The Early History of Western Pulsed Power

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Invited Paper

***Abstract*—The development of submicrosecond pulsed power in the U.K. and USA between 1960 and 1970 is described. Novel short-pulse (tens of nanoseconds) X-ray tubes driven by stacked solid dielectric striplines were devised at the Atomic Weapons Research Establishment, Aldermaston, U.K. for radiography. The importance of nuclear weapons effects simulation then motivated a very rapid development of new types of pulse generator in the USA to drive scaled-up tubes of this type. Prominent among these pulse generators were the Marx-driven liquid dielectric pulse lines that form the basis of many present-day pulsed power generators.**

***Index Terms*—Electromagnetic pulse (EMP), electron beams, pulse generators, pulsed power, pulsed X-rays, switching, weapons effects simulators.**

I. Introduction

BEGINNING in 1960, J. C. "Charlie" Martin and his group at Atomic Weapons Research Establishment (AWRE) demonstrated that two electrodes with centimeterlike dimensions and spacing in a modest vacuum could produce and support electron currents of tens of kiloamperes and voltages of several megavolts, provided that the pulse duration was kept to tens of nanoseconds or less. They devised a vacuum interface with an inductance low enough to allow such a "vacuum diode" to be driven with such fast rising currents. They demonstrated these features at up to about 4 MV using novel pulsers (pulse generators) consisting of stacked solid-dielectric strip transmission lines switched with many solid-dielectric spark gaps that were replaced after each shot. The application of the AWRE group was flash X-radiography of explosive events.

Then, an increased need arose for short, intense X-ray pulses to simulate radiation from nuclear weapons. For this application, laboratories in the USA adopted the AWRE diodes and vacuum interfaces, scaled up greatly in size, and developed improved types of pulse generators to drive them. The most successful U.S. pulse generators consisted of a Marx generator charging a single liquid-dielectric transmission line system that was switched by liquid spark gaps; this system could operate repeatedly without refurbishment other than liquid flow. Physics International (PI) Company built the first of these generators in 1964 using oil dielectric, exceeding the AWRE pulsers in output; by 1970, PI scaled their design to about three times the voltage, ten times the current and one hundred times the energy. The PI workers coined the term "pulse power" to describe their technology. The U.S. organizations' willingness to engineer rapidly on a large scale was a critical factor in this growth period. By 1968, the U.S. Naval Research Laboratory (NRL) had designed, fabricated and tested a water-dielectric transmission line pulser that delivered a current in the 1-MA range at a lower voltage, $\sim$1 MV; this was charged by a PI Marx and water intermediate store.

The AWRE group adopted U.S. technology, and contributed ideas that were incorporated in U.S. hardware; Charlie gave important support to U.S. labs and programs. Many of the familiar features of today's single-shot submicrosecond pulse power generators were developed in the USA in the 1964–1970 period; the higher power levels of many later systems such as Aurora (Section III-E) and Sandia's 3-MV 20-MA Z accelerator (the subject of many publications since 1997) were achieved mainly by finding ways to synchronize many such pulse power "modules" and to transport their power to a common vacuum load region. Use of the new pulse power to develop vacuum loads much more complex than the first electron diodes was well under way in the USA by 1970.

Now, approaching fifty years after Charlie Martin's group began work, many workers in pulse power (now more often called *pulsed* power) are not familiar with the field's early history. This paper will summarize in Section II the early work at AWRE, and in Section III, the developments at U.S. laboratories up to 1970, when the technologies of Marx-driven oil and water pulsers were well established and that of electromagnetic pulse (EMP) simulators was developing rapidly. The author has drawn on his first hand experience in Charlie Martin's group from 1960 to 1966 and at PI from 1967 to 1976. He has also drawn on the knowledge of colleagues at AWRE (Mike Goodman) and PI (Bernie Bernstein, Phil Spence), and on the knowledge of colleagues from other U.S. laboratories active in pulse power in that period: Ion Physics (IP) Corporation (Stewart Graybill, Roger White), EG&G (Walter Crewson), NRL (Ihor Vitkovitsky, Gerry Cooperstein), Sandia National Labaratories, Albuquerque (Ken Prestwich), Maxwell Labs (Walter Crewson, Richard Miller), Cornell University (David Hammer), and Field Emission Corporation (Francis Charbonnier).

The author acknowledges that his description of work at AWRE and PI is the most detailed. This is because he was present—and also because much of the AWRE work has not been described in the literature. But the author has tried not to omit at least the main points of any important advances made elsewhere. He credits the organizations responsible for the

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advances, but does not list or name individuals except in a few cases. The author also thanks David Price (L-3 Pulse Sciences) for valuable suggestions, and thanks the L-3 Pulse Sciences publications staff. To all these colleagues named above he and this paper owe a great deal.

Published references do not exist for much of the work described. Before November 1965, there is only one published paper for the AWRE work, and none of the internal AWRE notes that were written and circulated later. There is no publication of PI's ground-breaking work on Marx-oil Blumleins until 1972, and little on the EMP generators of the late 1960s that are described here. Old government reports can be found with difficulty in some cases. For all work described, therefore, detailed references by project or results are not provided; but general sources where more information can be obtained are given in [1] and [2] for AWRE work from 1965 on; for U.S. X-ray and electron beam sources in [3]; and for EMP simulators in [4] and [5].

II. Early Work at AWRE

Charlie Martin joined AWRE in 1949, two years after the U.K. resumed the development of nuclear weapons. His field was hydrodynamics, and he participated in nuclear weapon design and in tests in Australia. He became convinced of the potential of X-radiography to aid the understanding of phenomena in implosions, and was instrumental in setting up a 35-MeV radio-frequency accelerator outside a concrete bomb chamber at AWRE to image explosive events within it.

The radiography facility came on line at AWRE in mid-1960. The author had had the responsibility to focus the accelerator's electron beam to a small spot on the bremsstrahlung target in order to obtain good resolution in the images. The focusing work introduced him to pulse power—building a small 40-kV capacitor bank discharged through an air spark gap into a coil that provided the final focus. The author then joined the pulse power group started a little earlier by Charlie Martin, attracted by Charlie and his vision that pulse power could provide much higher intensity X-ray sources than RF accelerators, and do so much more cheaply. Charlie's goal was what he called "core punching," imaging of full-scale mock-ups of imploding nuclear weapon primaries near the time of maximum compression. He estimated this to require an X-ray source that could provide about 300 R at 1 m, from bremsstrahlung produced by electrons of 6 MeV or more. Charlie believed that if a voltage of $\gtrsim$6 MV was applied to a simple gap between electrodes in vacuum, the gap would not be able to break down (short out) for at least an estimated 30 ns, because there would not be time for electron-ion avalanches to form. During that short time, the diode would have a finite impedance, and the currents of order 100 kA that were necessary to make the 300 R at voltages in this range should be attainable. This insight of Charlie's was what motivated his group.

A. Early AWRE Pulse Generator Initiatives

Before the author joined Charlie's group, the group's first members had investigated on a small scale some ways to create short high-power pulses using transformer oil as a dielectric. One result for the group was a disliking for transformer oil in any significant quantity. In terms of contamination of hardware and personnel, deionized water was more attractive. Moreover, water's permittivity of about 80, compared with 2.3 for oil, made its energy density more promising for realizing the group's goal of a 300 R generator not much larger than a desk.

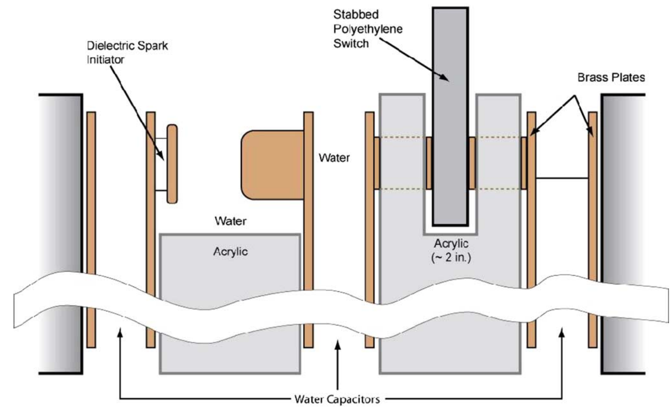


Fig. 1. Water Marx illustrating two switch types.

Therefore, water was tried next, in two different experimental pulser approaches. In one, a six-stage Marx generator in air or Freon gas, switched by open spark gaps, charged "Dreadnought," a set of water transmission lines in an acrylic box that was roughly a meter cube. A self-closing water spark generated ~30-ns pulses in two water lines in parallel, and the outputs of the lines were connected in series; the voltage gain was less than hoped, but more than 1 MV was generated. The Kerr effect in water was used as a voltage diagnostic. The voltage was applied to a vacuum tube; this early diode indeed did not short, and although its behavior was not resolved in detail the electron beam caused anode damage that suggested some pinching.

The group's second approach using water was a Marx of pulse-charged water capacitors. The capacitors were formed by ~2$-$ft^2 brass plates spaced about 2-in apart in water, attached to acrylic slabs in which the switches were embedded. A first design used water switches, which self-closed with inadequate simultaneity. Then, a six- or eight-stage Marx was built using "stabbed" solid dielectric switches (described in Section II-B). Being less time dependent than water, these broke down quickly after the first switch closed and produced some increase in voltage on the others, coupled through a liquid resistor load. Fig. 1 illustrates the water Marx and both switch types. Both Marxes were charged in ~2 μs to up to ~350 kV, through parallel isolating inductors that were wire wound and potted in epoxy, from air-cored pulse transformers devised by the group. Stripped coaxial cables were wound around a ~3-ft single turn transformer primary, initially potted in epoxy but later insulated by polyethylene sheet and tubing in air.

The gain of the water-Marx pulsers into high-impedance loads was less than the number of stages, for reasons that were not entirely understood, but voltages of over 1.5 MV were obtained. The water Marxes were not connected to vacuum tube loads, because the group's interest had turned to the use of solid dielectrics and the stacked stripline pulsers that became

Fig. 2. 1.5-MV stacked stripline pulser "Dagwood." The pulser is at the lower right. Above it is a gas-filled box containing the vacuum tube under test, evacuated by the pump on the left.

their main pulser approach. The group did not use oil, water dielectric, or Marx generators again until a few years later, after interactions with the U.S. community began.

B. Stacked Stripline Pulse Generators: Dagwood

Fig. 2 is a photograph of an early AWRE "stacked-stripline" solid dielectric pulser. This general construction was the basis of their generators until they adopted U.S. designs. Though they later constructed pulsers larger in size and different in topography, "Dagwood" illustrates all the types of component. An acrylic box 4 × 3 ft by about 1 ft wide contained fourteen polyethylene (pe) Blumleins side by side, each of which followed the same zigzag path (seen on the left-hand side of the pulser box in Fig. 2) from the farther switch end to the load end nearer the camera. The path length of 10 ft gave a two-way transit time and Blumlein pulse duration of ~30 ns. Fig. 3(a) illustrates the switch end and Fig. 3(b) the load end of two adjacent Blumleins. Each Blumlein (impedance ~15 Ω) consisted of two 1/16-in sheets of polyethylene and three copper conductors about 2-in wide and a few mils thick, forming two ~8-Ω transmission lines with a common central conductor. Adjacent Blumleins were separated by 1/2-in of polyethylene. The whole resembled a large sandwich of polyethylene and copper, and was named after the cartoon character Dagwood Bumstead, who liked sandwiches with many layers. Spaces between layers were filled with slightly conducting water, which spread the charge voltage out over a distance from the conductor edges much larger than the conductor thickness, reducing electric fields near the edges to values safe for both polyethylene and water.

A simple capacitor bank provided the charge voltage. The central conductor in each Blumlein was pulse charged to as

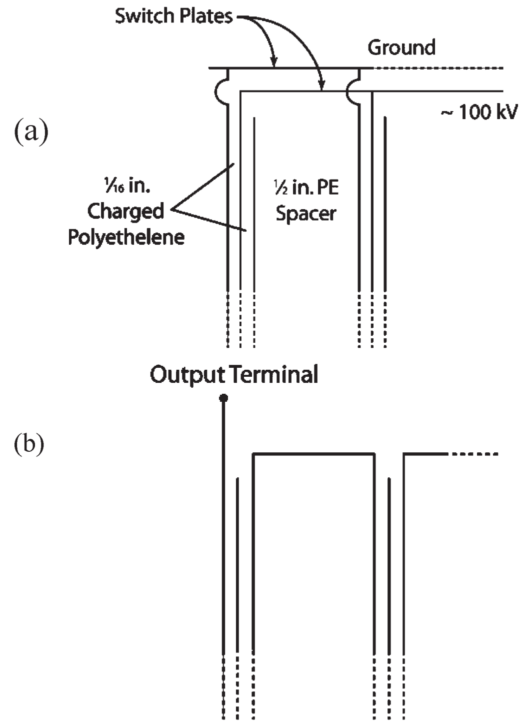


Fig. 3. Blumlein connections in Dagwood. (a) Connections to common switch. (b) Connections at load.

much as 120 kV in about 1 μs while the other two conductors remained at ground. A single switch region then actuated all Blumleins in parallel [Fig. 3(a)]. At the load end all Blumleins were connected in series by connections around the 1/2-in polyethylene spacers [Fig. 3(b)]. The open-circuit output voltage was reduced from an ideal $2 \times 14 = 28$ times the charge voltage mainly because the high voltage produced by the series connections created electric fields far outside the Blumleins and this drained energy. This effect was viewed by the group as driving a parallel, external transmission line load that had a "back impedance." In Dagwood, the open circuit gain was reduced from the ideal 28 to the 12–15 range, depending on the rise time of the type of switch used. The maximum open-circuit voltage of Dagwood was therefore about 1.5 MV. This output pulse was delivered to a region above the water that was usually filled with a Freon gas (CF_2Cl_2) at atmospheric pressure.

Fig. 3(a) suggests how the charged and uncharged conductors of the switched lines of each Blumlein were attached to separate horizontal conducting plates that formed the electrodes of the common switch, immersed in the water that filled the pulser; details of the interleaved insulation are beyond the scope of this paper. Fig. 4 shows end views of these plates and the switches that short them after charge is complete. In Fig. 4(a), the switch is a single 1/16-in sheet of polyethylene that has a "stabbed" region about half an inch square. Forty-five Singer sewing needles with their points coplanar were driven manually into the polyethylene from the positive surface to a preselected depth and withdrawn, leaving a void filled with air. Under the applied voltage, the air ionized to form an array of field-enhanced conductors, and breakdown of the polyethylene initiated from the tips of one or more stabs. The breakdown voltage was dependent on the stab depth (Fig. 5), was independent of charging

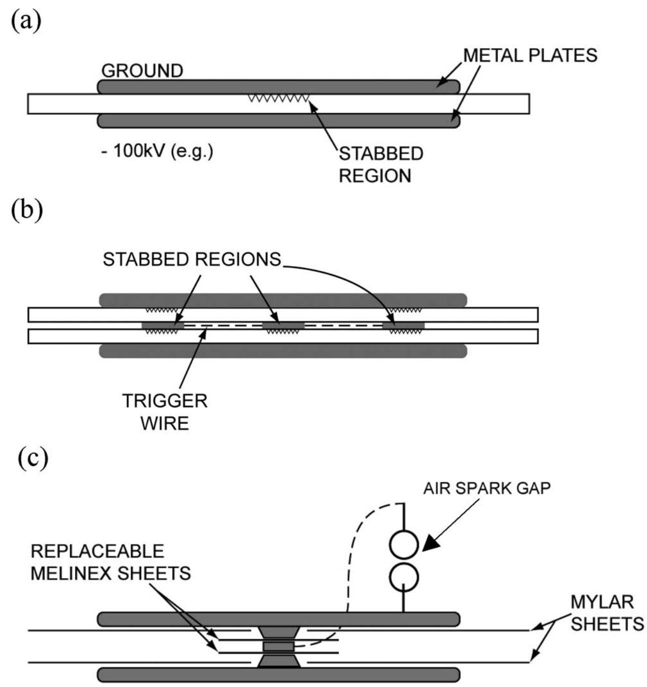


Fig. 4. Solid dielectric switches used in Dagwood. (a) Single self-break stabbed polyethylene switch. (b) Two-element triggered stabbed switch (as used in the larger pulsers Polaris, SMOG, and Spastic). (c) Triggered Melinex switch.

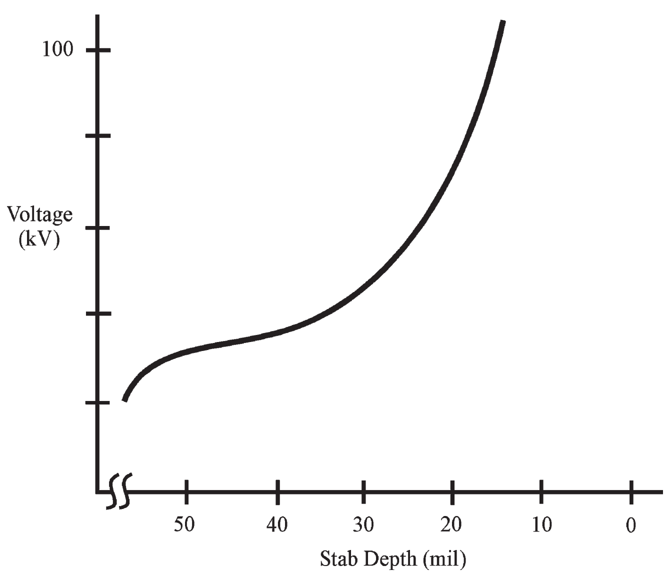


Fig. 5. Approximate self-break voltage of 1/16-in stabbed switch versus stab depth.

time, at least in the tens of nanoseconds to a few microsecond range, and had a standard deviation of 2%–3%. With the $\sim$1-μs charge of Dagwood, breakdown almost always occurred from just one stab. The 10%–90% rise time was roughly equal to the 30-ns pulse duration, with contributions from the inductance of the arc (only a few nanohenries) and of connections to the Blumleins, and from the resistive phase—the time that an arc resistance takes to fall from $\sim$10 to $\sim$0.1 times the impedance that it switches.

When more gain or better pulse shape was needed, the switch scheme illustrated in Fig. 4(b) was used initially. The two 0.04-in polyethylene sheets each had two switch sites where each layer was similarly stabbed, with an intermediate trigger foil electrode. One sheet also had a trigger switch region with slightly deeper stabs that broke down first and transmitted a fast-rising pulse along wires to the trigger foils of both switch sites, rapidly overvolting one sheet in each site and causing it to break in a number of channels initiating from the stabs. This still more rapidly overvolted the adjacent stabbed sheet, which broke down in tens of channels. The rise time was roughly a half that of the switch in Fig. 4(a), limited mostly by resistive phase and connection inductance.

Fig. 6. Fork and spoon X-ray tube.

An improved single-site switch used later in Dagwood [Fig. 4(c)] consisted of two sheets of Melinex, an Imperial Chemical Industries plastic, up to 5-mil thick. After charge, an electrode between the two sheets was swung in potential by the self-breaking air gap, and the sheets broke in turn, both usually in a single channel. The rise time of less than 10 ns was due mostly to connection inductance.

Dagwood was built around 1961. Like the water pulsers described above and Polaris and "SMOG" (below), it was built by the group by hand, except for some of the containment tanks, which were ordered from AWRE workshops. Dagwood was used for many years for the development of vacuum interface technology and studies of diodes and short pulse insulation, which were conducted in the Freon-filled region above the output end. The solid dielectric switches could be replaced in a few minutes. In Fig. 2, the output pulse is being delivered to a glass vacuum interface containing a cathode and anode that were a fork and spoon from the AWRE cafeteria [Fig. 6]. This was used to radiograph the AWRE Director's watch, in order to demonstrate how simple and flexible the short pulses made vacuum tube design.

C. Largest Solid Dielectric Pulsers: SMOG

The elements described in Dagwood were used in two much larger pulsers at AWRE, "Polaris" and "SMOG" (six megavolts or goodbye). In these, the Blumleins were lower impedance, formed from copper sheets $\sim$24-in wide with the 10-ft length needed to give a 30-ns pulse laid out straight. Again, the copper and polyethylene sheets were immersed vertically in weakly conducting water. In SMOG, the largest machine of this type built at AWRE, there were twenty Blumleins, charged in parallel, switched by individual switches, and connected in

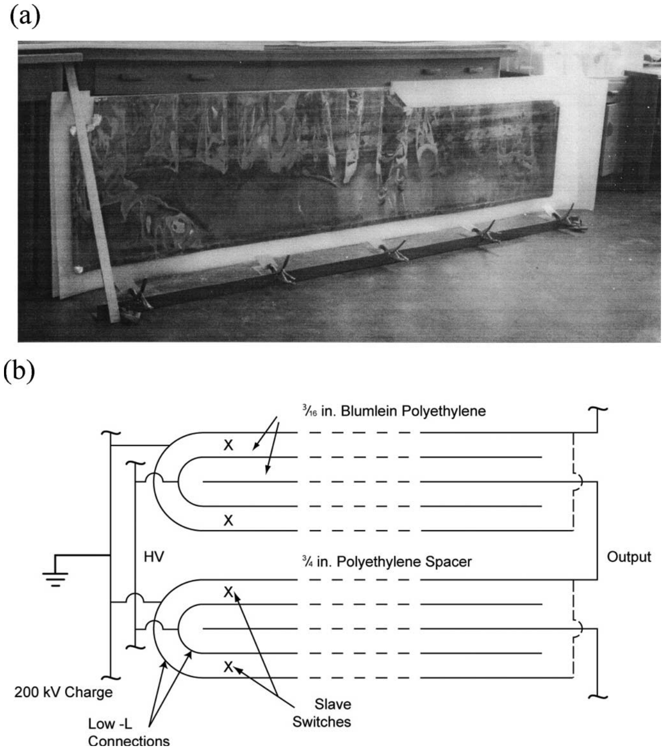


Fig. 7. SMOG Blumleins. (a) Blumlein preassembled in air. (b) Connections of adjacent SMOG Blumleins at input and output.

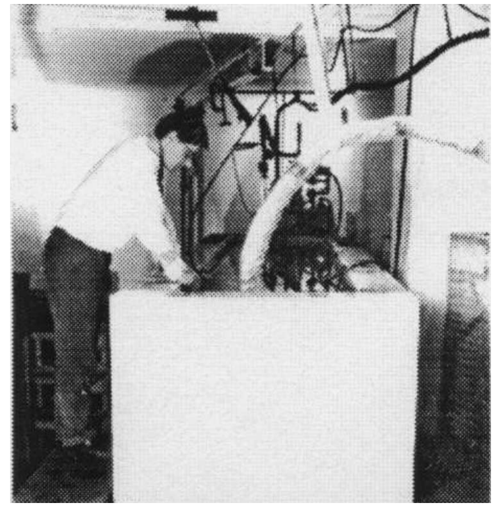


Fig. 8. 4-MV Pulser SMOG.

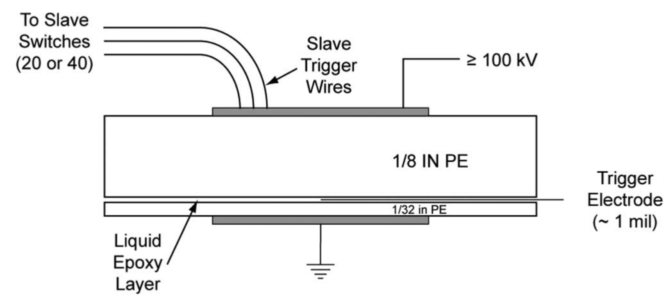


Fig. 9. Solid dielectric field distortion switch used as master switch in SMOG.

series. The Blumleins were charged to about 200 kV from a capacitor bank in Freon gas, and the output developed on the X-ray tube was just over 4 MV.

Fig. 7(a) shows a SMOG Blumlein before installation and Fig. 7(b) sketches the cross sections of adjacent Blumleins at the input and output ends. The Blumleins were two-sided, rather than one-sided as in Dagwood. Five copper conductors separated by four layers of 3/16-in polyethylene formed a $\sim$4-Ω Blumlein on each side of the central conductor; the two sides in parallel made a $\sim$2-Ω output impedance. The central and the two outer conductors remained at ground while the intermediate conductors, connected by a low-inductance strip of copper, were charged to $\sim$200 kV. The two outer transmission lines contained switch sites near one end where electrodes penetrated the 3/16-in dielectric and were separated by a stabbed switch consisting of two 1/16 layers of polyethylene, each like that in Fig. 4(a). A trigger foil between the two layers in each switch was connected to a trigger-wire, which exited the top of the Blumlein. After charge was complete, a common master switch pulsed all twenty trigger wires, breaking the switches down as in Dagwood Fig. 4(b). Switch jitter was probably subnanosecond. Each Blumlein switched $\sim 200\ \mathrm{kV}/1\ \Omega = 200\ \mathrm{kA}$, making 4-MA total, with a rise time of $\sim$20 ns.

The twenty SMOG Blumleins and the polyethylene spacers that separated them were assembled vertically by hand in a fiberglass tank in dilute copper sulfate solution, taking care to avoid air bubbles. The assembled pulse generator is shown in Fig. 8; the charge voltage is delivered by the bundle of stripped cables entering from the right, and is distributed under the water to each Blumlein. The short-pulse electric fields at the output were insulated by 1-atm Freon gas inside the white double-walled fiberglass vessel containing the Blumlein stack and by water and polyethylene between the output conductors and the walls of this vessel.

On a firing of SMOG, each solid-dielectric switch broke down in perhaps six channels on the first half to break and perhaps 20 on the second. Switching created gas and carbon debris, and when the switches were replaced after each shot care was taken to remove as much of this as possible and not to introduce air with the new switch. To shorten the switch replacement time, often only one of the two switch sites of each Blumlein was used, and the other was blanked off; the low inductance connecting the two transmission lines resulted in the one switch delivering a pulse to both Blumleins, though with a longer rise time.

The sets of polyethylene switches required for a shot on SMOG were made in quantity and their breakdown strengths remained constant over a shelf life of at least months. Once immersed in water their breakdown strengths climbed slowly (for an unknown reason), and it was necessary to shoot within an hour or so of installation.

The SMOG master switch was at first a single sheet of 1/16-in polyethylene, stabbed a little deeper to make it self-break at a slightly lower voltage than the others. This was replaced later with the triggered switch shown in Fig. 9. This consisted of two unequal-thickness sheets of plastics such as polyethylene and acrylic, e.g., 1/8- and 1/32-in thick, separated by a layer of unpolymerized epoxy resin containing a tongue of thin ($\sim$1 mil) metal aluminum foil as a trigger electrode. When

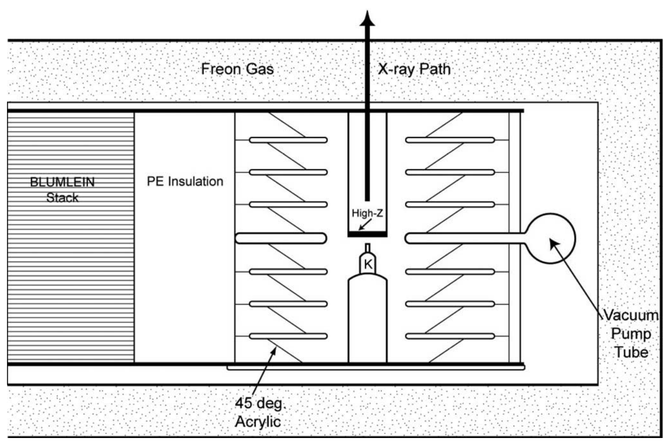


Fig. 10. Output or load region of SMOG.

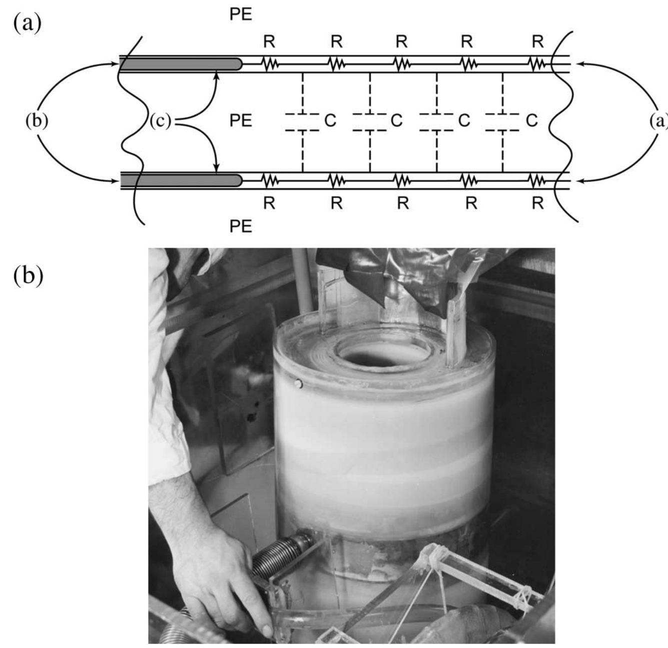


Fig. 11. AWRE edge grading. (a) Circuit representation. (b) Air-cored pulse transformer using this technique, tested at up to ~4 MV.

the trigger electrode was pulsed, many breakdown channels initiating in the resin at the edge of the trigger electrode bridged first the thick and then the thin plastic. This patented field-distortion switch was tested to ~1-MV pulse charged. It was also used in ~1-m-long switches that broke down in many channels as the trigger pulse propagated along their length; these switches were demonstrated with both pulse and dc charging. The dc switch immersed the trigger electrode in a grease layer, because grease conducted dc but developed high pulsed fields on triggering because of its low permittivity.

The output of SMOG was, like that of Dagwood, reduced by a "back impedance," about ~200 Ω. The output impedance of the stack of twenty 2-Ω Blumleins was ~40 Ω, so that there was a voltage loss of about 20%. The rise time was such that the voltage did not quite reach peak in the 30-ns duration. At 200-kV charge, the open-circuit voltage was therefore just over 6 MV, and driving a ~100-Ω diode the voltage was about 4 MV.

The output of SMOG was delivered to a volume roughly a 2–1/2 ft cube, formed by extensions of the Blumlein conductors at the ends of the stack (Fig. 10). The voltage was balanced about ground by the symmetry of the configuration. The voltage on the SMOG X-ray tube (discussed in Section II-E) was thus ±2 MV. It was measured by a center-tapped resistive divider of copper sulfate solution in an acrylic tube. The unshielded nature of the pulser created a harsh noise environment, but very clean waveforms were displayed on oscilloscope tubes that had ~2-kV/cm sensitivity; built by Ferranti, Ltd., these used ~25-kV electron guns and balanced, 200-Ω two-wire transmission lines that deflected the beam over a path of ~1 cm, giving very good bandwidth. This approach, on first principles more logical for pulse power measurements than attenuating to much lower levels and then amplifying in a more heavily shielded environment, was implemented using oscilloscope assemblies built by the group. These oscilloscopes had exponential time bases (provided with time markers), which showed both early and late-time information in an economical way.

AWRE's stacked polyethylene stripline technology was superseded in 1965, as described in Section III. This paper may be its first publication in any detail. Nevertheless, the technology was important in many ways. Reproductions of SMOG were used to radiograph explosive objects at AWRE Aldermaston and at the open firing range at AWRE Foulness, and as early U.S. weapons-effects simulators (Section III-B). Mylar versions, mostly unstacked, with solid switches and later gas switches, were used as lower voltage and impedance generators at Sandia, PI, Cornell University and the University of Maryland around 1970. Stabbed switches found use in early small U.S. water and Mylar dielectric pulsers at EG&G, Sandia, and PI. Meter-long versions of the switch in Fig. 9 were used to discharge > 100-kJ capacitor banks at AWRE and launch flyer plates that delivered impulses to military hardware; these sub-nanohenry switches also found use in the USA The technology prompted Charlie's assertion of the volume dependence of the breakdown of polyethylene (see next section). This important step allowed his group to later establish similar dependencies for liquid breakdown on area, and the resulting understanding of the importance of size effects and their statistics is an underpinning of modern pulsed power. Finally, the stripline generators allowed new diode and vacuum interface technology to be developed at AWRE and made available to the USA. These technologies are the subject of Sections II-E and F.

D. AWRE Insulation Technology

Fig. 11(a) illustrates the use of weakly conducting dilute copper sulfate solution to insulate the edges of AWRE's solid dielectric striplines. The potential difference between the two conductors spreads with time over increasing lengths of the electrolyte layers (a) as the resistance of the layers charges the capacitance of the dielectric sheet beyond the conductors, (b). The process follows the same equations as the diffusion of heat, and the diffusion constant can be adjusted so that as the voltage rises the electric field in the layer stays below a desired value, e.g., 100 kV/cm, independent of the sharpness of the conductor edges. The liquid conductivity required is typically in the $1\text{-k}\Omega \cdot \text{cm}$ range. With the field in the liquid below its breakdown strength the impulse breakdown strength of the system is then that of the polyethylene or other solid.

The field in the water in the uniform field region (c) will be low even in the absence of conductivity, e.g., if pure water is used, because of the high permittivity of water, $\sim$80, or $\sim$35 times that of polyethylene. If a much lower permittivity liquid (e.g., oil) is used it will develop a higher field and initiate breakdown at a lower voltage, even if thick, radiused conductors are used to lower the fields at the edges. AWRE showed that if polyethylene or another solid is pulse charged when immersed in oil it may break down at the low field levels characteristic of oil. Under dc, the oil will conduct unless it is very pure, and the strength of the solid can be attained.

The AWRE group found that the single-shot impulse strength F of polyethylene (pulsed in water or electrolyte or dc in oil) depended on the volume v stressed, as $F \sim 3\,v^{-0.12}$ (MV/cm, cc), consistent with the standard deviation at each volume being about 14% of the mean. This dependence of breakdown strength on size was recognized by Charlie Martin. It was counter to existing notions of "intrinsic electric strength." Applied by AWRE to other solids and later to liquids, the principle (as noted earlier) has become an important practical guide to pulser design that is still used today. With its volume of stressed polyethylene of about 6 l, Dagwood operated at up to 0.7 MV/cm; SMOG, approaching 100 l, at only 0.4 MV/cm.

AWRE found a similar dependence of breakdown strength on volume for other solids, with different values of the constant and volume exponent. The highest strength material found at AWRE, Mylar, was combined with the edge grading method to produce a patented tape-wound air-cored pulse transformer design that achieved low inductance and fast charge. A version shown in Fig. 11(b) was tested to 4 MV ($\pm$2 MV). The electrolyte used to grade the edges of conductors in this transformer was introduced by vacuum impregnation in order to fill all voids in the winding. Mylar was also used in an air-insulated dc-charged Mylar Blumlein, actuated by driving a nail through a Mylar switch that was used to drive a 100 kV, $\gtrsim$10 kA X-ray tube.

Many other aspects of solid dielectric breakdown were noted by AWRE that are not published, even in note form.

E. Vacuum Interface Design

The group had an immediate need for an improved vacuum interface that could withstand megavolt pulses over shorter lengths than existing technology, in order to reduce the inductance of X-ray tubes and allow fast rise times to high currents. In addition, the glass tube technology in general use was unsuitable because the large currents needed to produce hundreds of R at 1 m would, when focused to the small spot size needed for good resolution, explode the anode and require expensive replacement or refurbishment of the glass, as well as of the anode. The solution was found after Charlie suggested placing the insulator surface at an angle to the general direction of the electric field so that electrons were accelerated away from the surface and did not collide with it and cause secondary electrons or release of adsorbed material. This approach was already known, as "sweeping" the insulator, but the AWRE group systematically optimized it. They found that for most plastic materials the highest average field between two flat plates was obtained when the angle between a conical surface and the electric field was $+45^\circ$ to 60° [Fig. 12(a)]; this angle was denoted positive or negative depending whether electrons were driven away from the plastic or into it. This was demonstrated both for plastic cone frustra with vacuum on the outside (a convenient test geometry) [Fig. 12(b)] and for plastic rings containing vacuum, the configuration of the first X-ray tubes built by the group [Fig. 12(c)].

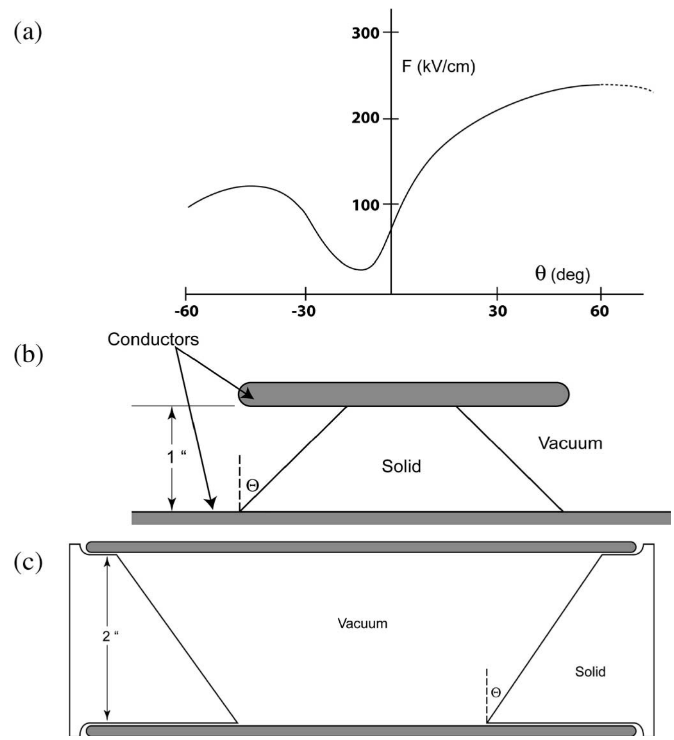


Fig. 12. Angled vacuum insulators. (a) The effect of angle (θ) on flashover strength (F). (b) Test frustrum ($\sim$40 cm^2). (c) Test ring.

As voltages increased, the need for very large diameter plastic was avoided by using a multistage design that used identical plastic rings 2–3-in thick separated by flat metal annuli named later by U.S. workers "gradient (or grading) rings." Fig. 10 illustrated the six-stage configuration used on SMOG. There the central gradient ring was the ground potential of the balanced drive, and was where the pump tube connected. This technology was the subject of the AWRE group's first open publication, and was patented. Later, it was recognized in the USA that this multistage approach can have the additional advantage of redundancy that makes it easier to achieve very high reliability. The multistage 45° vacuum insulator remains a standard design today.

The SMOG tube, like most of AWE's early designs, used insulators of transparent acrylic or pmma, with the tradename Perspex. Other plastics such as polyethylene and epoxy resin that had slightly higher flashover levels than acrylic in small samples proved not to be superior at the SMOG scale. Epoxy was used later in a racetrack shape tube with a single embedded gradient ring—in the 500-kV lower impedance (10-Ω) "Moomin" system (named after another cartoon character). The use of rubber insulators with vacuum surfaces coated with sulfur was considered, because tests of small frustrum-shaped samples showed that these achieved high flashover fields at smaller angles ($< 10^\circ$), potentially reducing tube size. A rubber X-ray tube was not pursued, and attempts to improve 45° insulators with coatings, e.g., ones with low secondary electron coefficient, were not successful.

As Fig. 10 shows, the diode region and the exploding anode were placed at the center of the SMOG insulator stack in order to minimize radial electric fields and the stack diameter. On each shot, the tube was removed from SMOG and disassembled; the anode and the cathode were replaced and the acrylic surfaces cleaned before reassembly, pumping, and replacement in SMOG. The acrylic surfaces were coated with a diffusion pump oil, Midland Silicones MS-704, the U.K. equivalent of Dow Corning F-704. This prevented metal debris from sticking and made cleaning easier. Several other coatings were found to degrade the flashover strength, but MS-704 had little or no effect, and had good vacuum properties. In later work in the USA, insulators were often coated with F-704 even when there was no debris to be cleaned and coating was not actually necessary. In the USA, oil was often also applied to the electrodes feeding the cathode and anode, again unnecessarily except that it may have reduced cathode emission in some cases.

David Sloan, a former colleague of E.O. Lawrence, visited AWRE in the period when U.S. interest in the field was increasing. Dave pointed out that on a $+45^\circ$ insulator between flat plates the permittivity of the solid skewed the field toward the anode, and he suggested that a Brewster's angle geometry would perform better because the field was uniform. He pointed out that this would also have the benefit of reducing reflected power; this was not important for the small X-ray tubes of that time, but Dave was probably already thinking of the large tubes that he would help build later at PI and the pulsers formed in oil-filled canyons that he hoped would follow. A Brewster's angle solid frustrum was made and found to be weaker than the standard design. (Later, U.S. workers showed that it is in fact better to skew the field toward the anode.) Dave Sloan also suggested dividing the insulator into very small lengths, because (at least for long pulses and dc) the breakdown field of small gaps was greater. Stacks of 10-mil Mylar disks with thin copper separators were tested, but it was found that the flashover strength was quite low for these crude designs. These ideas of Dave's were tested while he was still visiting.

Consequent to Dave's visit the group came to the view that excessive enhancement of the anode field by the permittivity caused the flashover field of plastics to decrease at angles $\gtrsim 50^\circ$; and in the higher permittivity materials (such as glass, the ceramic pyrophylite, and mica-loaded epoxy) that they tested, this decrease occurred at lower angles and fields, and flashover strength at reverse voltages was especially low.

Inspection of the 45° insulator surface after flashover revealed trees on the surface that branched densely from a single point at the anode, which the group took to confirm that flashover started at the anode. At moderate and small angles, faint trees were found that instead branched weakly from a single point at the cathode, which was considered to show that, as expected, at small angles the cathode triple-point initiated breakdown.

The group considered making insulators slightly conducting as a possible way to improve their performance by grading electric field or removing surface charge. After recognizing that materials with the conductivities of $< 10\ \Omega \cdot \text{cm}$ needed to control the potential distribution on the 30-ns pulse timescale were not easily available, the group considered conductivities that would at least remove surface charges between pulses. Materials with controlled conductivities in the kiloohms–centimeter range were made by an AWRE fabrication group; it was found that flashover field decreased slowly as conductivity increased.

The group therefore considered the best design to be the 45° acrylic insulator between flat plates. Shortly after the period that this paper is documenting, Charlie Martin attempted to quantify the flashover field for 45° acrylic as F (kV/cm) where $Ft^{1/6}A^{1/10} = k = 175$ and t is the effective time in microseconds and A the insulator area in square centimeters. Nowadays, we would take the constant k as $\sim$220 for acrylic and $\sim$240 for Rexolite. The AWRE value was probably lower in part because in the small ($\sim$40 cm^2) solid frustra that provided Charlie's data the anode ends were small enough that the field there was more enhanced than usual. Other early data existed at AWRE for rings up to 2000 cm^2 that yielded similar results, but for these the anode end was close to the outside edge of the acrylic, and this probably also lowered the breakdown strength.

Charlie described the flashover strength in his equation as the "conditioned" value. The AWRE stacked striplines produced pulses that were followed by a voltage reversal caused by the stack being shorted at the switch end. At voltages well below those that caused the insulator to flash on the main pulse, the reversal caused test insulators to flash over at low levels, and these flashovers raised the forward breakdown level by about 10%. That conditioning was not useable in a single-shot operation like that of SMOG.

The group was unable to resolve the fall of voltage on insulator flashover. The best resolution, on Dagwood, showed a fall to essentially zero in about a nanosecond. The inability of the discharge to couple much energy in this short time clearly contributed to the fact that flashover did not significantly degrade the surface for future pulses. This was a great benefit for the short pulse regime that the group pioneered. (The group found that for longer times to breakdown, in the microsecond range, flashover did degrade the strength.) Another benefit was that the vacuum that the insulator required for 30-ns pulses was no better than about 10^{-2} torr, which made the demountability needed by the exploding anode quite practical. The diode itself, where the electrons were created and used, required only slightly better vacuum.

F. Diodes

Charlie Martin's expectation that high-current electron beam diodes could operate for tens of nanoseconds without shorting proved correct for anode–cathode spacings of $\lesssim$1 cm on SMOG, and less at lower voltages. To minimize X-ray spot size and maximize image resolution, the smallest possible spacings

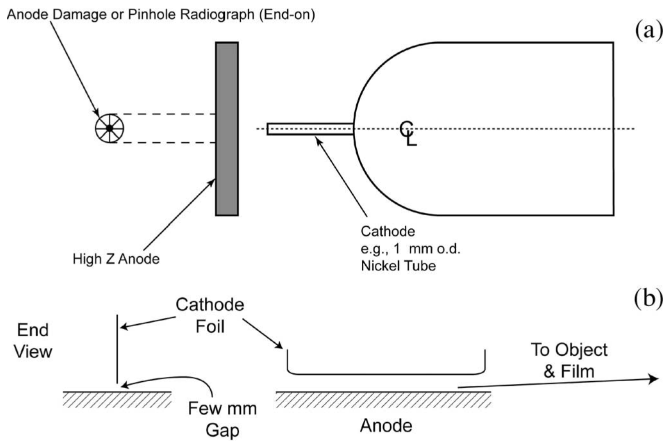


Fig. 13. (a) Diode geometry used on SMOG at ~4 MV showing anode beam pattern on SMOG (schematic); and (b) geometry of ~10-Ω diode used at ~500 kV.

were used on SMOG, and the cathode was made relatively small in diameter. The anodes were usually platinum or lead. The influence of the anode material and adsorbed anode gas was undetectable in tests on Dagwood that included pulsing while the platinum anode was raised to white heat by dc current. With sharper cathodes such as a fine wire or sharp needle, diodes shorted a little earlier than 1–2-mm diameter annular or blunt-ended cathodes, and therefore the observed shorting was associated with cathode-initiated processes. The group lived with these processes without investigating them in detail. Mesyats has since shown that the electron emission is from plasmas formed when whiskers on the cathode emit electrons, heat, and release gas. These plasmas expand at a few centimeters per microsecond and produce the observed shorting.

Anode damage patterns and X-ray pinhole images showed that the beam outside diameter at the anode was roughly the anode–cathode spacing at ~4 MV on SMOG, where the beam had an intense core and an outer annulus connected by radial spokes, like a cartwheel [Fig. 13(a)]. These were viewed as evidence of beam instability and pinching at higher currents. At lower voltages the beam diameter was larger, e.g. at < 1 MV, it was more than twice the anode–cathode spacing, the radial spokes were absent, and the central core was less intense.

The impedance of this type of diode was found to be proportional to anode–cathode spacing, and for most types of cathode roughly 100 Ω at 1 cm at a few megavolts, increasing as $\sim V^{-1/2}$ to V^{-1} as the voltage was reduced to ~1 MV and then below. The reduction of impedance with increased voltage was interpreted as a characteristic of space-charge limitation, added to by the tendency of the cathode emission area to increase with voltage. On the AWRE generators of this period, only the diode voltage was measured, and the diode impedance and hence current were estimated from the loading on the generator, the impedance of which was approximately known. At 4 MV on SMOG, the current was ~40 kA. The X-ray pulse measured by a photodiode had an full-width at half-maximum (FWHM) $\lesssim$20 ns, reduced from the nominal 30-ns generator pulse duration by the rise time and the strong dependence of dose rate on voltage. The dose in the forward direction was about 10 R at 1 m. From a paraxial 40 kA, 20-ns electron beam the dose at 1 m would be ~40 R; this was reduced by large electron angles with the axis and perhaps by the diode voltage being lower than the measured ~4 MV because of inductive drop along the anode and cathode conductors.

The SMOG diodes operated not much below 1 μm of mercury, a vacuum easily attainable in an hour or so of pumping, even using acrylic vacuum insulators pumped through long tubes of the same material extending from the vacuum pump into the middle of SMOG.

The 500-kV radiographic source Moomin used a different diode geometry to achieve lower impedance; a 10-cm-long metal foil cathode spaced 2–3 mm from the anode [Fig. 13(b)]. The long X-ray source was viewed end-on to give a small effective spot size. The Moomin tube was driven with flat-plate oil and water Blumleins, as the group later turned their attention back to liquid dielectrics in the light of U.S. work.

Thus, the potential and practical nature of < 100 ns multi-megavolt high-current diodes and vacuum tubes were clearly demonstrated. Energy densities that exploded the anode were handled easily by the demountable low-inductance vacuum interface and its modest vacuum requirements. Most of the development of more complex electron diodes, other vacuum loads, and external electron beams occurred, mostly in the USA, shortly after the work described here so far, and the earlier of these developments initiating in the 1960s will be described in the next section. But it will be noted here that the AWRE group experimented in the early 1960s with wire loads in vacuum on Dagwood–although little energy was coupled. Dielectric cathodes were also demonstrated by the group in the late 1960s.

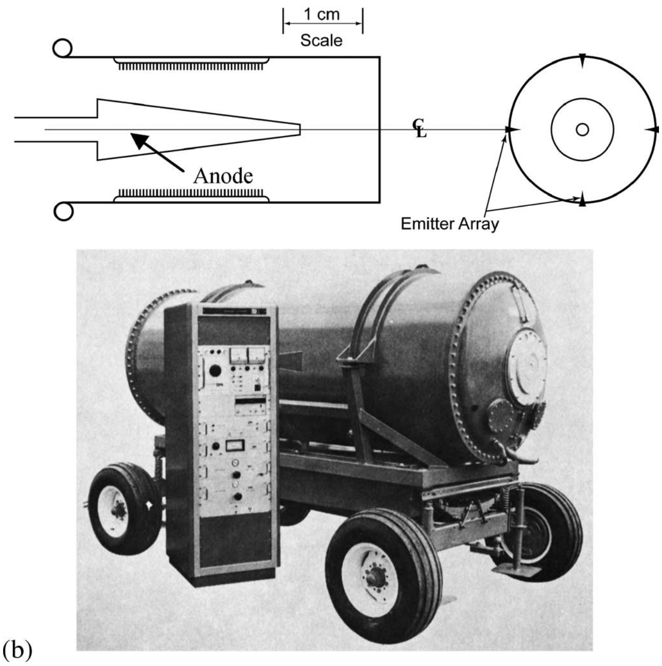
III. Modern Pulsed Power Generators Are Born in the USA

A. U.S. Players

Around 1963 an increased need arose for nuclear weapons effects simulators (NWESs), laboratory devices that could produce high-energy X-rays (to simulate the "prompt gamma flash"), soft X-rays, nuclear EMP or more complex radiation driven currents [source region EMP (SREMP)]. Indigenous U.S. X-ray sources existed that were pressed into use to simulate effects over small volumes. However, sources were needed that could simulate effects of concern over the volumes of military systems.

The U.S. Department of Defense (DoD) government agencies that pursued the acquisition of simulators included the United States Air Force Ballistic Missile Division (BMD), later the Space and Missile Systems Organization; the Air Force Weapons Laboratory (AFWL) and Special Weapons Center (AFSWC); the Army's Harry Diamond Laboratory (HDL); and the Defense Atomic Support Agency (DASA), later the Defense Nuclear Agency (DNA) and now the Defense Threat Reduction Agency. AFWL conducted some research into X-ray sources in-house, as did the NRL. But for the most part the DoD agencies contracted the development of NWES to industry. The Atomic Energy Commission, now the Department of Energy, gave responsibility for simulation associated with the warhead package to their contractor Sandia Laboratories, Albuquerque, who began their development in-house with help of AWRE.

(a)



(b)

Fig. 14. (a) Diode of 300-kV Febetron (courtesy Francis Charbonnier). (b) 2.3-MV source.

The DoD's first contractors for the development and in some cases operation of simulators included Ion Physics (IP) Corporation in Boston MA, a division of High Voltage Engineering Corporation (HVEC), whose staff included a number of immigrants from Britain, including two from AWRE (but not from Charlie Martin's group); Physics International (PI) Company, formed in 1962 in Berkeley, CA, moving in 1965 to San Leandro, CA; and Edgerton, Germeshausen and Grier (EG&G) in their Bedford, MA, division. Maxwell Laboratories, Inc. (MLI) was formed in San Diego, CA, in 1962 to make energy discharge capacitors and soon began to develop Marxes and pulsers.

The indigenous U.S. source already available was from Field Emission Corporation in McMinnville, OR, a company founded in 1958 to make X-ray sources based on a 300-kV device developed by Walter Dyke at the Linfield Research Institute in McMinnville. FEMCOR developed similar sources, known as Febetrons, at voltages as high as 2.3 MV and as low as 100 kV. Pulses of typically 1 to 10 kA were produced by Marx generators, the stages of which were pulse forming networks of capacitors potted in solid insulation. These pulsers drove sealed glass tubes (initial vacuum $\sim 10^{-8}$ torr). Lower voltage tubes contained cathodes that were arrays of precisely etched tungsten points surrounding a high-voltage conical tungsten anode [Fig. 14(a)]. Field emission from the cathode points led to the creation of plasma, and the tens of nanosecond pulse was over before the plasma reached the anode. Using the X-rays emerging along the cone axis made the effective radiographic spot size small [much as in Fig. 13(b)]. Lifetime of the larger tubes was typically 500 to 1000 pulses. A 2.3-MV source first built around 1962 and used mainly for NWES is illustrated in Fig. 14(b).

FEMCOR's sources were in wide use for radiography, and many were purchased by Los Alamos, Sandia, and Lawrence Radiation Lab (Livermore), who all may have funded some development of the larger sources. Many single-pulse sources were purchased for NWES, e.g., by aerospace companies, especially the 2.3-MV sources. These produced about 2 R at 1 m, and had great reproducibility (a few percent). They were often used to expose small objects at short distances. Electron beams were available, extracted through thin windows; these beams found applications in radiolysis too. The lower voltage sources could operate for cine-radiography at up to 1000 pps (limited by recovery of the CO_2 gas spark gaps in the Marx), in bursts of up to 50 or 60 pulses (limited by anode heating).

The use of FEMCOR sources became less important for NWES when the more powerful sources described in the next section came into being. But they are still in wide use today. In 1973, Hewlett Packard purchased FEMCOR and put the technology to other uses including field medical X-rays. PI bought the technology in 1994.

B. Flash Gamma Simulators: Competing New Technologies Emerge

Initial emphasis in NWES was on the simulation of "prompt gamma flash" X-rays. This required pulses tens of nanoseconds in duration, in the range of the AWRE pulsers, and voltages as high as the 4 MV they had produced and higher. X-ray output increased as a high power (~ 3) of the voltage, and voltage was therefore the most important parameter. X-ray output was only linear with current, which was therefore less important, and prompt gamma simulators are synonymous with "high impedance" pulsers (tens of ohms) and diodes (up to 100 Ω).

The U.S. contractors IP, EG&G, and PI had in some cases visited Charlie's group, and Charlie had visited them all. Thus, all of the initial efforts at prompt gamma flash simulation adopted the AWRE stacked 45° vacuum insulator. In the vacuum, simple gaps again formed the diode, with some field enhancement at the cathode to encourage prompt electron emission, but usually with larger dimensions than the ~ 1 cm that had been used at AWRE, so that the electron beam was larger and lower energy density and the high-Z anode or bremsstrahlung target was not damaged by the pulse and did not need to be replaced. There was little or no reduction in dose in a test object if the beam size was as large as the object itself. The larger spacing in the diodes allowed increased pulse duration.

Although the U.S. groups all adopted the AWRE vacuum tube technology, they had different strategies for providing the pulse generators that drove the vacuum tubes. From the outset, IP used the Van de Graaff technology of its parent corporation, HVEC, in a novel way (see below). PI began using the AWRE stacked solid dielectric line design, while developing its own novel approach. Sandia arranged for AWRE to fabricate and install a stacked line generator at Sandia, in preparation for which Sandia personnel visited AWRE to learn the technology.

The simulator that AWRE delivered to Sandia in the autumn of 1964 was similar to SMOG, but had 23 Blumleins instead of 20. It reached perhaps 4.5 MV at the diode, and produced about 15 R at 1 m compared to the 10 R of SMOG. It did

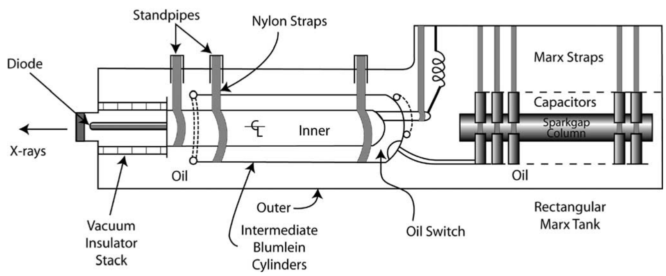


Fig. 15. Schematic of a PI Marx-Blumlein system like the 730 Pulserad.

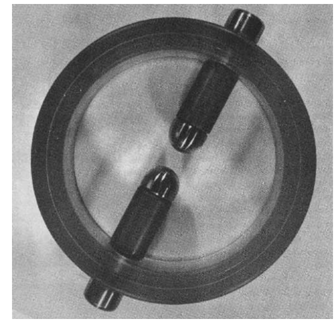


Fig. 16. Marx stage used on the first pulserads.

important work as a simulator until 1967, but Sandia found it difficult to operate firing many shots per day instead of the occasional radiography shot for which the technology was intended. Each shot required 23 used solid dielectric switches (described earlier) to be carefully removed from the Blumlein stack, and 23 new switches to be inserted without introducing air. The lack of an electromagnetic shield around the pulser and its fast-rising 4 MA at the switch end also posed difficulties; in the first check-out tests, each shot was followed by a steady ring on the lab phone for a duration that was a good indicator of the power or dose attained. Sandia chose the name Spastic for the simulator.

PI was also having similar problems in California attempting to operate versions of the polyethylene stacked-line generators for external users. PI placed the Blumleins flat in their water tanks, and lifted the stacks out of the water to replace switches. PI's largest device of this type comprised two line stacks that drove the vacuum tube from two sides, a step toward a coaxial geometry; the vacuum tube anode was grounded to allow test objects to be placed adjacent. The dose reliably obtained never exceeded a few R at 1 m.

The author helped deliver Spastic in Albuquerque, and on the way delivered the AWRE group's first publication–on insulator flashover, the stacked 45° insulators, and (briefly) the stacked-line generators–in Boston MA. There Don Martin of PI told the author that the 10 R at 1 m of the AWRE machines was good, but PI was building a machine that would produce 50 R at 1 m. Trying to provoke Don into revealing the design of the machine, the author expressed disbelief that instead drew successive statements that the design could achieve 500 R, then that it could achieve 5000 R, and then that there was a national need for 50 000 R at 1 m and Don felt this was achievable. The addition of successive zeros after the same 5 was interpreted by the author as spontaneous fantasizing, but he later spent several years working for Don on the last two of these machines.

Late in 1964 PI unveiled their 50 R source, the first of the generation of Marx-oil Blumleins. This was the Pulserad 730, with a 7-ft diameter Blumlein charged by a 30-stage Marx. The steel tank that enclosed both Marx and Blumlein was painted blue and the 730 was often referred to as B^2, for Blue Boy. The design, sketched in Fig. 15—a slight elaboration of a figure in PI's patent—exemplifies that of many later machines. The Blumlein consisted of three concentric cylinders about 12-ft long suspended in oil by nylon straps; the outer cylinder was the grounded tank, and the intermediate cylinder was pulse charged to high voltage (as much as about 4 MV) in $\sim$1 μs by the Marx. During this time, the inner cylinder was held near ground by an inductive connection from a $\sim$1-ft diameter cylinder that passed through an aperture in the intermediate cylinder. Roll ups relieved the electric fields at the edges of this aperture and of the other end of the intermediate cylinder. When the pulse-charge voltage neared peak, an oil spark occurred between inner and intermediate in the switch region, which was at the Marx end. This discharged the Blumlein into an X-ray tube connected to the inner cylinder at the opposite end. The oil switch spacing was hydraulically adjusted so that it closed at the desired time, which required a spacing of about 1 in/MV, and the bubbles and carbon formed in the switch by the discharge were removed after the pulse by turning on an oil pump.

The Marx was laid out in a rectangular section tank, collinear with the Blumlein and extending from the switch end of the Blumlein high-voltage cylinder to the grounded end of the tank. It consisted of 30 0.4-μF Aerovox capacitors suspended in two rows in the oil by nylon straps attached to their metal cases. A voltage of up to 125 kV could be applied to one of the two terminals of each capacitor, the other terminal remaining at ground and the case at half potential. The Marx spark gaps were in a single column formed of epoxy rings penetrated by diametrically opposite electrodes; a Marx stage of this type is shown in Fig. 16. The gas in the switch column was a mixture of carbon dioxide and argon. The switch nearest ground was triggered to initiate the "erection" of the Marx—the breakdown of all gaps, roughly in sequence from the low-voltage end to high-voltage end. The mechanism for the erection was that the placement of successive capacitors alternately in the two rows meant that when one spark gap closed the next received an increase of voltage because the capacitive coupling was strongest between alternate capacitors. In early PI Marx designs, the line of sight joining all spark gaps through the gas transmitted UV that was expected to promote gap breakdown and Marx erection, but prevention of tracking from one gap to the next required acrylic plates to be introduced between gaps. This also stopped transmission of UV, but the Marx still erected in $\gtrsim$1 μs. The Marx inductance (which should be minimized to speed Blumlein charge, and which for a given design is proportional to the number of stages, and hence voltage) was 15–20 μH/MV.

The vacuum tube (Fig. 15) was a several foot-long stack of 36-in diameter acrylic rings with 45° inner surfaces, separated by aluminum gradient rings—an enlarged AWRE design. A metal cathode stalk passed through the tube on axis from the high-voltage electrode and would end in various kinds of blunt or sharp points as much as one foot from the tantalum anode.

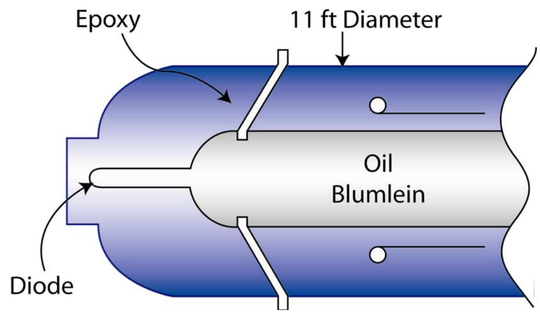


Fig. 17. Brewster's angle vacuum interface used on Pulserad 1150.

The Blumlein, of impedance about 40 Ω, drove the diode with a current of about 50 kA at about ∼4 MV for a 40-ns pulse. The dose on axis 1-m away was up to 50 R.

The minimum time between shots was determined by the Marx charge time and oil switch flow time, which could both be as little as a minute—though the cycling of the test object being irradiated usually took at least 10 min. The tantalum anode in the vacuum tube was not damaged by the electron beam, and rarely needed replacement. Operation was therefore simple and rapid.

A new technology had been born, and the field was about to be renamed by PI "pulse power." More than that, a sea change had occurred, to large-scale engineering of pulsers, an approach that led to rapid progress, as we shall see. The Pulserad 730 was a big step from any predecessor. Before joining PI, Don Martin and Bernie Bernstein had experimented with air-insulated Marxes at Lawrence Radiation Lab (Livermore), now Lawrence Livermore National Laboratory (LLNL), and had built small low-voltage coaxial Blumleins using rolled-up Mylar sheets as dielectric at first, then polyethylene. The 730 was built on internal PI funding, and patented; it started perhaps 2-ft in diameter, but Dave Sloan, now at PI, argued for a bigger system until the budget limited growth. The first Marx used in the 730, while PI was still in Berkeley, CA, was a vertical stack of low-inductance General Electric capacitors known as clamshells. In San Leandro, the strap-hung Marx was substituted and the tens of roentgen (R) dose range was achieved. By that time PI had initiated, and less than a year later built, the Pulserad 1150 (or B^3, Big Blue Boy) under BMD funding, and this achieved 500 R at 1 m.

The design of the 1150 was a scaleup of the 730, with up to 6 MV on the Blumlein and over 7 MV on the tube, and with a longer pulse duration. Initially, a new design of vacuum interface was built and used an 11-ft diameter epoxy cone forming a Brewster's angle window [Fig. 17]. This worked successfully at first, but eventually developed electrical damage that caused it to fail mechanically under the differential pressure of 1 atm plus oil head. Much of the roughly 40 000 U.S. gallons of oil was spilled in the lab. The replacement X-ray tube was a longer version of the 3-ft diameter acrylic stacked insulator in the 730, and this worked reliably. The Pulserads 730 and 1150 operated together at PI as simulators serving users, often in use continuously during two shifts (day and swing) while being maintained on the third (graveyard).

In between the appearances of the Pulserads 730 and 1150, in early 1965 came the first IP simulator—the FX-1. The design of the FX family is illustrated in Fig. 18. A horizontal Van de Graaff dc charged an extension of its high-voltage terminal that formed with the outer tank a coaxial transmission line in high-pressure gas, and the end of this terminal sparked in the gas to the cathode plate of the stacked ring vacuum insulator [Fig. 18], to switch the transmission line into the diode. The gas was a mixture of nitrogen and SF_6 at a few hundred pounds per square inch, and the housing of the pulser was a massive steel pressure vessel. The vacuum insulator, usually acrylic, was sometimes surrounded by a second pressure vessel of glass bonded to steel annuli, which supported most of the gas pressure, although the gas between the vessels was at greater than atmospheric pressure. The gas output switch was a trigatron, with a trigger generator within the high-voltage terminal that was optically controlled from ground.

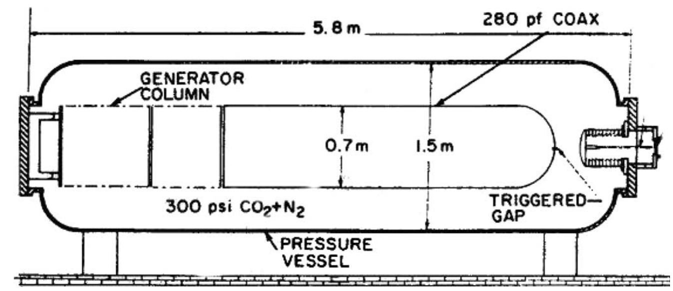


Fig. 18. IP FX-35 Van de Graaff-charged pulse generator.

In operation, gas was first pumped into the pulser vessel from external storage tanks. The dc voltage was progressively raised while the high-voltage terminal sparked to ground and the surfaces were conditioned by the sparks until operating voltage was reached. The gas was pumped back into the storage tanks when intrusive maintenance had to be performed or when the pulser was not to be used for a long time.

In the FX-1, the Van de Graaff typically charged the 50-Ω gas coax to 3.5 MV, and the voltage on the diode, which had somewhat higher impedance than the coax, was $\gtrsim$2 MV for a pulse duration of only 20 ns and a dose of ∼8 R at 1 m. The name of the FX-1 was changed to the FX-35, and the association of the name with ten times the charge voltage was then continued for the whole FX series. The FX-35 was operated as a facility at IP, and a number of smaller machines (FX-15, FX-25) were built for various customers. In 1966 and 1967, an FX-45 was delivered to the U.S. Army's HDL and operated for about 25 years as the high intensity flash X-ray (HIFX) facility; and the FX-75 was delivered to Boeing. The FX-75 delivered 5 MV for 40 ns and almost 100 R at 1 m.

Much higher doses, tens of kR, were obtained over small areas on the faceplates of the Pulserad and FX machines. Also, in 1965 intense electron beams were extracted from both types of machines for the first time, at both PI and IP. Fig. 19 shows a 2.5-MeV 17-kA beam that has passed through a thin metal foil anode on the FX-35 and is propagating through air at about 0.2-torr pressure. The beam can be seen to pinch twice under its self-magnetic field before trajectory spread smears out the beam envelope. IP and PI explored beam propagation at a wide range of pressures and PI showed that at higher pressures than in Fig. 19 beam current returning in the gas within the beam envelope reduced the beam's magnetic field and allowed the

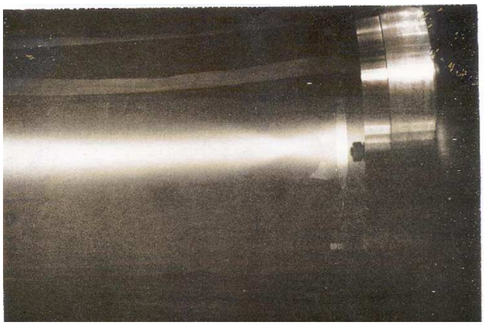


Fig. 19. FX-35 electron beam extracted into gas in November 1965.

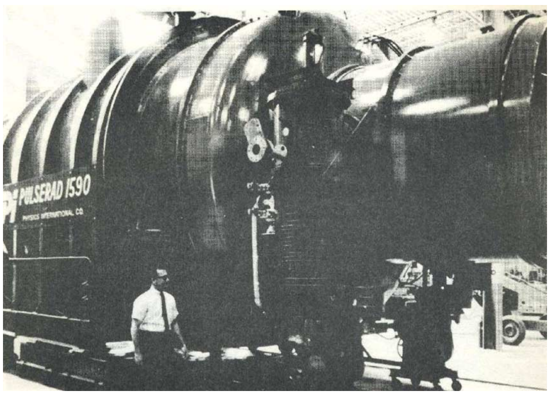


Fig. 20. 1590 Pulserad.

beam not to pinch but to expand "current neutralized." Electron beams were used to deposit energy in materials to simulate the absorption of softer X-rays.

C. AFSWC Transient Radiation Effects in Electronics (TREE) Facility

In the mid-1960s, AFSWC decided to create the largest prompt gamma flash simulation capability to date, the TREE Facility in Albuquerque, NM. The goal was now 5000 R, with uniformity specified throughout a 0.75-m-long 0.75-m-diameter cylindrical test volume. This required a more powerful machine than any to date. The Marx/oil Blumleins had achieved higher output doses than the Van de Graaff-charged FX machines, but the latter had some attractive features. The controlled dc charge resulted in very reproducible output, whereas the Blumlein oil switch self-closed at voltages that varied $\pm 5\%$ or more, causing X-ray dose to vary as much as $\pm 20\%$. The use of dc charge also avoided prepulse voltages produced on the diode as the Blumlein pulse charged. The greater simplicity compared with the Marx (with its many switches) and Blumlein also appealed to many.

The AFSWC TREE facility was to house an IP "FX 100" and a PI oil Blumlein (Pulserad 1590) to allow test objects to be irradiated simultaneously or at short intervals with pulses from two directions at right angles. The building layout required the Pulserad 1590 to be built with the 90-stage Marx in one leg of an L, connected at right angles to a Blumlein in the other leg. The total length of the L was about 100 ft. The 15-ft diameter outer tank was cylindrical throughout. The 1590 (Fig. 20) was sometimes known as B-4.

Fig. 21. 3-T 13-ft-diameter epoxy Brewster's angle vacuum interface cast by PI for the Pulserad 1590.

The 1590 Marx generator had two 0.5-μF Aerovox capacitors similar to those of the 730 in parallel per stage. The Marx configuration was two rows of capacitors, one on each side of the spark gap column, of which a stage was shown in Fig. 16. The Marx and the 26-Ω Blumlein were again hung from nylon straps.

A vacuum insulator long enough to hold off more than 10 MV needed to have a larger diameter than the 36 in used in the 730 and 1150 in order to grade the voltage reasonably well along its length. Brewster's angle insulators 16 ft in diameter over their flanges were constructed using thermosetting epoxy resin. One of the monolithic castings, weighing three tons, is shown in Fig. 21. These insulators were poured at PI and cured in large specially constructed ovens. But because of the failure of the 1150 Brewster's angle interface, those built for the 1590 were never installed on the machine. Instead, a stacked 45° tube was designed and built, about 10-ft long, with twenty-four 90-in diameter insulating rings of the same epoxy. This worked well except that dendrites grew in the epoxy from particles that settled on it. A polypropylene shield above the tube eliminated this problem, but it was decided that in the future tubes in oil would, if possible, not be epoxy.

The author arrived at PI in January 1967 and made an AWRE contribution to the 1590, based on experiments he had done at AWRE. The 90-stage Marx was breaking down to ground from the cases of capacitors at the high-voltage end, both along the nylon straps from which it was suspended and in clear oil. Because the work at AWRE had shown that even small dc fields reduced the impulse strength of oil, the dc charge of the Marx was changed to a balanced plus and minus, placing the capacitor cases at dc ground instead of 50 kV. Balanced charging eliminated the breakdowns in the 1590 and has been the usual Marx charging method since.

One other problem was then encountered with the 1590; at full $\lesssim$10 MV charge, the $\sim$10-in-long oil spark in the Blumlein switch had an inductive rise time too long for the $\sim$50-ns pulse. Extensions in the intermediate and inner Blumlein cylinders, about 11 and 8 ft in diameter, were quickly made in a shop in San Leandro. Over a long weekend, PI welders and technicians removed the two Blumlein cylinders, cut them through the middle, inserted the additional length, smoothed the welds, and reassembled the 1590. The Marx was shortened to make room for the longer Blumlein.

With a pulse duration increased from 50 to ~70 ns, a test-volume dose of 4000 R was obtained in May 1967—in the specified range, though below target. In order to meet the dose uniformity specification a large diameter cathode was used, an array of sharp points about 10 in in diameter, to spread the electron beam in space. The cone formed by the directions in which X-rays had half of the maximum on-axis intensity had a half-angle of 35°; this reduced the dose at 1 m to only 2700 R. After the successful tests, the 1590 tube was opened in the presence of Air Force personnel, and was found to contain a coffee cup, a box of Kleenex, and some rags used to oil the epoxy surface; thus the AWRE/PI tube design was shown to be robust.

Resistive voltage monitors consisting of copper sulfate solution in flexible polyvinyl chloride (PVC) tubing were devised for the 1590, and recorded $\lesssim$10 MV on the Blumlein and a $\gtrsim$10 MV on the vacuum tube. Based on the loading of the Blumlein, the current was estimated as well over 200 kA; direct-reading current monitors were not introduced at PI until shortly after the 1590 was tested.

By the time the tests on the 1590 were complete, tests at IP on the FX-100 had encountered difficulties, and so AFSWC modified the TREE facility to allow the 1590 to be installed more optimally, as a straight line rather than an L-shape. A problem with contract language delayed shipment to New Mexico for some time. The 1590 then operated in the TREE facility for more than ten years.

One difficulty with the FX-100 was mechanical. The longer Van de Graaff column needed for > 10 MV charge had difficulties cantilevering the weight of the high-voltage conductor, now extended in length to give a pulse duration of ~100 ns. Failures of the column resulted. The FX-100 was shipped to the TREE facility but was operated at relatively low levels, because it did not spark condition to full voltage. These problems suggested that the Van de Graaff-charged approach did not scale to very large power as well as the Marx and oil Blumlein.

D. Sandia and AWRE Adopt PI's Technology

When the design and performance of the Pulserad 730 became known, the Sandia simulation group also embraced the Marx-oil Blumlein approach for flash-gamma simulators in place of the stacked-line system. However, Sandia did not acquire simulators from PI, as other organizations had begun to do, but set out in 1965 to build their own in-house capability. With little aid from PI, who wished to retain the technology they were developing, Sandia made many developments of their own. They also asked AWRE to assist them again. Charlie Martin's group was still reluctant to adopt large volumes of oil themselves, but were very interested in PI's technology and were motivated to assess its possibilities for their own benefit as well as Sandia's.

AWRE gave Sandia their views on Marxes and possible variants including the LC-generator published by Richard Fitch. Fitch had been active in pulsed power in a different group at AWRE and later moved to Maxwell Labs, where he worked on the Aurora Marx (see Section III-E) and many other developments. The AWRE group investigated the limits of breakdown in oil and other liquids, particularly water, which they had experimented with earlier as described in Section II-A. Water was also of interest to NRL in particular, and to Sandia. AWRE characterized the mean uniform breakdown fields of both water and oil by the equation $Ft^{1/3}\ A^n = k$, where F is the electric field, t the stress time, A the electrode area and n and k are constants characteristic of the liquid. The equations, with the constants modified by U.S. work, are still in use. AWRE found that in uniform fields water breakdown always originated from the positive electrode, and when the limiting field was that on the negative electrode, as when it was the inner of a coax, the breakdown field was about twice the value obtaining when that electrode was positive; AWRE patented this polarity effect. Breakdown of liquids from sharp points to larger electrodes was also characterized by AWRE.

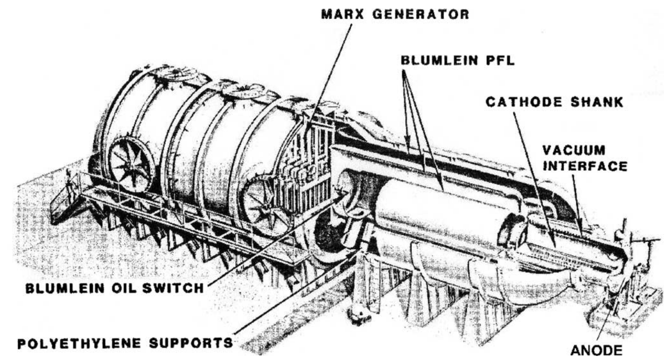


Fig. 22. Sandia Hermes II.

Sandia then built a Marx-oil Blumlein system, the 4-MV 80-kA Hermes I (1966). This test of the technology was later converted to the REBA (relativistic electron beam accelerator) facility, in which the Marx could charge either of the two Blumleins used as separate simulators. Sandia then proceeded to build Hermes II in 1968 (Fig. 22). Hermes II had a 34-Ω 87-ns Blumlein, charged to about 11 MV. The Marx was made from "ICSE" capacitors, 0.5-μF 100-kV units made by British Insulated Callendars Company (BICC). About 7 MJ of these capacitors had been purchased by the United Kingdom Atomic Energy Authority to power the Intermediate Current Stabilized Experiment, a toroidal plasma system planned as a follow-on to the well-known Zeta but then canceled. The surplus capacitors were utilized in many systems in the U.K. and the USA. The ICSE capacitors were torpedolike with a 100-kV terminal at one end, and in Hermes II were hung upright from nylon straps with the terminals at the top. The 93 stages were arranged in rows of three, providing an improved capacitively coupled erection mechanism similar to that of a gas-insulated Marx tested at AWRE (see below). Individual spark gaps were used. The Hermes Marx had a significantly lower inductance (~6 μH/MV) than the PI Marxes described above.

The Hermes II Blumlein at 16 ft in diameter was the largest built to that date. Instead of straps the Blumlein intermediate cylinder was supported on polyethylene "legs" from the outer tank and the inner on similar legs from the intermediate. The inner cylinder was plastic coated to increase the breakdown threshold in the oil. The 45° rings of the vacuum tube were initially 4-ft diameter epoxy, later 6-1/2-ft-diameter castings of

Rexolite, a proprietary product of C-LEC Corporation. Later, tests showed that the flashover strength of Rexolite can be about 10% greater than that of acrylic; it is also more resistant to electron damage.

Hermes II developed about 12 MV on the tube. For the diode, a "Tom Martin" cathode was devised; a 6-in-diameter cylindrical stalk capped with a smooth hemisphere, the radius chosen so that the 360-kV prepulse did not initiate plasma formation. This resulted in an impedance in the 100-Ω range and an electron beam that converged slightly at the anode, resulting in a dose of up to 6000 R at 1 m, more than twice that of the 1590. The forward cone of the X-rays (half angle about 10°) contained less X-ray power than that of the1590 because the current was lower; it was suitable because the Hermes II test volume was not large like that of the 1590.

Transients produced by the Blumlein discharge at first caused breakdowns between rows of capacitors in the Hermes II Marx. Sandia devised an oil-switch diverter that grounded the Marx and inner Blumlein cylinder through a resistor soon after Blumlein switch closure. This eliminated these breakdowns and reduced "post-pulse" damage in the diode caused by residual late-time energy.

For AWRE's own applications, which now included both NWES and flash radiography, Charlie Martin's group had proceeded toward the PI Marx/oil Blumlein technology and its large oil volumes in reluctant steps. They built a small parallel-plate oil Blumlein [wide oil Blumlein (WOBL)] to drive the 500 kV "Moomin" X-ray tube mentioned in Section II. The group made the system entirely by hand; the ~10-ft-long 2-ft-wide plates were of wood covered in copper foil, and immersed in oil contained in a wooden box lined with PVC. This oil Blumlein was soon replaced with a much smaller parallel-plate water Blumlein, water equivalent-WOBL but other parallel-plate oil Blumleins were also built.

In 1966, the AWRE group built a nominally 4-MV Marx from 100-kV ICSE capacitors. Rather than oil insulation, they used atmospheric-pressure Freon gas (CF_2Cl_2), which has a density four times that of air and almost three times its breakdown strength. Freon was later determined to have the disadvantages that sparking or corona in it deposits conducting residues. Except for the capacitors, the group fabricated the Marx by hand, making a PVC bag to contain the Freon gas. The ICSE capacitor stages were arranged horizontally in sequential rows of four (Fig. 23), and after every fourth stage a connection was made back to the next stage, which was the first in the next row of four. This layout increased the overvoltage of each switch in the erection sequence to a nominal four-times increase. The spark gaps were in four vertical acrylic tubes containing higher pressure Freon.

The Marx worked well up to about 2.8 MV. A similar design was used later, with oil insulation instead of gas, in the first AWRE Marxes that drove oil Blumleins. However, first the AWRE group considered a last alternative to all-oil pulsers. Before leaving the group to join PI, the author suggested a water Blumlein design with an impedance increased to the desired > 20-Ω range. The ground and output conductors were metal cylinders placed symmetrically on each side of the charged conductor, which was a wide plane, in an acrylic box [Fig. 24].

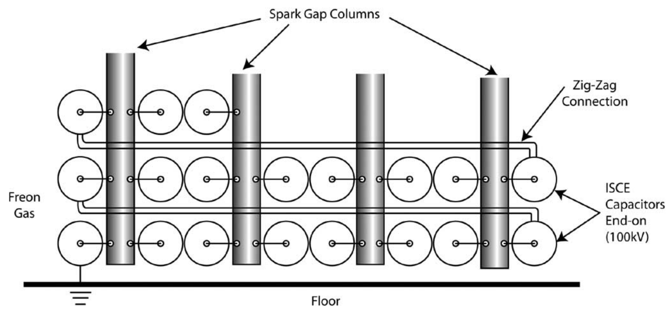


Fig. 23. Layout of the gas-insulated ICSE-capacitor Marx built by AWRE.

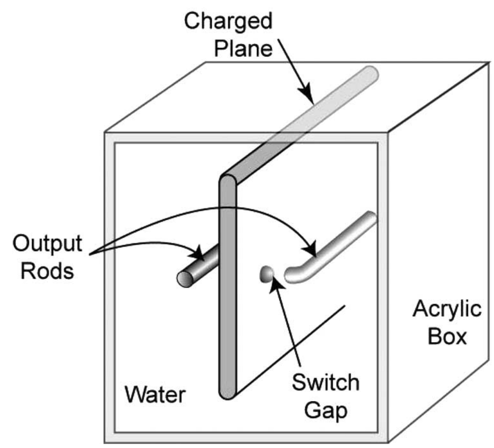


Fig. 24. High impedance water Blumlein concept.

During charge, the cylinders were negative to take advantage of the polarity effect. The positive plane had lower fields because its edges were far from the cylinders—which also minimized capacitive coupling between the cylinders and hence energy loss. A half-size 3-MV version ("Agamemnon") of a 6-MV design was built and connected to the Freon-insulated Marx. The author's colleagues wisely abandoned the tests after he left, and then proceeded to build Mogul (4.2 MV, 1967), the first of a series of Marx-oil Blumlein radiography systems that form the basis of AWE's "core-punch" (see Section II, Introduction) facilities today.

The Marx-oil Blumlein was also reproduced in France in the late 1960s; e.g., in the few-megavolt "Francitrons."

E. Development of Aurora

In 1967, DASA asked for proposals to address the national need for 50 000 R that Don Martin had spoken of in 1964. This was now defined as being actually 50 krad Si, about 55 kR, at the center of a test volume 1 m in diameter and 1-m long, uniform to better than a factor of two throughout the volume, and delivered in $\lesssim$100 ns FWHM. The ~20-fold increase from the 1590 performance meant that a modular machine would be needed; for one reason, the low impedance necessary was too low to obtain with good volumetric efficiency in a single oil coax. Therefore, synchronization of Marx-oil Blumleins was needed to much better than 100 ns.

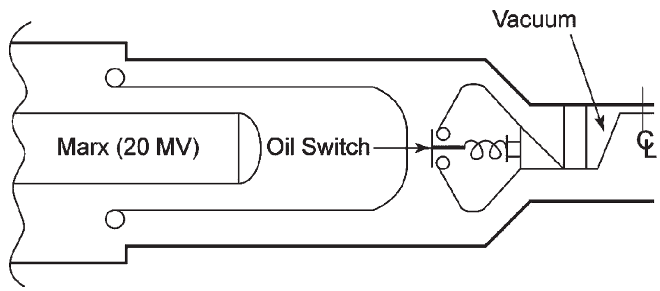


Fig. 25. PI concept for 10-MV Aurora module.

To attempt to demonstrate this synchronization PI funded and built two Pulserad 1140s. One was later sold commercially and the other remained at PI as a commercial simulation facility—it operates there today. The two machines were placed side by side and a self-closing oil switch inside a cylinder connecting the outer conductors of the Blumleins delivered trigger pulses to blades that passed through switch regions between outer and intermediate conductors of each. At a Blumlein charge of 4 MV some nonreproducible evidence of triggering was obtained.

PI and IP then made proposals for the "50 000 R machine," based on "Phase 1" studies of possible designs. IP's proposal used vertical FX-type coaxes, to avoid cantilevering the inner conductors. The maximum allowed diode voltage was 10 MV, and PI estimated that a total current of 3 MA was needed (30 TW for 100 ns or 3 MJ). The design PI presented to DASA and its advisors at the Pentagon had five pulser modules, each supplying 600 kA. Instead of a 10 MV Blumlein, the pulse-forming lines were simple coaxes with their inner conductors pulse charged to 20 MV and discharged by series triggered oil switches. Fig. 25. This roughly halved the oil-switch current and, assuming the same number of switch channels closing under the same field, halved the inductive rise time—at the expense of switching at twice the voltage. (It later proved that triggering oil switches became easier as the voltage increased). The diameter and length of the Marx tank were reduced by hanging the high-voltage section of the Marx (an extended 1590 Marx) inside the inner coax cylinder.

PI presented a preferred configuration in which the five modules were arranged in a circle and connected by oil coaxes to a single central stacked 45° vacuum insulator and diode. Using five separate insulators and diodes was an alternative, but that required the power to flow some distance in the vacuum to diodes near the test volume. One issue was that the 3.3-Ω diode was over what we now call the self-pinch limit. Perhaps the rapid pace of development in 1967 helps to explain why many people did not understand the pinch limit and its effect. This apparently included the immediate reviewers and all of the PI presenters except for Dave Sloan, who had not expressed concern about it because he felt the effect would not reduce current density as had been suggested, but would result in pinching to higher current densities—but of course the electron beam profile and angles would probably have been inappropriate.

Discussions about the diode continued, with external magnetic fields considered as a way to keep the electron beam uniform in a single diode. But the uncertainty and the cost of the PI design (probably more than $10 M) caused DASA to delay an award. At this point, the future of the project was uncertain.

Then Charlie Martin wrote to DASA and suggested that the machine could be built at much lower cost. His rationale included increasing the limit on diode voltage to 12 MV, at which Charlie estimated that a current in the 1-MA range for 100 ns would suffice. He sketched a design with four oil Blumleins in a square array, each delivering ~250 kA, only ~20% increase in current and voltage from the 1590. He proposed that the Blumlein dimensions could be made considerably less than those of the 1590 by coating the steel electrodes with plastic to increase the breakdown fields in the oil; this suggestion was based on small-area tests at AWRE and Sandia. The Blumleins drove individual vacuum tubes from which power was transported to the diodes in vacuum coaxes in which the inner conductor was perhaps liquid-coated to avoid electron emission. The impedances of the individual diodes were in the range of the 1590 diode. The number of Marxes was reduced to one by using capacitors of larger energy—16 kJ, 40-kV units made by BICC for $\lesssim$MJ capacitor banks AWRE was building for flyer plate work. A low-inductance Marx design was proposed in order to keep the Blumlein charging time in a good range.

Charlie's design would certainly have cost much less than the PI design: half the power, and further reductions in Blumlein size and Marx component number. DASA decided to fund a technology program at PI to investigate these and other approaches for improving the design of the machine and reducing its cost. They allowed an even greater increase of diode voltage, to 15 MV, and they named the machine Aurora. The Aurora "Phase II" development program was to be about one year in duration, and had a price a little over $2 M, including a subcontract that PI placed with Maxwell to develop a low-inductance Marx generator of Maxwell's own design to charge the Blumleins rapidly.

The results of this program were that even at 15 MV the estimated power needed was still 24 TW, with 1.6 MA; the coatings on Blumlein electrodes proved to have only a small effect; and PI was not able to obtain benefits from coating cathode electrodes with the large areas needed for Aurora. But Charlie's proposal had caused DASA to recognize the need for a development program, and this was actually what Aurora required in order to establish the appropriate technology advances on a reasonable scale before building such a large machine. Throughout the development of Aurora, Charlie was a member of DASA's panel reviewing the PI program, and he was a strong supporter of the PI program, both in this role and in regular correspondence direct with PI. The four-square Blumlein array he had proposed was the configuration chosen for Aurora; the actual Aurora machine is shown in Fig. 26. The increase to 15 MV ruled out the simple coax in favor of the Blumlein; the reduction in current allowed fewer modules, and four was chosen by PI over two. The configuration satisfied DASA's new specification for horizontal X-rays.

Much space is given here to the development of Aurora, partly because it generated many new technology features that are important today. It was also significant as a transition to large, synchronized modules with their outputs converged on one test region. It was by far the most powerful pulser built before the 1980s, and it remains to date the largest physically.

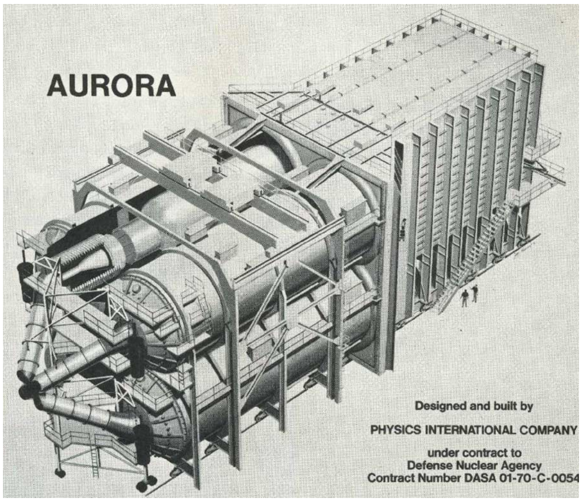


Fig. 26. Aurora machine built by PI at HDL, Adelphi, MD, and completed in 1972.

The Aurora Phase II development program, carried out in 1968 and 1969, included building several large test facilities in San Leandro, as well as much small-scale testing and theoretical work. The resulting design was then further demonstrated at the Aurora scale by constructing a quarter of Aurora—one Blumlein of the four planned, driving one vacuum coax and diode. This effort was called the Aurora diode experiment (ADE), because the features of Aurora most difficult to scale from the San Leandro tests were the vacuum coax and the diode. Computer simulations of the Aurora diode were made by Varian Associates, and similar simulations had begun at Sandia, but these were not yet considered reliable as predictions. Because the radiation output of ADE was too great for the city of San Leandro, it was built at PI's explosive test site in the hills near Tracy, about 40-mi away. A vacuum coax extended down into a tunnel dug in a hillside; this buried the anode, and distance to a similarly buried control bunker provided the remaining X-ray attenuation required. ADE hardware is illustrated in Fig. 27.

The advances and novel features demonstrated by the combination of the San Leandro Aurora Phase II development program and ADE are summarized below.

A new Marx was developed. This PI Marx started as a backup design, but Maxwell's design proved more expensive and needed more time to demonstrate. Also, the benefits of its lower inductance were small, because of the weak time-dependence of the safe operating field in oil, and the increased prepulse if the Blumlein was charged very fast. The BICC Marx was not pursued because it had very large energies per spark gap and was hard to maintain.

The ADE and Aurora Marxes used Scyllac-style capacitors, with two in series and two in parallel per stage. These capacitors (made by Aerovox and Sangamo) were identical to the 1.85-μF 60-kV units that had been developed for the LANL "Scyllac" capacitor bank, and for which a reliability database existed. The 508 pressurized SF_6 spark gap developed for the Aurora Marx [Fig. 28] substituted an individual stage switch for the spark-gap columns previously used by PI. The use of two Scyllac-style capacitors in series switched by a 508 spark gap remains a common Marx approach today.

(a)

(b)

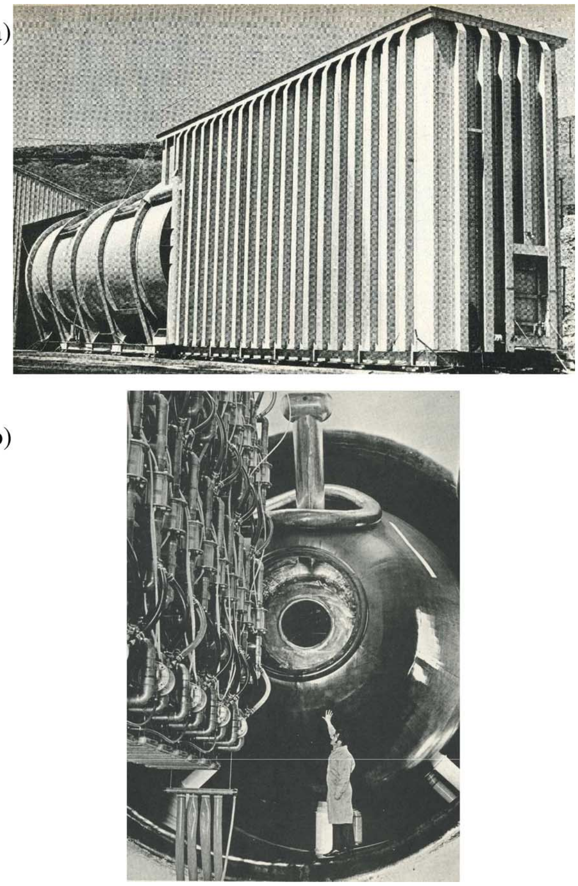


Fig. 27. ADE hardware. (a) External view of Marx and 23-ft-diameter Blumlien. (b) Marx high-voltage end and Blumlein.

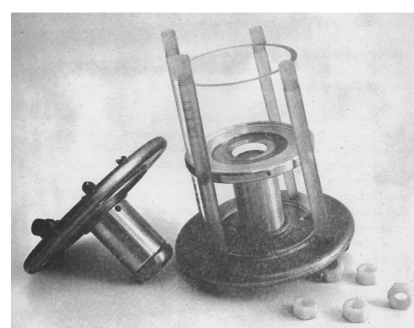


Fig. 28. 508 Spark Gap (triggered version).

The erection scheme of the Aurora Marx, partly seen in Fig. 27, was a hybrid of the capacitively coupled overvoltage previously used by PI and resistive triggering. A purely resistive trigger scheme had been employed in a five-stage Marx built by PI for University of Maryland, and soon afterward was independently proposed, analyzed, and advocated by Charlie Martin. The $\sim$100 stages needed for Aurora were laid out in the simple up-and-down zigzag, omitting the back connection from zig to zag shown in Fig. 23, in order to reduce inductance. Some spark-gaps (without trigger electrodes) received overvoltages, and those that did not had mid-plane trigger electrodes connected by resistors to earlier Marx stages. The inductance was reduced from the $\sim$15 μH/MV of previous PI Marxes to about 3 μH/MV, and this allowed the charge time of the Blumlein to

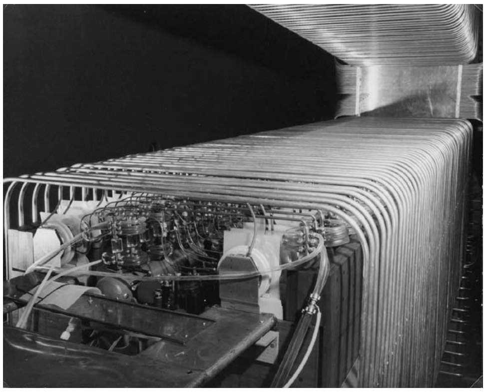


Fig. 29. Maxwell 5.8-MV 185-kJ dual-Marx system.

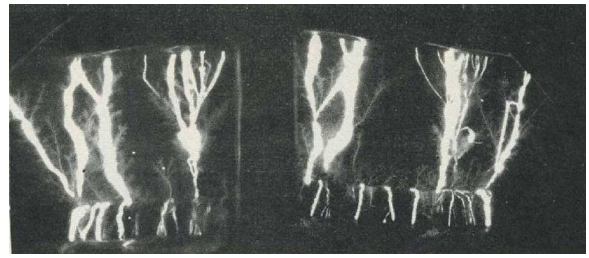


Fig. 30. 12-MV 1-MA triggered oil switch at ADE.

remain in the 2-μs range. The inductance of this Marx design was reduced below 2 μH/MV later simply by using the voltages of 100 kV that became available in similar capacitors and using the same 508 envelope at higher pressure, so that the $\pm$60-kV Marx stage became a $\pm$100-kV stage—a change initiated by Sandia. The single 92-stage Marx in ADE was the first to store more than 1 MJ (1.35 MJ maximum test). At an SF_6 pressure of 30 psig (self-break pressure was $\sim$2 psig), erection time was $\sim$700 ns and jitter was $\gtrsim$10 ns.

Marxes erecting simultaneously with low jitter in proximity and with close capacitive coupling were demonstrated using two Marxes made from the two-terminal Aerovox 0.5-μF 125-kV capacitors mentioned earlier and smaller versions of the 508 spark gap, making in effect half-scale Aurora Marxes.

The Maxwell Marx program demonstrated a system of many separate close-packed Marxes, using a low-energy pilot–or "Mickey"–Marx to trigger each stage. After the PI Marx was adopted for Aurora, Maxwell in 1968 built and tested two parallel Marxes, each with 65 $\pm$45-kV stages, triggered by a single Mickey–Marx, and delivering 5.8-MV open circuit and a total of 185 kJ to a high-impedance load after an output switch closed. This Marx [Fig. 29] was not hung from straps but cantilevered from a V-shaped Permali structure. The inductance of each Marx was under 2 μH/MV. This Marx system was later used to charge Maxwell's first water-dielectric machine, Blackjack 1— Section III-F.

The 12-MV 21-Ω Aurora Blumleins, at 23-ft outer diameter and 40-ft long, were the largest built before or since. For the first time, PI used the AWRE formula for the breakdown strength of oil to design them. Large-scale tests in Phase II ($> 3 \times 10^5$ cm^2 using a 10-ft diameter coax) reduced the extrapolations from AWRE data by > 30 in area and $\sim$3 in voltage; the constants k and n in the AWRE formula (Section III-D) needed adjustment by only about 5%. The Blumlein cylinders were coated with polyurethane, which Phase II tests showed could increase the oil breakdown strength, though only $\sim$10%.

A 12-MV triggered oil switch, scaled from a 4-MV switch tested in Phase II, discharged the 12 Ω inner line of the Blumlein and carried a current of about 1 MA. The photograph in Fig. 30 is of a 20-in ADE switch gap triggered by a 48-in diameter field distortion electrode 3 in from the inner cylinder. The trigger electrode is swung beyond the inner electrode potential to break first the long and then the short side of the switch, both closing in multiple channels. The jitter measured at ADE was < 10 ns.

The oil switch was triggered by gas switches—the first "V/N" SF_6 spark-gap and a point-plane SF_6s switch in series, both closing at 1 MV, and located inside the inner Blumlein cylinder. In a V/N switch, a field-distortion trigger electrode is spaced a small fraction of the switch gap from the positive electrode and swung positive by a trigger pulse, here delivered by a cable. The point-plane switch, an AWRE development (see the SIEGE-II simulator, Section III-H) was set to close 100 ns after the V/N trigger time in case of a trigger circuit failure.

A self-closing multisite oil prepulse switch was devised to reduced the prepulse from $\sim$750 kV on the Blumlein to $\sim$150 kV in the vacuum region.

The Aurora vacuum envelopes consisted of 40 4-in-long acrylic stages, 9-1/2 ft in diameter. A tube voltage of $\sim$15 MV was recorded at ADE.

A major challenge was the design of the vacuum coaxes to transport the power from the large spacings required by the vacuum tubes to diodes adjacent to the $\sim$1-m sized test volume. Phase II tests showed that surface coatings of oil enabled areas of < 1 ft^2 to hold 1 MV/cm without emitting significant electron currents, but such coatings could not be maintained in much larger areas. At other labs, it had been recognized that the magnetic field around a cathode cylinder could prevent electrons from being lost to a surrounding anode. An IP report proved that when a cathode stalk passed through a pumping spool a local wave impedance greater than the diode impedance resulted in the magnetic field around the stalk preventing individual electrons emitted by the stalk from reaching the spool. This suggested to PI attempting to use this "magnetic insulation" to transport power over long distances, and this was demonstrated in a straight 10-ft-long 1-ft-diameter coax at 6 MV in Aurora Phase II.

Based on this result, four 15-ft-long 4-ft-diameter vacuum coaxes were then designed to drive the planned 37.5-Ω Aurora diodes, and their wave impedance was made 30% higher at 48 Ω. These coaxes had to be fed by 45° bends (seen in Fig. 26), and in this region the outer diameter was increased to up to 6 ft in order to raise the local impedance and the impedance ratio. The current waveforms measured at ADE by resistive shunts at the input of the vacuum coax and at the input to the diode showed $\sim$450 kA at both locations and very little change in pulse shape (Fig. 31). These traces were at a Blumlein charge of 12.5 MV, a 4% overtest; the 125-kV ($\pm$62.5 kV) dc charge was above the 60-kV capacitor rating.

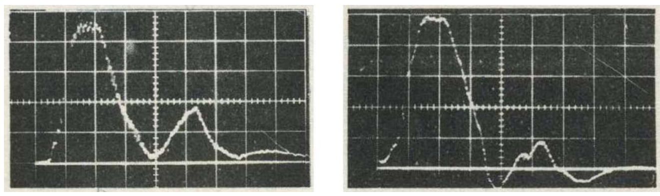


Fig. 31. ADE current waveforms (100 ns/div) at the input to the vacuum coax (left, 100 kA/div) and at the diode (right, 96 kA/div).

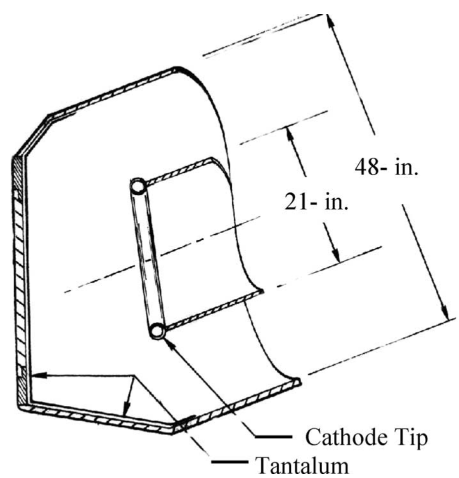


Fig. 32. ADE diode region.

The diode region at the end of the ADE vacuum coax is shown in Fig. 32. It was scaled from a 6-MV diode tested in Phase II. The 21-in diameter of the inner of the vacuum coax ended in a 2-in-diameter torus roughly parallel to the anode. The voltage at the diode was less certain than the current, but the average voltage recorded on the vacuum tube by a copper-sulfate divider was $\gtrsim$14 MV at the end of the current flattop at 12-MV Blumlein charge. It was estimated that the desired diode power of 6 TW had been obtained, but at 5%–10% lower voltage and higher current than intended, with a diode impedance of 32–33 Ω rather than the planned $15\ \mathrm{MV}/400\ \mathrm{kA} = 37.5\ \Omega$.

It was pointed out by Russian workers after Aurora was in operation that when space-charge limited electron emission from the cathode was considered rather than trajectories of single electrons, the 48-Ω coaxes would behave as somewhat lower impedance structures with electrons flowing in a "parapotential" manner along the coax and striking the coax endplate, along with electrons emitted in the diode region. The full understanding of parapotential flow both in vacuum transmission lines and pinched diodes (see Section III-F) then followed. The impedance expected nowadays for parapotential flow in the vacuum coax at 14 MV is $\sim$40 Ω; if we use for the inner coax diameter the larger diameter of the cathode torus this becomes 35 Ω.

The anode survived each pulse with the aid of thin low-Z sheets on top of the tantalum to relieve pressure during the pulse and to stop low-energy postpulse electrons. The dose at 1 m from the anode of ADE was 12 kR. The exchange of design voltage for current noted above reduced the dose in the test volume; but with the front corner of the test volume placed against the anode the dose predicted at the center was just over 50 krad—helped by an X-ray pulse FWHM 20% longer than the specified 100 ns. The uniformity was within specification except that the dose at the back corner fell to 25% rather than the desired 50%. Computer calculations of the dose distribution in the design phase, assuming an idealized electron beam, had indicated that for increasing electron beam convergence angles, the dose would fall below specification at the back corner of the test volume, but would remain about 50 krad at the center.

It is of interest that the calculations of X-ray distribution and the early diode simulations by Varian were the only computer calculations made in the design of ADE or Aurora. Electrostatic fields were evaluated using analysis, conducting paper, or electrolytic tanks. Circuits were evaluated analytically by hand. But computer circuit simulations were beginning at other labs and were initiated at PI a short time later, and computer simulations of beams and power flow were advancing rapidly.

It is also of note that the decision to build ADE was taken in May 1969; then detailed design (concurrent with that of Aurora itself), fabrication and assembly of a machine whose size can be gauged from Fig. 27, and seven months of experimental and developmental testing were completed only 19 months later, at the end of 1970.

The date of the end of ADE testing is also the end of the decade that this paper reports on. However, it will be added that Aurora itself was in construction in 1970 and was fully tested by April 1972 by PI and the HDL's very competent pulsed power staff—many of whom who had previously worked at IP. The importance of Aurora was such that its construction and ADE went ahead simultaneously at full speed. ADE was to prove much of the design of Aurora as soon as possible in order to minimize any retrofit. In fact, the only retrofit needed was to eliminate the Hermes-II style polyethylene legs that initially supported the ADE Blumlein, which were not reliable at the higher stress, and to revert to the PI-style nylon straps; some of which held the inner cylinders of the lower Aurora Blumleins *down*—they were made buoyant during operation. At Aurora, a Blumlein charge of 12 MV was demonstrated, and 50 krad were obtained at the test volume center; though minimum dose at the back corner was less than 20% of that at the center, and it was also decided in view of some early Blumlein breakdowns not to operate above 11-MV Blumlein charge.

The cost of building and testing Aurora was roughly $\gtrsim$\$10 M, and the cost of the design and the development in San Leandro and at ADE was roughly \$5 M, costs that inflate to perhaps \$50 M and \$25 M today.

F. First "Low Impedance" Initiatives

A few years after the beginning of the development of high-impedance flash gamma simulators, development began in the USA of machines of comparable power at voltages of 1 MV and below. Purposes included testing the effects of soft X-rays on circuit components and using low-energy short-range electron beams to test the response of materials to soft X-rays. This required much lower impedance pulsers. Use of water dielectric in the pulse lines instead of oil, because its higher permittivity, reduced the impedance by about six—and similarly reduced the length of the transmission line. Low-impedance pulser

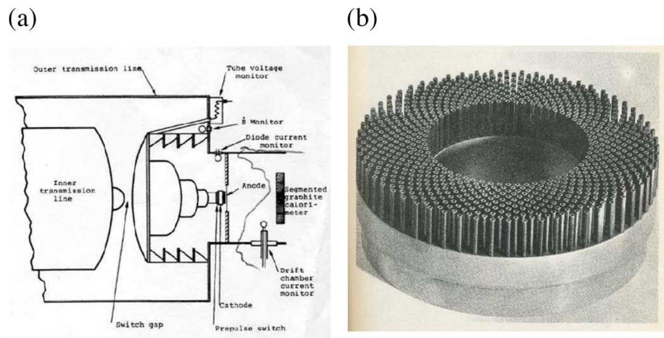


Fig. 33. Low-impedance 730. (a) Sketch of oil switch and vacuum tube. (b) Roll-pin cathode.

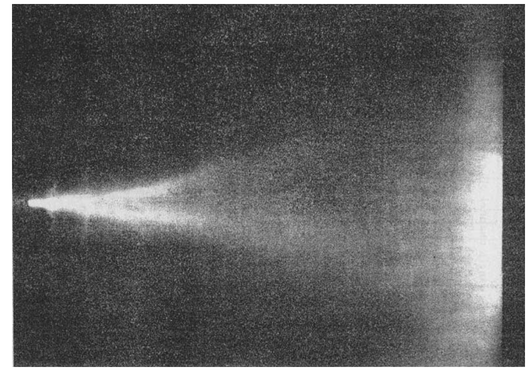


Fig. 34. Open-shutter photograph of a high ν/γ beam leaving the 730 diode.

development was initiated by NRL, who built Gamble I and Gamble II.

But before Gamble I, very low-impedance diodes were developed at PI, where in the autumn of 1967 the Blumlein of the Pulserad 730 was replaced by a simple 8.5-Ω coax that was charged by the Marx to over 3 MV and switched into the vacuum tube by a self-closing oil switch. The simple coax was preferred over a Blumlein because for the same load current the switch current is lower by a factor of two. An important limitation in high-current pulsers is that the rise time of a single-channel switch closing at a constant electric field is proportional to current The reason is that voltage and inductance are both proportional to switch spacing, so $di/dt \sim$ V/L is roughly constant—independent of voltage. The 730 (later the 738, with eight added Marx stages) delivered currents of $\sim$150 kA at $\sim$1 MV into a nearly matched load and over 300 kA mismatched into loads of less than 0.5 Ω at 150 kV or less. A similar, higher power modification was made of PI's Pulserad 1150 in 1968.

The low-impedance 730 vacuum tube was a short low-inductance stack of 45° acrylic insulators. The cathodes of the first subohm diodes were 2.5-in diameter planar arrays of sewing needles spaced as close as 2 mm to flat anodes; the needles were later replaced with roll pins, which were less easily damaged by the exploding anodes. With the close spacing and field-enhanced cathodes, reducing prepulse on the cathode was important. The prepulse on the 730 tube was produced by the stray capacitance across the oil output switch as the coax charged, and was reduced by placing an inductor across the insulator stack in the oil. To further reduce the prepulse and energy available at the cathode itself, a vacuum flashover switch placed behind the cathode was devised, and became a common feature of future diodes. The configuration of the oil switch and diode is sketched in Fig. 33(a); note the Rogowski coils first used by PI on the 730 to record current waveforms. Fig. 33(b) shows a roll-pin cathode.

Tests on the low-impedance 730 resolved the uncertainty (see discussions of the early Aurora design) about what would happen in diodes well above the self-pinch limit. The total current was reduced from the one-dimensional space-charge limited value, but very high-current densities were produced, as predicted by Dave Sloan, when part of the electron beam pinched to the axis. With the 2.5-in cathodes used to obtain subohm impedances, about one-third of the current, or $\sim$100 kA, pinched to diameters of order millimeters on the axis; the fraction pinching was greater for smaller cathodes used in $\sim$1-MV 150-kA diodes. The pinches produced large X-ray doses on axis when a high-Z anode was used.

When the anode was a thin foil, the 730 results also showed that beams with $\nu/\gamma \gg 1$ could propagate external to the diode. Here, ν is a measure of the linear beam charge density and γ the usual relativistic factor; at $\nu/\gamma = 1$ the transverse energy of an unneutralized beam created by its self-magnetic field becomes comparable to its total kinetic energy. For the 730 beams, ν/γ exceeded 50, but electron beams could indeed be propagated in a few torr of air, their current, and self-magnetic field neutralized by return currents in the gas within the beam. Fig. 34 shows the beam from a subohm diode on the 730. The pinched part of the beam is seen to diverge at a modest angle, and it was easy to obtain a wide range of electron beam intensities on a test object by placing this at different distances from the anode foil. It was also found that the beam from the pinch could be transported efficiently, even around bends, in a $\sim$1-in conducting tube.

The major advance in low-impedance pulse generators came at NRL, where considerable previous pulse power experience existed. In the early 1960s, workers at NRL had built parallel-plate water capacitors (up to $>$ 300 kV) and Mylar capacitors (up to $>$ 600 kV) switched out by self-breaking Mylar switches to energize exploding conductors. In the mid-1960s, they used Mylar Blumleins to drive θ-pinches at $>$ 300 kV, switched by AWRE-type field enhanced triggered solid switches (like that in Fig. 8) in a 50-cm-long stripline version. NRL had also built a 7-Ω 500-kV coaxial water Blumlein.

In 1967, NRL devised Gamble I, a coaxial water-dielectric pulse line, designed to deliver $\lesssim$1 MA at $\lesssim$1 MV for 50 ns. To obtain a current two or three times higher than that of the 730, the di/dt limitation of a single-site switch mentioned earlier in this section was overcome in part by charging the pulse line and switch in a much shorter time of about 200 ns to increase the switching field, and partly by switching out only 500 kA at 2 MV and then transforming to 1 MA at 1 MV in a tapered-impedance "transmission-line transformer." Such water line transformers had previously been analyzed at EG&G, and Dave Sloan had sketched a concept called The Whip that delivered 1 MA at 10 MV. NRL built the coaxial 4-Ω 4-MV Gamble I pulse line, the transmission-line transformer,

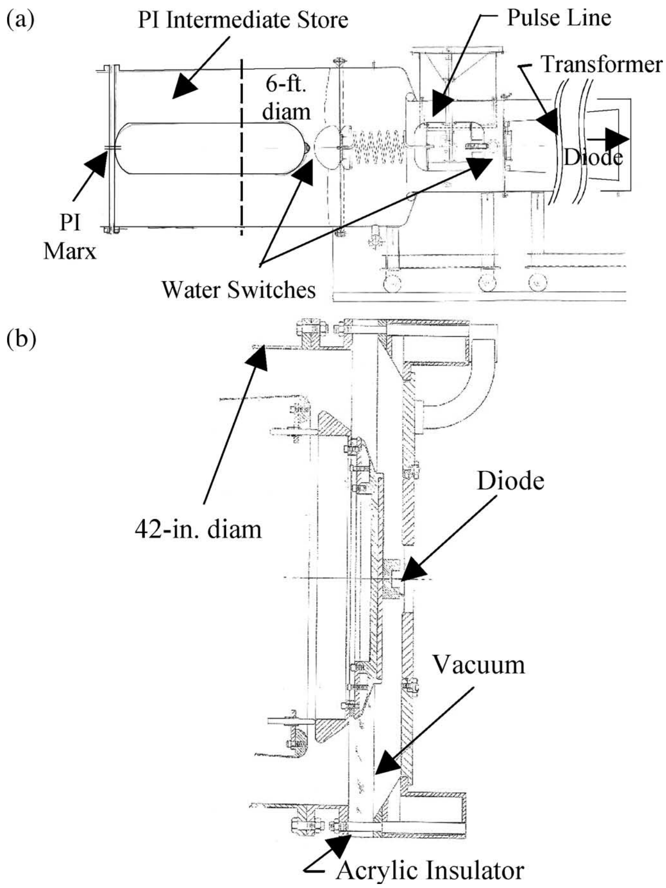


Fig. 35. NRL Gamble I. (a) Schematic of pulser. (b) Diaphragm tube.

and the vacuum tube. To fast-charge the pulse line, PI provided a Marx and a coaxial water-dielectric "intermediate store" or "transfer capacitor" that charged the pulse line through a self-closing water switch. NRL and PI both made use of AWRE's characterization of the area-dependent breakdown strength of water, as modified by NRL.

Gamble I began operation in 1968. It is illustrated schematically in Fig. 35. The water switches were replaced with SF_6 switches in the early 1970s, with the help of IP. The vacuum insulator [Fig. 35(b)] was a simple acrylic diaphragm, with the desired angle between the surface and the electric field provided by the shape of the inner and outer electrodes. This design has low inductance and facilitates cleaning diode debris from the insulator surface.

In mid-1970 Gamble II, a larger pulser of similar design, became operational at NRL and achieved over 1 TW—1 MV at $\sim$1.5 MA. It still operates today. The Gambles were the first $\sim$1 TW generators in the megavolt range—later referred to as "superpower" generators. They led immediately to current densities approaching 1 MA/cm^2 of 1-MeV electrons in pinched diodes that generated doses of over 50 krad (Si) nearby and to very high-current densities in electron beams externally transported in longitudinal magnetic fields.

Water-dielectric technology was also pursued at other laboratories in the late 1960s. EG&G's pulse power group (who also built some $>$ 100-kJ capacitor banks to launch flyer plates) built the COGEN (coaxial generator) series of coaxial water lines switched out by stabbed polyethylene switches—input from Charlie Martin and his group helped launch these. The largest, COGEN IV, was a 1-Ω coax charged to 400 kV in 200 ns by a Marx (earlier ones were charged by pulse transformers). One COGEN was delivered to Sandia. In 1969, Sandia developed a solid-switched water line called Nereus, of which a number were built for various laboratories. At IP, Neptune C was a 750-kV charge 3.5-Ω 50-ns water coax (originally a more powerful Blumlein was planned) charged by an LC-generator and discharged by gas switches.

EG&G made an attempt to use multisite self-closing water switches in COGEN IV, but only $\sim$3 channels closed, too few to create the desired short rise time. PI had the same experience in 1967 with a $\sim$0.7-Ω $\sim$1-MV water coax with a longer pulse and charge time. These results proved that for such a high-power water line, unless it was fast charged by an intermediate store it was desirable to trigger parallel channels in the output switch, as in Neptune C. PI later devised a 4.5-MV triggered water switch for this purpose. Maxwell in 1970 used parallel gas trigatrons in the 2.3-Ω 2-MV pulse line of Blackjack 1; this was charged by a four-Marx array formed by reconfiguring the 5.8-MV 185-kJ dual Marx mentioned in Section III-E into two 2.9-MV systems in parallel.

But, the way of the future for superpower generators was to use intermediate stores like that of the Gambles combined with multisite self-closing field-enhanced water spark gaps to switch out the fast-charged pulse forming line. Some work was done on this approach at NRL, and then it was developed and implemented by Maxwell on later Blackjack machines built for DNA, and by Sandia. The multiple sites entirely eliminated the di/dt limit mentioned earlier in this section. The low jitter of the field-enhanced switches enabled the sites to close in parallel. It also enabled Sandia and PI to then develop triggered gas spark gaps as intermediate switches and thus obtain a total jitter (of intermediate and output switches) low enough to synchronize modules. That was the step that enabled modular water dielectric pulsers like Double Eagle, PBFA-1, and today the $\sim$60 TW Z at Sandia. Few ohm modules like those of Z in parallel are more efficient volumetrically than much lower impedance water coaxes where only the outer region stores energy, and are easier to switch.

In 1967 and the following years, PI developed Mylar-dielectric Blumleins with charge voltages up to about 400 kV as alternative low-impedance pulse generators for output voltages of 100 to 400 kV and currents up to $\sim$0.5 MA. The Blumleins were placed flat in shallow horizontal tanks of copper sulfate solution to allow easy insertion of solid dielectric switches and inspection for air and other defects. The solid switches were later replaced by multichannel SF_6 rail switches. Several such systems were deployed as operational facilities; but as with the AWRE pulsers they proved vulnerable to occasional destructive tracking and unsuitable for use at much larger energies and voltages.

Around the same time, a 250-kV 0.4-Ω 120-ns Mylar Blumlein was built at University of Maryland with NRL assistance, for plasma studies. At the newly formed Cornell Plasma Physics Laboratory, a 4-Ω 600-kV Mylar Blumlein was built with assistance from AWRE staff, who also helped extract an electron beam and drifted beam energy up to 20 m. Charlie Martin gave a week of lectures on pulsed power at the new laboratory.

G. *Vacuum Loads Start to Proliferate*

During the latter part of the 1960–1970 decade, many new ways to use the new very high-power short-pulse generators were devised, mainly by the U.S. labs. From 1965, electron beams were extracted at many labs and used in simple drifting-beam mode. External magnetic fields began to be used at several labs to prevent pinching in the diode, to transport the electron beam to a test object, and to compress the beam to higher current density in a region of increased magnetic field. Collective ion acceleration in electron beams was demonstrated by IP in 1969. Impedance collapse in diodes was quantitatively related to plasma motion. Signs were noted at NRL of lower impedances in diodes that filled with plasma during prepulse. An "advanced" X-ray converter, in which thickness and X-ray absorption is reduced to increase soft X-ray output (the double diode, or later reflex triode) was proposed by PI and subjected to preliminary testing in 1968. At PI, in the mid-1960s, attempts were made to couple Blumleins to very fine wires and heat the resulting plasmas to produce X-rays (it is reported that spiders' web fibers were also tried, in order to minimize mass). An array of up to 15 synchronous small Marx generators made by FEMCOR and based on the technology previously mentioned in Section III-A was fabricated for AFWL to drive fine wires with 70-kA pulses (the HEDS machine). Prepulse or inadequate current or both made these wire experiments ineffective, but they were the first steps toward the successful tests of single wires on the ~1-MA NRL pulsers and of imploding wire arrays on the 4-MA PITHON (PI thaumaturgic onset) that lay ahead as more ways were found to exploit pulsed power.

H. *EMP Simulators*

The development of sources to simulate EMP radiated by high-altitude nuclear explosions and SREMP produced by radiation from nuclear explosions at low altitude also occurred a few years behind the development of flash gamma simulators. These simulators produced very different, longer duration time signatures than the pulsed power sources described to date, and did not need a vacuum interface, but the requirements for fast rise time and large voltage and energy meant that they shared much pulser technology.

The topologies suitable for EMP simulators were explored and defined by Carl Baum at AFWL; his concepts have formed the basis for most or all subsequent EMP simulators. One concept, the vertically polarized bounded-wave simulator, consists of a flat conducting plate or wire-array above and parallel to a ground plane with which it forms a transmission line. A test object is placed on the ground plane, a fast rising pulse is injected through a sloping transition into one end of the line, part of the wavefront is incident on the object, and the pulse is terminated at the other end of the line. Fig. 36 shows an early example, ALECS (AFWL Los Alamos EMP Calibration and Simulation) at AFWL. ALECS was driven by an IP pulser,

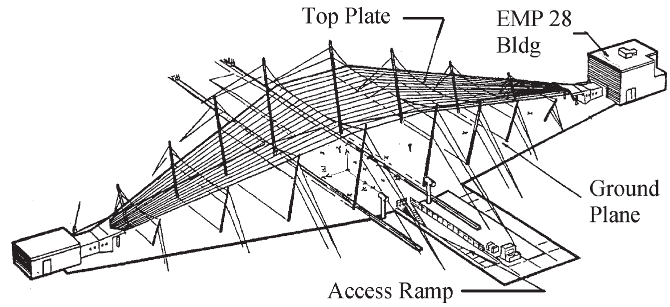


Fig. 36. ALECS bounded wave EMP simulator.

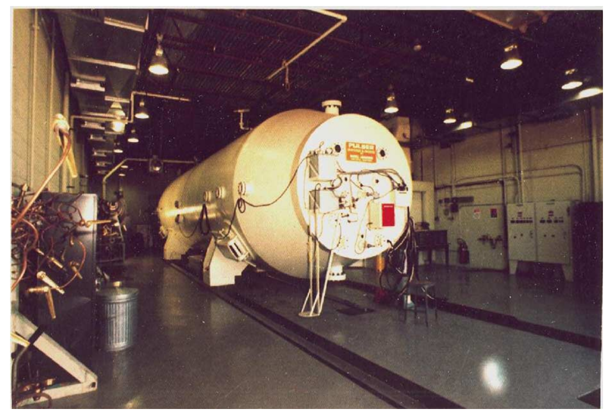


Fig. 37. IP-built pulser for the ARES EMP simulator.

"EMP 28"; a Van de Graaff generator dc-charged a series-stack of capacitors to > 2 MV in high-pressure gas, and then an output switch was triggered to discharge the capacitors into the input of the ~100-Ω transmission line. The capacitors (made by Toby Deutschmann Company), were disks of reformulated mica, and were low enough in inductance to provide a ~5 ns 10%–90% rise time to 2 MV in the line; the RC decay time was a few hundred nanoseconds. ALECS operated into the 1990s.

Most later bounded-wave simulators were driven by Marx generators fitted with peaking circuits (see RES-1, just below). But in 1968, following the decision to have PI build Aurora, DASA awarded IP a contract to build the pulser to drive DASA's large ARES bounded-wave simulator on Kirtland, AFB, Albuquerque, NM, and IP then constructed a low-impedance (15-Ω) FX-45 pulser similar in size to the FX-75 [Fig. 37]. The Van de Graaff-charged energy store did not use capacitors as in ALECS, but was the long coaxial terminal in gas; this gave the waveform and spectrum from ARES less than ideal shapes associated with the terminal transit time. The output switch had six trigatron electrodes and closed in multiple channels. The pressurized output housing was of ceramic, and contained oil; a coaxial oil line then led the pulse to an oil-gas interface after which it diverged in SF_6 until the field became low enough for an interface to the air at the ~0.8 atm of Albuquerque. The ~5-MV pulse had a 5-ns rise time that was maintained on the conic line that led to the test volume, 30-m high.

Many other EMP simulator concepts required light-weight pulsers that operated high above the ground or in flight. The first such pulser was developed for AFWL by PI in 1967–1968.

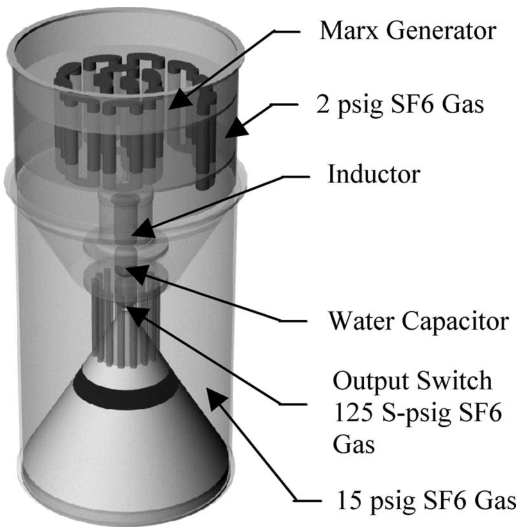


Fig. 38. Pulser and biconic region of RES-1/HAG-1.

Two almost identical pulsers were constructed, and drove the centers of resistively loaded dipole antennas that were airborne, carried by a helicopter; one antenna was vertical and the other horizontal. The central section of each antenna was a 150-Ω bicone driven at its apex by the pulser, and this radiated a fast rise time and a magnetic field equal at any distance to the dc field of a current 1.6 MV/150 Ω. Beyond the bicone, the horizontal antenna was a tapered inflated balloon (made by Goodyear) with a resistive outer layer; the vertical antenna extended from the bicone as wire sections joined by resistors. In both cases, a 1.6-MV 1-nF capacitor was discharged into the bicone apex and charged the open-circuit antenna to $\sim$1 MV for hundreds of nanoseconds. Both simulators originally had the title Research EMP Simulator 1 (RES 1); the pulsers were later designated as High Altitude Generator (HAG) 1A and 1B.

The 1.6-MV $\sim$1-nF RES 1 capacitor was an $\sim$8-in length of $\sim$8-in-diameter water coax, charged in $\sim$1 μs and switched into the antenna apex by a self-closing uniform field 1.6-MV 100-psig SF_6 switch [Fig. 38]. This type of switch had been proposed at Stanford Linear Accelerator Center in 1965 as a way to obtain a few nanoseconds rise time in a $\sim$500-kV 10-ns 10-pps oil Blumlein needed to drive a streamer chamber—a new Russian type of particle detector. AWRE had assisted SLAC in the design of the pulser, then explored self-breaking SF_6 switches and used a 2.5-MV version in parallel-plate oil Blumlein ("Plato") in 1966. In RES-1, the water capacitor output interface was insulated by the high-pressure SF_6 of the switch, into which it was closely coupled, as illustrated in Fig. 38.

PI initially used a General Electric clamshell capacitor and air-cored transformer of the AWRE type in Fig. 11(b) to charge the 1.6-MV RES-1 water capacitor; however, in lab tests, tracking occurred occasionally in the transformer. PI then devised a lightweight Marx insulated by SF_6. This was placed in a 5-ft-diameter metal cylinder on one side of the RES-1 bicone, which was pressurized to a few psig of SF_6. Tubular plastic-cased capacitors parallel to the antenna and cylinder axes formed $\pm$50-kV stages that spiraled in from the "ground" potential cylinder to 1.6 MV at the center. In order to reduce the influence of the Marx circuit on the voltage waveform of the antenna, the pulse-charge time of the water capacitor was made > 1 μs by placing an oil-encapsulated inductor between the Marx and the water-coax and inductively loading the Marx.

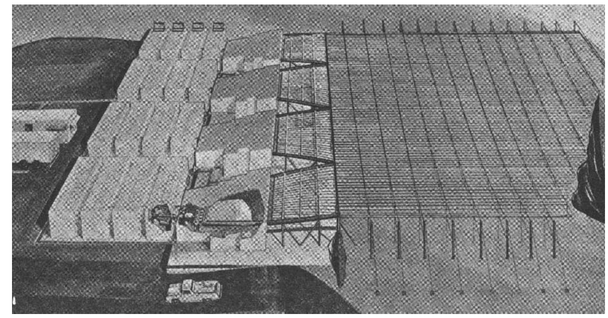


Fig. 39. Concept of the AFWL SREMP simulator "SIEGE II."

When the fabrication of RES-1 was well under way, NRL sent the PI design team (too late for use) a published text on how to design a "peaking circuit" to reduce the rise time of an inductive source into a resistive load. The small-value peaking capacitance is chosen so that the inductive source pulse-charges it with a peak current, reached at the time its voltage has risen to that of the source, that is equal to or slightly less than the current needed by the load. At that voltage, a peaking switch connects the circuit to the load and a fast-rising step output results. Had this circuit been used in RES-1, the water coax would have had been greatly reduced in size; added inductances could have been avoided; and the times of electrical stresses, especially on the output switch, could have been greatly reduced.

The two RES-1 simulators were used for a number of years for field-mapping at less than threat levels. The recorded waveforms showed 10%–90% rise times of a few nanoseconds, limited by diagnostics. Eventually, the pulsers were put into storage. In the 1990s, when shorter rise times became important, Pulse Sciences pointed out that the calculated rise time was about 1.5 ns. The two pulsers were reactivated and rise times of 1 to 1.5 ns were recorded with more modern diagnostics. The aged pulsers could reliably operate only up to about 1.2 MV, but were returned to service first for AFWL and then for the Army at White Sands Missile Range, where one was refurbished by Pulse Sciences in 2005.

Our last example of the technology advances of the 1960s is the ground-based transportable SREMP simulator SIEGE II. The AFWL concept is illustrated in Fig. 39. A $\sim$2-MV wave with a rise time of < 10 ns is propagated across the ground in air by applying 2 MV to a wire "plate" spaced $\sim$2 m above the ground and about 100-m wide. Good wave planarity is obtained by feeding the plate at four points with conic transmission lines that diverge from source regions with dimensions of order 1 m in atmospheric-pressure Freon (CF_2Cl_2) gas. The wave is terminated in a resistor array, and the total current of 100 kA flows on and between two arrays of rods that penetrate deep into the ground on each side of buried hardware. The pulse has a 50-μs e-fold decay time, and a total energy of 5 MJ is delivered to the four feed points–in the PI pulser shown, by sixteen 2-MV Marx

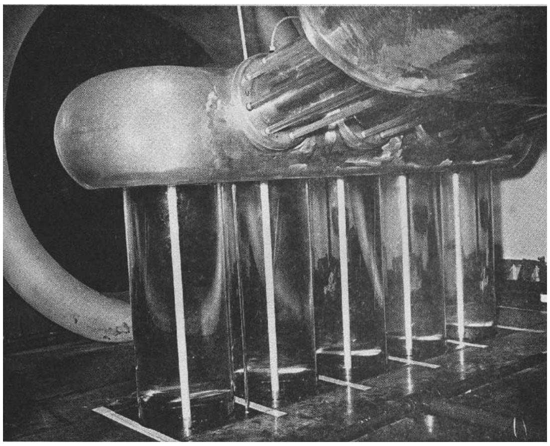


Fig. 40. SIEGE II Marx output, peaking circuit, and input to conic line in Freon.

generators. Each Marx is housed in a separate oil-filled tank about 12-ft^2 and 35-ft long, a size allowing transport by road between test sites. There are oil-filled connections between the oil tanks at each feed point and through a fiberglass diaphragm into each of the Freon enclosures, which are demountable for transport.

The full SIEGE II was not deployed, but the pulsed power system for one feed point was developed for AFWL by PI and in 1970 was tested as a quarter-SIEGE II system. The Freon gas box connected to a 2-m-high 2-MV plate and a ground plane, which formed a transmission line above ground that was terminated after ∼50 m.

The SIEGE II Marxes used the 508 spark gaps newly developed for Aurora and three of the same 1.85-μF 60-kV capacitors in parallel in each half of a ±60-kV stage. The 16-1/2 stages forming each Marx were hung by nylon straps in one line in the oil tank. The output of the Marx closest to the transmission line connected through the fiberglass oil-Freon interface to a peaking circuit and then drove the diverging conic line in Freon [Fig. 40], providing the fast rise and the initial part of the output waveform. This first Marx also connected through ports between oil tanks to the three other, identical Marxes; these were connected hard in parallel and erected into an effectively open circuit, as they were connected to the first Marx via an inductor in the oil that reduced the effects of erection transients of the three Marxes on the waveform delivered by the first. Resistive coupling of midplane electrodes was employed to erect the Marxes; the first Marx, which had to be synchronous with the other three quarters of the full SIEGE II, had a jitter of < 2 ns. Trigger pulses were supplied to all four Marxes from a dc-charged 50-kV SF_6 rail spark gap that had a jitter of < 0.5 ns.

The ∼1-nF peaking capacitor consisted of vertical acrylic tubes full of deionized water. To synchronize the closures of peaking switches in all four feed points, the original plan was to use triggered uniform field SF_6 spark gap peaking switches. In the SIEGE II development, such a switch was demonstrated, with a trigger electrode at V/3, that had jitter ∼1 ns at up to 1.4 MV. Scaling to 2 MV was projected, and later experience

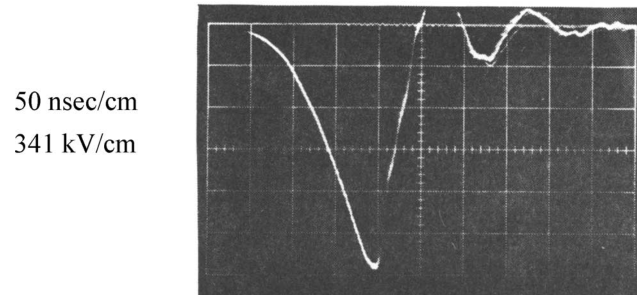


Fig. 41. Six overlaid waveforms (50 ns/div) of one of the four parallel SIEGE II output switch breakdown of a point-plane SF6 switch.

at up to 3 MV justified that. However, Charlie Martin, who participated in AFWL's project and also followed progress in direct communications with PI (a role that he played in many U.S. projects), suggested a much simpler method—the use of self-closing SF_6 "point plane" spark gaps instead. AWRE's test data showed that when pulse charged these self-closed with very low jitter—presumably because the breakdown initiated very early in the voltage rise from the point (or more usually the sharp edge of a cylinder, which wore more slowly) and proceeded reproducibly in the pure, homogeneous gas. In the SIEGE II and Aurora programs, PI extended the AWRE data at a few hundred kilovolts and a few atmospheres to > 10 atm and over 2 MV. PI found that the scatter in breakdown voltage was ∼2% rms for pulse charge times of 2 μs, reducing to $< 0.5\%$ at 50-ns charge. PI also found that for moderate to high pressures the breakdown strength of these switches was proportional to $p^{1/6}$ and was twice as high when the point was negative as when it was positive; it had a time-dependence that increased with pressure.

For the ∼100-ns charge time of the SIEGE II peaking switch the jitter was < 1 ns, as illustrated in the test-switch waveforms of Fig. 41. The overall jitter of a SIEGE II quarter system, a combination of Marx and peaking switch jitter, was about 2 ns. Fig. 40 shows four adjacent point-plane switches mounted on each peaking capacitor; several would close in parallel. The 10%–90% rise time launched into the Freon-insulated conic line was 7 ns. The design level of 2 MV was achieved, though at full voltage breakdowns occurred across the Freon–air interface, probably due to transients from the termination that raised the voltage above 2 MV. A stored energy of > 1 MJ (1.25 MJ) was attained using such Marxes (four in parallel) for the first time.

IV. Conclusion

The growth of pulsed power capability in the USA between 1964 and 1970 was very rapid. PI's invention of the Marx/oil Blumlein in 1964 was followed by 1970 by three PI machines that increased output energy by more than a hundred and laid the foundation for another step of four and a power of $\gtrsim$20 TW by 1972. At the same time, low-impedance pulers using a higher energy-density–water–liquid dielectric were being built at > 1 TW (at NRL), evolving toward technology for "superpower" generators at PI and Maxwell and for Sandia's

60-TW modular Marx/intermediate store/water pulse forming line systems today. Different ways to extract the vacuum tube energy–X-rays and electron beams in various energy ranges, and ion beams–had been demonstrated at these organizations and at IP. EMP simulators of many kinds were developed in this period in U.S. industry; these and ionizing radiation simulators both stored more than 1 MJ by 1970. The theoretical underpinnings of pulsed power were advancing rapidly too, along with the development of computer programs to simulate circuits and particle beams.

This progress was made possible by willingness to innovate and engineer on a large scale, foresight, and rapid planning by U.S. government agencies to exploit that capability, and hard work in the laboratories and plants of the major fabricators. Operations were often round the clock in U.S. industry. The largest industrial pulsed power group, at PI, numbered about 130 people in 1970, and their annual spending escalated to $2006 was over $50 M.

This progress was greatly speeded by starting with the tens of nanosecond diode capability and low-inductance vacuum interface design, both with newly practical vacuum requirements, that was demonstrated by the AWRE group under Charlie Martin using novel pulse generators based on solid dielectrics for both energy storage and switching. Charlie's charismatic encouragement of U.S. government agencies and input to designers made him a very important factor in this period and beyond.

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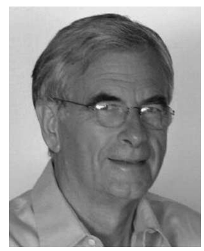

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