WINDOW MATERIALS DESIGN AND PROPERTIES FOR USE IN HIGH POWER KLYSTRONS*

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Summary

This paper discusses the design of and material for klystron output windows to be used on the Stanford 20-GeV linear accelerator. Alternative window geometries are considered in view of the requirements of the SLAC application. Criteria for choice of window material are presented along with physical properties of several dielectric materials, and results of experimental evaluations of various window materials are described. The necessity for, and effectiveness of, techniques for reducing multipactor are discussed. Reasons are given for the choice of the present SLAC klystron window.

Introduction

A window for klystrons used on the Stanford two-mile, 20-GeV accelerator should be capable of transmitting up to 24 MW of peak power and 22 kW of average power for a period considerably longer than the tube lifetime. Because the power handling capability of the output window has proved to be a basic limitation on the power and the life of an evacuated microwave tube, a window study program has been conducted as part of the research and development work on klystrons at SLAC.

The specific objective of the window program at Stanford is the development of a window which will operate reliably with high vacuum on both sides. This paper discusses the empirical aspects of the choice of a window design, the criteria for choosing a window material, and the results of the experimental evaluation of a number of window materials. Window studies have also included diagnostic experiments intended to identify the nature and causes of various types of window failure, which have been described in another paper.[1] Because single-surface multipactor heating is recognized as a major cause of window failure, the necessity for measures to inhibit this multipactor (and the effectiveness of window coating in particular) are discussed as part of the general consideration of window material design.

Considerations in Choosing a Window Design

The variable elements of a microwave window design are: (1) the geometrical configuration of the dielectric and surrounding waveguide, (2) the vacuum-tight seal between the dielectric and waveguide, and (3) the dielectric material itself. Only the choice of the dielectric material will be considered in detail.

A wide variety of alternative structural window designs are available to the tube designer and many of these configurations are described in the literature.[2,3] The high peak power requirements and the possibility of multipactor on both surfaces have largely determined the designs considered for the SLAC klystron window. Cylindrical windows, operating in the dominant mode of propagation in cylindrical waveguide (TE_{11}), are preferred because of the reduction of electrical fields at the critical dielectric-metal seal area. Orientation of the dielectric element perpendicular to all adjacent waveguide surfaces and parallel to the electric field vectors reduces the number of possible multipactor modes. Most of the high power window testing has been performed using single thin disk windows, mounted in either of two geometries. The configuration most used to date has been the "Model A" geometry (a pillbox window matched in a narrow bandwidth by inductive irises) which has been used on the klystrons at the Stanford 1-GeV Mark III accelerator since 1950[4]. Most recent and current testing is being done in symmetrical pillbox configurations identical or similar to that now being used on SLAC klystrons.[5] In the latter designs, impedance-matching of the vacuum-dielectric interface is performed by the adjacent rectangular-circular waveguide transitions.

The vacuum seal between the dielectric window and the metal waveguide is usually made by a brazed joint, but can also be accomplished by compression; both sealing methods have been described in detail elsewhere.[6,7] Most of the test windows treated in this study have been mounted by shrink-fitting into circular waveguide sections, allowing performance of the window to be analyzed separately from the complicating factors introduced by use of a brazed dielectric-metal seal. The use of the shrink-fitting technique is justified on the assumption that a well-constructed window seal does not contribute to the types of window failure considered here.

Choice of the dielectric material to be used for the window is determined by various physical properties. Published values for most of the pertinent electrical, thermal, and mechanical properties of window materials considered in this study are listed in Table I. A number of important physical properties have not been included in the table, because data is not available or is too subjective to serve as the basis for realistic comparison. Secondary emission coefficient, resistance to shock, chemical stability, machineability, and operating temperature limitations are included in this category. No one material has optimum value in all physical properties. The best that can be done is to choose that material which

*Work supported by the U.S. Atomic Energy Commission.

best combines high dielectric strength, low dielectric loss, low thermal conductivity and coefficient of expansion, and high mechanical strength. Many of the more promising dielectric materials to be considered for window service have been experimentally evaluated at SLAC and are discussed individually below.

High Power Window Test Results

Window material tests in the SLAC window study have been performed in resonant rings and resonant cavities[1] capable of providing actual or equivalent powers in excess of that available from present microwave power sources. Two ring resonators, capable of 175 Mw, 160 kw and 90 Mw, 45 kW respectively, were used for nearly all of the window tests described here. Comparative material testing was done on the lower power ring, LN trapped, oil-diffusion-pumped to operating pressures of 10^{-5} to 10^{-4} torr. Most of the testing of multipactor suppression has been done in the high-power all-metal ring ion-pumped to pressures of 10^{-8} to 10^{-7} torr. Data available during ring operation includes power level, match and gain of the ring, operating pressure, X-ray radiation intensity, temperature gradient from edge to center of the window, and visual observations and photography through viewports on either side of the test section.

Window Material Comparison Testing

Results of the high power tests performed in the material comparison study are summarized in Table II. All of the material samples compared were tested in Model A geometry in the oil-diffusion-pumped ring except as noted in the text.

The standard test procedure is to gradually raise peak power to the maximum available ring power (70 to 90 Mw) or until dielectric failure occurs; then to change from 60 pulse per second operation to 360 pps (3×10^{-6} sec pulse length); and finally, to raise average power to maximum ring capability of 45 kW or to point of thermal failure. Performance characteristics of the window materials are discussed individually along with reasons for consideration of the specific material.

Alumina -- With the exception of secondary emission coefficient, alumina possesses in some degree all of the requisite properties of the ideal window material. Dielectric loss, dielectric strength, and mechanical strength are particularly good. Alumina is available from many commercial sources in a variety of shapes and sizes and is easily metallized for brazing into a vacuum-tight window assembly. More than 200 alumina windows have been tested in resonant rings or cavities. Sixty windows, 0.125 inch thick x 3.000 inch diameter, tested in Model A geometry, provide a broad comparison base for evaluation tests on all other window materials. Five separate alumina bodies from three different manufacturers have been tested and all brands have shown similar operational characteristics.

Most of the alumina windows tested have shown definite symptoms of single-surface multipactor, and all of these windows have eventually failed with continued operation. Failure usually occurs when the window cracks, "Thermal Failure", under an excess of multipactor induced thermal stress; but may also take the form of punctures and/or internal failure, "Dielectric Failure", during high peak power operation at a low pulse repetition rate. It has become possible to recognize the visible indications of multipactor and to distinguish the various anomalous surface glow patterns associated with it from the benign gas discharge glow pattern which changes as a function of electric field and is present on all windows. In nearly all cases where the multipactor symptoms are not present, the window does not fail or if it does, the failure is due to dielectric breakdown at high peak power rather than because of thermal stress. Attempts have been made to relate alumina window multipactor to variations of the surface roughness or to imperfections in mounting the window; neither of these approaches has yielded correlative data. At present the factor determining susceptibility to multifactor is assumed to be variations in the material itself or the presence of thin films of impurities which could change secondary emission.

Discussion of alumina is not complete without mention of single crystal alumina (sapphire). Sapphire windows must be zero-oriented with respect to the direction of power transmission in order to prevent complex mode coupling. The price of zero-oriented sapphire windows at S-band is prohibitively high, considering that samples which were tested in a resonant cavity showed no definite superiority over similarly tested polycrystalline alumina.

Beryllia -- One of the most promising alternatives to an alumina window is beryllia, because of its extremely high-thermal conductivity. Beryllia is not particularly strong mechanically, however; additionally the potential danger in handling such a toxic material is a definite drawback. Although only one beryllia window was tested in this study, the judgment that beryllia shows no clear superiority to alumina under SLAC conditions, is backed-up by experience with a number of beryllia windows which were used on SLAC klystrons. All SLAC Beryllia windows including the one tested on the ring were mounted in a symmetrical matching structure.

Quartz -- High quality fused quartz possesses many of the characteristics of an "ideal" window material. Dielectric loss and breakdown strength, in particular, are extremely good; but the thermal properties of quartz are severe drawbacks. The low coefficient of thermal expansion makes it difficult to fabricate a vacuum-tight quartz window which will operate throughout the wide range of temperature normally encountered in tube service, and low thermal conductivity causes quartz to be extremely susceptible to thermal failure.

The difficulty in sealing quartz was not a factor in these tests because of the shrink-fit mounting used. All of the quartz windows tested suffered catastrophic thermal failures except for those windows which were grooved for multipactor suppression. A meaningful analysis of the weaknesses of quartz windows was made difficult by the anomaly of performance characteristics from sample to sample. The effect of poor thermal conductivity was identifiable from the extremely high temperature gradients (up to 600°C) attained immediately prior to failure. The success achieved by grooving quartz indicated that multipactor was responsible for the thermal failures suffered by flat quartz samples.

Boron Nitride -- The outstanding property of boron nitride is its low secondary emission coefficient, not shared by any of the other choices of window material. Boron nitride as normally produced in hot-pressed form, however, is pervious to gases and is extremely hygroscopic. Only the recent development of pyrolitic boron nitride has permitted this material to be considered for window service at all. Pyrolitic BN is not hygroscopic, is impervious to gases, and has very favorable thermal conductivity parallel to the surface of its deposit substrate. Although BN also has an extremely high dielectric strength, unfortunately the greater strength is normal to its surface of deposition. Consideration was given to the possibility of constructing boron nitride windows made by depositing layers of the pyrolitic material on a body of homogenous (hot-pressed) BN. Three types of hot-pressed BN were tested, all failing at moderate power levels and showing a definite susceptibility to internal failure. A combination BN window does not presently appear to merit further consideration. A single sample of recently produced pyrolitic material performed quite well, mounted with its substrate plane parallel to the electric field thereby taking advantage of its maximum thermal conductivity. This sample indicates a definite improvement over pyrolitic BN available two years ago when the material showed a strong disposition toward separation between laminations, and consequent susceptibility to electrical breakdown within the interlaminar spaces.

Magnesia, Zirconia -- Both of these materials were found to be unsuitable for window service on the basis of samples that were tested. Failure of the magnesia appeared to be the result of low dielectric strength, but the rather low density of the samples tested did leave open the possibility that a denser magnesia body might prove more serviceable in window duty.

Zirconia showed even less promise than magnesia. The high dielectric constant (≈ 18) made it quite difficult to match a zirconia window. Poor thermal conductivity and excessive dielectric loss combined to produce thermal failure due to high temperature gradients (600° to 700°C) at very low power levels.

Tests of Multipactor Suppression Techniques

Most window failures during high average power operation are the direct result of electron-multipactor overheating. Since secondary emission coefficients greater than unity are common to nearly all the window materials considered, efforts have been made to suppress secondary electron emission on commonly used window material. Single surface multipactor was first described by Priest and Talcott,[9] as was the titanium coating method of multipactor inhibition. Subsequent work at Eitel McCullough has resulted in improved coating, techniques and development of an alternative means of suppressing multipactor,[10] in which grooves on the both surfaces of a disc-shaped window are oriented perpendicular to the prevailing electric field direction.

Initial high power tests of the grooved window design were performed at SLAC in cooperation with Dr. Oskar Heil of Eitel McCullough, Inc. Results of the tests on grooved windows of alumina and quartz are included in the summary of material evaluation tests (Table II). It was found that grooved alumina windows with titanium suboxide coating sputtered onto the ridges of the grooves would effectively prevent window multipactor and failure. Alumina windows which were grooved but not coated showed indications of reduced multipactor, but were quite susceptible to dielectric breakdown. Failure usually occurred in the form of punctures in or near the areas of high electric field gradient in the dielectric at the bottoms of the grooves. Grooved alumina windows were also tested with coatings of silicon dioxide and silicon monoxide, neither of which appeared to be as effective as titanium suboxide. Of the quartz windows which were tested with grooves, only one window failed while the grooves were oriented perpendicular to the electric field. The other failure occurred, as expected, when the window was purposely mounted with the grooves parallel to the prevailing electric field. Titanium coating was not necessary for the successful operation of grooved quartz windows. The effectiveness of coating alone on quartz window has not yet been evaluated. A single sample treated with sputtered titanium suboxide coating suffered persistent surface breakdown, apparently because of an excess of window coating.

Titanium coating has come to be the most convenient and commonly used method of multipactor prevention. All klystron windows made at SLAC have been coated since the completion of a device which applies sputtered coatings of titanium. An evaluation of the effect of the SLAC coating was begun on the all-metal resonant ring soon after it was completed. Attempts were made to measure the relative effectiveness of different degrees of window coating and the stability of the coating. To date it has not been possible to demonstrate an absolute lower limit for the effectiveness of the coating, although it is possible to detect excessive coatings by surface resistivity measurement and thus avoid overheating due to resistive loss. Experiments have indicated that coatings are stable throughout the tube bake cycle and normal window operation. The coating may be dissipated by persistent surface arcing, but this is not likely to occur except at extremely high peak power levels. The all-metal ring is presently being utilized for pre-testing of windows before installation on SLAC klystrons. This precautionary measure acts as a safeguard on window reliability and will be continued until satisfactory control of the coating procedure has been achieved.

Conclusions

Comparative evaluations of window materials have thus far restricted the choice of a window material to polycrystalline alumina, sapphire, beryllia, grooved quartz, or pyrolitic boron nitride. All of the alternatives except alumina have one or more characteristics which discourage their use on the SLAC klystrons. Sapphire is prohibitively expensive. Beryllia is a potential safety hazard. Grooved quartz and pyrolitic boron nitride are both quite difficult to seal because of low thermal expansion coefficient. While all of these materials are potential alternatives for other microwave window applications, none appears to be more suited for use on the SLAC klystron than alumina. Present alumina windows, however, must be coated with titanium oxides before they can be relied upon to perform satisfactorily.

Further work should be devoted to identification of the window failure mechanisms and their causes: this knowledge would permit a better definition of window material specifications and would indicate improvements or modifications of existing dielectric materials which would make them more suitable for window use. Part of this effort should be directed toward a better understanding of the specific physical properties and limitations of various materials, especially alumina.

On a more practical basis, continuing effort will be devoted to control of window coating with the eventual objective of obviating the present necessity for window pretesting. Comparative material evaluation is continuing with tests of improved glass windows. Other materials, or improved versions of materials already considered may also be evaluated when they become available.

Acknowledgement

The authors wish to thank Drs. J. Lebacqz and P. Szente and Messrs. G. Merdinian and W. Schulz, for their valuable technical advice in this effort. They also thank G. Cunningham and D. Scule who conducted the tests reported here and other members of the Stanford Linear Accelerator staff who have contributed to this work. They wish also to acknowledge the cooperation of the manufacturers of dielectric materials evaluated; in particular, Western Gold & Platinum, Union Carbide, and Norton Refractories who have supplied courtesy samples.

References

1. J. Jasberg, and J. V. Lebacqz, "High Power Microwave Windows," Fifth International Conference on Hyperfrequency Tubes, Paris, (September, 1964).

2. D. B. Churchill, "Superpower Microwave Windows, Final Report," Sperry Gyroscope Company, NA-8240-8372, (January 1964).

3. Floyd Johnson, "High Power R-F Window Study Program, Final Technical Report," Varian Associates #304-1F, RADC-TDR 63-510 (November 1963).

4. J. V. Lebacqz, J. Jasberg, H. J. Shaw, and S. Sonkin, "High Power Windows at Microwave Frequencies," Proc. IEEE 105, (Part B, Supplement No. 11), 617-622 (1958).

5. J. V. Lebacqz, "High Power Klystrons," IEEE Particle Accelerator Conference, Washington, D.C., March 10-12, 1965.

6. L. Reed, et al., "Metallurgical Research and Development for Ceramic Electron Devices," Quarterly Status Reports 1962-1964, Eitel-McCullough, Inc., San Carlos, California.

7. A. C. Grimm, and P. D. Strubhar, "Dielectric to Metal Seal Technology Study," RCA Technical Report, RADC-TDR 63-472, (October 1963).

8. W. B. Westphal, "Dielectric Constant and Loss Measurements on High-Temperature Materials," Laboratory for Insulation Research, Massachusetts Institute of Technology (September 1963).

9. D. H. Priest, and R. C. Talcott, "On the Heating of Output Windows of Microwave Tubes by Electron Bombardment," IRE Transactions on Electron Devices ED-8, 243-251 (May 1961).

10. R. Hayes, "Research on Microwave Window Multipactor and its Inhibition, Final Report," Eitel-McCullough, Inc., report on work supported by the U. S. Army Electronic Research and Development Laboratories (1962-1964) [Includes work of Heil and Priest]

TABLE I. Physical Properties of Window Materials.

Material	Manufacturer	Dielectric Strength (volts/mil)	Dielectric Constant	Dielectric Loss Factor	Thermal Conductivity (ca/cm²/sec/°C)	Thermal Expansion Coefficient	Tensile Strength (PSI)	Compressive Strength (PSI)	Flexural Strength (PSI)
Alumina									
AL-300	Wesgo	1100 *	9.4**	.005**	0.064	8.5×10^{-6}	---	250,000	46,000
AL-995	Wesgo	800 *	9.4**	.002**	0.070	6.9×10^{-6}	---	300,000	62,000
AD-96	Coors	220-240	8.9	.073	0.048	3.7×10^{-6}	26,000	300,000	49,000
AD-99	Coors	220-240	9.4**	.002**	0.070	3.5×10^{-6}	34,000	300,000	54,000
4462	Frenchtown	225	9.2	.003	0.071	6.11×10^{-6}	---	425,000	55,000
Sapphire	Linde	1700	9.4**	.002**	0.06	7.7×10^{-6}	58,000	300,000	65,000
Beryllia BD-96	Coors	238	6.6	.003	0.60	9.23×10^{-6}	---	225,000	32,000
Fused Quartz Amersil	Engelhard	410	3.72**	.001**	0.0033	0.54×10^{-6}	7,000	190,000	---
Boron Nitride									
Hot-pressed	Union Carbide	300	4.78**	.0015**	0.045	0.33×10^{-6}	---	---	15,000
Pyrolitic	Union Carbide	>3000	5.12**	.0005**	0.15	0.1×10^{-6}	---	---	15,000
Magnesia	Norton	---		---	0.100	---	---	---	---
Zirconia	Norton	---	~ 20	---	0.02	9.1×10^{-6}	---	---	2,300

*Measured in oil

**Values are at 3 to 6 Gc and were taken from reference (8) (All other values are quoted from manufacturer's data sheets.)

TABLE II. Comparative Material Test Data.

Material	Samples Tested	*Surviving Samples	Failing Samples: Dielectric Failures	Failing Samples: Thermal Failures	Remarks
Alumina					
a)(Untreated)	46	13	18	10**	Multipactor on 60% of windows tested.
b)(Grooved)	7	1	4	2	Multipactor reduced, more susceptible to dielectric failure.
c)(Grooved and Coated)	7	3	4	--	No multipactor, still susceptible to dielectric failure.
Beryllia	1	0	--	1	Multipactor
Quartz (Flat)	5	0	--	5	Multipactor-heating, high temp. gradient, catastrophic failure.
(Grooved)	6	5	1	--	Only failure during mismatch at 80 MW, no multipactor.
Boron Nitride (Hot-pressed)	8	0	8	--	No multipactor.
(Pyrolitic)	3	1	2	--	Interlaminar breakdown in older samples, new sample survived.
Magnesia	5	0	5	--	Most failed at low peak power (< 7 MW)
Zirconia	3	0	--	3	All failed at low average power (≈ 2 kW)

*Surviving maximum available powers ≥ 70 MW peak (1.8×10^{-4} duty factor) and 40 kW at 1.08×10^{-3} duty factor.

**Five samples which were not tested at high average power had suffered severe multipactor during peak operation, and would most likely have failed thermally.