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# HIGH POWER MICROWAVE WINDOWS*

by

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# I. INTRODUCTION

The two-mile-long, 20 GeV linear electron accelerator, now being constructed at Stanford University under contract with the U. S. Atomic Energy Commission, will be powered by 240 klystrons with a design power output of 24 megawatts peak and 22 kilowatts average. Because past work on windows, in connection with the 1-GeV Mark III accelerator at Stanford, had shown that window life had an important effect on klystron performance and life, a window study program was started in conjunction with the research and development effort on klystrons at the Stanford Linear Accelerator Center. This paper will report work done under this program.

The studies reported here were all done at a single frequency, 2856 Mc/sec, on windows operating with high vacuum at both the tube and load sides. The pulse length was 2.5 μsec, with repetition frequencies varying from 60 to 360 pulses per second. Power levels up to 175 MW peak and 160 kW average were used.

The specifications listed above were dictated by the accelerator requirements and differ from usual communications practice in that a single frequency and an evacuated load were used. The first of these fortunately allows us to avoid the difficult broad band problem. The second, however, poses two new problems: (1) the cooling is now done mainly by conduction, and (2) multipactor can occur on both faces of the disk.

Although other structures have been tried at Stanford, the work here is concerned only with circular disk type structures normal to the waveguide axis. A number of variations of this basic type were used. The goals of the program were (1) to obtain a better understanding of the nature of window failure,

(2) to determine the relative merits of promising window materials and techniques, and (3) to evaluate window designs.

This paper will discuss the test apparatus, the types of failures observed, results of the testing program, protective devices, and the conclusions reached.

In 1958, we reported on the window work being done in connection with the Mark III accelerator at Stanford,[1] and it may be appropriate to bring that subject up to date at the present time. Since that paper, a major change in the operation procedure of this accelerator has been introduced which has resulted in an improvement of the window mean time to failure from approximately 1500 hours to well over 12,000 hours. This was accomplished by always turning power on at a rather low value (approximately one-fifth full power) and increasing to full power in about 6 seconds. It is believed that this procedure allows gradual clean-up of absorbed gas from the window and waveguide surface after a turn-off, thus preventing excessive pressures and possible breakdown in the system. As before, the major type of window failure still occurring on this machine is the puncture of the window disk. No disks fail by cracking only, but some disks exhibit both cracking and puncturing, which is felt to be due to excessive heat occurring after the window has been badly damaged by punctures. As will be seen below, it is unlikely that this machine (which has average powers of about 2 kilowatts flowing through the window) will have window failures due only to thermal shock.

## II. TEST APPARATUS

Initial window studies at Stanford were made by direct observation on klystrons, but most of the tests done in this program have been performed in two resonant rings or in two cavities. An existing resonant ring pumped by an oil diffusion, liquid nitrogen trapped system was initially used. Later, two resonant cavities, both ion pumped (one sealed with O-rings and the other with all-metal gaskets), were put into operation (see Fig. 1). Most recently, a resonant ring of all-metal construction and pumped by a large ion pump has been used in addition to the cavities (Fig. 2).

Window tests in cavities and rings should complement each other because the windows in resonant cavities are tested under conditions of a short-circuited system while those in the ring are tested under well matched conditions. In practice, however, it is found that the simpler and less expensive cavity is more difficult to keep in tune and it is much more susceptible to variations in loading caused by the test window. Therefore, by far the majority of these tests have been done on resonant rings. The cavity does have the advantage that effects of loading are more easily observable. In the case of the effects causing breakdown, it was found that results obtained from either cavities or rings agree reasonably well with each other. The rings have viewing ports allowing observation of both sides of the window under operation; the cavities allow viewing on only one side. Infra-red thermometers were used to measure the operating temperature of the test window, but it was necessary to use care in order to avoid measuring reflected heat from hot spots within the cavity or ring. All systems were equipped with ionization gauges to measure the ring vacuum conditions as near as possible to the windows under test.

Completed window assemblies have been tested in the rings, as have large numbers of samples which were shrunk into cyclinders. Shrunk-in samples were also employed in all of the cavity tests. This technique has proved a valuable tool for testing materials because the assembly does not have to be leaktight in a completely evacuated system, and moderate pressures insure good electrical contact. This method is also faster and much less expensive than tests using completed window assemblies. The windows can be studied without being affected by the sealing techniques, and any detrimental effects from sealing can be evaluated separately. It has been found that the metal-to-ceramic seal, if properly done, does not affect the performance of disks in the circular geometries used for these tests.

In addition to the test apparatus described, a life test facility consisting of a klystron driving 6 windows connected in series and terminated by a dummy load has been operated. The windows are evacuated by a large ion pump and the vacuum on both sides of the disk is measured by ion gauges. Provision is also made to measure direct and reflected power between each window.

## III. TYPES OF WINDOW FAILURES

During this program three types of window failures have been observed, both on klystrons under test and in the test devices described above. These types of failures are (1) punctures, coupled with internal damage; (2) simple cracking, with no other damage present; and (3) melting of the ceramic material by excessive heat. One window, which failed on a klystron, had all three types of failure.

A. <u>Punctures</u>

Punctures are thought to occur in disk windows in the following manner: As the power is raised in the system, a level is reached at which internal breakdown takes place within the window. If the power is allowed to remain on, breakdown will occur continuously within the window in many different paths. When connecting paths reach both surfaces, a leak will occur. As the power is initially raised, surface arcing (Fig. 3) is sometimes seen to occur across the face of the window but leaves no visible damage upon it. Other internal breakdowns have occurred with no previous surface arcing. The destroyed window generally exhibits many small craters on its surface (see Ref. 1). Within the body of the window there may be a small to a massive amount of internal destruction of the material. This type of internal breakdown should be distinguished from punctures through the disk due to charging of the disk with high energy electrons. This is a well understood effect and is cured by shielding the window from the source of energetic electrons. In tests at Stanford we were unable to cause puncture by bombarding ceramic disks unless the opposite side was in air or was coated with a highly conductive material.

During the internal breakdown a broad diffused path of arcing can be seen (Fig. 4a), which is quite distinct from the sharp, lightning-like arcing which occurs over the surface. With most types of thin alumina disks, the resulting destruction can be readily seen by back illumination (Fig. 4b). For some time it was believed that these destructive arcs originated from the surface because we failed to find internal destruction unrelated to a surface puncture. However, while working under a subcontract to Stanford, Dr. L. S. Nergaard of RCA Laboratories, Princeton, New Jersey, showed that internal damage existed in every case of punctured windows, and suggested that internal damage was always responsible for window failure by puncture. By careful monitoring and by stopping tests as soon as any evidence of internal failure had occurred, we were able to obtain samples showing no external defects but with definite internal damage.

Another puzzling aspect of these tests was the failure for some time to produce internal damage on windows in the ring at 25 MW levels, even though these levels were many times higher than those which damaged windows on tubes. It was only after the ring power was raised to about 50 MW that systematic breakdown of window samples was observed. It appears that under matched operating conditions, the voltage gradients within the window are insufficient to cause breakdown even at full power. However, if any breakdown occurs elsewhere in the system, then fields equivalent to as much as four times the power can occur, causing breakdown in the window. Testing systems must therefore be capable of at least four times the power under which the window is designed to be run.

As might be expected, this type of internal puncturing of ceramics also causes large numbers of small localized cracks in the vicinity of the puncture. Punctures near the surface will also cause large burst of gas within the system. The level at which puncturing is apt to occur has not been found to change significantly when the pulse repetition frequency is changed.

B. Cracking

The simple cracking of a microwave ceramic window is due to excessive thermal stress caused by heating. At the power levels considered here, this heating is caused primarily by multipactor along the surface of the window, as described by Priest and Talcott.[2] Operation of a window with pressure on both sides reduces the heating to that due to loss tangent. The multipactor is nearly always accompanied by a strong diffuse glow on the surfaces of the window (Fig. 5). Windows operating in this manner have failed when passing just a few kilowatts. Other windows which did not have multipactor have handled up to 165 kilowatts, so the seriousness of the problem is evident. Very little is gained by cooling the window edge, because this does not reduce the thermal gradient significantly. Decreasing the thermal gradient through the use of a good conductor such as beryllia is helpful. However, this helpfulness is not as much as might be indicated by beryllia's increased conductivity over alumina because of the lower mechanical strength of beryllia. The best solution is to prevent multipactor in some manner.

C. Melting

Melting of windows is caused by a power arc which stays at the window surface for some time. This phenomenon has not been observed in any of our test apparatus, but has occurred rarely and only on klystrons which were improperly operated; it is caused by inoperative protective devices and very poor vacuum conditions. While it is an important effect in pressurized systems, it is not believed to be of consequence here.

## IV. TEST RESULTS

More than 250 windows were tested in arriving at the general conclusions on the nature of window failures described above. The most striking result of these tests is the wide range of powers over which failure occurs, even though test conditions are kept as constant as possible. For example, samples from a single batch of alumina have failed due to internal damage at power levels from

25 MW to 175 MW peak power. Other samples of this material failed by cracking from 5 kW to 165 kW average power. It is obvious that a large number of samples must be used in each test. In practice, a reasonable number of samples (i.e., six) may only give sufficient evidence to indicate a trend, unless a drastic change is noted.

A. Internal Damage

If most windows failed internally when the field gradients in the disk exceeded the dielectric strength of the material, the explanation of this type of failure would be reasonably complete. The maximum electric field in a 3-inch-diameter circular waveguide is given by $E^2_{max} = 58.5\ P$ volts/mil when the power $P$ is expressed in megawatts. At 175 MW, the field computed by this expression is 320 volts/mil, which is approximately equal to the published dielectric strength for aluminas. However, the majority of samples fail at much lower levels. Either the dielectric strength (which is usually measured at dc or low frequencies) must be lower at microwave frequencies, or higher fields than those predicted by the measured power must exist at the window.

Although ghost modes and trapped resonances at both the fundamental and at harmonic frequencies can exist, these have been avoided by careful design and by the relative absence of harmonics in the test apparatus. Furthermore, the breakdown is always in the general direction of the dominant mode field and occurs in the region of highest field strength. The only exception to this was found in a resonant cavity where asymmetry had allowed coupling to the orthogonal mode; the resulting breakdown was at an angle to the expected direction. Therefore, while not conclusive, there is at least circumstantial evidence that the major difference occurs in the material.

Internal voids have long been suspected as a contributing factor in window failure. Six samples of alumina were tested which had approximately 7 percent by weight of five mil spherical voids. All of these failed at 40 ± 10 megawatts, while six controls made from identical material failed from 30 to 80 megawatts. In another test, a glow discharge was observed to occur in holes of comparable size drilled into the disk. One might postulate that chains of voids might cause breakdown; the gradient across the intervening ceramic would be high because of the small drop through the voids. Random occurrence of voids would then cause the wide spread of breakdown observed. Unfortunately, we have as yet been unable to detect any evidence of voids with low energy x-rays.

Tests have been performed to determine the breakdown levels for three types of alumina, two types of boron nitride, and one type each of quartz, beryllia, magnesia, zirconia, and zero-oriented, single-crystal sapphire. None of these materials was found to be superior to alumina with respect to breakdown, although the early failure of sapphire by cracking makes it difficult to evaluate its dielectric strength from this test. The magnesia and zirconia samples tested were distinctly inferior. Boron nitride is too fragile to be suitable for a vacuum tight window. Among the aluminas, statistical fluctuations have so far hidden any possible superiority that one type might possess.

B. Multipactor

All of the materials except boron nitride have exhibited multipactor. Again, a wide spread of data is obtained from any batch of material when tested as received, owing to the critical dependence of the multipactor upon surface conditions and therefore upon the history of the window up to, and including, the test. In addition to the mode-free multipactor described by Priest and

Talcott,[2] we have observed windows with a mode existing between a few megawatts and about 20 megawatts. Erratic jumping from no multipactor to multipactor conditions has also been seen. In all cases a magnetic field has increased the multipactor. Multipactor can be stopped by application of a high resistance coating having a secondary emission ratio less than unity[3] or by reducing the area available for multipactor. The initial work on this subject was done in cooperation of Dr. Oskar Heil, who also provided the samples.[4]

V-shaped grooves ground on both faces of the disk and placed normal to the maximum field completely eliminate multipactor on quartz and confine it to the tips on alumina. Multipactor again exists when the grooves are placed parallel to the fields. Firepolishing the quartz samples and retesting them under the above two conditions gave the same results, showing that this effect was not due to the increased roughness caused by grinding. A series of tests was performed on alumina samples of varying roughness (20 to 200 rms microinches), and the degree of roughness showed no effect on multipactor. An unfortunate result of grooving is the tendency of the sample to puncture at the sharp bottoms of the grooves. Samples have been prepared with rounded bottoms, but it is not yet known if this is an improvement.

Rather heavy coatings applied to the tips of the grooved alumina windows completely eliminated multipactor. Lighter coatings on smooth disks of quartz and alumina gave the same results. These coatings were applied by Dr. Heil by sputtering titanium monoxide in a mercury atmosphere. At Stanford, coatings have been prepared by sputtering from titanium in an argon atmosphere, and have given the same results. The thickness has been varied over a considerable range with no essential difference in performance. The thickness has not been determined, but the color on white alumina varies from barely perceptible to a light tan. It appears that any coating that covers most of the surface and is thin enough to prevent excessive resistive loss is satisfactory.

Reasonable care must be taken to prevent contamination of the coating. Baking windows in a dirty vacuum system or when surrounded by unfired parts has resulted in windows which ran hot. Windows baked in clean vacuum systems and surrounded by clean metal show no loss in coating effectiveness on test, and such windows have been used successfully on Stanford klystrons. Coated disks have been stored for six weeks with no deterioration.

Coated windows have shown stable operation up to power levels where surface arcing occurs. The coating is apparently evaporated from the region of the arc, and multipactor occurs in this area. When repeated arcing occurs, the temperature rises rapidly and the window fails by cracking. Six coated windows have been in operation at 10 kW average for 2600 hours in the life test facility without failure. This test is continuing.

C. Vacuum Tests

We have attempted to determine if the vacuum has an effect on window failures, by varying the pressure within the systems used. With resonant rings, essentially no difference in operation nor any breakdown has been evidenced until the vacuum has been degraded to the point where glow discharge fills the system and reduces the power to a very low level. In resonant cavities, however, a decrease of Q with an increase of pressure has been observed with many samples. This loading is not consistent from sample to sample and may depend on incidental contamination of the disk.

Almost all of the failures now experienced on tubes operating into loads which are sputter-ion pumped are from thermal shock. This fact may perhaps be because of the freedom from breakdown in this type of system. Therefore, it is believed that clean vacuum systems with pressures of the order of $10^{-7}$, or better, do give improvement in performance, particularly with respect to freedom from punctures. Accordingly, a clean, all-metal vacuum system has been specified for the SLAC accelerator.

D. Window Geometry

To facilitate sealing and to avoid high fields as much as possible at the metal-to-ceramic seal, circular geometries have been used. Within this restriction no essential difference among windows of various geometries was found. Windows have been tested both in symmetrical and in assymetrical locations within a pill box type structure of short dimensions. Windows with additional half-waves added on both sides of the pill box behave similarly. Some slight evidence of a greater tendency for internal breakdown in half-wave windows has been found, but this is not at all conclusive. One of course must avoid ghost modes in such thick structures. At one time it was suspected that slight tilts of the window (of the order of a few tenths of a degree) are detrimental. Additional tests have failed to definitely confirm this assumption. The use of cone, dome, or tilted windows has been avoided because previous experience has shown that these are much more prone to multipactor than geometries which are tangential to the electric fields.

## V. PROTECTIVE DEVICES

In order to protect the window from damage we have in the past used a vacuum interlock system which shuts off the klystron in the event that the vacuum in the load exceeds a preset level. Both fast-acting electronic and meter relay circuits have been used for this purpose. About the same results have been obtained in either case, because in many systems the propagation of a vacuum increase is the limiting factor.

In order to provide a faster-acting detecting scheme, a reflected power detector will be installed on the SLAC accelerator. It will shut off the system if the reflector power exceeds a preset level. As the first unit containing this system has just begun operation, its effectiveness is now unknown. The detector and coupler are placed as close to the window as possible to eliminate trouble from breakdown in this region.

In addition, use of the slow power turn-on, which was effective on the Mark III accelerator, will be continued. It may be of interest to note in this connection that there is always an increase of gas at approximately the half-megawatt level in both loads and accelerator systems. It is therefore useful to limit the lower level of power to something like two megawatts power.

## VI. CONCLUSIONS

At the present time we believe that window failures in tubes used for linear accelerators are of three types, each of which is reasonably well understood and each of which can be corrected or protected against.

(1) Puncturing of the window is caused by initial internal arcing which gradually extends to the surface and produces a vacuum leakage path across the window. Elimination of this type of failure requires operation with the maximum E field applied to the window reduced by a reasonable safety factor from the published values of the dielectric strength of the material. Because the E field may be doubled temporarily by faults in the waveguide and its load, it is essential to operate the system in a very good vacuum, taking all possible

precautions to prevent load arcs or at least not permitting them to last more than one pulse.

(2) Failure by cracking is associated with heating of the window. The heating is caused not only by the dielectric losses within the material, but also by surface losses associated with multipactor action. Coatings reducing the secondary coefficient of the window have been found effective in reducing the multipactor and the tendency of the window to run hot at power levels of a few megawatts peak.

(3) The melting observed on the surface can be caused only by a localized arc moving to the surface of the window. This type of failure can probably be eliminated by adequate protective circuitry to turn off the power within a few pulses of the initiation of the arc.

The wide variation in power levels at which internal breakdown occurs probably stems from lack of homogeneity in the ceramic materials. We suspect that improvement in fabrication techniques of the ceramics to increase the density will at the same time decrease the range of powers over which ceramics fail internally. One may also wonder if other materials should not be again considered for window application; for example, glasses are usually reported as having a low frequency dielectric strength, between two and three times higher than that of ceramics. If this is the case, thought might be given to the use of low loss glasses, provided that the other physical characteristics of glasses lend themselves to use as microwave windows.

LIST OF REFERENCES

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

3. R. C. Talcott, "The Effects of Titanium Films on Secondary Electron Emission Phenomena in Resonant Cavities and at Dielectric Surfaces," IRE Trans. on Electron Devices ED-9, 405-410 (September 1962).

4. O. Heil and D. H. Priest, "Research on Microwave Window Multipactor and its Inhibition," Eitel-McCullough, Inc., San Carlos, California, Fourth Quarterly Progress Report on work supported by the U. S. Army Electronics Research and Development Laboratories (1963).

LIST OF ILLUSTRATIONS

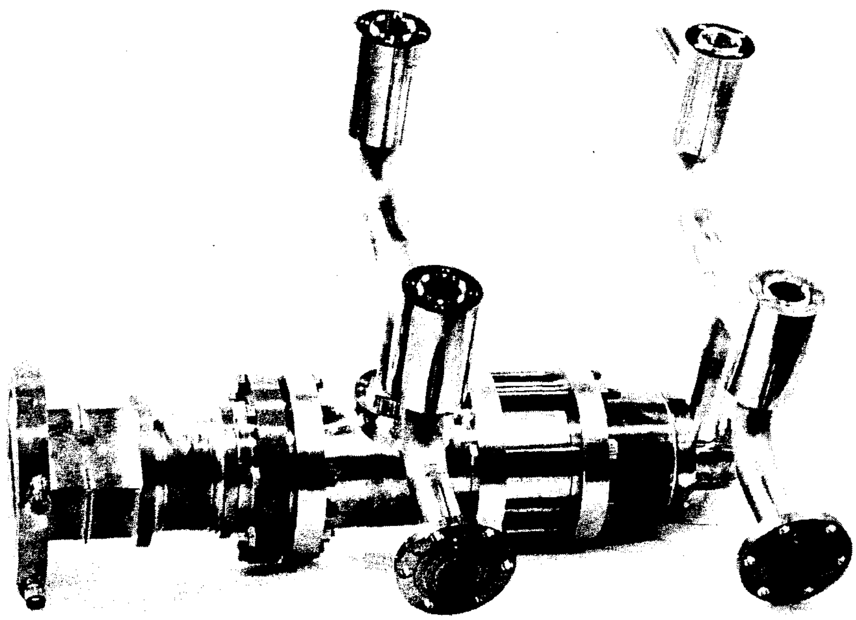

FIGURE I

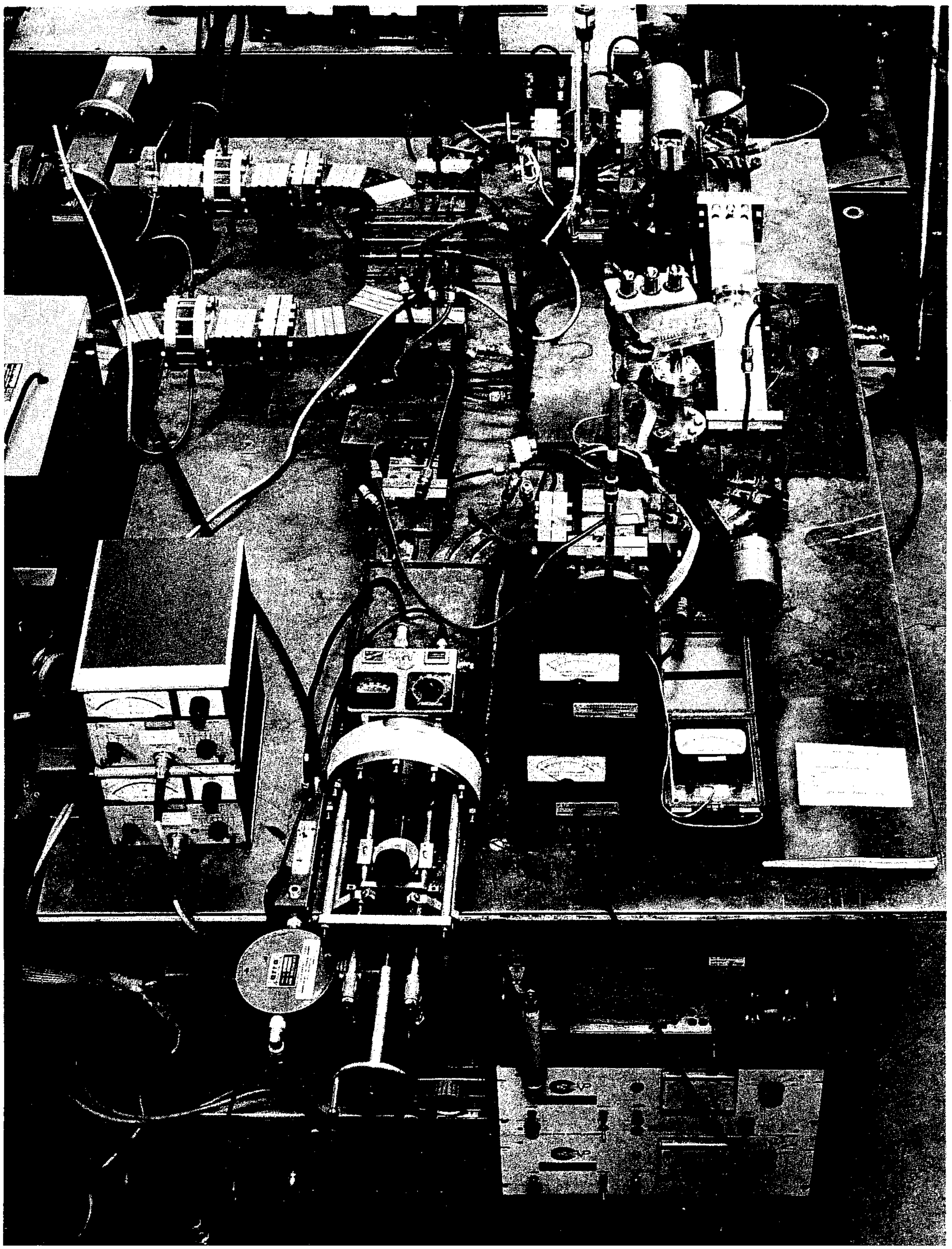

FIGURE 3

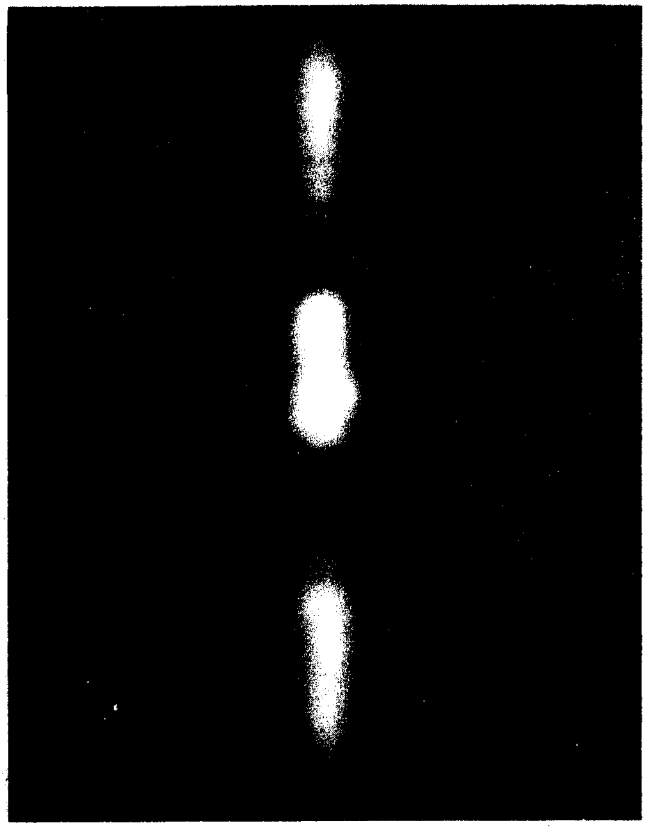

FIGURE 4a

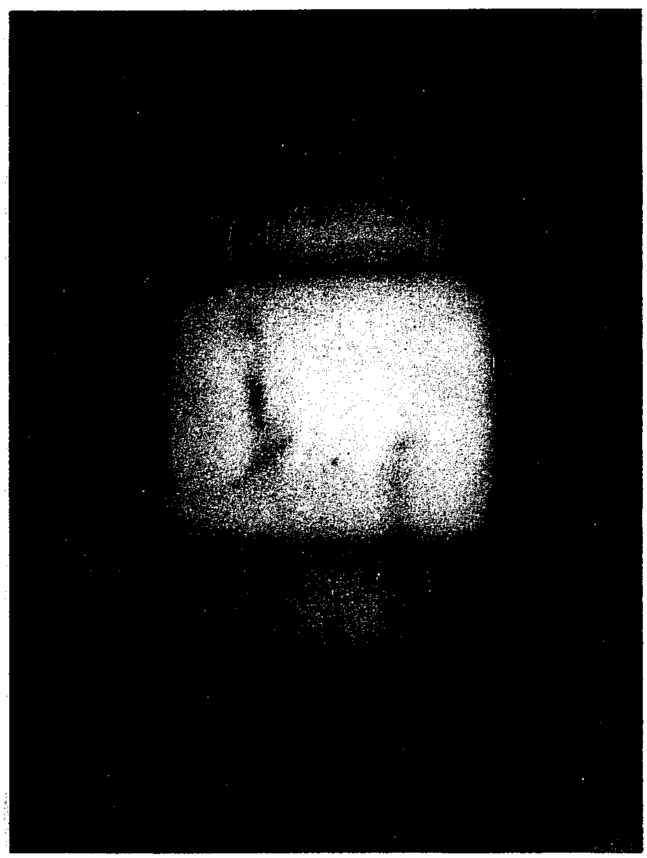

FIGURE 4b

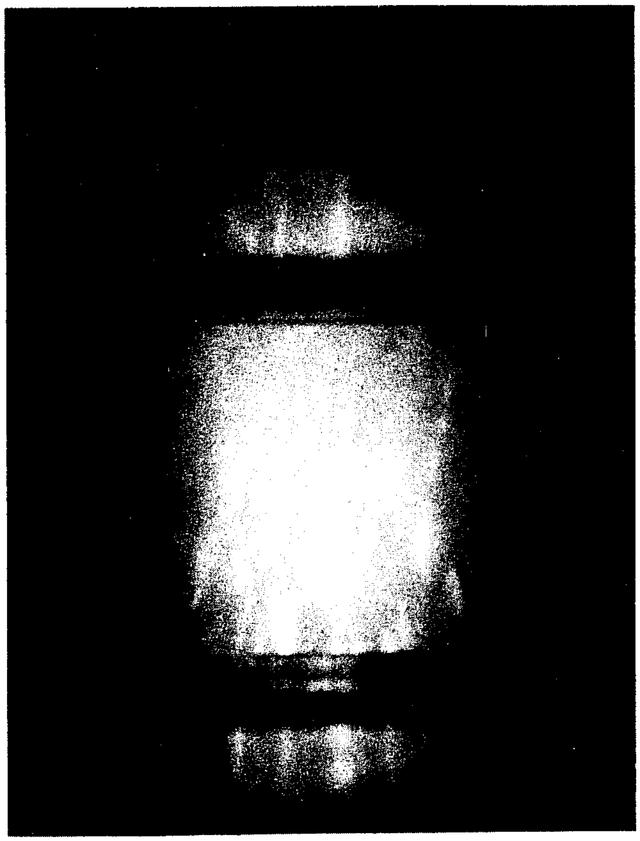

FIGURE 5