



EXPLODING WIRES

For nearly two centuries it has been known that a fine wire will explode when suddenly subjected to a large flow of electrical current. During much of that time the effect has been looked upon as a curious but not very useful phenomenon, and even now there is no general agreement on the exact mechanism involved in such an explosion. Modern technology, however, has found many ways of using exploding wires, and a resurgence of scientific interest has led to three conferences on the subject in recent years. The following brief review of the field includes a report on the latest conference, held in March of this year.

By William G. Chace

The nearly 200 delegates who met at the Kenmore Hotel in Boston on March 10th to discuss the exploding-wire phenomenon were assembled to continue the study of a phenomenon first described before the Royal Society in London in 1773.¹ In the intervening years, such notables as Michael Faraday, Lord Rutherford, and the late John A. Anderson, the astronomer of Mt. Wilson Observatory, have experimented in the field.

In spite of the length of time since the exploding-wire phenomenon was first described and of the caliber of some of the scientists who have been interested in it, a great many physicists really know very little about it, so, before describing the conference itself, perhaps a word about wire explosions might not be amiss.

A wire explosion is what happens when a very large current is forced suddenly through a small wire, for example, 150 000 amperes through a 0.5-mm diameter copper wire in 1.5 microseconds. The explosion itself lasts around 50 nanoseconds (50×10^{-9} sec). There is a bright flash of light, a report like a detonating 40-mm shell, and a destructive power like a squib of high explosive.

Although this sounds spectacular and quite useless, actually exploding wires are now important devices in a number of large-scale operations. Probably their most outstanding use depends on their ability to set off high explosives directly, without the usual sensitive fulminate intermediate. In a missile or a satellite rocket this is an important attribute, and exploding wires are used in great numbers for this purpose. Also, the recently developed process of explosive forming can be used for routine production of small parts with wires as the "explosive".

Before these recent developments, exploding wires had few practical uses. Nairne, our pioneer, did, in 1774, make use of exploding wires to prove that current in all parts of a series circuit was the same, a not at all obvious idea to the natural scientist of the 18th century; there was a good possibility that the "electric fluid" was consumed as it flowed toward "earth." Nairne put a wire at various positions along a 48-foot conductor and reported, "I could not perceive that there was the least difference, in the melting of the wire, on its being placed in different parts of the circuit." But this was an isolated case, and it was not until the 1920's that wire explosions were again put to work, this time by J. A. Anderson, who used them

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to attain high temperatures for spectroscopic research. Anderson became so much interested in exploding wires that he made fundamental investigations on the phenomenon and published about half a dozen papers on the subject.

After World War II, important uses were found for wire explosions. They served as a light source for high-speed photography, and for taking photographs of explosives. It was found that by arranging for a fuse to explode rather than just to "burn out", very-high-voltage circuits could be protected by exploding fuses.

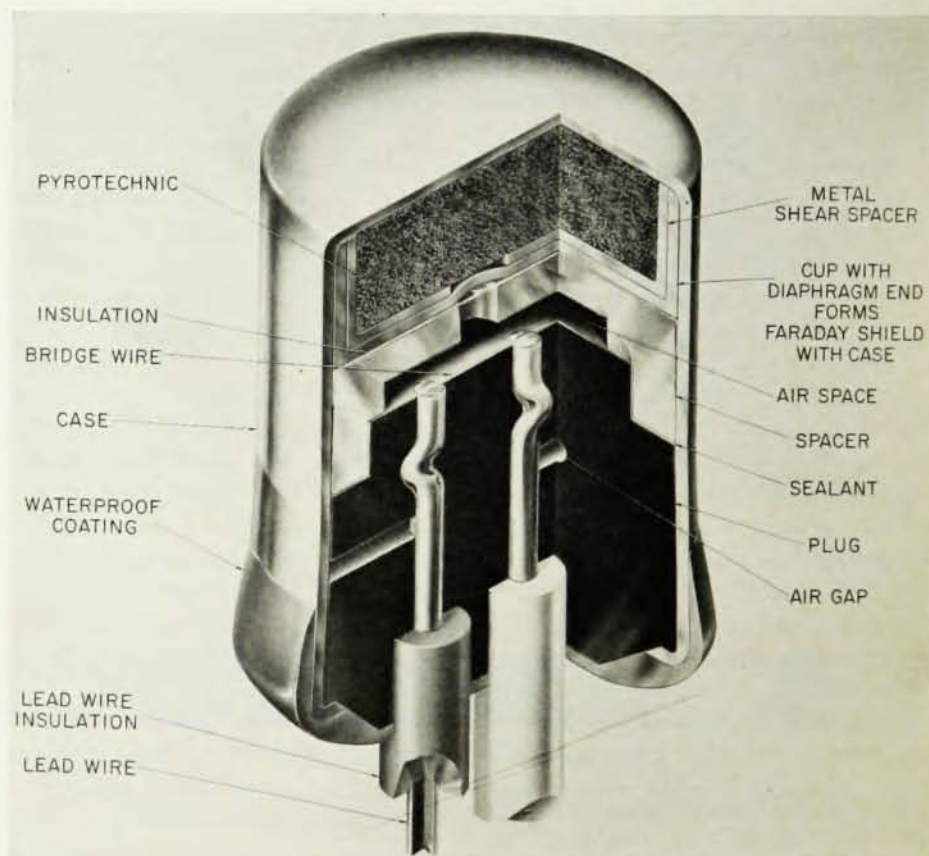
At present, as has already been said, exploding wires find numerous uses in missiles and space. The high-power electromagnetic radiations used with a missile or a satellite (control, radar, and beacon signals) present a serious problem to the explosive items so important to this type of operation. Explosive bolts separate the stages; explosive ignitors fire the rockets as needed; and some control and safety devices are explosively actuated. The high explosive in such a device is traditionally ignited by a train of events starting with a "bridge wire", a fine wire which is heated to ignite a sensitive (black powder or fulminate) explosive, which in turn ignites one less sensitive (e.g., PETN), which ignites the main charge. Now it is easily possible for that fine bridge wire to be

raised to igniting temperature by absorption of rf energy, igniting the charge at the wrong time. To prevent this malfunction, the ordinary bridge wires are replaced with exploding bridge wires (EBW). The probability of accidentally delivering enough rf energy to a wire to explode it is very, very small. Furthermore, the highly sensitive primary explosive may be eliminated, since EBW's will ignite PETN directly. (See Fig. 1.) This represents a major use of exploding wires.

Another problem of space technology which exploding wires help to solve is that of reactions to very-high-velocity micrometeorites. The high energy density of an exploding conductor can be used to accelerate micron-size projectiles for study of micrometeorite damage. Several papers on this topic were given at the Second Conference,² and a paper by Bohn, Nadig, and Simmons³ tells of further progress on this technique at the most recent meeting. There is also the possibility that the high energy density of a wire explosion, which means high specific impulse, may be used for satellite guidance and attitude control in space.

All this is brought about by discharging the energy from a charged capacitor bank into the wire. The capacitor bank is made up of special low-inductance condensers, the connecting leads are very carefully arranged to keep inductance at

Fig. 1. Exploding bridge-wire squib for igniting high-explosive charge in a ballistic missile.



a minimum, and the switch is designed especially for the purpose. A picture of a bank for exploding-wire research is shown in Fig. 2. It has a capacity of 90 μF , and can be charged to 20 kV. Each of the six 15- μF capacitors has its own triggered gap switch, and the leads are flat copper plates separated by thin mylar insulation.

The phenomenon is studied by electrical measurements, by high-speed photography, by spec-

troscopy, by interferometry, and most recently by x-ray pulses of nanosecond duration.

Measurement of the very large (100 000 to 200 000 amperes), rapidly changing electric current is made with specially designed coaxial shunts (Park shunts⁴), or by magnetic probes whose output, (dI/dt) can then be integrated by an RC integrator to give $I(t)$. Typical traces of I and dI/dt might look like Fig. 3. The current curve

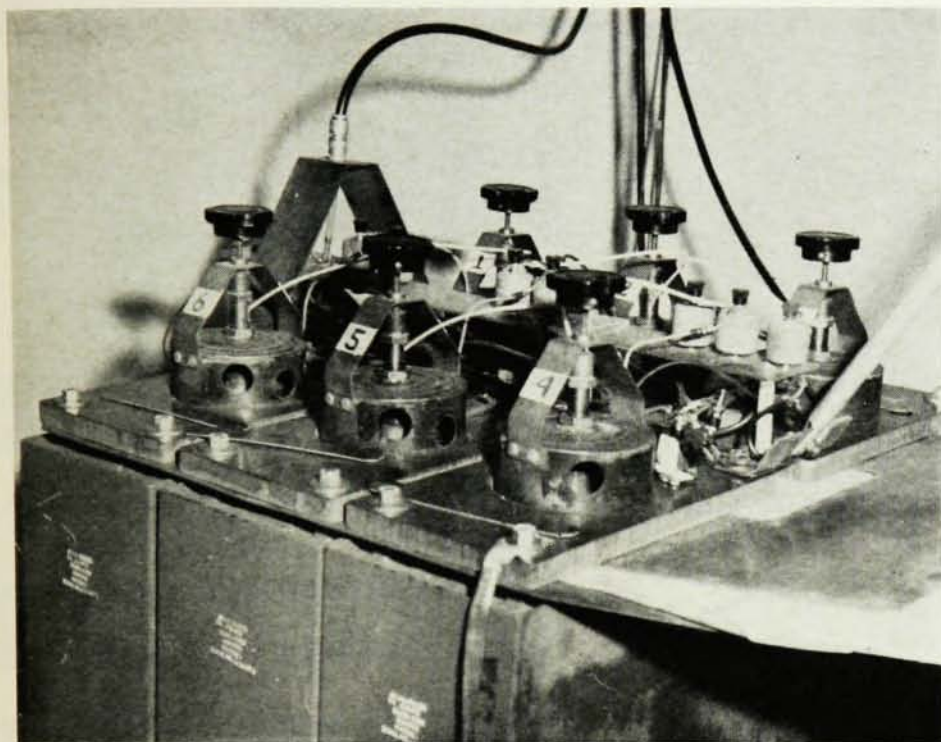


Fig. 2. Exploding-wire energy source shown at left has six capacitors, each with its own triggered gap switch.

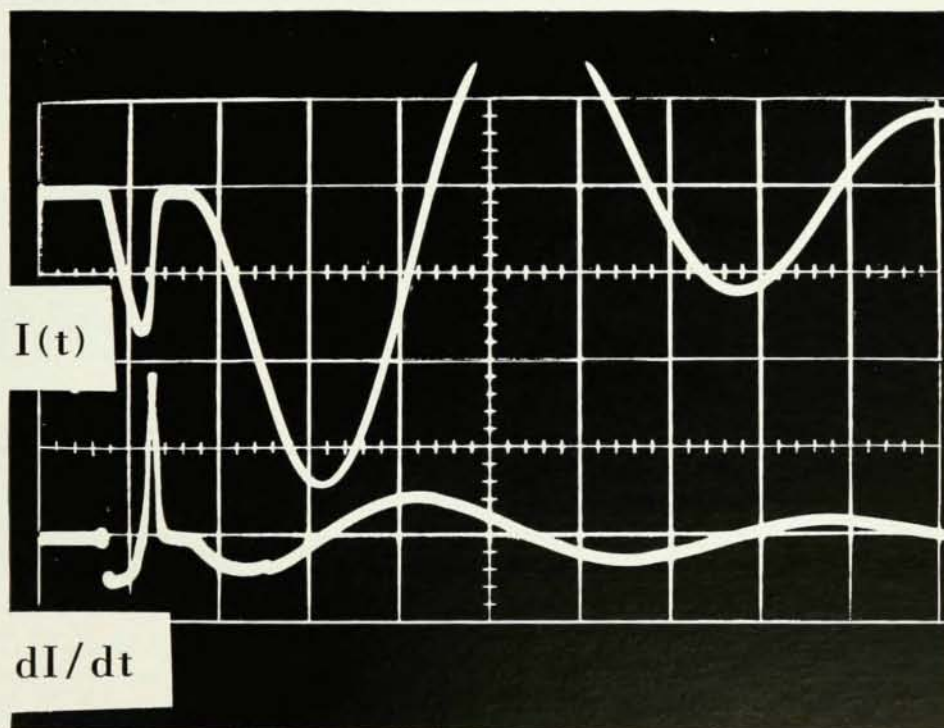


Fig. 3. Oscilloscope traces of current and dI/dt in a wire explosion. (#24 copper, 3 inches long; 12 kV, sweep speed 2 microsec/div.

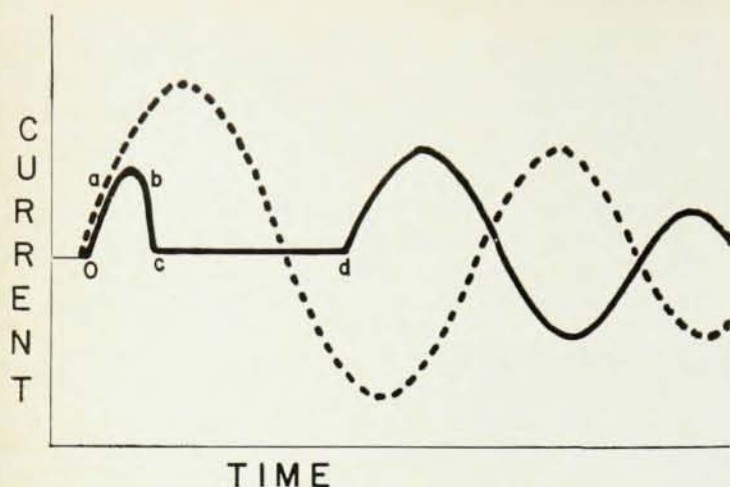


Fig. 4. Idealized exploding-wire current trace.

is idealized in Fig. 4. If the wire did not explode, the condenser discharge circuit would be a typical underdamped oscillating discharge like the dotted line. However, when the wire explodes (as in Fig. 4), the current, which has been around 150 000 amperes, drops suddenly to near zero (about 150-200 A), where it remains for a relatively long time (up to 200 μ sec); then it suddenly rises and continues as a damped oscillation until the condensers are discharged. The period of low current is called "the dwell" and the sudden rise at the end of the dwell, "the restrike".

There is much that is not accurately known about exploding wires, hence there is no general agreement on the exact mechanism of the explosion. However, the picture given below will meet with the approval (at most points) of the average scientist in the field and might even find complete agreement among a few.

When the switch is closed, current starts to flow and builds up as predicted by the usual *RLC* circuit equation.

$$E = RI + L \frac{dI}{dt} + (1/C) \int Idt.$$

Linear solutions of this equation cannot be used, however, since *R* and *L* are changing because of the heating of the wire. In a few nanoseconds the wire reaches its melting point, and another nonlinearity is introduced since the two phases have different resistances at the transition temperature. Now in the type of wire explosion under investigation in the author's laboratory, the time spent in the liquid state is so short that no significant change in shape occurs; i.e., the wire remains a liquid cylinder whose various developing instabilities are only of second-order importance. However, if the external circuit limits current rise so that the wire remains in the liquid

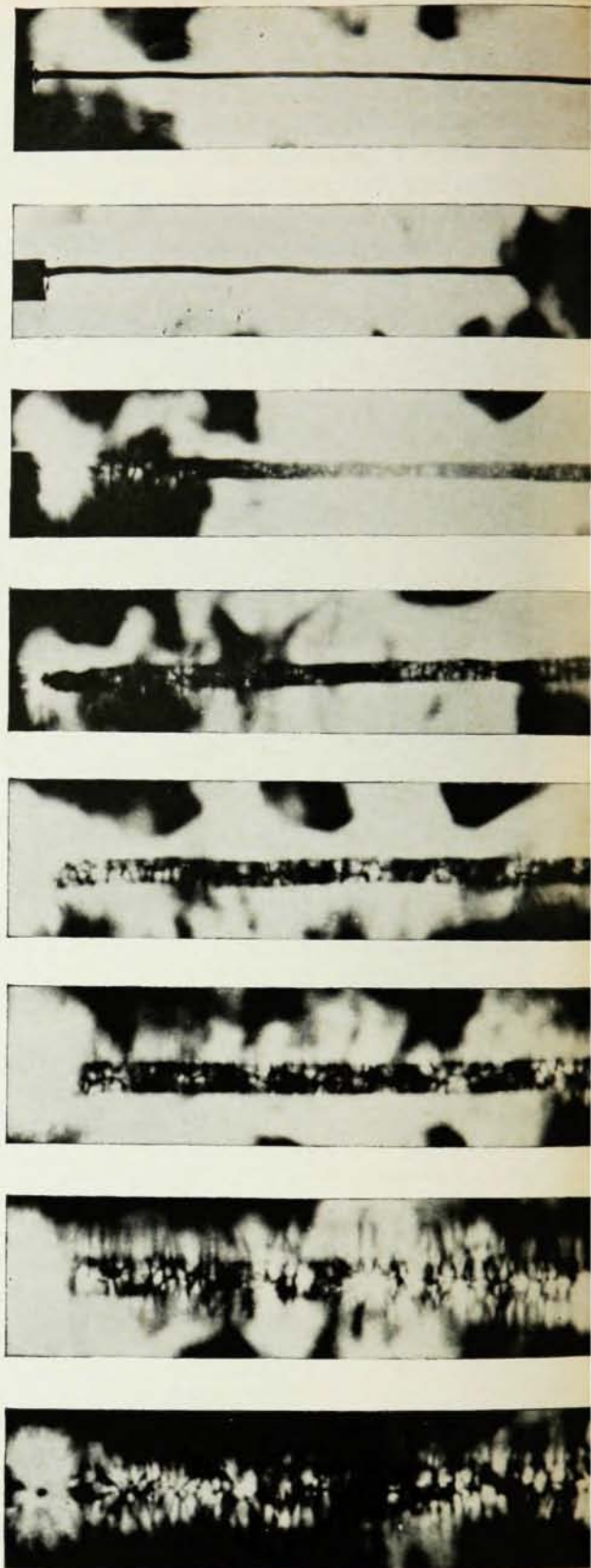


Fig. 5. Copper wires (0.5 mm in diameter by 10 cm long) exploded with 10 kV. Exposure 0.5 microsec; interval between pictures about 0.75 microsec. The irregular white area behind is an exploding-wire backlight. Top frame shows wire before switch closed.

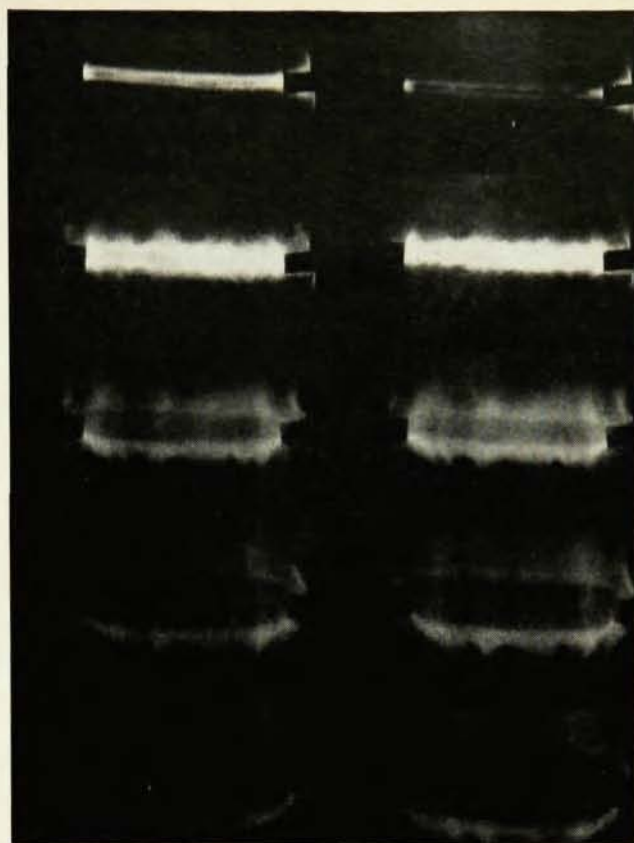
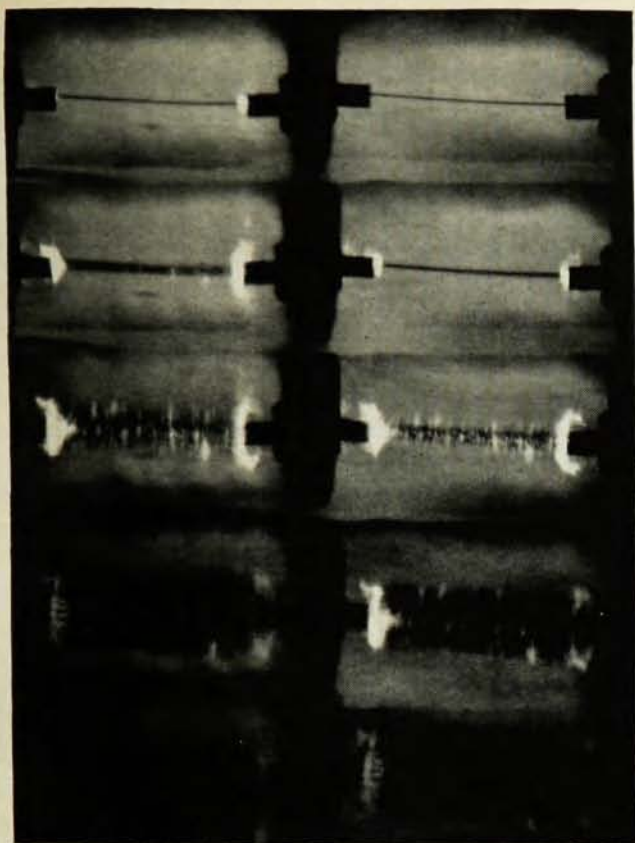


Fig. 6. Copper wire (0.5 mm in diameter) exploded at 6 kV. Exposure 0.1 microsec; interval 0.5 microsec. Series at left, atmospheric pressure; at right, 5×10^{-4} mm Hg pressure. Each photo has ten frames whose sequence is: top row, right to left; second row, right to left; etc.

phase for several microseconds, then instabilities do produce significant changes in shape (e.g., unduloid development), and a new complication is introduced.

Following the simpler, more rapid course, the cylinder of liquid is further heated by the ever-increasing current until it reaches the normal boiling temperature. Because of lack of nucleation points within the liquid and along the surface, the liquid metal ("supported" only by inertia) does not boil but becomes superheated, in fact highly superheated. As the liquid metal superheats, it continues to expand. The exact way in which this expansion occurs is still under investigation, in fact papers by F. D. Bennett, and M. L. Coffman at the conference discussed this problem. In whatever manner the expansion occurs, expanded metal has a much higher resistance. The increase, according to theory, is as some high power of radius. Eventually, as the expansion continues, there comes a time when the material no longer behaves as a metal. Current is then cut off, a very high-inductive ($-L dI/dt$) voltage results, and the wire explodes. Somehow, during this explosion, the wire material assumes the characteristics of

a vapor. Its density is very high (pressure approximately 34×10^3 atm) and its temperature is some tens of thousands of degrees K. Because of the high density and short mean free path, ionization by impact (avalanching) does not occur, and the small current which does flow is carried by electrons and ions generated by thermionic and thermal ionization. Nothing except inertia and the surrounding atmosphere prevents expansion, so the cylinder of gas rapidly expands, its density falls, and the mean free path increases. When the mean free path reaches the critical value for avalanching, the number of available carriers is multiplied to that in an arc and the restrike occurs. The resulting arc dissipates the remaining condenser charge.

High-speed photographs of the explosion of wires are shown here. Figure 5 is a composite, made from pictures of different wires taken each at a later stage of the explosion, exposure about $0.5 \mu\text{sec}$. Figure 6 shows several framing camera pictures of exploding wires. Here each series follows the explosion of one individual wire.

The apparatus used to supply energy, to control the process, and to make measurements must,

above all, have low inductance. For this reason, all elements of the circuit are most carefully designed. This includes capacitors, leads from capacitors to wires, switching system, measuring transducers, and wire holders. While the ideal has not yet been achieved, this part of the exploding-wire problem has been quite well resolved, and at this year's conference, for the first time, apparatus was not a major item of interest. One paper only, that by Trolan, Charbonier, Collins, and Guenther, described new methods of energy supply and control.

The 1964 Exploding-Wire Conference

The Conference, held at the Kenmore Hotel in Boston, was attended by about 200 delegates from 22 states and 5 foreign countries. The program consisted of 26 contributed papers, and an invited paper on exploding-wire research in Germany by H. Bartels and J. Bortfeldt of the Institut für Plasmaphysik of Hannover. The final item was a panel discussion scheduled to review the disclosures of the conference, but actually covering the whole field of exploding wires. The only scheduled social event was a buffet supper.

The outstanding feature of the conference was a feeling of maturity which was different from the earlier conferences. This was no doubt due in part to the fact that now, after two previous conferences, the workers in the field have become acquainted. Each has become earmarked by his specialty, by his pet theories, his personality. Thus it was no surprise that Howard Leopold talked about exploding bridge wires, that Dr. Sakuri continued his rigorous application of shock-wave theory to exploding wires, that Dr. Maninger applied down-to-earth electrical engineering theory to the phenomena, or that the AEC group from Sandia and Los Alamos described more uses of their "action integral".

Some newcomers added youth and vigor, so our maturity was not "middle-aged stodginess". A paper by Linhart and Schenk from the CERN Frascati Lab brought the plasma physicists' methods to bear on wire explosions. This is certainly a promising approach. M. L. Coffman of Oklahoma City University attempted the difficult job of applying thermodynamics to the very early stages of a wire explosion. From the Boston area, Rothstein gave a most interesting comparison of a wire explosion and the arc spot and sputtering. The similarity, so far wholly qualitative, was most thought provoking.

An entirely new use of wire explosions, inorganic synthesis of binary compounds, was the sub-

ject of a paper by M. J. Joncich and D. G. Reu. They described the successful synthesis of iodides, sulfides, and carbides of magnesium and aluminum with yields as high as 60 percent.

The invited paper presented by Dr. Bortfeldt gave a review of the work done at Europe's most active center of exploding-wire research. The most convenient source of high-density plasmas, said Dr. Bortfeldt, is an exploding wire, and work at Hannover is directed at studying these plasmas as such, and also at using them as a source for other plasma studies. In one experiment that he described, a large condenser bank is discharged into the plasma cylinder produced by exploding a wire a few μsec earlier. The resulting pinch is studied electrically and also by the fine time resolved optical system devised by Bartels⁵ in 1950, and referred to in this country as a "gallery camera". This was used to give simultaneous smear and framed photos and also simultaneous smear pictures and time-resolved spectrograms. Numerous slides illustrating the technique were shown. A lively question period followed.

Four papers were given on the subject of exploding bridge wires. H. Leopold of the Naval Ordnance Laboratory described experiments in which wire parameters, length, diameter, and material were related to reliability, time reproducibility, and vigor of explosion. Tucker and Cnare, in a pair of related papers, described how the EBW system may be precalculated from knowledge of burst current and "action" (I^2dt). Blackburn and Reithel of Los Alamos discussed methods of studying the EBW-explosive complex with sweeping image techniques.

In summary, it may be said that the conference showed the increasing use of exploding wires in EBW systems, for accelerating small particles, and for generating shock and stress waves.

The success of some of the applications seems to have reduced the amount of fundamental research being done, for there was a distressing lack of papers on fundamental exploding-wire phenomena as pure science and on quantitative studies of the exploding-wire phenomenon itself.

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