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OUTPUT DEVICES

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COMMUNICATION SATELLITE
OUTPUT DEVICES

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INTRODUCTION

A COMMUNICATION SATELLITE operating at microwave frequencies is not constrained to the use of a vacuum tube for generating an output signal. Various semi-conductor devices are also available and, though they are subject to certain limitations, they offer advantages which make their use attractive in some applications. Both semiconductors and vacuum tubes have been subjected to intensive development for use in the unique environment of space-craft. As a result, semiconductors are available with improved resistance to damage by charged particle flux, and semiconductor circuits are available whose performance is less influenced by temperature variation. Similarly, extremely light weight vacuum tubes have been developed which utilize heat transfer without fluid flow.

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In general, for communication satellite operations, either type of device must have a long operating life with high reliability at the lowest possible cost in system weight. The cost in system weight in this case includes the weights of the output stage, any high level driver stages which may be necessary, the associated voltage conversion and regulation equipment and the associated prime power or energy source. The relative ability of semiconductor devices, such as tunnel diodes, transistors, and varactor diodes and vacuum tube amplifiers such as triodes, klystrons, amplitrons and TWTs to generate signal power efficiently at frequencies of 1 to 10 kMc and power levels of 0.1 to 100 watts is the primary concern of this paper.

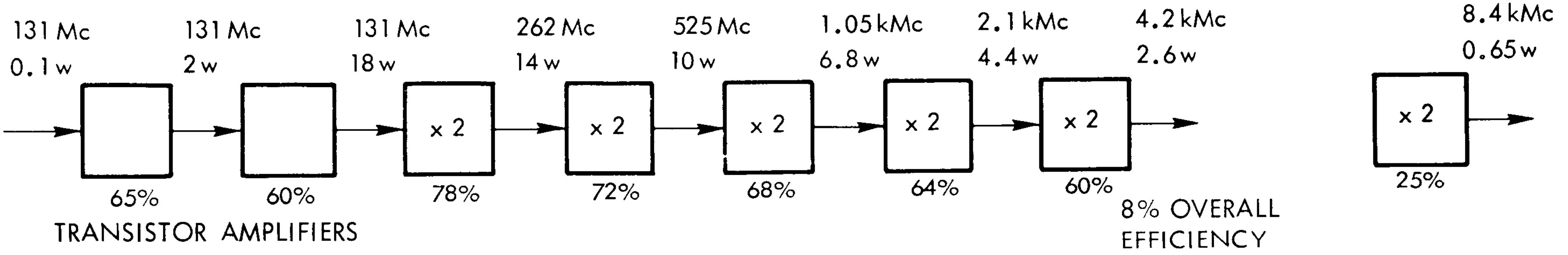
II. SEMICONDUCTORS

Semiconductor devices currently considered for output stages are the tunnel diode, the transistor and the varactor. Tunnel diodes are presently restricted to power outputs below 100 milliwatts.(1) In fact, most tunnel diode amplifiers and oscillators in the 1 to 10 kMc range have power outputs in the 0.01 mw to 20 mw range. Because of their low power, tunnel diodes are not useful as output stages for communication satellites when one or a few diodes are used, since they provide too low an information rate for the ground terminal investment.(2) To overcome this limitation, techniques for using these devices in large arrays(3,4) have been proposed, but such schemes are dependent on the development of suitable techniques for erecting and pointing arrays. The low incident signal levels at the tunnel diode result in essentially linear operation so that except for a more restricted bandwidth, large arrays of tunnel diodes would be comparable to large passive reflectors.

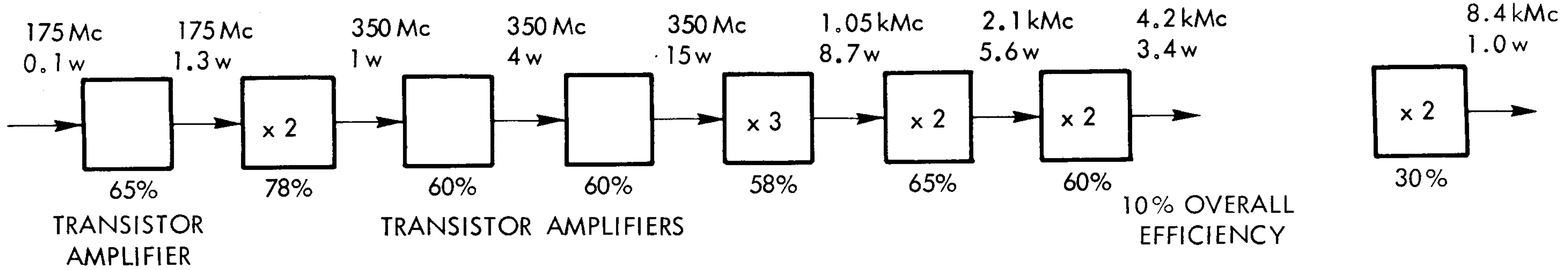
Although present transistors are able to provide about 1-2 watts at 1000 Mc in laboratory units,(5,6,7,8) only about 1 to 10 mw are available now at 4000 Mc.(8) Transistors have just begun challenging vacuum tubes at the 5 to 25 watt level in the 100 to 500 Mc range.(9,10,11) It will be years before this range is extended upward significantly, because of the difficulties of fabricating the higher-frequency power transistor. Thus the transistor is not a sufficiently high-power output device at about 4 kMc for use now as the output stage of an active communication satellite.

Continuing research can be anticipated on space arrays employing large numbers of low to intermediate power solid state devices such as tunnel diodes and transistors, in order to solve the problems of generating high power in space, of radiating large quantities of waste heat i.e., plate or collector dissipation, and of lifetime and reliability. In principle, the antenna gain possible with arrays may for some applications offer a means of avoiding the first two problems, while the high redundancy of the devices may permit solutions to the last two problems.

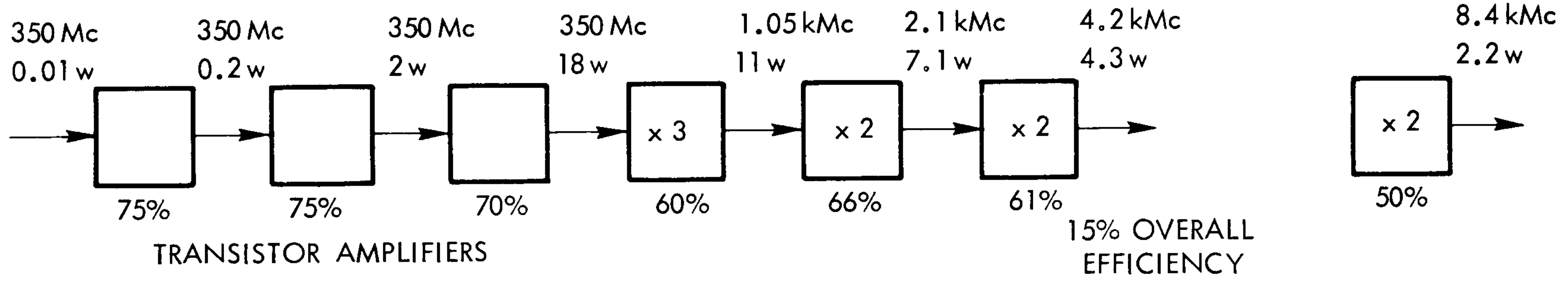
Solid-state medium-power generation today above 1 kMc utilizes varactor diodes.(8,12) One method uses varactors as frequency multipliers(12,13,14,15,16) as shown in Figs. 1a through 1c At the present, doubler circuits using single diodes can yield up to 20 watts at 1000 Mc.(17) Using devices which are now becoming available, 15 per cent overall efficiency at 4 kMc at the few watt level should be achievable.



(A) TYPICAL CURRENT TECHNOLOGY



(B) LABORATORY R & D



(C) NEAR-TERM FUTURE TECHNOLOGY

Fig. 1—Solid state multiplier chains

Figure 1c shows one method by which such improvement may be obtained. A similar gain in efficiency could be realized through greater improvements in diode efficiency or in higher-frequency transistors. Microwave amplification and parametric frequency multiplication within a single transistor(11) may eventually offer better efficiencies than the combination of a transistor and a separate varactor diode.

Another approach to solid state varactor power generation is shown in the circuit of Fig. 2--a parametric upconverter(12,13,18,19) in which the pump power is generated in a narrow-band (0.1 to 0.5 per cent) varactor multiplier chain. By virtue of the narrow bandwidth permissible for the transistor amplifier, driver, and multiplier, the pump chain offers higher efficiency than can be obtained in the broader-bandwidth circuits assumed in Figs. 1a through 1c for processing a communication signal. The increased efficiency of the chain cannot, however, fully offset the power loss of the upconverter from pump to output frequency. Typical converter efficiencies,(18,19,20) i.e., output power/pump power, are about 50 per cent for frequencies from 2 to 8 kMc. Thus there is a net loss of efficiency compared to the multiplier circuits of Fig. 1; but there is an important difference in the characteristics of the two in that the multiplier chain multiplies (i.e., expands) the signal bandwidth as well as its center frequency, while the upconverter produces a pure frequency translation. A high intermediate frequency of 200 Mc or more (the upper sideband) and filtering are desirable to facilitate rejection of the carrier and lower sideband, as well as other frequency components present in the upconverter pump signal. Although upconverter bandwidths have been limited to 0.1 to 0.2 per cent based on output frequency, 1 to 2 per cent has recently been demonstrated, without

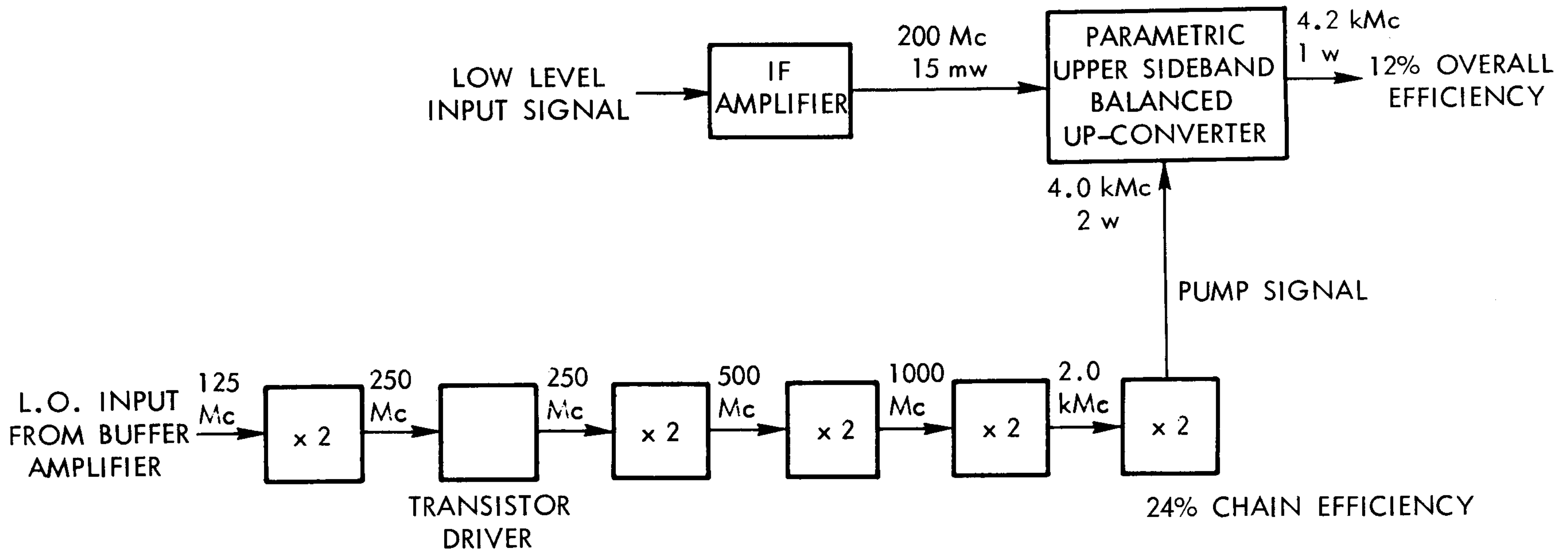


Fig. 2—Solid state up-converter circuit

sacrificing efficiency. The corresponding bandwidths based on the input signal range from 10 to 50 per cent for signals from 25 to 500 Mc.

In order to obtain the power levels and efficiencies cited in Fig. 1, a rather sophisticated technology has evolved. The proliferation of companies engaged in research and development on solid-state multipliers, and the diversity of their applications, has resulted in a dynamic technology with widely disparate achievements. The comments which follow attempt to reflect general experience in this area, but are oriented toward space applications rather than competitive volume production. Today the obstacle to achieving results comparable to those shown in Fig. 1c is not primarily due to the inability to manufacture devices capable of such performance but rather due to the limited supply of highly skilled circuit designers and of funds and time for optimizing the design. This problem may continue to exist because the market for equipment which squeezes the last drop of efficiency out of components is a limited one; for example, until the space age, the design of high efficiency microwave tubes at the 2 to 20 watt power level was essentially an academic problem.

To handle the drive powers or to obtain the efficiencies shown in Fig. 1, it is sometimes necessary to parallel varactors. This can be done in the conventional manner, or in a balanced microwave configuration with little loss in efficiency but with a doubling of the allowable power level and other advantages.(21) Operating at a lower power level per diode permits higher efficiencies to be obtained, as is evident from Figs. 3 and 4. The data in these figures are based on circuit performance at room temperature for a single stage as furnished primarily by one manufacturer,(16) but they are fairly typical. The exception in both figures

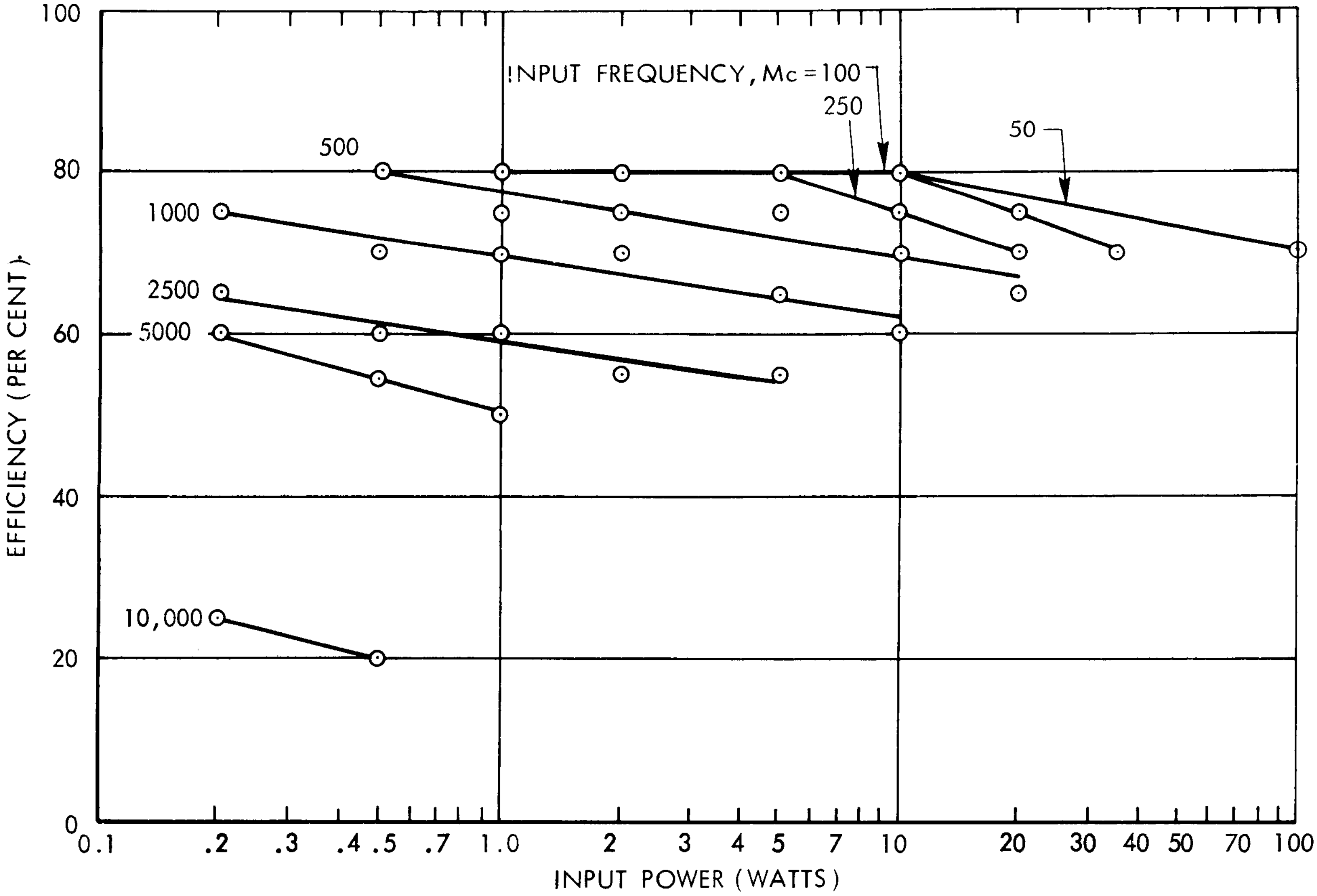


Fig. 3—Single stage doubler efficiency

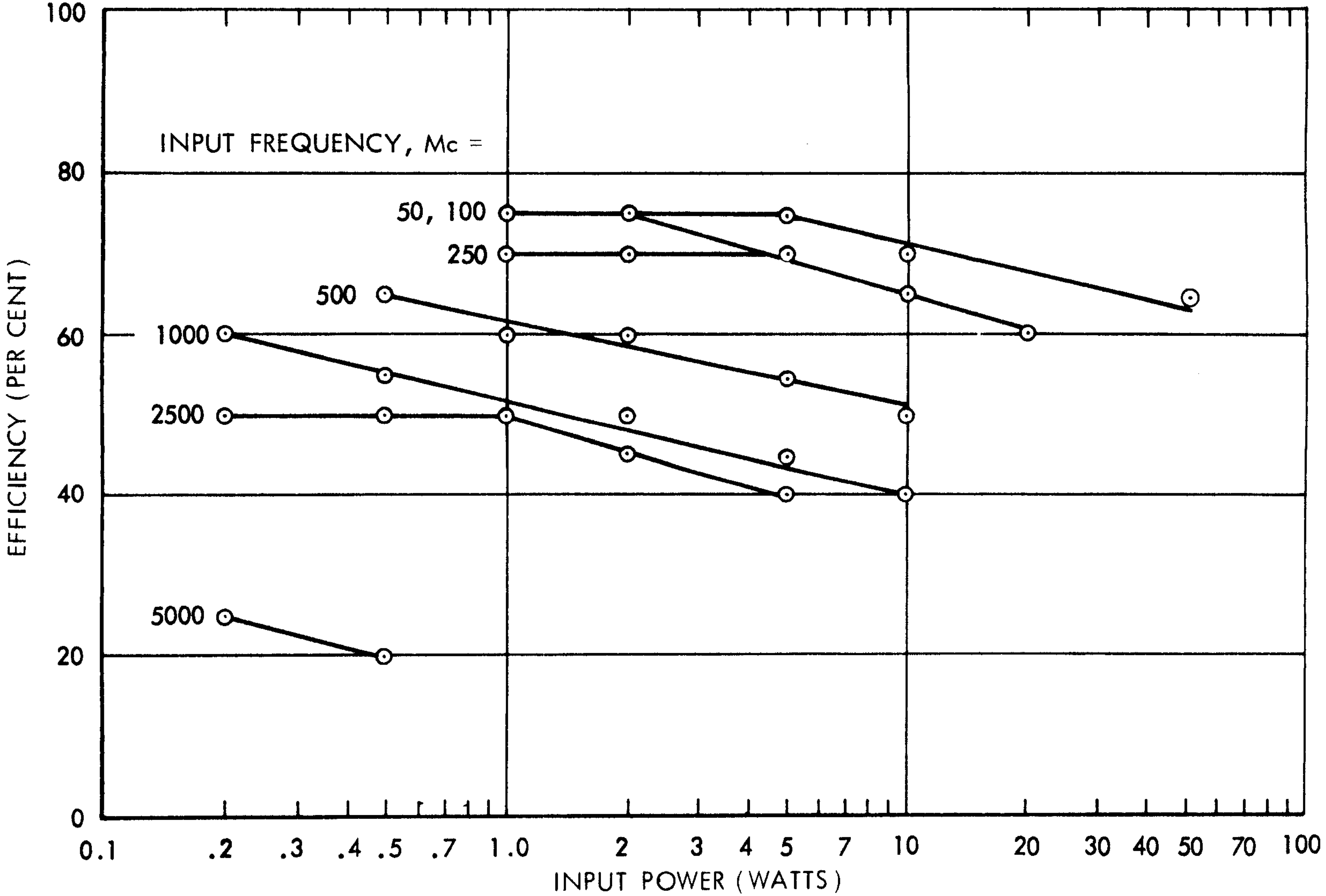


Fig.4—Single stage tripler efficiency

is the one point furthest to the right.(17,22) More recent experimentally determined efficiencies by the same manufacturer(1) are somewhat lower at the 2.5 kMc input frequency and substantially lower at 5.0 kMc input for doublers, but are substantially higher for triplers at 5.0 kMc input. Since the performance of varactor circuits as calculated from the diode parameters has not correlated precisely with measurements,(8) manufacturers have begun to characterize the devices by means of the circuit parameters of frequency and power level. It may be noted from Figs. 3 and 4 that varactor multiplier efficiency is much more sensitive to the operating frequency than to the power level.

To obtain optimum efficiency, the diode must be selected in each stage to suit the drive level.(23) For diodes emphasizing "snap-off", step-recovery or charge storage effects(15, 17, 24, 25) this restriction becomes less important. At the higher frequencies, breakdown voltage and thus allowable drive power becomes limited if the varactor is to have high Q (and thus high efficiency). Even optimally selected diodes can handle less power and are less efficient at the higher frequencies, as is evident in Figs. 3 and 4. For still higher power levels, paralleling numbers of diodes is being studied. Paralleling complete multiplier chains is possible, but results in a 1 to 2 db loss at present relative to the sum of the powers.(26) Paralleling transistors in the varactor chain driver is also possible(27) but requires careful matching of DC and RF characteristics, and results in a loss of some gain and efficiency.(28) Typical 3-db bandwidths of the complete chains in Figs. 1a through 1c are 1 to 5 per cent.

Larger bandwidths e.g. 10 to 20 per cent (27) are obtainable by trading efficiency. (1, 29)

Where bandwidth is important, doubler chains are in general preferable to chains using triplers. As far as efficiency is concerned, however, the lower efficiency of the tripler is offset by the fewer number of stages required, assuming the terminal frequencies are about the same. Thus Fig. 5 shows that for 2 watts input, the power at 400 Mc and again at 3200-3600 Mc is about the same, using typical varactor efficiencies from Figs. 3 and 4. The point is that the efficiencies arrived at in Figs. 1b and 1c are not due to any inherent advantage of triplers. The choice between doublers and triplers is made on the basis of available high-efficiency transistors providing moderate gains, and by consideration of the terminal frequency. (27) Cost of diodes and reliability favor the tripler; lower power dissipation per diode, (12) ease of design and tuning plus greater overall bandwidth (27) favor the doubler.

Cascaded multiplier stages must have more bandwidth and must be carefully matched over a larger band than will be used, to allow for bandwidth shrinkage (27) and to avoid spurious oscillations and instability. High efficiency broadband stages may require further decoupling with a subsequent loss in efficiency. (29) Interstage coupling losses may reduce overall multiplier efficiency to less than that of a single higher order stage, particularly at the lower frequencies. (1,12) The difficulties increase with the number of cascaded stages. (1)

The preceding figures are for operation at +20°C. As the ambient temperature is raised, efficiency falls. (23) Assuming that the change in diode junction capacitance is compensated for, the diode stages still

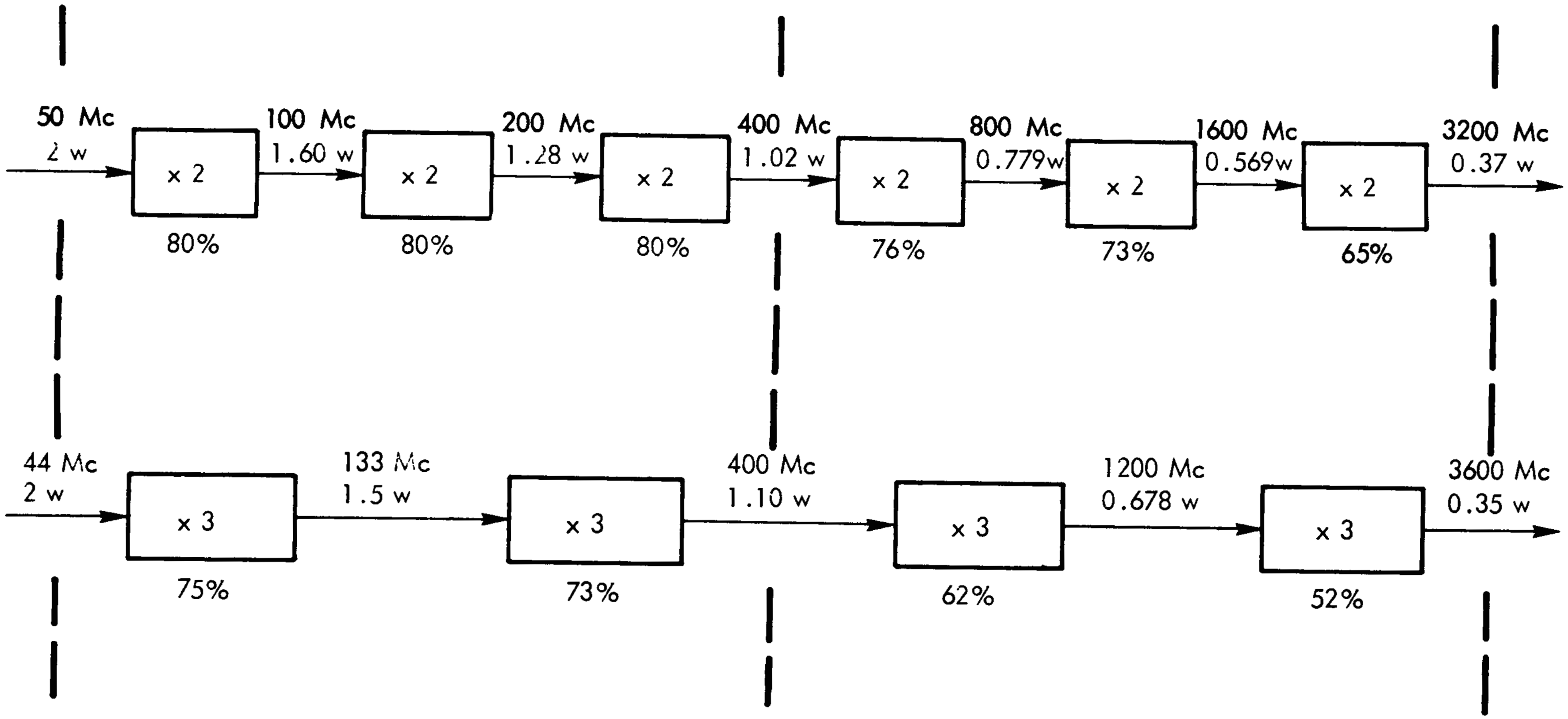


Fig.5—A comparison of doubler and tripler varactor multiplier efficiencies

degrade with increased temperature due to the series resistance. If the transistors have adequate cooling and are operated in the safe area(8) to prevent thermal instability, a typical decrease in the overall chain efficiencies of Fig. 1 would be about 25 per cent as the temperature increases from +20°C to +80°C(29,30) Some units, however, show little change.(1,23,31)

For present transistor and varactor technology, to obtain maximum power requires driving at 50 to 100 Mc and multiplying thereafter;(24) for maximum overall efficiency, however, driving should be at 350 to 500 Mc. In order to realize the drive power levels of Fig. 1 with high overall efficiency, the transistor driver may require a higher voltage than the typical 28-volt supply, e.g., 40 volts.(28,29) Where such a regulated supply is available the solid state circuitry can operate directly off the supply, thus eliminating the need for the voltage conversion equipment associated with vacuum tubes.

Using the three transistor drive levels of Fig. 1c and various combinations of doublers and triplers (from four doublers through three triplers), a set of twelve block diagrams were prepared reflecting the near-future technology of Fig. 1c. The overall driver-multiplier efficiencies of these twelve combinations are plotted in Fig. 6 as a function of output power level, and cross-plotted in Fig. 7 to emphasize the frequency dependence of efficiency.

The choice between the varactor multiplier and the upconverter approaches is made primarily on the basis of the signal characteristics and the signal processing requirements for the specific application. Although the efficiency of the upconverter approach is lower, it may approach the efficiency of the wider bandwidth varactor multiplier chain.

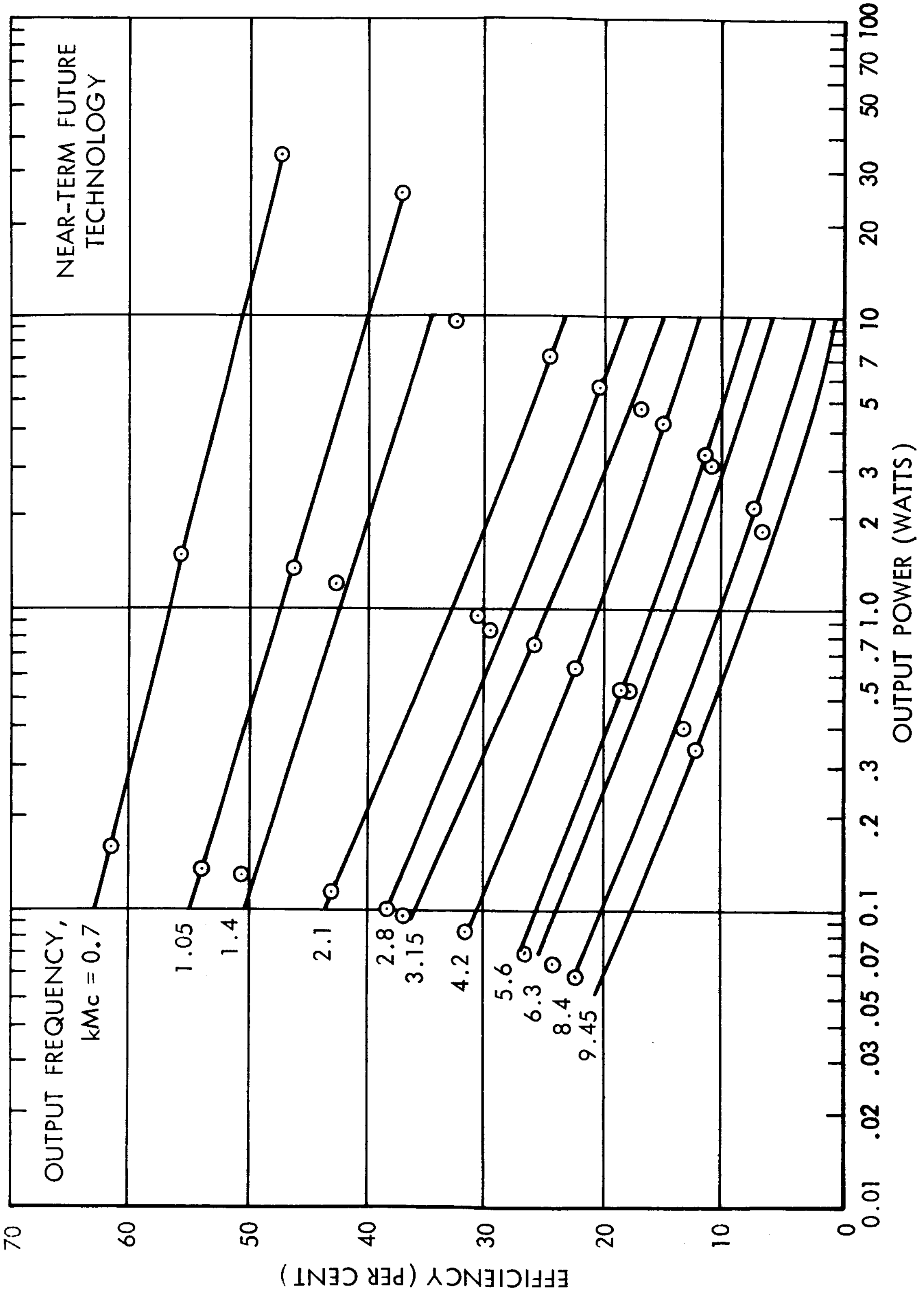


Fig.6—Calculated overall efficiency of transistor amplifier—varactor multiplier chain

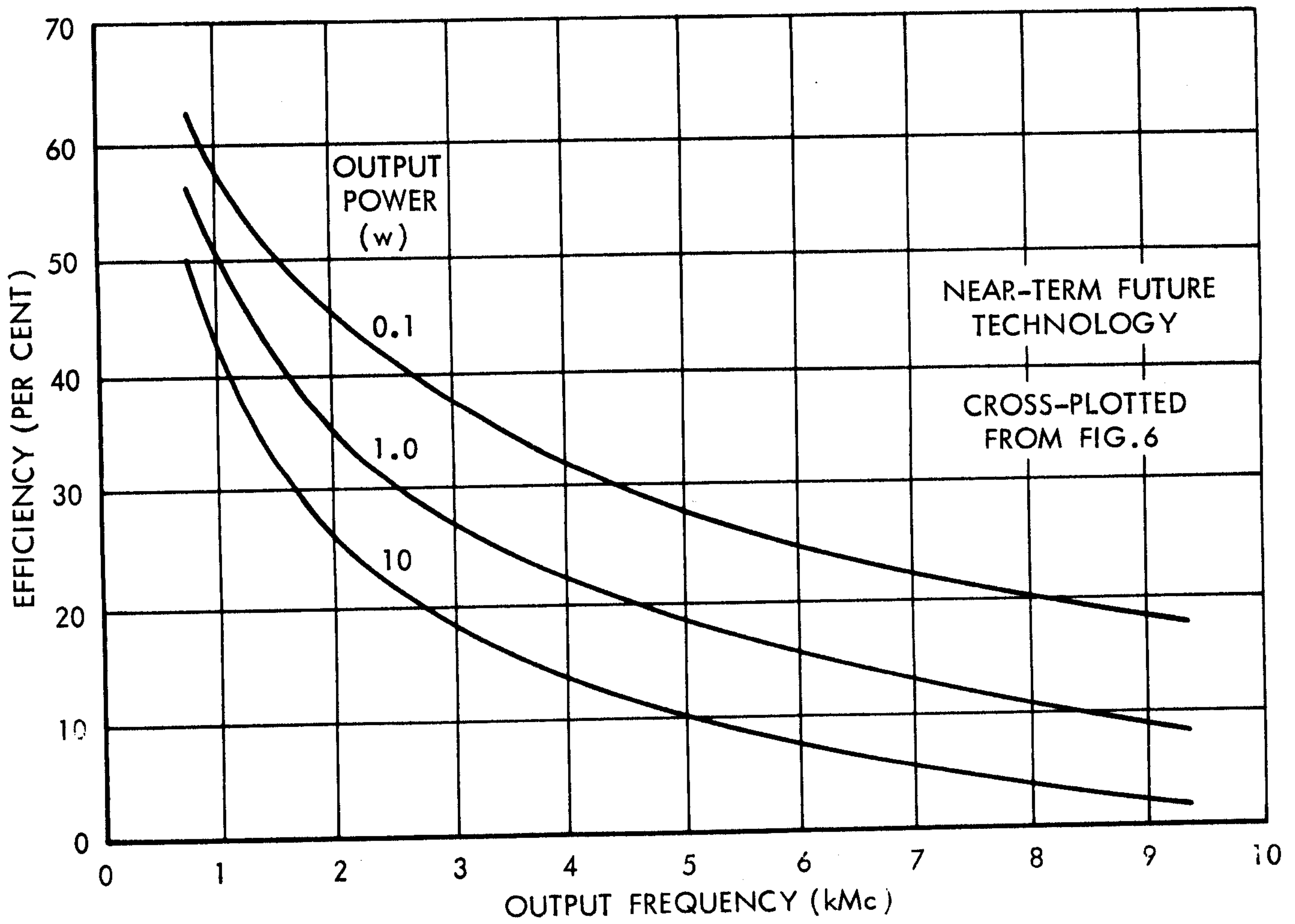


Fig. 7—Overall efficiency of transistor amplifier, driver, and varactor multiplier chain

Thus the results of Figs. 6 and 7 may be considered as applicable to both approaches.

At present the higher-performance solid-state devices are in only limited production, and short-term performance characteristics are not always reproducible. Few data are available on their long-term performance. Since the space environment may present further difficulties due to charged-particle flux and temperature and drive level variations, it should not be assumed that the high reliability normally associated with solid-state circuitry will invariably be achieved with such devices in space communication applications.

III. VACUUM TUBES

The four primary types of vacuum tube amplifiers considered for communications use in space vehicles are triodes,(32,33) klystrons,(34,35) amplitrons(36,37) and TWTs.(38,39,40,41,42)

Triodes

Appreciable power is available from triodes at 1 kMc(43) in cavity amplifiers; but above this, power output, gain and efficiency fall rapidly with frequency. Furthermore, at higher frequencies, long life and high efficiency become incompatible.

The JPL Ranger transponders at L-band used an improved version of the ML 6771, i.e., the ML 546 in a pair of cascaded triode cavity-amplifiers. The second triode has a 3-watt output[*] and an efficiency of 38 per cent, so that the two-stage overall efficiency is 25 per cent at 960 Mc. Complete telemetry transmitter packages at 2200-2300 Mc offer 4-5 watts output with over 10 per cent overall efficiency--(45,46) and a minimum life of 5000 hours with servicing and maintenance.(45) Although overall efficiencies at 2 kMc (including heater power) of 15 to 20 per cent for a several-stage triode amplifier are possible at the 10 to 20 watt level,(9) this drops to 10 per cent at the 1-to-2 watt level; using reliable tubes operated to obtain a 25,000 to 50,000 hr life(32,33) results in roughly half these efficiencies, assuming one starts with a few milliwatt drive signal. About the

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[*] For plots of the output power variation as a function of filament voltage over an interval of 16,000 hrs, see Ref. 44.

best that is possible without derating for extremely long life is exhibited by the Mariner C triode transponder.

The Mariner C planned to use the Siemen's RH7C,(47) or an improved version (the V251) in the 2200-2300 Mc telemetry band.(48) The standard commerical version is rated for 4 watts at 4 kMc in a cw oscillator at 14 per cent efficiency (4.8 watts of heater power and 28.8 watts of plate power) but exhibits parameter changes after 1000 hr and has a typical life of 2000 hr. The 6000 to 8000 hr life desired for the Mariner application is not obtainable in present tubes at the 10-watt level at 2 kMc. JPL funded the development of an improved tube (the V251) at Siemen's, having an objective of 1 db degradation in 10,000 hr. Although the original tube was designed to permit operation up to 6 kMc, this will no longer be possible, as the internal spacings are being increased and the emission density lowered to obtain more reliable operation at 2 kMc. Since the equipment is designed to operate from -10° to $+75^{\circ}$C, the output cavity must be temperature-compensated; stabilization is accomplished by a tuning slug which is hydraulically actuated by the fluid in a bellows. At the 8 to 10 watt level the 2295 Mc V251 cavity amplifier has a gain of 13 db, a heater power of 4.0 watts, and a plate efficiency greater than 27 per cent (600 volts, 50 ma) for an overall single stage efficiency of 23 to 33 per cent. The 3 db bandwidth is 7 Mc or 0.3 per cent.

Negative grid tubes have been used at higher frequencies than 2 kMc with long life. Using the WE416B(49) (designed for the TD-2 overland microwave link) for example, a 100 Mc bandwidth is achievable at 4000 Mc (2.5 per cent) with extremely long life. The output power level is 50 mw at 9 db gain, or 500 mw at 5 db gain; the plate efficiency is less than 10 per cent, and the overall efficiency of the single stage is less than 5 per cent.

Klystrons

Efficient, reliable, high-frequency operation has long been a characteristic of power klystrons, and, in the range of 1 to 10 kMc, tubes are readily available at power levels from 1 kw to 100 kw cw. Although high-power cw klystrons have typical beam efficiencies in the 30 to 45 per cent range (without collector depression), low and medium-power klystron amplifiers are rather poor in this regard because they have concentrated on gain, noise figure, and stability.

Low to intermediate power klystrons focused only by electrostatic fields in the electron gun, e.g., Varian's VA-832, have had overall efficiencies of only 5 to 10 per cent; an improved version, however, the VA-411, has demonstrated 18 per cent beam efficiency at 104 watts cw at 8.8 kMc.(50) Little further improvement in efficiency is anticipated.

ESF (electrostatically focused) klystrons are light in weight (2 lb or less since they eliminate the conventional heavy permanent magnet), narrowband (and thus may require no output filtering), relatively insensitive to load VSWR (possibly eliminating an output isolator), and small (3¼" diameter x 4½" high at S-band for a 20-watt tube). They are also relatively less sensitive to power supply ripple or other supply voltage fluctuations than are synchronous beam devices, and may have automatic protection against positive ion bombardment of the cathode due to the ion trapping by the focusing potential gradients.

In the L3910 tube,(34,35,51) an ESF klystron using lens electrodes between the input and output cavities, and developed under the Apollo program, an overall efficiency of 29 per cent has been demonstrated at the 20-watt level without depressed collector operation. Saturated gains are typically 15 to 45 db and bandwidths are 0.1 to 0.3 per cent; high gain in low-power klystrons has always been associated with narrow bandwidth.

The demonstration of high efficiency in klystrons (65 per cent) by means of biased output gaps and also by means of distributed interaction structures,(51) and the associated increase in bandwidth of the latter approach,(51) has aroused interest in the development of hybrid klystron-traveling wave tubes from 20 to 500 watts for space communications.

Moderately high-power klystron tubes have demonstrated lifetimes of 5000 hr, and some tubes have exceeded 15,000 hr of operation. With proper derating of the cathode emission density and with ion trapping, a lifetime of 50,000 hr or more in low-power tubes should be readily achievable since the gun design is similar to that of TWTs of the same power level (for which such lifetimes have been demonstrated). Since ESF configurations differ significantly from conventional klystron design, their capability for long life operation cannot be taken for granted; it remains to be demonstrated. Thus availability of a flight rated electrostatically focused klystron is several years away.(52)

Amplitrons

A lightweight amplitron (a crossed-field continuous cathode reentrant beam backward-wave amplifier) for space applications was thought to be impossible some years ago because of the large magnet weight considered essential for even a low-power tube. Since then a 20 to 25 watt, 2-lb tube (including magnet) has been developed(36,37) which has an overall efficiency of 40 to 55 per cent while offering in addition a moderately good gain, 17 db, instead of the 8 to 10 db characteristic of high-power amplitrons. Other tubes have been built and operated at from 10 to 100 watts for up to 1500 hr. Since high-power pulsed magnetron life has been raised in recent years from a typical figure of 50 hr to values as high as 1000 to 5000 hr, one might expect a low-power cw amplitron to perform at least as well. If so, the low-power amplitron would possess a reasonable life for some space applications. It is unfortunate that no life data are available on recently fabricated tubes to indicate if the low-power amplitron is in the 5000 hr life class.

To protect the driver stage from reflected output power (the backward insertion loss is less than 2 db) as well as from reverse-directed power generated within the amplitron, a circulator or isolator is desirable at the input to the tube. The tube is not stable under short-circuit conditions nor at low RF drive levels, but would not be damaged under these conditions. Like all backward-wave mode tubes, the amplitron is voltage-tunable and thus sensitive to power supply voltage; in addition, a constant current regulator is required to stabilize the output power level. Heater power must be varied from start to operation; it also varies from tube to tube. To avoid shortening cathode life, a feedback loop must regulate cathode temperature. Logic circuitry is required to ensure proper mode acquisition, i.e., to recycle the anode output voltage automatically if drive power is momentarily lost.

Despite these complications, an overall transmitter efficiency of 38 per cent including all power supply and control circuits has been reported(51) using a QK-1300, 20 watt cw S-band tube. As part of the LEM program (Lunar Excursion Module), RCA awarded a subcontract to Raytheon for a large number of transmitters at about 40 per cent efficiency at the 25 watt level at S band.

The space amplitron has been under development for several years, but the funding has until recently been at too low a level to supply any answer to the life question, or to produce electrically reliable reproducible tubes. The scope and funding of the LEM amplitron package development should be adequate to establish the capability of the amplitron approach.

Traveling Wave Tubes

With the demonstration of 30,000 hr life on a dozen 5-watt M1789 prototype TWTs for the Bell System's TH link (the production version is the WE444A) and the use of M1958 TWTs in a missile guidance system,(55) by late 1959 the TWT emerged as the best contender for communication satellite use above 1 kMc at power levels of a watt or more.*

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*The choice of triodes for the Advent program about October 1958 led to the obsolescence of the communications payload design relative to current technology within a short interval, and contributed to the need for reorientation of the program.(53,54)

NASA programs in communication satellites took cognizance of their potential for reliable, efficient power generation, resulting in TWTs for Telstar, M4041;(38,55) Relay, A-1245;(42,56) Syncom, 314H;(39,57) with a backup TWT for the latter, WJ-237.(58) TWT developments for Advent, WJ-231;(59) Surveyor, 349H;(39) and MACS, WJ-251(40) and the X-1131; Apollo, 394H;(39) Pioneer, 214H; Mariner 4, 216H; Lunar Orbiter, 220H; Application Technology Satellite, 384H; Early Bird, 215H; and Saturn Telemetry, 212H were also funded. These programs represented diverse frequencies and power levels and two focusing schemes--field reversal and periodic permanent magnet (PPM) focusing. Straight-field permanent-magnet (PM) focusing has been displaced by the lighter one- or two-field reversal permanent-magnet approach,(38) and bifilar helix electrostatic focusing has been eliminated(41) by PPM focusing. The power levels of the space tubes range from 2 to 35 watts of saturated power, although TWTs at the 100- to 1000-watt cw level for airborne and ground use are readily available from 1 to 10 kMc.

The heater requirements of some of these tubes are shown in Fig. 8.* The higher heater powers sometimes correspond to larger cathodes. This is necessary if longer life is required, since the emission density must be lowered. A larger cathode and a higher

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*The reader is cautioned not to draw conclusions regarding the relative merits of the various manufacturers' tubes inasmuch as these data are not based on the same criteria. Some figures represent objectives, some best values on a single prototype tube, others are average values based on measurements on a significant number of tubes, while still others are guaranteed values.

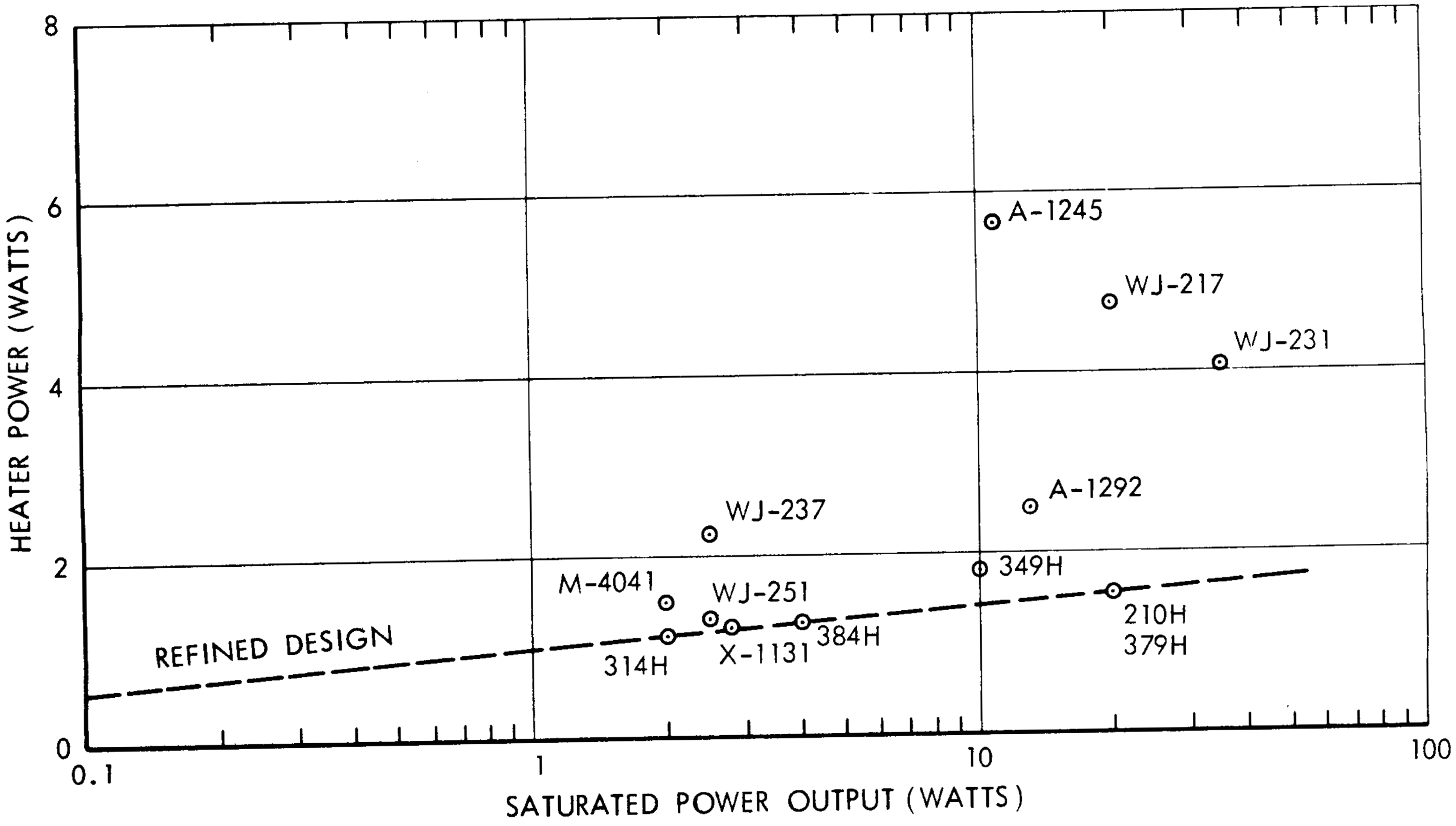


Fig.8—Space traveling wave tube heater power

convergence (cathode area to beam area) gun is then designed. The data of Fig. 8, according to manufacturers' predictions, correspond to a 30,000 hr or more life. The dashed line represents the lower bound set by present technology. Some of the tubes above this bound are designed for 80,000 hr life. End of life is set by oxide depletion,(39,60) inadequate diffusion rate of the reducing agent,(39) or by inadequate chemical reaction rate of the coating.(38) Further test data (beyond the roughly 26,000 hr accumulated to date on each of a dozen tubes) are required to substantiate the 20,000 to 90,000 hr life predictions in the case of some of the Hughes tubes because of their radical departure(39,57) from proven BTL technology.(38)

Beam efficiencies (RF out/DC input) of 30 per cent are now readily obtainable. After careful optimization, the average beam efficiency of sixteen 394-H tubes was 35 per cent, the average of fifteen 215-H tubes and of one batch of sixteen 384-H tubes was 39 per cent. The median efficiency was approximately equal to the average. The minimum efficiencies in the samples were 2 to 4 per cent below the average. The preceding figures were for rated voltages, a limited frequency band, best drive level (values are 2 per cent less for non-optimum drive), and ambient temperature. These results are similar to those achieved by other manufacturers of space TWTs.(52) Many of the factors degrading TWT efficiency(61) may prove amenable to improvements. If such techniques as tapered slow-wave structures (velocity or phase taper), high perveance solid or hollow beams, and multiple stage depressed collectors (two or three instead of just one) are used, for example, it may be possible to obtain much better than

40 per cent beam efficiency. Traveling wave tube efficiency, using such an optimized 40 per cent beam efficiency figure and the lower-bound heater power curve, is shown in Fig. 9.

In present TWTs used for space communication, so many parameters are involved in design tradeoffs that the dependence of beam efficiency on either frequency or output power is completely masked. Thus, a constant beam efficiency of 40 per cent has been assumed. Tubes often provide a higher power output at a particular frequency in the band, and selected tubes often provide appreciably more power output than the average.(57) Thus 50 per cent beam efficiency can probably be demonstrated at particular frequencies by selected tubes operated under optimum conditions. Overall efficiencies approaching 50 per cent including heater power would then be possible. At present the required tubes are selected from a larger group which have passed quality assurance tests. Optimization and selection may permit 45 per cent overall efficiency at the 10 to 20 watt level to be achieved within a year.(62) Combinations of the techniques previously mentioned plus a variety of other approaches may result in even higher efficiency. Several contracts have been funded to provide high efficiency in a 20-watt TWT transmitter package (45 per cent for the tube, 85 per cent for the converter-regulator)(52,62) and to explore the possibilities of large improvements in TWT efficiency.(63,64)

Comparison of Vacuum Tubes

So far in this section the present technology in microwave amplifiers for use in space has been examined briefly for negative grid tubes, for klystrons and for amplitrons, and in somewhat greater

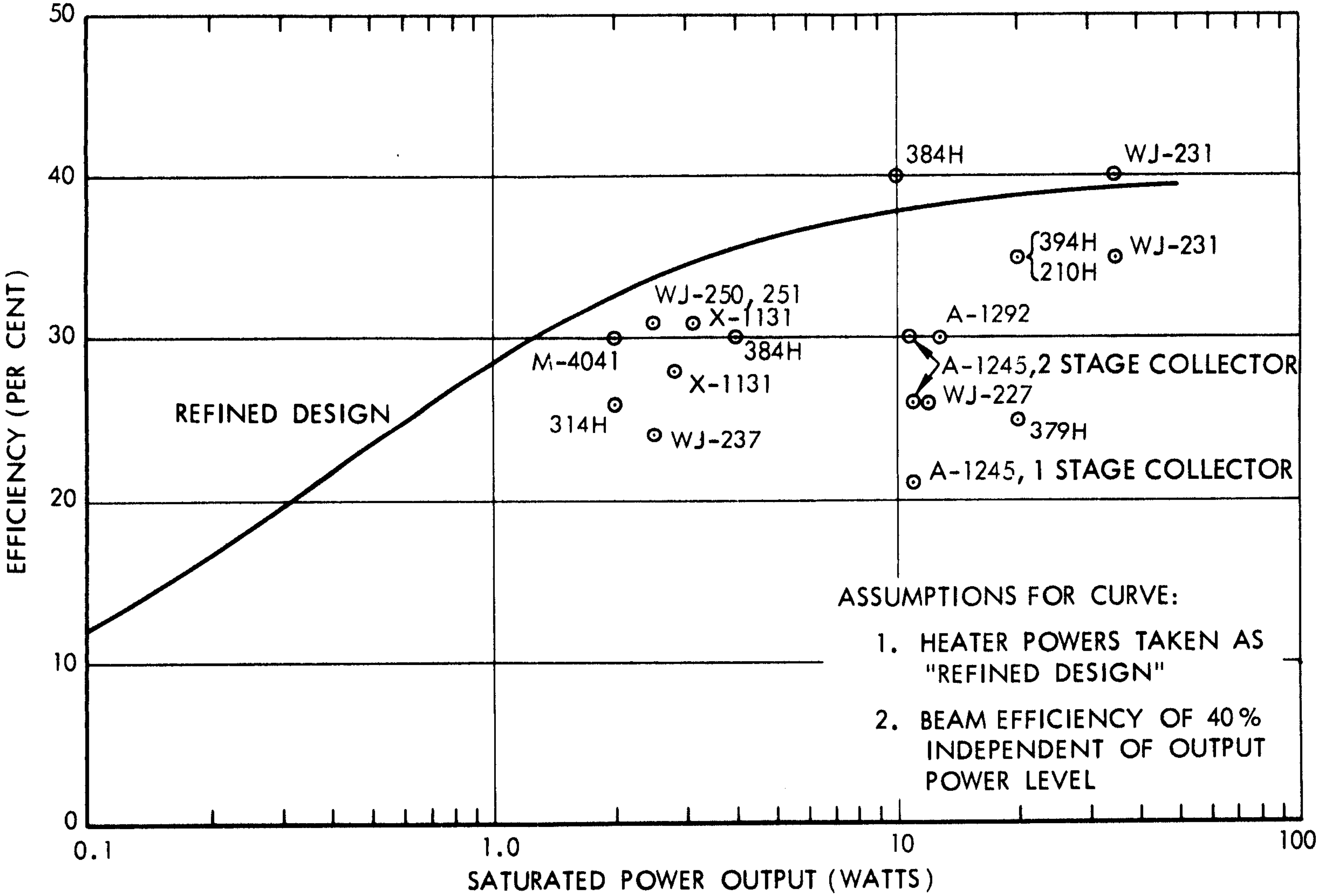


Fig. 9—Overall traveling wave tube efficiency including heater power

detail for TWTs. In choosing between these four vacuum-tube devices some of the factors most often considered are efficiency, power level, gain, frequency, temperature sensitivity, modulation, life, size,(65) weight,(65) reliability, resistance to charged particle radiation and resistance to shock and to vibration. As a result of the design choices made by tube designers having space requirements in mind, many of these factors no longer provide assistance in making a choice within the frequency range of 1 to 10 kMc at intermediate power levels. Thus with a proper choice of materials, particle radiation need not be a problem for vacuum tubes at these power levels; none of the four tube types appears to be inherently unreliable on basic principles; with attention to mechanical design, shock and vibration environments can be tolerated even where the tubes must operate during launch; the space amplitron and the electrostatically focused klystron are certainly competitive in size and weight with the triode cavity amplifier and the TWT. Thus the significant differences which permit making a selection lie in the remaining factors. These, however, tend to be interrelated and their interactions must often be considered.

Modulation involves such characteristics as stability, linearity and bandwidth. Temperature sensitivity and narrow bandwidth are common to both the triode cavity amplifier and the klystron, since both use high-Q tuned cavities. Integral cavity triodes(66) and stagger-tuned (approximately maximally flat) multicavity klystrons(67) providing 10 to 20 per cent bandwidth are feasible in high-power tubes, but at the few-watt level at high efficiency, 3 db bandwidths of 0.3

to 1 per cent for triodes and 0.1 to 0.3 per cent for klystrons are typical. The space amplitron, however, has a constant-voltage bandwidth of 1 to 2 per cent; while for space TWTs, 10 to 50 per cent is typical. The need for cavity temperature compensation of the triode circuit complicates the design and lowers the reliability, but may do so to a far greater extent for the klystron. Shift of the klystron center frequency by a large fraction of the bandwidth due to temperature is generally not tolerable in such a very narrow-band device. Field-reversal PM-focused TWTs and PM space amplitrons can be relatively insensitive to temperature change. PPM-focused TWTs for space use often utilize the new magnetic material platinum-cobalt which has a sufficiently low temperature coefficient of magnetic field that it makes possible relatively temperature-insensitive operation.(60)

The factors of life, efficiency, power level, gain, and frequency, are closely interrelated and must be treated as a group. For the present, both the ESF klystron and amplitron cannot be considered for communication satellites because they have not yet demonstrated adequate life on even a few samples. Advantages to the klystron may lie in such areas as frequency and phase stability, linearity, variable-power level of operation, noise figure and efficiency.(35) Under efficient operation, klystron output power level can be varied by changing fewer power-supply voltages than on the TWT. Where efficient operation over a wide power range is essential, the simpler klystron power supply can represent an advantage. At high power levels, where efficiency is particularly important, the space klystron may perform better than the TWT--given a comparable investment in resources for the development. In communications systems, however, the requirement for higher power is often a consequence of the demand for higher information rates. Thus, high power levels are associated with large bandwidths. In view of the narrow bandwidth and temperature sensitivity of the conventional cavity klystron, its value in communication satellites may be limited. Hybrid tubes, however, are a promising long range development.

For communication satellite use the amplitron would have to demonstrate a life in excess of 30,000 hr to be suitable. For space missions, 10,000 hr might suffice. The amplitron not only requires a more complex power supply than the TWT, it places a number of constraints on the input signals, and has significantly lower gain, and so it must provide a significant efficiency improvement over the TWT to be worth consideration. Part of its efficiency is offset by the cost in power and complexity of generating the higher drive signal. At the 20-watt level, a 50 per cent efficient amplitron appears necessary to compete with a 45 per cent efficient TWT purely on an efficiency basis. At the 500-watt level, a 55 per cent efficient amplitron might offer a substantial advantage over a 45 per cent efficient TWT, but these characteristics are meaningless in the absence of life data.

If the amplitron proves to have short life, this would not eliminate crossed-field devices from further consideration for long-life space applications--it may only eliminate the continuous or distributed emission cathode. Crossed-field forward-wave amplifiers(68) using injected beams(69) would circumvent this problem while offering many of the advantages of the TWT. Such a space tube is considered feasible by research workers at CSF.

At power levels of 1 watt or more, triodes cannot compete with TWTs on an efficiency basis when lifetimes of 30,000 hr or more and frequencies above 1000 Mc are considered. The low-gain-per-triode stage above 1000 Mc and the high heater power per tube strongly penalize triodes in an overall efficiency comparison with the TWT. Below 1000 Mc, the situation may reverse--but this is also the frequency domain in which triodes must compete with solid-state devices.

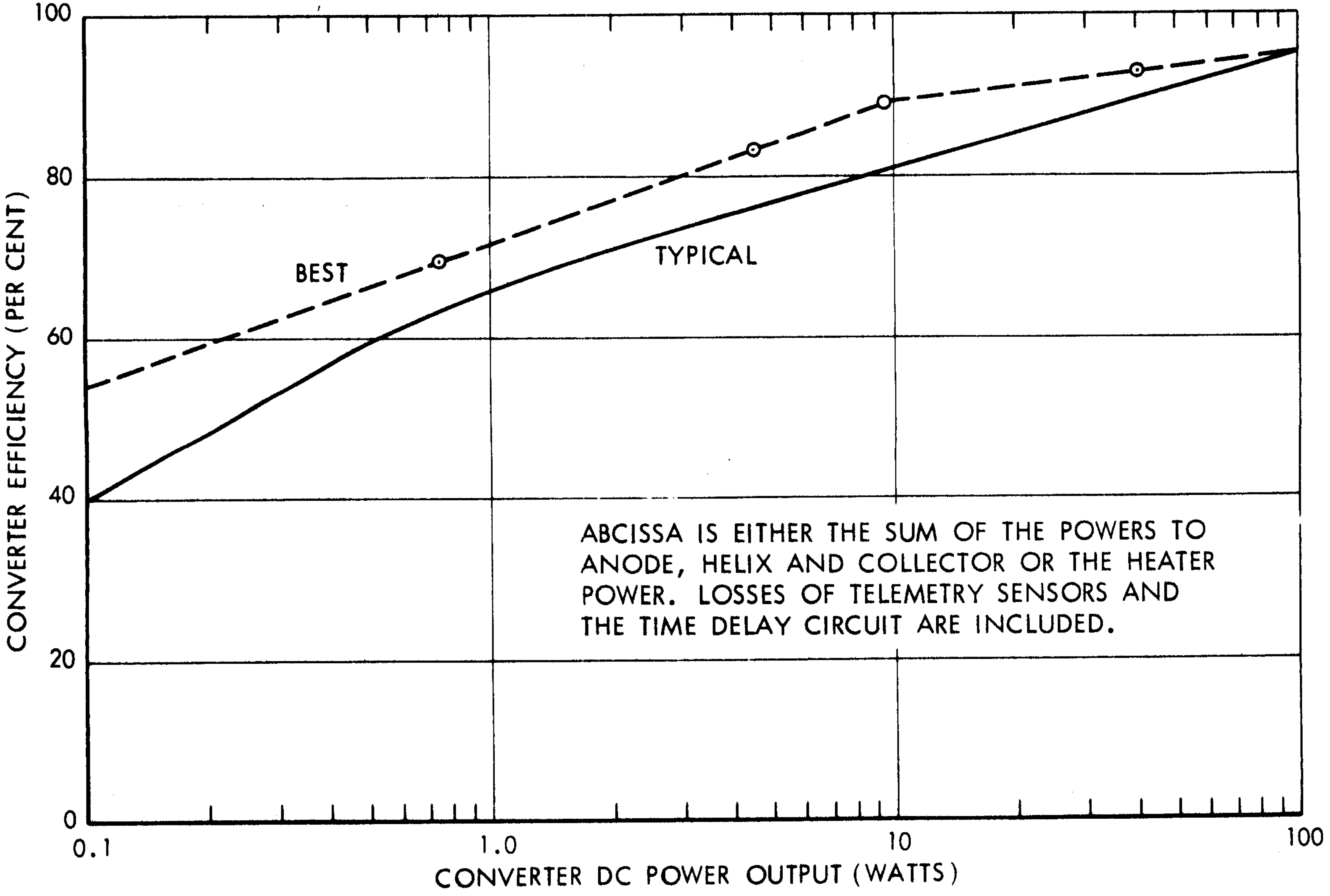
At about 1000 Mc and 10 watts cw, negative grid tube circuits will predominate(51) so long as they continue to offer cost advantages over solid-state designs; but for those few applications where extremely long life, reliability and efficiency are the dominant factors, solid-state circuits already may offer an advantage without requiring any breakthrough in the solid-state field. At higher power levels, the superior power-handling ability of tubes places current solid-state devices at a disadvantage. Requirements for shorter life, lower frequencies, lower power levels, and lower bandwidth tend to enhance the potential efficiency of the triode. The extensive use of the triode is a reflection of its low cost and ready availability, of the widespread understanding among electronic engineers of the techniques for coaxial-cavity amplifier design, and of the ubiquitous preference for in-house fabrication of hardware.(48)

Satellite TWT Voltage Converters

Solid-state microwave output devices can be operated directly from a low-voltage regulated supply. In communication satellites, they are the major load on the supply so that it is reasonable to optimize the energy source output voltage for this load. Vacuum tube devices, on the other hand, require a DC-to-DC high-voltage converter to supply the correct voltages. Thus the inefficiency of a voltage converter must be charged against the TWT but not against the solid-state supply. For the comparisons of this study, regulator performance will be ignored because regulators are present in both systems, and therefore will not have a significant influence on the comparisons.

Voltage converters are less efficient at low power levels because of fixed power requirements.(60) At the higher power levels there is little room for improvement. The lower curve of Fig. 10 shows typical satellite TWT converter efficiency, and the upper one shows about the best that has been achieved to date.(70,71)

For optimum overall efficiency, the voltage converter must be designed to be used with a particular TWT. Thus the converter must be changed when the tube is changed. The same is true for the amplitron, but not for the triode and klystron. Since the varactor multiplier does not require voltage conversion while the TWT does, a combined efficiency for the TWT has been calculated using the curves of Figs. 8 and 10. The curve of Fig. 11 is calculated using the "refined design" curve of Fig. 8, the assumption of a 40 per cent beam efficiency independent of output power and the "best" voltage conversion efficiency curve. The latter curve is used twice, once



ABCISSA IS EITHER THE SUM OF THE POWERS TO ANODE, HELIX AND COLLECTOR OR THE HEATER POWER. LOSSES OF TELEMETRY SENSORS AND THE TIME DELAY CIRCUIT ARE INCLUDED.

Fig. 10—Satellite TWT DC to DC voltage conversion efficiency excluding regulator

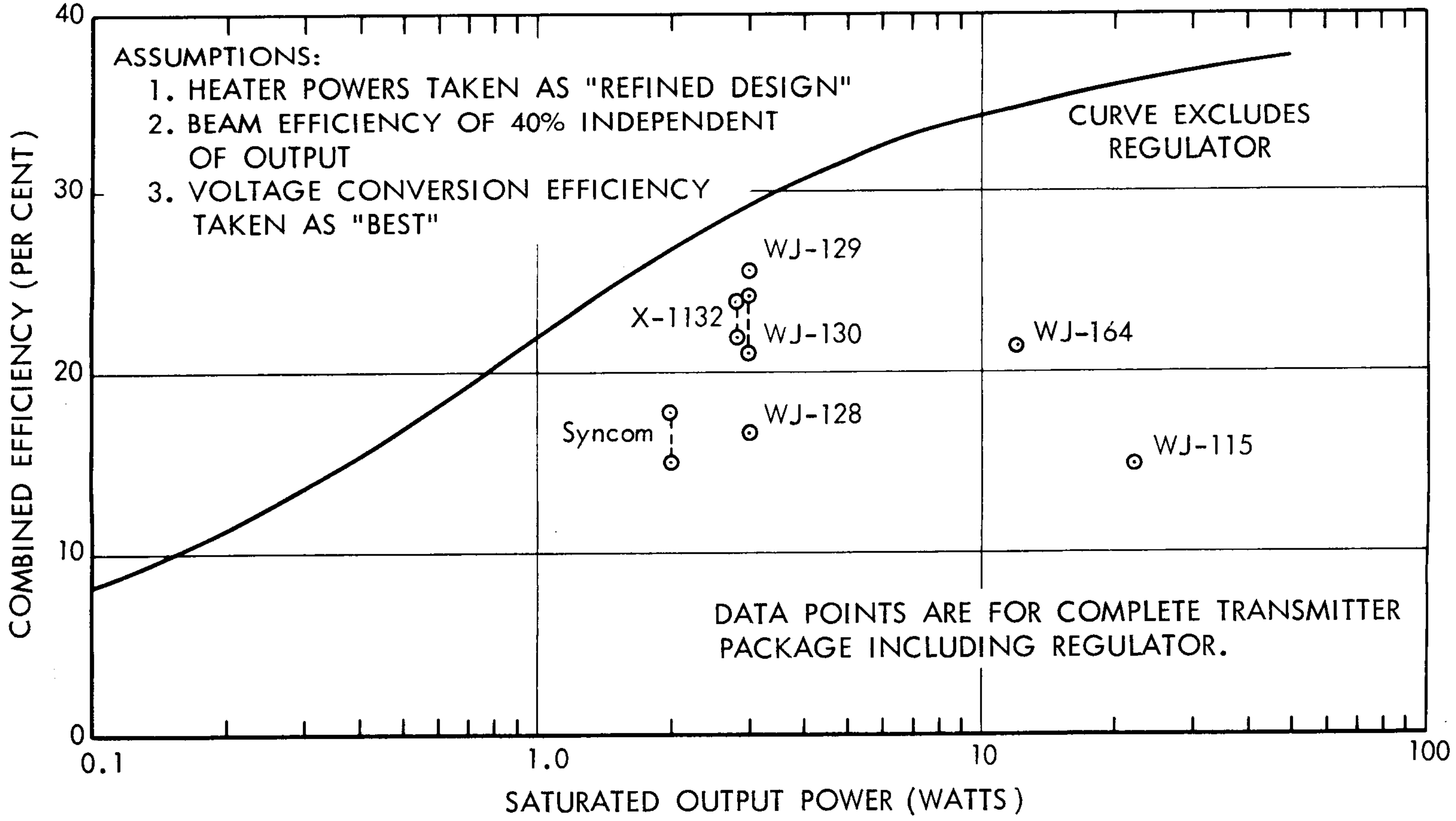


Fig. 11—Efficiency of traveling wave tube plus voltage converter

for the regulated power required for the heater and once for the beam power.

In summary, the TWT has no immediate competitor in the vacuum tube field above 1 kMc for power levels of 1 watt or more and lifetimes in excess of 30,000 hr. Therefore the primary contenders in the near future for intermediate level power generation for communication satellites at 4 kMc are varactor multiplier chains (often with parametric upconverters) and TWTs.

IV. COMPARISON OF VARACTOR MULTIPLIERS AND TWTS

A fairly complete comparison between solid-state devices and microwave tubes would require detailed quantitative examination of over a dozen characteristics. To reach conclusions about a preferred choice would involve different weightings of these characteristics for each application considered. To indicate that a single line of demarcation can be drawn(72) is misleading. The transition region between two such broad technologies can be expected to be broad, e.g., ranging over perhaps two decades in power level for six decades of the frequency domain.(73) To examine the crossover between varactor-multiplier chains and TWTs for only one parameter, efficiency, is to focus on one important variable for which meaningful quantitative comparisons can be made. A single line of demarcation may be a valid guide in this case.

Using the TWT plus voltage converter combined efficiency curve of Fig. 11 as a function of output power level, and the varactor multiplier chain efficiency curves of Fig. 6 as a function of output power level, the locus of equal efficiencies has been plotted in Fig. 12. Thus near-term future performance of the solid state multipliers is compared with TWT developments in the same time period. In Fig. 12, power is terminated at about 50 watts at 1000 Mc; for a one or two diode output stage, this power limit may remain for some time.(17)

At the higher frequencies and power levels the TWT has a decided advantage. At lower frequencies and powers the solid state approach has an advantage. Thus, for frequency-stable local oscillators and for low-level drivers, the solid state approach is preferred. The lighter weight of the solid state approach at the low power levels tends

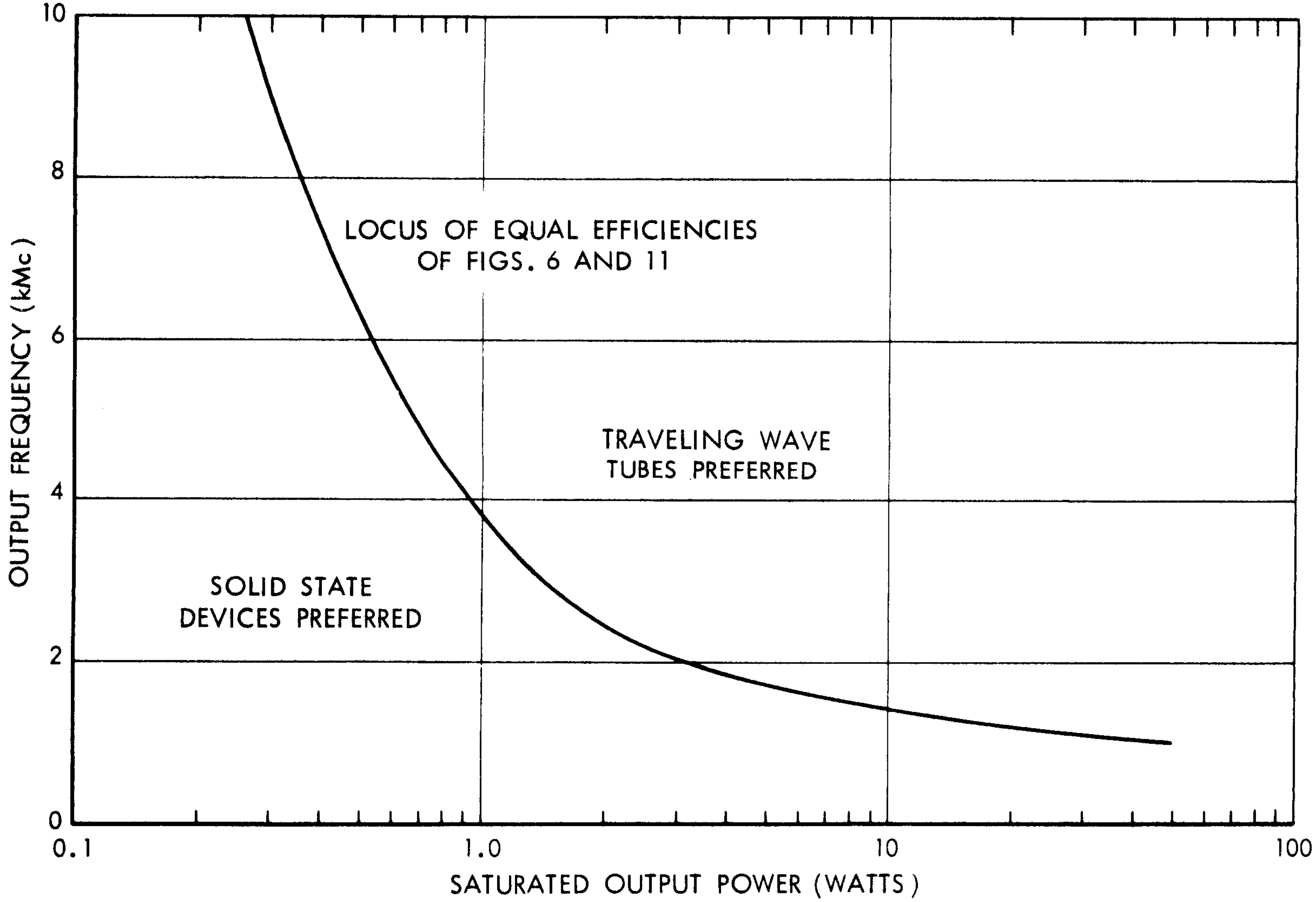


Fig. 12—Solid state devices compared to traveling wave tubes; near-term future technology; +20°C environment

to favor solid state even more than is indicated by the efficiency comparison alone. The instant operation without warmup and possibly smaller size of package which the solid-state approach could provide(74) are not significant in this application. Under the conditions of a 60° C change in ambient, the crossover with TWTs, whose efficiencies are relatively insensitive to temperature, may be moved radially inward as much as is shown in Fig. 13. For a 60° C change in temperature, there is, however, a small change in the TWTs magnetic focusing and in the converter output voltage; each may cause a 2-4 per cent decrease in efficiency.(60) Solid-state chains offer the in-house design convenience of the triode without the delay and expense of contracting for a TWT optimization program.

Both the TWT and the varactor multiplier chain are sensitive to drive level variations. Whereas the change in output power for a TWT is only a couple of per cent for a 1 db change in input signal level, the change in multiplier output may be many times this much. It is a function of the type of diodes, the circuit design(1) and the number of cascaded stages.(27) For a self-biased tripler, it may be as little as 5 per cent or as much as ten times this.(1)

The saturated TWT, the varactor multiplier and the parametric upconverter are all non-linear devices. This does not, however, preclude their use in communication satellites for processing the output signal. It does mean that due regard must be given to their characteristics and limitations (and that of the mixers, IF amplifiers and other devices in the signal path) as a function of the modulation, the number of independent signals involved, and their relative strengths. A substantial body of literature exists on the theory and characteristics

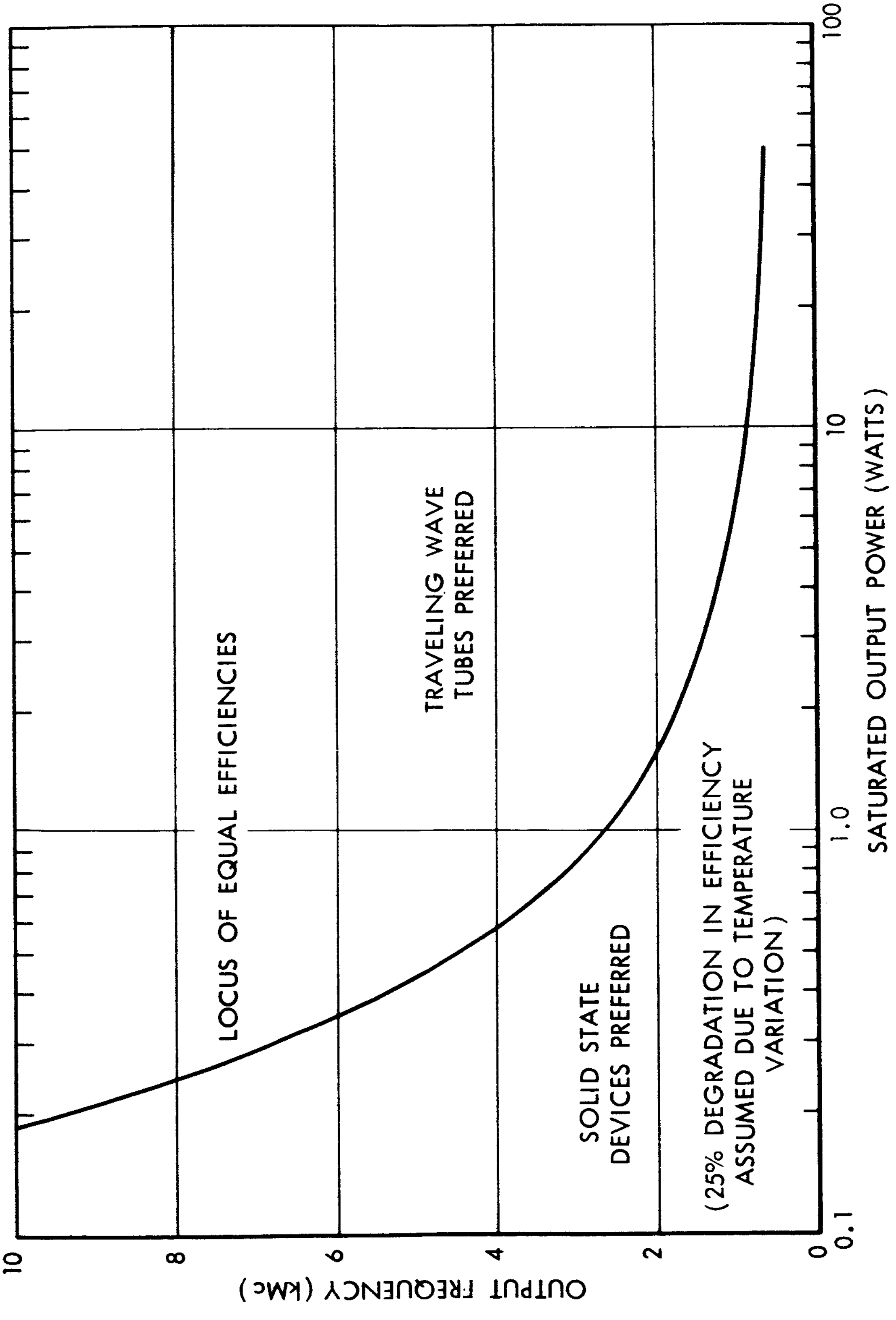


Fig. 13—Solid state devices compared to traveling wave tubes; near-term future technology; +20°C to +80°C environment

of the TWT under large signal conditions and on its characteristics under multiple signal operation.(75-82) Much less is available on the multiple signal characteristics of the varactor multiplier(1,83) and the parametric upconverter.(84) The all solid state communication satellite built by Lincoln Laboratory and now in orbit (LES-2) processed the radiated signal through two cascaded parametric upconverters.(20,31,85) Two tone intermodulation tests on a parametric upconverter show that the third order product increases relative to the carrier as the output signal to pump efficiency improves e.g., -50 db at 1% and -17 db at about 50% efficiency.(84) The TWT third order intermodulation product is about the same amplitude when the tube is near saturation.(80)

It appears that for lifetimes in excess of 30,000 hr, and for frequencies about 1000 Mc, TWTs and varactor multiplier chains have no competitors of comparable efficiency at present. The engineering choice between them is made primarily on the basis of frequency, power level and modulation considerations, but is influenced by a variety of system and circuit design decisions. For some types of communication satellites, the relative importance of some of the factors may be greatly altered or new constraints may be introduced, e.g., no stray magnetic field. Only after a detailed specification of requirements has been made can a single one of the devices discussed be selected as optimum for a particular application; no one vacuum tube or semiconductor device is the answer to every system.

Although Telstar, Relay and Syncom all obtained most of their gain at IF and used a saturated TWT output, (a uniformity worthy of note), other circuit configurations have also been under study. Linear output stages, TWT reflex techniques and solid state multiplier circuits were among those considered. A highly linear TWT (to be operated 4 db below saturation) development was funded for Advent.(53) Given the costs of prime power in space, the efficiency penalty of linear systems makes them unattractive; thus they have been discarded for the present. The simplicity of TWT reflex techniques and other direct microwave amplification schemes was first thought to offer a saving in system weight;(86) more recent studies based on laboratory hardware show improved reliability(87,88) instead. In addition, they may offer larger bandwidth,(87) less phase distortion, time delay and AM/PM conversion, and better amplitude linearity and gain flatness then the IF approach.(82) A laboratory demonstration of two way simultaneous communication through deviation multiplying repeaters (both a doubler and a tripler were used) was reported on and analyzed on Project Relay.(83)

Advances in technology coupled with widening applications for communication satellites will result in considerable diversity among future communication satellite systems. When the information rates of interest span the range from a few bits per second to tens of thousands of voice channels or tens of color television channels, and the multiple access requirements may range from two terminals to 1000 ground terminals operating through one satellite, a single satellite design is inadequate.

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