In Memoriam

On the morning of 16 Jan., Robert J. Van de Graaff suffered a fatal heart attack. The pages of this article had already been approved and returned to the printer when Physics Today learned of his death. We chose not to make any changes in the article, hoping that as it is, it stands as a fitting memorial to the man.

Van de Graaff, the Man and his Accelerators

The scientist whose name has become associated with a class of electrostatic generators used throughout the world has continued to develop improved accelerator designs and to pursue his early ambition of fusing heavy elements.

by E. Alfred Burrill

LAST SUMMER Robert J. Van de Graaff received the 1966 Tom W. Bonner Prize "for his contribution to and continued development of the electrostatic accelerator, a device that has immeasurably advanced nuclear physics." The occasion was the banquet ceremony of the American Physical Society meeting in Mexico City, held jointly with the Mexican and Canadian Physical Societies.

It is appropriate that this Southern-born scientist-inventor should have received this particular award, because Tom W. Bonner's meticulous and fundamental research achievements had been obtained through use of Van de Graaff particle accelerators. It is also appropriate that this award should have been bestowed at the Southwestern meeting of the American Physical Society, because many of Bonner's protégés are to be found at several of the universities in southwestern US and in Mexico. They too obtained much of their training and scientific reputations through their researches with Van de Graaff accelerators, first at Rice University and later at other laboratories.

To many of the attendees at the Mexico City meeting, 65-year-old Robert J. Van de Graaff had been merely a notable name on the roster of senior scientists whose major contributions to nuclear physics had been made during the early 1930's. It was surprising to them that this man was not only continuing his quest for nuclear knowledge but also outlining possibilities of fusing uranium nuclei by dc particle-acceleration techniques.

The invention

The original patent for Van de Graaff's electrostatic invention expired several years ago, but particle accelerators and radiation-producing machines using this principle continue to be constructed to the extent that there are well over 500 Van de Graaffs now in use for research, medicine and industry in more than 30 countries throughout the world. It is impossible to assess the innumerable electrostatic generators that have been built by students for science fairs and by laboratory assistants for physics lecture demonstrations and by research workers for stable sources of high-voltage direct current. The patent (US Patent No. 1,991,236) was issued in 1935, after an arduous but effective siege of writing out in detail the concept with expert guidance from Vannevar Bush, then vice president of Massachusetts Institute of Technology.

The physics community first became aware of Van de Graaff's generator in 1931 when he demonstrated production of more than a million volts between the spherical terminals of two belt-driven generators.[1] Karl Compton (who had recently been elected president of MIT) was by his side as the National Research Fellow from Princeton University nervously explained the principles of his invention at the American Institute of Physics inaugural dinner. Van de Graaff now recalls with a chuckle the difficulty of obtaining necessary funds (less than $100) from Henry D. Smyth to build this set of machines (which are, incidentally, still in occasional use for lecture demonstrations at the Palmer Physics Laboratory at Princeton).

Two years before his public demonstration, Van de Graaff had proved the principle of operation to his own satis-

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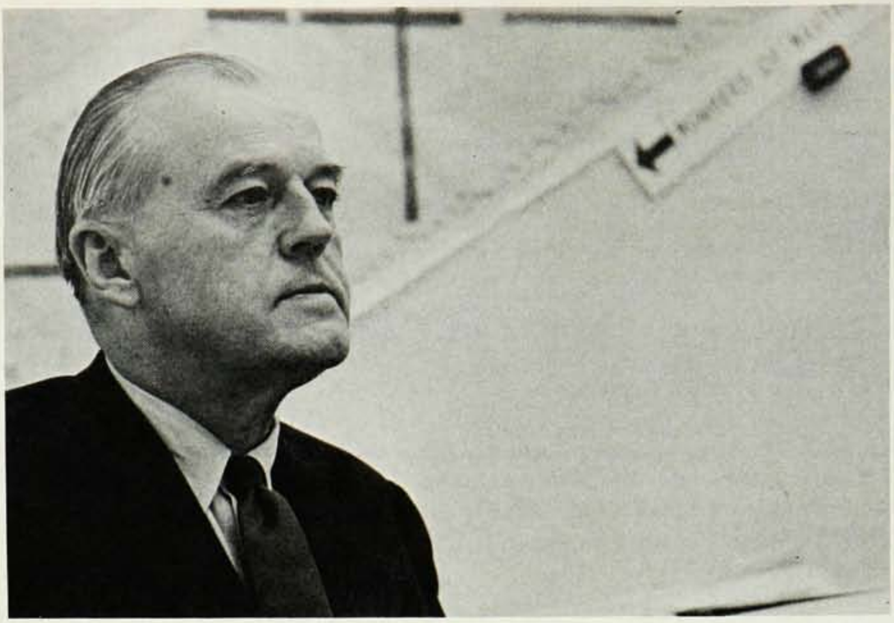

VAN DE GRAAFF TODAY is considering the fusion of two uranium nuclei, which would result in a new type of exothermic reaction far exceeding uranium fission in energy release per fused nucleus.

faction. Compton described this rudimentary model in 1933. "It was built in Princeton in the fall of 1929, being made out of a tin can, a silk ribbon and a small motor, at no expense. This model developed 80 000 volts, being limited by the corona discharge from the edges of the can."[2] What Compton omitted from his description was that Van de Graaff beleaguered local millinery shops in his search for pure silk and, indeed, shattered the tranquility of at least one establishment by calmly setting fire to a sample to determine whether the silk was pure or "loaded" with tin salts.

What started Van de Graaff's thinking of high-voltage dc power and its application to nuclear physics was a fortunate sequence of opportunities and the influential people associated with them. The sequence occurred shortly after his graduation as a mechanical engineer from the University of Alabama in 1922. He had long been interested in the conversion of heat into mechanical energy, and his work experience with the Alabama Power Co. enhanced his curiosity by exposing him to electric power generators having gaps in their magnetic circuits far in excess of those he had believed possible. (This simple observation would eventually lead him to his second important invention involving the generation of high-voltage dc power.)

Van de Graaff was dissatisfied with pragmatic methods to change heat into work. He sought for a deeper understanding of individual natural events and the forces that caused them. At this stage he went to the Sorbonne in Paris to study. To this day Van de Graaff finds more satisfaction in viewing a single nuclear track in a photographic emulsion than in a statistical summary of many events of the same nuclear reaction. Perhaps his interest in individual events was aroused during Marie Curie's physics lectures at the Sorbonne when Van de Graaff became fascinated by the clicks from a loudspeaker, representing the detection of individual alpha particles by a Geiger counter.

Homogeneous alpha particles from natural radioactivity were to make an impression again on this young convert to physics. While he was a Rhodes Scholar at Oxford University, working toward his PhD in physics, Van de Graaff read the 1927 anniversary address by Ernest Rutherford to the Royal Society which gave further evidence to the need for work on particle accelerators. In his address, Rutherford expressed his long-standing ambition "to have available. . .a copious supply of atoms and electrons. . . transcending in energy the alpha and beta particles from radioactive substances."

As a mechanical engineer, Van de Graaff had been trained to consider the transformation of energy in large quantities. As a physicist he required precise controllability in any energy-conversion process that would provide intense beams of nuclear particles. And he needed freedom to choose whatever species of particle would be appropriate for investigation.

Van de Graaff knew that charged particles could be accelerated by high voltages, but conventional methods of electric-power transformation would not provide enough particle energy or beam homogeneity for his purposes. Electrostatic characteristics of the atomic nucleus provided the key to the solution. "The nucleus of every atom is at high voltage," he said recently. "Even the lighter atoms have approximately one million volts locked up inside of them. The uranium atom is at about 15 million volts." Van de Graaff decided to use the direct-current electrostatic method of generating high voltages "to meet the atom on its own terms."

Using a moving belt to transfer charge continuously into the interior of an isolated conducting sphere, Van de Graaff overcame voltage limitations of existing electrostatic devices. Karl Compton recognized the force of this idea, and he supported it continually thereafter, from the early conceptual days at Princeton, through the many successful research and development projects at MIT until his death in 1954. The basic simplicity of Van de Graaff's invention made it readily adaptable for acceleration of many types of charged particles for a variety of purposes, as he predicted.

The ambition

Over the span of 35 years, two quotations bracket Van de Graaff's continuing ambition:

"Homogeneous beams of protons. . . could be used for many simple experiments of fundamental nature. Among these would be an investigation of the effect of their impacts on uranium and

VAN DE GRAAFF EXPLAINS his electrostatic generator to Karl Compton, MIT president, after demonstrating it at the 1931 AIP inaugural dinner.

thorium. . . .It might be that the proton would be captured by the [uranium] nucleus, thus opening up the possibility of creating new elements of atomic number greater than 92." (1931).

"One exciting possibility is the fusion of two uranium nuclei, which would result in an exothermic nuclear reaction greatly exceeding uranium fission in the energy release per fused nucleus." (1966). It would be important, says Van de Graaff, to control the energy of the bombarding uranium nucleus to such a precise degree that "a nuclear soft landing" would take place with a minimum of excitation energy imparted to the composite nucleus.

Between these two dates several consecutive projects were directed or influenced by Van de Graaff, as associate professor at MIT from 1934 to 1960, either to advance toward his ultimate objective or to sample other alternative avenues of research. In association variously with John G. Trump, an MIT professor of electrical engineering, and William W. Buechner, who became head of the MIT physics department, Van de Graaff became involved in construction of a half dozen different accelerator designs from 1931 to 1946. Each model pressed the technologies of insulating higher voltages, generating more intense currents, achieving superior beam homogeneity or attaining greater compactness.[3]

The uses to which these accelerators were put demonstrated the great adaptability of the Van de Graaff to cancer therapy, industrial radiography and research in physics and chemistry with electron and x-ray beams of several MeV. Ironically most positive-ion research activities were performed at other universities where accelerators had been independently constructed according to the Van de Graaff principle. Not until after the end of the second world war was there a concerted program of precise nuclear-structure research with positive-ion beams at MIT, under Buechner's direction.

Nonetheless Van de Graaff and his associates transcended—in energy, intensity and homogeneity—the beta particles of Rutherford's radioactive substances in a set of simple experiments with homogeneous beams of accelerated electrons. Prewar scientific literature showed a great disagreement between experiment and theoretical prediction of elastic and inelastic electron scattering. Most experimentation had been done with beta sources. Van de Graaff, Buechner and their coworkers demonstrated unambiguously that existing theories satisfactorily explained observed phenomena.[4, 5]

Van de Graaff gradually came to realize that he could contribute more effectually to the advance of nuclear physics by concentrating on the improvement of his accelerator technology than by immersing himself in actual nuclear experimentation. When High Voltage Engineering Co. was formed, he turned more and more toward this enterprise as consultant, teacher and board member until 1960 when he resigned from MIT to become the company's full-time chief scientist.

The rediscovery of the tandem acceleration principle in 1951, by Luis W. Alvarez at University of California, Berkeley,[6] imparted additional impetus to Van de Graaff's shift in emphasis. In any event, Van de Graaff devoted increasing effort to develop an accelerator that could double or triple particle energies then available from direct-current machines. In 1956 the Chalk River Laboratories of Atomic Energy of Canada Ltd. purchased the first tandem designed and manufactured by the company.

Chalk River's early experience with acceleration of several types of heavy ions resulted in new kinds of information regarding multiple Coulomb excitation, inverse nuclear fission and measurement of very short nuclear lifetimes. This type of research gave Van de Graaff added encouragement in planning for tandem accelerators of higher particle energy, greater intensity and different species of particles for "a complete freedom of choosing nuclear collisions." He envisaged the opportunity of independently selecting projectile and target nuclei from the entire periodic table. "Now if we can open up and be limited no more to just a few percent of the possible [nuclear] pairs [projectile and target] and can be free to choose any pair, then this is a marvelous new field of science." Thus was the largest model Emperor tandem, conceived (PHYSICS TODAY, October, page 81). Van de Graaff has also inspired the design concept of an even larger tandem for investigating the transuranium realm of artificial elements, unusual radioactive isotopes and fusion of the very heavy nuclei.

The inventor

As early as 1933, Van de Graaff acknowledged that a particle accelerator needed more than a good high-voltage supply and that particle acceleration-tube performance might limit the ultimate voltage that could be impressed on charged particles. He is quick to recall that even Wilhelm Roentgen, during his early experiments with x rays in 1895, had observed the limitation in his electron-accelerator performance, imposed by the design of the evacuated acceleration tube. As machines became more compact and of higher voltage, the tube problem became increasingly acute. The multiple-electrode design of William Coolidge sufficed up to a point, but, for very high gradients, drastic redesigns would be necessary.

Among the first of these was the uniform-field electrode configuration, invented by Van de Graaff and Buechner during their wartime radiographic project at MIT. Five 2-MeV Van de Graaff x-ray generators had been designed and constructed for the US Navy, and only by virtue of this novel tube design could they be made operational.

Several years later preliminary experimentation on a 6-MV acceleration tube was directed by Van de Graaff, to reduce the "total-voltage" effect. It was necessary to stop backward-streaming electrons in such a tube from attaining full energy, thereby loading down the high-voltage generator. By periodically inclining the electric fields of acceleration, light electrons were deflected so that they could not attain large energies, whereas injected particles could traverse the tube. Later in various tandems, combinations of electric and magnetic fields were used to guide even the heaviest ions along acceleration tubes that insulated more than 10 million volts. The success of the larger tandem accelerators is partly due to this invention.

In the early 1950's, Van de Graaff could see that particle-acceleration techniques would eventually demand more direct current than could be supplied by the belt-powered electrostatic generator. Conventional transformer-rectifier sets could provide more than enough current, but at relatively low voltages. Without sacrificing his requirement of direct current, Van de Graaff conceived a voltage-generating principle that essentially replaced the electrostatic charging belt by a magnetic flux as the means of transforming power to high-voltage direct current. To do this meant providing a magnetic core that would insulate the high voltage so that electric and magnetic fields could exist simultaneously in the same space. He divided the magnetic core into segments insulated from one another even though this would obviously increase the reluctance of the magnetic circuit.

The basis for this approach was derived from Van de Graaff's observation at the Alabama Power Co., over a generation earlier. As he recently recalled, "One of these hydroelectric generators was opened up, and I was delighted [to inspect it]. To my utter amazement I found that I could put my hand down between the pole pieces and the field. I'd always had the idea that an efficient magnetic circuit must be very closed. . . .I can still see the picture—my mind is entirely visual—of my hand in that gap. It struck my sense of wonder and never left it." The concept of introducing a series of small gaps in the magnetic core therefore did not disconcert him in laying out the principles of what has become known as the insulating-core transformer.

Today, this invention is being increasingly used as the source of high-voltage dc power for particle acceleration in industrial radiation processing and for a variety of applications in electric-power utilities and equipment manufacturers. Van de Graaff is urging the development of other embodiments of the insulating-core principle for generation of dc power at very high voltages in larger tandem accelerators. His goal is to remove as far as it is possible all limitations to the production as well as to the utilization of intense charged-particle beams of any species. He has also explored many methods for manipulating intense particle beams after their acceleration, to enhance their usefulness to research applications. Various designs of nuclear targets, particle-detection systems, and beam pulsing were inspired by him over the years.

The teacher

In his continual efforts to draw people toward his line of reasoning, Van de Graaff relies extensively on simple models and other dramatic visual aids, rather than the written word. He readily admits to a reluctance to write and a preference for visualization rather than to formulation of ideas into words. The models or graphs, on the other hand, readily take shape under the pressure of his desire to share his thrill of discovery and analysis with others.

Occasionally, a word picture springs out of a relaxed conversation with Van de Graaff that permits a glimpse of his probing into new research. In projecting the importance of bombarding nuclei with very heavy ions, he suggests "it could be interesting to create known elements by bringing together two isotopes in the middle of the periodic table to create something at the far end so that the electronic structure would suddenly assemble, and one would see the atomic processes occurring at the birth of an atom."

Scientific history is often invoked by Van de Graaff to support his enthusiasm. In defending the importance of having a complete freedom of choosing nuclear collisions, he has reflected on the analogous accomplishments of the past. "Gradually, with the work of Rutherford at first, it became possible to bring nuclei together to see what happened. In this way Rutherford discovered the nuclear model of the atom, Chadwick discovered the neutron and Hahn discovered fission." □

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