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WELDING INDUSTRY: POTENTIAL FOR ENERGY CONSERVATION

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ABSTRACT

This work presents an estimate of the annual primary energy consumption by welding processes in the U.S., as 3.2 - 8.8 x 10^{16}J (3.0 - 8.4 x 10^{13} Btu), and discusses energy conservation opportunities.

The estimate has been confined to the primary energy required to actually produce coalescence. Indirect energy consumption—such as that for joint preparation, preheat, postweld heat treatment, fume removal, or other operations required by welding—has been discussed but not included in the total.

The heat content of fuels used in most U.S. power plants is termed primary energy, and it is the amount of primary energy required for welding that is estimated in this work.

Welding processes have been categorized as follows: those for which energy consumption may be related to use of consumable materials, those for which it may be related to quantity of manufactured product, those for which it may be related to the number of welding machines, and those for which only limited data are available. Methodologies have been developed to estimate the energy consumption for the first three categories.

The major consumers of welding energy are oxyfuel gas welding, arc welding, and resistance welding. It is significant that arc welding accounts for over 90% of electrode and filler wire consumption, yet oxyfuel gas welding accounts for about 47% of energy consumption. Arc welding consumes about 39%, and resistance welding less than 15% of the total welding energy.

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WELDING INDUSTRY: POTENTIAL FOR ENERGY CONSERVATION

INTRODUCTION

The welding industry is, by its nature, energy intensive. Welding, a family of processes utilizing heat to cause coalescence between materials, is generally recognized to be the most energy-intensive joining technology. Within the U.S. the metal fabrication industry consumes about 6% of the total energy produced.[1,2] Within this industry, welding is a major industrial process and is used in the production of nearly all types of fabricated metal products. However, the total energy consumption by welding processes has not previously been quantified.

Objectives

The objectives of this report are to present an estimate of the annual U.S. energy consumption by welding processes (for the year 1978), establish the relative importance of welding energy consumption to industry, and discuss the potential for welding energy conservation.

In all studies of this type, a great many assumptions and simplifications are required to arrive at the energy consumption estimate. This is especially true for the welding industry, which is extremely diverse and segmented. Because of this diversity, and because welding is often a single step integrated into a series of manufacturing operations, this report discusses only direct welding energy consumption, even though such consumption may be a minor part of the total energy associated with producing a weldment, and a very small part of the total energy consumed to produce a manufactured product. This report will also be limited to the welding of metals, even though polymeric and ceramic materials may also be welded.

General Description of Welding Processes

Welding is defined as "a materials-joining process used for making welds, where weld is defined as localized coalescence of metals or nonmetals produced by heating the materials to suitable temperatures, with or without the application of pressure, or by the application of pressure alone, and with or without the use of filler materials."[3]

The heat source used for welding may be very localized, such as an electric arc, oxyfuel gas flame, or photon beam, or it may be nonlocalized, such as a gas or electric furnace. Various welding processes are characterized by such factors as the type of heat source, the method by which filler material is added to the weld, the method by which the weld is protected from oxidation by the atmosphere, and the relative melting temperature of the filler metal and base metal. (The term "base metal" refers to the metal pieces which are to be joined by welding.)

Description of Welding Energy Consumption

Welding processes require energy, as indicated schematically in Figure 1, to produce coalescence. This may be in the form of either electrical or chemical energy. Electrical energy is produced by the consumption of a fossil or nuclear fuel (or by a hydroelectric source), the energy content of which is termed primary energy. It is this primary energy, including chemical energy, which is estimated in this report.

Indirect energy is also consumed to produce the weld in the product. Prior to welding, energy may be required to produce a suitable joint configuration for welding or to preheat the base metal for

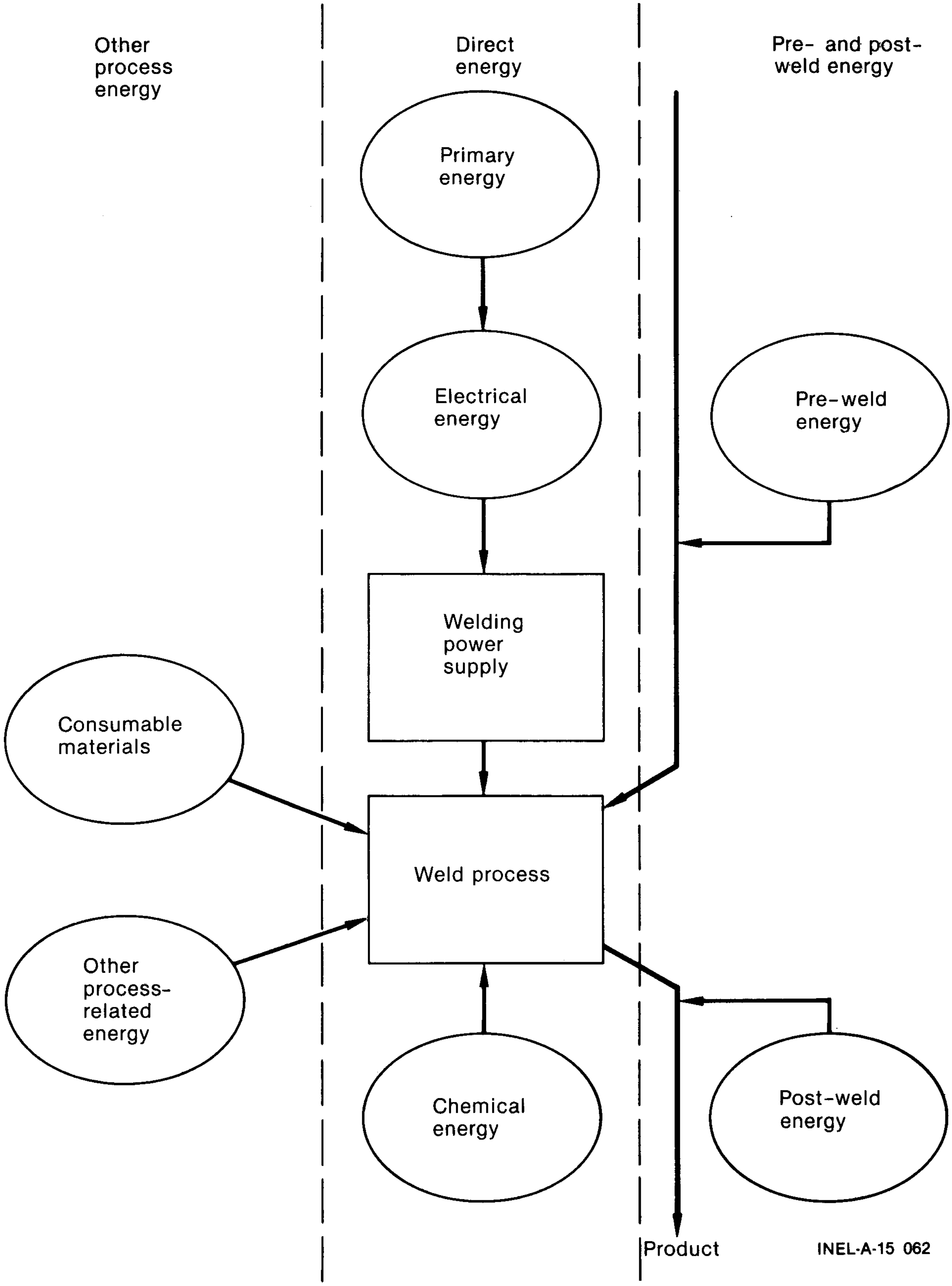

Figure 1. **Welding energy consumption.**

metallurgical reasons. During the welding process, various materials may be consumed. These may include filler materials, shield gases, fluxes, and slags, depending on the particular process employed. All of these have an effective energy content, i.e., that energy required for their production and distribution.

Additional energy may be used during welding by such operations as general heating of the product, ventilation or fume extraction, and positioning of the product. Following the welding process, energy may be required for stress-relieving, heat treatment, straightening, grinding, or other operations associated with the characteristics of the weld.

THE WELDING INDUSTRY

American Welding Society

The American Welding Society (AWS)[4] was established in 1919 to advance the art and science of welding. Since that time, through its various technical committees, annual conventions, product shows, journal, publications, and local sections, it has provided the major technical leadership in the industry. The terminology and process descriptions defined by the AWS are used in this report.

The AWS defines 63 welding processes and at least 22 allied processes. Although it is beyond the scope of this report to estimate the energy consumption by each of these processes, the AWS Master Chart of Welding and Allied Processes is shown in Figure 2. This chart organizes the processes into related groups. The AWS Welding Handbook[3] defines individual processes.

Welding Facilities

Welding is used extensively by the aerospace, appliance, automotive, construction, electronic, energy utilities, heavy fabrication, mining, oil, and shipbuilding industries among others. There is no known estimate of the number of captive welding operations, but it certainly must be very large.

There are probably about 10,000 businesses specializing in custom or vendor type welding operations. The 1979 *Thomas Register*[5] has 1116 listings under "Welding for Hire." Additional listings are found for brazing and soldering. The authors estimate that this represents about 10% of the actual number of vendor or custom welding businesses. In addition, numerous home and farm workshops contain arc or gas welding equipment or both. In 1978, the sales of arc welding machines exceeded $400 million while the sales of gas welding equipment exceeded $200 million.[6] Over 300,000 welding machines are sold annually.[7] While it is probable that many of these machines are applied to non-welding functions, the large sales volume indicates a very large number of welding operations, captive or otherwise.

Major Welding Processes Used By Industry

The majority of the individual welding processes listed in Figure 2 are used by industry. However, for this study the list of processes has been greatly simplified as described below. This simplification reflects in part the relatively small economic and energy consumption importance of many of the unique welding processes.

The process selection was based on numerous discussions with people in the welding industry, as well as experience and data on relative process use and is intended to give an indication of the relative energy consumption of certain processes. For example, the authors recognize that laser beam welding (LBW) is not a major welding process. Yet it has been included in this study to give an indication of the relative importance of LBW energy conservation opportunities.

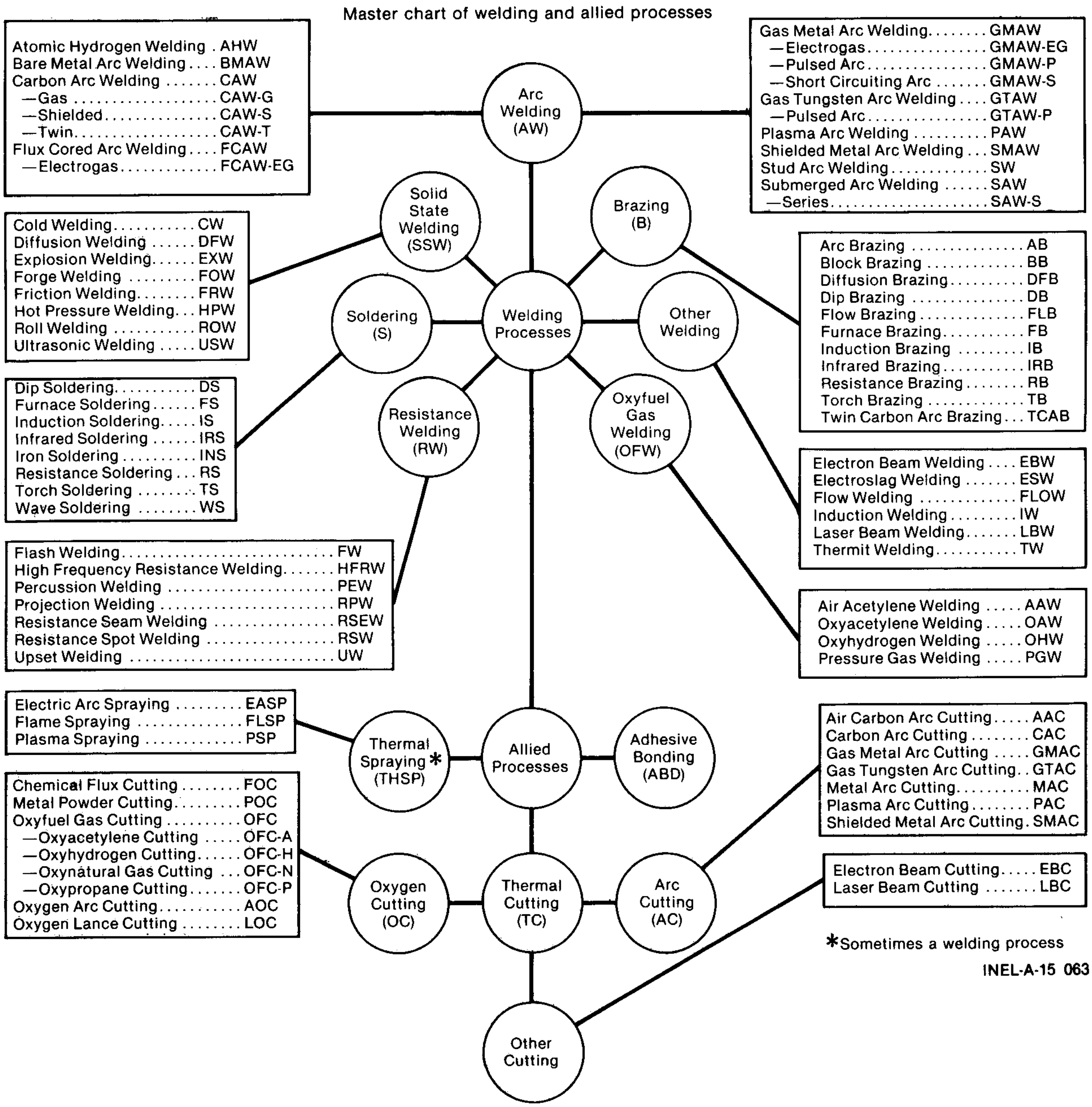

Figure 2. Master chart of welding and allied processes.

Arc Welding. Shielded Metal Arc Welding (SMAW), Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), and Submerged Arc Welding (SAW) are industry's major arc welding processes. With the exception of GTAW, these processes use an electric arc between a consumable electrode (filler wire) material and the base metal as the heat source for welding. Distinction between the processes is based primarily on the method of shielding the molten metal from oxidation during welding. In this report, Flux-Cored Arc Welding (FCAW) is considered to be a variant of GMAW. The GTAW process uses an electric arc between a nonconsumable tungsten electrode and the base metal as the heat source for welding.

Resistance Welding. The heat source for Resistance Welding (RW) is heat generation across the joint due to resistance to electrical current.

Oxyfuel Gas Welding. Oxyfuel Gas Welding (OFW) uses the heat of combustion of a fuel gas, such as acetylene, to provide the heat for welding. The same equipment may be used for brazing, cutting, and perhaps soldering. It is also used as a general heating source for thawing frozen pipes and other operations requiring heat.

Other Types of Welding. Friction Welding (FRW) uses the friction resulting from relative motion of base metal pieces as the heat source for welding. Melting of the base metal generally does not occur.

The Electroslag Welding (ESW) process passes an electric current from the filler material through an electrical conducting molten slag which is above the weld. Heat generated in the slag by resistance melts the edges of the base metal and the filler materials.

The Electron Beam Welding (EBW) and Laser Beam Welding (LBW) processes use focused, high energy density beams of electrons and photons (light) respectively as the source of heat for welding.

Brazing and Soldering. Brazing (B) and soldering (S) are two sets of welding processes in which no melting of the base metal occurs but the filler metal used does melt. The distinction between brazing and soldering is based on temperature. In brazing, the filler metal has a liquidus temperature in excess of 450^{o}C (840^{o}F) but less than the solidus temperature of the base metal. In soldering, the filler metal has a liquidus temperature less than 450^{o}C. Brazing and soldering are not included in the total estimate of welding process energy consumption in this report.

Equipment and Consumable Materials

There are hundreds of manufacturers and suppliers of welding equipment and consumable materials. Among these, the industry also has several large manufacturers with associated distributors who supply complete lines of related equipment and consumables. Major product lines include arc welding power supplies and equipment; electrodes, filler wires and fluxes; oxyfuel gas welding, brazing and cutting equipment; and industrial gases.

Power supplies and equipment for other processes, such as resistance welding, laser, electron beam, and friction welding, are frequently offered by companies which specialize in unique fields of welding. Positioning equipment is often manufactured by companies which make no other welding hardware. Safety equipment, on the other hand, may be offered by companies with broad or narrow product lines.

Additional major manufacturing operations related to welding include joint fabrication, heat treating, grinding, and inspection, among others. A comprehensive listing of manufacturers and suppliers of welding equipment and consumable materials is available.[8]

ESTIMATED ENERGY CONSUMPTION

Primary Energy Conversion

Inherent in the consumption of electrical energy is the requirement of generating and transmitting it to the use site. Electrical energy in this country is produced mainly by a mix of nuclear, fossil fuel, and hydroelectric plants with a wide range of transmission distances.

The energy content of the fossil or nuclear fuel consumed by the generating plant is termed "primary energy."

Considering the types of generating plants in the U.S. and typical transmission losses, a conversion factor from primary energy to electrical energy of 10,500 Btu/kWh,[9] has been derived.[8] It may be noted that 1 Btu = 3413.04 kWh. The value 10,500 Btu/kWh is *not* a unit conversion factor but indicates the efficiency of conversion of primary energy to electrical energy and transmission losses, i.e., $\frac{3413.04 \text{ Btu/kWh}}{10500\text{Btu/kWh}} \times 100 = 32.5\%$.

In this report, the units Btu or Btu/lb are used for primary energy. Units of kWh or kWh/lb are used for electrical non-primary energy. Units of Btu, Btu/lb or Btu/ft^3 are used for thermal energy. These units are included parenthetically behind the appropriate value in SI units.

Direct Energy Consumption Methodologies

Evaluation of the consumption of energy in the welding industry showed that a single method could not be applied to all segments of the industry. Therefore, the following methodologies were used.

First, for processes such as SMAW (shielded metal arc welding) for which the energy consumption per unit weight of deposited electrode metal may be determined from ample data, and for which data are also readily available on total electrode sales, the energy consumption estimate was based on the amount of consumable materials sold.

Second, for resistance welding, for which the energy required to produce a typical weld in a given product may be determined, the number of welds in the product is known, the total sales of the product is known, and estimates of the amount of welding to produce the product relative to the total amount of RW done by industry are available, the energy consumption estimate was based on product quantity data.

Third, for processes such as laser beam welding (LBW) for which estimates of the total number of welding machines are available, and the characteristics of a typical machine are known, the energy consumption estimate was based on facilities data.

Fourth, for some processes, such as thermit welding, induction welding, and brazing, reliable data are not readily available; energy consumption for these is not estimated.

Consumable Materials Method. Industry sales data of equipment and consumables used for arc welding and oxyfuel gas welding, are available from at least two sources.[7,10] Data are also available in the Census of Manufacturers[11]; although in most cases it is difficult, if not impossible to separate welding-related data from nonwelding data. Reference 7 also presents data showing the quantities of welding consumables from about 1967 or 1968 up to 1978.

Annual production of arc welding electrodes and gas welding filler rod is shown in Figure 3. The arc welding electrode sales data are broken down by process in Figure 4. Quantities of certain industrial gases used for welding are shown in Figures 5, 6, and 7.

The electrode and filler rod data, Figures 3 and 4, are somewhat ambiguous. Virtually all of the SMAW electrodes are used for that process; however, electrode wire for the SAW process may also be used for ESW. For 1978, 15% of the electrode wire listed for GMAW was flux-cored, with the remainder being solid wire. Such solid wire is also suitable for use with the GTAW process. An unknown amount of the oxyfuel gas filler rod, which is in the form of cut-length rods, also includes filler wire used for GTAW. No distinction is made in the data for amounts of ferrous vs nonferrous electrode or filler wire material. The U.S. Department of Commerce has estimated that aluminum electrode sales were about 0.2% of ferrous electrode sales, based on 1970 data[12], but they are not able to make a current estimate. However, a recent estimate of 2.7×10^6 kg (6×10^6 lb) of aluminum electrode annual usage has been obtained from Reference 13.

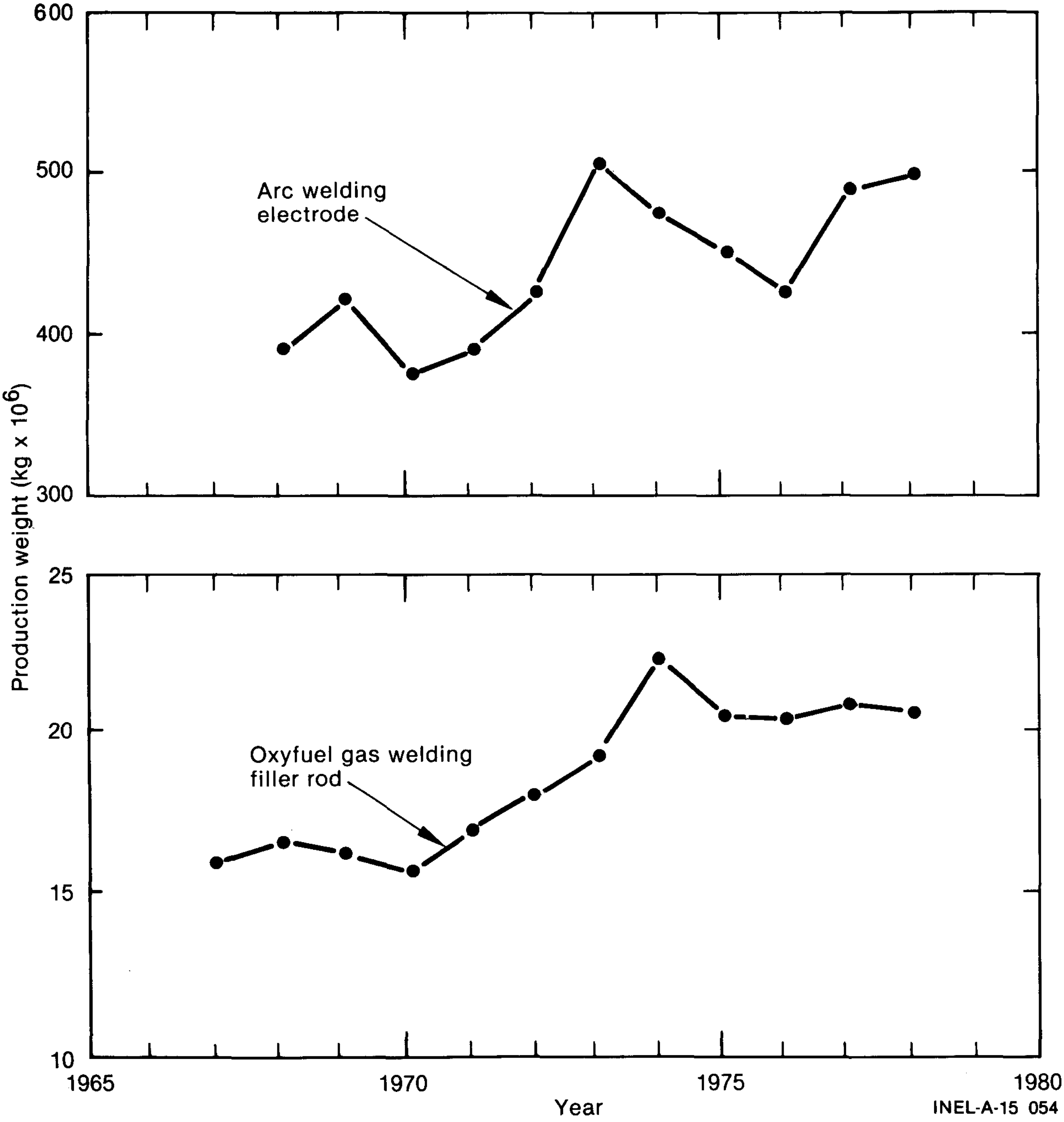

Figure 3. Annual production of arc welding electrodes and oxyfuel gas welding filler rods by weight.

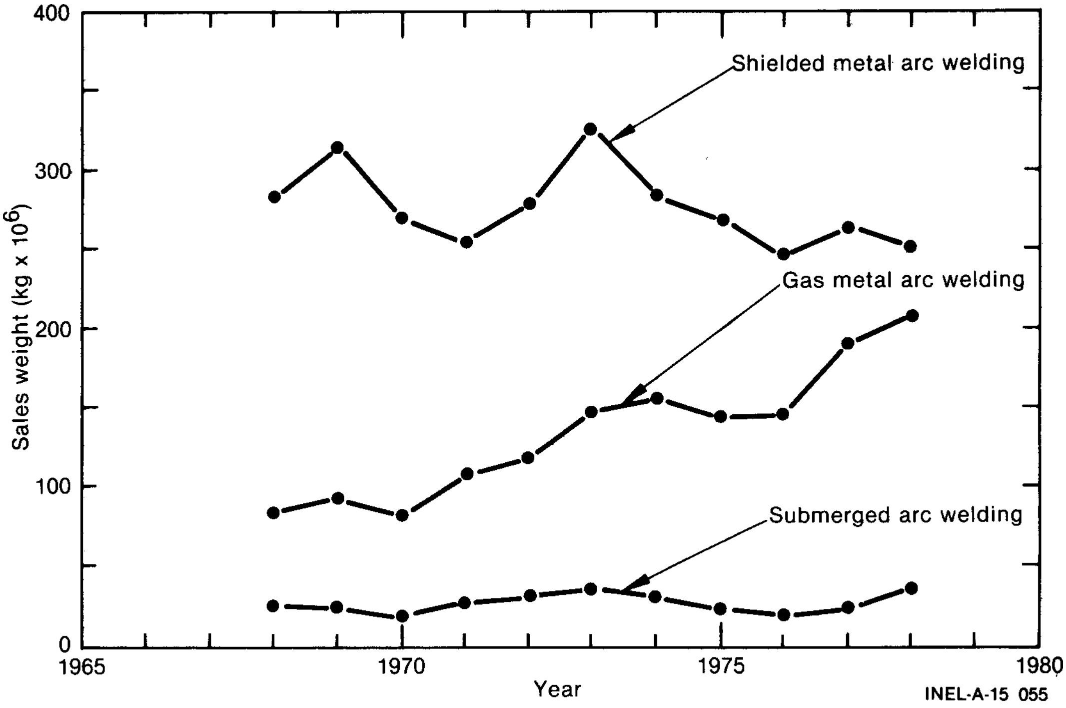

Figure 4. **Annual arc welding electrode sales by process.**

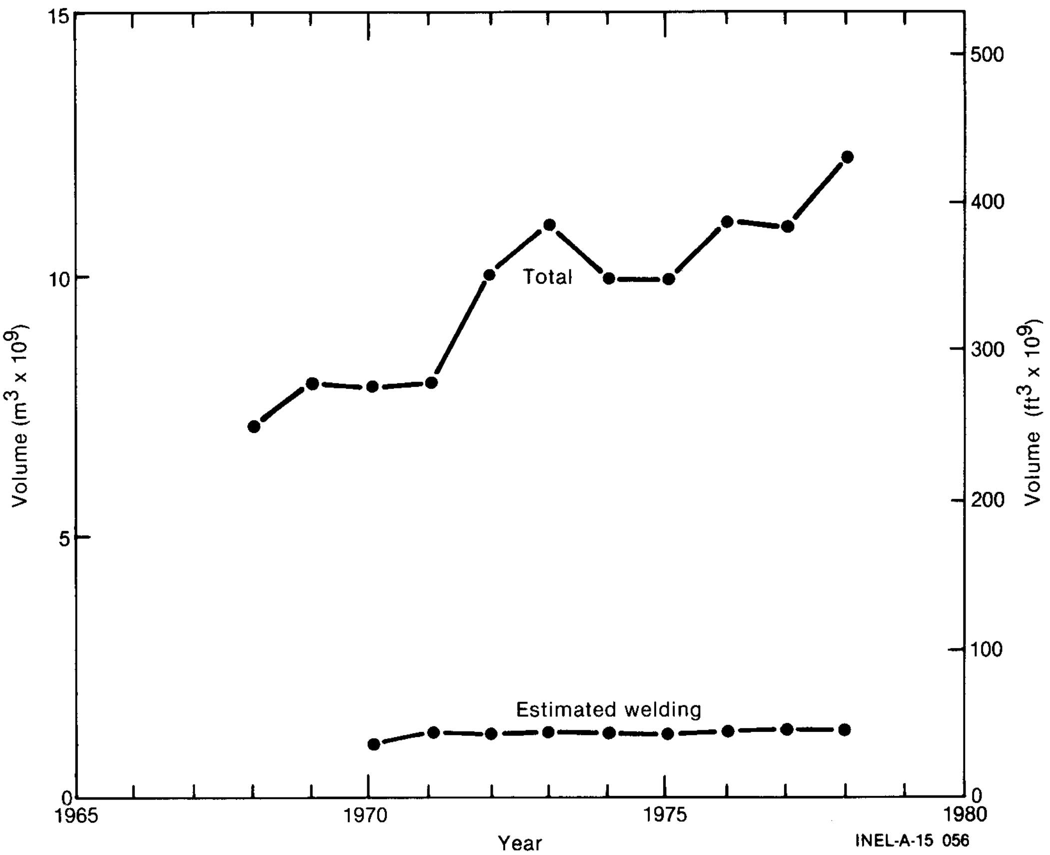

Figure 5. **Total annual production and estimated welding use of argon, acetylene, and oxygen.**

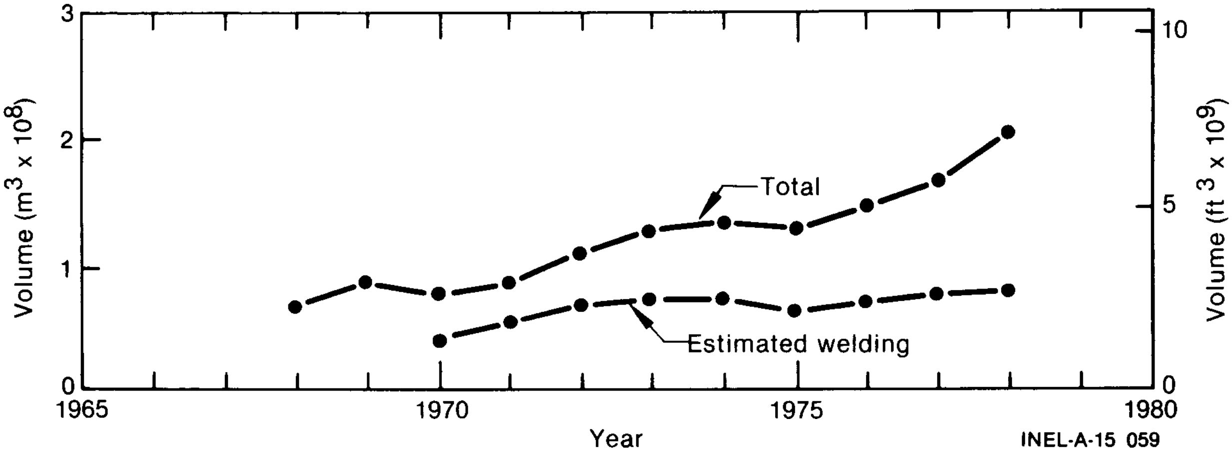

Figure 6. Total annual production and estimated welding use of argon.

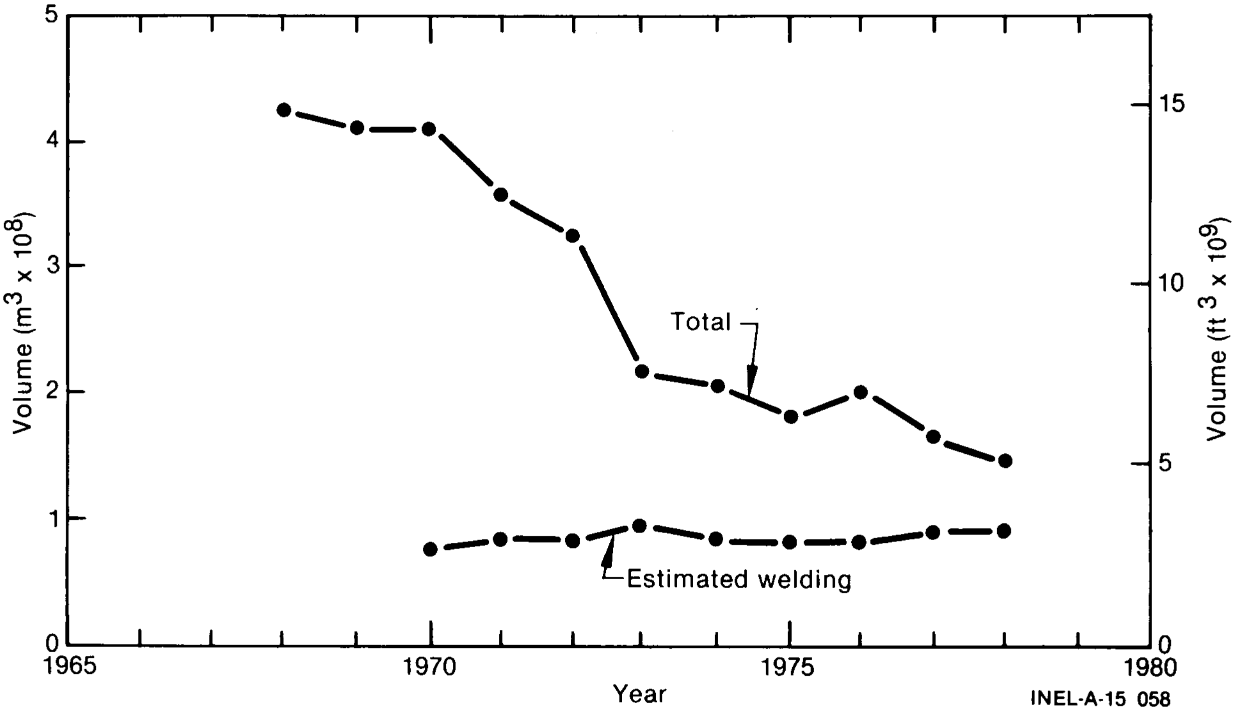

Figure 7. Total annual production and estimated welding use of acetylene.

Method of Calculation—Energy consumption of consumable materials is calculated as follows:

AW In an arc welding process, the energy consumption, E_a, in the arc is given by

$$E_a = I\ V\ t \tag{1}$$

where I and V are the arc current and voltage, respectively, and t is time.

The specific energy consumption $E' = E_a/w$ is found by

$$E' = \frac{I\ V\ t}{w} \tag{2}$$

where w is the weight of *purchased* filler metal required for welding during the time t.

The total annual arc energy consumption, $E_{a(total)}$ is given by

$$E_{a\ (total)} = E'\ W = \frac{I\ V\ t}{w}\ W \tag{3}$$

where W is the total weight of filler metal sold annually for the process. However, for any arc welding process there are numerous welding parameters used, each with its own specific energy consumption value E'_i. Equation (3) is valid only if E' is typical of the set of E'_i values. Arbitrarily assuming the average value of specific energy, $E' = \frac{1}{n}\sum_{i=1}^{n} E'_i$, to be typical of the process, Equation (3) may be rewritten as

$$E_{a\ (total)} = E'\ W = \frac{1}{n}\left(\sum_{i=1}^{n} E'_i\right) W \tag{4}$$

Neglecting energy losses between the power supply and the arc, due for example to cable resistance, the total power supply input energy is

$$E_{in\ (total)} = \frac{E_{a(total)}}{\eta_1} = \frac{W}{\eta_1}\ \frac{1}{n}\sum_{i=1}^{n} E'_i \tag{5}$$

where η_1 is the typical power supply efficiency.

The total primary energy consumption E_p is

$$E_p = \frac{E_{in\ (total)}}{\eta_1\ \eta_2} = \frac{W}{\eta_1\ \eta_2}\ \frac{1}{n}\sum_{i=1}^{n} E'_i \tag{6}$$

where $\eta_2 = 0.325$ (see Primary Energy Conversion).

By using the value for annual filler metal sales for W, Equation (6) gives the annual primary energy consumption.

The specific energy consumption values which are used in this work are based on data from References 14 and 15. Normal curves representing the distribution of specific energy values for the AW processes are presented in Figure 8. They show maximum and minimum values calculated from the process data sets. The associated mean and standard deviation values from the data sets are given in Table 1.

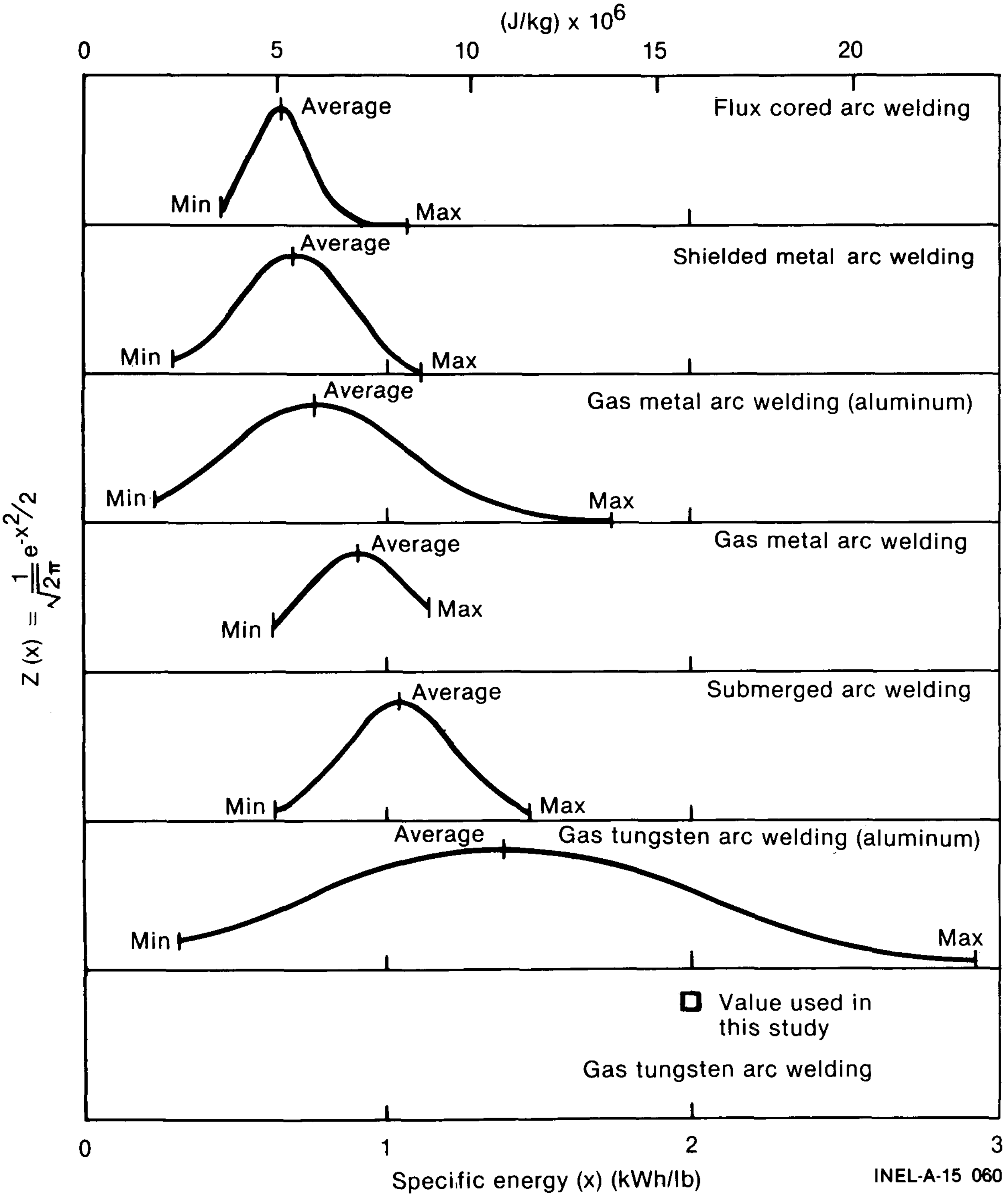

Figure 8. Normal distribution curves for process specific energy consumption per unit weight purchased electrode.

TABLE 1. SPECIFIC ENERGY CONSUMPTION VALUES

Welding Process	Mean	Standard Deviation
Flux Cored Arc Welding	5.1×10^6 J/kg (0.64 kWh/lb)	7.7×10^5 J/kg (0.097 kWh/lb)
Shielded Metal Arc Welding	5.5×10^6 J/kg (0.69 kWh/lb)	1.5×10^6 J/kg (0.63 kWh/lb)
Gas Metal Arc Welding (Aluminum)	6.1×10^6 sJ/kg (0.77 kWh/lb)	2.4×10^6 J/kg (0.30 x kWh/lb)
Gas Metal Arc Welding	7.1×10^6 J/kg (0.90 kWh/lb)	1.6×10^6 J/kg (0.20 kWh/lb)
Submerged Arc Welding	8.2×10^6 J/kg (1.04 kWh/lb)	1.5×10^6 J/kg (0.19 kWh/lb)
Gas Tungsten Arc Welding (Aluminum)	1.1×10^7 J/kg (1.38 kWh/lb)	5.2×10^6 J/kg (0.65 kWh/lb)
Gas Tungsten Arc Welding	1.6×10^7 J/kg (2.0 kWh/lb)	

Results—Energy consumption based on consumable materials has been determined for the SMAW (shielded metal arc welding), SAW (submerged arc welding), and GMAW and GTAW (gas metal arc welding and gas tungsten arc welding) processes. The energy estimation process was conducted in two parts. First, the specific energy consumption, in units of energy per unit weight of purchased electrode consumption, was determined. Second, the total energy was determined from the total weight of purchased electrode and power supply efficiency; the total energy was then converted to primary energy.

SMAW For shielded metal arc welding sheet and plate of various thicknesses, the energy consumed per unit *purchased* electrode weight was calculated for butt, corner, edge, lap, and tee joints in flat, horizontal, vertical, and overhead positions using data from Reference 14. Calculations were made for 284 different cases. The data in Reference 14 include joint geometry, plate thickness, current, time required for foot of joint welded, and pounds of electrode to be purchased per foot of weld. The arc voltage was calculated for each case by[16,17]

$$V = 20 + 0.04\ I \tag{7}$$

where V is voltage (V) and I is current (A). The data are for welding of steel, thus neglecting SMAW of aluminum. However, considering the low relative usage of aluminum welding electrodes[13] this should not affect the results significantly.

The average specific energy consumption for the SMAW process is 5.5×10^6 J/kg (0.69 kWh/lb). Average specific energy values are used in this report arbitrarily; it is not obvious that a better choice can be easily determined. The total primary energy consumption was found by using the average specific energy consumption value, the typical power supply efficiency, the total SMAW electrode sales weight for 1978, and the primary energy conversion factor in Equation (6). The total annual primary energy consumption is 6.3×10^{15} J (6.0×10^{12} Btu) from Equation (6):

$$\frac{(5.5 \times 10^6\ \text{J/kg})\ (2.60 \times 10^8\ \text{kg})}{(0.70)\ (0.325)} = 6.29 \times 10^{15}\ \text{J}$$

The above calculation is based on a power supply efficiency of 0.70 (70%). This value was taken from data obtained for typical welding power supplies, Figure 9.

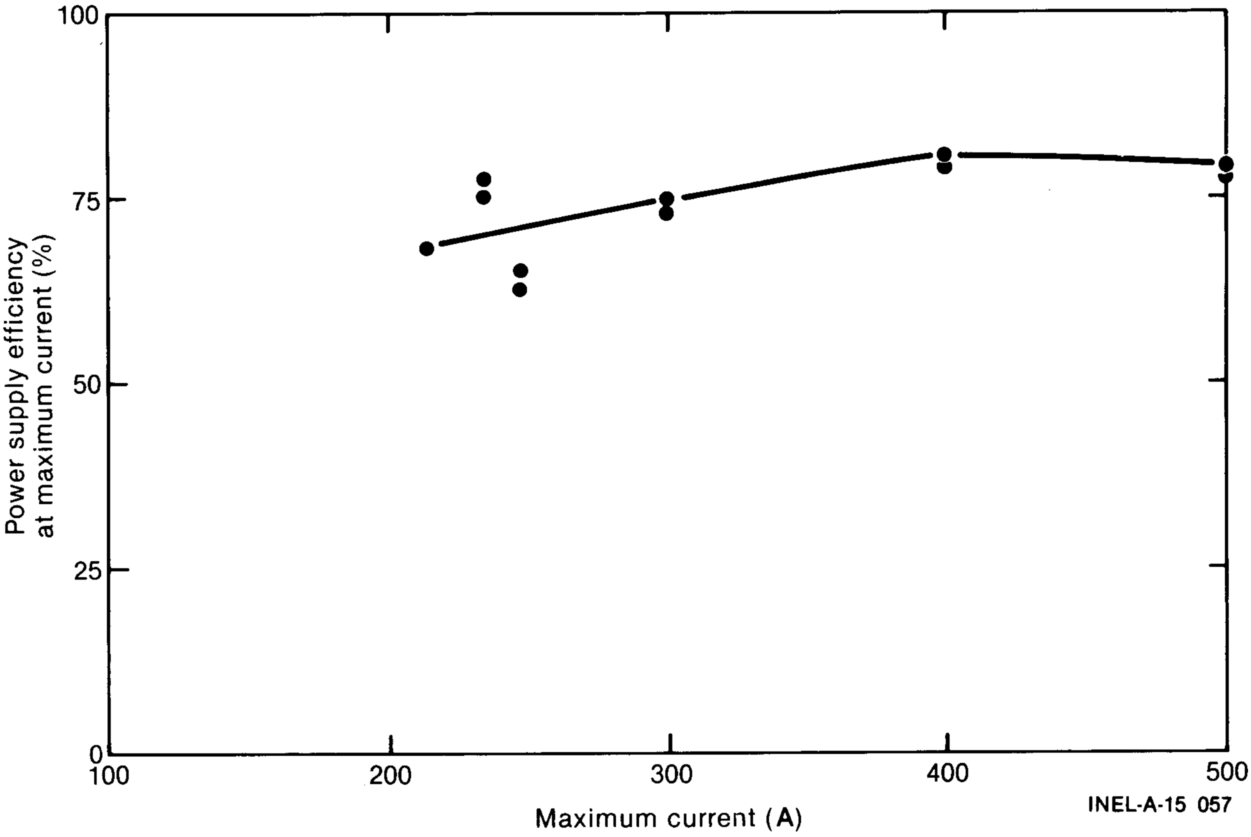

Figure 9. Efficiency of typical welding power supplies.

SAW The energy used per unit purchased electrode weight for the SAW process was calculated for sheet and plate steel of various thicknesses for butt, corner, lap, and tee joints in flat and horizontal (tee joints) positions using data from Reference 14. Calculations were made for 340 different cases. The data include joint geometry, plate thickness, current (amperes), voltage (volts), total time (h/ft of weld), and electrode consumption (lb/ft of weld).

The average specific energy consumption is 8.4×10^6 J/kg (1.1 kWh/lb). Using a power supply efficiency of 0.70 (70%) the total annual primary energy consumed by the SAW process is determined to be 1.3×10^{15} J (1.2×10^{12} Btu), calculated from Equation (6):

$$\frac{(8.4 \times 10^6\ \text{J/kg})\ (3.6 \times 10^7\ \text{kg})}{(0.70)\ (0.325)} = 1.33 \times 10^{15}\ \text{J}$$

GMAW & GTAW Handbook data of the type used for the SMAW and SAW processes are available for GMAW and GTAW of aluminum (Reference 15). However, data for GMAW of steel are less readily available and data for GTAW of steel are limited.

ALUMINUM The energy used per unit consumed electrode weight for the GMAW and GTAW processes was calculated for aluminum of various thickness for butt, corner, edge, and tee joints in flat, horizontal, vertical, and overhead positions using data from Reference 15. Calculations were made for 86 and 82 different cases, respectively, for the GMAW and GTAW processes. The data include joint geometry, plate thickness, current (amperes), number of passes, and filler wire consumption for GTAW or electrode consumption for GMAW (lb/100 ft of weld). For GMAW, the arc voltage was given. For GTAW, the arc voltage was calculated from the equation

$$V = 10 + 0.0125\ A, \qquad (8)$$

based on data in Reference 18 (Figure 27.7, Reference 18, using argon as a shield gas).

The average specific energy consumption is 6.0×10^6 J/kg (0.76 kWh/lb) for GMAW and 1.1×10^7 J/kg (1.4 kWh/lb) for GTAW, both for aluminum welding. If it is arbitrarily assumed that 75% of aluminum welding is by GMAW and 25% is by GTAW, the annual primary energy consumption for aluminum welding is 8.6×10^{13}J (8.2×10^{10} Btu), calculated from Equation (6):

$$\text{GMAW}\quad \frac{(6.0 \times 10^6\ \text{J/kg})\ (2.7 \times 10^6\ \text{kg} \times 0.75)}{(0.70)\ (0.325)} = 5.34 \times 10^{13}\ \text{J}$$

$$\text{GTAW}\quad \frac{(1.1 \times 10^7\ \text{J/kg})\ (2.7 \times 10^6\ \text{kg} \times 0.25)}{(0.70)\ (0.325)} = 3.26 \times 10^{13}\ \text{J}$$

$$\text{TOTAL}\quad 8.60 \times 10^{13}\ \text{J}$$

STEEL The energy consumed per unit weight of deposited electrode for GMAW of steel was calculated using data for assorted joint types and plate thicknesses from Reference 19 (15 cases), bead-on-plate welding data from Reference 20 (20 cases), and butt and fillet welding data from Reference 14 (16 cases). The data from Reference 14 gave an average specific energy consumption of 7.2×10^6 J/kg (0.91 kWh/lb). This value is about 16% greater than that calculated from the data in Reference 20, which is about 8% greater than that calculated from Reference 19 data. However, the above value is used as the data are believed to be more typical of production welding.

Data from Reference 14 (210 cases) for the flux-cored arc welding (FCAW) variant of GMAW, gave an average specific energy consumption value of 5.1×10^6 J/kg (0.64 kWh/lb).

Data for GTAW of steel (Figure 3.14, Reference 3), indicate that the specific energy consumption value is about 1.6×10^7 J/kg (2 kWh/lb). Data from Reference 19 are too limited to determine a typical value, but indicate that lower values of specific energy consumption are attainable. It may be noted that for aluminum welding, for which there are good data on both GMAW and GTAW processes, the average specific energy consumption for GTAW is about 1.8 times that of GMAW. If we assume that the same ratio is true for welding of steel, then the specific energy consumption value for GTAW should be about 1.3×10^7 J/kg (1.6 kWh/lb). Based on these limited indications, a specific energy consumption value of 1.6×10^7 J/kg (2 kWh/lb), as indicated by Reference 3 data, is used in this report.

It is known that of GMAW wire sales, 64% is solid wire and 36% is flux-cored wire.[6] Flux-cored wire is not suitable for GTAW. Therefore, the GTAW share must come from the 64%. But the GTAW process may also use filler wire listed as oxyfuel gas welding filler wire. Unlike GMAW, GTAW may be used without filler wire (autogenous welding). Because data are not available on the relative use of the GMAW and GTAW processes, two arbitrary cases will be considered.

First, assume that the GTAW process is not used (or that its specific energy consumption may be approximated by that of GMAW and ignore autogenous GTAW). In this case the total annual primary energy consumption is 5.9×10^{15} J (5.6×10^{12} Btu), calculated in the following manner from Equation (6):

$$\text{GMAW} \quad \frac{(7.2 \times 10^6 \text{ J/kg})(2.09 \times 10^8 \text{ kg} \times 0.64)}{(0.70)(0.325)} = 4.21 \times 10^{15} \text{ J}$$

$$\text{FCAW} \quad \frac{(5.1 \times 10^6 \text{ J/kg})(2.09 \times 10^8 \text{ kg} \times 0.36)}{(0.70)(0.325)} = 1.69 \times 10^{15} \text{ J}$$

$$\text{TOTAL} \quad 5.90 \times 10^{15} \text{ J}$$

Second, assume that 50% of the GMAW solid wire and 50% of the oxyfuel gas welding wire is used for GTAW and that there is an additional 50% GTAW energy consumption by autogenous welding. In this case, the total annual primary energy consumption is 1.1×10^{16} J (1.0×10^{13} Btu), again calculated from Equation (6):

$$\text{GMAW} \quad \frac{(7.2 \times 10^6 \text{ J/kg})(2.09 \times 10^8 \text{ kg} \times 0.64 \times 0.5)}{(0.70)(0.325)}$$

$$= 2.12 \times 10^{15} \text{J}$$

$$\text{FCAW} \quad \frac{(5.1 \times 10^6 \text{ J/kg})(2.09 \times 10^8 \text{ kg} \times 0.36)}{(0.70)(0.325)}$$

$$= 1.69 \times 10^{15} \text{J}$$

$$\text{GTAW} \quad \frac{(1.6 \times 10^7 \text{ J/kg})(2.09 \times 10^8 \text{ kg} \times 0.64 \times 0.5 + 2.08 \times 10^7 \text{ kg} \times 0.5)}{(0.70)(0.325)}$$

$$= 5.44 \times 10^{15} \text{J}$$

$$+ \text{ Additional 50\% autogenous GTAW} \quad 2.72 \times 10^{15} \text{J}$$

$$\text{TOTAL} \quad 1.20 \times 10^{16} \text{J}$$

Effective Power Supply Efficiency—The calculations thus far ignore the typical operating pattern of welding processes. The 0.70 (70%) power supply efficiency term represents the efficiency of the power supply during the time the arc is on. However, the power supplies use energy even when the arc is off. Typical welding power supplies have duty cycle ratings ranging from 20% to 100% with 60% to 100% common for industrial units. Duty cycle is defined as "The percentage of time during an arbitrary test period, usually 10 minutes, during which a power supply can be operated at its rated output without overloading."[3] Yet, it is estimated that the ratio of arc time to total power supply on-time is probably less than 0.20 (20%) for most welding.[21]

Data obtained on arc welding power supplies indicate that the typical power supply consumes in the range of 0.5 to 1 kJ/s (0.5 to 1 kw) of power under idle conditions. The same machine may consume about 5.6 kJ/s (5.6 kW) power when welding (based on 150 A current for SMAW with a 0.70 (70%) efficiency) Thus, for example, assuming a 20% duty cycle, during a 100-hour operating period the machine will consume 2.2 x 10^8 J (60 kWh) of energy at idle, 4.0 x 10^8 J (111 kWh) when actually welding, and have a useful energy output of about 2.8 x 10^8 J (78 kWh). Thus, the effective operating efficiency of the power supply is about 0.45 (45%). It is recognized that operating efficiency is process dependent. As an example, for GTAW, using argon shielding gas and voltages of 9 to 10V at 150A current, the efficiency under conditions similar to those described for SMAW would be about 29%. However, the 45% value calculated below for SMAW is used in this work.

From Equation (7), the arc voltage is

$$20\ \text{V} + 150\ \text{A}(0.04\ \frac{\text{V}}{\text{A}}) = 26\ \text{V}$$

$$\frac{(150\ \text{A})\ (26\ \text{V})}{(0.70)}\ (1\text{W/VA})\ (1\text{J/w s}) = 5.57\ \text{kJ/s}.$$

For 100 hours operation

$$(100\ \text{h})\ (1-0.20)\ (0.75\ \text{kJ/s})\ (3600\ \text{s/h}) = 2.16 \times 10^5\ \text{kJ}$$

$$(100\ \text{h})\ (0.20)\ (5.57\ \text{kJ/s})\ (3600\ \text{s/h}) = 4.01 \times 10^5\ \text{kJ}$$

$$\text{Total}\quad 6.17 \times 10^5\ \text{kJ}\quad \text{input}$$

$$(100\ \text{h})\ (0.20)\ (26\ \text{V})\ (150\ \text{A})\ (1\text{W/V-A})\ (1\ \text{J/W-s})\ (3600\ \text{s/h}) = 2.81 \times 10^5\ \text{kJ output}$$

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{2.81 \times 10^5\ \text{kJ}}{6.17 \times 10^5\ \text{kJ}} \times 100 = 45\%.$$

The effect of idle time on the total arc welding primary energy consumption is to increase it by about 0.56 (56%), i.e.,

$$\frac{\frac{Ep}{0.45} - \frac{Ep}{0.70}}{\frac{Ep}{0.70}} = 0.56 \text{ or } 56\% \tag{9}$$

The 0.45 (45%) efficiency value is used to calculate the maximum arc welding energy consumption; the 0.70 (70%) efficiency value is used to calculate the minimum arc welding energy consumption. These calculations are made using the appropriate efficiency value in Equation (6). Results obtained using an efficiency value of 0.70 (70%) may be converted to values for 0.45 (45%) efficiency by multiplying by the ratio (0.70/0.45).

Total Arc Welding—The estimated total annual primary energy consumption by arc welding processes is summarized in Table 2. This estimate is from 1.4 to 3.1 x 10^{16} J primary energy annually. The low value is based on a 0.70 (70%) power supply efficiency and neglects GTAW of steel. The high value is based on a 0.45 (45%) power supply efficiency and assumes that 50% of GMAW solid wire and 50% of OFW filler rod is used for GTAW and that autogenous GTAW accounts for an additional 50% GTAW energy consumption.

TABLE 2. ARC WELDING ENERGY CONSUMPTION

Maximum Annual Primary Energy Consumption (J)	Welding Process	Minimum Annual Primary Energy Consumption (J)
9.78 x 10^{15}	Shielded Metal Arc Welding	6.29 x 10^{15}
2.07 x 10^{15}	Submerged Arc Welding	1.33 x 10^{15}
1.34 x 10^{14}	Gas Metal Arc Welding[a] Gas Tungsten Arc Welding[a]	8.60 x 10^{13}
3.30 x 10^{15}	Gas Metal Arc Welding	4.21 x 10^{15}
2.63 x 10^{15}	Flux-Cored Arc Welding	1.69 x 10^{15}
8.46 x 10^{15}	Gas Tungsten Arc Welding[b]	--
4.23 x 10^{15}	Gas Tungsten Arc Welding, Autogenous	--
3.06 x 10^{16}	TOTAL	1.36 x 10^{16}

a. Aluminum.

b. With filler material.

OFW. The estimate of energy consumption by OFW (oxyfuel gas welding) has also been made on the basis of consumed materials. In this case, the quantities of consumed gases have been used. In 1978, the U.S. production of acetylene was 1.5 x 10^8 m^3 (5.3 x 10^9 ft^3). It is estimated that 9.2 x 10^7 m^3 (3.3 x 10^9 ft^3) of this acetylene was used for welding. The U.S. production of oxygen was 1.2 x 10^{10} m^3 (4.3 x 10^{11} ft^3) of which 1.4 x 10^9 m^3 (4.9 x 10^{10} ft^3) are estimated to have been used for welding. All quantities given here are taken from Reference 6.

The oxygen-to-fuel-gas volume ratio for a neutral flame is about 1.1 to 1 for acetylene.[22] This leaves an excess of about 1.3 x 10^9 m^3 (4.6 x 10^{10} ft^3) of oxygen above that required by the acetylene consumption. This indicates that the consumption of fuel gases other than acetylene is in excess of 5.1 x 10^8 m^3 (1.8 x 10^{10} ft^3) as calculated below, based on a ratio of 2.5 volumes of oxygen to one volume of fuel gas.[3]

1.	Acetylene used for welding[6]	O_2: Acetylene Ratio	Oxygen Required
	(9.237×10^7 m^3) x	(1.1) =	1.02×10^8 m^3
2.	Oxygen used for welding[6]	Oxygen Required	Excess Oxygen
	(1.38×10^9 m^3) -	(1.02×10^8 m^3) =	1.28×10^9 m^3
3.	Excess O_2	O_2: Fuel Gas Ratio	Other Fuel Gas Required
	(1.28×10^9 m^3)/	(2.5) =	5.11×10^8 m^3

However, the above estimate ignores the use of oxygen-fuel gas flames for cutting. The volume ratio of oxygen to acetylene for cutting is about 15 to 1.[23] Assuming arbitrarily that 10% of the acetylene consumption was for cutting, 2.3×10^8 m^3 (8.1×10^9 ft^3) of oxygen would be required by the acetylene consumed. The appropriate calculations are given below.

1.	Acetylene total[6]		Acetylene used for cutting
	(9.237×10^7 m^3) x	(0.1) =	9.237×10^6 m^3
2.	Acetylene used for cutting	O_2: Acetylene Ratio	Oxygen Used for cutting
	(9.237×10^6 m^3) x	(15) =	1.386×10^8 m^3
3.	Acetylene total	Acetylene used for cutting	Acetylene used for welding
	(9.237×10^7 m^3) -	(9.237×10^6 m^3) =	8.313×10^7 m^3
4.	Acetylene used for welding	O_2 : Acetylene Ratio	Oxygen used for welding
	(8.313×10^7 m^3) x	(1.1) =	9.145×10^7 m^3

5. Oxygen used for welding	Oxygen used for cutting	Oxygen weld/cut total
(9.145×10^7 m^3) +	(1.386×10^8 m^3) =	2.300×10^8 m^3

This leaves an excess of 1.15×10^9 m^3 (4.1×10^{10} ft^3) of oxygen and indicates that the consumption of fuel gases other than acetylene is about 3.1×10^8 m^3 (1.1×10^{10} ft^3), calculated below, on the basis of an arbitrary ratio of 2.5 volumes of oxygen to one volume of fuel gas for welding and a ratio of 15 volumes of oxygen to one volume of fuel gas for cutting, and the use of 10% of the fuel gas for cutting.

6. Oxygen total[6]	Oxygen weld/cut total (see 5 above)	Excess oxygen
(1.38×10^9 m^3) -	(2.300×10^8 m^3) =	1.15×10^9 m^3

7. Excess oxygen	O_2: fuel gas ratio weld	O_2: fuel gas ratio-cut
(1.15×10^9 m^3) =	(2.5) x (0.09X) +	(15) x (0.1X)

where X is the total amount of fuel gas other than acetylene required by the excess oxygen (see 6 above). Thus, 0.9X is the amount of fuel gas used for welding and 0.1X is the amount used for cutting. Then,

8.

Excess Oxygen

(1.15×10^9 m^3) = 3.75 X

9.

Fuel gas (other than acetylene) required

X = 3.07×10^8 m^3

The heat produced by burning acetylene is about 5.5×10^7 J/m^3 (1470 Btu/ft^3) and is assumed to be about 8.9×10^7 J/m^3 (2400 Btu/ft^3) for other fuel gases, such as propane and methylacetylene-propadiene.[23] Thus, the total heat of combustion for OFW processes is estimated at 5.1×10^{16} J (4.8×10^{13} Btu) annually, ignoring cutting. Including the use of 10% of the fuel gases for cutting, the total heat of combustion annually is estimated at 3.2×10^{16} J (3.1×10^{13} Btu). The calculations involved in this estimate are given below.

---

1. Assume no cutting Acetylene consumed	Heat of combustion	Total heat of combustion
(9.237×10^7 m^3) x	(5.5×10^7 J/m^3) =	5.08×10^{15} J

Other fuel gas consumed	Heat of combustion	Total heat of combustion
$(5.11 \times 10^8\ m^3)$ x	$(8.9 \times 10^7\ J/m^3)$ =	$4.55 \times 10^{16} J$
	Total	$5.06 \times 10^{16} J$

2. Assume 10% cutting

Acetylene consumed	Heat of combustion	Total heat of combustion
$(9.237 \times 10^7\ m^3)$ x	$(5.5 \times 10^7\ J/m^3)$ =	5.08×10^{15} J

Other fuel gas consumed	Heat of combustion	Total heat of combustion
$(3.07 \times 10^8\ m^3)$ x	$(8.9 \times 10^7\ J/m^3)$ =	$2.73 \times 10^{16} J$
	Total	$3.24 \times 10^{16} J$

In a similar manner, it may be shown that if, arbitrarily, 50% of the fuel gases were used for cutting, the total heat of combustion annually would be 1.16×10^{16} J (1.1×10^{13} Btu). The reason that the total heat of combustion decreases with increased cutting is that less fuel gas, other than acetylene, is required. In this report the total heat of combustion for no cutting is used as the maximum estimate for OFW energy consumption while the value for 50% cutting is used as the minimum estimate.

It may be noted that the total heat of combustion of acetylene is about 10% of the total OFW energy consumption if cutting is ignored. However it is about 44% of the total OFW energy consumption if 50% of the fuel gases are used for cutting. The implications of this are that estimating energy consumption on the basis of excess oxygen is probably valid if in fact a large percentage of the fuel gases used for OFW are used for cutting. However, if only a small percentage is actually used for cutting, the method is less valid. Unfortunately, determination of the validity of the method requires detailed knowledge of the actual consumption of all fuel gases used for OFW processes. Obviously, if such data were available, the appropriate quantities of fuel gas and respective heats of combustion could be used directly to determine annual OFW energy consumption.

Product Quantity Method. In contrast to arc welding processes, the energy consumption for resistance welding (RW) has been related to the quantity of product produced. If the energy to make a typical weld in a given product is E_o, there are N_w such welds in the product, and the total, annual number of such product items produced is N_p, then the energy associated with welding that product is

$$E' = E_o N_w N_p \tag{10}$$

where E' is also the welding power supply output. The power supply input, converted to primary energy E_p , is obtained by

$$E'_p = \frac{E'}{\eta_1 \eta_2} = \frac{E_o N_w N_p}{\eta_1 \eta_2} \tag{11}$$

where η_1 is the power supply efficiency and η_2 is the primary energy conversion factor.

The electrical energy E_o required to produce a weld is

$$E_o = I\ V\ t \qquad (12)$$

where I and V are the current and voltage, respectively, in the secondary circuit of the welding machine, and t is time. Thus,

$$E'_p = \frac{I\ V\ t\ N_w\ N_p}{\eta_1 \eta_2} \qquad (13)$$

If the fraction of total, industry-wide resistance welding which is done to produce the given product is X, then the total primary energy used by industry for resistance welding is

$$E_p = \frac{E'_p}{X} = \frac{I\ V\ t\ N_w\ N_p}{\eta_1\ \eta_2 X} \qquad (14)$$

No attempt has been made to differentiate between the various types of resistance welding. Estimates[24] indicate that about 60 to 70% of domestic resistance welding is done in the automotive industry. Since the amount of resistance welding done by the automotive industry is well documented, it has been used as the basis for the energy consumption estimate.

Process data on resistance spot welding has been obtained from General Motors Corp.,[25] Ford Motor Co.,[26] and Chrysler Corp.[27] There are approximately 5000 spot welds per vehicle. Of these, 50% are made with hand-held guns using about 16 volts in the secondary circuit. The other 50% are made with press-type machines using about 8 volts in the secondary circuit. The "average" spot weld in the automotive industry joins 0.91-mm (0.036-in.) thick steel sheets using about 12,500 A at 12 V for ten cycles. (Ten cycles of a 60 Hz current waveform results in a time period of 1/6 second.) Thus, the "average" weld consumes about 2.5×10^4 J (6.9×10^{-3} kWh).

Motor Vehicle Manufacturers Association[28] domestic production and sales data for cars and light trucks shows a combined production of approximately 10.5×10^6 vehicles for 1978. An additional 2.4×10^6 heavy trucks and buses were produced but are not counted in this report, as it is understood that resistance welding is not used in their manufacture to the extent that it is used for automobiles and light trucks.

Using an energy consumption value for the "average" weld of 2.5×10^4 J (6.9×10^3 kWh) 5000 such welds per vehicle, (veh^{-1}) and a total of 10.5×10^6 vehicles (veh), the energy consumed by the automotive industry, in the secondary circuit of RW machines, is about 1.3×10^{15} J (3.6×10^8 kWh). Assuming this to be about 65% of all resistance welding, and assuming a 90% efficiency for RW power supplies, the total energy consumed by industry annually for RW is about 2.2×10^{15} J (6.1×10^6 kWh). This requires a consumption of about 6.9×10^{15} J (0.65×10^{12} Btu) of primary energy annually.

From Equation (14)

$$E_p = \frac{(12500\ A)\ (12\ V)\ (1/6\ s)\ (5000\ veh^{-1})\ (10.5 \times 10^6 veh)}{(0.90)\ (0.325)\ (0.65)}\ (1W/V\text{-}A)$$

$$(1\ J/W\text{-}s) = 6.90 \times 10^{15} J.$$

Facilities Method. Energy consumption estimates based on the number of welding machines in use have been made for the EBW (electron beam welding), LBW (laser beam welding), and FRW (friction welding) processes.

If there are N_s welding machines in use, the output power of the typical machine is P_s, and the machines are used annually a total time T, the total primary energy consumption E_p of the machines is

$$E_p = \frac{N_s P_s T}{\eta_1 \eta_2} C_d \tag{15}$$

where η_1 is the power supply efficiency, η_2 is the primary energy conversion factor, and C_d is the fraction duty cycle.

EBW. There are approximately 450 EBW systems in use[29] for welding. Of these about 10-15% are typically 15-20 kJ/s (15-20 kW) nonvacuum units. The remaining 85-90% are typically 7.5 kJ/s (7.5 kW) vacuum units. About 70% of these machines are believed to be used in high-volume (three-shift) production. Duty cycles are about 15%.

Thus, the average EBW machine is an 8.75 kJ/s (8.75 kW) unit, operated about 2500 hours per year (based on 250 work days per year). Given 450 such machines, the total beam energy consumption is 5.2×10^{12} J (1.4×10^6 kWh). Using a 90% power supply efficiency,[29] the primary energy consumption annually would be: 1.8×10^{13} J (1.7×10^{10} Btu). However, this ignores energy consumption by the power supply with the beam off (as well as the energy required to pump down the welding chamber in vacuum-type machines). An upper limit on such energy consumption may be estimated by assuming a 100% duty cycle; the primary energy consumption, calculated below, then becomes 1.2×10^{14} J (1.1×10^{11} Btu).

1. Average machine beam power

   $$(7.5 \text{ kJ/s})\ (0.875)\ +\ (17.5 \text{ kJ/s})\ (0.125) = 8.75 \text{ kJ/s})$$

2. From Equation (15)

   $$E_p = \frac{(450)\ (8.75 \text{ kJ/s})\ (2500 \text{ h})\ (0.15)}{(0.90)\ (0.325)} (3600 \text{ s/h}) = 1.82 \times 10^{13} \text{J}$$

3. Assume 100% duty cycle

   $$1.82 \times 10^{13} \text{ J } \frac{(1.00)}{(0.15)} = 1.21 \times 10^{14} \text{ J.}$$

LBW. There are estimated to be two large lasers (over 1.0 kJ/s; 1.0 kW) and about 30 small lasers (about 200 J/s; 200 W) in production welding use, believed to be limited to one shift a day, with about four hours of use per shift.[30,31] Thus, assuming the large lasers to be 2.01 kJ (2.0 kW) units, the average laser used for welding is about a 313 J/s (313 W) unit used about 1000 hours per year. The total beam energy consumed would be about 3.5×10^{10} J (9.6×10^3 kWh). The primary energy consumed annually would be about 1.1×10^{12} J (1.0×10^9 Btu), assuming[32] a 10% power supply efficiency and 100% duty cycle. The calculation is shown below.

1. Average machine beam power

   $$\frac{2\ (2.0 \text{ kJ/s}) + 30\ (200 \text{ J/s})}{(2 + 30)} = 312.5 \text{ J/s.}$$

2. From Equation (15)

$$E_p = \frac{(32)\ (312.5\ \text{J/s})\ (1000\ \text{h})\ (1.00)}{(0.10)\ (0.325)}\ (3600\ \text{s/h}) = 1.11 \times 10^{12}\text{J}.$$

FRW. There are believed[33] to be about 200 to 300 friction welding (FRW) machines in use. Of these about 75% are used for automotive production. The typical machine is rated at 2.3 x 10^4 kg (25 tons) and has an 18.6 kJ/s (25 hp) motor. Assuming 1000 hours use per machine annually, and assuming the motor's rated output is used 50% of the machine use time, the energy consumption would be 8.3 x 10^{12} J (2.3 x 10^6 kWh). The primary energy consumption would be 2.9 x 10^{13} J (2.7 x 10^{10} Btu) annually, based on a motor efficiency of 90%:

From Equation (15)

$$E_p = \frac{(250)\ (18.6\ \text{kJ/s})\ (1000\ \text{h})\ (0.50)}{(0.90)\ (0.325)}\ (3600\ \text{s/h}) = 2.86 \times 10^{13}\text{J}.$$

However, the above estimate would result in the production of about 5 x 10^8 welded parts, since the typical machine described above has a cycle time of approximately 15 to 20 seconds. Given that the major use of FRW machines for high volume production is associated with the automotive industry, it is believed that this number of welded parts (50 per vehicle) may be an order of magnitude too high. Thus, the energy consumption estimate may likewise be an order of magnitude too high.

Summary of Total Primary Energy Consumption

The total annual primary energy consumption by all welding processes included in this study is estimated to be between 3.2 x 10^{16} J (3.0 x 10^{13} Btu) and 8.8 x 10^{16} J (8.4 x 10^{13} Btu). The results for the various processes are summarized in Table 3. Using the average of the maximum and minimum estimated values, the relative primary energy consumption of the processes is shown in Table 4 and Figure 10.

TABLE 3. WELDING PROCESS ENERGY CONSUMPTION

Maximum Annual Primary Energy Consumption (J)	Welding Process	Minimum Annual Primary Energy Consumption (J)
3.06×10^{16}	Arc welding	1.36×10^{16}
5.06×10^{16}[a]	Oxyfuel gas welding	1.16×10^{16}[b]
6.90×10^{15}	Resistance welding	6.90×10^{15}
1.21×10^{14}	Electron beam welding	1.82×10^{13}
1.11×10^{12}	Laser beam welding	1.11×10^{12}
2.86×10^{13}	Friction welding	2.86×10^{13}
8.83×10^{16}	TOTAL	3.21×10^{16}

a. Assumes no cutting.

b. Assumes 50% cutting.

TABLE 4. RELATIVE DISTRIBUTION OF WELDING PROCESS ENERGY CONSUMPTION

Welding Process	Energy Consumption Distribution		Average
Arc welding	Max	$\frac{3.06 \times 10^{16} J}{8.83 \times 10^{16} J} \times 100 = 34.7\%$	38.6%
	Min	$\frac{1.36 \times 10^{16} J}{3.21 \times 10^{16} J} \times 100 = 42.4\%$	
Oxyfuel gas welding	Max	$\frac{5.06 \times 10^{16} J}{8.83 \times 10^{16} J} \times 100 = 57.3\%$	46.7%
	Min	$\frac{1.16 \times 10^{16} J}{3.21 \times 10^{16} J} \times 100 = 36.1\%$	
Resistance welding	Max	$\frac{6.90 \times 10^{15} J}{8.83 \times 10^{16} J} \times 100 = 7.8\%$	14.7%
	Min	$\frac{6.90 \times 10^{15} J}{3.21 \times 10^{16} J} \times 100 = 21.5\%$	
Other types of welding	Max	$\frac{1.51 \times 10^{14} J}{8.83 \times 10^{16} J} \times 100 = 0.17\%$	0.16%
	Min	$\frac{4.79 \times 10^{13} J}{3.21 \times 10^{16} J} \times 100 = 0.15\%$	
		Total	100%

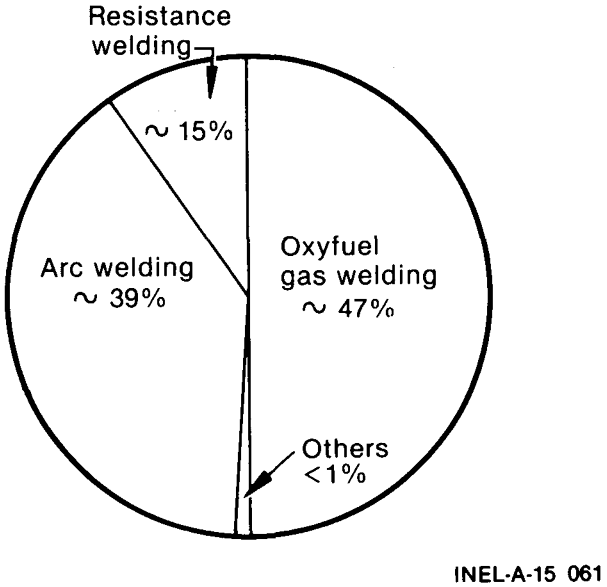

Figure 10. **Relative welding primary energy consumption.**

The OFW processes use about 47% of the welding energy. Arc welding processes use about 39% of the total primary energy, and resistance welding about 15%. The other welding processes considered consume well under 1% of the total welding energy.

PROJECTED CHANGES IN ESTIMATED ENERGY CONSUMPTION

Oxyfuel Gas Welding

During the period 1968-1978, the production of filler rod for oxyfuel gas welding increased at the average rate of about 5.9×10^5 kg (1.3×10^6 lb) per year. However, since 1975 the consumption has remained essentially constant at about 2.0×10^7 kg (4.4×10^7 lb) annually. The estimated use of acetylene for welding and, more importantly, oxygen has remained essentially constant at about 8.5×10^7 m^3 (3.0×10^9 ft^3) and just under 1.4×10^9 m^3 (5.5×10^{10} ft^3), respectively, during the past five years. This indicates that large changes in the use of the OFW process, and therefore changes in the energy consumption by the process, are not likely.

Arc Welding

During the period 1968-1978, the overall production of arc welding electrode wire increased at the rate of about 1.1×10^7 kg (2.4×10^7 lb) per year. If this rate of increase continues, electrode production should increase from about 5.0×10^8 kg (1.1×10^9 lb) in 1980 to about 6.4×10^8 kg (1.4×10^9 lb) in 1990. Thus, arc welding energy consumption may increase about 20% over the next decade.

Within arc welding, the production of SMAW electrodes has been decreasing at an approximate rate of 2.2×10^6 kg (4.9×10^6 lb) per year over the past decade. During the same period GMAW electrode wire production has increased at the rate of about 1.2×10^7 kg (2.7×10^7 lb) per year, while SAW electrode wire production has increased at the rate of about 9.1×10^5 kg (2.0×10^7lb) per year. This increased production of GMAW and SAW electrodes may result in an even greater increase in energy consumption than the 20% increase over the next decade expected on the basis of total arc welding electrode production. This is due to the fact that the specific energy consumptions of GMAW and SAW are greater than that of SMAW. However, this may be offset somewhat by increased use of the FCAW process which has a lower specific energy consumption.

Resistance Welding

The most significant changes in resistance welding over the next decade will probably occur in the automotive industry. It is reasonable to expect increased application of lightweight materials such as aluminum and especially plastics for body panels. However it is not possible to determine the extent to which this will change the energy consumption for resistance welding without detailed estimates of lightweight material usage including the associated product design changes.

Other

On the basis of present information, it does not appear that increased application of existing processes, such as electron beam welding, or development of new processes will change total welding energy consumption to a significant extent.

Summary of Projection

Overall the energy consumption by welding can be expected to increase over the next decade. The most significant increase is expected in arc welding where it appears that a 20% increase in energy consumption may occur. The authors recognize that this projection is based on limited data[6] without consideration of mitigating economic factors or technological developments.

OPPORTUNITIES FOR ENERGY CONSERVATION

As part of considering the opportunities for welding energy conservation, it is worthwhile to examine the relative importance of the current welding energy consumption to industry. The total United States annual (1978) energy consumption was 8.2×10^{19} J (7.8×10^{16} Btu). Of this, the total annual (1975) energy consumption by industry was 2.3×10^{19} J (2.2×10^{16} Btu).[2] The six major industries (chemical, primary metals, petroleum, paper, stone-clay-glass-concrete, and food) consume 1.9×10^{19} J (1.8×10^{16} Btu) annually (1975).[1] Thus, the remaining segment of industry consumes about 4×10^{18} J (4×10^{15} Btu) annually; it is assumed in this report that this value represents the manufacturing/fabrication industry and includes most welding.

Welding, which consumes about $3.2\text{-}8.8 \times 10^{16}$ J ($3.0\text{-}8.3 \times 10^{13}$ Btu) primary energy, uses about 1.5% of the energy consumed annually by the manufacturing/fabrication industry. It may be noted that manufacturing/fabrication consumes about 18% of the total energy used by industry and 6% of the total United States energy consumption. Although welding represents a very small part of the total U.S. energy consumption, the magnitude of the energy consumed is great enough to consider energy conservation opportunities.

Opportunities for welding energy conservation are presented from three standpoints. The first two of these, the effects of power supply efficiency and arc welding specific energy consumption constitute, in effect, sensitivity analyses of the energy consumption estimates. The third discusses the substitution of one process for another. These are not intended to include all opportunities for energy conservation, but are examples which represent the magnitude of potential savings.

Power Supply Efficiency

As indicated in the section Direct Energy Consumption Methodologies, the efficiency of arc welding power supplies may be considered in terms of the actual efficiency when delivering power, the effective efficiency which takes into account power losses when the power supply is turned on but not delivering power, and typical use of the power supply.

First, consider the effect of increasing the effective power supply efficiency. Assume that the power supply energy consumption during idle is reduced to zero (this represents the maximum possible energy savings). It has been shown previously, Equation (9), that the effect of idle time is to increase primary energy consumption by about 56%. Thus, elimination of idle time power losses will reduce arc welding energy consumption by about 36%. This represents a saving of about 8.0×10^{15} J (7.5×10^{12} Btu), calculated below, which is about 14% of the total primary energy consumed annually by welding

1. Reduced energy consumption by idle elimination

$$\frac{E_I}{E_W + E_I} = \frac{0.56}{1 + 0.56} = 0.36 \text{ or } 36\%$$

where E_I and E_W are "idle" and "weld" energy consumption respectively.

2. Average total primary arc welding energy consumption

$$\frac{(1.36 \times 10^{16}\ J) + (3.06 \times 10^{16}\ J)}{2} = 2.21 \times 10^{16}\ J.$$

3. Energy savings

$$(2.21 \times 10^{16}\ J) \times (0.36 = 7.96 \times 10^{15} J$$

4. Total savings

$$(0.36 \times (0.386) = 0.139 \text{ or } 13.9\%$$

Second, consider the effect of increasing the actual power supply efficiency. Assume that the actual efficiency is increased from 0.70 (70%) to 0.85 (85%). As shown above, elimination of power losses during power supply idle reduces arc welding energy consumption by about 36%. Thus, about 64% of arc welding energy consumption occurs when the power supply is delivering power. Increasing the actual power supply efficiency as described above would reduce arc welding energy consumption by a factor of $1 - \frac{0.70}{0.85}$ or 0.18. This represents an annual primary energy saving of about 2.5×10^{15} J (2.4×10^{12} Btu), which is about 11% of total annual arc welding primary energy consumption and about 4% of the total welding annual primary energy consumption. The calculations are shown below.

	Average Total Primary Arc Welding Energy Consumption	Fraction Consumed During Power Delivery	Fraction Consumption Reduced		Primary Energy Savings Annually
1.	$(2.21 \times 10^{16}\ J) \times$	$(0.64) \times$	$\left(1 - \frac{0.70}{0.85}\right)$	=	$2.50 \times 10^{15} J$

2. Percent Arc Welding Savings

$$\frac{2.50 \times 10^{15}\ J}{2.21 \times 10^{16} J} \times 100 = 11.3\%$$

3. Percent Total Savings

$$(0.113) \times (0.386) = 0.044 \text{ or } 4.4\%$$

Thus, a saving of about 18% of the total annual welding primary energy consumption would be achieved by the combination of reduced idle power consumption and increased power supply efficiency.

Welding power supplies with actual efficiencies of 0.80 (80%) or higher are manufactured by the major sources of arc welding power supplies. In addition, at least two companies have built arc welding power supplies, utilizing high frequency current, which are claimed to have *significantly* higher efficiencies.[34,35] Thus, the hypothetical 0.85 (85%) efficiency discussed above, is believed to be technologically feasible. However, there is at least one inhibiting factor which must be considered. Manual welding by the SMAW process requires a power supply which has "drooping" output characteristics. That is, the output voltage decreases rapidly as the output current increases. This is necessary to give the operator adequate manual process control. Drooping characteristics are normally obtained by using a loose-coupled transformer. Unfortunately, such transformers have low inherent efficiency (about 60%).

Power supplies which have essentially constant output voltage over their current range use close-coupled transformers which have relatively high efficiency ($\sim$80%). Such power supplies are generally used for automatic or mechanized welding. A drooping output from such a power supply may be synthesized by use of solid state controls. However, this increases the cost significantly. Thus, it is not realistic to project the use of high efficiency power supplies for all arc welding.

There are no known arc welding power supplies which have the capability of going to an essentially power-off condition when idling. But it is technically feasible to produce such a power supply using a microprocessor "monitor" and solid state switches. Such a power supply would consume only a few joules per second (watts) of power at idle. However, the cooling system for the power supply would also have to turn off. Thus, the duty cycle would be reduced, or the power supply would have to be redesigned for a 100% duty cycle, perhaps using passive heat transfer elements such as heat pipes. Certainly the cost would be increased.

There are about 300,000 arc welding power supplies sold annually.[7] The total population size is unknown but it is probably well in excess of 10^6. The average power supply lifetime is probably at least ten years. Considering the time required for development of new models it is probably realistic to expect significant utilization of high efficiency power supplies to require one or more decades, and to be limited to probably less than one half of the total power supply population at best.

Reduced Specific Energy Consumption

The average specific energy consumption for the SMAW process has been calculated as 5.6×10^6 J/kg (0.70 kWh/lb) based on data from Reference 13, published in 1973. Similar data, published in 1957, gave an average specific energy consumption of 6.1×10^6 J/kg (0.76 kWh/lb). Thus, the average specific energy consumption for SMAW decreased only about 8% in 16 years.

Most welding is done to a federal, national, or company procedure. Significant alteration of the process parameters requires recertification of the procedure. There are literally thousands of such procedures nationwide. Significant reduction in welding energy consumption by reduced specific energy consumption would require extensive development funding following demonstration of technical feasibility. Thus, it is not probable that reduced specific energy consumption by improved process efficiency will occur to any major extent over about the next decade.

Process Substitution

This section considers substitution of high-efficiency AW processes for low-efficiency AW processes, substitution of AW for OFW, and substitution of EBW for AW.

High-Efficiency Arc Welding for Low-Efficiency Arc Welding. The specific energy consumption values presented in this report give the arc energy required per unit weight of purchased electrode. The specific energy value on a per unit weight deposited basis is found by dividing the former value by the process deposition efficiency.[14] These values are listed in Table 5. Examination of Table 5 and consideration of the characteristics of the arc welding processes, indicates that substitution of GMAW for GTAW, and FCAW for SMAW should be considered.

TABLE 5. ARC WELDING SPECIFIC ENERGY AND DEPOSITION EFFICIENCY

Welding Process	Specific Energy Per Unit Weight of Purchased Electrode (J/kg)	Deposition[13] Efficiency (%)	Specific Energy Per Unit Weight of Deposited Electrode (J/kg)
Shielded Metal Arc Welding	5.6×10^6	65	8.6×10^6
Submerged Arc Welding	8.4×10^6	100	8.4×10^6
Gas Metal Arc Welding	7.2×10^6	92	7.9×10^6
Flux-Cored Arc Welding	5.1×10^6	82	6.3×10^6
Gas Tungsten Arc Welding	1.6×10^7	92	1.7×10^7

In 1978 the production of GMAW solid wire was 1.34×10^8 kg (3.0×10^8 lb). Assuming that 50% of the OFW filler wire was actually used for GTAW there would be an additional 1.04×10^7 kg (2.3×10^7lb) produced for a total of 1.44×10^8 kg (3.2×10^8 lb). The use of this wire by the GMAW process would consume 7.1×10^{15} J (6.7×10^{12} Btu) of primary energy. This represents an annual saving of 15% of the total AW primary energy consumption for 1978. The Calculations are given below:

	Total GMAW Wire	Fraction Solid Wire	GMAW Solid Wire
1.	(2.09×10^8 kg) x	(0.64) =	1.34×10^8 kg

2.	OFW Filler Wire	Fraction Used by GTAW	
	(2.08×10^7 kg) x	(0.50) =	1.04×10^7 kg
			Total
	(1.34×10^8 kg) +	(1.04×10^7 kg) =	1.44×10^8 kg

3. From Equation (6)

$$\text{GMAW} \quad \frac{(7.2 \times 10^6 \text{ J/kg})\ (1.44 \times 10^8 \text{ kg})}{(0.45)\ (0.325)} = 7.09 \times 10^{15} \text{J}$$

4.	Original GMAW Estimate	Original GTAW Estimate	Total
	(3.30×10^{15} J) +	(8.46×10^{15} J) =	1.18×10^{16} J
	Total		Savings
	(1.18×10^{16} J) -	(7.09×10^{15} J) =	4.67×10^{15} J

5.	Savings	Total Original AW (MAX)	Percent Savings
	(4.67×10^{15} J)/	(3.06×10^{16} J) x 100 =	15.3%

The above calculations are based on a power supply efficiency of 0.45 (45%) and ignore autogenous GTAW.

In 1978, there were approximately 2.58×10^8 kg (5.7×10^8 lb) of SMAW electrode produced. Assuming no other losses, there were only 1.68×10^8 kg (3.7×10^8 lb) of this electrode deposited, based on a deposition efficiency of 0.65 (65%). Thus substitution of FCAW for SMAW would require an annual production of 2.0×10^8 kg (4.5×10^8 lb) of flux-cored wire. The primary energy consumption would be 1.0×10^{15} J (9.9×10^{11} Btu) annually, based on a power supply efficiency of 0.45 (45%). This would result in annual savings of 8.73×10^{15} J (8.3×10^{12} Btu) primary energy, which is about 29% of AW primary energy, consumption. Again, the calculations are presented

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1.	SMAW Electrode Production	Deposition Efficiency	Electrode Deposited By SMAW
	(2.58×10^8 kg) x	(0.65) =	1.68×10^8 kg

2.	SMAW Electrode Deposited	FCAW Deposition Efficiency	Required FCAW Electrode Production
	(1.68×10^8 kg) x	(0.82) =	2.05×10^8 kg

3.		From Equation (6)	
	FCAW	$\frac{(5.1 \times 10^6 \text{ J/kg})(2.05 \times 10^8 \text{ kg})}{(0.45)(0.325)}$	$= 1.05 \times 10^{15}$ J

	SMAW Energy Consumption	FCAW Substitution For SMAW	Savings
4.	$(9.78 \times 10^{15}$ J) -	$(1.05 \times 10^{15}$ J) =	8.73×10^{15} J

	Savings	Total Original AW (MAX)	Percent Savings
5.	$(8.73 \times 10^{15}$ J)/	$(3.06 \times 10^{16}$ J) x 100 =	28.5%

The above calculations indicate that about 44% of AW primary energy consumption could be saved by substitution of GMAW for GTAW, and FCAW for SMAW. However, implementation of such substitution would require extensive procedure recertification. In addition, it is doubtful that weld quality and process characteristics are sufficiently interchangeable to allow such substitution for all GTAW and SMAW applications. It is conceivable that perhaps half of the indicated savings could be achieved.

Arc Welding for Oxyfuel Welding. The heat of combustion required per unit weight of deposited filler has been calculated for the OFW process (data from Table 4, p. 574, Reference 18) using oxygen and acetylene for welding 12 different wall thicknesses of steel pipe. The average specific energy value is 2.6×10^7 J/kg (1.1×10^4 Btu/lb). The individual values ranged from 1.1×10^7 J/kg (4.9×10^3 Btu/lb) to 4.6×10^7 J/kg (2.0×10^4 Btu/lb) with a standard deviation of 1.3×10^7 J/kg (5.5×10^3 Btu/lb).

In order to properly evaluate the relative use of AW and OFW processes, it is necessary to consider the energy required to produce, compress, and transport the oxygen and fuel gas consumed by OFW. The total energy consumed by the above will not be presented here. However, it is estimated[36] that the production of essentially pure liquid oxygen would require about 4.2×10^6 J/m^3 (33.3 kWh/1000 ft^3) of electrical energy. During welding under conditions corresponding to the average specific energy value for OFW, each kilogram of deposited filler metal would require the consumption of about 0.47 m^3 (16.6 ft^3) of acetylene and 0.52 m^3 (18.4 ft^3) of oxygen. It requires about 6.8×10^6 J (6.4×10^3 Btu) primary energy to produce the above amount of oxygen. The sum of the primary energy to produce the oxygen plus the heat of combustion is 3.3×10^7 J (3.1×10^4 Btu):

	OFW Average Specific Energy Consumption	Acetylene Heat of Combustion	Acetylene Required
1.	$(2.6 \times 10^7$ Jkg)/	$(5.5 \times 10^7$ J/m^3)=	0.473 m^3/kg

	Acetylene Required	0^2: Acetylene Ratio	Oxygen Required
2.	(0.473 m^3) x	(1.1) =	0.52 m^3

3.	Oxygen Required	Electrical Energy to Produce O_2[35]	Primary Energy Conversion Factor
	$(0.52\ m^3)\ \times$	$(4.24 \times 10^6\ J/m^3)/(0.325) =$	$6.78 \times 10^6\ J$

4.	Heat of Combustion	O^2 Primary Energy	Total energy for kg Deposited filler
	$(2.6 \times 10^7\ J)\ +$	$(6.78 \times 10^6\ J) =$	$3.28 \times 10^7\ J$

The primary energy consumed by AW processes is about 6.8 times the specific energy.

5. From Equation (6)

$$\frac{1}{(0.45)\ (0.325)} = 6.8$$

Thus, the average primary energy per unit weight of deposited filler metal for AW process ranges from about 4.3×10^7 to 1.2×10^8 J/kg (1.9×10^4—5.2×10^4 Btu/lb), values obtained by multiplying the appropriate quantities in Table 5 by 6.8. The values are all in excess of the total energy for OFW calculated above. Certainly the energy required for the acetylene consumed needs to be considered, but this is probably not greater than that required for the oxygen.

In summary it does not appear to be advantageous to substitute AW processes for OFW on the basis of energy consumption.

Electron Beam Welding for Arc Welding. Data from Reference 37 indicate that similar welds made using the EBW and GTAW processes require significantly less energy when processed by EBW. The beam energy required per unit length of weld by EBW is about 5 to 10% of the arc energy required by GTAW. It is probably safe to assume that substitution of EBW for any AW process would result in about a 90% energy savings.

EBW equipment requires precise positioning and fit-up of joints due to the narrow beam size. It also requires X-ray shielding and may require a hard or soft vacuum chamber in which to weld. Thus, the equipment is relatively expensive and is probably best suited for either very large volume production as part of a fully automated manufacturing system or for use on small volume production of very expensive products requiring the unique characteristics of EB welds.

The substitution of EBW for GTAW or GMAW is continuing to be implemented in the automotive industry. A major reason for this is the increased welding speed of EBW relative to the other processes. This certainly reduces welding energy consumption, but it is probably not realistic to expect a major decrease in welding energy consumption due to increased use of EBW.

CONCLUSIONS

Methodologies have been developed to estimate the annual primary energy consumption directly associated with coalescence by arc welding (AW), oxyfuel gas welding (OFW), resistance welding (RW), and certain other welding processes.

The total annual primary energy consumption by welding processes in the U.S. during 1978 has been estimated to be in the range of 3.2 to 8.8 x 10^{16} J (3.0 - 8.3 x 10^{13} Btu). Of this amount, AW processes consume about 39%, OFW about 47%, RW about 15%, and the other processes considered less than 1%.

Opportunities for energy conservation exist. The development and implementation of high efficiency arc welding power supplies with reduced idle energy consumption could reduce the annual arc welding energy consumption by about 18%; although it is probably not realistic to expect to achieve more than about a 9% reduction. It would probably require several decades to achieve this level of savings. The substitution of AW processes such as FCAW for SMAW and GMAW for GTAW could potentially reduce AW primary energy consumption by about 44%, about one-half of which could realistically be obtained.

Future studies of welding energy consumption should determine the energy consumption by brazing (B), soldering (S), and induction welding (IW) processes. Data are needed on the consumption of fuel gases other than acetylene for OFW. The primary energy content of consumable materials, including filler wire and fuel gases, is also needed. Finally, a study of energy consumption by indirect welding-related operations such as fume ventilation, preheating, stress relieving, and joint preparation should be made.

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