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THE REQUIREMENTS PLACED ON ELECTRON TUBES FOR SPACE APPLICATIONS

by W. H. Kohl, C. M. Veronda, and R. W. Wilmarth

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THE REQUIREMENTS PLACED ON ELECTRON TUBES FOR SPACE APPLICATIONS*

By W. H. Kohl, C. M. Veronda, and R. W. Wilmarth
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SUMMARY

This Technical Note reviews the requirements that must be met by electron tubes intended for space applications. After some remarks on the basic concepts of reliability and the weight and size penalties imposed by space missions, the environmental parameters of temperature, vibration and shock, radiation, and particle bombardment are discussed. The special requirements imposed by the absence of a gravitational field and by the sensitivity of magnetometers to stray magnetic fields are also mentioned. While the feasibility of producing highly reliable microwave tubes for space missions has been demonstrated in the past, there remain areas where additional effort is required to reduce the weight penalty now imposed, particularly in cooling systems. The introduction of more efficient heaters and cathodes would greatly alleviate this problem.

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*Presented by W. H. Kohl at the Eighth National Conference on Tube Techniques, New York, N. Y., September 20-22, 1966.

INTRODUCTION

This Technical Note reviews the requirements that must be met by electron tubes intended for space missions. Reliable communication over millions of miles depends crucially on the availability of high-frequency power. Solid-state devices cannot fulfill this need so that there is indeed still a place for tubes in space applications. It is more than likely that this state of affairs will prevail for some time, so that efforts directed toward the further improvement of electron tubes for space applications are a serious concern of the National Aeronautics and Space Administration. Work carried out, or supported, by NASA's Electronics Research Center (ERC) at Cambridge, Mass., is aimed at this improvement. The environment to which a tube is exposed during a space mission can be briefly characterized by the following parameters:

1. Shock and vibration
2. Ambient temperature fluctuation
3. Radiation and particle impact
4. Zero gravity.

The effect of these constraints on the operation of an electron tube will be discussed in the following sections after some remarks have been made on the basic concepts of reliability. In a final part of this Technical Note, practical solutions to the design problems and future trends will be outlined. The discussion will be limited to microwave tubes so that sensing devices and image display tubes are not included, although they have great importance in space missions.

During the past 15 years, a substantial effort has been made to upgrade the reliability of electron tubes for military applications and also for commercial use in critical environments. Both glass and ceramic envelope tubes are now available which have a Mean-Time-Before-Failure (MTBF) of thousands of days, thus assuring lifetimes on the order of 100,000 hours. Submarine cable tubes with a life expectancy of well over 20 years are now being made with ceramic envelopes. To a large extent, the experience gained in these developments is applicable to tubes intended for space missions.

RELIABILITY[1,2]

It is self-evident that the pursuit of space missions requires assurance that all components entering into the construction of the spacecraft or satellite are of a quality that is commensurate with the expected performance. Such missions are very costly indeed. The launch cost for a satellite is about $6,000,000, and its first-year cost of operation on the basis of a mean life of 100,000 hours is on the order of $20,000,000. These costs are reduced when the mean life is extended or when more than one satellite is put into orbit in a given program.[3] Expenditures for reliability programs represent a substantial part of this cost and are a necessity.

The manufacturer of microwave tubes for space missions must therefore concern himself with the theoretical and practical aspects of reliability. Unfortunately, military specifications do not adequately cover all tube types and all the varied applications in different circuits. There remains a wide area of interpretation of the few existing specifications where the manufacturer has to use his judgment and apply tests that seem to be best-suited to the case in hand.[4]

A large amount of literature fortunately is available for guidance, as indicated in the list of references at the end of this Technical Note. Of the authors who have addressed themselves specifically to the subject of "reliability for electron tubes," we mention Rodenhuis, Santing, and Van Tol,[5] Champeix and Huber,[6] Schütze and Dlouhy,[7] and Noelcke.[8] The work done during the development of submarine cable tubes,[9] mentioned above, also is a valuable source of information.

Bearing in mind that reliability is expressed by the probability of survival of the member of a group of tubes subjected to specified operating conditions for a period of time, it behooves us to perform tests on a large enough sample so that statistical analysis is justified. This condition is not easily fulfilled with specialized and expensive tubes. The environmental parameters to be encountered in service must be simulated during the test and held at a constant level or be changed periodically, as conditions require. A static life test under normal operating conditions, as they apply to a commercial product, is therefore just the beginning of a whole series of tests that must be conducted at different levels of temperature, humidity, pressure, vibration and shock, and in the presence of radiation. Such a test program, to be effective, requires a substantial amount of test gear, trained personnel to operate it, and an organization concerned with reliability, quality control, and traceability procedures that is set apart from production and has jurisdiction over it.

During production for the commercial market, a battle will often ensue for the relaxing of apparently tight tolerances, and the degree to which this desire is satisfied will of course be reflected in the quality of the end product. No such compromises are permissible in the production of tubes for military or space applications. It would lead us too far afield to attempt even a rudimentary introduction to the principles of reliability in a short presentation such as this. As a convenience for the newcomer to this field, some important concepts are highlighted in the following remarks.

The life history of a given lot of tubes taken directly from the first test where inoperatives have been culled out can be represented by the curve shown in Figure 1 where the ratio n/n_o is plotted as a function of time on linear scales (n_o is the number of tubes put on test, and n is the number of survivors at any time thereafter). During an initial "burn-in period," T_1, the population of survivors decreases fairly rapidly owing to blatant faults, such as poor welds, open heaters, or leaky envelopes. In the "useful life period," T_2, "chance failures" predominate that can most readily be appraised by mathematical analysis. Finally, "wear-out" sets in at T_3, where the emission from cathodes may become exhausted owing to a number of different reasons.[8] When plotted on logarithmic scales, the survival, or reliability, curve $R=n/n_o$ takes on the form shown in Figure 2 where the exponential decay of the reliability curve $R=e^{-\lambda t}$ during the useful life period is apparent. The well-known "bath tub curve" (Figure 3) describes the failure rates, λ, over the three periods in question. It should be mentioned that failure rates are not equivalent to removal rates, as pointed out by Strauss,[4] because a significant number of tubes is removed from circuits without/containing defectives. Total reliability therefore is a composite of inherent reliability and contributions from test maintenance practices, including human errors and logistics of supply.[10] Only 5 percent of magnetrons and klystron amplifiers studied in one survey died of "old age" (wear-out failures), whereas reflex klystrons had 20 percent in this category. In commercial practice, 80 to 90 percent is a common figure for low power, or emission, failure defects.[4]

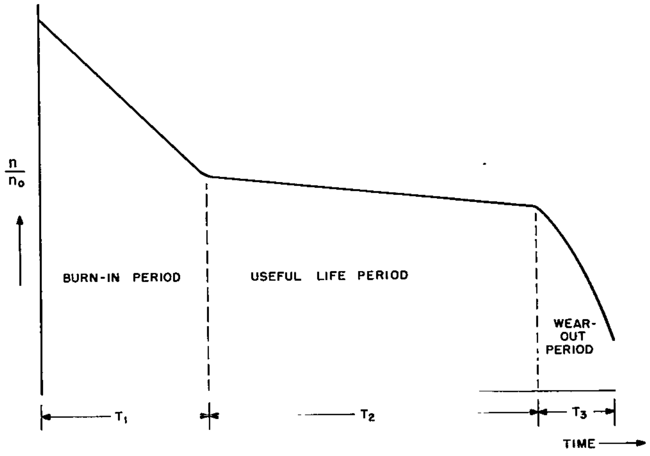

Figure I. - Survival Curve for a Lot under Test

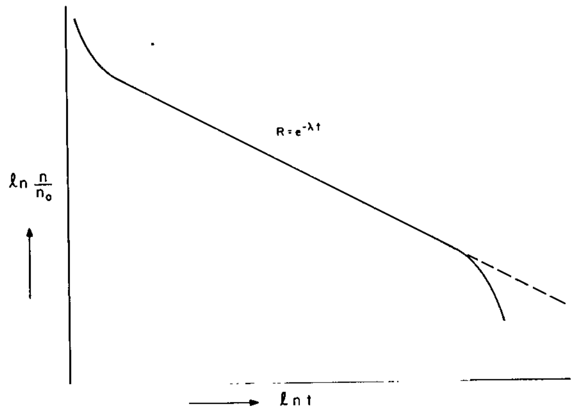

Figure 2. - Logarithmic Plot of Survival Rate

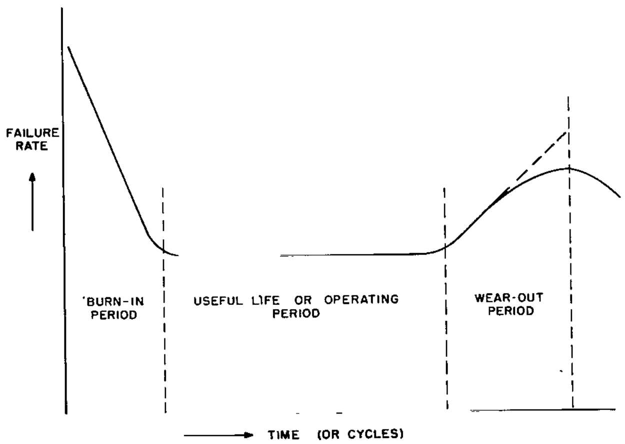

Figure 3. - Bathtub Curve Showing Failure Rate versus Time

As neither a Gaussian distribution nor an exponential function describe the full extent of the reliability curve, Weibull[11] has introduced a function $R(t) = \exp - [(t-m)^{\beta}]/\theta$ in which β determines the general form of the curve, m fixes the position of the curve with respect to the origin of the time axis, and θ expresses the failure rate;* for $\beta = 1$, the Weibull function approaches the exponential distribution, and for $\beta = 2$ the Gaussian distribution results, as shown in Figure 4. Initial failures are therefore represented by the Weibull function with $\beta < 1$, statistical failures during the normal operating period by $\beta \sim 1$, and wear-out failures by $\beta > 1$. Experimental determinations have shown that the exponent assumes higher values for less complex tubes.[6]

The practical measures to be adopted for the design of satellite tubes, such as travelling wave tubes (TWT's), have been described by Bodmer et al.[12] Conservative cathode loading (85 mA/cm^2), low operating temperature (730°C), painstaking outgassing of all tube components, judicious selection of electrode materials, and, above all, a long burn-in period (1000 hours) followed by an evaluation of cathode performance that gives meaningful correlation with life expectancy (dip test[13]), are some of the measures taken to ensure reliability.

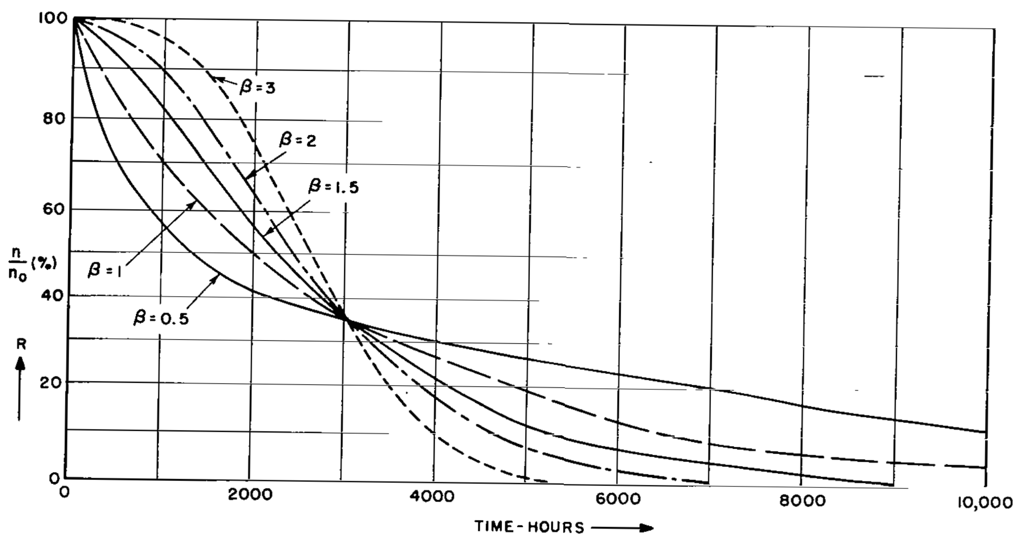

Figure 4. - Weibull Survival Function $R(t) = e^{-(t/\theta)^{\beta}}$ for θ = 3000 hours

*θ gives the time in the survival curve where $1/e$ = 36.8 percent of the tubes remain in service; it is also equal to the mean life M of the lot when $\beta = 1$, and to 1.12 M for $\beta = 2$.

LOW WEIGHT AND SIZE

After reliability considerations, the overall weight and size of a tube is the next most important factor in space applications. The total weight and size of the vehicle is necessarily limited to very definite values depending on the booster and on the type of mission. The fraction of the total launch weight that can be assigned to technical and scientific equipment varies from <1 to 10 percent, so that a premium is put on device efficiency. The amount of fuel required per pound of payload ranges from 10 to 100 pounds, depending on the mission, and the cost of launch per pound of payload is on the order of $500 to $1,000.

The total mission weight for the electron device includes the weight of primary power, power conditioning, heat radiator, and other auxiliaries made necessary by the tube. Improvements made in space power sources and power conditioning equipment will significantly alter the numbers to be assigned for such gear, but it is possible to give a useful average weight penalty for the present.

For regulated and conditioned power in a typical spacecraft, the figure is 250 lb/kW for the lower power levels used at present. Larger, projected spacecraft power supplies, such as 50-kW units, will total about 65 lb/kW (50 lb/kW for the solar panel and 15 lb/kW for power conditioning). The size of such units is expected to be about 500 in.^{3}/kW for power conditioning (1500 in.^{3}/kW for small supplies of about 100 Watts). The area required for the solar panel is on the order of 250 ft^2/kW. This compares to a weight penalty of about 30 lb/kW for a ballistic rocket mission and to about 60 lb/kW for a large aircraft electrical system including fuel weight for a usual scheduled flight. The anticipated weight penalty for spacecraft using solar cells for larger blocks of primary power is therefore about the same as that for aircraft, while present weight penalties for smaller blocks of power are higher. Table I summarizes these data. The advent of thermionic and thermoelectric converters using solar or radioisotopic power sources must also be taken into account.

Efficiency affects the total weight and size of the tube package by virtue of cooling requirements. Ultimately, all waste heat must be radiated into space, and different methods have been used to get the heat to this transfer point. One klystron now being developed for space application utilizes a tungsten electron collector the outside of which is operated in an auxiliary vacuum space formed by a "searchlight"

TABLE I

APPROXIMATE LOADING FACTORS FOR SATELLITES AND SPACE MISSIONS

COST OF LAUNCH OF SATELLITE	\$ 6 million
FIRST-YEAR OPERATING COST	\$20 million
COST OF LAUNCH PER POUND OF PAYLOAD	\$500-1000
WEIGHT OF FUEL PER POUND OF PAYLOAD	10-100 lbs
WEIGHT OF REGULATED AND CONDITIONED POWER:	
a. PRESENT SMALL POWER UNITS (100W)	250 lb/kW
b. FUTURE LARGE POWER UNITS (50 kW)	65 lb/kW
SIZE OF SMALL POWER UNITS (100W)	1500 $in.^3$/kW
SIZE OF LARGE POWER UNITS	500 $in.^3$/kW
AREA OF SOLAR PANELS	250 ft^2/kW
ELECTRICAL POWER WEIGHT PENALTY FOR BALLISTIC ROCKET	30 lb/kW
ELECTRICAL POWER WEIGHT PENALTY FOR AIRCRAFT	60 lb/kW

reflector and a sapphire infrared window. This collector is designed to radiate waste heat directly into space. Other spaceborne tubes utilize conduction cooling that either requires auxiliary circulatory cooling systems or a massive conduction path to the outside surface of the spacecraft. Conduction cooling becomes unattractive as power requirements increase. In unmanned spacecraft, a circulatory cooling system would be very unattractive in view of reliability considerations and also on account of adverse effects of the circulating mass on the stabilization of the satellite orientation. The absence of gravity rules out cooling by natural convection. The utilization of surface tension effects makes various capillary-action-cooling schemes attractive for space applications, and they will undoubtedly be used to an increasing extent. The cooling of electron tubes for space applications is not well developed at present, and much work remains to be done to reduce the weight and size required for a cooling system.

ENVIRONMENT

Temperature

A number of studies has been made on the adverse effect of ambient temperature variations on electron tube operation, both at ground level and at high altitude.[14] With conventional glass envelope tubes, severe derating of normal operating parameters is necessary if reliable operation is to be maintained at elevated temperatures. This comment applies to electronic components in general. For a wide variety of airborne electronic systems, mean life seems to decrease about 10 percent for each 5°C increase in equivalent ambient temperature.[3] This trend is indicated by the curves in Figure 5 where the failure rate, λ , in percent per 1,000 hours, is plotted versus bulb temperature for miniature and subminiature tubes with a maximum rated bulb temperature of 220°C, and where the ratio of operating power to rated power (including heater) is shown as a parameter.[3] To maintain a given failure rate, or mean life,* at increasing temperatures, derating of the power level is necessary, as mentioned above.

The failure rate of microwave and power tubes is much higher than that of receiving tubes and may range from 4 to 10 percent per 1,000 hours, largely because higher temperatures prevail within the tube, and failure mechanisms are thereby accelerated. Recourse is therefore taken to external cooling to maintain ambient temperatures at conservative levels. As an example, the Telstar TWT Type M 4041 specification prescribes thermal cycling from 15 to 90 to 15°F (-26 to 32°C), and MIL-STD-202, which is frequently applied, calls for temperature cycling between -55 and +85°C (-67 to 185°F).

The great emphasis put at one time on tubes capable of operating at the 500°C-level[14] has largely disappeared, because other components in the circuit, particularly solid-state devices, could not survive such high temperatures. However, the need for baking out tubes on the pump at temperatures of 600°C, and higher, is generally recognized as a necessary measure to ensure low gas content and long life. Aluminosilicate glasses or ceramics, in conjunction with stable metals, must then be chosen for the envelope and the methods of joining must be suitably adapted.[15]

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*Mean life, mean time between failure (MTBF), mean time to failure (MTTF), and mean time to first failure (MTTFF) have been used interchangeably in reliability discussions; this is justified only when the failure distribution is exponential; otherwise, these terms do not describe the same thing.

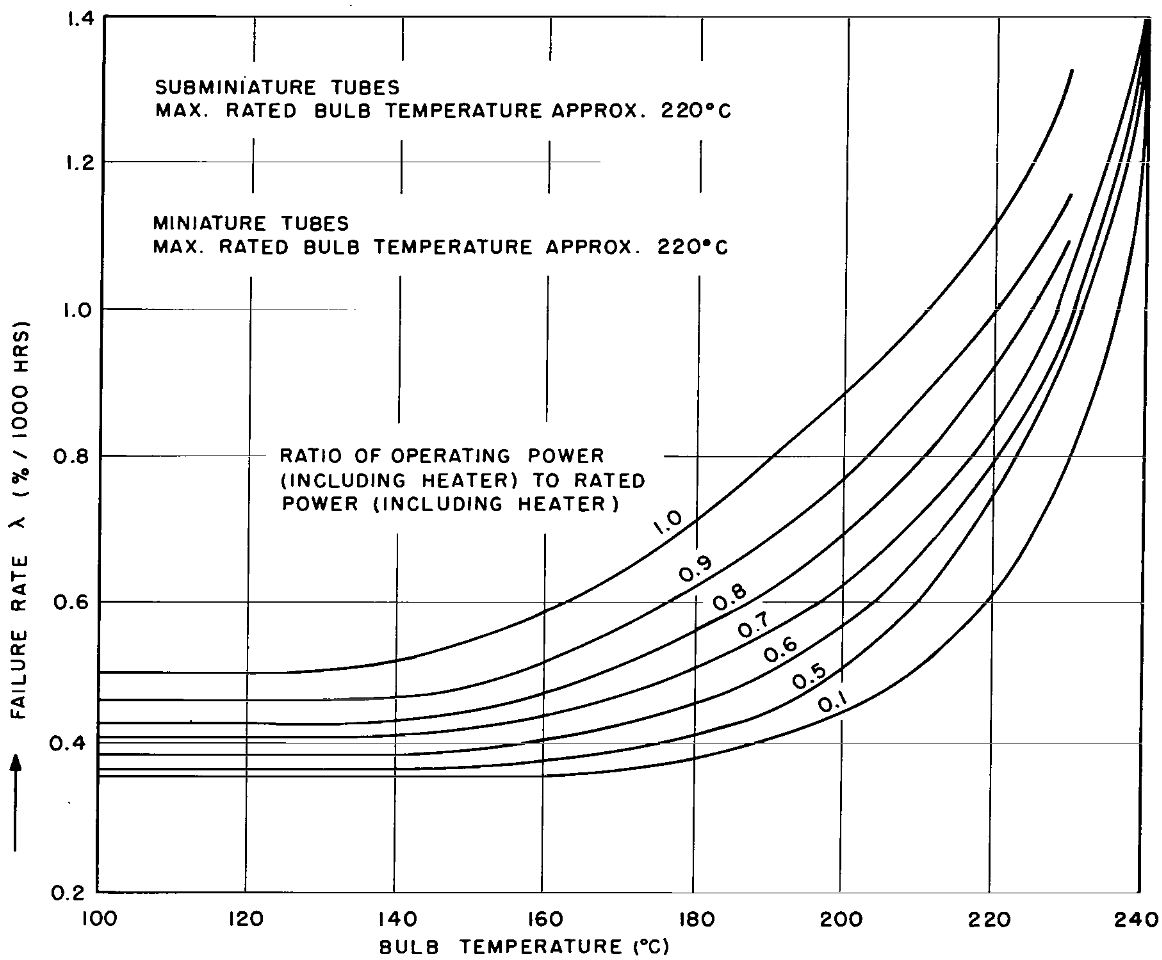

Figure 5. - Typical Receiving Tube Failure Rates as a Function of Bulb Temperature

Vibration and Shock

The importance of these parameters has been well recognized in the design of tubes for military applications. Equipment has been developed to simulate shock in the intensity range from a few g at 15 to 20 msec up to 1,000 g in less than 1 msec and to measure the shock spectrum resulting from the different types of excitation. Vibration at constant and swept frequencies is also routinely applied to tubes and usually covers the range of 5 to 2,000 Hz at 20 g in all three directions at a sweep rate of 1 octave per minute. An extensive investigation of the reproducibility of electron tube vibration test data was conducted at the Illinois Institute of Technology* several years ago and showed up the difficulty of obtaining consistent results from different exciters.

Vibration and shock encountered by tubes during space missions are negligible except for the severe excitation during launch. Sudden application of thrust on initiation of the last stage of burning may cause steady acceleration of 30 to 50 g.[3] In cases of "hard lander" missions, severe shocks on the order of 10,000 g for 1 msec are encountered. Travelling-wave tubes developed for missile guidance systems have successfully survived more than 100 launches without failure.[12] The vibration test applied to a final TWT package was 15 to 50 to 15 Hz at 0.3 inch displacement (3.5 to 38 to 3.5 g), 50 to 100 to 50 Hz at 20 g, 100 to 2,000 to 1,000 Hz at 10 g. All guns and helices were subjected to vibration using 50 to 2,000 to 50 Hz at 20 g during fabrication to remove foreign particles. Four guns were vibrated at 15 to 2,000 Hz from 4 to 20 g after 11,000 on-off cycles of the heater; four guns were shock-tested at 3 to 400 g without harm, one to destruction at 1,600 g, after 11,000 on-off cycles; and five heater-cathode structures were vibrated over 100 to 3,000 Hz at 40 g.[12] These data serve well to illustrate the degree of shock and vibration resistance that can be achieved.

Radiation

The radiation encountered on some space missions is about 6 orders of magnitude greater than that present at the Earth's surface; it is most severe in the Van Allen belts of trapped radiation around the Earth. In deep space, the radiation intensity is orders of magnitude below the peak of that

*Armour Research Foundation, Contract AF 33(600)-31879.

prevailing in the Van Allen belts but equivalent to about 2 orders of magnitude above that on the Earth's surface. The radiation encountered in the Van Allen belts should be considered in the design and operation of electron tubes, but commonly used tubes are less subject to radiation-induced failure than are most solid-state devices; in spacecraft, the latter outnumber tubes by a large factor.

The radiation environment encountered by a tube varies widely for different missions, and it also depends on the particular location of the tube in a given spacecraft and on the shielding provided by the spacecraft skin. Some typical values from published[16] and unpublished sources* will give an idea of the order of magnitude of the radiation problem.

In Earth orbit, the Telstar average equivalent dose amounted to 6×10^6 particles/cm^2-sec with energy equivalent to 1 MeV electrons, or roughly a dose of 6 R/hr.

A plot of the electron flux is shown in Figure 6 where the omnidirectional flux of electrons with energies over 0.5 MeV is used as the parameter on the coordinates of latitude versus altitude, expressed in units of Earth radii. From this plot it can be seen that peak fluxes at about a 1,200-nm** altitude over the equator (1.35 Earth radii above the center of the Earth) reach a value near 3×10^8 electrons/cm^2-sec. The flux rises very rapidly at altitudes above 600 nm to a peak and then falls rather slowly with increasing altitude. Plots of flux for electrons with different energies vary widely in detail but are basically alike.

A similar plot of omnidirectional proton flux for energies above 50 MeV is shown in Figure 7. The proton flux here reaches a peak value of 4×10^3 protons/cm^2-sec; the structure of the inner and outer belts is also apparent.

In deep interplanetary space, the fluxes consist of very hard cosmic rays and of the solar wind. The cosmic rays give a dosage equivalent to a moderate 10 R/yr, or roughly 100 times the rate prevalent at the Earth's surface. The solar wind has a high particle density of about 10^8 particles/cm^2-sec, but it is effectively shielded by even the thinnest spacecraft skin, because particle energies are so very low, i.e., approximately 1 keV, equivalent to about 500 km/sec.

*nm = nautical mile

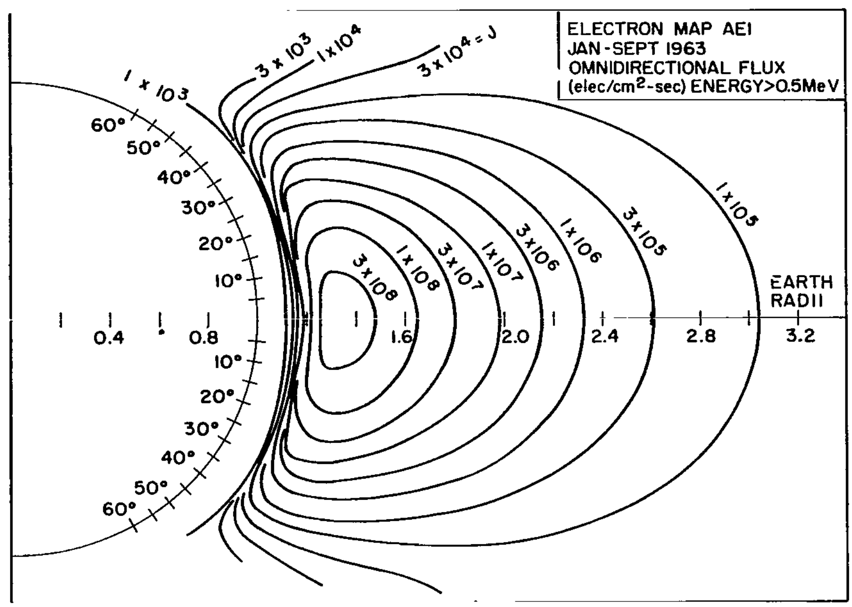

Figure 6. - R - λ Flux Map for AE1 (E> 0.5 MeV)

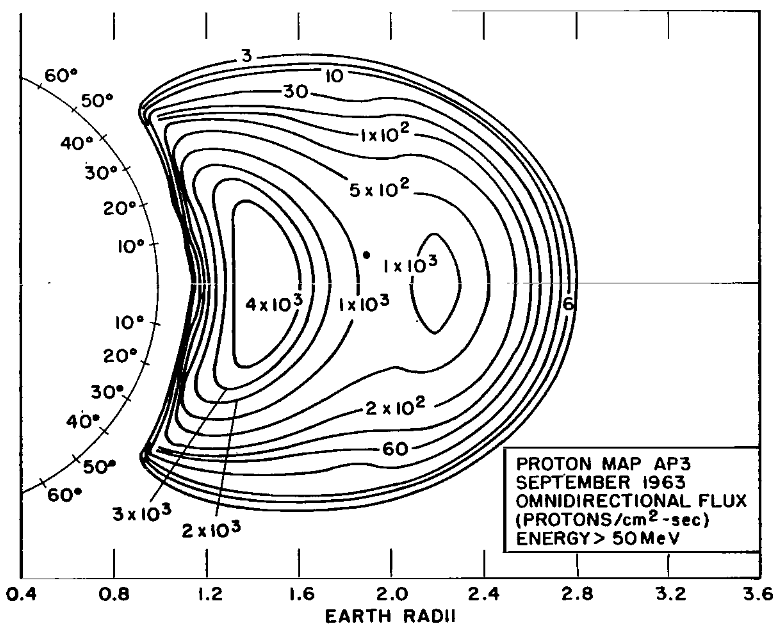

Figure 7. - R - λ Flux Map for AP3 (Contours Are the Omnidirectional Flux above 50 MeV)

Micrometeoroids

These particles present a unique environmental hazard in space. The micrometeoroid particles have a wide range of sizes and velocities, but the probability of catastrophic events is suitably low for very moderate skin thickness, so that electron tubes are not affected. Optical surfaces of cameras or special devices with sensitive surfaces may suffer erosion when exposed to outer space.

Sterilization

It is an established policy of the United States Government to insist on sterilization of a spacecraft that has any significant chance of impacting on another planet. This measure will prevent the propagation of life from the Earth and possible destruction of life forms on other planets before they can be scientifically scrutinized. Two procedures are used for sterilization of spacecraft, viz., heat soaking of subassemblies at 125°C for many hours and final surface sterilization by treatment with ethylene oxide. No harmful effects of such treatment on the performance of electron tubes has come to our attention. In fact, internal sterilization of the tube is achieved by the usual high-temperature bake-out on the pump. On the outside of the tube, materials that would be attacked by ethylene oxide must be avoided.

SPECIAL REQUIREMENTS

Low External Magnetic Field

Many spacecraft contain sensitive magnetometers that place much more stringent requirements on the allowable external magnetic leakage field from an electron device. These magnetometers can accurately measure planetary and interplanetary magnetic fields of a few gamma.* Some degaussing of the spacecraft to compensate for leakage fields is possible, and indeed necessary, to cancel effects of a direct current flow in the vehicle. The maximum permissible leakage field from components is 10 gamma at a distance of 3 to 5 feet from the component.

Center of Gravity

The center of gravity of a spacecraft must be well-defined and not subject to alteration. The location of an electron device in the system, and even the desirable shape factor, may be critical because of this. Any dynamic change of the center of gravity caused by uneven flow of a coolant, or by any other mechanical motion within the craft, would place an added burden on the attitude stabilization system and must therefore be avoided. Stabilization systems of the future will have to maintain attitude to within 10^{-2} and eventually to 10^{-5} degree.

Utilization of Vacuum of Outer Space

The possibility of taking advantage of the high vacuum of outer space for nude tubes has been considered from time to time. Such tubes would be free of the contaminants released within a closed envelope from inadequately processed components and therefore promise to have a longer life. Sensing devices could be freed of the limitations presented by the optical characteristics of the window. In fact, a photomultiplier used in an ultraviolet spectrometer was opened to outer space at high altitude in a recent experiment. However, tubes will have to be

*1 gamma = 10^{-5} Gauss.

produced in an Earth-bound atmosphere. The mechanics of opening the tubes later without exposure to shock or to contaminants present in the space capsule will offer severe complications.

More Effective Heaters

A fruitful area of endeavor, where a substantial improvement of the long-term performance of satellite tubes could be made, relates to the heater-cathode system. A highly efficient cold cathode would indeed relieve the adverse heat balance of the tube, but attempts in this direction have not been very successful so far. The introduction of radio-isotopic heaters is presently under investigation and expected to find wide application in a number of microwave tubes.

Another interesting development, originated at the Los Alamos Scientific Laboratory, is the heat pipe which is able to conduct heat along its length at a rate much higher than that of a solid copper rod of equivalent size. The heat pipe consists of an evacuated tubular structure that is lined with capillaries on its inner wall. Being partly filled with a high-vapor-pressure fluid, the tube conveys heat from its input end to the output where the vapor condenses and gives up its heat of condensation; the fluid returns to the input end through the capillary channels. The heat transfer mechanism is therefore not dependent on the presence of a gravitational field.

CONCLUSIONS

The feasibility of producing highly reliable microwave tubes for space applications has been demonstrated in successful missions in the past. To achieve this aim requires extraordinary care at all stages of development, that is:

1. In design, where only well-established procedures and proven methods can be accepted for the device and where the stringent environmental conditions to be encountered must always be kept in mind;

2. In prototype development, where the reliability of each component used in the device and that of the entire assembly must be ensured by controlled tests;

3. In the overall engineering organization, where a special effort must be made to imbue the team with the earnest conviction that aiming for perfection at all cost must be the guideline in all operations.

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125-22-03-12

REFERENCES

1. Peck, D.S., and Shennum, R.H.: Long-Life Electronics. Space/Aeronautics, Vol. 45, March 1966, pp. 81-90.

2. Peck, D.S., and Wooley, M.C.: Component Design, Construction, and Evaluation for Satellites. B.S.T.J., Vol. 42, July 1963, pp. 1665-1685.

3. Myers, R.H., Wong, K.L., and Gordy, H.M.: Reliability Engineering for Electronic Systems. John Wiley & Sons, Inc., New York, 1964.

4. Strauss, R.: The Reliability of Microwave Tubes. Proc. 10th National Symp. on Reliability and Quality Control, Washington, D.C., January 7-9, 1964, pp. 458-466. The Inst. of Electr. and Electronic Engineers, New York, N.Y., 1964.

5. Rodenhuis, K., Santing, H., and VanTol, H.J.M.: The Life and Reliability of Valves. Philips Tech. Rev., Vol. 18, December 1956, pp. 181-192.

6. Champeix, R., and Huber, H.: I--Laws of Reliability, Statistical Aspects of Electron Tube Reliability. Onde Electrique, Vol. 43, September 1963, pp. 880-891. II--Technology in the Service of Electron Tube Reliability. ibid., Vol 43, September 1963, pp. 941-956 (in French).

7. Schütze, H.J., and Dloughy, F.: Means for the Improvement of Electron Tube Reliability. Telefunken Röhre, Vol. 40, October 1961, pp. 169-186 (in German).

8. Noelcke, C.L.: Deterioration Mechanisms in Electron Tubes. ARINC Research Corporation, Publication No. 101-4-127, November 7, 1958.

9. Holdaway, V.L.: VanHaste, W., and Walsh, E.J.: Electron Tubes for the SD Submarine Cable System. B.S.T.J., Vol. 43, July 1964, pp. 1311-1338.

10. Kirkman, R.A.: Fallacies in Failure Concepts and Application of Modern Reliability Theory-- Physics of Failure in Electronics. Goldberg, M.S., and Vaciaro, J., editors; Proc. Symp. on Physics of Failure in Electronics, September 26-27, 1962, Chicago, Illinois, Spartan Books, Inc., Baltimore, Md., 1963; pp. 123-145.

11. Weibull, W.: A Statistical Distribution Function of Wide Applicability. J. Appl. Mechanics, Vol. 1-8, September 1951, pp. 293-297.

12. Bodmer, M.G., Laico, J.P., Olsen, E.G.,and Ross, A.T.: The Satellite Travelling-Wave Tube. B.S.T.J., Vol. 42. July 1963, pp. 1703-1748.

13. Bodmer, M.G.: Dip-Testing, A New Method for Measuring Cathode Activity. I.R.E. Trans. PGED-5, Vol. 43, January 1958.

14. Kohl, W.H., and Rice, P.J.: Electron Tubes for Critical Environments. Final Report, Stanford Research Institute for Wright Air Development Center. Contract AF33(616)-3460, July 1957; WAD Tech. Report 57-434; PB 131852; $3.50, AD 151158.

15. Kohl, W.H.: Handbook of Materials and Techniques for Vacuum Devices. Reinhold Publishing Corporation, New York, 1967 (in press).

16. Vette, J.I.: Models of the Trapped Radiation Environment--Vol. 1: Inner Zone Protons and Electrons. NASA SP-3024, 1966.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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