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Reflections Concerning Criteria for Design of a High-Gradient Accelerating Tube

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

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Joseph L. McKibben

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REFLECTIONS CONCERNING CRITERIA FOR DESIGN OF A HIGH-GRADIENT ACCELERATING TUBE*

by

Joseph L. McKibben

ABSTRACT

The difficulty of designing a high-gradient accelerating tube is emphasized. In an effort to recognize all the factors involved in discharges and sparking within an accelerating tube, a list of 15 criteria for construction of a good tube is discussed. The author's experience that has led to the development of the criteria is traced from development work at the University of Wisconsin through the design and development of the large vertical Van de Graaff of LASL's Group P-9. Finally, the design of a tube that meets these criteria is sketched and it is suggested that such a tube might be capable of operating at a gradient of 3-4 MV/m.

I. WHAT IS THE SECRET OF A GOOD ACCELERATING TUBE

A. The Difficult Problem of a Van de Graaff

The most vexing problem of building a good electrostatic accelerator is getting a good accelerating tube into it. While reasonable tubes are commercially available, none of these meet the strict criteria that must be satisfied in order that a high-gradient tube may be built. By a high-gradient tube, I mean one that will operate at 3 or 4 MV per meter.

Certainly these statements are purely a matter of judgment. It will take a lot of work to prove that a 4-MV/m tube can be built in a useful length. So perhaps I am presumptuous in my optimism about the possibility of a high-gradient tube since I have not worked on accelerating tubes since 1960. I have watched with interest, however, the development of several commercial tubes in this period. I have been inspired to present this paper by the fact that not one of the commercial tubes incorporates certain

principles that my own experience would have led me to use and that I believe to be important.

B. New Concepts in Accelerating Tubes

Since 1960 we have seen several new concepts developed. Each has, at times, been promoted as a major breakthrough. These are: inclined field electrodes, magnetic suppression, better alloys, and a notable and masterful development of a hard vacuum tube. Yet today there is no tube that I know of that operates at more than 50% higher gradient than the 1.6 MV/m that my associates and I had in operation on a 1.7-m-long tube in 1945. Meanwhile, a lot of research work has gone into trying to find the causes of vacuum sparks and other discharge phenomena.¹

C. The Many Aspects to the Problem

Apparently we have the situation that about every discharge mechanism that anyone has conceived is present in an accelerating tube. Moreover, the critical voltages for these various processes in a tube of useful length are not very different. So an enthusiastic designer with a good idea may well solve one problem, but in doing so he may aggravate another problem.

* A shorter version of this report was presented at the 1973 International Conference on the Technology of Electrostatic Accelerators, 5-7 May 1973, Daresbury, England, under the title "Reflections upon Design Criteria for a Good Accelerating Tube."

It is to call attention to the many factors that enter into the design of a good accelerating tube that I am proposing the following list of design criteria. Naturally, they come out of my personal analysis of what takes place in an accelerating tube.

The secret of a good accelerating tube is a well-balanced design, and this cannot be done unless we recognize all the factors. Incidentally, I discovered several of these factors by inadvertently violating them.

II. DESIGN CRITERIA

A. Clean Optics

The tube must transmit ion beams without varying deflections or degradation of emittance. Obviously this requires that the beam be shielded from charges on the surfaces of the insulators. The inclined field tube gets a poor mark on this criterion.

B. Good Vacuum

As a minimum, the vacuum must be adequate to allow the ion beam to be transmitted without loss due to scattering or charge exchange. In the case of heavy ions, this imposes a very stringent requirement. If ion-exchange loading is controlled by high vacuum alone, immaculate freedom from organic vapors, alkali vapors, etc., is required.

C. Good Insulator Material and Shape

The insulators must be resistant to puncture and to surface flashover. The shape is determined primarily by II-I. An insulator shape that is subject to puncture should be avoided.

A commonly used insulator shape made with glass gets a poor mark on my score card. In the author's experience, glass-bonded mica is preferable to both glass and porcelain.

D. Good Electrode Material and Shape

The proper material and shape are best determined from tests on individual gaps. Besides satisfying the several other criteria, the material must be reasonable to fabricate and adequately match the thermal expansion of the insulators. Criteria II-H & I determine the electrode shape to a large extent.

E. Good Bonding between the Insulators and the Electrodes

A good bond is not only required for mechanical rigidity and for a vacuum seal but is especially important for a high-gradient capability. A gap

between the insulator and the metal electrode leads to the well-known negative corner problem. In the author's experience, the use of vinylacetate adhesive is a good solution to the problem if the fillet of adhesive is washed away with a solvent. With this technique, very high gradients have been achieved on tubes of short length.

Ray Herb, at the University of Wisconsin and more recently at National Electrostatic Corporation (NEC), has pioneered the use of hard seals that will support high vacuum and provide absence of organic vapors. This technique requires very advanced technique to avoid field emission at the junction to the negative electrode. I suspect that his high-vacuum technique, as beautiful as it seems to be, does not yield high-gradient bonding. My judgment is clouded by lack of information on what NEC has achieved in the sense of this criterion and II-H.

Any program of making a new type of seal, especially involving hard vacuum, must be associated with a test program on vacuum flashover if useful technique is to be developed.

F. Low Field Emission

Field emission has been observed to take place from whiskers² or other sharp projections. Buffing and electropolishing are used to eliminate these points.

The titanium alloys, such as Ti-6Al-4V,³ seem to be an ideal choice, for they have shown to hold the highest gradients of any material where short gaps are used. Field emission is the dominant limitation in short gaps.

G. Ion-Exchange Loading Eliminated

This process has been frequently rediscovered. It is widely referred to as microdischarge. Good discussions are now available.^{4,5,6,7,8,9}

The process seems to be sputtering. As the voltage between two large area electrodes is increased, a value is reached at which the positive ion component of the sputtered atoms at one electrode and the negative ion component of the sputtered atoms at the other electrode can sustain a discharge. It can be seen in its purest form in particle beam separators,¹⁰ and accelerating tube designers should observe their developments carefully. It is primarily a large gap phenomena, i.e., for gaps over 1 cm in length.⁴

A multiplicative process does not explain the presence of sparks. In some situations, sparks are associated with a tiny amount of ion-exchange loading while in other configurations rather large currents can be maintained without appreciable sparking. In accelerating tubes, I am inclined to believe it is the electrons from the process violating criterion II-0 that causes the sparks; however, sparks are observed in the beam separators^{10,11} where II-0 would not seem to apply.

Methods of control utilize grids, back biasing of electrodes, elimination of organic contaminants, and a leak of a clean gas such as helium. Conical electrodes and back biasing of electrodes should be used together as I shall explain below.

Titanium and its alloys¹² also rank high as a material for low ion-exchange loading, especially in a clean vacuum system.

H. Low Charging of Insulators

Charging of insulators is, in my opinion, the major cause of sparking in accelerating tubes. The flashover process is poorly understood, however, as can be seen by reading the various Proceedings of Discharges and Electrical Insulation in Vacuum.¹

We now know that insulator surfaces become positively charged.¹³ It is also known that even a tiny gap between the insulator and the negative electrode is a source of electrons. These charge the insulator positively because they release more electrons when they strike the insulator. Filling the gap with adhesive is a good way of reducing the effect. Another widely used method is to shield the corner. It is essential that the metal surface in the vicinity of the corner has an especially good polish, for the insulator is very sensitive to field emission in this area.

Anyone who can develop an insulating structure that is insensitive to electron bombardment will make a major contribution in this field. It is important that any development work on bonding be done in cooperation with tests on vacuum flashover, and must include tests on the effect of electron bombardment of the insulating structure.

I. Surge Resistance

Individual gaps of a tube must be highly resistant to surges in order that sparks not be propagated along the tube. Fortunately, it has been shown that insulators can be shaped to withstand

very high voltages for ~25 nsec if they have a conical shape. A factor of ~4, depending upon angle, has been observed.^{14,15}

One suspects, therefore, that corrugated shapes should also have their advantage. The use of insulator shapes that are better able to hold off a short overvoltage can be expected to produce a tube more resistant to the propagation of sparks.

J. Freedom from Debris or Other Sources of "Clumps"

Tiny pieces of matter can become charged, by induction or bombardment, and be accelerated to strike the opposite end of a tube section with enough velocity to create a hot spot or to vaporize the projectile. The process was first proposed by Cranberg¹⁶ and is well known as the "clump hypothesis."

One tends to think of a spark passing through the entire length of the center of the accelerating tube to be associated with such an event. If that happened we should often see terrific x-ray pulses with spark-down of the accelerator. This we don't--in fact the larger x-ray pulses tend to be associated with very small "kicks" in voltage. However, sparks seen in beam separators^{10,11} may generate large x-ray pulses. If one considers space charge, it is evident that such an event would create a burst of current that is intercepted by electrodes. The result is that the potential distribution is upset sufficiently to trigger a spark to propagate along spark gaps.

Two sources of clumps have come to my attention, pieces of adhesive broken loose by insulator flashover, and droplets of metal formed from molten jets of metal ejected by a spark. It seems prudent to wash away the surplus adhesive. Preventing droplet formation is tricky but isolation of the tube from the large capacitance ring to ring of the column should help considerably.

K. Protection from Deteriorating

Experience has shown that the life of a tube depends markedly upon its design, upon its protection system, and upon how carefully it is used.

Ideally it can stand abuse; however, none that I know of can do that. It is helpful if the tube can be easily rejuvenated after failure--NEC, for example, has a tube that can be disassembled and its interior can be cleaned by blasting with glass beads without disturbing the vacuum seals of the

insulators. Development work on the fabrication of a better design that is capable of withstanding internal flashover needs to be done. The test work should be done with capacitors of various sizes--the capacitors should have very low inductance since the stored energy within a column of an electrostatic generator has very low inductance.

In order to prevent sparks from propagating from electrode to electrode inside the tube, the common practice is to provide spark gaps for the surge to propagate along. Now one doesn't want to set the gaps any closer than necessary so it is important that the surge resistance be high as explained in II-I.

Another problem of deterioration can be ion-beam induced, particularly heavy-ion induced. Two particularly suspicious ions are oxygen and sulfur. According to Goldie¹⁷ there have been problems and there have been successes. The implication is that one can successfully put a well-collimated beam through even an inclined field tube and it will not deteriorate if it is kept off of the electrodes.

Another problem seems to be the mere presence of an electro-negative gas, such as SF_6 , in the tube. Obviously, the mere presence of any decomposition products on the surface of electrodes may be expected to assist the ion-exchange process--just what we don't want. According to Goldie,¹⁷ there have been suspicions raised but no definite experience to cite.

L. Isolation from the Column

One must expect the individual tube gaps to spark occasionally, and the less energy available the less damage may be expected to the gap. If the tube is sufficiently isolated from the column, then the stored energy available is only what is present in the particular gap of the tube. This common sense rule has been frequently violated; I have made a serious error in the design of the large vertical Van de Graaff at LASL in this respect.

Of course, one cannot isolate the tube from the stored energy of the high-potential terminal and of the interpotential shells. Obviously at these junctions no isolation should be attempted.

There is evidence that the high distributed capacitance along the column has lowered the operating voltage of Tube C and E with respect to the test generator, as will be discussed later.

Obviously, if a discharge event occurs at a local region of a tube, the less distributed capacitance that may be attached to it, the quicker the voltage drops in that particular region and the less is the tendency for the discharge event to spread to other parts of the tube.

There is another type of problem that may occur if the accelerating tube is too close to the hoops. This involves the transmission line characteristics of the hoops. For example, a spark between the hoops at a point opposite the tube will cause the voltage to be doubled at the tube for 10-20 nsec.

All of these effects can be eliminated by locating the tube in the middle of the column with adequate isolation.

M. Separate Distribution System

With II-L in effect, it seems prudent to provide the tube with its own potential distribution system. This also allows the modular spacing of the tube to be chosen completely independently of the modular spacing of the column. The important advantage is that all possibility of energy transfer from the column to the tube is eliminated. NEC accelerators are built using this principle, and Ken Purser is testing the value of the principle on the Rochester MP tandem.

N. No Insulating Films on Electrodes

Higher breakdown voltages in simple vacuum gaps have been obtained where the cathode has been covered with an insulating film.¹⁸ The insulating coating has also been demonstrated to function within the large gaps of particle beam separators,¹⁹ yet they don't seem to be used in practice.¹⁰ The insulating film apparently improves performance by covering over the field emitting points and thereby catching charge to mask the point.¹⁸ However, having observed a case in air where large negative currents were emitted from a painted surface under voltage stress, I am suspicious. In fact, Malter²⁰ observed such an effect in vacuum back in 1936. The presence in accelerating tubes of many currents and photons may well lead to charging of such films, and, instead of reducing the current, such films might even increase the current. Even without developing the currents, charged films may be detrimental to beam optics, and the well-demonstrated possibility of a spark damaging the films violates criterion II-K.

0. Charges Directed away from Electrodes

Several cases of sparking in tubes can be explained, it seems to me, by electrons striking electrodes. A high-gradient section should be made with ends shaped to direct electrons away from the electrodes.⁵ Since a fair fraction of the electrons are scattered with near elastic energies from electrodes, particularly high-Z materials, an appreciable number of the electrons that strike the electrodes may arrive at the insulator. This, of course, violates criterion II-H.

An important possibility is that a burst of charge may concentrate on a few electrodes and may thereby disturb the potential distribution sufficiently to trigger a spark along the spark gaps. It is important to analyze what may develop from a hot spot created by a clump hitting either the negative or positive end.

III. THE CRITERIA AND MY UNIVERSITY OF WISCONSIN EXPERIENCE

A. The Criteria and My Personal Experience

These criteria came out of the analysis of accelerating tubes that I have been able to observe. Naturally, those tubes that I have seen built or have personally built have had the greatest impact and so I shall analyze these. A large influence has been my contact with Ray Herb which started when I entered graduate school in 1935, although my work on tubes did not start until 1938. Of course, the works of others have had their impact in many ways, and I shall try to acknowledge these.

B. Herb's First Tube

The tube of Fig. 1 was one that had already been developed by Herb when I arrived, and it was used in the electrostatic generator under construction at that time by Herb, Parkinson, and Kerst.²¹ Herb had been influenced in the development of this design by association with Tuve, Hafstad, and Dahl²² at the Department of Terrestrial Magnetism. Note that the vacuum seals were made by sealing wax, a material that was still in use in those days on containers for preserving food! Clearly, Herb has made enormous progress in vacuum technique since then. Nevertheless, if one ignores the wax seals and the many leaks that had to be repaired, this tube satisfied many of the criteria on the list fairly well. The judgment is, of course, in terms of the

Fig. 1. Herb's 1936 accelerating tube. [Reproduced from Phys. Rev. 51, 75 (1936) with author's consent and notification of Physical Review.]

technique and materials then available. The optics was reasonably clean. Ion-exchange loading, if present, was not evident. Moreover, the tube was well isolated from the column. One suspects that the insulator design was quite good from the standpoint of withstanding voltage surges.

Herb's tube was the first used in a pressure insulated Van de Graaff. Prior tubes were used at atmospheric pressure and mostly had straight-wall glass cylinders for insulators.

C. Short-Tank Tube

The tube of Fig. 2 was developed by R. L. Burling and myself under the direction of Herb. This was assembled and installed in August 1939 in an electrostatic generator we started building in

Fig. 2. Short-tank accelerating tube--built 1939.

1937. We progressed from using wax to make the vacuum seal to the use of natural rubber dam 1-4-mm thick. We tested a number of arrangements of insulators and electrodes to develop the design of Fig. 2. It was frequently observed that a discharge arose at the corner of the insulator and the negative electrode. The cure we developed was to shield this corner. The electrode was also shaped with a large radius of curvature to minimize field emission, for the effects of field emission were obvious in our tests. We also had the best results with a general conical shape of the electrode, provided the polarity was such as to draw electrons away from the insulator rather than towards it. We naturally assumed this had to do with charging of the insulator and you can see from Fig. 2 that we incorporated this shape into the final electrode design. The electrodes were fabricated by being spun out of steel. The shape of the insulator was also probably very good for voltage surges.

A single section was briefly tested in the generator and went to 150 kV where external flash-over occurred. The installed tube was well isolated from the rings of the column and was connected to the single potential distribution system by springs as inductors. No spark gap protection was used and nothing ever happened to suggest that it was needed, even though the insulators were made with wet process porcelain.

When we started to use the tube we saw that there were large currents present that we did not understand. An electron barrier was placed at the ground end of the tube and, while it was a definite help, it didn't eliminate the problem. It was suggested that electron multiplication was occurring along the electrodes, so several inserts were installed; one insert shows in Fig. 2. This installation did not help, although it should have if electron multiplication was in operation. So finally rings were mounted on these inserts at a tilted angle and the assemblies were alternated in the angle of insertion so as to provide a ziz-zag electrical field that would sweep out the ions formed in the residual gas. This trick did seem to reduce the current and the voltage was soon limited by the insulators of the column at 1.7 MV. It was not a clear-cut experiment because the vacuum measurements were made poorly, so it was not published; however,

the tilt ring inserts were used throughout the life of the tube.

The accelerator was moved to Los Alamos in 1943, where it became known as the "short tank." Since we needed it to get above the threshold for neutrons from protons on lithium at 1.89 MeV, the column was rebuilt in the fall of 1943. The tube was reused as it was built in Madison. We did find it desirable to install a liquid-nitrogen trap as an appendix on the oil-diffusion-pumped vacuum system. Eventually it was used for taking data at 2.7 MeV. Inasmuch as the tube was made with only 26 porcelain sections and was only 1.7 m long, this was a high gradient, especially for that period. The research activity using the accelerator was finally phased out and the accelerator was retired in 1963. At that time the tube would still operate at 2.2 MV. Clearly, the design of this tube was well-balanced and the deterioration rate was low. In fact, there had been several bad vacuum accidents that may have caused most of the deterioration that was observed.

D. Herb's Long-Tank Tube

The tube of Fig. 3 is probably better known since it is the one Ray Herb, Clarence Turner *et al.*^{23,24} used in their famous "long tank." This name was acquired in Los Alamos. They took the design from our tube, scaled down the weight and diameter, and simplified the electrode shape from the

Fig. 3. Long-tank accelerating tube--built 1940. (Reproduced from *Encyclopedia of Physics* with permission of Springer-Verlag.)

standpoint of the metal spinner. This tube was approximately 4-m long and was operated routinely up to approximately 3.5 MV. In an early test, it did go to 4.5 MV. This tube also did not seem to have difficulty with ion-exchange loading, perhaps because of its smaller inside diameter. On the other hand, its operating gradient was somewhat less than that of the "short tank." This tube did not have spark-gap protection, and three or four porcelain rings did puncture during its lifetime and created pressure-sensitive leaks that were very difficult to locate. Still, the tube satisfied many of the criteria very well. This tube also had a very long life and contributed to a great deal of neutron research at Madison, then Los Alamos, and finally back at Madison.

IV. THE CRITERIA AND DESIGN OF THE P-9 ELECTROSTATIC ACCELERATOR

A. Description of the P-9 Van de Graaff

In 1946 I became group leader of P-9 at Los Alamos. This group had the responsibility of designing and building a large Van de Graaff. It was hoped that this accelerator would operate up to 12 MV in order to produce neutrons in the 10-14 MeV range as well as at many other energies. Because at that time this goal was a large step forward, I designed a machine²⁵ with a great deal of flexibility. It had ease of access to the interior as a special feature. The large Van de Graaff's designed previously were quite difficult to work upon. Figure 4 is a drawing of the machine. An important component was a gas-tight separation column (see Fig. 5) that permitted the vessel to be lifted out of the way without decompression of a large quantity of insulating gas. It has permitted rapid access (under 3/4 hour) and rapid return to use (also under 3/4 hour).

The basic design of this electrostatic accelerator has met the design specifications as tests without the tube have shown. No ring in the separation column has ever failed, although it is subjected to considerable surging during a spark. The rings were made of glass-bond mica and were specially molded for this column. It has been necessary to use only a tiny quantity of SF₆ or Freon 12 in the normal insulating gas in order to reach 12 MV.

The accelerating tube, however, has held the top performance down to voltages in the range of 4-8.5 MV. The top value depends upon the particular tube installed and upon its condition, as will be explained below. I now believe the failure to get better results is mainly due to the fact that, in designing this structure, I violated criterion II-L cited above, which says that the tube must be isolated from the column. To compound my error, the separation column has more than 10 times the ring-to-ring capacitance of any other Van de Graaff. I was unaware, at the time, of the error I was making, or I would have found a way to put more room around the tube. I made the error because I was trying to put too much in the space available and because the logical place to put the tube was needed by the charging belt. Ironically, with the pelletron-charging chains now available, it would be relatively easy to rebuild the inner-column structure and correct the error, but funds for such an improvement are difficult to obtain.

B. Early P-9 Tube-Development

I did consider that an important step in building the accelerator was to find a better way to make the accelerating tube. In 1946, I was impressed by a technique being used by Robert Cloud working in John Trump's laboratory at the Massachusetts Institute of Technology. He was using flat-steel electrodes, short-glass rings, and polyvinylacetate to bond them together. I set up a test program whereby samples of insulators 51-mm in diam were mounted between electrodes with rounded edges. The entire structure was placed within a vacuum system and numerous tests with voltage across the electrodes were performed.

Fairly rapidly R. K. Beauchamp and I got the impression from these tests that vinylacetate was an ideal way of joining the ceramic to the electrode. We also observed that distinctly better results were obtained if the surplus vinylacetate was washed away with acetone. I was particularly impressed that this method of mounting greatly reduced the negative corner problem that had given us so much difficulty at Madison. In fact, now when the corner was shielded we got less voltage, and we interpreted this as being due to the fact that shields reduced the gap and therefore increased the field strength.

Fig. 4. LASL's P-9 Van de Graaff--built circa 1950.

Fig. 5. Separation column, 50-1/2 in. o.d.

Other significant results were that we got better results using glass-bonded mica insulators than using glass, including Corning 7070. We also got the best results by using an aluminum-alloy electrode provided it was buffed. So the blame for starting the use of aluminum for accelerating tube electrodes belongs to me and my associates at the time.

Tests on voltage vs gap indicated that the gradient increased with a decreasing gap down to approximately 10 mm and then remained constant.²⁶ Since then, others have observed this general shape.⁴ Inasmuch as the beam would be easy to shield from the charges on insulators in a 10-mm gap, I settled on a 3/8-in. thickness for the insulators and a 1/8-in. thickness for the aluminum electrodes. The modular spacing of the separation column had been set at 1-1/2 in. so that left two electrodes floating in between. Our tests with floating electrodes in the test generator indicated no difficulty.

Fortunately, the rings of glass-bonded mica were ordered with a deep contour on their inside surfaces even though the tests in the test generator did not show this to be an advantage. The poor results I had seen with straight interior wall vs corrugated interior-wall insulators at Madison influenced me into making that decision. In spite of the fact that this groove gave us many annoying vacuum leaks due to the tendency of a ring to split at the groove, it was a fortunate choice because, in this manner, I had inadvertently satisfied criterion II-I.

In this tube, I believed that I had increased the gradient capability as spelled out in criteria II-C, II-D, and II-E by a factor of at least 2 over what we had worked out at Madison.

C. Unrecognized Problems

Unfortunately, I was in deep trouble with three of the criteria that I have listed in Section II, but I didn't know it. 1) The close proximity of the tube to the column has already been mentioned; 2) ion-exchange loading would find the large-diam flat-electrode tube ideal for its purpose. My experience at the University of Wisconsin had not prepared me for this eventuality; in fact, my first experience⁵ came from a 2-ft-long section in the test generator only a few months before our first tube was installed. Herb was to encounter ion-exchange loading somewhat later; 3) resistors were needed on the floating electrodes as mentioned above.

There were some problems with the Van de Graaff, too. The chief one was that the corona-needle system that I was familiar with from Wisconsin would not function on the large generator. Sparks melted the points, so we had to obtain resistors and learn how to shield them to make them functional. Incidentally, Herb still uses corona distribution successfully in his NEC accelerators, so the problem must have been due to the significantly larger amount of energy that had to be dissipated in a spark. A fair amount of time was also required to get the charging system to function up to the design aim.

V. THE CRITERIA AND EXPERIENCE WITH THE P-9 ACCELERATOR

A. Tube A--A 12-1/2-in.-O.D. Tube Using Ceramic Insulators

The first tube in the accelerator was tested and used in the period 1950-53. It was eventually stacked to 12 ft in height, or 6 sections in length. The top voltage of 4.2 MV was disappointingly low when compared to what we had obtained with a single section in the test generator. Something appeared to start discharges that produced a gray area on the inside edges of the electrodes. We got better performance by adding diaphragms. There was no spark gap protection on this tube and we did have electrical puncture of some of the insulating rings made of porcelain but not of any rings made of glass-bonded mica.

B. Tube B--Trump's Tube Built by HVAC

In 1952 John Trump convinced us that we should try a tube like he was using at M.I.T. in his OMA generator. Unfortunately, his tubes were made with a 1-in. modular spacing. The P-9 tube had to have either a 1-1/2-in. modulus or a 3/4-in. modulus. He chose 1-1/2. It was made up by High Voltage Engineering Corp. using his "the Nest" contour of electrode diameter, i.e., the inside diameter was 5 in. on the ends and 3 in. somewhat above the middle. Mercury diffusion pumps were installed at P-9 so that the vacuum system would be up to his standard. The column was stretched to the full 30-ft length and the tube was installed. Unfortunately, this tube did not condition up in voltage; in fact, it deteriorated. Cracked areas appeared quite soon on the interior of the glass; apparently these were due to aluminum evaporated from electrodes by sparks. I now believe this was positive evidence of the error in respect to criterion II-1 that has already been mentioned; however, wishful thinking did not let us recognize the fact for some years. The logical explanation, it now seems to me, is that the energy stored in one place of the column is too great to be dissipated in a single tube gap without damage.

Another problem we had in using this tube was a tendency for the beam to shift position suddenly and without warning. The explanation for this effect had to be that a sudden shift in the charge on the surface of one or more insulators occurred. This effect was markedly reduced by placing a diaphragm 4 ft from the top and placing a back bias on the top side of it.

C. Tube C--A 10-1/2-in. Tube Using Nine Ceramic Insulators.

In 1955 we put in a 10-section tube of the same construction as first tried; a drawing of this tube in its final form is shown in Fig. 6.²⁷ This time a set of diaphragms was installed at every other junction or 4 ft apart. Shortly after installation, we placed a resistor chain on this tube and were able to recognize for the first time that ion-exchange loading was present in the same form that we had seen in the test generator. Previous to the installation of the resistors, the tube would spark rather than draw a continuous current. The experience suggests that it takes but a small current to

the floating electrodes to trigger a spark along the electrodes of the tube. Now a method of back biasing²⁷ of the diaphragms to stop the ion-exchange loading was readily improvised. This is diagrammed in Fig. 6. This improvisation raised the top usable voltage to 21 KV, at which value the tube would spark without warning.

While this tube had no spark gaps per se, we inadvertently had out on spark gaps in that the resistor holders we used functioned quite well as spark gaps.

Fig. 6. Tube C--used 1955-59.

D. The Ad Hoc Committee for Tube D

With the failure of the HVEC tube, a meeting was organized of the best experts on sparking in vacuum that could be assembled and was held in Los Alamos in June 1955. That meeting was followed by a series of ad hoc committee discussions concerning the problem of the P-9 tube. The objective was to understand the problems we were encountering in a long tube and to see if a solution could be found. The discussions did cover all aspects of sparking in vacuum but the reason that the voltage which a vacuum gap held apparently increased as only the square root of the length was the main consideration. Insulator flashover and those items covered by II-C, B, and D got almost no discussion. We were getting good gradients on sections of tube C when placed in the test generator.

There were two discharge processes of special interest: 1) the clump hypothesis of Cranberg¹⁶ and 2) the ion-exchange hypothesis that I proposed. Clearly both involved long lengths of a tube. The clump hypothesis was simple in concept and seemed to explain the very poor increase of the voltage with length. Yet, the presence of dark currents could be demonstrated and moreover they could be eliminated by back biasing of the end of the tube as shown in Fig. 6. However, the ion-exchange phenomenon does not explain the presence of sparks--some other process has to go with it.

The best solution was thought to be the use of diaphragms and so I was urged to use many diaphragms in the new tube. In fact, Cranberg and Henshall²⁶ tested a tube section like that in Fig. 6, but which contained four intermediate diaphragms, and got a very good voltage. I resisted their solution because I could not see how we could tolerate such poor pumping speed. It seemed futile to build a glow discharge tube.

To provide both pumping and yet have many diaphragms, I developed the design as shown in Fig. 7. The central diaphragm and the back-biased diaphragm at the junctions were provided with pumping around their exteriors. Three diaphragms with large holes blocked the paths made possible through the outside of the diaphragms with the small holes.

When installed in the large Van de Graaff this was a poor tube. The highest voltage achieved was 5.9 MV with 5.5 MV being the highest usable voltage.

After an apparent exposure to mercury vapor, it deteriorated to the point that it had to be replaced after only a year's service.

E. Tube D and the Criteria

The most obvious error in the procedure of designing tube D was that only one section should have been built and that tested carefully before a decision was made on construction of the full tube. This would have shown up the two errors that I will describe. In fact, I was aware that we might be in trouble with each of these problems upon testing the first section in the test generator. In fact, the design of Fig. 7 was a modification of the first design. However, it was too late to correct the error made in purchasing insulators with straight sides.

What I now consider to be a bad design error slipped up on me. We had many vacuum leaks with the glass-bonded mica rings that had grooves on their interior. Inasmuch as results on samples 51 mm in

Fig. 7. Tube D--used 1959.

diam showed no appreciable advantage of the groove, and my Madison tests were fading in my mind, I elected to use straight sides on the inside of the rings. As I started to test the tube, I began to suspect that I had overlooked the fact that the resistance for voltage surges had been greatly increased by the shape of the earlier rings. This suspicion seemed verified when I later heard of the results of tests made by I. D. Smith¹⁴ and still later by A. Watson and J. Shannon.¹⁵ They found that tapering the inside of the insulator greatly increased the capability to insulate short pulses of voltage. It is this experience that accounts for criterion II-I.

What I now consider to be another error was due to the fact that the diaphragms could emit electrons that are directed towards the electrodes since the diaphragms were open on the outside. These electrons can get scattered into the insulators. It matters little whether the electrons arise from field emission or ion-exchange loading. I knew from my experience at Madison that electrons directed towards insulators did reduce the voltage, but in concentrating on getting rid of the long tube effect I forgot about that. In this manner, I became aware of the importance of criterion II-O. Since then, I have observed many other cases where this criterion seems to explain poor tube performance.

F. Chain-Sparking Concept

In looking back, I believe the concept of an accelerating tube as constituting a chain of spark gaps that somehow get triggered did not get the attention that it deserved by the ad hoc committee. I rather imagine that the sparks initiated by clumps were pictured in our minds as going the entire length of the tube through its center. In that case, if the clump struck the negative end of the tube and it sparked down, a terrific x-ray pulse should accompany the event. Since then I have seen many cases recorded on a 4-channel recorder that show almost no x rays with complete spark down. The largest pulses seem to be mostly associated with no appreciable drop in voltage.

If one tries to estimate how long it takes to build up a spark through the center of a tube, he soon sees that space charge plays an important role. Positive ions must come from the other end to neutralize space charge of electrons from a hot spot,

but by the time the positive ions arrive in the vicinity of the hot spot it has cooled off.

In going back over my notes, the performance of a 2-ft-long section of tube D in the test generator is interesting in this regard. In one test, we were able to coax it up to 1.6 MV, i.e., by being very careful we had gotten the voltage up to this value without a spark. Then I noticed that a few kicks or slight dips in voltage occurred. These produced x rays but were slow; judging from other tests the pulse length was ~1 msec. Following these kicks, a rapid spark took place that produced almost no x rays. We had evidence that the spark was less than 1 nsec in length. After that spark, it would not hold 1.4 MV until many minutes later.

Let me now interpret this observation. Obviously, some process had caused a burst of current through the center of the tube since x rays were observed. We don't know what initiated the central kick; there are several possibilities, including a clump striking the end. No matter what the event may have been, no spark occurred because space-charge neutralization in the central portion of the tube is too slow. However, this event did release enough electrons from the outer circumference of the diaphragms to charge the insulators. Then came a spark along the insulators. Such a spark can develop very rapidly since there is little waiting for space-charge neutralization. After the sparks, the insulators were heavily charged so one had to wait until they became discharged. I am emphasizing this observation because it gives insight into the nature of many sparks within accelerating tubes.

G. Tube E--Tube C Rejuvenated

With the failure of Tube E there seemed to be only one thing to do, namely, put tube C back. I did have the diaphragms revised, a drawing appears elsewhere.²⁷ They were also made smooth and the inside diameter was reduced to 5/8". They were also placed at every junction. We also washed away the fillets of adhesive with acetone this time since there were many pieces of adhesive scattered around inside tube C when it was dismantled.

H. Tests on a Single Section in the Large Van de Graaff

During a period of one month early in 1960, Beauchamp and I did test some different types of sections within the Van de Graaff. These were

single sections and were mounted at the bottom of column. They showed that a relatively minor modification was good for 1.1 MV whereas we only had 0.9 MV for a section of tube E. Under the pressure of the time we did not try to take advantage of the better shape. This type of test would have been very fruitful if it had been done about 5 years earlier.

We did find that with four channels recording x rays, vacuum column current, diaphragm current, etc., one could learn a great deal about different types of events that took place. In fact, one type of event that we saw seemed to be a sharp pulse of positive current. There was no spark down of the voltage, just a small but sharp kick. The events appeared to me to be what a clump type breakdown would be like if one remembered to fold in the space charge limitation. It occurred in a tube section that had many molten drops of metal on the bottom diaphragms and I suspected that occasionally one of these got picked up by the field. The same type of pulses were not seen in a tube that had not been sparked a great deal. Hence my comment on criterion II-J.

We were frequently perplexed that the voltage we were able to hold on a section in the test generator was much higher than that we were able to hold on the same tube section in the large Van de Graaff. Part of this discrepancy turned out to be the result of a false indication from the resistors. Their resistance value was a function of the voltage. Incidentally, the values of Cranberg and Henshall²⁸ on the voltage they got across their tube section with frequent diaphragms needs to be reduced to 2/3 of their published voltage for this very reason.

Even so, there still remained a discrepancy of about 300 kV for a section of tube E. I suspected that it had to do with the high ring-to-ring capacitance of the column and hence my criterion II-L. The discrepancy was not due to deterioration because when it was tested again in the test generator, the same higher value of voltage was obtained.

A recent speculation is that higher distributed capacitance sustains a local discharge event so that it can better spread to another part of the tube. The two electrodes of the tube, located between the electrodes connected to the planes of the column, acquire so much charge from the discharge event that a

spark is triggered. It has already been mentioned in V-C how this tendency for the tube to spark in the presence of ion-exchange loading was stopped by the installation of a resistor system on the tube. The resistor values are too great to be of appreciable help in a violent discharge event so the explanation can be similar.

An obvious solution would be to make the inside diameter of the two rings in between the planes of the column to be somewhat larger so that the current from the discharge event is collected at the electrodes of the planes. A still better solution would be to isolate the tube.

I. Changes in Objectives

With the placement of tube E in service my research and development work on accelerating tubes came to a close. It had been nearly 10 years since we had first started using the accelerator and the desire of the nuclear physicists using the facility was that our efforts on improvement should go in another direction. Cranberg was interested in neutron time-of-flight work, and I went to work developing a better pulsed source for the terminal. Moreover, the concept of adding a tandem Van de Graaff to our facility was developing, and I took on the responsibility of making a negative ion source for this accelerator. During this period we did develop a direct extraction ion source that is widely used.²⁹ Richard L. Henkel took on the responsibility of designing the installation for the tandem facility. In 1965 I started to work on the polarized ion source with George Lawrence and in 1969 Richard Henkel assumed the full responsibility of being Group Leader of P-9.

It has been a considerable disappointment to me that we found it necessary to abandon our efforts to make use of the high voltage capability that exists within this Van de Graaff. Without the tube it easily goes to 12 MV. The limit seemed to be set by the charging belt. The pelletron charging chains now made by NEC apparently will work at higher gradients and would charge the generator at much higher voltage. With SF₆ in the outer region and with the many interpotential shells, 18-20 MV might be reached. So we have the situation that there is a great deal of capability that is dormant.

J. Tube E--12 Years of Service

In the early 60's the tube seemed to spark only in the region located between snails high up along the column and not in the high capacitance region at the bottom. I once had an analyzed proton beam out of the tube at 9.25 MeV; however, a spark occurred and I never could get the voltage to return. It was operated for some time with voltages up to 8.5 MV.

Three-stage operation started in 1964, i.e., it became a 7 MeV source of H^- or D^- for the FN Tandem. In some ways the tube operated better for negative ion acceleration than for positive ions. On the other hand one has to have very stable operation for injection into the tandem and 7 MV turned out to be about the best dependable voltage.

A problem with negative operation was the tremendous x-ray intensity produced at the base of the tube. The level was in fact in the lethal range. When the tube was assembled in 1960 it would have been easy to have installed magnets at the diaphragms in the junctions between sections and then the electrons would have been deflected out before they got to high energy. This did not get done and now the tube is so contaminated with tritium that one does as little as possible either in inspecting it or changing components within it.

The tube has deteriorated relatively little in 13 years (12 years of service). The bottom 2-ft-long section did deteriorate considerably at some time and was recently replaced. It is hard to give an estimate of the deterioration of the full tube because recent operation is by different people and with different back-bias values. The figure is 1-2 MV.

This tube did have three rows of spark gaps in it during about its first 10 years of service. Now, there was a tendency for a gap to get out of adjustment and so they were taken off even though it was clear that they had been triggered frequently. However, the resistor holders are still on the tube --examination shows that they have been sparked.

I started this paper with a conviction that we had experimental proof that this tube which was constructed with a fine modulus was more resistant to deterioration by sparking than the more conventional construction. I think I got this feeling from observation on the performance of Tube A. It still may be true but Tube E did have spark gap protection.

If one examines the resistor holders, it is easy to see that they have been functioning as a spark gap many times, particularly in the high capacitance region of the column. So now I have come around to the view that the reason for the good life of the tube is its good surge resistance (II-I), adequate spark gaps (II-K) and removal of fillets of adhesive (II-J). The use of glass-bonded mica for the insulating rings may have contributed, at least they have never suffered puncture.

The tube is now used with back bias applied over a shorter length than shown in Fig. 6; in fact, with considerable ion-exchange loading present. Under these conditions, it rarely sparks, although it takes over 2 hours to condition up to 6-1/2 MV from its initial value of 4.5 MV--a value it will decondition to overnight. Recently it has been conditioned up to 7.3 MV without a spark occurring. If a higher value of back bias is used, one seems to get rid of the ion-exchange loading, but one has considerable sparking present. Those who operate the Van de Graaff now feel that they can get more voltage by the lower bias. The deconditioning rate³⁰ is ~ 0.6 MV per hour--a very high value that indicates the presence of a high value of contamination. Unfortunately, we do not have the deconditioning rate from back in 1960. Then I found full back bias satisfactory and so did not have to struggle with conditioning it up again every time we wanted to use the tube at a higher voltage.

K. Back Bias and Violation of Criterion II-0

The performance characteristic mentioned in V-H is suggestive. Low bias is better than zero bias because a smaller area of the diaphragm is involved in ion-exchange loading. However, as the bias is increased the barrier is closed to two-stage ion-exchange loading, so loading shifts to three-stage ion-exchange process. The field concentration is now high on certain electrode edges and many electrons are emitted from these edges. Unfortunately, these electrons can cross over the center of the tube and strike electrodes on the other side. This is a violation of my criterion II-0 and leads to charging of the insulators. It doesn't matter whether the electrons are due to field emission or ion-exchange loading; both sources may be present on the electrodes with a strong field upon them.

Obviously, electron trajectories that are possible need to be calculated to verify the hypothesis.

L. Tube F--Hyder's Tube Built by Dowlisch

The use of Tube E was interrupted during 1971 when a tube made by Dowlisch Developments, Ltd., was used. The tube was designed by Dick Hyder at Oxford University and features inclined-field electrodes arranged in a helical pattern. The insulators were glass and were similar to those in the 1953 HVEC tube and had the same 1-1/2-in. modulus. The electrodes are aluminum and have considerable pumping speed by virtue of some cutout areas outside the central holes.

Shortly after the tube was placed in use damaged areas appeared inside several of the glass rings. These were quite similar in appearance to ones that appeared on the inside of Tube B. Unfortunately, the magnets that were used in the upper 4-ft length of the tube were incorrectly installed and a great deal of time was spent in trying to get an ion beam through the tube. The failure was believed to have been caused by the beam striking electrodes. The explanation has its logic, for the process would result in charging of the insulator or violation of criterion II-H. While the tube was operated for several months, it continued to deteriorate. Quite recently a new Dowlisch tube has been installed but its voltage capability has not been established as yet.

M. The New Tube F and Criterion II-L

The performance of the Dowlisch tube in this machine is interesting from the standpoint of a tube designer because of the very high capacitance between rings of the column. Unfortunately both Tube B and Tube F developed damaged areas visible in the glass quite early in their use--perhaps because they were allowed to spark down too many times. The aluminum electrode in the vicinity of the area on the glass was badly roughened in the case of Tube B; Tube F was contaminated with tritium and has not been inspected on the inside. Naturally the question comes up: Will this tube get into the same condition? Whereas in this generator the tube is very tightly coupled to the column, in the Oxford Van de Graaff the same type of tube is well isolated and the ring-to-ring capacitance is normal for a Van de Graaff. So a comparison of the performance in the two cases will bear on the

validity of criterion II-L as it applies to this tube.

If there is a destructive effect due to the high capacitance, then it can only occur when there are sparks. So extreme care that there be no sparks may be essential for good life of this tube in this Van de Graaff.

It is my contention that, if the inner column were rebuilt and the tube located in the center with adequate space around it, then the Dowlisch tube could perform as well in the P-9 Van de Graaff as in the Oxford Van de Graaff. On the other hand, the tube I shall now describe has a good chance to go to twice the voltage in the same column.

VI. SUGGESTIONS ON TUBE DESIGN THAT SATISFY THE CRITERIA

A. Hard Vacuum Vs Organic Bonding

Let us now explore some ideas on how these criteria may be satisfied in a single tube. I think some very good possibilities exist. However, it does seem to me that it will be very difficult to combine hard vacuum and a high gradient in one tube. I am not an expert on hard-vacuum seals, so I am going to discuss high gradient in quite good vacuum but not in a tube with hard-vacuum seals. There are ways to achieve elimination of ion-exchange loading without hard vacuum and these will be discussed. The use of polycarbonate adhesive should result in a quite good vacuum. Whereas the commonly used AYAT vinylacetate is heated to 180°C to get it to flow enough to make a bond, one heats Lexan 147 polycarbonate to $250 \pm 5^\circ\text{C}$ to make a seal. That suggests that the vapor pressure is significantly lower. Better than 10^{-8} Torr in the LAMPF injector tube has been achieved using polycarbonate adhesive.

B. Choice of Tube Materials

In reading about the work of others, I have been impressed by the titanium alloys. The popular Ti-6Al-4V alloy seems to be a good choice as explained above. My choice of insulating materials is glass-bonded mica ceramic, especially if the rings are cut out of sheet stock. This material has a very high dielectric strength; in fact, we have not had it to puncture in service at P-9. The dielectric strength parallel to the sheet in the old Mykroy 38 was only 1/2 as large as normal to the sheet. Therefore, charges flung into the interior

surface of an insulator can be expected to escape without damage to the insulator in the normal direction. The material is relatively inexpensive as long as the size of the rings is such that it can be cut from a standard sheet; one company advertises 19-1/2 in. x 26-1/2 in. in thicknesses from 1/8 in. to 1 in. Nowadays this material can be obtained made with synthetic mica, whereas all the material we obtained 20 years ago was made with natural mica. The material made with synthetic mica has greater homogeneity and will withstand higher temperatures, but is not advertised to have as good a dielectric strength as the material made with natural mica.

As already mentioned, my choice for bonding adhesive is polycarbonate. The plasticity so necessary to bond materials of different values of thermal expansion is quite low in the case of the polycarbonate adhesive, so it is necessary for the two materials to have a good match. Fortunately, the glass-bonded mica ceramic made with synthetic mica has a close match to Ti-6Al-4V, and I have been informed that with a little work the match could be made much closer.

C. Surplus Adhesive Removal

Getting rid of the surplus adhesive is important in my experience, and is therefore prescribed in criterion II-J. In the case of vinylacetate, this was done by filling the tube interior with acetone and agitating vigorously; a paddle wheel driven by a drill press head for ~5 minutes worked with excellent results. This was followed by a quick rinse with clean acetone, and then with another of alcohol. Alcohol does not cool the tube by evaporation nearly as rapidly as does acetone. Finally, the tube was placed back into the gluing jig and heated to $\approx 120^{\circ}\text{C}$ to drive off the solvent. In my opinion, this method does not undercut the adhesive as much as hand-brushing, as the time for absorption of the solvent is minimized. Incidentally, it takes approximately 2 weeks to soak a ring loose by immersing it in acetone, so one need not be in a big hurry. Now in the case of the polycarbonate, the solvent is methylene chloride. Hopefully, a similar washing technique can be worked up for the polycarbonate.

D. The Easy-to-Satisfy Criteria

Many of the criteria are not difficult to meet. For example, criterion II-A is easily met if flat electrodes located a cm or two apart are used and the assembly jig is adequate. We have already discussed technique for getting good vacuum. This, however, is complicated by the poor pumping speed associated with the design we want to use. Criteria II-C, D, and E have been well covered above. If the electrodes are well polished II-F is generally satisfied. Skipping over II-G and H, we note that surge resistance, criterion II-I, can be satisfied by choice of the proper insulator shape.^{14,15} Again we have discussed surplus adhesive removal, an important part of criterion II-J. The avoidance of droplet formation is a tricky matter, but if titanium or one of its alloys is used together with II-L fulfilled, I doubt that it would be present. Criteria II-L and M concern the isolation of the tube and that depends upon the design of the Van de Graaff, for example in this Van de Graaff it requires rebuilding of the inner column but not the separation column. And my plan does not call for insulating coatings on the electrodes, so II-N is satisfied.

E. The Difficult Criteria

We are now confronted with what is the tough design problem--stopping ion-exchange loading without charging of the insulators or triggering of sparks by bursts of current. In my examination of evidence for tube breakdown, I have seen many cases in which it appeared that ions and electrons directed towards the electrodes led to sparking. It is seldom possible to say whether the building up of charge on the insulator, or a sudden disruption of the potential distribution led to the spark. It appears that both are possibilities for some cases seem to demand one explanation and other cases seem to demand the other explanation. We must, therefore, protect against both possibilities.

It is in the manner of meeting this problem that the attitudes of tube designers diverge greatly. There are several ways of reducing or stopping ion-exchange loading but all are plagued with the side effects of insulator charging and triggering of sparks by bursts of current.

For example, the inclined-field tube is certainly in violation of II-H and O since electrons

released within the tube are directed towards the electrodes. Their shape, however, has been designed to make it more difficult for electrons to get to the surface of the insulators. Now perhaps two or three semielastic scatterings off the electrodes are required instead of one or two as in the case of Tube C or E. The darkening that is often seen on the inside surface of the glass rings of an inclined-field tube is caused by electrons penetrating into the surface of the glass.

The inclined-field tube is also in violation of II-0 in the sense that bursts of charge are directed towards the electrodes and can thereby disturb the potential distribution enough to trigger a spark-down of the Van de Graaff. On the other hand, the "clumps" that do get accelerated cannot travel very far along the tube and so don't have enough energy when they strike an electrode to produce a serious hot spot. Consequently, the inclined-field tube is in a good position with respect to criterion II-J.

I have been informed by Goldie¹⁷ that HVEC has obtained 5.5 MV on a tube 100 in. long and 15.3 MV on a set of MP tandem tubes being tested in their TU Tandem. The later tube has 4 sections on each end of the high potential dome with each section being 6 ft. long. These gradients are 2.2 MV/m and 2.1 MV/m, respectively.

F. Example of a High-Gradient Tube

Whenever I think of a high-gradient tube, I think of the short-tube section that James Henshall and I constructed in 1959. See Fig. 8 for a drawing of this tube. The insulating rings were the same 3/8-in.-thick rings used in the tube of Fig. 6. The 2024 aluminum electrodes were turned with a conical surface, so the gap increased from 3/8 in. at the insulator to over 7/16 in. at the inside edge. This tube in the test generator went to 1.05 MV without loading or significant conditions required. That is 87 kV per insulator.

G. The Progressive-Walk Shape

The shape was chosen so that whatsoever ion-exchange loading is present, the exchange trajectories do progressively walk towards the center where they escape from the gap. If one calculates the trajectories of charged particles, one readily sees that they must progressively walk towards the wide end of a tapered gap in the manner first

pointed out by Arnal.⁶ The conical shape of the electrodes insures that such ion-exchange loading as may be present in the gap adjacent to the ring does not charge it. In the conventional-shaped electrode, the taper is such that the ion-exchange loading progressively walks towards the insulator rather than away from it.

Now the same conical shape was used on the ends of the tube of Fig. 8. Again, ion-exchange loading progressively walks towards the center where the ions escape through the holes. The absence of ion-exchange loading in the test section shows that the concept was effective. The high voltage achieved also suggests that we are successfully keeping the charge off the insulators. So, here in one technique, we have satisfied three of the most difficult criteria, namely II-C, H, and O and experience with Tube E suggests that II-K is good.

H. Combining High-Gradient Sections

Now the remaining question is, can we use the sections of Fig. 8 as building units to make an effective long tube? Another way of looking at the problem is, can we join these sections together to get a good long tube in the manner of the test made by Granberg and Henshall.²⁸ That such a tube would have very poor pumping speed matters much less than 15 years ago for now we have several types of pumps

Fig. 8. High-gradient section--built 1959.

we can use along the tube. Naturally, the vacuum problem would be simpler if we had hard-vacuum sections like in Fig. 8, but we are not restricted to hard-vacuum seals by the dry-type pumps, i.e., cryogenic pumping is not limited in this way.

Obviously, a sequence of sections of Fig. 8 will create an ion beam through their central hole. We have to be careful or we will make it possible for ion-exchange trajectories to develop between one side of a hole in one section to the opposite side of the hole a few sections along the tube. Here some computer studies of diaphragm shapes and trajectories would be valuable. Obviously, the trajectory of an ion that spills into the central hole should have very low radial velocity so that it can be stopped on a back-biased diaphragm a few sections away.

It, therefore, seems to me that the best way of combining the high-gradient sections would be to provide diaphragms with as small a hole as possible for the beam at distances of 60-150 cm apart. The stopping diaphragm could be made of material with low production of secondary ions, or it could be back biased, or both. The holes at the ends of the high-gradient section should be large enough so that most of the spilled ions are intercepted by the stopping diaphragm and the number of ions that can get through is small. I believe with some time to work out possible trajectories, a good compromise can be worked out among the various requirements.

I. The Stopping Diaphragms

The logical place for the stopping diaphragms is at, or quite near, the junctions of tube sections. The zero field area at the junction makes it easier to use back bias in an effective way. This junction would seem to be the logical place to attach pumping.

In V-K it was pointed out that the edge of back-bias electrodes is a source of electrons that can pass over the center and strike electrodes. We are in much better shape now with the several diaphragms between the high-gradient sections to intercept these electrons. However, it is best to use the back-bias diaphragm only on the positive end not only because positive ions don't scatter as much but they are also much less numerous than electrons.

On the negative end we can suppress the emission of negative ions from a stopping diaphragm. Years ago, Henshall and I found that magnesium,⁵ if heated to 375°C, developed a high threshold voltage for ion-exchange loading. Presumably this was due to the fact that it absorbed the contaminants from its surface. Magnesium, and other metals too, seem to be a poor source of negative ions; however, production of negative ions by sputtering is a tricky matter as has been observed by Mueller and Hortig.³¹ In the test by Henshall and myself it was not necessary to keep the magnesium hot. However, one can imagine that it would be helpful if the magnesium stopping diaphragm were mounted so it could be easily changed, for example, through a port at the junction between the sections.

Another method of retarding the ion-exchange process at the negative end of the tubes consists in using a grid. These can be fairly coarse provided the radial velocity of the electrons escaping from them is not allowed to be large. This method, if combined with bias of the stopping diaphragm behind the grid, will suppress ion-exchange and still not choke off pumping too much.

This method has not been applied to accelerating tubes although it was used early by Joe Kennedy's group.⁷ It has been used without biasing of the stopping plate in a beam separator.³² Don Liska is building a beam separator of our design for LAMPF in which the one side is at ground potential and consists of a grid of parallel bars with a biased plate behind them. The high voltage is on one side only and is brought in through a pair of NEC accelerating tube sections acting as bushings. This separator is to be used in an extremely high radiation environment and could not be built without the use of NEC's ceramic-to-metal seals. Organic adhesive is not expected to be able to withstand radiation of the magnitude involved.

Clearly, the development of proper diaphragms for joining the tube sections of Fig. 8 will take some effort but several possibilities seem to exist.

J. Cryogenic Pumping

Cryogenic pumping with a helium-cycle refrigerator, as recently used by Purser in the terminal of the University of Rochester MP Tandem, would be ideal if done at a few places along the tube. This refrigerator gives 1-2 watts at 20°K and that is

cold enough to pump everything but helium, hydrogen, and neon. We are using the technique to pump argon in our polarized ion source.

It would be especially nice if the compressor could be located outside of the column. In that case, the fluid that is passed up and down the column has to have a much higher dielectric strength than ultra-pure helium. The fluid might be SF_6 if a bellows is used to separate the helium and SF_6 . The cycle used by one of the commercial helium-cycle refrigerators appears to be a good possibility. Again, some development work will be required but the product would be very useful for a high-gradient accelerating tube.

K. Conclusion

The set of 15 criteria, being the opinion of one man, needs to be broadened to include the judgments of many other workers in the field. I hope someone will undertake a survey paper with this goal in mind.

A plan for a high-gradient tube capable of holding 3 or 4 MV/m in tubes of reasonable length has been presented. Hopefully, someone can find the resources to test and build it. LASL's P-9 vertical electrostatic accelerator would be an ideal place to use this tube, provided that the inner column were rebuilt.

The technique might be extended to hard-vacuum construction, but I suspect that the ceramic-to-metal joint would be difficult. Therefore, I suggest that the first development work be done using the best organic adhesive available. When the technique is worked out, then it can be extended to a tube with hard seals.

ACKNOWLEDGMENTS

The criteria being based upon a lifetime experience, acknowledgment of all the assistance I have received in the work would be impossible. My work started at the University of Wisconsin under the guidance of Raymond G. Herb, and we have had many interactions since then. The accelerating tube of Fig. 2 was done with the assistance of Richard Burling.

The concept of a separation column (see Fig. 5) was suggested to me by Clarence M. Turner. I was influenced in several ways by discussions with John

Trump and Robert Cloud during the late 40's and early 50's.

The existence of the P-9 Van de Graaff is due to efforts by the late John Williams, Norris Bradbury, John Manley, J. M. B. Kellogg, and many others in the late 40's.

Important test work during the 50's was done by Keith Boyer and James Henshall. Richard Beauchamp has assisted over a 27-year period. I am also indebted to R. F. Taschek, J. E. Perry, Jr., L. Cranberg, W. T. Leland, and the late R. Thomas and many others in the 50's.

I have watched with interest the work of the LAMPF injector group and Earl Meyer has made suggestions on the use of polycarbonate adhesive.

It has been a pleasure to assist Richard Woods in working with the FN Tandem tubes. The responsibility of being Group Leader of P-9 was taken over by Richard Henkel in 1969 and the recent changes and testing of the tube within the vertical Van de Graaff have been done under his direction.

NOTES FOLLOWING MY EUROPEAN TRIP

As a result of my trip to Europe and to the Daresbury Conference, April 26-May 14, 1973, certain points have come up, mostly points that tend to verify the criteria. Rather than rewriting the paper, I am adding these points as notes since the paper was completed just before my trip.

A. Use of Titanium Alloy

Jean Huguenin et al. at CERN have done a great deal of interesting work on accelerating tubes for injectors and had already listed some of the criteria³³ of this paper. Perhaps the most interesting contribution of this group has been to show that a titanium alloy (TA6V) will sustain a very large voltage difference provided it is used under conditions of low organic contamination.³⁴ In this paper three curves are shown with voltages of 350 kV, 530 kV, and 650 kV for a 5-cm gap. Huguenin showed me mass analysis curves that were obtained in association with the tests and these indicated that the partial pressure of organic vapor was 140, 6.8, and $<1 \times 10^{-10}$ Torr, respectively. Since the gap was between the flat ends of cylinders 25 cm in diameter, one must expect ion exchange to be an important process, and this seems to me to be a dramatic

verification of the usefulness of titanium used in a clean system. He reminded me that R. Charpentier of HVEC has studied the use of titanium as a tube electrode for several years.³⁵ The reason HVEC has not used titanium in their accelerating tubes has never been stated to my knowledge. Perhaps the advantage of titanium is mainly in very clean systems which HVEC has not used.

B. What Is the Best Name for Ion-Exchange Loading?

As explained in II-G the word microdischarge is synonymous with ion-exchange loading and is used by most people who have done research on vacuum discharge processes. However, as the Daresbury conference progressed, it became evident that many of the users and builders of accelerating tubes tended to use the term for localized sparks within their tubes; that is, they did not understand the proper meaning of the word microdischarge. It is this semantic problem in the name "microdischarge" that has led to my use of "ion-exchange loading." Still, G. Hortig of Heidelberg objected--he is accustomed to the name "microdischarge" and to him "ion exchange" implied a process taking place in the gas rather than on the surface. We tried to compromise; certainly "exchange sputtering" would be a name that would lead to less confusion. This word makes it clear that the process involves only the surfaces of electrodes and thereby satisfied Hortig's objection.

C. Does the Experience with Magnetic Suppression Fit the Criteria?

One puzzle to me has been the value of magnets in accelerating tubes as reported by Howe;³⁶ however, the experience reported by Langsdorf³⁷ of Argonne on tubes in their Radiation Dynamics machine is illuminating in regard to their value. Before they installed magnets in the exterior of their tube, they were very conscious of the x rays produced in the tube, both from the ion-exchange loading during conditioning and from the electrons released by the beam in the residual gas in the tube during operation. The current to the walls of a pressure insulated generator caused by the x rays releasing ion pairs in the insulating gas (the Turner effect) is easily monitored in the case of a Dynamitron by the insulated electrodes on the walls. With no beam, it was easy to use this current as a means of monitoring conditioning and it was observed that gas evolution within the tube and this

conditioning were associated. When magnets were installed that deflected the electrons into electrodes, the Turner current was reduced by ~ 30 but the threshold for ion-exchange loading and the associated evolution of gas was not noticeably affected. Inasmuch as the x-ray intensity outside of the tank with a large beam in the tube was $\sim 100R$, this represents an important gain.

A difficulty developed in that the tube was damaged. Electrodes became pitted due to sparking and this occurred in areas associated with darkening of the glass. The electrons deflected by the magnets did not strike the insulators, except through scattering, but this did take place because darkened areas were seen. This experience is a strong verification of my criteria II-G, H, and O and to the concept that stopping the return of electrons does not eliminate ion-exchange loading but does eliminate the x rays.

D. Effect of SF_6 in a Tube

In II-K I mentioned that the presence of SF_6 in an accelerating tube is regarded with suspicion. Roche Desrochers pointed out to me that during the initial conditioning of the Dynamitron for the Universite de Montreal,³⁸ a partial pressure of $\sim 10^{-7}$ Torr of SF_6 was present in the tube due to a small leak. This caused no difficulty during conditioning; however, when the intense beam was turned on considerable deconditioning took place. This fits the concept presented above for the SF_6 gas at a pressure of 10^{-7} Torr would not be expected to be absorbed on the surface of the electrodes; however, several of its products of decomposition might be expected to be absorbed. The resulting source of negative ions on the cathode would reduce the threshold for ion-exchange loading as was observed. So the danger of SF_6 contamination depends upon the presence of a heavy current to decompose it.

E. Ion-Exchange Loading - Further References

Hyder of Oxford pointed out that I had not made use of some Russian references--here my several years absence from the field shows up. Gerasimenko's³⁹ theoretical concepts correspond to observations and theory by I. D. Smith¹⁴ and I remember thoughts I had along the same line. The experiments of Pivovarov and Gardienko⁴⁰ on microdischarge phenomena are interesting in that they were extended to hard vacuum and also to elevated

temperatures. The materials that they used, namely, copper, molybdenum, nickel and lead, are poor electrode material for accelerating tubes. They came to the conclusion that the effect of outgassing and heat treatment occurred primarily on the anode. This is different from the ideas of this paper that the effect is primarily the removal of contaminants from the cathode electrodes that can make negative ions. The materials used for accelerating tubes, namely, aluminum, stainless steel and titanium, form highly passive oxide films, particularly when buffed. Their experiments should be extended to these materials. Incidentally, their experiments were stimulated by considerations of Ionov⁴¹; however, their experiments did not support his hypothesis--not nearly so well as some work by the old group at Washington University⁷ does.

It would not be fair to say that the concept of ion-exchange loading has universal acceptance. A quite recent review paper by Davies⁴² does not mention microdischarge--or an equivalent name. Perhaps this is because research in breakdown in vacuum tends to be done by idealists who insist on very high vacuum and considerable outgassing of the electrodes. But, as Pivovar and Gardienko⁴⁰ and others have shown, the microdischarge process is absent under such conditions. Now, Herb and his NEC have not achieved freedom from ion-exchange loading in a practical accelerating tube even though good high vacuum technique was employed. On the other hand, Davies did emphasize in his review paper that the mechanism leading to sparking in gaps greater than approximately one centimeter is not understood.

One of the most elegant studies of breakdown for large gaps in clean conditions has been made by Rohrbach.⁴³ For gaps below ~1 cm field emission seems to dominate, 1 cm gaps seem to involve the transition, and gaps of 2.5 cm or greater for which 5 cm breakdown times are common. It is suggested by Rohrbach that "microparticles" are needed to initiate the breakdown but some additional time is needed to release the microparticles. It seems to me that the concept that is needed is that the microparticles are released by some sort of ion-exchange process between the surfaces.

Hortig voluntarily expressed to me at Daresbury his belief that clusters of atoms are associated with the microdischarge phenomenon. Now in the

absence of violation of criterion II-0 in a dirty system there seems to be very little tendency for a spark to accompany the ion-exchange loading; however, in a clean system there seems to be a considerable tendency for a spark to be present. Perhaps the fraction of the ions that are large clusters gets rapidly larger as the system becomes free of organic contamination. Hopefully, someone will do research on this point.

F. Tube Isolation

It was suggested in V-M that the comparison of the performance of the tube designed by Hyder and built by Dowlish Development Corp., which is now installed in the LASL Vertical Van de Graaff Electrostatic Generator, to the performance of a quite similar tube in the Oxford Vertical Van de Graaff Electrostatic Generator was a good test of the effect of capacitance. This is especially true since the tubes have the same length, 20 feet, and modules in construction, 1.5 inches. This may still be true but the tube on the upper 8 feet portion of the Oxford Vertical Electrostatic Generator is very close to the hoops. The present Dowlish tube is being operated to 6.8 MV at LASL whereas Hyder reported 7.5 MV as their top voltage. The tube shows much more promise than the other two glass-aluminum tubes that were used for awhile in this electrostatic generator. Considering the factors other than stored energy, such as the great care used in bringing the voltage up and adjustment of spark gaps on the tube, no significant comment upon the difference in stored energy is possible at this time.

Perhaps more to the point on tube isolation, Purser reported at Daresbury on putting a separate resistor system on a somewhat "sick" tube section in the Rochester MP tandem, on how this rejuvenated the section, and on how it got "sick" again when he took the resistors back off for use at another place.

G. Daresbury Tube Plans

The Daresbury group have built a tube section using the tapered electrode principles mentioned in VI-G. This section is 75 cm long and was taken to 2.3 MV in the Aldermaston Van de Graaff. This generator is no longer available to them but they are building an excellent test generator that can test a tube four times this length with room for joining sections. Since terminating plates on the tube when tested were in violation of criterion II-0 but are

easily corrected, I am hopeful that they are on their way to a high gradient tube.

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