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A COMPARISON OF THE PHYSICS OF
GAS TUNGSTEN ARC WELDING (GTAW),
ELECTRON BEAM WELDING (EBW), AND
LASER BEAM WELDING (LBW)

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16. ABSTRACT

The physics governing the applicability and limitations of gas tungsten arc (GTA), electron beam (EB), and laser beam (LB) welding are compared. An appendix on the selection of laser welding systems is included.

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A COMPARISON OF THE PHYSICS OF GAS TUNSTEN ARC WELDING (GTAW), ELECTRON BEAM WELDING (EBW), AND LASER BEAM WELDING (LBW)

INTRODUCTION: FUSION WELDING

The purpose of this report is to explain the physics of gas tungsten arc welding (GTAW), electron beam welding (EBW), and laser beam welding (LBW) to show why GTAW and EBW may, in some circumstances, profitably be replaced by LBW and why, in some instances, LBW may even be able to accomplish what would be impossible for GTAW or EBW.

All three of these processes are categorized as fusion welding processes. In fusion welding a small, localized volume of the workpiece is melted by an intense source of heat and this molten metal, the weld puddle, when passed along a seam leaves solid metal in its wake and thus joins the edges of the seam together in a weld.

Welding heat sources differ in various ways and are by no means interchangeable, however. When two methods can produce a given weld, one is usually preferable.

DIFFERENT KINDS OF HEAT SOURCES: GTAW, EBW, LBW

Figure 1 illustrates the main features of three common kinds of welding heat source.

GTAW generates heat through an electrical arc at the surface of the workpiece. An atmosphere is required to generate an arc, but the atmosphere must be inert to keep the metal from oxidizing. An inert atmosphere is supplied by a flow of helium or argon or a mixture of the two around the tungsten electrode which generates the arc. Within the arc, electrons and positive ions stream past one another in opposite directions (the electrons moving considerably faster) to carry the arc current. Typical currents encountered run up to several hundred amps with a voltage of around 10 to 20 V.

The GTAW arc is inherently short, a few millimeters long. A longer arc would either extinguish itself or become uncontrollable. The arc jets against the workpiece due to self-induced magnetic circulation of charge carriers, but the jet is not powerful and as a heat source the arc is not very concentrated.

EBW generates heat by impacting high kinetic energy electrons upon the workpiece surface. An atmosphere would stop these electrons after a short distance, so this process has to take place in vacuum. An electron beam can be focused by magnetic lenses to yield a very intense beam.

ELECTRODE (−)

AIR

SHIELD
GAS

ARC

GAS TUNGSTEN
ARC

SHOWN IN
DIRECT CURRENT
ELECTRODE NEGATIVE
—DCEN—
OPERATIONAL MODE

FILAMENT

CATHODE

ANODE

ELECTRON
GUN

VACUUM

ELECTRON

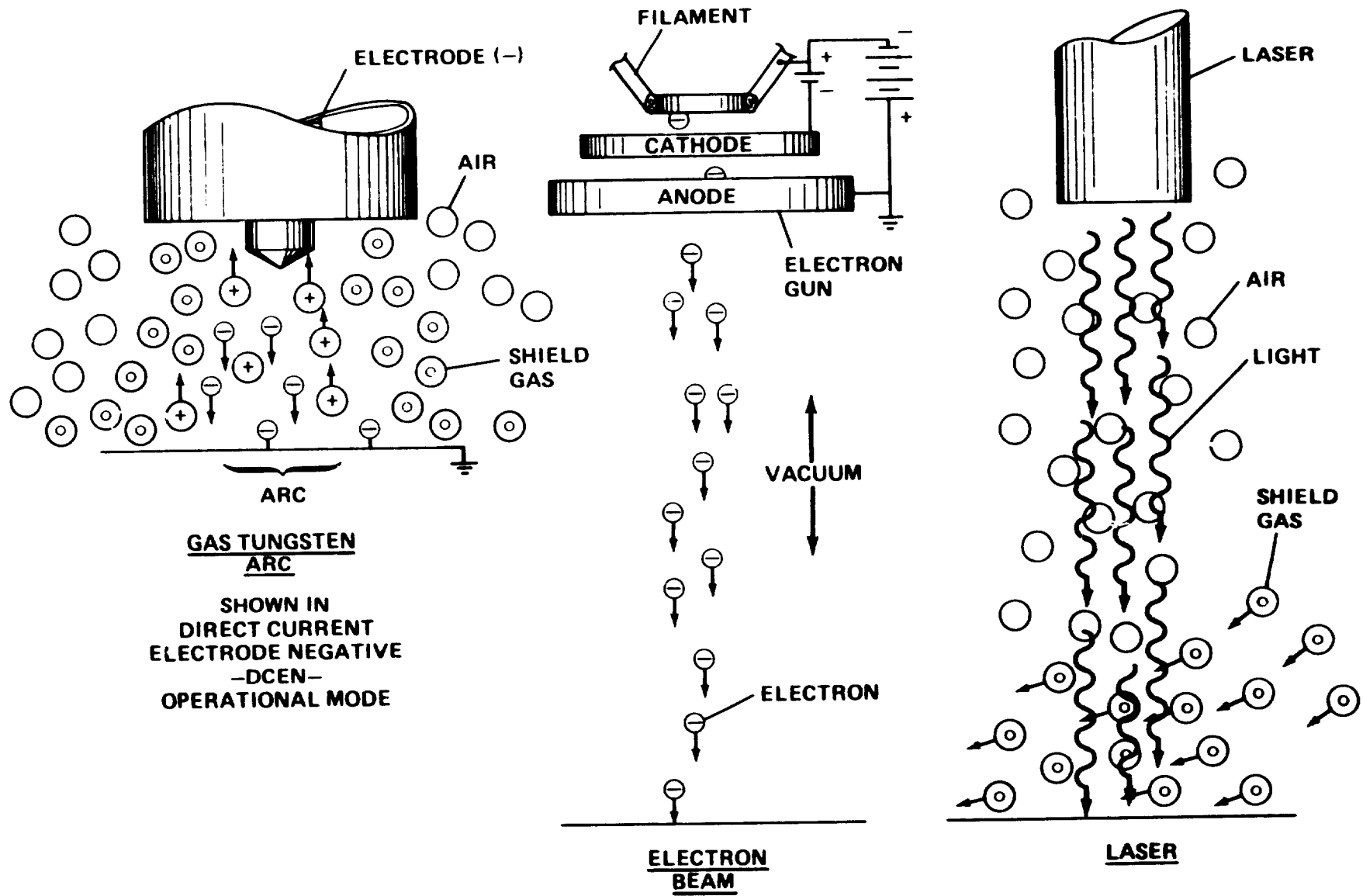ELECTRON
BEAM

LASER

AIR

LIGHT

SHIELD
GAS

LASER

Figure 1.   Three kinds of welding heat source.

LBW generates heat by directing high intensity light onto the workpiece. A laser beam can be focused by lenses or mirrors to yield a very intense beam comparable to an electron beam in intensity.

A schematic illustration of a laser welding system is shown in Figure 2. The heart of the system is the resonant cavity. Here the high intensity beam is produced by a process of "reverse absorption." A light beam passing through atoms or molecules excited to abnormally high energy states picks up energy as it passes through the lasing medium by stimulating the excited atoms or molecules to omit light which then adds to the transmitted beam. Without the energy available to the beam in the excited atoms or molecules in the lasing medium, the beam would lose energy during transmission and, instead of increasing in power, would be gradually absorbed.

Crystals "pumped," i.e. excited, by high intensity flash lamps are used as a lasing medium for low power (less than 1 kW) laser welding systems. A frequently used crystal is yttrium aluminum garnet doped with neodymium, Nd-YAG, producing infrared light of 1.06 micron wavelength, not far above the visible spectrum which runs from 0.4 to 0.7 microns. Heat generated in the lasing medium limits the power capability of solid state lasers. Emitting the beam in pulses enhances the intensity of such beams over what would be the "continuous wave" power output.

Large welding lasers (up to 25 kW) generally use a low pressure gas mixture (e.g., 14 Torr He/5 Torr N_2/3 Torr CO_2), which yields a 10.6 micron infrared beam, as a lasing medium. The 10.6 micron radiation is generated through a vibrational transition of the CO_2 molecule, hence such lasers are called CO_2 lasers. The lasing gas can be stimulated intensely by means of an electric arc and the heat is removed by circulating the lasing gas through a heat exchanger. The beams produced are too intense to be passed through solid lenses. They are directed by mirrors (typically copper with water cooling). The pressure drop between atmosphere and the low pressure lasing cavity is bridged by a pressure gradient deliberately produced by a flow of gas in an aerowindow. Mirrors, it should be noted, are called upon to reflect a defocused beam. The beam is focused upon the workpiece. The focused beam is intense enough to cause electron emission and to generate a plasma at the metal surface [1]. The plasma substantially raises absorptivity of the laser beam (from 10 percent to 50 percent for a cited aluminum sample). A cavity, either the keyhole vapor cavity or the joint slot itself, further enhances absorption of the beam.

Resonant cavities produce characteristic radiation standing wave patterns. Lasers produce beams with variations of intensity over the cross section, i.e., with particular transverse electromagnetic modes (TEM). The Gaussian or TEM_{00} beam, a bell shaped variation of intensity with neither circular nor planar nodes, is generally regarded as optimal as it permits the narrowest focus and avoids complications of multiple hot spots on the workpiece surface. A mode close to TEM_{00} is hard to obtain and multimode operation is common. Some respondents in a survey of laser welding operations taken by MSFC and Rocketdyne [2] were of the opinion that the emphasis on the need for a high quality (near TEM_{00}) beam has been exaggerated.

3

FOCUSING MIRROR

BEAM
DISTRIBUTION
SYSTEM

RESONANT CAVITY

AEROWINDOW

LASER

PLASMA REMOVAL JET

TRAILER
SHIELD

WORKPIECE

WORK STATION

TRANSVERSE
ELECTROMAGNETIC
MODES (TEM)

00
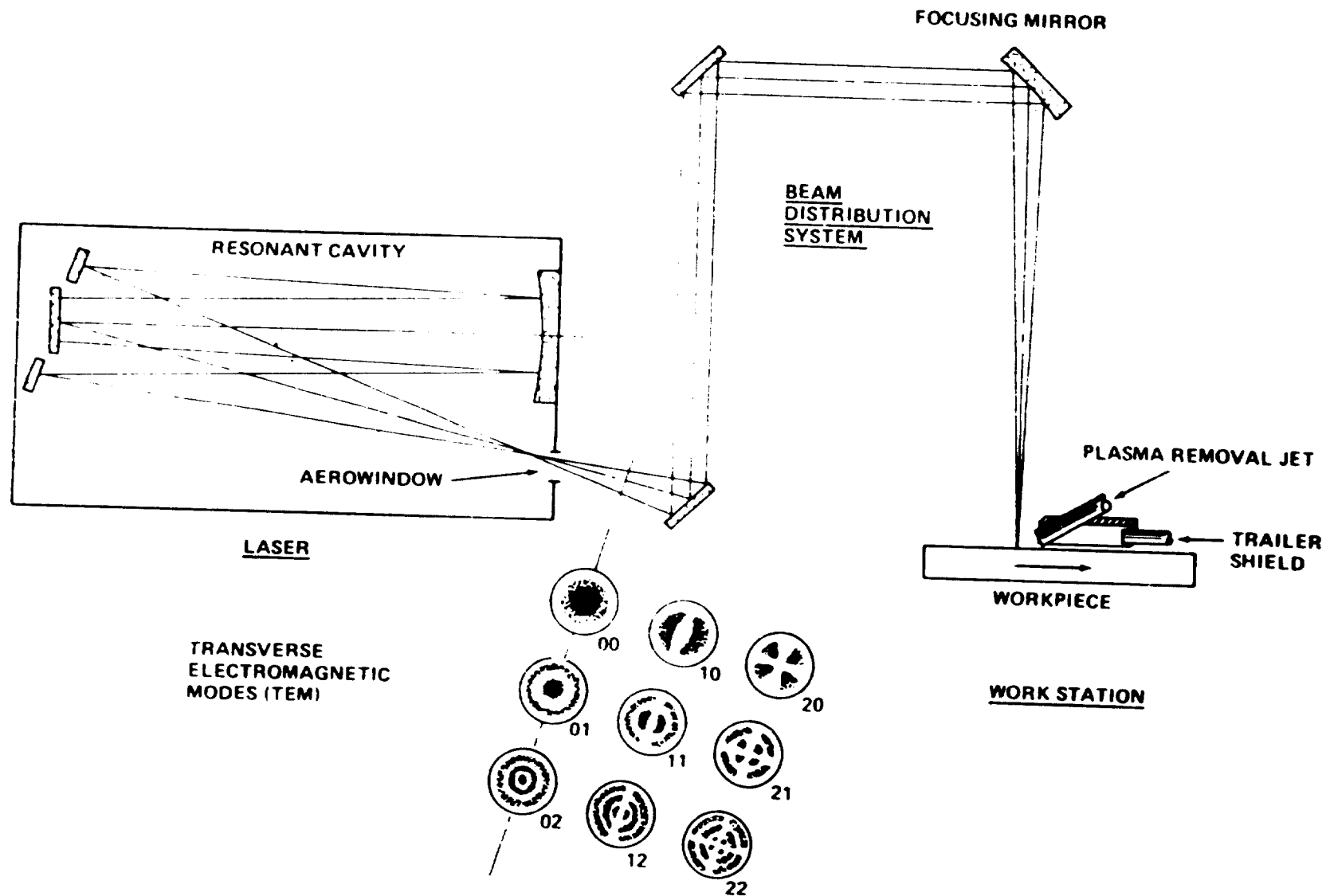
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20

01

11

21

02

12

22

Figure 2.   Laser welding system.

DIFFERENT KINDS OF METAL/HEAT SOURCE INTERACTIONS

A source of heat applied to the surface of a metal causes the temperature to rise just enough to produce the temperature gradients needed to conduct the heat away as fast as it comes in. At slow speeds and low intensities the isothermal surfaces around a heat source tend toward hemispheres as the temperature gradient is almost the same in any radial direction away from the source.

If the power density absorbed at a metal surface is sufficiently high, the surface temperature will rise above the melting or even above the vaporization temperature. In the former case a puddle of molten metal is produced at the point of impingement of the beam. The puddle, when on the surface and not close to the workpiece underside, tends toward a hemispherical shape, but speed, the proximity of a bottom surface, and circulations of molten metal in the weld puddle driven by magnetic pumping or surface tension gradients modify the puddle shape considerably. A puddle fully penetrating a metal plate tends toward a cylindrical shape due to the approximate radial symmetry of the temperature gradients.

Power densities exceeding 10^6 W/cm^2 produce surface vaporization. A vapor channel extends down into the workpiece. The channel extends to a depth at which it either penetrates the workpiece ("keyholing") or until the sloping walls of the vapor cavity present a large enough area to the beam so as to be able to dissipate the power without further vaporization. A simplified mathematical treatment of the vapor cavity and keyholing is presented in the Appendix.

The two kinds of surface interaction, "conductive," where there is no vapor cavity, and "keyholing," where a vapor cavity is present, are illustrated in Figure 3. As can be seen, the interactions are quite distinct.

GTAW is restricted to conductive interactions due to its relatively low power intensity. Both EBW and LBW make considerable use of keyholing which they can achieve through focusing of beams to a very high local intensity.

WELDING PROBLEMS: RELATION TO DIFFERENT PROCESSES

Access to Seam and Control

The physics of a weld process determines how the process can be used.

The localized arc operating in atmosphere encourages hand-held manual operation in GTAW. Welds with too complex a geometry to be automated are frequently accomplished by manual GTAW. It is anticipated that many of these welds will be automated through robotic systems in the future. The same features that support manual welding also make GTAW welding suitable for robotic applications.

EBW is not suitable for manual operations because of the vacuum requirements. An exception to this statement might be the in-space hand-held 80 kV EBW system proposed as early as 1965 [3]. It appears the system was never developed.
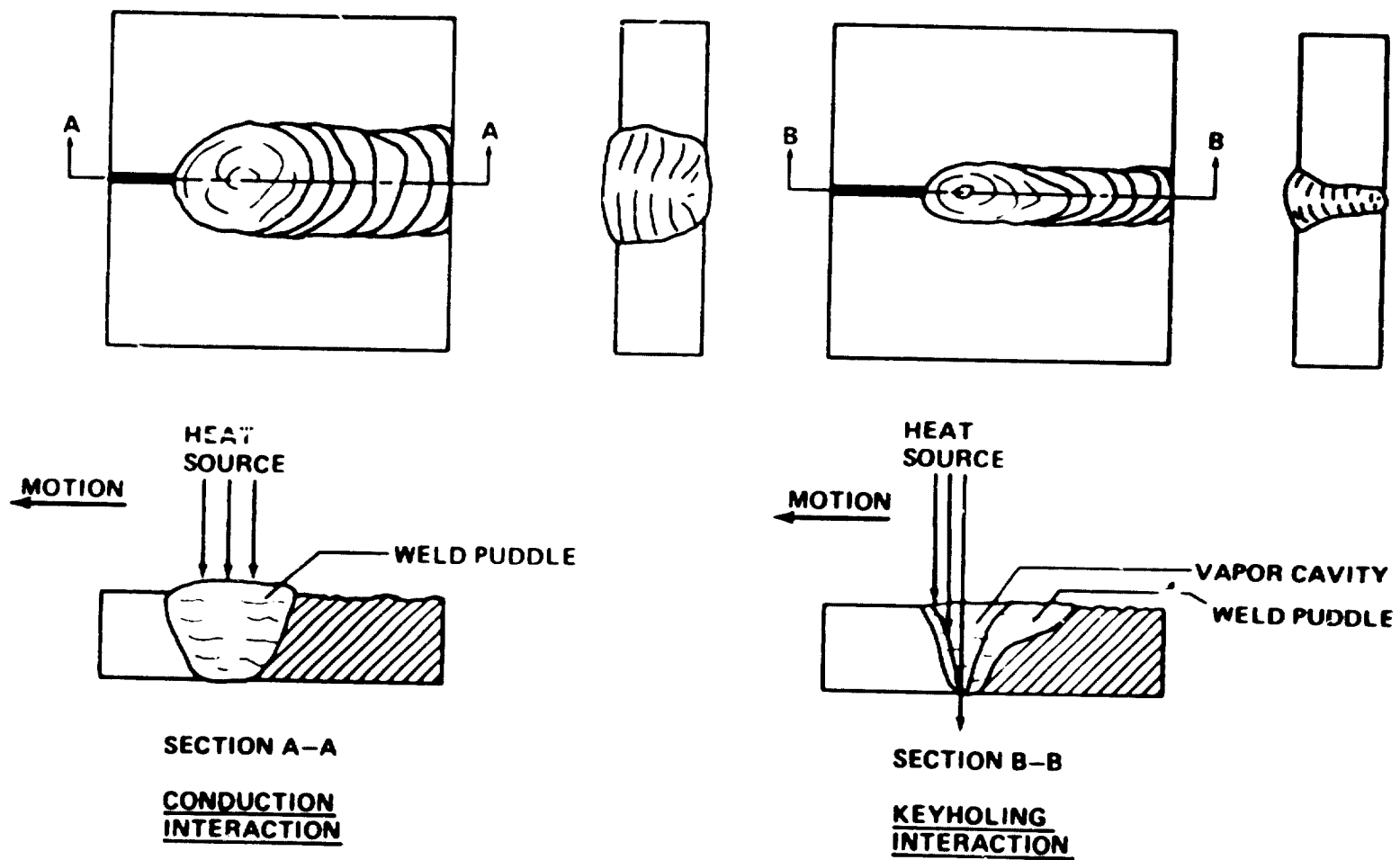
Figure 3.   Two kinds of metal/heat source interaction.

Both EBW (in space) and LBW would appear difficult to control safely by hand due to the relatively lengthy operational portion of the beam. That is, in a moment of inattention it would be quite easy for a manual welder by a simple twist of the wrist to turn the welding beam upon himself or upon some other vulnerable target. At the same time this feature makes both systems more amenable to automatic control. Small deflections of the electron beam are accomplished by magnetic coil, larger deflections by mechanical translation in one EBW system, for example. The laser beam is typically controlled by mirrors, which permit especially great freedom. With a mirror a laser might weld a circumferential pipe joint from the inside, a feat impossible for EBW and difficult, perhaps also impossible for very small cross sections, for GTAW. Through mirrors a laser may be mated to a robot. A 5 kW laser mater to a robot was exhibited at the 1984 American Welding Society Show [4]. An electron beam gun could, in principle, be mounted on a robot, but its applicability would be restricted by the vacuum requirement.

Penetration and Overpenetration

The depth to which the weld puddle can penetrate is a measure of the capacity of a fusion welding device.

The broad, rounded GTAW puddle must either melt a great deal of metal with associated damage to the workpiece and high power consumption or its penetration must be limited. With this system, thick plate would likely be welded by machining bevels or grooves along the edge of the joint to permit access of the torch and to limit the initial penetration requirements. Then the weld would be built up with a series of multiple passes, each contributing a fraction of the cross section of the total weld. The use of many passes to make the same weld is by no means economical. The added opportunity for defect generation poses an additional penalty.

EBW and LBW are both capable of very substantially greater penetration than GTAW due to their ability to form the vapor cavity necessary for keyholing.

The high energy electrons of the electron beam penetrate very well in vacuum. The electrons which pass all the way through a fully penetrating keyhole have sufficient energy to produce thermal damage in any metal below the keyhole. Thus, it is often necessary to place backing below the weld root to protect the material underneath it. It is inconvenient and expensive to have to use backing, particularly when welding above a narrow cavity from which it may be difficult or impossible to remove the backing.

Unlike the electron beam, which passes easily through any vapor generated within the keyhole, the laser beam is defocused and stopped by a plume of ionized gas issuing from the keyhole. To penetrate deeply, the plasma plume must be blown away by a blast of inert gas. Even so, considerable defocusing may be expected in the vapor cavity. Hence, the tendency of the laser to overpenetrate and damage material underneath the weld is appreciably less than that of the electron beam. A laser might be able to weld into a blind cavity without damaging the cavity walls while an electron beam could not. Thus, where overpenetration is a problem with EBW, LBW should be considered.

Magnetic Deflector

Both GTAW and EBW are sensitive to magnetic fields due to the action of the Lorentz force on their moving charge constituents. Ferromagnetic materials in a fixture or workpiece can easily become magnetized in the presence of welding currents and can cause erratic behavior of the arc/beam. Current flow itself can also generate magnetic fields, but such fields can probably be avoided through design. Whenever dissimilar metals are welded, a thermocouple is set up and a magnetic field causing an electron beam to veer off the seam is produced by the large thermoelectric currents generated [5]. Particularly severe irregular deflections are to be expected when one of the dissimilar metals is ferromagnetic.

Workpiece Distortion

As shown in Figure 4, uneven shrinkage produced by uneven melting patterns causes distortion. Thus, the shape of the weld puddle affects distortion due to welding. Taper in the puddle produces distortion and is undesirable.
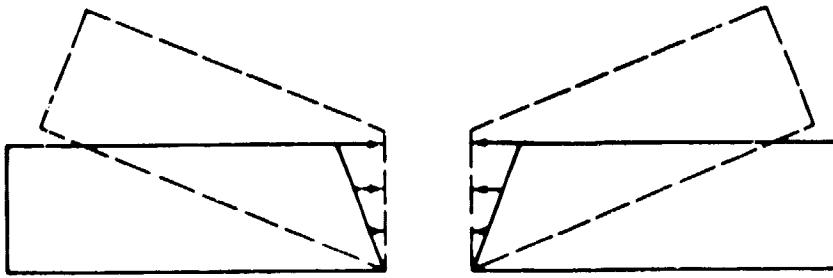
UNEVEN SHRINKAGE CAUSES DISTORTION
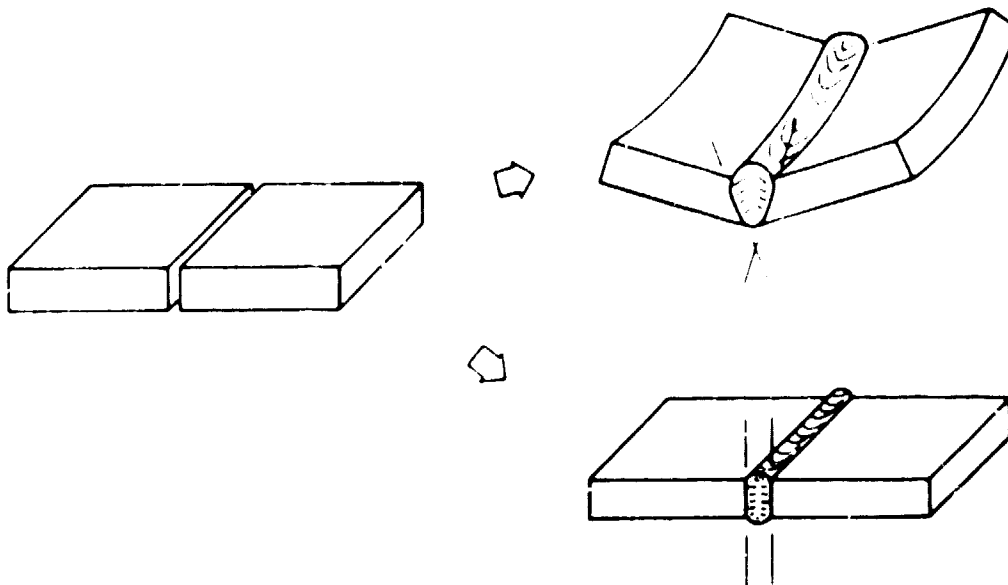
UNEVEN MELTING PATTERNS CAUSE
UNEVEN SHRINKAGE

Figure 4.   Workpiece distortion.

The rounded GTAW puddle has a tendency to produce distortion under circumstances where the puddle gives its rounded shape to the weld cross section. Distortion can be reduced by rigid clamping of the workpiece (if feasible) or by substituting a number of small passes for a single large pass. When feasible, distortion may be removed by straightening operations, which bend the workpiece back to its original shape through mechanical force.

The straighter, narrower welds produced by keyholing in the EBW and LBW processes produce substantially less distortion than GTAW, pass for pass. Not only is the shrinkage more evenly distributed over the weld cross section, but less metal is melted and less shrinkage occurs.

Internal Defects

Common internal defects (i.e., those defects encountered inside the weld fusion or heat affected zones and not penetrating to the surface) are cracks, contamination, inclusions, and porosity. Of these only porosity, a very frequently encountered defect, will be discussed here.

Porosity in welds is commonly caused by effervescence of gas dissolved in the weld metal. It is avoided in GTAW practice by maintaining strict cleanliness of the surfaces to be welded and ~h purity of weld gas and weld metal. Weld position, favoring the escape of gas bubbles, and speed, slow enough to permit outgassing of the puddle or fast enough to avoid the start of effervescence, are factors that affect and help control porosity. Porosity is removed by removal of the porous metal and rewelding.

In the absence of an atmosphere, one of the potential sources of porosity is missing in EBW. However, vapor generated at the bottom of deep partially penetrating vapor cavities is sometimes trapped. This weld root porosity is associated with tooth-like variations in penetration depth. The latter phenomenon is called "spiking."

LBW is similar to EBW except that with the presence of an atmosphere more opportunities for porosity exist. Nevertheless, with appropriate practice porosity appears not to be a problem with LBW.

The effect of weld speed on cooling rate and of cooling rate upon weld metal properties and weld strength should be noted in passing. A weaker internal structure may, perhaps, be considered a kind of internal defect.

External Defects

With the exception of distortion (including peaking), which has been discussed, and mismatch, a function of joint fitup, external weld defects such as incomplete penetration, lack of fusion, undercut, suckback, lack of fill, folds, cracks, dropthru, oxidation, etc. are often traceable to "operator error." This can be minimized by automation of a developed and successful process. All of the processes considered here can be automated effectively. Except for distortion proneness, no external defect factors that would differentiate the processes suggest themselves.

It should, however, be kept in mind here that the strength of welds is affected by the geometry of the weld fusion zone. An inferior fusion zone geometry might be considered a kind of external defect.

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CONCLUSIONS

Table 1 summarizes major differences and similarities of the GTAW, EBW, and LBW processes. The information of Table 1 permits a process selection.

For example: If it is desired to take advantage of the deep penetration and relatively low distortion afforded by keyholing, GTAW is excluded. If it is necessary to operate in air, or if magnetic field disturbances are present, EBW is excluded, leaving only LBW.

TABLE 1. PROPERTIES OF WELDING HEAT SOURCES

Welding Heat Source

	GTAW	EBW	LBW
Conduction Interaction	Yes	Yes	Yes
Keyholing	No	Yes	Yes
Interactions:			
Air	No (but contamination can occur with improper shielding).	Electron Beam is stopped by air (requires vacuum).	No (except for some attenuation with distance).
Shiny Metal (Mirror)	Arc is bounded by electrical conductor (plasma is extinguished).	Electrons enter metal, give up thermal energy near surface.	Beam is partly reflected. Extent of reflection (high for mirror, lower for workpiece) is determined by focus and surface conditions.
Ionized Gas (Plasma)	Ionized gas is present in the arc. Not a concern.	Minor effect in vacuum except (possibly) in very deep penetration.	Beam is defocused. Requires gas management system to blow away plasma for deep penetration.
Magnetic	Arc is deflected.	Electron Beam is deflected.	No effect.

APPENDIX

SELECTION OF LASER SYSTEMS POWER REQUIREMENTS

The power output required of a laser system is determined by the penetration required of the system.

Figure 5 shows a highly simplified model of a weld vapor cavity. The following treatment departs from work of Leskov et al. [6] on electron beam vapor cavities. A cylindrical beam of diameter d and power P assumed uniformly distributed over the beam cross section encounters the tilted elliptical area cutting off the bottom of the vapor cavity and is absorbed through heat conduction losses assumed uniform over the area of the impingement surface and through absorption in the latent heat $\mathcal{L}$ of the phase change occurring as the cavity moves forward (to the left in Fig. 5) with weld velocity V. A heat balance at the elliptical interface where the beam is absorbed determines the penetration depth Z which is maintained under steady state conditions:

$$\rho \mathcal{L} \left(\frac{\pi d Z}{4} \right) V = P - \dot{q} \left(\frac{\pi d \sqrt{Z^2 + d^2}}{4} \right) \tag{1}$$

where ρ is the weld metal density, or

$$Z = \frac{4P - \dot{q} \pi d \sqrt{Z^2 + d^2}}{\pi d \rho \mathcal{L} V} \tag{2}$$

or, if a latent heat $\mathcal{L}'$ is defined such that it incorporates heat conduction losses,

$$\mathcal{L}' = \frac{\mathcal{L}}{1 - \dfrac{\dot{q} \pi d \sqrt{d^2 + Z^2}}{4P}} \tag{3}$$

then

$$Z = \left(\frac{4}{\pi d \rho \mathcal{L}'} \right) \frac{P}{V} \tag{4}$$

Further, if the total power P of the laser beam enters the vapor cavity and ultimately leaks out through the vapor cavity into the metal and if the heat flux is the same from all parts of the cavity then
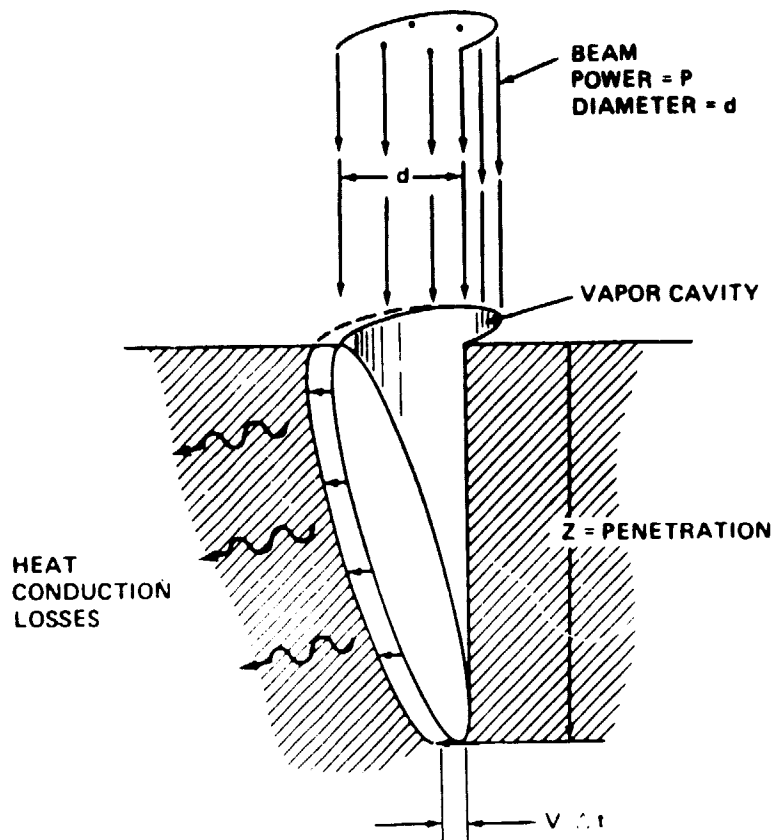
Figure 5. Simplified model of weld vapor cavity.

$$\frac{\dot{q}\pi d \sqrt{Z^2 + d^2}}{4P} = \frac{\sqrt{1 + \left(\frac{d}{z}\right)^2}}{2 + \sqrt{1 + \left(\frac{d}{z}\right)^2}} \tag{5}$$

or, if penetration is deep and $Z \gg d$,

$$\frac{\dot{q}\pi d \sqrt{Z^2 + d^2}}{4P} = \frac{1}{3} \tag{6}$$

and

$$\mathcal{L}' = \frac{3}{2}\mathcal{L} \tag{7}$$

Bearing in mind that metal may be transferred from the beam impingement surface to the liquified throat behind it by melting and flowing around the cavity or by explosive emission of small chunks of metal we expect an underestimate of the penetration

when it is taken to be the latent heat of vaporization. For iron, taking d to be 0.03 in., a not unreasonable value, we estimate for melt transfer ($\mathcal{L}$ = latent heat of melting):

$$Z = 9.8 \frac{P}{V} \tag{8}$$

and for vapor transfer ($\mathcal{L}$ = latent heat of evaporation)

$$Z = 1.7 \frac{P}{V} \tag{9}$$

Where Z is penetration in inches, P is power in kilowatts and V is weld speed in inches per minute.

Empirical values [7] yield a range of constants for a rimmed steel:

$$Z = 3.8 \text{ to } 5.3 \frac{P}{V} \tag{10}$$

Neglecting explosive particle transfer, the above value would be equivalent to about 35 percent melt transfer with vapor transfer responsible for 65 percent of the mass transfer across the puddle. Thus, empirical and theoretical calculations are compatible, but the theoretical calculation is too sensitive to unknown details of the penetration mechanism to yield realistic penetration values without recourse to empirical data. If one were to rate the penetration of a given machine at a velocity of 100 in./min, then from equation (10) one would expect to get 0.04 to 0.05 in. penetration per kilowatt of beam power for steel. As the latent heat of nickel is such that the penetration based on the vapor transfer mechanism would be similar to that of steel, a similar value might be expected for Inconel 718.

Estimates of the rated penetration in Inconel 718 given verbally by manufacturers for laser welding systems of various powers are plotted in Figure 6 and yield a rough 0.05 in. penetration per kilowatt of beam power.

Thus, if one needs to penetrate 0.5 in. plate, the task requires a 10 kW laser beam.

The total range of accessible power levels is also important. A range of 1 to 15 kW power output is attributed to one manufacturer's laser; 0.5 to 20 kW to another. Figure 6 would assign penetration ranges in Inconel 718 of from 0.05 to 0.8 in. in the first case and 0.025 to 1.0 in. in the second. This seems adequate for most conceivable low power operations considering that welding speed increases can also attenuate penetration.

The first manufacturer cites noise pickup and resulting beam inconsistency as the factor limiting the power reduction and recommends operation above 2 kW with attenuation of penetration through increased weld speed. The second manufacturer points out that while a low power laser would be unnecessary for welding at low penetration levels, for precision cutting in the low range a smaller laser with a precision controlled beam would be desirable.
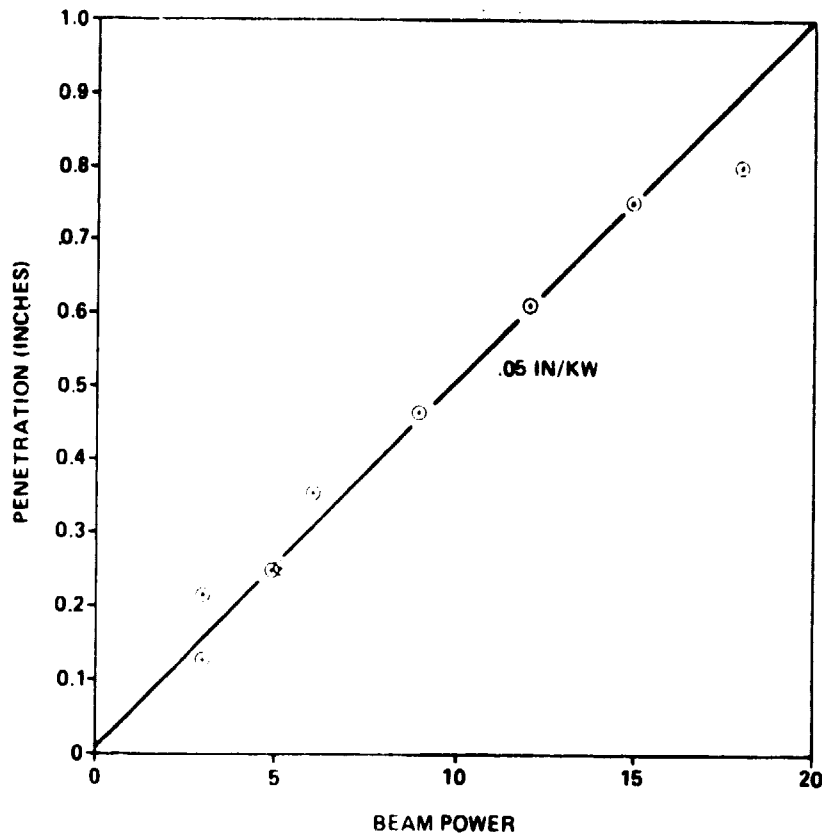
Figure 6. Manufacturer's rated maximum penetration versus
rated beam power for Inconel 718.*

As would be expected bigger lasers cost more. Estimated costs of typical laser welding systems as given verbally by manufacturers are plotted versus rated beam power in Figure 7.   The system comprises work stations, manipulators, etc. and not merely the laser alone.   Thus, the "typical" cost is subject to considerable variation depending upon the options purchased.   As a rule of thumb it appears one can expect to pay $100,000 (1985 dollars) per kilowatt of power for a laser welding system.

As with any production tool, reliability is an important factor in laser welding performance.   Considerable experience has been obtained with laser welding systems up to 5 kW.   Users surveyed by MSFC and Rocketdyne [2] cited uptimes of 75 to 80 percent.   In response to a subsequent query, one manufacturer cited an uptime of 90 percent for 100,000 hours of operation after the initial running-in period. Manufacturers of the larger (15 to 20 kW) lasers maintain that scaleup does not entail any reduction in reliability.

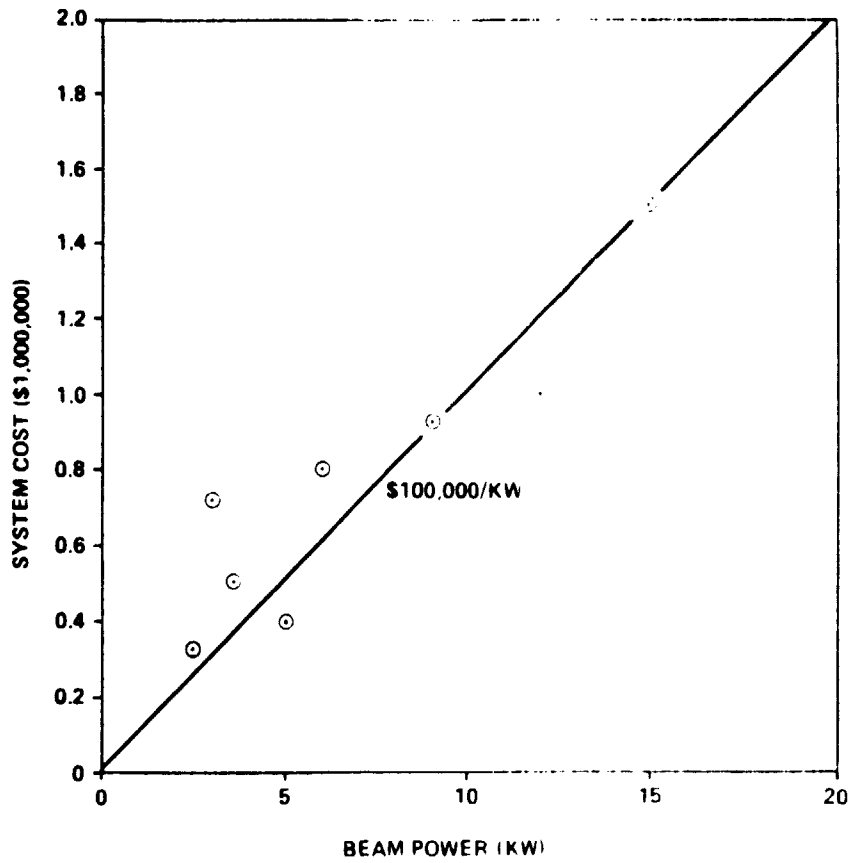*Inconel is a registered trademark of Huntington Alloys, Inc.

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Figure 7. Manufacturer's estimated cost of a typical laser welding system (1985 dollars) versus rated beam power.
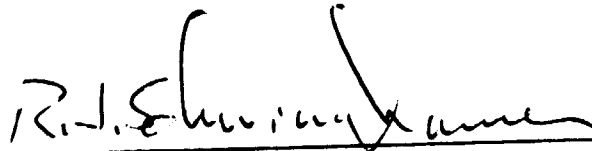
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APPROVAL

A COMPARISON OF THE PHYSICS OF GAS TUNGSTEN ARC WELDING (GTAW), ELECTRON BEAM WELDING (EBW), AND LASER BEAM WELDING (LBW)

By A. C. Nunes, Jr.

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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Laboratory