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Joining Electronic Materials

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Most of the methods used for joining materials have been adapted for use by the electronic industry. Special techniques were required for the miniature world of microelectronics. Discussed in this paper are the processes most commonly used for soldering, brazing, and welding electronic components. Also included is a discussion of the attributes and limitations of soldering, brazing, and laser, electron-beam, and ultrasonic welding. Briefly discussed are some of the specialized techniques which have limited, but important, applications. Also discussed are several applications of some of these joining techniques, as they have been used on large electronic components at the Stanford Linear Accelerator Center.

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The subject of joining of the materials used for electronics is so vast only a few selected techniques can be discussed. In presenting some of the tried-and-true, unique, and modern joining techniques, it should be evident that the electronics industry is meeting the challenges presented by itself.

Considered in this paper are the new applications of an old technique, soldering, some aspects of brazing, and some of the "modern" welding techniques which sometimes hold "more promise than practice." A short discussion, plus references, are then given for the more highly-specialized techniques only now under development or having limited application. Finally discussed are several comparison criteria which may be considered when selecting a particular joining technique.

Soldering

Billions of soldered joints are made each year in the electronic industry. In the face of the onslaught of modern electronic devices and exotic joining techniques, soldering has stood its ground in most areas of electronic joining techniques. The reasons why soldering maintains this strong position are low cost, established technology, high production rates, and high reliability for most applications.

Long thought to bond materials by molecular attraction, soldering actually bonds materials by producing a very thin but important surface layer of intermetallic compound.(1) (2) The formation of this compound takes place at temperatures above the melting point of the solder, but below the melting point of the substrate (and even below the melting points of the bond components) by means of solid-state diffusion of tin into the substrate. This compound formation points out the important role of tin in solders. Although pure lead can be made to wet some metal surfaces, bond strengths are weak. A minimum tin content of about 3% tin is necessary to promote the formation of a substrate compound,(3) (4) but commercially 15 to 20% tin solders exhibit more reliable solders with a marked improvement in wetting and overall bond strength. Because tin is the expensive component in the Pb-Sn solders (tin costs almost 10 times more than lead), special fluxes and pre-tinning with higher tin content solders assist in reducing the tin content, and cost, of the bulk solder alloy. Small quantities of antimony, at one-third of the cost of tin, are many times substituted for tin. Antimony additions above 5 to 7 percent reduce joint ductility, tensile strength, and shock resistance of a soldered joint. The lead-tin base solders constitute the majority of those used in the electronic industry, especially those near the eutectic composition of 63 Sn, 37 Pb. These solders have the highest "fluidity" and melt at the lowest temperatures. It should be noted that the full range of lead-tin compositions is not used for electronic soldering because of high cost and undesirable mechanical properties. Also useful are some of the high-tin/antimony solders which have found use for "high" temperature applications.(5) (6)

The hand-soldering techniques first employed for joining electrical components was closely followed by dip soldering of printed circuit boards which were completely immersed in the solder bath.(7) With the advent of semiconductors and micro-electronic components, soldering requirements included protection of the components(8) which could change electronic characteristics if subjected to the heat of dip soldering. Therefore, high production rate soldering was developed which minimized the relatively long time at high temperatures found in dip soldering. One form of this type of soldering employs a longitudinal wave(9) of molten solder which touches only the "joint side" of printed circuitry in a semi-automatic process. Figure 1 illustrates how wave soldering is performed.

Figure 2 shows the important steps of the wave soldering process which include loading, fluxing, preheating, defluxing, cleaning and unloading. This process is most useful for printed circuitry where all leads are on one side of the board. Cord-wood circuitry does not readily lend itself to this type of soldering.

Soldering almost always requires a flux which performs a two-fold function. First, fluxes chemically interact with surface films (oxides, dirt) to effectively remove them from the surface of the part so they won't interfere with wetting by the solder. Second, fluxes are designed to protect the part surface from oxidizing during heating. Chemical fluxes can be replaced by ultrasonic soldering[10] which provides similar surface reactions through a different energy mode. By nature, fluxes are corrosive (especially those fluxes used for high-production rates) and their removal is important so that subsequent corrosion products won't form. Moisture in the service environment can initiate corrosion in areas where entrapped fluxes are retained. Accelerated corrosion can then proceed when stray electrical currents enhance localized galvanic cells. Microminiaturization creates additional flux-cleaning problems because of the surface tension of the solvent, carry-over of highly soluble flux residues in rinse waters, and compact geometries which may appear good from a design standpoint but, which fails to consider removal of entrapped fluxes. [11, 12, 13, 14]

Components which may be damaged[15] by the relatively long times (3 to 5 seconds) at near-soldering temperatures (500° F) can sometimes be protected by heat sinks. Low-temperature solders for temperature-sensitive components can also be used, especially during the last joining steps.

Brazing

Brazed metallic joints fall between the categories of soldering and welding in that brazing is performed in a manner similar to soldering (furnace brazing, dip brazing, torch brazing, etc.) but provides joint strengths nearer to those acheived by welding. To determine, therefore, whether brazing should be used, some considerations come forth.

1. Why not weld? The heat supplied by brazing usually cannot be localized as can weld heat — what effect will this have on dimensional control and distortion of the final product? If component leads are sufficiently exposed to facilitate torch brazing, they can usually be welded.

2. Why not solder? Soldering can join almost all dissimilar metals that can be brazed, but the strength of soldered joints can limit the service environment if high temperatures, moderately high stresses, etc., are required.

In the electronic industry, brazing is best applied to components requiring dimensional stability (high-joint strength) where welding is difficult, and/or where no other joining process will work (metal/ceramic, metal/glass, and ceramic/ceramic bonds), or where electrical characteristics demand certain filler materials.

With the development of electronics came the necessity for joining ceramics, as well as glasses, to various metal structures.[16] Ceramic materials are used as seals and joints in electrical feed throughs, stand-off insulators, vacuum seals, printed circuitry bases, etc. Bonded to the ceramics were metallic heat dissipators and electrical leads and metallized circuitry using ceramic wafers as support materials. A number of methods[17] [18] have been developed for joining these two types of seemingly incompatible materials — brazing, and sometimes soldering, is the joining step used to produce an integral, strong, gas-tight assembly. The literature is filled with descriptions of techniques used for joining ceramics and metals. In most ceramic/metal seals, the important considerations are to keep the brittle, low-tensile strength ceramic in compression (especially at service temperatures) and the metal in tension, the most desirable of possible conditions.

Some examples where brazing was the only possible fabrication technique occured during the manufacture of circular wave guides for the SLAC two-mile accelerator. Approximately 150 components, some of which are shown in Fig. 3, were furnace brazed (Fig. 4) to form a 10-foot long circular waveguide to within ±15 mils of the design length. Figure 5 shows a finished waveguide and Table 1 lists the sequence of step-brazing operations performed. These waveguides are tuned and then assembled onto a support and alignment girder (Fig. 6). 240 of these girders form the two-mile accelerator. (Fig. 7)

The manufacture of klystrons, or high-power microwave amplifiers, is another area where brazing is required. Since klystrons operate at high power levels and require bonds between ceramics and metals, brazing is the only joining process that can be used. Figure 8 shows typical klystrons ready for service.

Welding

Welding of electronic components can be broken down into the major categories used for almost all welding processes, which are 1) resistance, 2) arc, and 3) gas welding. A fourth category which lumps new welding techniques can be called "special" welding since it plays a numerically small, but important, role in electronic joining.

Table 2 lists several processes used in welding electronic components. Again, space does not permit a full description and comparison of all of these welding processes, so only the few welding techniques having the greatest value, impact, or potential will be discussed.

Resistance Welding[19, 20, 21] Really a form of spot welding, several resistance welding techniques have been developed to accommodate various welding design problems, such as: wire to wire, dissimilar metals, wire to electroplate, "one-side" joining, etc. The principal behind this welding technique is the creation of sufficient I^2R heating, to produce fusion (a weld nugget) or a diffusion bond (no nugget — recrystallizated weld interface only) with significant bond strength.

There are several closely-related resistance welding techniques that create the heat necessary for bonding in slightly different ways. Spot welding, of course, is the classical welding process in which two electrodes provide the force and carry the current necessary for welding. Cross-wire welding is typical of this process.[19, 20, 22] Parallel-gap resistance welding evolved when fragile and brittle electronic component designs prevented having electrodes on both sides of a joint — especially lead-wire welds to a plated circuitry. Parallel-gap welding heads are shown in Fig. 9 (Ref. 14, 19, 21, 23). Thermo compression micro welding bonds materials by creating plastic deformation at moderate heat and temperatures. Percussive welding[21] [24] is a micro-adaptation of "stud welding" wherein the materials to be joined are heated by an electric arc from a charged capacitor. The arc is then quenched and the two materials driven together to cause fusion.

Sometimes the coatings,[22] typically silver, gold, tin or lead, used on lead wires interfere with welding. Reliable welds can be made if these coatings are thin enough or if weld parameters are adjusted to compensate for these coatings. Once a set of weld parameters is established, high automated and programmed welders are used to remove human operator errors.

Other Conventional Welding Techniques. Miniature gas,[25] plasma,[26] and arc[27] welding equipment has been developed to accommodate the reduced heat and/or current requirements for joining small wires to other wires and components that can't be handled by resistance welding. The latter technique is most suitable for joining lead wires between 10 and 40 mils in diameter but is usually not intended for joining wires below 5 mils. These other welding techniques usually employ hand operation for specialized joining or repair problems where other more conventional, miniature-joining techniques won't work. The advantages, sometimes moot, among TIG welding with small (down to 10-mil diameter) electrodes and low currents (8 amps and below), small gas torches and the plasma needle-arc process will not be discussed.

Special Welding Techniques. Laser beam welding, electron beam welding and ultrasonic welding are included in this category which is characterized by relatively expensive setups and which have some degree of inflexibility. Joints made by laser, electron beam, or ultrasonics can usually be produced by the more conventional techniques described above, but there are some inherent advantages of these "special" weld methods that make them unique.

Laser Weld energy is provided by an especially designed solid-state (usually ruby) system. (Other laser systems, employing materials such as gas, liquid, and semi-conductors, either have power levels too low to effect welds or are continuous-wave power emitters, which is undesirable.) The ruby laser (see Fig. 10) uses pulsed power, which is controlled to prevent vaporizing work piece. When one realizes that up to 10^9 watts can be released in a spot about 10^{-4} cm^2 in as little as 10^{-6} seconds, the control of laser energy becomes paramount in importance. These power densities can vaporize any material known. The controlling factors of laser welding are spot size, peak-power output, length of time of power, coherency, and monochromatism (focusing) which boils down to pulse duration and configuration.

Laser welding[28, 29, 30, 31, 32, 33] is a skin effect; welding depends upon the thermal diffusivity of the material being welded. The items to be controlled are the beam power, duration, and time between pulses so enough heat is generated in the workpiece to produce a weld without vaporizing the material. Sometimes surface vaporization can act as a self-cleaning operation.

Advantages of laser welding include small heat-affected zone, low heat input, excellent weld joint strength (up to 100%), and welding of a large number of metals in a variety of atmospheres (air, inert gas, vacuum). Also, the workpiece does not come in contact with the welding apparatus because the weld energy is conducted by a beam of light. The welding head can be located outside a transparent plastic or other transparent chamber containing the workpiece and special atmosphere to make repair welds (vacuum tubes) or when joining refractory metals.

Disadvantages of laser welding include expensive setup time, close tolerance positioning of the workpiece, and inability to "steer" the welding beam. Also, highly reflective metals will not absorb enough energy to weld and absorptive coatings are sometimes necessary. For instance, to vaporize gold requires over 600 times the energy needed to vaporize Nichrome. When coated with an absorber, only 30 times the energy is required.

Electron beam welding[14, 19, 34] is slowly being adapted for joining electronic components. EB welding has another degree of flexibility over laser welding in that the beam of electrons may be more easily steered. The limiting aspects of EB welding stem from the fact that the most efficient welding is carried out in a vacuum (10^{-5} torr) which prevents degradation of the beam. Although welding can be performed in a reduced vacuum or even air, the increased costs of higher-voltage electron guns and higher-capacity vacuum pump equipment produces a strain on the economic aspects of this technique. The short pump-down time (5 - 10 minutes) of the vacuum chamber is enhanced by large capacity chambers containing automatic X-Y positioners for accurately lining up the work-piece and beam. Again, however, the expense of such auxiliary equipment can be high.

Electron beam welding employs a stream of collimated, focused electrons that impinge onto the workpiece. Heating takes place when the kinetic energy of the beam is converted to thermal energy as the electrons are slowed down by the metal structure. The collimated electron bundle literally punches its way into the work piece, which melts along the interface. As the beam moves on, or is stopped, this molten material is rapidly chilled by the adjacent metal and produces a long, thin weld nugget with a very narrow heat-affected zone. See Fig. 11. Power input is easily controlled at the "gun end" of the welder.

Most of the advantages listed for the laser are pertinent to EB welding with the exception that EB welds usually take place in vacuum or near-vacuum conditions. Of course, vacuum is an excellent and pure "atmosphere" to prevent weld contamination. However, the vacuum requirement precludes welding of high vapor-pressure materials. EB welding is best applied in situations where filler-metal additions are not required. Although distortion is minimal, some does occur.

Disadvantages, besides the need for vacuum processing, include locating components relative to the beam and the high initial cost of electron-beam equipment. Costs, however, are not prohibitively high for most electronic welding work, which usually can be done with small-chamber, low-power equipment which is not expensive.

Work currently in progress at SLAC includes the characterization of several types of pure copper (OFHC, ETP) to assess cracking susceptability as a function of base-metal chemistry surface preparation, etc. One piece of EB-welded copper (Fig. 12) shows undesirable weld spatter and resulting weld cavitation due to gas formation in the weld. Only one instance of weld cracking has been observed on a thick section of ETP copper and none with OFHC.

Ultrasonic welding[12, 14, 35, 36, 37, 38] has been successfully used for encapsulation of transistor elements, lead attachment to transistors, and welding of transistor elements to support headers. The process provides many advantages which include ability to join an almost unlimited range of dissimilar metals, no weld area contamination, no need for ultra-clean room procedures, low ohmic resistance of joint, low electronic "noise" level, excellent weld strength, and no external heat required, therefore no grain growth or heat-affected zone or embrittlement.

Weld energy is provided by a combination of clamping force with vibratory stresses which produce extremely large pressures on micro-sized areas in the weld zone. These vibratory pressures disrupt surface oxides to force clean metal into intimate contact and produce diffusion-like welds. Since a measurable heat rise occurs only in the weld, ultrasonic welding is well suited for joining heat-sensitive electronic components.

Other Joining Processes

Highly specialized joining techniques are being developed continuously. Although of only specialized interest now, some of these processes may replace those currently in vogue as developments continue and/or new electronic components, devices, packaging techniques, and joining requirements are set forth. Some of these specialized processes and their references are given here.

Catalytic soldering[12] employs catalytic combustion to confine heat for localized bonding.

Liquid-metal joining[12] techniques amalgam-like mixtures with gallium. These mixtures have excellent wetability with materials which have been difficult to attach with current leads. Upon standing, these gallium mixtures harden and form extremely high melting point alloys with the parent material.

Resistance brazing and soldering, although an old, established process, has not had its usefulness fully exploited, probably because of the difficulty in setting up control variables with the various workpieces and braze or solder materials.

Conductive adhesives.[13] Some work is being performed on epoxy resins filled with conductive metal fillers. Good conductivity is achieved with 25% to 30% filler metal and the resin is still mobile enough to mix and apply. Typical filler metals are silver-flake, silver-coated copper, and gold. The silver-coated copper does not exhibit the same tendency as silver does to migrate under a dc potential. Problems still to be solved include the requirement for very clean surfaces needed to achieve good bonds and the slow curing rates at room temperature or slightly above.

Metallizing. New work by Adams at MIT promises some possible joining of heretofore difficult-to-join materials. This new technique provides a loosely adherent titanium film by metallizing (usually ceramic surfaces) in a vacuum. The loose layer of titanium promotes "tunneling" of liquid metal solder or braze alloys that would otherwise bead up (dewet) and provide holidays in the finished joint. Currently, this process is not operative below 1400/1500° F but the concept seems to hold promise for lower temperature applications in the future.

Others. Almost every process, except perhaps Thermit welding and explosive bonding, described in the handbooks on welding has been scaled down to accommodate the low-energy requirements for joining electronic components. They will not be reviewed here. Even die casting[39] has been used as a joining process.

Comparing Joining Processes and Problems

There are probably as many criteria for determining the joining process to be used as there are joining processes. Each process seems to have some unique attribute that, in its special instance, qualifies its use above others.

Joint failure must not become the failure mode of the electronic circuit, so you strive for a failure rate of 10^{-9} to insure good joint reliability. There seem to be few distinct advantages when comparing soldering and brazing. Welded joints tend to be less reliable than those which have been soldered or brazed. Here, inspection techniques play an important role with the percentage of joints inspected.

Service environment can affect the reliability of a joint. Aging that takes place at slightly elevated temperatures can weaken a soldered or brazed joint (through surface diffusion) whereas a welded joint may become stronger by annealing out weld stresses and through diffusion around the weld nugget heat-affected zone. Weld strength is usually 10 to 20 times that of a soldered joint, but rarely is this kind of joint strength required. A welded joint retains its strength above 700 - 1000° F, brazed joints above 500 - 700° F and solder loses strength rapidly above about 300° F, depending upon the filler metal used, of course.

Since welding joins the base materials, one can expect the best possible joint. Brazing and soldering both introduce fluxes, intermediate materials, and sometimes corrosive cleaning compounds for flux removal; corrosion problems can result. Usually, the corrosion problem is manifest sometime after installation and operation.

Heat-sensitive electronic components can be affected by the joining process. Brazing subjects most circuitry to temperatures of 550° F for 3 seconds when soldering is performed. Most of the time, brazing can locally confine heat input to the joint area — usually wire leads some distance from the semiconductor. Welding is no cure-all if heat is a problem during joining, although the majority of weld heat is usually contained in the leads. Stray electrical currents can short out components when proper grounding techniques are not applied during welding, however.

Because many weld-metal combinations between electronic component material (e.g., aluminum and gold, iron and copper, copper and aluminum) produce brittle joints, an intermediate connection material, usually nickel, is interposed to provide ductile, weldable joints. Adding such an intermediate material increases handling operations and decreases system reliability because of the increased number of joints required.

Operating conditions for the finished component should be considered. Circuits now operate at high pressures deep in the ocean, in the vacuum of outer space, in the cold of cryogenic fluids, in several kinds of corrosive environments, and under various kinds of mechanical stress, both static and vibrational. Time complicates these problems, complications which accelerated functional testing may not reveal. The migration of silver in silver-containing solders, when subjected to a dc potentional and humidity, is a problem of this type. Another is the growth of metal whiskers on positive electrodes at high over-voltage. These whiskers can grow long enough to cause short circuiting, etc.

If weight saving and compactness is required, welding, on the surface, appears best since heavy solders and braze alloys are eliminated. However, designs of complicated circuitry must consider line-of-sight accessibility of joints which may prove bulky compared to some solder/braze designs.

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Table 1. Step-Brazing Sequence For Circular Waveguide

Braze Sequence	Components	Braze Alloy	Braze Temperature°C
1	Microwave Input and Output Couplers	35Au/65Cu	1025
2	Coupler to Circular Waveguide Transition	50Au/50Cu	985
3	Coupler-to-Stack	72Ag/28Cu	800
4	Water Cooling Pipe to Waveguide	62Ag/24Cu/24In	720

Table 2. Several Processes Used in Welding Electronic Components

General Welding Process	Electronic Welding Adaptation
Gas	Miniature Gas Torch
Arc	TIG — small diameter electrode Spark - discharge
Resistance	Cross-wire welding Parallel Gap Thermocompression Spot welding Percussive
Special	Laser Electron Beam Ultrasonic

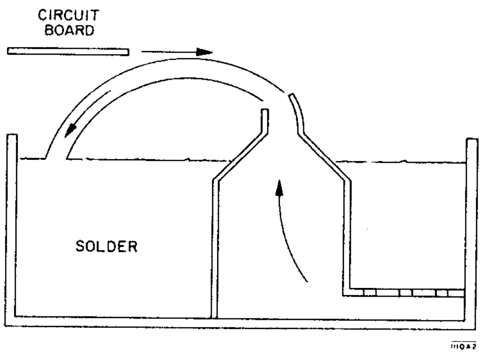


Fig. 1. Wave soldering machine.

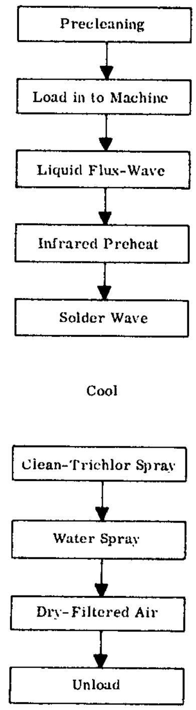


Fig. 2. Wave soldering process.

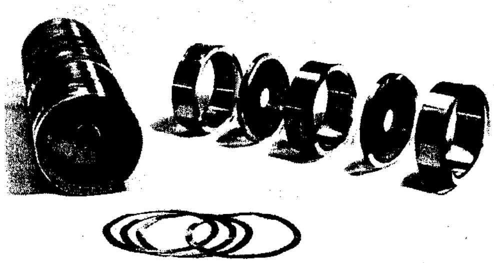
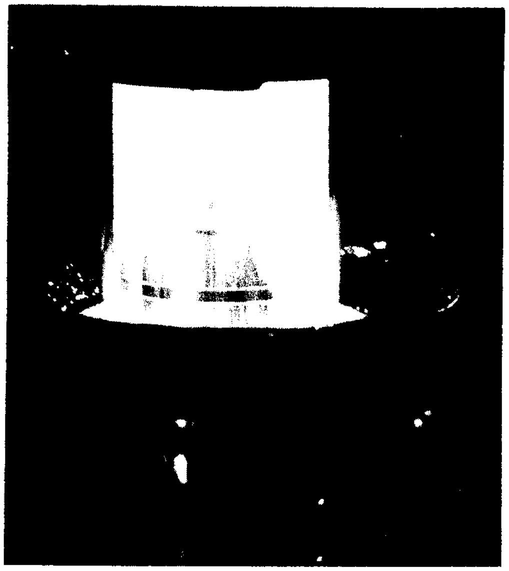


Fig. 3. Circular waveguide components.



M166

Fig. 4. Furnace brazing of circular waveguide.

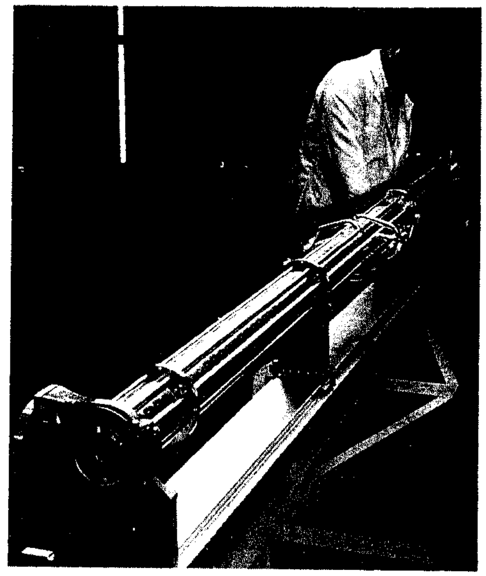
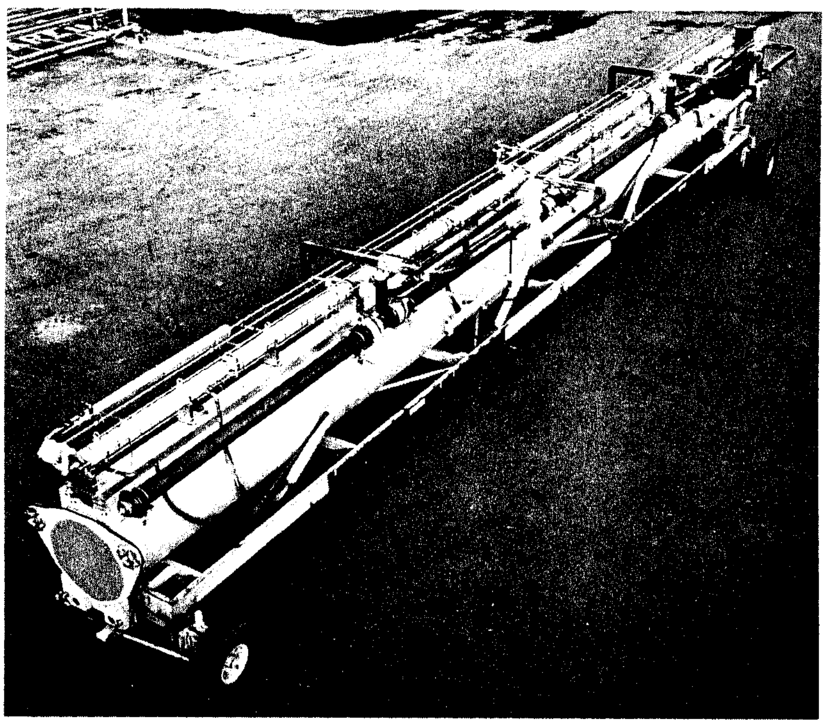


Fig. 5. Finished 10-foot circular waveguide. M1114



M1140-6

Fig. 6. Four waveguide sections on support girder.

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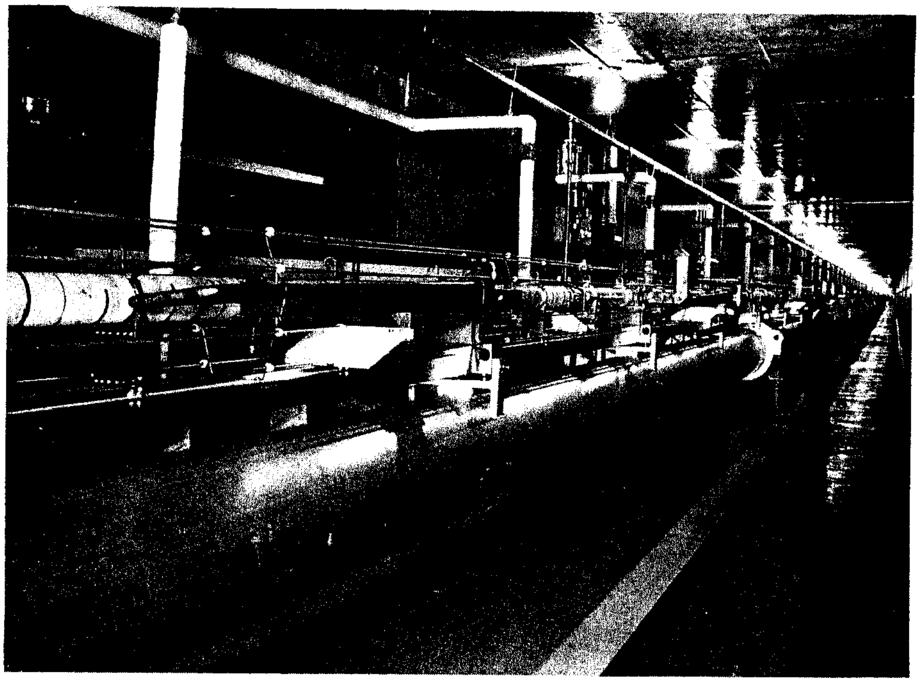

Fig. 7. Two-mile accelerator. M1535

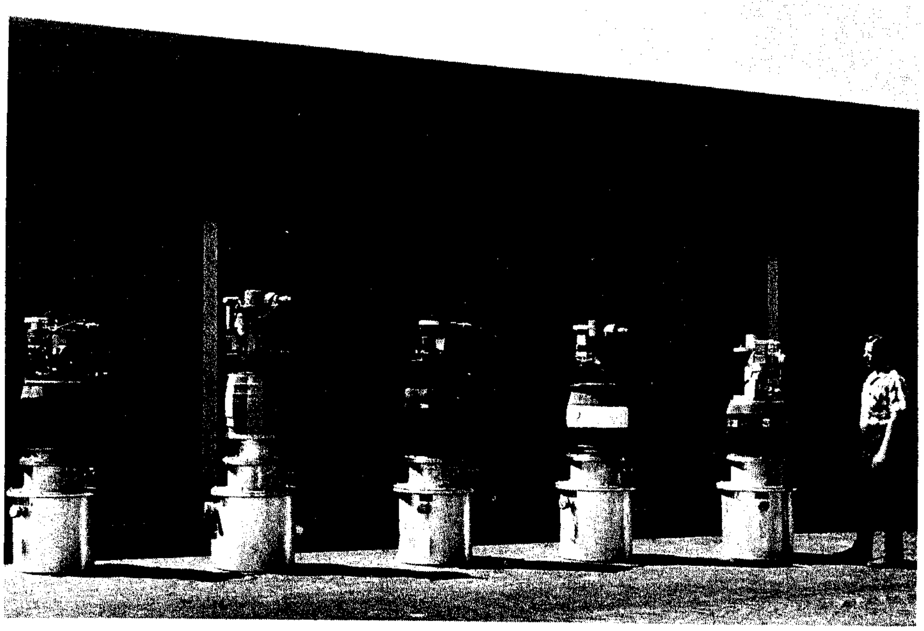

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Fig. 8. Klystrons for microwave amplification. M1683

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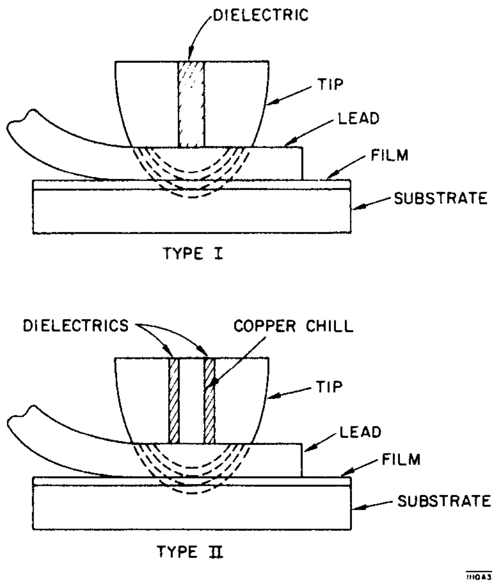

Fig. 9. Parallel-gap welding heads.

Fig. 11. Electron beam weld in copper

print in file under 1110A4

neg. in 1110 file

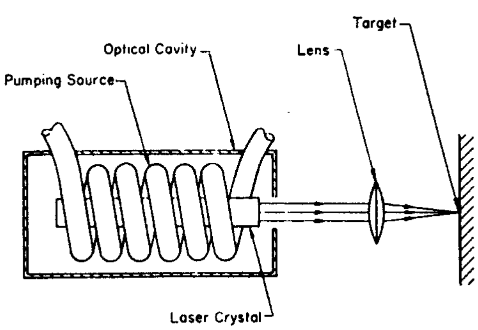

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Fig. 10. Schematic diagram of a laser welder.

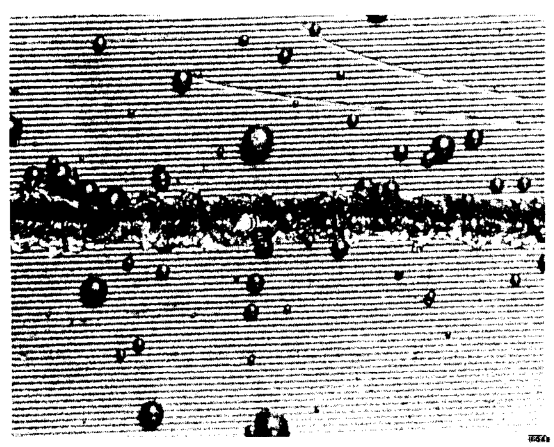

Fig. 12. Electron beam weld in copper--surface spatter.

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neg. in 1110 file

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