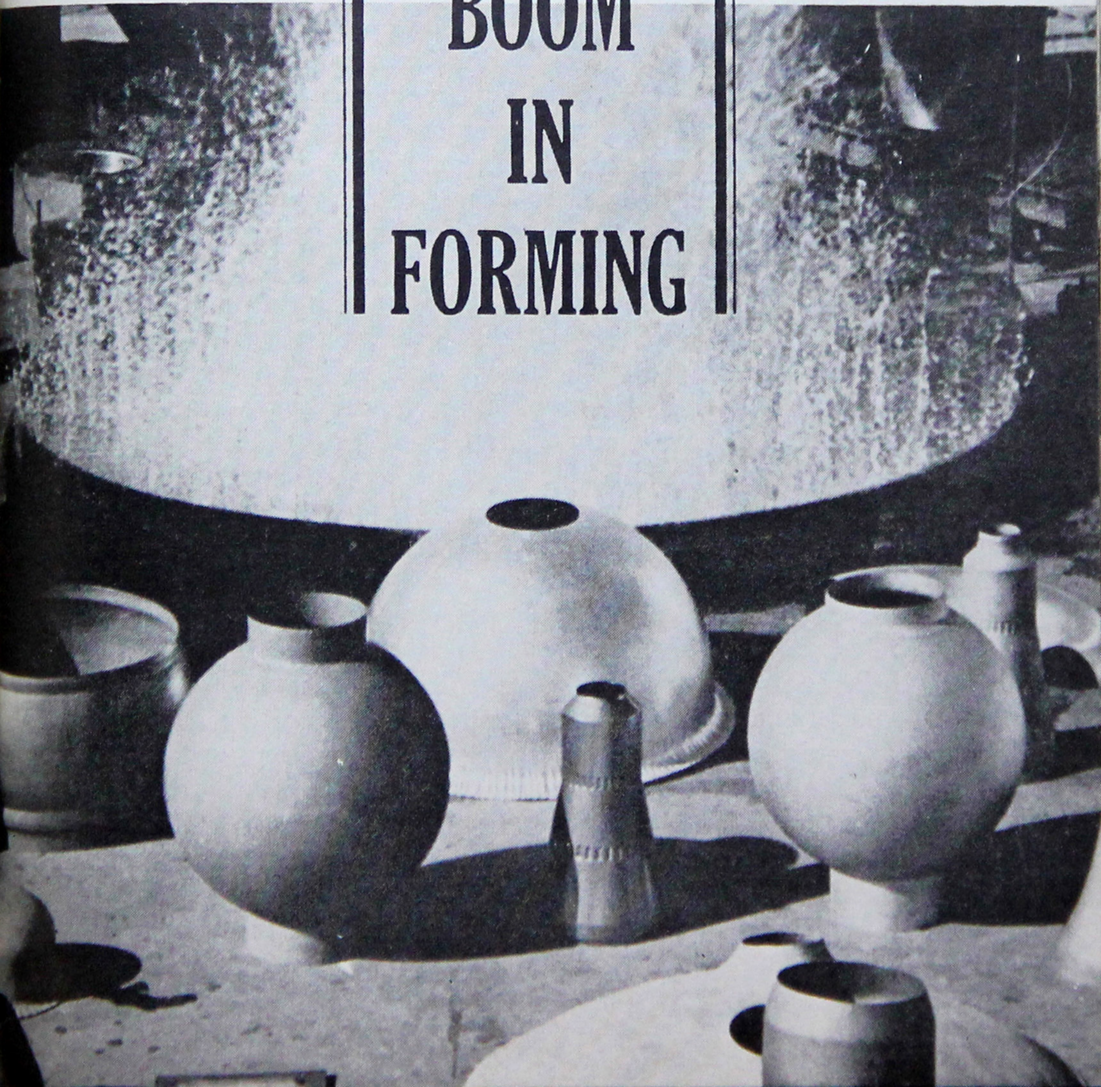
BY WILLIS CAIN . . . and by "boom" Cain isn't kidding!

They used to use explosives for tearing things apart. Now they use them to put them together.

THE BIG BOOM IN FORMING



■ It's always fun to speculate on science's historical near-misses. Like Leonardo's flying machines, or that unsung color photography method of the 1800s. Ideas which sometimes don't catch on until centuries later, whereupon everybody says, "Why didn't they think of it sooner?"

The subject of our article could have been one of these near-misses.

In many of our great industrial plants, in spaces only recently vacant, in odd corners of loft and yard, groups of white-coated men with new and different-looking machines are—perhaps belatedly—setting up shop. Curious passers-by are occasionally startled by such effects as bangs, booms, whoooshes and thunderclaps, complete with lightning flash.

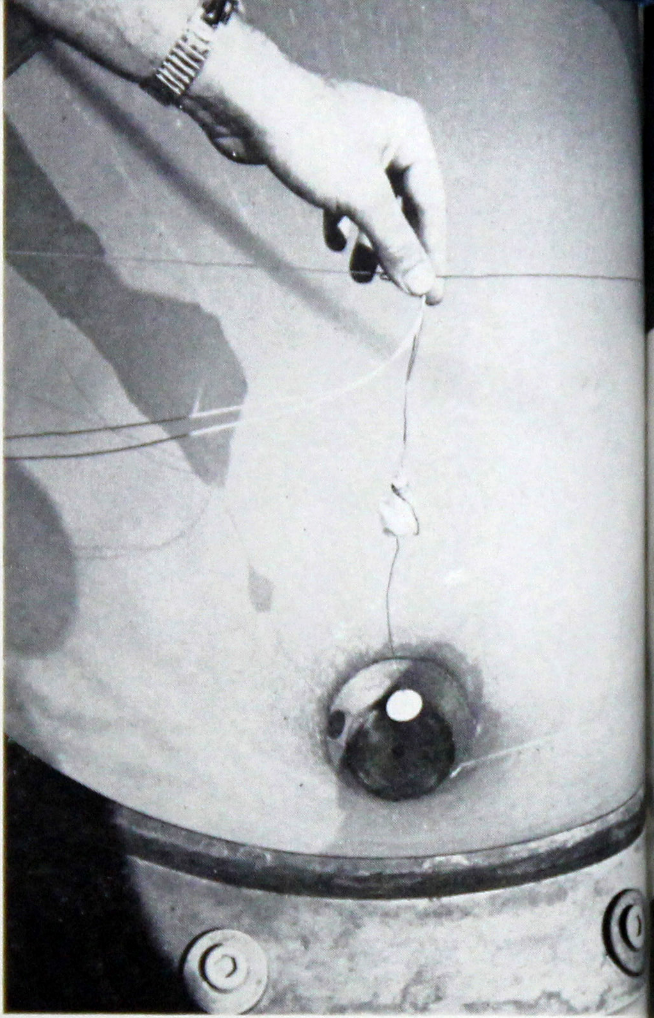
Strange goings-on perhaps, but it's not as spooky as it all might sound. The white-coated gentlemen are neither reincarnated alchemists nor mad-scientists-bent-upon-destruction; on the contrary, their motivations are consummately constructive. (But come to think of it, what they're doing is—by accepted metal working standards—not far short of Magic, at that!)

With High Energy Forming (HEF) methods now available, this new breed of engineering specialist is currently rewriting the book on Forming. Metals? You name 'em, they form 'em: tungsten, tantalum, beryllium, titanium—all the hard-to-work "problem" metals, not to mention the newer high-strength, high-temperature and refractory alloys. As a matter of fact, any metal with any degree of elongation, as well as metal powders, plastics and ceramics are now being easily formed.

Man, with his cantankerous urge to shape things nearer his heart's desire, has for centuries now, been busily torturing recalcitrant metals into more or less desired shapes—by melting, hammering, bending, stretching and otherwise belaboring 'em. Doing it the hard way, definitely.

The great strides in metalworking which took place during the industrial revolution were due in a large part to an increased ability to harness and work with higher levels of energy. Indeed, we've come a long way from the days when swords were hand-beaten into plowshares—and vice versa—to the conventional forgings, castings, presses, and drop hammers we employ today. And one of

The next five photos show some of the steps involved in explosive sheet metal forming at General Dynamics Astronautics, San Diego. Supervisor Art Wright (back to camera) helps secure the workpiece to the top of the die.



Handling half-ounce of dynamite suspended on end of wire, engineer at General Dynamics/Astronautics places the explosive in precise position in die at explosive-forming facility recently established at plant. The dynamite explosion will "bulge" or push metal plate over die into an exact shape for use as a missile part. The entire shock waves travel through the water to compress or "push down" metal to be formed for other parts.

the reasons why we enjoy the durability, reliability and tolerances they provide has been our ability to apply increasingly higher levels of energy to the workpiece.

But no amount of forming energy handled so far, has approached the tremendous forces released by the new HEF techniques—forces in the order of millions of pounds per square inch.

High pressures alone are not the complete story, however. We've known for some time what they do to materials inside the earth and have seen them duplicated in a modest way in the production of synthetic diamonds. But we seem to have had a tendency to overlook a most interesting and important factor—the amount of *time* required to form.

Modern HEF methods utilize the high energy obtained from (1) explosives, (2) high physical impact

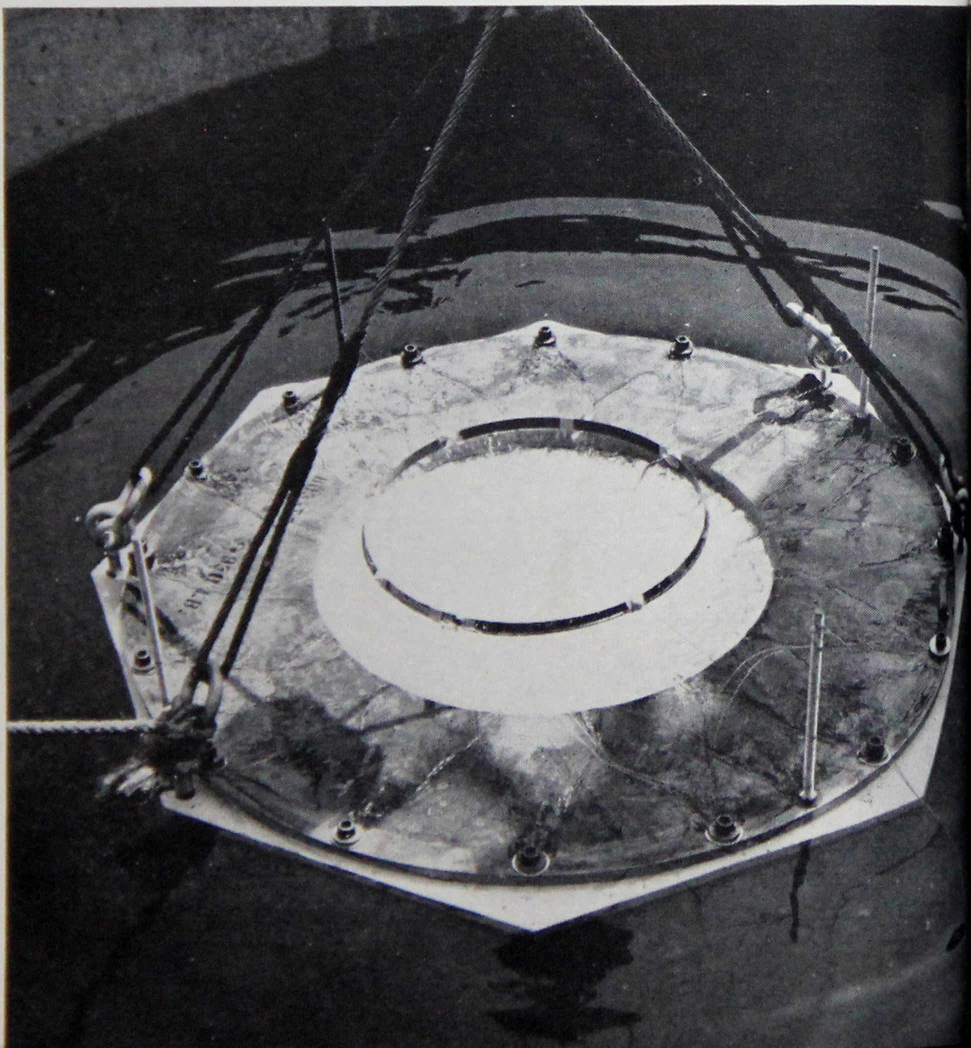
Next, Engineer Bill Wilson connects wires from the detonator.

from expanding gases and (3) the direct conversion of electrical energy to its mechanical equivalent by means of high voltage capacitor discharge. With all of these methods the actual forming is accomplished in a matter of split seconds—in the proverbial "twinkling of an eye."

What this business of extremely high forces applied in fractions of a second actually does to the stuff being formed is still being kicked around. When metals are subjected to displacement rates of one hundred to four hundred feet-per-second, or about one hundred times the velocities attained with conventional drawing and forming, you'd think "something's got to give." But it has been known for some time that metals can withstand *momentary* stresses and elongations which would cause failure by ordinary methods. Just why they should behave differently under ultra-high, rapid stress loading than under the gradual stress application of conventional forming is still a good question. It is a fact, however, that HEF somehow enhances the metallurgical properties; hardness is increased, grain flow patterns are formed such as to improve the part structurally, and the metal's entire component crystalline structure is more uniformly distributed.

That these new techniques are economical there is little doubt. For one thing, scrap loss is negligible, and in most cases, annealing between forging operations is eliminated. Die costs vary. Materials include steels, Kirksite and concrete-epoxy formulations. Some applications have had troubles keeping the awesome forces involved from breaking heavy metal dies; others require only light, plastic dies. Still others use no die at all! Add to all this the low cost of capital

Lower away! Workpiece, charge and die are lowered into the tank.



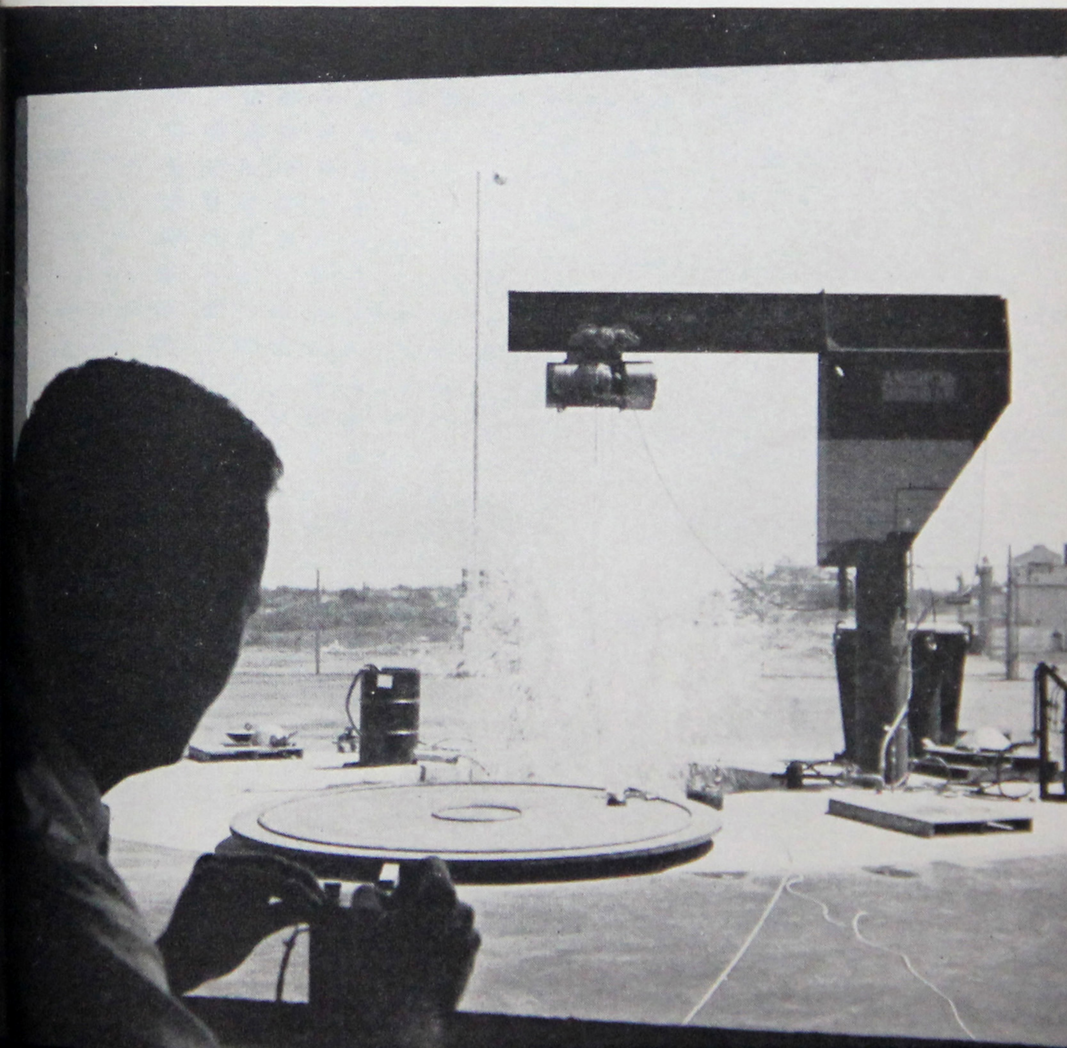
equipment—those shiny new machines are simpler than they look—and you have a convincing argument.

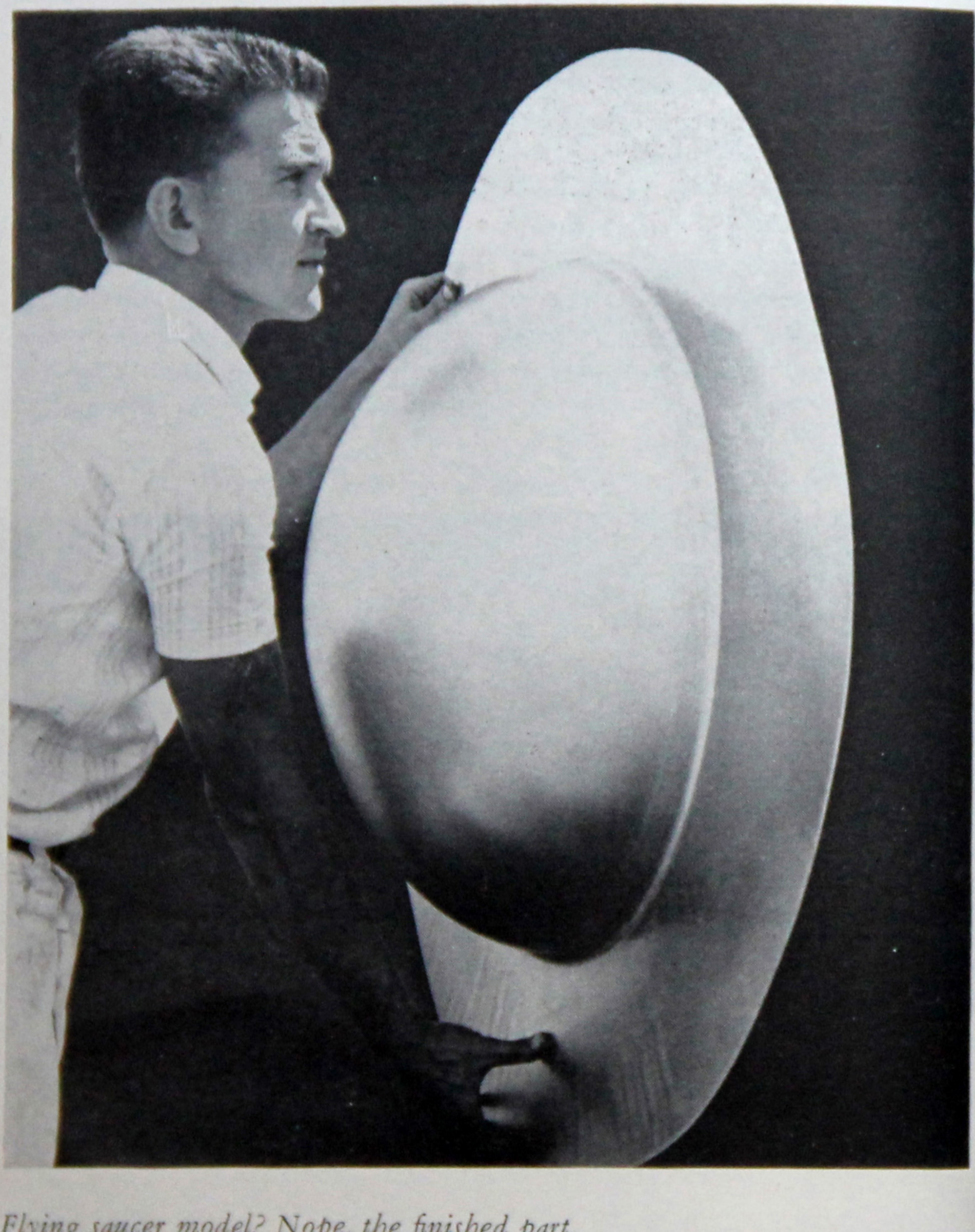
If HEF is so all-fired good, and the basic principle so simple, why haven't we had it sooner? Well, as opined at the start of this article, we *could* have. Sources of high energy have been available, of course, for all sorts of purposes, just waiting to be tapped; and we've tapped 'em, from water-power to atomic power—but not for forming.

Let's see, though; the Chinese had rockets—solid-fuel-type, of course—as far back as 1230 AD. No slouches as Great Wall builders, they also had quite an arsenal of mean-looking metal weapons; pikes, swords, knives, et cetera.

Wonder what would have happened if some arm-weary but inventive Chinese weapon-maker had decided to have a go at explosive forming. . . . Of course, even if he had succeeded in achieving the proper

The charge is exploded.





Flying saucer model? Nope, the finished part.
(Acually a test run forming of a helium bottle shroud.
The perfected part has a considerably deeper draw.)

BOOM!—and another part is explosively formed.
In the foreground are some of the shapes being fabricated by
the Ryan Aeonautical Company's facility at San Diego.
In the background are some of the dies used.

chemical mixture, he might have blown himself up in the attempt. But he also might have survived to produce a better battle-ax.

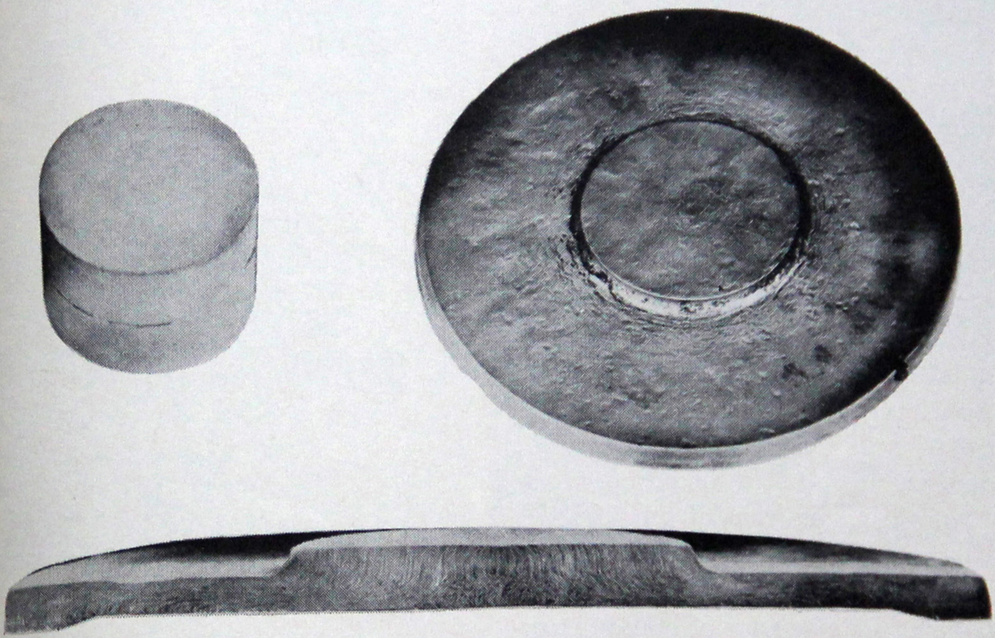
Descriptions of land mines appear in early military writings as far back as 1403, and were apparently ready for use in the Siege of Pisa in that year, but somehow never got in the act. With the advent of gunpowder, people were generally too busy shooting at each other to pay much attention to such details as detonation velocities, pressure-time relationships, expansion patterns, et cetera. Still, much was learned about the geometry of explosive charges.

The Russians are reported to have used underwater explosive forming during World War I to repair damaged ship's plates, and sooner or later they'll undoubtedly try to claim it as another first. It appears though, that they will have to bow to one Charles Edward Monroe of this country, who, in 1888 used explosive charges to simulate embossing and engraving effects in the decoration of metal plates and gun barrels. Monroe's experiments in explosive forming have netted him some small claim to immortality. Early references to the subject called it the Monroe, or Shaped-Charge Effect. It remained for a Walter Claude Johnson, an Englishman, however, to receive the first explosive metal forming patent in 1897. These gentlemen seemed to have fired the imagination of other experimenters at about the turn of the century. A vast library of material regarding various HEF processes has accumulated since then, but it has generally

Dynapak machine with power package.

PART NO. 640961—DIAPHRAGM
Material—Halcomb 218
Billet Size—1.400 Dia. x .959 Lg.
Billet Coating—Copper Plate—Flasi
Die Material—Halcomb 218—44 Rc
Punch Material—Halcomb 218—44 Rc
Die Coating—Colloidal Graphite in H2O

Forging Temp.—Soak at 1650°F. for 30 Min. Heat to 2000°F. Hold 15 Min.
Dynapak Forged:
1 Blow at 600 PSI Fire Pressure
7" Total Stroke
Time From Furnace to Impact—9 Sec.

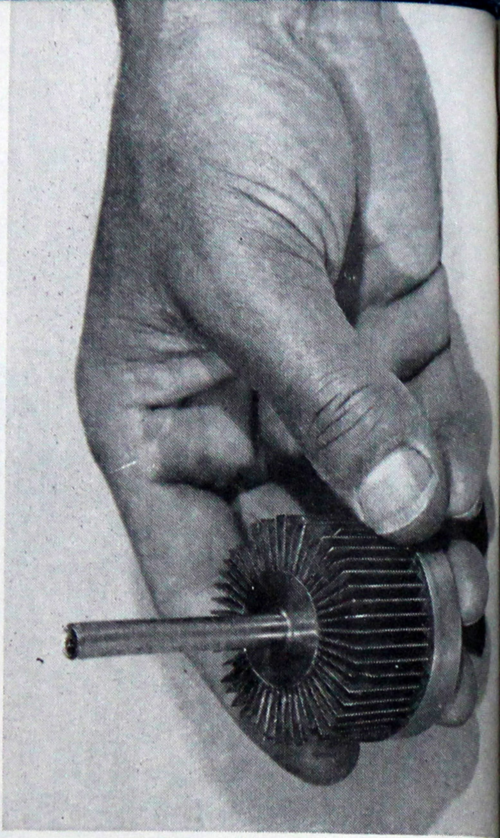


Dynapak-formed. Note direction of grain flow.

failed to attract much attention to the subject until recent years. Some operations such as piercing, dimpling, riveting and flaring were performed, but on a limited basis. What's happened is that Space Age demands for parts with difficult-to-form shapes of tougher, lighter materials, have spurred various government-sponsored HEF research projects. These studies have touched off an industry-wide chain reaction, and the scramble to tool up for HEF has begun.

How do you get started in HEF? Well, for explosive sheet metal forming, first you dig a hole in the ground and line it with reinforced concrete. Then you place a female half-die of the desired shape into the hole, place the metal to be formed over the die and fill the hole with water. Finally you hang an explosive charge over the whole setup, detonate it, and BOOM!—you're in business!

It's not quite that simple, of course, but darned near—if you know what you're doing. The configuration of the shot must be carefully calculated from certain precise parameters derived from an accumulated mass of know-how; literally the blood, sweat and tears of dedicated HEF researchers. And this is why they warn that explosive forming is definitely NOT a backyard, do-it-yourself project. It's a job for experts. (Unless there be those who care to run the risks of our hypothetical Chinese weapon-maker.)



Some important considerations are: (1) the metallurgical properties of the metal to be formed; (2) the pressure required to form—based upon the type, amount and propagation rate of the explosive; (3) the distance of the explosive from the workpiece; and (4) the nature of the propagating or transfer medium.

Regarding the latter consideration. water is generally preferred to air because of its efficiency of energy transfer, its reduced compressibility and its impedance-matching characteristics. Underwater detonation minimizes both air and ground shock and eliminates the possibility of flying particles. Other materials used as a transfer medium include oil, rubber, plastics, talcum powder and clay, with effectiveness evaluated in roughly that order.

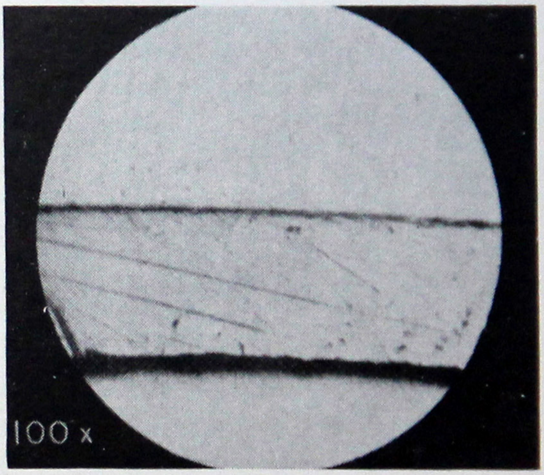
The explosives used may be either the low—deflagrating—or the high—detonating—types. The low explosives are usually black or smokeless powders which don't actually explode, but burn rather rapidly at the rate of several hundred feet per second. Expansion of the gases evolved produces a wave front which passes through the transfer medium, forcing the metal into the contour of the die. These explosives are generally used in smaller, closed-chamber, closed-die systems.

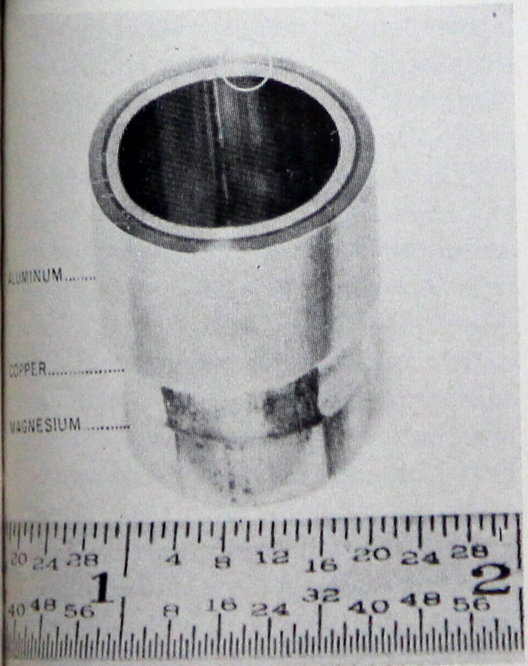
The high explosives used bear such familiar designations as Dynamite, TNT and Nitroglycerine. Others not so familiar still pack formidable but varying wallops: RDX, PETN, TETRYL, et cetera. They all detonate in millionths of a second, liberate energy at a constant rate regardless of the degree of confinement, and can produce shock waves in the order of millions of pounds per square inch. High explosive, open-die, underwater systems usually provide for the evacuation of air from the space between the workpiece and the die in order to prevent wrinkling or burning of the surface next to the die due to the heating of entrapped air.

Left:
Vacuum tube anode formed in one blow first attempt, Dynapak.

Below:
Joining of dissimilar metals with Hi-Vo-Pac.

Right:
Micrograph of dissimilar metal junction.





Also, the die should be as smooth and clean as possible. Specks of dust or dirt—even fingerprints—are faithfully reproduced on the formed part!

Although the detonation rates of the high explosives are much higher than those of the low explosives, they don't necessarily produce more total power. The high explosives are usually fired as bare charges in open systems where they provide a high intensity pulse of relatively short duration. The low explosives are normally used in enclosed systems where the effect of containment allows their lower pressures to be sustained for longer periods of time. The size of the charge is carefully tailored to develop maximum energy at the workpiece. Winchester-Western has developed closed systems using blank cartridges for the safe and convenient forming of smaller parts.

Another important factor is the shaping and placement of the charge, which has developed from a fine art into a science. For instance, a charge of Primacord hung in a circle over the workpiece has been found effective at General Dynamics/Astronautics, San Diego, for forming certain parts. (See illustration.)

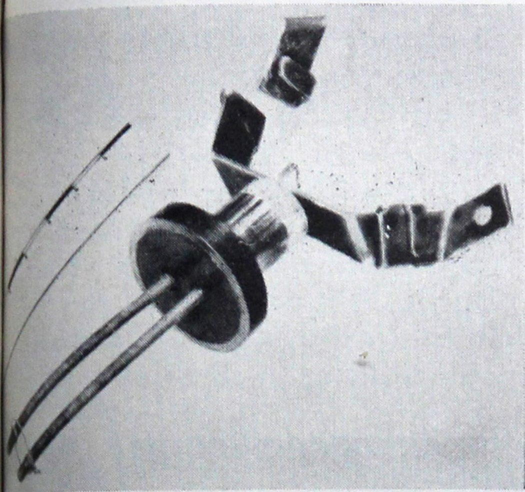
Die holder, machine in background.

Another forming technique in use at Astronautics is called "decoction forming." The sheet metal workpiece is made air-tight over the top of the die. Air between the die and the workpiece is then evacuated, pulling the metal inward to be shaped by the die. Decoction forming is not exactly a high energy process, as the time required to form is considerably longer. However, a combination of decoction and explosive forming has been found effective. The metal is partially sucked inward, then completely formed by an explosive charge.

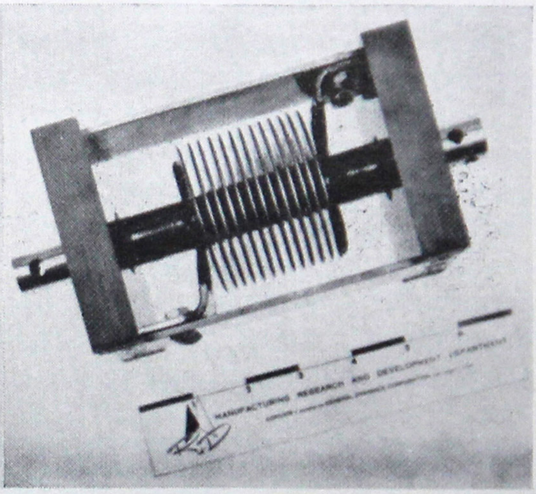
One of explosive forming's better selling points is that increasingly larger parts are being successfully made. At the General Dynamics/Astronautics installation, the original twelve foot tank will soon be dwarfed by a new one twice as big. Explosive forming also lends itself particularly well to the formation of spheres, hemispheres, domes and bulged shapes. (A technician has remarked: "My wife must have been explosively formed!")

The Aerojet-General Corporation of Azusa, California, is producing some beautiful seamless fifty-four inch missile pressure-vessel domes. Also, this is the outfit with (1) a camera capable of making 2,400,000 exposure a second; (2) some X-ray machines which deliver consecutive bursts of one ten-millionth of a second; and (3) a raster oscilloscope capable of measuring to within 20 milli-microseconds, which is 20 billionths of a second! Formidable research tools indeed, for a clearer glimpse into the temporal mysteries of shock wave development within an explosive charge.

Certain sheet metal parts may be explosively formed without dies, es-



Hi-Vo-Pac spark gap, initiating wire.



Magnepak flux concentrator coil.

pecially if close tolerances are not a prime concern. The shape of the charge is important, and the explosion must be "aimed" to approximate the desired configuration. A midwestern manufacturer is reportedly producing some very satisfactory jet shroud liners by this method.

The Rohr Aircraft Corporation of Chula Vista, California, has explosively-formed thousands of sound suppressor tubes for the Boeing 707 Jetliner, and the original tools are still being used.

More explosively-formed articles now in use: skirts for the Polaris missile made from AM355 stainless steel welded cylinders . . . ball-sockets of L605 cobalt-base super-alloy for a Grumman Navy carrier plane . . . tailpipes for the Air Force's Q2C drone, from 347 CRES corrosion-resistant, non-magnetic, chrome-nickel steel. . . . Douglas DC-8 Jetliner de-icer cones from 6061-T6 corrosion-resistant aluminum alloy (formerly drop-hammer formed in five pieces, now explosively-formed in one piece) . . . Army helmets of titanium, formed in a transfer medium of alluvial sand . . . the bulkhead for the Titan missile . . . gore shims for the Saturn vehicle . . . and the bell-shaped LOX sump for Centaur, by General Dynamics/Astronautics.

Explosive forming has unquestionably made a definite impression upon the contemporary industrial scene. True, there's more to that lovely part than meets the eye. But it's also likely that it will be formed to finished size, to within a tolerance of ± 0.005 inches—or better, if desired—and with no annoying tendency to springback, as with conventional methods.

Another interesting version of HEF is the high energy impact method. Probably the most notable source of high impact energy presently available is the General Dynamics "Dynapak" machine. Unlike the various explosive forming methods, the Dynapak process employs no explosives, deriving its power solely from highly compressed gas. Also, whereas explosive forming generally produces large sheet metal parts using large open dies, Dynapak is used primarily to forge smaller, more complicated parts in closed die systems. The metal to be formed is forced into a state of plastic flow within the die by the sudden application of pressures in the order of 80,000 to 100,000 pounds per square inch. The die and workpiece may or not be heated, depending upon the degree of metal flow desired. Such high pressures within the die direct the grain flow pattern of the metal so that the grain size is refined, and the part is improved structurally. The metal is also prevented from folding back upon itself, which eliminates the possibility of voids and cracks. The closed-die setups permit the use of a variety of metal-shaping processes such as forging, upsetting, gathering and extruding.

Originally called the "HYGE (pronounced 'High-G') Dynactor," this apparatus has undergone considerable redesign. Whereas the original version employed a horizontal configuration, the improved Dynapak stands vertically, and looks somewhat like a modernized version of three post punch press. Two twelve-inch cylinders are mounted in line at the top of the machine. The upper cylinder contains compressed nitrogen at a pressure of 2,000 pounds per square inch, and a triggering valve. The lower cylinder contains the business end, a one-ton piston-ram.

When the triggering valve is opened, the escaping gas sends the

Cross section of cable, ordinary swaging.

Cross section of cable, Magnepak swaging.

piston-ram hurtling downward like a hammer of Thor, at a velocity of several hundred feet a second—but with a complete stroke of only a few inches. WHAM!—it strikes a punch in a closed die, forming the part in 3 to 5 thousandths of a second.

In the case of conventional presses or drop hammers, the forces and loads are reacted by stiff structures rigidly attached to the floor. Dynapak, however, utilizes the principle of energy absorption rather than static reaction. The very high energy output is absorbed by a reaction system with a dynamic inertia mass consisting of a die holder called a "bolster" which hangs suspended by three pneumatic shock absorbers. Thus most of the machine "floats" with respect to the floor.

Dynapak is proving attractive from an economy standpoint. Die techniques used with the process are currently eliminating up to eighty per cent of the metal used in processing ordinary forgings. Chip and scrap waste is practically nil, as is subsequent trimming and machining of the finished part. Current overall production rates are about equal to those of a conventional forging press and are being improved.

Die breakage was somewhat of a problem in the early development of the machine, due mainly to a lack of data regarding its tremendous power potential. The new model sports a simpler but more precise adjustment for such factors as pressure and length of stroke, which provides the operator better control. Also—borrowing a leaf from the explosive forming book—they're now using a new water die which further dampens the shock and seems to have completely cured the breakage problem.

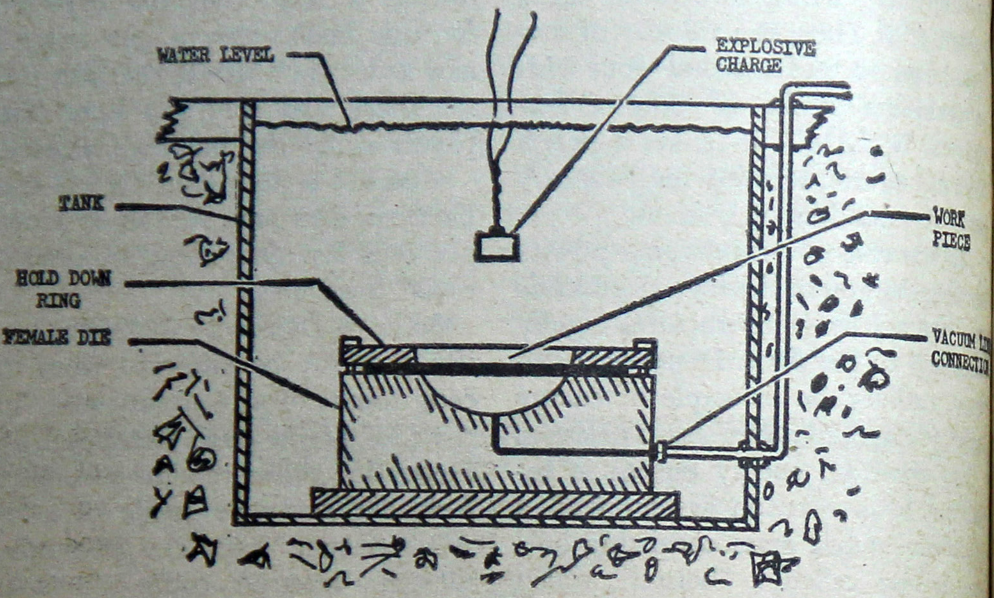
And it's a fact that the costs of Dynapak dies now run about ninety per cent less than those of conventional form dies.

Some of Dynapak's intriguing possibilities may be glimpsed from the early results of a feasibility study for the Eitel-McCullough Company. The illustration shows the first attempt to form the complete anode of a big power vacuum tube. The specs called for an "electron collector" to be formed in one blow from a round billet of oxygen-free copper. The vanes or fins were to have a tolerance of 20 thousandths at the hub, and 10 thousandths at the ends. Previous production of the part involved over twenty operations. Photos are not yet available of the perfected part, but it is reported that the results of the study are "very encouraging." Reportedly, the new tube with the Dynapak-formed anode refuses to become "gassy."

Sylvania's Dynapak machine is reportedly extruding some tubes from powdered tungsten, with a density approaching one hundred per cent. Subsequent sintering—heating—operations are eliminated.

Western Electric reports the compaction of 200-mesh Alnico 5 powder with a density of ninety-six per cent, in the production of large permanent magnets.

General Dynamics/Pomona's com-



Underwater Sheet Metal Explosive Forming Setup.

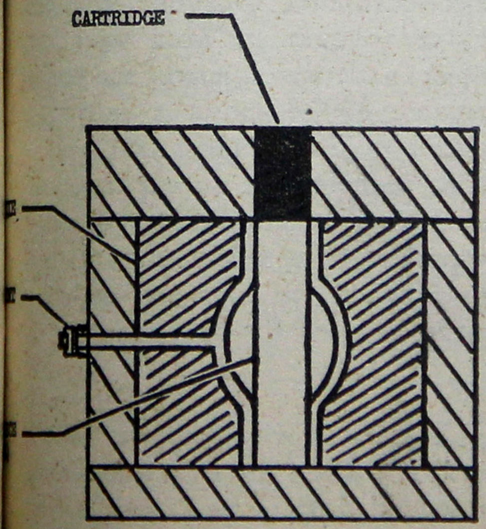
paction of 200-mesh powdered potassium bromide has yielded an infrared lens of excellent optical quality in a pilot run for the Corning Glass Company.

One of Dynapak's merits, to some users, is the fact that you don't have to work outdoors in some back corner of the property, as with explosive forming. But there are other ways to bring HEF indoors. These involve the use of high voltage electricity as the energy source.

That the shock wave associated with electric capacitor discharge might be a usable source of high energy was apparently first recognized by the French team of Michele-Levy and Maraour in 1934. They proceeded to describe the heating to incandescence of a copper cylinder and a carbon thread when struck by shockwaves from a spark source. They may have got the basic idea from the German, Svedborg who produced metal suspensions by means of condenser discharge in a liquid, in 1905. From the thirties on, various researchers, mostly in this country and in the Soviet Union began to probe the mysteries of the high intensity electric spark. (And let's not forget Dr. Frankenstein of Transylvania, with his kites!)

It was found that when an electrically charged condenser with a potential difference of several kilovolts is suddenly discharged across a spark gap, a pressure pulse—actually a sound wave—propagates out from the spark radially, with great speed and force, as a high energy shock wave. Early attempts to convert this acoustical energy to a mechanical equivalent were pretty feeble, however, in the order of about one per cent efficiency. Früngel and Keller of Germany later raised this to fifty per cent by bursting a container of water with an underwater spark in 1957. They also presented an interesting comparison of spark discharge energy versus that of explosives. They calculated that the energy discharge of a 0.02 mf condenser at 20 kv could be made roughly equal to that of 1 mg of an explosive such as cast TNT.

One of their contemporaries, a W. Schaafs, studied the spark discharges in bromobenzine and trichloroethylene by means of high-speed radiographs. He determined the velocities of the shock waves which were evolved, and suggested that dynamic pressures of up to a million pounds per square inch were possible. Also, at about the same period, some Soviet researchers were busy recording shock wave velocities and pressures at the wave front in both air and liquids. Thermal action was also observed.



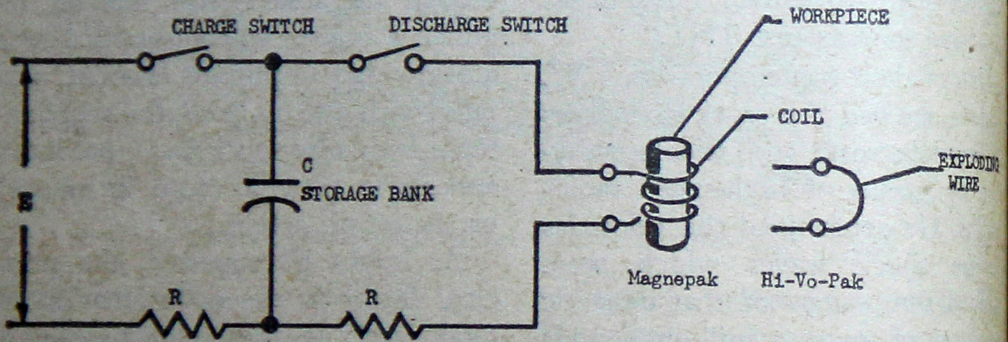
Die Cartridge Explosive Forming.

The upshot of all this research was to more clearly define the energy parameters involved in both the "electrospark" (air) and the "electrohydraulic" or "hydrospark" (underwater) methods. Much knowledge was gained regarding the respective physical processes and the most efficient circuitry required for each. Although the underwater method requires a higher voltage applied as a quick, high-amplitude current impulse with a steep front, the short, intense hydraulic shock wave produced appears to provide more "brissance" or shattering action.

As might be expected, the principal factor in the determination of total work is the voltage applied, with energy increasing as the square of the voltage. Since we're dealing with electricity, the energy output of a system is readily calculable. For example: one watt-second equals one joule equals 0.74 foot-pounds. Therefore, in a 5400 watt-second machine, the maximum output would be: 5400/0.000040 (seconds) equals 135,000,000 joules equals 99,000,000 foot-pounds.

The focusing of energy is different in water than in air. In air, the mechanical action on the workpiece is in a direct line from the electrode; in water, the force is perpendicular to the line of action of the spark. Placement of dies and metals to be worked in relation to the spark is also important. Zones of action were discovered surrounding the spark. In the "zone of rupture" nearest the spark discharge area, nearly all materials are subdivided into small particles. A little farther out, cold-working occurs; metals placed here can be work-hardened. In the next zone out, elastic action takes place. Still further out is the zone of compression; here the pressure drops off sharply with distance.

the gap. The system was pioneered by the General Dynamics/Fort Worth division and is the brain child of R. H. Wesley and D. W. Cole. Research papers on electric wire explosions, notably those of the Physics Department of the College of Engineering at New York University and E. David of Germany provided source material and inspiration. Actually, the principle involved is sort of a combination of explosive and electrohydraulic forming. Somewhat lower voltages are used than with other underwater spark methods—around 4,000—but at a current of over a million amperes. All work is done indoors, and no explosives are used. A wire across the spark gap is vaporized by a sudden current surge to produce the high energy shock wave required for forming.



Electric Forming Generalized Circuit Diagram.

Quite a few outfits are now doing good work with spark-gap forming, including the Republic Aviation Corporation of Farmingdale, New York. The heart of their "spark bomb" rig is a bank of condensers in parallel which are charged to 30,000 volts and then discharged across a 1¼ inch gap in 40 millionths of a second. The machine will operate from any 110, 220 or 440 volt shop supply and has been used to produce a variety of parts, including some bulged shapes from tubes.

The General Dynamics "Hi-Vo-Pac" machine features an interesting variation in high energy electric forming—an exploding wire across

Let's watch what happens in slow motion: When the switch is thrown, a sudden flow of very high current heats the wire to a temperature of

10,000 degrees Fahrenheit almost instantly. Inertial forces, assisted by magnetic fields, are able to contain the wire material in a solid state temporarily. But within 10 millimicroseconds enough energy has been placed in the wire to transform it into a highly plastic state. By now the current has risen to a peak value and is starting to fall off at a rate about twice as fast as its rise. During this period, however, large amounts of energy are still being placed in the wire, as the voltage is still continuous and at a high enough level to furnish sizable power inputs.

By 12 millimicroseconds, increased magnetic pressures, caused by the high current flow have raised the temperature to a point where the wire starts to vaporize; from a minimum at its surface, to a peak along its axis. Initially, the wire's surface began to vaporize off into the surrounding medium—water—at a pressure of about one atmosphere. But things are happening pretty fast, now; the next vapor layer hasn't moved much before the next underlying layer is vaporized. Huge pressures are building up, causing progressively higher vaporization temperatures—possibly in the order of millions of degrees! Increasing pressures of several hundred thousand atmospheres continue to hold the hot atoms—actually ions—in the lower layers close enough together to conduct for several millimicroseconds while the material is still in the vapor state.

But by 17 millimicroseconds enough energy has been developed to completely vaporize the wire. When this happens, explosive expansion begins, and the wire is transformed into a nonconducting gas, interrupting the current. The expanding metallic vapor radiates out as a powerful shock wave, pushing cooler vapor and water layers before it. A somewhat complicated rarefaction effect is also known to occur along with everything else that's happening, but its interest and importance is probably largely academic. Suffice it to say that great amounts of energy are applied to the workpiece.

In early work with Hi-Vo-Pac, wires of various materials were tried. But oddly, it has been established that the type of metal used in the initiating wire plays no significant part in the plasma phenomena of the spark channel. Aluminum wire and ribbon are being used quite successfully; one advantage being that wire and foil of such material may be easily shaped to a desired configuration, resulting in a shock front of specific shape. This technique has proven effective for concentrating the energies required for certain blanking or forming operations.

During these experiments, attempts were made to establish a swaging procedure using a two-inch diameter circle of 0.033 stainless steel wire. A one-inch tube of T-6 aluminum—with both ends taped to keep out water—was placed in the center of the circle described by the initiating wire. The tube was crushed impressively. The same principle was used to swage a knurled rod end in a T-3 aluminum tube and collars on electrical cable.

A more ambitious swaging experiment was performed using tubes of magnesium, copper and aluminum which slip-fit within each other. The same setup was used as in the previous examples, except that water was allowed to pass through the center tube to avoid crushing. After firing, it was obvious that the water did act as a mandrel and that the tubes had held their shape. Photomicrographs with up to two hundred times magnification fail to disclose any voids at the interface of the three layers of material. The perfect joining of such dissimilar metals should hold much promise for the field of welding and metal joining.

Another application of the high voltage forming principle—actually a variation of Hi-Vo-Pac—is seen in the General Dynamics "Magnepak" system. Differing from Hi-Vo-Pac only in the application of output energy, Magnepak is currently being used mostly for swaging operations.

Electromagnetic gadgets are pretty familiar stuff by now; motors, generators, transformers, et cetera. But not until recently has anybody been able to harness the principle for the purpose of forming metals. As an outgrowth of controlled fusion research by the General Atomics division of General Dynamics at San Diego, a "pinch effect" demonstration unit was assembled into an exhibit for the Atoms for Peace conference in Geneva. In 1958, General Dynamics/Convair of San Diego was assigned the task of developing production applications for use of the principle.

In the Magnepak setup, a work coil is substituted for the exploding wire used in Hi-Vo-Pac. Conductive metal parts are introduced into the coil in such a manner that they are flux-linked with it, acting to all intents and purposes as short-circuited secondary single-turn coils. This means that the primary work coil will carry maximum current, due to the "shorted" secondary. Consequently, when high electrical energy is applied to the work coil, a net resulting magnetizing force is applied to the workpiece. When this energy exceeds the material elastic limit of the workpiece, permanent deformation occurs. In other words, the stuff is "scrunched"!

Since the work coil, as well as the part, is subject to intense stress, considerable design effort has been put forth in the development of a reliable permanent-type coil. The "flux concentrators" designed by Dr. Kolm and his associates at M.I.T. were an inspiration in the development of a completely machined helix-type coil. The turns are insulated with epoxy and fiberglass and are baked dry; then the entire assembly is prestressed under compression with heavy end plates drawn together with steel bolts.

Another school of thought reasoned, "If the work coil wants to blow up, why not let it?" This led to the use of expendable-type coils for certain swaging applications. These consist of a few turns of cheap, plastic-insulated copper wire, wound on mandrels to the same size as the outside dimension of the part. Connection is made to the electrodes of the machine and the parts to be joined are inserted inside the turns.

The switch is thrown: Dunder und Blitzen!—the parts are beautifully joined. Needless to say a guard is necessary for protection against flying pieces of copper debris.

End fittings for the control rods in the control linkage system of the Convair 880 Jetliner are joined by Magnepak swaging. Tensile, fatigue, vibration and torque tests-to-destruction have broken the rods themselves, but never the joints.

At this stage of the game, industry and the designer are viewing HEF with cautious optimism. Production of a wide variety of articles is increasing steadily, and the proof-of-pudding results are impressive. The enthusiastic proponents of HEF feel at the very least, that any industrial process in the good old American tradition, namely Cheaper, Faster and Better, is bound to be accepted. They make it a point to tell you, however—perhaps diplomatically—that if the job can be performed satisfactorily by conventional methods, to stick with 'em. But they always hasten to add that if those methods leave something to be desired, why not take a look at HEF?

The advent of high energy forming may alter our basic concepts regarding the Ways of Making Things generally. What it amounts to is that the future potentialities of HEF, and its applications, are limited only by the imagination and ingenuity of the designer.

Automobile bodies are a "natural" for explosive forming, and already they're talking in terms of mass-produced, hemispherically-shaped houses. On a larger scale, carefully-tailored, "clean" atomic explosions might be used to shape enclosures for anything from Kublai Khan's "pleasure dome" to those domed cities under the sea, on the moon and on other planets.

(Note: The Analog Editorial for August suggested a super advertising "engraving" on the surface of the moon which would be visible from Earth, by means of a Monroe-effect explosion.)

The General Dynamics/Fort Worth division being in Texas, it is entirely appropriate that HEF engineers there "think big" about explosive forming.

"We'd like to use the Gulf of Mexico for a forming die!" says one.

Not to depreciate Texas, if such were possible, but another, considerably larger high energy forming job has already been done—the Solar System.

For that matter, how about the Universe itself? One school of thought holds that all the elements were formed in the first thirty minutes. What a beautiful job of dieless forming!

Or what if the Master Designer *did* use a die—maybe psi? ■