}$$

where P_{rf} , P_{DC} , P_{F} , and P_{in} represent rf power
 output, (all in kW), DC power input and focusing
 power, if any, and rf power input.

- 4.1.10 Gain of the amplifier or amplifier chain: 40 dB min.

- 4.1.11 Input and Output VSWR: 1.05 max., into a 50 ohm
 impedance.

4.2 Mechanical and Thermal Tube Characteristics

4.2.1 Vibration

<u>Sinusoidal</u>		<u>Random Density</u>	<u>RMS Accel.</u>
<u>Frequency</u> (cps)	<u>Peak</u> <u>Amplitude</u>		
20-400	5.0 g	0.082 g^2/cps	5.4
400-3000	15.0 g	0.15 g^2/cps	17.9

4.2.2 Shock, 8 m sec duration, 30 g min.

4.2.3 Thermal System

4.2.3.1 The thermal system for the AM applications shall be designed to handle the thermal loading corresponding to steady state rf output power from minimum picture power, plus sound power, to peak picture power plus the sound power. These are 2.05 kW to 3.25 kW for 850 MHz and 1.4 kW to 2.8 kW for 2 GHz.

4.2.3.2 The thermal system for the FM application shall be designed to handle thermal loading corresponding to 5 kW CW of rf power output.

4.2.3.3 Tube cooling method: Radiation into space.

4.2.4 Tube Weight

Tube weight is defined as the total weight of: Tube, focusing structure, filters, if any, preamplifiers required for power amplification from 0 dBw to 40 dBw, couplers and other passive or active components required for tube operation but not including power supplies and power conditioning.

4.3 Tube Life

Tube life, 20,000 hours min.

The definition of tube life is the time in hours after which the tube ceases to operate entirely, or fails to be restarted, or when the power output decays to 90% of the nominal value or when the tube no longer satisfies one of the operational characteristics listed in 4.1.4 to 4.1.10.

4.4 Environmental Characteristics and Conditions for Tube Operation

4.4.1 Satellite's altitude (synchronous orbit) - 19,300 N.M.

4.4.2 Orbital plane = equatorial plane

4.4.3 Relative orientation of satellite components:
Antenna - toward earth, solar array - toward sun.
It may be assumed for the purpose of this study
that heat rejection (radiation) over a solid angle
of less than 2π in certain directions may be con-
sidered as unobstructed radiation into a background
at a very low absolute temperature. (See also
figures 1a, 1b, 2a, and 2b.)

4.4.4 Gravitational Environment: Less than 5×10^{-7} g

4.4.5 Background Vacuum: Less than 10^{-12} torr

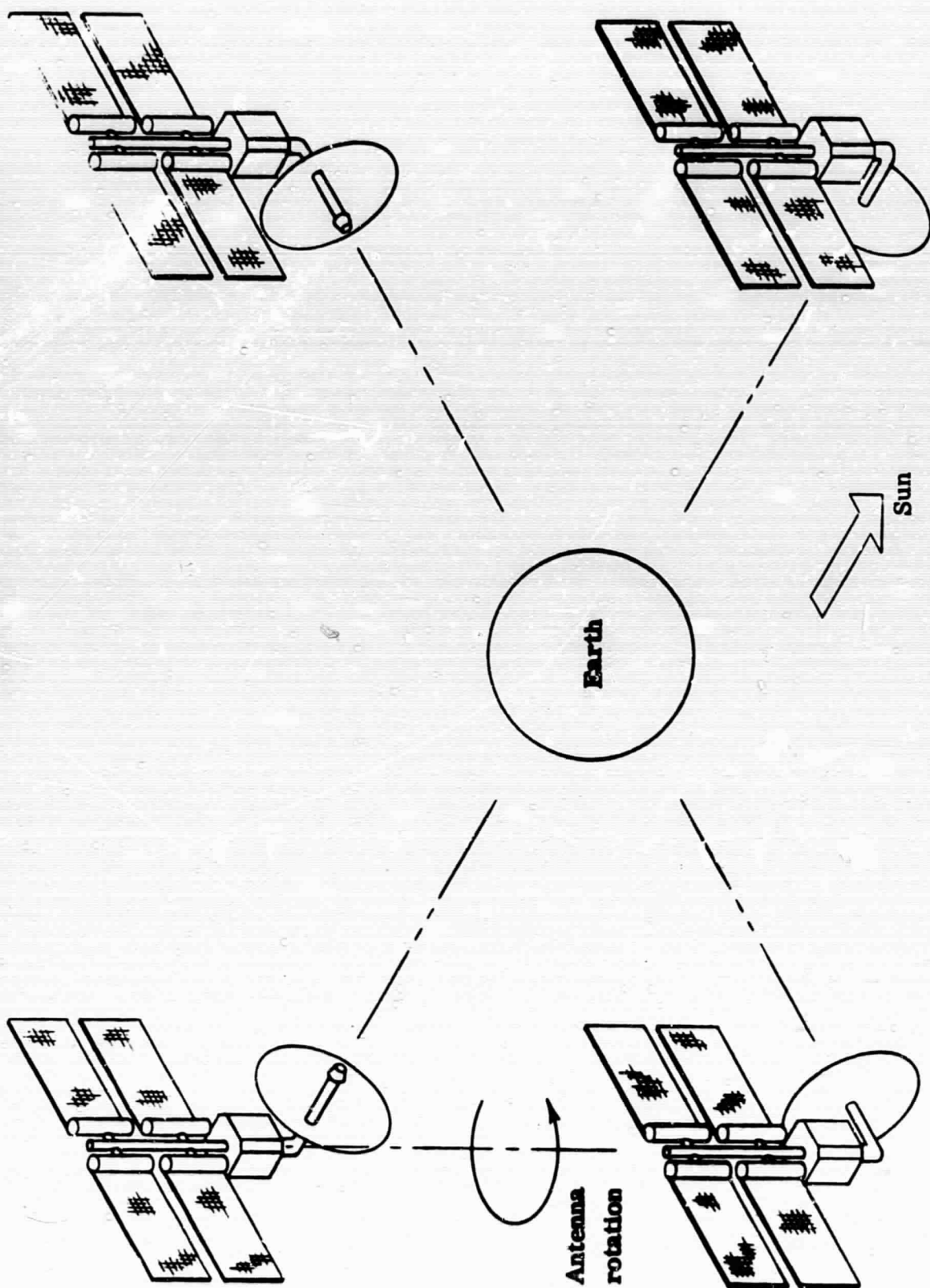
4.5 Operation in Space

4.5.1 Mode of Operation: Minimum 22.5 hours per 24 hours
Maximum 24 hours per 24 hours

4.5.2 Maximum restarting required: Once in 24 hours within
less than 5 minutes fol-
lowing a command signal.

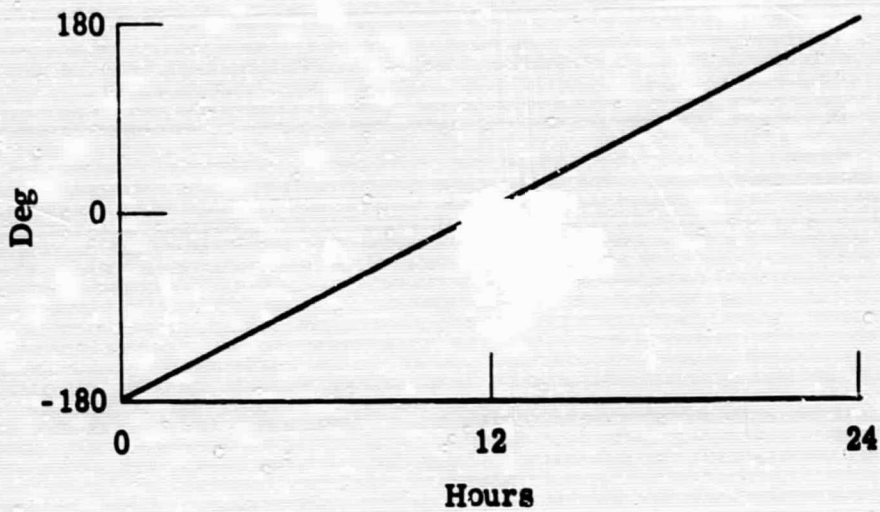
4.5.3 Number of restarts in life time: 180 min.

Figure 1a

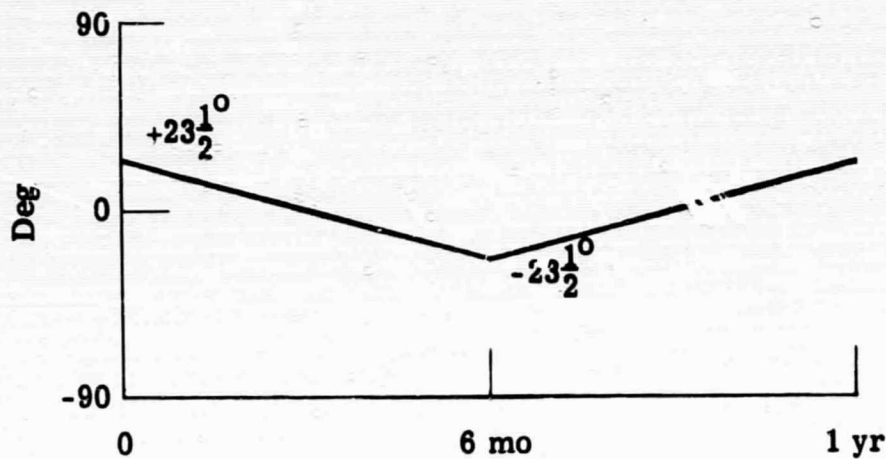


S/C and Array Motion I

Figure 1b



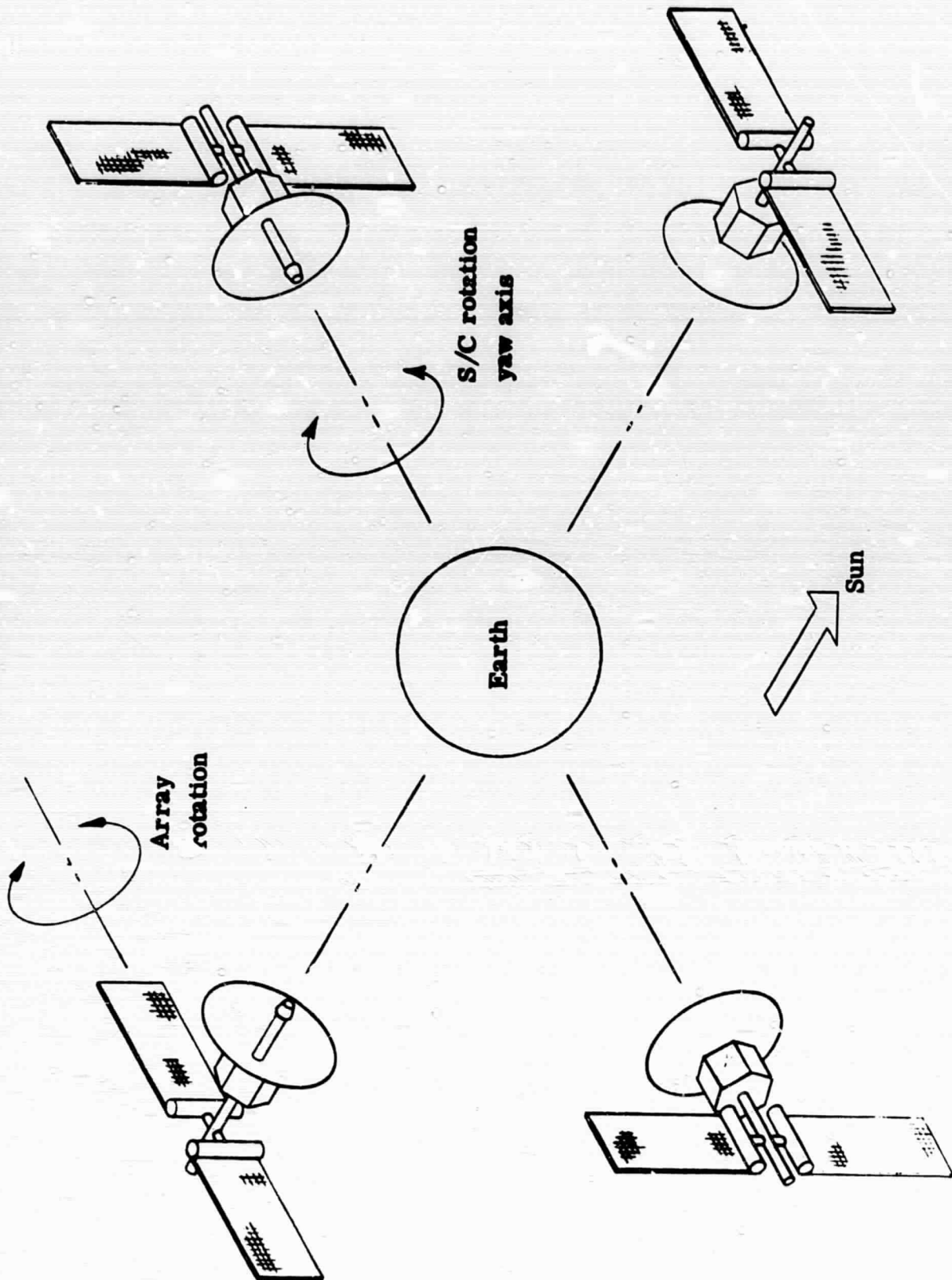
Antenna rotation
rate $\approx 15^\circ/\text{hour}$,
continuous



Solar array
rotation
Maximum rate
 $\approx 96^\circ/\text{yr}$

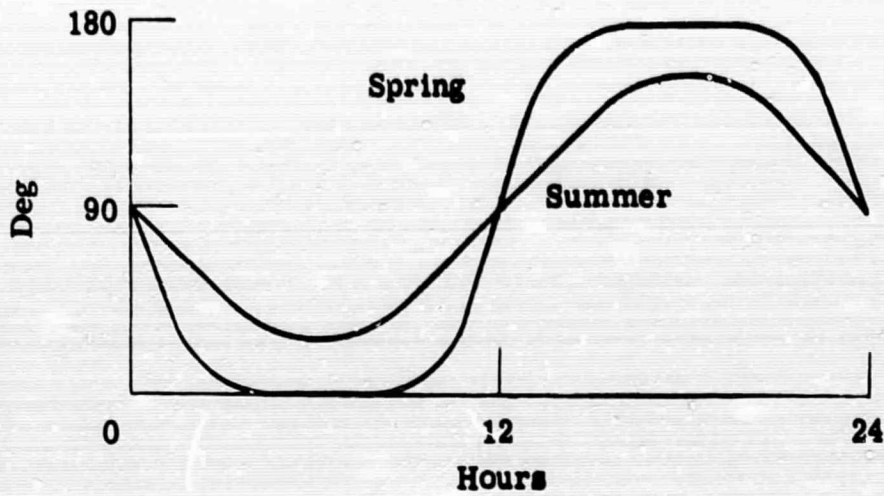
S/C and Array Motion I

Figure 2a

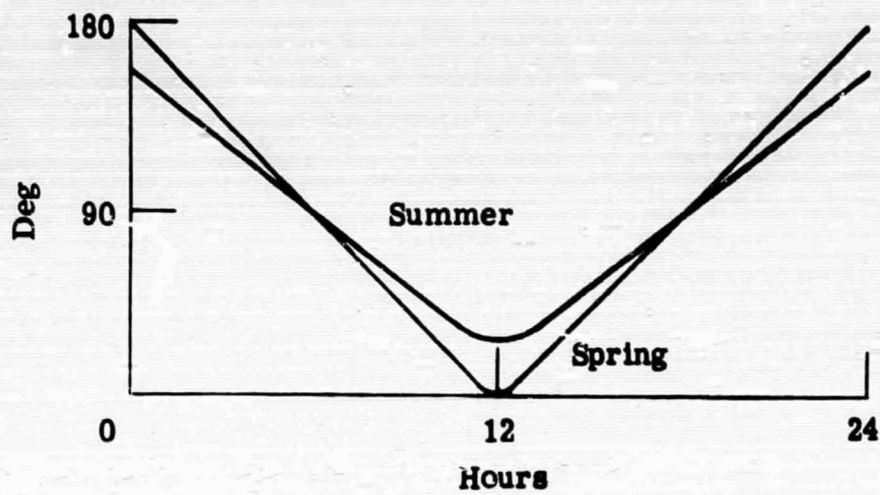


S/C and Array Motion II

Figure 2b



S/C rotation,
yaw axis max-
imum rate $\approx$
 $75^\circ/\text{hr}$



Solar array
rotation
maximum
rate $\approx 15^\circ/\text{hr}$

S/C and Array Motion II

APPENDIX II

TIME-SHARING COMPUTER PROGRAM FOR
CALCULATING TWO-CAVITY PI-MODE
RESONATOR GAP COUPLING COEFFICIENT
AND BEAM LOADING CONDUCTANCE


```

LISTNH
100 PRINT "PROGRAM FOR CALCULATING TWO-CAVITY PI-MODE RESONATOR"
105 PRINT "GAP COUPLING COEFFICIENT AND BEAM LOADING CONDUCTANCE"
106 PRINT
110 PRINT "BEAM VOLTAGE (KILØ VØLTS)"
120 INPUT V
130 PRINT "BEAM CURRENT (AMPS)"
140 INPUT I
150 PRINT "GAMMA A (RADIANs)"
160 INPUT G1
170 PRINT "GAMMA B (RADIANs)"
180 INPUT G2
190 PRINT "GAMMA D (RADIANs)"
200 INPUT G3
210 PRINT "FREQUENCY (MHZ)"
220 INPUT F
230 PRINT "GAMMA P (RADIANs)"
240 INPUT G4
300 LET U=7.38E8*SQR(V)
310 LET W=F*6.28E6
320 LET G=W/U
330 LET A=G1/G
340 LET B=G2/G
350 LET D=G3/G
360 LET P=G4/G
370 LET J=I/(20.2*B^2)
380 LET W1=((1.83E10)*J+0.5)/((1.0E3)*V)+0.25
390 LET R=1.0/(SQR(1.0+(2.0/G2)^2))
400 LET W2=W1*R
410 LET W3=W2/W
420 LET H=(.5*G2*(1.-W3)+.0625*(G2*(1.-W3))^3)^2
425 LET M1=((1+.25*(G2*(1.-W3))^2+.0156*(G2*(1.-W3))^4)^2)-H
430 LET M2=M1/(1+.25*(G1*(1.-W3))^2+.0156*(G1*(1.-W3))^4)^2
440 LET P1=(SIN(G4*(1.-W3)/2.))^2
445 LET M3=M2*P1*((SIN(G3*(1.-W3)/2.))/(G3*(1.-W3)/2.))^2
450 LET H1=(.5*G2*(1.+W3)+.0625*(G2*(1.+W3))^3)^2
455 LET M4=((1+.25*(G2*(1.+W3))^2+.0156*(G2*(1.+W3))^4)^2)-H1
460 LET M5=M4/(1+.25*(G1*(1.+W3))^2+.0156*(G1*(1.+W3))^4)^2
470 LET P2=(SIN(G4*(1.+W3)/2.))^2
475 LET M6=M5*P2*((SIN(G3*(1.+W3)/2.))/(G3*(1.+W3)/2.))^2
480 LET M=(SQR(M3)+SQR(M6))/2.
490 LET C=(0.127)*(M3-M6)/W3
500 PRINT "DRIFT TUBE RADIUS (INCHES)"
510 PRINT A
520 PRINT "BEAM RADIUS (INCHES)"
530 PRINT B
540 PRINT "CAVITY GAP SPACING (INCHES)"
550 PRINT D
560 PRINT "GAP-CENTER TO GAP-CENTER SPACING (INCHES)"
570 PRINT P
580 PRINT "NORMALIZED REDUCED PLASMA FREQUENCY (OMEGA-Q/OMEGA)"
590 PRINT W3
600 PRINT "GAP COUPLING COEFFICIENT"
610 PRINT M
620 PRINT "NORMALIZED BEAM LOADING CONDUCTANCE"
625 PRINT "(ELECTRONIC CONDUCTANCE/DC BEAM CONDUCTANCE)"
630 PRINT E
640 PRINT "NEW VALUE OF GAMMA P? YES<TYPE 1;NO,TYPE 0"
650 INPUT C
660 IF C=1 THEN 230
670 PRINT "DO YOU WISH TO CONTINUE? YES,TYPE 1;NO,TYPE 0"
680 INPUT Y
690 IF Y=1 THEN 110
700 END

```

END