PHYSICS OF THE WELDING ARC IN MAGNETIC FIELDS

A Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science

by

William Francis Peck

The Ohio State University

1966

Approved by

Advisor

Department of Welding Engineering
ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to Professor C. E. Jackson for his encouragement and resourceful counseling throughout this thesis program. His guidance in technical writing has been most helpful in preparation of this manuscript.

I wish also to acknowledge: the Welding Research Council for its financial support under a grant from the University Research Committee, Mr. Merle Rhoten for his advice on photographic techniques, the Motion Picture Department of OSU for general cooperation and in particular, Messrs. Richard Sherman and John Friend for shooting the high-speed films, Mrs. Natalie Hudec as manuscript typist, the Alcoa Company for contributing aluminum filler wire and base material, and the Union Carbide Linde Division for general cooperation and making welding equipment for this thesis available.

I am indebted to Mr. G. K. Hicken, who preceded me in the study of arc magnetics and constructed the electromagnet and field control system used.
# TABLE OF CONTENTS

**LIST OF FIGURES**                                      v
**LIST OF TABLES**                                       viii
**ABSTRACT**                                              1
**INTRODUCTION**                                          5
**ARC MAGNETICS: A REVIEW OF THE LITERATURE AND**        8
**DEVELOPMENT OF FUNDAMENTAL THEORY**
  **THEORY ON MAGNETIC FIELDS**                           8
  **REVIEW OF THE LITERATURE ON ARC MAGNETICS**           16
  **THEORIES ON ARC DEFLECTION**                          21
  **WELDING ARCS IN PARALLEL AND TRANSVERSE**             33
    **FIELDS**                                            
      **Gas-Tungsten-Arc**                                33
      **Submerged-Arc**                                   44
      **Gas-Metal-Arc**                                   47
  **CURRENT STATUS OF ARC MAGNETICS**                     49
**PURPOSE AND OBJECTIVES**                               51
**EXPERIMENTAL PROCEDURE**                               52
  **LABORATORY EQUIPMENT**                               52
  **PHOTOGRAPHIC TECHNIQUES**                             60
**SUMMARY AND PRESENTATION OF DATA**                     65
**SUMMARY OF DATA**                                      65
PRESENTATION OF RESULTS

Gas-Tungsten-Arc Slides

Gas-Metal-Arc Slides

Drawings from High-Speed Films

Movie: "The Gas-Metal-Arc in Transverse Magnetic Fields"

DISCUSSION

INITIAL ARC PHYSICS CONSIDERATIONS

Thermal Aspects of Metal Arcs

Color-Temperature Analogy

Plasma Streaming Resulting from Self-Magnetic Compression

EXPLANATION OF SLIDES AND HIGH-SPEED FILMS

Gas-Tungsten-Arc: Still Photographs and Sketches

Gas-Metal-Arc: Still Photographs and Sketches

High-Speed Films

CONCLUSIONS

BIBLIOGRAPHY

APPENDIX

A. MAP OF MAGNETIC FIELD

B. MAGNETIC PINCH AND PLASMA STREAMING

C. SAHA'S EQUATION FOR ARC TEMPERATURE

D. SPECTROGRAPHIC DTERMINATION OF
LIST OF FIGURES

2. Left-Hand Rule for Arc Deflection.
5. Anode Spot Displacement as a Function of Applied Transverse Field Strength.
6. Arc Rotation Speed as a Function of Arc Current.
7. Arc Velocity as a Function of Applied Field Strength.
8. Change in Plasma Length as a Function of Applied Field.
9. Area of Metal Melted as a Function of Applied Field.
10. Weld Bead Appearance on HY-80 at 15 ipm Travel Speed; With and Without Applied Field.
11. Photograph of Laboratory Equipment.
12. Photograph of Special Base Plate Fixture to Reduce Effect of Extraneous Fields and Aerodynamic Drag.
13. Schematic of Electromagnet and Field Control System.
15. Gas-Tungsten-Arc; Normal Stable Mode.
17. Gas-Tungsten-Arc; Semi-Stable Deflection.
18. Gas-Tungsten-Arc; Stable Deflection.
22. Gas-Tungsten-Arc; Approaching Extinction.
23. Gas-Metal-Arc; Stable Deflection.
24. Gas-Metal-Arc; Metal Transfer Outside of Plasma.
26. Gas-Metal-Arc; Metal-Vapor Stream.
27. Gas-Metal-Arc; Unstable Deflection.
30. Gas-Metal-Arc; Stable Deflection.
32. Gas-Metal-Arc; Stable Deflection.
33. Gas-Metal-Arc; Unstable Deflection.
34. Gas-Metal-Arc; Impending Extinction.
35. Gas-Metal-Arc; Transition to Instability Leading to Extinction.
36. Gas-Metal-Arc; Typical Sprag Transfer at High Current Density for 1/16" Dia. Filler Wire.
37. Gas-Metal-Arc; Sprag Transfer in Magnetic Field Leading to Tumbling of Droplet Transferred Outside the Arc Core.
38. Gas-Metal-Arc; Pushing Molten Metal Ahead of the Weld Pool.
40. Gas-Metal-Arc; Spiral Whipping of Filamental Neck Leading to Break-up into Fragmentary Droplets.
41. Stream Lines and Velocity Profile of a 200-Ampere Carbon Arc. 50
42. Radial Temperature Distributions for the 5 mm. Argon Arc, 200-Amps and 400-Amps. 54

D1. Optical System for Spectrographic Analysis of the Welding Arc. 55
D2. Optical Arrangement Showing the Zonal Division of the Plasma.
D3. Observed (Left Section) and Cross-Sectional (Right Section) Iso-intensity Contour Maps of the 300-Amp, 5 mm, Atmospheric Argon Arc.
LIST OF TABLES

TABLE I. Data for High-Speed Films.
TABLE II. Data for Gas-Tungsten-Arc Slides.
TABLE III. Data for Gas-Metal-Arc Slides.
TABLE IV. Data for Sketches from High-Speed Films.
TABLE V. Table of Contents for Movie: "The Gas-Metal-Arc in Transverse Magnetic Fields."
TABLE VI. Structure of the Gas-Metal-Arc on Steel.
TABLE A-II. Data for Mapping Applied Field on Stainless Steel.
TABLE A-III. Data for Mapping Applied Field on Aluminum.
**LIST OF ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCRP</td>
<td>Direct Current Reverse Polarity</td>
</tr>
<tr>
<td>DCSP</td>
<td>Direct Current Straight Polarity</td>
</tr>
<tr>
<td>M/S</td>
<td>Carbon Steel</td>
</tr>
<tr>
<td>S/S</td>
<td>Type 308 Stainless Steel</td>
</tr>
<tr>
<td>Al</td>
<td>Type 5083-H113 Aluminum</td>
</tr>
<tr>
<td>β</td>
<td>Magnetic Induction, Flux Density Gaussian</td>
</tr>
<tr>
<td>H</td>
<td>Magnetizing Force, newtons</td>
</tr>
<tr>
<td>μ</td>
<td>Permeability of Free Space = $4\pi \times 10^{-7}$ webers/ampere-meter</td>
</tr>
<tr>
<td>I</td>
<td>Current, Amperes</td>
</tr>
<tr>
<td>V</td>
<td>Voltage, Volts</td>
</tr>
<tr>
<td>$L_0$</td>
<td>Electrode Spacing</td>
</tr>
<tr>
<td>$F_L$</td>
<td>Lorentz Force, newtons</td>
</tr>
</tbody>
</table>
ABSTRACT

Still and high-speed photography have been employed to study the response of gas-tungsten arcs and gas-metal arcs to transverse magnetic fields of up to 200 gauss. Carbon steel, stainless steel and aluminum were studied using straight- and reverse-polarity arcs. A 30-minute color movie has been produced which demonstrates the effects of a constant transverse magnetic field on the gas-metal-arc.

Photographic techniques were developed for 35-mm. color slides to yield realistic color and reveal metal transfer within the arc column while retaining definition of the plasma components. An 85-B color correction filter and 1.0 neutral density filter were used on an Exakta camera with a 135 mm. telephoto lens. Exposures at 1/1000 sec. on Kodachrome II daylight film were decreased 3 f-stops from those indicated by light-meter measurements. Color movies at 4000 fps using the same f-stop and filter adjustments showed metal transfer without the use of backlighting.

Study of the effects of magnetic fields on welding arcs requires an understanding of what each color and component of the plasma represents. This understanding is developed by considering four aspects of the arc plasma: (1) composition, (2) temperature, (3) color and (4) streaming. It is first shown that ionization of metal vapor is responsible for electrical conduction in metal vapor arcs. Saha's
equation is then applied to calculate arc temperatures based on current density and ionization potential of the arc. A relationship is established between plasma temperature and color radiated to relate composition and temperature to the visual appearance of the arc. Finally, plasma streaming due to self-magnetic compression is related to the structure and dynamic behavior of the arc.

The ferrous gas-metal-arc has four components. The blue-white core of ionized and excited metal vapor and excited argon atoms has a reported temperature of 6,000° K and high velocity due to the constriction at the electrode. The core originates from the end of the electrode and decreases in current density towards the base plate. A red-orange inner sheath of excited iron-oxide vapors originates from the electrode above the core. A blue outer sheath is composed of lower-temperature excited metal and argon atoms. Blue metal vapor and red iron-oxide vapor appear as tail flames at the base plate due to dispersion of the electrode plasma stream.

Fleming's left-hand rule is useful in determining arc deflection but must be interpreted to consider the high velocity of plasma streams in the conducting core of the arc. Arc deflection is evidence of a skewed velocity distribution of the plasma stream from the electrode. Distortion of a deflected arc occurs as the magnetic pumping action is unbalanced by the applied field producing an arc with high directional stability on one side and a lower velocity streaming on the other.
Deflection of the main plasma stream from the electrode away from the base plate is accompanied by development of a plasma stream from the base plate. Streaming from the base plate occurs because the normal suppressing action of the electrode plasma stream is reduced and because the active spot on the base plate is constricted which results from a decrease in heat transferred to the active spot from the electrode stream. Plasma streams from the base plate do conduct current as evidenced by their deflection in magnetic fields. Anode and cathode streams are deflected in the same direction.

Strong applied fields separate the cores of anode and cathode streams permitting study of streaming, plasma structure and metal transfer. Electrode streams may be deflected so far as to become parallel to each other. Electron conduction then occurs through the region between the visible plasma cores without emission of visible radiation due to low current density. The inertia of these plasma streams causes continuation of their motion even after they stop conduction but visible radiation disappears soon after the loss of Joule heating.

Two forms of plasma instabilities exist that often lead to arc extinction but do not always occur as the arc extinguishes. Horizontal rotation of the electrode plasma stream occurs through about 90° and is accompanied by separation of the stream from the base plate. Vertical spinning of the electrode plasma stream may progress
through several revolutions causing a pinwheel appearance. Spinning
is accompanied by migration of the active spot on the base plate away
from the electrode. Spinning and rotation do not usually occur simul-
taneously but either can lead to arc extinction in less than 1/1000
second. When spinning begins, forces are exerted on the electrode
tip of sufficient strength to bend the end of a 1/16" diameter electrode
into a U shape through a radius of less than 1/4" in a 150-gauss field
as shown in high-speed films.

Arc extinction in strong applied fields occurs as the result of
excessive disturbance of the direction and symmetry of the velocity
distribution of the plasma stream from the electrode. Development
of a plasma stream from the base plate further deflects the stream
from the electrode. Extinction occurs when the plasma streams from
the two electrodes are separated so widely that current density be-
tween streams is so low that the plasma cools to the point where it
will no longer conduct the arc current.
INTRODUCTION

In 1808 Davy and Ritter generated an electric arc between horizontal charcoal rods. Because of the thermal convections this first arc was bent upwards, hence its name "arc" which is still in use today. By 1815 the high temperature of the arc was known and in 1821 Davy described the action of a magnetic field on an arc. The illuminating aspects of the arc were under investigation by 1850 while the systematic physical investigation of the arc was not begun until the late 1860's. Twenty years later Luggin and Lecher determined by the first probe measurements that the arc voltage consists of three separable regions; the anode drop, the cathode drop and the plasma voltage. In 1934 Elenbass and Heller published their theory on the arc plasma.\textsuperscript{50}

More recently, considerable extension of the operating parameters, especially towards greater currents and higher pressures, has resulted in broadening of the earlier arc mechanism concepts. Increasingly-accurate electrical and thermal data for the arc region have been determined as the technology for arc welding expands. Jackson\textsuperscript{51} has defined the welding arc as "a sustained electrical discharge through a high-temperature conducting plasma, producing sufficient thermal energy so as to be useful in the joining of metals by fusion".
The electric arc was first applied as a heat source for welding around the turn of the century. The basic patents for the gas-metal-arc process were obtained in 1930; successful development work resulted in their release to industry in 1948. At this time, the gas-metal-arc was fundamentally a high-current density process. Since then the short-circuiting arc and pulsed-arc transfer mechanisms have expanded the gas-metal-arc's versatility. The gas-tungsten-arc, patented in the 1930's, gained popularity during World War II and now is in wide use.

The fact that electric arc plasmas are "flexible conductors" and as such will be subject to forces in magnetic fields was recognized early in the study of arcs. In the early 1930's magnetic arc blow was basically understood and external magnetic fields were applied to the inert-gas-shielded welding arc in the late 1940's. During the 1950's, many of the aspects of controlling and modifying the arc welding processes with magnetic fields were explored in the laboratory and several patents arose out of these investigations. In the early 1960's, Soviet investigators advanced the technology on arc magnetics substantially. The approach of the Soviet investigators has been more technical than the development-oriented work sponsored in other countries.
The following thesis is a study on arc magnetics with particular attention to the inert-gas-shielded arcs in transverse magnetic fields. Fundamental theory on magnetic fields is developed using metric units. Following this, the concept of the "self-field" is developed and the motor-rule deflection resulting from interaction of the self-field with an external field is studied. Nomenclature for parallel, transverse and longitudinal magnetic fields is proposed.

The literature on arc magnetics is first reviewed to consider the theories on arc deflection and then to consider the individual investigations discussing specific field-process interactions.
ARC MAGNETICS: A REVIEW OF THE LITERATURE
AND DEVELOPMENT OF FUNDAMENTAL THEORY

THEORY ON MAGNETIC FIELDS

The basic phenomena resulting from interaction of arcs and magnetic fields are derived from Fleming's rule which determines arc deflection. Although the concept of Fleming's rule is well known, its derivation and system of units are often poorly understood. It seems appropriate that the theory of magnetic fields should be considered with particular emphasis on units before the literature on arc magnetics is reviewed.

Magnetism, like gravity and electricity, is a field phenomenon. Although the nature of the magnetic field is not thoroughly understood, vector quantities for the interaction of fields and the transmission of forces through a field can be readily calculated.

The magnetic field consists of lines of force or flux. All lines of flux are equivalent but each one must originate at a north magnetic pole and end at a south magnetic pole. The strength or intensity of a magnetic field at any point is represented by a vector quantity, $\beta$, called magnetic induction. The magnetic induction at any point may be defined as the force per unit north magnetic pole acting on any pole placed at that point.

$$\beta = \frac{F}{P_n}$$ (1)
Where $\beta$ is measured in webers per square meter, the force, $F$, will be in newtons and $P_n$ is measured in ampere-meters. The direction of the magnetic field at any point is the direction of the force that a north magnetic pole placed at that point would experience. Magnetic induction can be thought of as a measure of the density of flux.

Coulomb found that the force acting between two magnetic poles is proportional to the product of pole strengths and inversely proportional to the square of the distance between the poles.

$$F = k \frac{PP'}{d^2} \quad (2)$$

In the MKS system, $k$ equals $10^{-7}$ webers/ampere-meter, and $P$ and $P'$ are the respective pole strengths in ampere-meters. The pole separation, $d$, is measured in meters. By combining Eqs. (1) and (2), the magnetic induction at a point near a single pole may be obtained.

$$\beta = kP/d^2 \quad (3)$$

In the MKS system, a line of induction is called a weber. In the CGS system, a line of induction is called a maxwell. ($1 \text{ weber} = 10^8 \text{ maxwells} = 1 \text{ volt-second}$). The total number of lines of induction passing through a surface is called a magnetic flux, $\phi$. Where the surface area, $a$, is normal to the lines of force:

$$\phi = Ba \quad (4)$$
In the MKS system, $\phi$, the total flux is measured in webers. The flux density, $\beta$, is often measured in gauss. (1 gauss = 1 Maxwell/cm$^2$ = 10$^{-4}$ weber/meter$^2$ = 10$^{-4}$ newton/ampere-meter).

Oersted discovered the interaction between electricity and magnetism in 1820, by observing the deflection of a compass caused by the proximity of a current-carrying conductor. Carter has used the magnetic circuit law* to distinguish between the magnetizing force, $H$, and the magnetic induction, $\beta$. $H$ is associated with the current that caused the field. Beta is associated with the effect of the field, making itself felt by forces on current-carrying conductors and on current loops within atoms of magnetized metals.

$$\beta = \mu_0 H$$  \hspace{1cm} (5)

where $\mu_0$ is the permeability of free space. For most non-ferromagnetic materials, $\beta/H = 1$. In the CGS system; $\mu_0 = 1$ in air, the unit of $B$ is gauss, and the unit of $H$ is oersted. Since one ampere-turn/meter equals $4\pi \times 10^{-3}$ oersted, $\mu_0 = 4\pi \times 10^{-7}$ webers/ampere-meter in the MKS system.

---

Magnetic Circuit Law* 42

\[ \int_C H \cdot ds = \sum I \]  \hspace{1cm} (equation 6.8.4 p. 96)

The line integral of $H$ around any closed path is equal to the total current linked with that path.

\[ \sum (H \times \text{length}) = \sum (\text{ampere-turns}) \]
A circular magnetic field is associated with the movement of both positively- and negatively-charged particles. Fleming's right-hand rule states that when a current-carrying conductor is grasped with the right hand such that the thumb points in the direction of current flow from plus to minus, the fingers will circle the conductor and point in the direction of the lines of magnetic flux. This "self-field" is strongest at the surface of the conductor and increases rapidly with the current density in the conductor. The self-field results in a pinch effect which contributes strongly to the nature of the plasma and to the mechanisms of metal transfer in consumable electrode welding. A second principal statement of magnetic pinch in combination with the conical geometry typical of most welding arcs results in an axial force directed from the smaller cross-section to the larger.

The field associated with a long current carrying conductor is derived from Boit's Law. The field structure is shown schematically in Fig. 1 and may be calculated by Eqs. (6), (7), and (8).

\[ B = \left( \frac{\mu_0}{2\pi} \right) I \frac{r}{R} \]  \hspace{1cm} (6)

\[ B = \left( \frac{\mu_0}{2\pi} \right) I \] \hspace{1cm} (7)

\[ B = \left( \frac{\mu_0}{2\pi} \right) I \frac{1}{r} \] \hspace{1cm} (8)

where:

\[ \mu_0 = 4 \times 10^{-7} \text{ weber/ampere-meter} \]

\[ I = \text{amperes total current} \]
Fig. 1. Self-Magnetic Field About a Current-Carrying Conductor.
\[ R = \text{radius of conductor - meters} \]
\[ r = \text{radius at point of interest - meters} \]
\[ \beta = \text{webers/meter}^2 = \text{gauss} \times 10^4 \]

From Fig. 1, it can be seen that the magnetic field is strongest at the circumference of the conductor and rapidly increases in strength with the current density.

The force on a current-carrying conductor in a magnetic field was discovered by Faraday in 1821, and is the principle upon which modern electric motors are designed. Because arc deflections in magnetic fields are based on this same principle, they are often referred to as motor-rule deflections.

Deflection of the arc plasma is the most obvious and most common result of applying either a parallel or a transverse magnetic field to the welding arc. The arc deflection results from the interaction of the self-field of the welding current and the component of the external field which is perpendicular to the current. The field interaction results in a Lorentz force which bends and distorts the flexible plasma. The magnitude of the Lorentz force, \( \vec{F}_1 \), is proportional to the vector product of the arc current, \( \vec{I} \), and the strength, \( \vec{\beta} \), of the external magnetic field.

\[ \vec{F}_1 = k(\vec{I} \times \vec{\beta}) \quad (12) \]

\( \vec{F}_1 \) will be in newtons when \( I \) is measured in amperes, \( \beta \) is measured in gauss, and \( k = 10^4 \). The vector designation for \( \vec{F}_1 \) indicates that
the magnitude, \( |F_1| \), \( F_1 = I \times \beta \times \sin \theta \) where \( \theta \) is the angle between \( I \) and \( \beta \) acts in a direction mutually perpendicular to \( \beta \) and \( I \). The direction of \( F_1 \) is determined by the left-hand or motor rule as illustrated in Fig. 2. To apply the motor rule, extend the thumb, forefinger and center finger of the left hand so as to form right angles with each other. When the forefinger points in the direction of positive current flow (from + to -) and the thumb points in the direction of \( \beta \) from north to south, the center finger will point in the direction of \( F_1 \).

Arc deflection may be understood intuitively if one thinks of the flux lines circling about the conductor (using the right-hand rule) adding to the applied field lines on one side and canceling the applied field lines on the other side. The current will then see a high concentration of flux on one side and a void of flux on the opposite side. Quite naturally, the arc will seek the path of least resistance and deflect toward the flux void.
Fig. 2. Left-Hand Rule for Arc Deflection.

\[ \mathbf{F}_L = k(\mathbf{I} \times \mathbf{\beta}) \]
REVIEW OF THE LITERATURE ON ARC MAGNETICS

Two broad generalizations stand out when the literature on arc magnetics is reviewed. First is that magnetic research directed from theoretical considerations has been conducted almost exclusively with gas-tungsten-arcs, and the gas-metal-arc process has not been considered extensively. The work conducted with the gas-tungsten-arc, although far from complete, has established a firm foundation for understanding the behavior of arc plasmas under the influence of external magnetic fields.

The extensive work of Finkelberg and Maecker using a carbon arc has contributed significantly to the understanding of general arc phenomena. The publications of Jackson and of Wood and Beall have furthered the understanding of metallic arcs. Many additional references on arc physics are cited in the bibliography of this thesis. With these understandings of the arc as a starting point, the gas-metal-arc requires further study of its behavior in external magnetic fields.

Aside from the works of Finkelberg and Maecker, the literature on arc magnetics is mainly American or Soviet. The second generalization is that American literature is possibly less technical but more comprehensive than the Soviet literature.

Extensive current activity of the Soviet investigators in the field of arc magnetics research suggests there is a direct profit incentive for pursuing the study of arc plasmas influenced by applied
magnetic fields. This thesis, however, will use a transverse magnetic field fundamentally as a probe to investigate the nature and composition of the gas-metal-arc plasma.

The following convention for nomenclature of magnetic fields associated with welding arcs will be used since it agrees best with that in the literature. Transverse fields are those which have flux lines normal to both the electrode axis and the weld travel axis. Motor rule deflection will be along the weld axis, either forward or backward. Those magnetic fields having flux lines parallel to the direction of travel will be called parallel fields. Parallel fields produce motor rule deflections to the left or right of the weld axis in the plane of the electrode axis. Longitudinal fields have flux lines parallel to the electrode axis and result in constriction and rotation of the arc plasma. The nature of the self-magnetic-field has already been explained. Magnetic fields developed by welding current returning to ground through the base material have been discussed by several investigators \(^{20, 21}\) and will not be considered here except as they are a part of the magnetic circuit of the welding arc \(^{10, 13}\) or as they contribute to the per cent error in experimental data. The neglect of the effects of these last fields is justified by the fact that all investigators have taken precautions to eliminate extraneous magnetic fields from the vicinity of their experiments or else they have analyzed the nature of the magnetic circuit of the welding arc and considered it in their
analysis. The nomenclature adopted for externally-applied magnetic fields is illustrated in Fig. 3.

A brief summary is appropriate before the literature is reviewed in detail. Nearly all investigations have been conducted on direct current arcs, most of which have been DCSP. All investigators have observed deflections consistent with the motor rule. The changes in deflection caused by reversal of either the welding current or the magnetic field polarities are interchangeable. It is noted however, that reversing the polarity of the welding current will have additional effects on the arc plasma and weld deposit.

Arc deflection forward in the direction of weld travel generally results in a more uniform weld that is wider but has less penetration. Forward deflection nearly always facilitates a considerable increase in the weld travel speed before undercutting occurs. Backward arc deflections over the metal just deposited characteristically produce high, narrow beads that have somewhat deeper penetration. The heavy undercutting, high-crown bead shape and necessity to reduce the weld travel speed resulting from backward arc deflections are undesirable.

Constant parallel fields are of little value since they produce non-symmetrical weld deposits. Reversing parallel fields (50 and 60 cps) however cause the arc to oscillate back and forth across the weld axis with a frequency equal to that of the applied field. The arc oscillation has a slight time lag with respect to the cycle of the applied
Fig. 3. Nomenclature for Applied Magnetic Fields.
field due to aerodynamic drag on the plasma. Where a consumable electrode is used, droplet detachment will occur at the instant of maximum arc deflection and will follow a path in the direction of arc deflection at the instant of separation.

The arc plasma loses stability in parallel and transverse fields when the applied field strength exceeds a critical limit determined primarily by the arc current and voltage. Most beneficial effects of applied fields occur at field intensities below the critical strength. It is possible to extinguish the arc by applying sufficiently strong parallel and transverse magnetic fields.

Longitudinal fields cause the plasma to rotate, however, the nature of this rotation is controversial. Several experiments have been designed to show whether the plasma is a solid shell of a cone arc or rapidly-rotating line element of plasma. The findings of these experiments are not in agreement. The change in pressure inside the cone arc has been studied. Both increases and decreases have been observed. In all cases, the longitudinal field stabilized the arc in space, and slightly constricted the plasma.

Arc deflections are accompanied by an increase in arc voltage due to two separate factors. First, the effective arc length is increased even though the electrode spacing remains fixed. Secondly, the plasma core is exposed more directly to radial cooling which result in higher radial power losses to the environment and lower conductivity of the plasma column.
Theories on Arc Deflection

Many investigators have approached the phenomena of arc deflection from a theoretical perspective. Several basic equations have been proposed to compute the dynamic and static equilibrium of the deflected arc. These equations have in turn been expanded and combined to yield calculated data suited for comparison with experimental data.

Bachelis' has proposed a simplified method for calculating the deflection of the DCSP gas-tungsten-arc in a constant transverse magnetic field. The arc is regarded as a straight conductor of constant cross-section with the properties of a rigid body. An elastic restoring force, \( Q \), is assumed proportional to the magnitude, \( X \), of arc deflection. The proportionality constant, \( k \), is a measure of the "arc stiffness".

\[
Q = kX
\]

(10)

The arc stiffness is independent of the position in space and dependent in general on the nature of the arc. An equation for the deflection of the anode spot, \( X_a \), as a function of the magnetic field strength, \( H \), can then be derived by summing the moments of the effective forces about a point in the arc column.

\[
X_a^2 - \frac{k I_o X_a}{2 \mu_0 H L_a} + L_o \, L^2 = 0
\]

(11)
where:
\[ L_o = \text{electrode spacing} \]
\[ L_a^2 = X_a^2 + L_o^2 = \text{straight arc length} \]
\[ \mu = 1.256 \times 10^{-8} \text{ oersted/cm} \]

Analysis of Eq. (14) yields critical values for magnetic field strength and anode spot deflection.

\[ H_{cr} = \frac{k}{4\mu_o L_a} \]  \hspace{1cm} (12)
\[ X_{a,cr} = L_o \]  \hspace{1cm} (13)

Critical values refer to conditions which will result in arc extinction.

Stiffness of the arc column can be derived from Eq. (14).

\[ k = 2 \mu_o H L_a (L_o^2 + X_a^2)/L_o X_a \]  \hspace{1cm} (14)

Bachelis has also determined an empirical formula for the arc stiffness:

\[ k = \mu_o C L_a^2/L_o \]  \hspace{1cm} (15)

where \( C \) is a dimensionless coefficient depending only on the nature of the arc. For the DCSP gas-tungsten-arc, burning in argon on a steel plate anode, \( C = 5.6 \).

Experimental investigations were carried out in an argon atmosphere and steel anode to determine the displacement of anode spot. Curves obtained for \( k \) as a function of \( I_a \) and \( L_o \) are shown in Fig. 4. Calculated and empirical data for \( H_{cr} \) are in good agreement. Empirical curves for \( X_a \) as a function of \( H \) are shown in Fig. 5 for
Fig. 4. Experimental Curves for Arc Stiffness, $K$, as a Function of Current, $I_a$, and Arc Length, $L_o$.  

$K \times 10^{-4}$ J/cm$^2$

$L_o = 0.8$ cm.  
$L_o = 1.7$ cm.  
$L_o = 2.5$ cm.

$I_a$ Amperes

$I_a = 120$ amps

$I_a = 80$ amps

$I_a = 50$ amps

$I_a = 32$ amps

$L_o$ cm
Fig. 5. Anode Spot Displacement as a Function of Applied Transverse Field Strength.

1. $I_a = 50$ amperes $L_0 = 2.5$ cm.
2. $I_a = 80$ amperes $L_0 = 2.5$ cm.
3. $I_a = 120$ amperes $L_0 = 2.5$ cm.
4. $I_a = 32$ amperes $L_0 = 0.8$ cm.
5. $I_a = 50$ amperes $L_0 = 0.8$ cm.
6. $I_a = 80$ amperes $L_0 = 0.8$ cm.

Anode Spot Displacement, cm.

Applied Field Strength, $A/cm.$
currents from 30 to 80 amperes and electrode spacings of 0.8 to 2.5 cm.

Despite the broad simplifying assumptions, Bachelis' analysis of arc deflection results in remarkable agreement with experimental data.

Research into carbon arcs\textsuperscript{39} burning in uniform transverse magnetic fields has shown that the arc column behaves as a flexible gaseous conductor "held" at the anode and "free" at the cathode.\textsuperscript{8} The axis of the arc column is distorted into a circular curve. The distortion begins at the cathode and increases continually towards the anode. The same phenomena, although in a dynamic condition, have been observed in an alternating transverse magnetic field.

Deflection of the plasma streaming from the cathode of metallic arcs makes the flow of vapors from the anode more readily visible. This occurs because the vertical velocity component of the cathode plasma stream is reduced thereby reducing the normal suppression of any anode plasma stream. This phenomena has been photographed by Serdyuk\textsuperscript{8} for Cu\textsuperscript{−} - Al\textsuperscript{+} and C\textsuperscript{−} - Cu\textsuperscript{+} arcs. The anode counter-currents are very pronounced with copper but less dominant for aluminum and even less for iron.

Serdyuk\textsuperscript{8} refers to arcs with the cathode stationary and the arc column distorted as "arcs distorted by magnetic fields". An equation of dynamic equilibrium is proposed to describe these arcs.
\[ M_a + \phi(v) + f(s) = F(s, t) \] (16)

\( M_a \) = the inertial force of the gas current in the arc.

\( \phi(v) \) = the aerodynamic resistance of the atmosphere through which the arc is moving with a velocity \( v \).

\( f(s) \) = the elastic regulating force of the magnetic field of the distorted column. This force is similar to that of Eq. (13) except that it is position-dependent.

\( F(s, t) \) = the external or disturbing force which is generally a function of both time and displacement.

Serdyuk\(^8\) has developed approximate equations for each of the terms in Eq. (16). "The principal property of the electrodynamic force \( F(s, t) \), is that its direction is always normal to the axis of the arc column, whatever the position and degree of distortion of the arc column. All of the counter-effective forces therefore are directed normal to the arc column axis, counterbalancing the effect of external disturbances."\(^8\)

The differential equation resulting from substitution of the separate terms into Eq. (16) is non-linear and cannot be solved by use of elementary functions. However, a theoretical relationship has been obtained relating current, the intensity of the controlling magnetic field and the radius of curvature of the arc column. The radius of curvature is found to be constant in a uniform transverse magnetic field.
Taren and Gagen\textsuperscript{12} have obtained an analytical expression for the aerodynamic resistance of the atmosphere to the movement of the arc plasma in a magnetic field. Two steel tubes with external diameters of 89 mm and wall thicknesses of 7 mm were placed on the same axis with a gap of 2.5 mm between their ends. Opposing residual magnetic fields were established by placing coils over the tube ends and passing opposing magnetizing currents through each coil. A residual flux of 25 gauss remained after the coils were removed. An arc struck between the ends of the tubes began to move rapidly in the gap along the internal edges of the ends of the tubes, with a variable angular velocity about the axis of the tubes. The speed of the arc reached a maximum and then decreased as is shown in Fig. 6. The higher the current the higher the maximum speed reached and the shorter the time required to reach maximum speed. The reduction of speed after the maximum is attributed to a reduction of flux density due to heating of the tube ends. The air resistance was found to be proportional to the speed of movement of the arc to the 0.8 power and not to the square of the speed as is the case of movement of a solid body in air. This lower power is explained by a "head wind"\textsuperscript{12} that ventilates the moving air column. Guile\textsuperscript{21} however suggests that the reason for such a deviation lies in the cathode emission mechanism. The transfer of emitting sites along the cathode surface generally exercises a dominant influence on the arc motion.
Fig. 6. Arc Rotation Speed as a Function of Arc Current.
Taren and Gagen\textsuperscript{12} have also studied the resistance of the cathode spot to displacement. An anode spot has almost unlimited mobility, but the rate displacement of the cathode spot is postulated as dependent upon the thermal inertia of the surface area of the cathode. Several investigators have established that the active spots do not move smoothly, but rather in jumps.\textsuperscript{4,12,21,23} Study of oscillograms\textsuperscript{12} has shown that as the temperature of the electrode surfaces increased to the melting point, the speed of the arc increased and the number of jumps made by the arc decreased. Evidently, as the temperature of the cathode spot increases, it becomes easier for the spot to move.

Guile\textsuperscript{21} has studied the velocity of an arc in a magnetic field in considerable detail. Self-magnetic drive was used to propel an arc between two parallel electrodes linked electrically by the arc plasma. Arc velocity increased with current magnitude, but wide variations were observed as a function of the electrode material. Arc velocity increased for all current levels as the strength of an external magnetic field was increased. The dependence of arc velocity on field strength is shown in Fig. 7.

"In DCSP welding arcs, the current density, magnetic field strength, and consequently excess pressure, all decrease from the cathode spot to the column, because the cross-section increases rapidly in this direction. The result is the formation of a plasma jet.
Applied (External Magnetic) Field Strength, gauss.

Fig. 7. Arc Velocity as a Function of Applied Field Strength.
streaming from the active spot along the normal to the surface and down the pressure gradient. Two phenomena are associated with the formation of the plasma jet in arcs; first the arc is established in space and secondly, it exerts a pressure on the molten pool. Both effects are proportional to the square of the current. Thus the arc can be likened to a conductor carrying both electrical charges in vector motion and a plasma jet in purely kinetic motion. "Kovalev\(^2\) has regarded the intrinsic magnetostrictive field and the arc stabilized by the directed motion of the plasma jet as a single entity whose deflection in a magnetic field depends on the relationship between the two types of forces involved.

A constant angle of arc deflection was selected to determine the relationships between \(H\), \(L\), and \(I_a\). The field strength required to maintain the arc at the prescribed angle of deflection increased linearly with current strength. \(H\) times \(L_0\) was a constant for a given angle of arc deflection. The displacement of the spot was found to be proportional to the square of the arc length, \(L\).

The basic limitation to the control of welding arcs by transverse magnetic fields is the limited ability of the arc to deflect without breaking. A deflected arc will break long before it reaches the critical breaking length for axially-symmetrical elongation due to collapse of the anode spot. \(^3\) The distance to which the active spot is displaced by the magnetic field will depend on the momentum of the jet and will thus be inversely proportional to \(I_a\). \(^3\)
The electrodynamic nature of the plasma flow in an arc is a result of the difference in velocity between the constituents of the plasma. Plasma velocities in the core of a carbon arc have been shown\(^3\) to be 10-100 times those in the outer sheath. Accordingly, the core and outer sheath undergo different deflections in a transverse magnetic field. The current-carrying core remains almost straight whereas the sheath deflects through a much larger angle and is bent into a smooth curve. Since the sheath acts as a heat-shield for the core, its displacement upsets the thermal balance within the core. The core is then cooled causing the voltage gradient along the arc deflected by a transverse magnetic field to increase more rapidly with length than if it were simply drawn out.

Deflections of the DCSP arc are predominately a function of cathode streaming due to magnetic pumping. If, however, constriction takes place at the anode as usually occurs between the active spot and the arc column, a plasma jet or stream will be formed at the anode. Moreover, a stream of metal vapor is often found at the anode of high-current inert-gas-metal-arcs. When the cathode and anode spots are arranged axially-symmetrical, both of the streams from the anode are suppressed by the stronger cathode stream.\(^3\) The formation of an anode stream stabilizes the anode spot. The combined effect of the stable anode spot and the reduced suppression of the anode streams when the cathode stream is deflected by a transverse magnetic field,
produces a distinct anode stream which is deflected in the same
direction as the cathode stream. Kovalev and Akulov\textsuperscript{3} theorize that
charged particles are ejected from the arc column at the point where
the two streams meet, and their loss must be compensated for by
additional arc voltage. Extinction of the arc is therefore attributed
to loss of thermal equilibrium at the point of stream impingement
resulting from arc deflection in a transverse magnetic field.

Welding Arcs in Parallel and Transverse Magnetic Fields

Many practical applications for the welding arc have been
obtained by modifying the arc with parallel and transverse magnetic
fields. The literature in this area is predominately American and
the result of either laboratory development work or innovations
originating from production welding problems. As such, the litera-
ture is less technical than that previously reviewed but has imme-
diate value in terms of immediate welding applications. The gas-
tungsten-arc, submerged-arc, and gas-metal-arc have all been
subjected to magnetic control or modification. The use of magnetic
control of the welding arc has increased production rates and the
quality of welded products usually resulting in lower costs.

Gas-Tungsten-Arcs in Magnetic Fields. Gas-tungsten-arc
has been the process most often subjected to magnetic control. In
addition to several papers on the theory of arc deflection which deal
with the gas-tungsten-arc, at least ten publications appear which
discuss practical advantages and applications of magnetic control
of the gas-tungsten-arc.

Hicken and Jackson\textsuperscript{14} have determined the visual and macro-
scopic effects of a constant transverse magnetic field applied to the
gas-tungsten-arc with special interest directed to the appearance of
the weld bead. Data were based on 180 bead on plate welds made on
two magnetic and two non-magnetic materials. Analysis techniques
included photographs of the arc and macro-sections of the weld beads.

Arc deflection was found to increase linearly as the applied
magnetic field was increased. Deflection slopes of 60 gauss/inch
for a 1/4" arc length and 40 gauss/inch for a 3/8" arc length indi-
cate that long arcs are more readily deflected than short arcs. Plasma
length as a function of applied field strength increased slowly up to
about 20 gauss. Above 20 gauss the slope increased and the curve
became asymptotic at about 30 gauss. Above 30 gauss the arc became
unstable. Deflection at 32 gauss was as much as 3/4-inch. The change
is plasma length as a function of applied field strength is shown in
Fig. 8.

The width of the weld bead produced in the absence of an applied
field could be reduced uniformly up to 50 per cent by applying forward
arc deflection with field strengths of up to 30 gauss. Weld width
variations respond very rapidly to changes in the applied magnetic
Fig. 8
Change in plasma length as a function of applied field using 190 amperes, 20 volts, 10 ipm, \(\frac{1}{4}\)\" arc gap and 20 cfm argon on stainless steel.\(^{14}\)
field, decreasing as the field strength increased. Macro-sections of the weld beads indicated that the area which represents the volume of base metal melted decreased as the magnetic field was increased. This relationship is shown in Fig. 9. Observations of weld appearance indicated that when the magnetic fields were sufficient to cause a noticeable decrease in weld width, the arc's tendency to wander decreased and the number of ripples seemed to be increased. The weld penetration was decreased by deflecting the arc forward, although this was not as significant as the change in weld width.

A magnetic field as low as 2 gauss was sufficient to cause significant arc deflection of the Al\textsuperscript{+} - W\textsuperscript{−} arc. "The welding arc on aluminum was characterized by an extremely large flame sheath region in comparison to the cathode flame region. The cathode flame produced with low applied magnetic field strengths was small in volume and the flame sheath was insignificant in size. As the applied field increased, the total cathode flame and flame sheath increased. The flame sheath increase was apparently in proportion to the increase in the cathode flame size. As the applied magnetic field was increased even further, the flame sheath increased in size and the area of the cathode flame in contact with the test material decreases as the visible arc plasma was displaced vertically away from the test plate."

The arc deflections observed on stainless steel indicated that welding current had little effect on variations in arc deflection but
Fig. 9

Area of metal melted as a function of applied magnetic field for stainless steel.\textsuperscript{14}
that arc deflection increased significantly as arc voltage prior to application of the external field was increased. In all cases where the anode was stainless steel, the arc became unstable and would be extinguished when the magnetic field had a magnitude of 35 gauss or more.

The gas-metal-arc subjected to a transverse magnetic field lost all symmetry and the plasma exhibited areas of varying brightness. Arc deflection in the aluminum plasma was the same as that observed on austenitic stainless steel. The major difference associated with the aluminum alloy was a greater increase in total plasma length as a function of applied field strength, and the reduction in visible plasma contact with the anode material. This is believed to have been caused by an increase in metal vapor present in the plasma due to the lower melting and boiling points of aluminum. When helium was added to the arc atmosphere the clarity between the cathode and anode flames became more obscured. "With the arc plasma deflected forward and the outer flame sheath separated from the main plasma, the heat associated with this flame sheath probably preheats the base metal before the main heat from the cathode flame produces the weld metal. The preheating effect of forward arc deflection may well be related to the increase in undercut free weld travel speed facilitated by forward arc deflection, which occurs in both magnetic and non-magnetic materials. The application of a 15 gauss transverse magnetic
field on maraging steel, for example, produced an undercut free weld at 350 amps and 50 ipm whereas 9 ipm was the maximum speed without arc deflection. A typical example of the improvement in weld appearance and increased weld travel speed associated with forward arc deflection is shown in Fig. 10.

Breymieier\textsuperscript{17, 18} attached a magnetic gas cup to the gas-tungsten-arc torch to produce a transverse magnetic field. An undercut free weld in 16-gage type 304 stainless steel was made at 250 amps and 50 ipm using this device whereas 30 ipm was the maximum possible without magnetic control. The gas cup established about a 90 gauss field in the arc region; some difficulty was encountered in starting the arc.

Miamidian\textsuperscript{19} has noted a slope of about 150 gauss/inch for forward deflection of a 200 ampere DCSP gas-tungsten-arc in argon. A maximum arc deflection of 0.3 inches was observed at 90 gauss just before arc extinction.

Serdyuk\textsuperscript{1} has studied the stability of an arc rotating between a circular water-cooled copper electrode and a concentric inner electrode used for welding tubes and tubular arrays. Straight polarity is designated as welding with the outer copper electrode negative. The magnetic coils were set up on the same axis so as to produce a transverse magnetic field. It was found that only DCRP (\textsuperscript{Cu}⁺ - \textsuperscript{Fe}⁻) was amenable to magnetic control. Cine movies revealed
Fig. 10

HY-80 using 288 amperes DCSP, 18 volts, 15 inches per minute travel. Weld on right subjected to transverse magnetic field of approximately 50 gauss.\textsuperscript{14}
that the causes of instability are related to the mobility of the anode spot and collapse of the arc column. "When the form of the arc is determined by a plasma stream from the tube as anode, it will rotate between the concentric electrodes without interruption. However, as soon as the cathode spot moves to the side of the copper electrode, the arc breaks. The reverse polarity arc between concentric electrodes will rotate stably over a wide range of controlling magnetic field strengths; most of the plasma streaming effect is permanently directed from the inner electrode (cathode) to the outer electrode in the direction of rotation. The cathode plasma jet streams ahead of the arc, and since the active spot is forced to move ahead with it the arc remains stable for long periods of time."

For stable motion, the active spot on the outer electrode must take the lead and the plasma jet must stream from the inner electrode to the outer. This can be accomplished only by making the inner electrode the cathode.

It has been shown that the displacement of the welding arc in a transverse magnetic field is determined by the streaming of the plasma from the cathode spot into the arc column. Based on this analysis, Kovalev has stabilized the deflected arc by injecting a stream of gas along the electrode axis. A "guide-wall" effect is produced for the arc in an alternating magnetic field by a former comprising a pair of parabolic-shaped graphite or copper shoes. This arrangement stabilizes the sheath at the extremes of magnetic field
alterations; at the same time the anode stream rebounds from the walls and meets the cathode stream head-on, thereby allowing maximum anode spot displacement. The guide-wall effect reduces the angle between the anode and cathode stream velocity vectors and stabilizes the sheath around the arc core. Keeping the anode and cathode streams on the same axis improves both the stability of the arc and the absolute limiting anode spot displacement. Using guide walls and a stabilizing current of shielding gas, \( H_{cr} \) is appreciably higher and the maximum anode spot deflection is 2 - 2.1/2 times greater. Arc penetration is reduced at the same time.

Cushman\(^{30}\) has placed 4 small ALNICO magnets in the gas-tungsten-arc gas cup to produce a field which reinforces the self-field on the sides of the arc and cancels the self-field on the ends of the arc along the weld axis. The small magnets produce a fan-shaped arc at currents up to 400 amps. The narrow restricted arc was used to reduce undercutting on stainless steel tube weldments.

Bachelis\(^{7}\) has studied the manner in which the DCSP gas-tungsten-arc burning in argon on stainless steel can be made to act as a split heat source by the action of an alternating parallel magnetic field. The arc plasma oscillates in synchronism with the intensity of applied magnetic field. The oscillation was approximately sinusoidal and the heat emitted in the anode spot was assumed constant and independent of arc deflection. The thermal characteristics of a dispersed
arc were then determined in relation to the position of the anode spot. Maximum heat emission was found to occur near the maximum deviation of the anode spot, thus causing the "split-arc" to act as two separate heat sources. Final size and shape of the molten weld pool depends not only on the arc power of these sources but also on their relative positions. If the heating spots from the two sources do not overlap appreciably, two separate welds may be formed on the parent material. As the strength of the alternating field was increased, the area of fusion in the parent metal decreased. This is attributed to a decrease in the total thermal efficiency of the process as a result of the higher rate of cooling of the moving arc column.

Skinner\textsuperscript{15} has summarized the work on arc magnetics conducted in the Linde laboratories prior to 1954. At that time Ford Motor Co., Boeing Aviation Corp., Republic Steel Corp., and Pratt & Whitney Co. were all using magnetic devices to control the Heliarc and Sigma processes. The advantages of magnetic control employed are listed below:

1) Increased welding speed on thin materials.

2) Arc stabilization in short intermittent welds by neutralizing magnetic arc blow.

3) Arc orientation control in welding magnetic to non-magnetic materials.

4) Reduced porosity on stainless steel welds.
Approximately 35 patents\textsuperscript{15} had been issued in the area of arc magnetics at the time of Skinner's survey.

**Submerged-Arcs in Magnetic Fields.** Mandel'berg and Lopata\textsuperscript{9} have shown that the magnetic field of the welding circuit exerts a substantial effect on the shape of submerged-arc welds deposited within tubes. The magnetic flux created by the welding circuit (no externally-applied field) is concentrated in the closed ferro-magnetic body of the tube. As the tube metal in the welding zone is heated throughout its thickness to above the curie point (approximately 1400\textdegree F), its loss of magnetic properties dissipates the flux in the welding zone. The dissipated flux takes the form of a transverse magnetic field in the vicinity of the arc causing motor rule deflection of the arc.

The motion of the tube relative to the arc deflection has been controlled so as to take advantage of the improved weld shape and reduced porosity associated with forward arc deflection. When welding with a.c., the effect on weld shape was much less due to a weaker field resulting from the development of eddy currents. Use of the twin-arc process resulted in the same effects on weld shape as when welding with a single arc. Use of d.c. on the trailing electrode caused the effect on weld geometry to be more pronounced. Increases in the diameter and thickness of the tubes were accompanied by marked decreases in the weld widths and depths of penetration because the magnetic flux was shunted more effectively by the larger unheated metal regions.
Most of the investigations were conducted on longitudinal seam welds. Circumferential welds made by rotating the tubes one way or the other are of nearly the same dimensions. When making spiral welds within tubes, the magnetic field deflects the arc along the longitudinal axis of the tube. The shape and penetration thus varies according to the angle of the spiral around which the weld is deposited. Weld shape is least satisfactory when the spiral angle is small.

Mandel'berg has shown that the welding speed can be doubled to 60 ipm on 1/4" thick steel by deflecting the submerged-arc forward with a constant transverse magnetic field. High field strengths resulted in higher consumption of welding composition due to the longer arc lengths. High arc currents required stronger field strengths to produce the desired weld shapes. The desired shape factor (width/depth) of 1.5 - 2.5 was achieved under every weld condition when suitable field strength was maintained. Increased field strengths resulted in shape factors of 4.0 to 4.5 accompanied by a decrease in arc stability. The magnetic field for ideal control increased with plate thickness because arc position, which determines weld geometry, depends only on the leakage portion of the controlling flux which passes through the arc region. Increasing plate thickness and increasing volume of metal above the Curie point cause the magnetic flux to be shunted away from the arc zone. Curvature and irregularities in the
plate being welded had a large effect on the intensity of the magnetic flux.

Kornienko\textsuperscript{13} has used a transverse magnetic field to control the depth of penetration and weld bead width in the submerged-arc, strip-electrode, hard-surfacing process. It is theorized that forward arc deflection in a transverse magnetic field reduces penetration by reducing the specific pressure exerted by the arc column on the surface of the molten metal pool. If the arc is deflected backward, the molten metal in the pool is forced out by the arc pressure. The base metal is then laid bare resulting in deeper penetration.

Shrubsall\textsuperscript{27} used a current-carrying water-cooled copper tube in the shape of a hairpin to produce a longitudinal field which eliminated the tendency of the submerged arc to wander. As the tube current was increased, the bead surface became smoother and wider and penetration decreased. Electrode stubs indicated that the degree of arc deflection decreased as tube current was increased.

Webb\textsuperscript{16} has shown that the influence of the magnetic susceptibility of Unionmelt composition is of negligible importance in arc deflection. It was observed, though, that forward arc deflection applied to high-speed welds produced a flatter bead. Webb also noted that a 500 gauss transverse magnetic field was sufficient to eject metal from the arc zone.
Gas-Metal-Arcs in Magnetic Fields. Three investigations\textsuperscript{6,11,19} have considered the gas-metal-arc in magnetic fields, other studies used cine movies as the basic analysis technique. Both ferro- and non-magnetic materials have been studied. Alternating parallel fields and constant transverse fields have been studied but only for DCRP arcs.

Deminskii and Dyatlov\textsuperscript{11} observed the aluminum-magnesium alloy arc in a 50-cps alternating parallel field. The arc oscillated across the weld axis at 50-cps resulting in a wider weld pool with shallower penetration. Oscillation amplitude and consequently weld width were directly proportional to the increase in flux density. Weld pool shape factors increased from 1.1 to 3.3 upon the application of a 50-gauss field. The different metal solidification conditions caused by magnetic control were found to reduce the amount of shrinkage cavities and gas porosity. Dimensions of the aluminum-magnesium inclusions formed at high welding powers were reduced. Grain size was substantially reduced, particularly close to the fusion zone. Substantial improvement in the mechanical properties of the welded joint occurred when magnetic control was applied.

Serdyuk and Kornienko\textsuperscript{6} have studied the Al-Mg gas-metal-arc in an alternating parallel field in more detail. Synchronized cinematography and oscillography techniques were employed to study arc deflection and metal transfer characteristics. Arc voltage oscillated with the same frequency as the applied field and reached
a maximum when the arc deflection is maximum. For relatively long arcs, the voltage peak lagged the maximum current in the field coils by $10^{-3}$ seconds. The arc deflection however, lagged the field by $2-3 \times 10^{-3}$ seconds due to the time constant of the welding power supply. The molten metal at the tip of the electrode is deflected along with the plasma as the magnitude and direction of the applied field change. The arc column is deflected in a curve that approximates the arc of a circle. Droplet detachment occurs at the point of maximum deflection. The inertia of the droplet often carries it outside the arc zone. Droplet rotation occurs after separation due to the neck of the drop being expelled at a greater velocity than the lower end. If the arc is deflected greatly, a counter-current or plasma stream may develop from the cathode which deflects the arc further.

Miamidian\textsuperscript{19} has measured the gas-metal-arc deflection in a transverse magnetic field. It was found that the maximum deflection was nearly linear up to 0.15" for field strengths up to 150 gauss using a mild steel electrodes. Droplet detachment and metal transfer were directed along the axis of the arc column. The applied field strength necessary to affect metal transfer increased as welding current was increased.
CURRENT STATUS OF ARC MAGNETICS

Magnetic fields influence the shape, size, and position in space of the arc and thus its technological properties. The interaction between electric arcs and magnetic fields are thus of practical importance from the point of view of offering new scope for the use of arc discharges in welding technology. Magnetic interactions alter the conditions governing heat flow to the work and thus offer further scope for regulating the resulting weld. Magnetically-controlling the depth of penetration is particularly useful on thin-gage metals. Perhaps the most outstanding application of arc magnetics is increase in under-cut free weld travel speed facilitated by forward arc deflection in a constant transverse magnetic field.

It is evident from the previous review of literature on arc magnetics that the gas-tungsten-arc has received the largest amount of investigation. These investigations, however, have been directed either at theoretically deriving an analysis of arc deflection or at the practical aspects of modifying the arc for production welding purposes. The gas-metal-arc has been subjected to only one serious investigation and this considered only an alternating parallel field with aluminum-magnesium electrodes.

The basic concepts of arc magnetics such as motor rule deflection and arc instability have been developed for the gas-tungsten-arc. In addition, recent theories proposing gas streaming in
arcs as the dominant mechanism for metal transfer in high current gas-metal arcs have greatly increased the understanding of consumable electrode welding processes. To fill in the background, several comprehensive reviews of current theories on arc physics help to develop a broad understanding of arc phenomena. With these understandings as a starting point, the gas-metal-arc in magnetic fields requires further study.

The author feels that in addition to studying the response of the gas-metal-arc to external magnetic fields in terms of deflection theory and stability limits, there is a great deal to be learned about basic arc phenomena by using a transverse magnetic field as a probe. By probing the metal-arc plasma with a magnetic field, the anode and cathode streaming action can be separated and the mobilities of the anode and cathode spots can be studied. The above studies may be developed by applying fields that exceed the critical limit for stability of the arc.
PURPOSE AND OBJECTIVES

The purpose of this thesis is to study the gas-metal-arc in transverse magnetic fields. An applied constant magnetic field has been used as a probe to explore the arc phenomena of anode and cathode streaming, metal vapor jets, plasma structure and mechanisms for metal transfer in the gas-shielded arcs.

The objectives of this thesis were to obtain still and high-speed photographs of the arc having realistic color showing details of metal transfer and definition of the arc components. These photographs were used to support arc physics theories on streams and jets in plasmas. Based on the photographs, movies and analysis of theories on arc physics, a system of nomenclature is proposed for plasma composition and arc phenomena.
EXPERIMENTAL PROCEDURE

LABORATORY EQUIPMENT

The laboratory equipment used in the research was comprised of five separate units:

1) A gas-tungsten-arc welding system

2) A gas-metal-arc welding system

3) Weld traverse mechanism and fixture for eliminating extraneous and ground current fields

4) Electromagnet and field strength control device

5) Photographic equipment

The welding voltage and current were recorded on Esterline-Angus strip chart recorders; arc voltage could be determined to ± 0.5 volts between 0-150 volts. Arc current could be determined to ± 3 amperes between 0-500 amperes.

A Linde HDA-500 transformer-rectifier which has a drooping V-I characteristic and a 500-ampere d.c. capacity, was used as the power supply for the gas-tungsten-arc. A Linde HW-10 500-ampere water-cooled torch equipped with a gas-lens and a 3/16" diameter tungsten electrode was used. Arc starting was accomplished by manually contacting and retracting the torch.

A Linde SVI-500 transformer-rectifier-inductor was used as the gas-metal-arc power supply. The SVI-500 is a constant potential
d.c. power supply with provisions for adjusting the slope, voltage, and inductance. A Linde SWM-11B wire feeder control was used in conjunction with the SVI-500. A Linde ST-12 700-ampere capacity water-cooled gas-metal-arc torch was employed. The SWM-11B and ST-12 were set up to feed 1/16" diameter filler wire.

Six cylinders of welding grade shielding gases were connected so as to facilitate the mixing of any two at a time. Shielding gases available included; argon, argon + 2% oxygen (M-2), argon + 25% CO₂ (C-25), CO₂, oxygen and helium. Gas mixtures were routed to the gas solenoids in both the HDA-500 and SWM-11B. Two stage flow meters were used to regulate the gas flow to 1±3 cfh.

A rack and pinion device was used to raise and lower the torch holder which was modified to hold the electromagnet. The rack, in turn, was mounted on a side-beam-carriage. A stationary torch was desirable for cine movie techniques and was also more convenient for still photography. In addition, the stationary torch eliminated the effects of aerodynamic drag on the arc plasma which would tend to conceal the magnetic arc deflection. In order to provide relative travel, the base plate was moved with the torch position remaining fixed. An Oxweld CM-37 machine carriage was used to traverse the base plate under the torch body. The speed of travel could be varied from 0 to 100 ipm, but for nearly all data taken the speed was maintained at 20 ipm. The base plate was always traversed
from left-to-right as viewed by the camera.

To further control the variables that influence arc deflection, a fixture was made to remove the arc from the magnetic field of the machine carriage. The fixture consisted of wood cantilever extension for the weld base plate. The extension was fabricated from wood 2" x 4" 's and covered with transite for thermal insulation. The extension, as it is mounted on the CM-37 is shown in Fig. 11. The fixture was designed so that ground current effects would be minimized. Two pieces of copper were inlaid as shown in Fig. 12 so that ground currents would flow in the direction of the weld axis. A 6" x 24" piece of 1/2" thick aluminum was placed on top of the copper inlays in the wood extension. All weld specimens were placed on the aluminum plate. The effects of extraneous fields and aerodynamic drag were minimized by the use of this fixture when welds were made in the center 12 inches of the fixture.

A constant transverse magnetic field was established in the vicinity of the arc by a 1300 turn electromagnet. Enamel coated No. 16 copper wire was wound around a 2". diameter x 8" long annealed mild steel bar. The magnetic flux was shunted to the arc zone by two "L" shaped annealed mild steel pole pieces. Current for the magnet was supplied by a variable auto-transformer. The output from the variable transformer was fed through a full-wave diode-bridge rectifier (Fig. 13) that reduced ripple to less than 5%. Magnetic field
Fig. 11. Photograph of Laboratory Equipment.
Fig. 12. Photograph of Special Base Plate Fixture Used to Reduce the Effect of Extraneous Fields and Aerodynamic Drag.
Fig. 13. Schematic Diagram of Electromagnet and Field Control System.
strength was varied by increasing the voltage output of the variable transformer without overshooting the desired level. Due to hysteresis effects in the core and pole pieces, an overshoot would result in a higher field strength than indicated by the position of the variable transformer. Gaussmeter measurements indicated that field strengths could be reproduced within 1% by increasing the variable transformer from 0 each time and carefully avoiding voltage overshoots.

A Model 110 gaussmeter manufactured by F. W. Bell, Inc. and a Model YBS-054 transverse hall probe were used to measure magnetic field strengths. The Model 110 reads directly in gauss and has several scales so that measurements can be made to an accuracy of 1%.

The poles of the electromagnet were maintained 1" above the work surface for all photographs. The bottom of the torch body for both the ST-12 and HW-10 was positioned 1-1/4" above the work surface. Arc length adjustments for the HW-10 were accomplished by extending or retracting the tungsten electrode.

A large vertical gradient existed in the applied field because of the 1" work-to-magnet separation. Data for field strength as a function of the setting of the adjustable transformer were taken at five levels directly under the electrode for carbon steel, stainless steel and aluminum work materials. These data are included in
Fig. 14. Variation of Applied Field Strength as a Function of Auto-Transformer Setting and Electrode Material.
Appendix A. The magnetic field has a vertical gradient of about 25% in the 1/2" above the base plate. Data for field strength, $\beta$, as recorded in this thesis, are taken at position 5 as indicated in Appendix A which is from 0 to 1/4" above the base plate. Despite the large vertical gradient in $B$, horizontal gradients were limited to 3% for positions within 3/8" from the center of the electrode.

Data for $\beta$ from Appendix A are plotted in Fig. 14 to illustrate the effect of permeability of the base material on the magnetic field strength in the vicinity of the arc. The steep curve for carbon steel indicates that about 60% of the magnetic flux is being shunted by the base plate. Since the magnetic properties of ferro-magnetic materials change to those of a nonmagnetic material when heated above the curie point ($1400^\circ F$), the field strength in the vicinity of the weld will increase as larger portions of the base plate are heated above the curie point. Hicken$^{29}$ has shown that the increase is approximately 25%.

PHOTOGRAPHIC TECHNIQUES

Obtaining high-quality photographs of the welding arc is dependent upon accurate analysis of the color-temperature and intensity of the arc. Visible portions of welding arc plasmas represent a broad range of temperatures. Olsen$^{54}$ has derived temperatures of 10,000$^\circ$ - 20,000$^\circ$ K from ionic and atomic spectral
line intensities of the 400 ampere argon arc. Photographic emulsions are best suited for exposure to a specific color-temperature light source. When the color-temperature of the source and film are not matched, the color-temperature of the source can be adjusted by placing a color-correction filter between the source and the film. If the color-temperature of the source is too high, as is the case for welding arc, the film will record the blues more pronounced than the reds. A high-temperature source is compensated for by using a filter that appears red to the eye, because it is actually filtering out the blues.

Many light meters can be equipped with an attachment that facilitates measurement of the average color-temperature of a light source. Measurements of the gas-tungsten-arc indicated an average color-temperature between 7,000 and 10,000°K depending on the current.

Kodachrome II daylight film for 35 mm slides has a color-temperature of 5,600°K, thus a red color-correction filter is needed to reduce the radiation from the arc by 3,000° - 4,000° K. An 85-B was selected since it has a color-temperature correction factor of 3,200° K. The 85-B was used on all photographs except a few shots where modified techniques were explored. Photographs taken through a PYX-10 glass filter from a welding helmet resulted in pictures with a deep blue-green cast. Photographs taken with no color-correction
appeared unnaturally blue. Photographs taken with Ektachrome film
(ASA-160) had the blue-green appearance typical of under exposure
even though an 85-B was used. In one series of tests, two 85-B fil-
ters were used in an attempt to enhance the red that often appears
as the outermost portion of the gas-metal-arc on ferrous materials
and about droplets transferred outside the arc column. The filters
increased the red so much that the arc had an unnatural appearance.

The high intensity of the arc can be compensated for in three
ways. First, it is desirable to use a low speed film such as Koda-
chrome Daylight II which has an ASA speed of 25. Secondly, the
camera lens can be stopped down to reduce the amount of light
striking the film. A decrease of one f-stop cuts the light in half.
Because of the added depth of focus provided by stopping down, it
is desirable to shoot at f-16 to f-32. The most convenient way to
reduce the intensity of the light from the welding arc is to use neutral
density filters which reduce the intensity of all wave lengths by an
equal amount. A list of common neutral density filters is given
below to show how the exposure may be reduced.

<table>
<thead>
<tr>
<th>Filter No.</th>
<th>Density</th>
<th>Per Cent Transmission</th>
<th>Stops Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>N. D. 1</td>
<td>0.30</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>N. D. 2</td>
<td>0.60</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>N. D. 3</td>
<td>0.90</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>N. D. 1.0</td>
<td>1.00</td>
<td>10</td>
<td>3-1/4</td>
</tr>
<tr>
<td>N. D. 2.0</td>
<td>2.00</td>
<td>1</td>
<td>6-3/4</td>
</tr>
<tr>
<td>N. D. 3.0</td>
<td>3.00</td>
<td>0.1</td>
<td>10</td>
</tr>
</tbody>
</table>

62
An Exakta 35-mm camera equipped with a Rodenstock-Yronar 135-mm telephoto lens and bellows extension was used to take still photographs of the arc. Clear glass cover slides 2-3/4" square were placed in front of the lens and filters to protect against weld spatter. A large dull black piece of cardboard was placed about 12" behind the arc as a neutral non-reflecting background. The light meter was placed 40" from the arc and the lens of the camera was placed 12 inches from the arc. Use of the inverse square law shows that the light intensity at the camera will be 10 times that at the light meter. Therefore by using a N. D. 1.0 on the camera, (which was required for most high voltage and high current photographs), exposure in terms of F setting could be read directly from the light meter. All photographs were taken at exposures of 1/1000 second.

The objective of the photographs was to obtain sharp detail in the arc plasma and reveal metal transfer while retaining definition in the less intense outer regions of the arc. The key to taking good photographs was to stop down 3 to 4 stops below what the light meter indicated. For example, if the light meter indicated an exposure of f-5.6 at 1/1000 sec., the photograph should be taken at f-16 or f-22 at 1/1000 second. Stopping down further produced better definition in the arc core and metal transfer, but the outer regions of the plasma were under exposed.
High-speed movies were taken at 4,000 frames per second using a Wallensak Fastax WV-3 16-mm camera. Ektachrome ER daylight film #7257 was used. All shots were taken using an 85-B color-correction filter and a N.D. 1.0 or 2.0. A Spectra Combi 500 light meter with photo-spot (30° spread) attachment was used to determine cine exposures. Exposures here were determined directly by placing both the camera and light meter at 37 inches from the arc and taking light meter readings through the neutral density filter to be used for the shot. As with still slides, exposures of 3 to 4 f-stops below that indicated by the light meter were used to obtain good movies of the arc plasma. A 153 mm lens and 4 mm extension tube were used to get full frame exposures of the arc. On films #6 and #26, a 50 mm lens was used to get a larger region about the arc in the frame.
SUMMARY AND PRESENTATION OF DATA

SUMMARY OF DATA

Data consisted of 40 rolls of 20-exposure 35-mm. color slides and 26 100-foot rolls of cine movies. The slides are lettered consecutively by rolls; i.e., A, B, C, ..., X, Y, Z, AA, BB, ..., MM, NN. The slides in each roll are numbered consecutively from 1 to 20. The high-speed films are numbered consecutively from 1 to 26 with the exceptions that #9 is omitted and an extra shot, 14a, falls between 14 and 15.

High-speed films were taken of both DCRP and DCSP gas-metal-arcs using carbon steel, stainless steel and aluminum electrodes. Field strength was varied from 2 to 120 gauss. In general, a stable and an unstable condition of arc deflection were photographed for each electrode material and each welding polarity. Details of the high-speed films are listed in TABLE 1.

Details of the 800 35-mm. slides are contained in Data and Computation Notebook No. 1 of Arc-Plasma Magnetics Research. This notebook is filed under Project Number 0693-522018 in care of Professor C. E. Jackson in the Department of Welding Engineering of The Ohio State University. A brief summary of this data follows.

Films A, B, and C were used to develop photographic techniques. Films D and E were of carbon arcs. Films F - I were of
<table>
<thead>
<tr>
<th>Cine No.</th>
<th>Electrode Material</th>
<th>Polarity**</th>
<th>Gas Shielding</th>
<th>I Amperes</th>
<th>V Volts</th>
<th>$\beta$ Gauss</th>
<th>Arc Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>280</td>
<td>36</td>
<td>2#</td>
<td>Undeflected</td>
</tr>
<tr>
<td>2</td>
<td>M/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>270</td>
<td>36</td>
<td>20</td>
<td>Stable</td>
</tr>
<tr>
<td>3</td>
<td>M/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>480</td>
<td>38</td>
<td>20</td>
<td>Stable</td>
</tr>
<tr>
<td>4</td>
<td>M/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>480</td>
<td>38</td>
<td>40</td>
<td>Stable</td>
</tr>
<tr>
<td>5</td>
<td>M/S</td>
<td>DCRP</td>
<td>Argon</td>
<td>330</td>
<td>34</td>
<td>60</td>
<td>Semi-Stable</td>
</tr>
<tr>
<td>6##</td>
<td>M/S</td>
<td>DCRP</td>
<td>Argon</td>
<td>330</td>
<td>34</td>
<td>60</td>
<td>Semi-Stable</td>
</tr>
<tr>
<td>7</td>
<td>S/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>290</td>
<td>36</td>
<td>10#</td>
<td>Undeflected</td>
</tr>
<tr>
<td>8</td>
<td>S/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>265</td>
<td>38</td>
<td>50</td>
<td>Unstable</td>
</tr>
<tr>
<td>10</td>
<td>M/S</td>
<td>DCSP</td>
<td>M-2</td>
<td>345</td>
<td>41</td>
<td>2#</td>
<td>Undeflected</td>
</tr>
<tr>
<td>11</td>
<td>M/S</td>
<td>DCSP</td>
<td>M-2</td>
<td>345</td>
<td>41</td>
<td>12</td>
<td>Stable</td>
</tr>
<tr>
<td>12</td>
<td>M/S</td>
<td>DCSP</td>
<td>M-2</td>
<td>305</td>
<td>35</td>
<td>2#</td>
<td>Undeflected</td>
</tr>
<tr>
<td>13</td>
<td>M/S</td>
<td>DCSP</td>
<td>M-2</td>
<td>300</td>
<td>35</td>
<td>12</td>
<td>Stable</td>
</tr>
</tbody>
</table>

* M/S - Carbon Steel  
** DCSP - Straight Polarity Electrode Negative.  
S/S - 308 Stainless Steel  
DCRP - Reverse Polarity, Electrode Positive.  
Al - Aluminum 5083-H113  
## 50 mm lens used rather than 153 mm lens.  
# - Residual Magnetic Field.

**TABLE I.** Data for High-Speed Films.
<table>
<thead>
<tr>
<th>Cine No.</th>
<th>Electrode Material*</th>
<th>Polarity**</th>
<th>Gas Shielding</th>
<th>I Amperes</th>
<th>V Volts</th>
<th>β Gauss</th>
<th>Arc Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>M/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>270</td>
<td>34</td>
<td>2#</td>
<td>Undeflected</td>
</tr>
<tr>
<td>14a</td>
<td>M/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>270</td>
<td>34</td>
<td>20</td>
<td>Stable</td>
</tr>
<tr>
<td>15</td>
<td>M/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>270</td>
<td>34</td>
<td>40</td>
<td>Unstable</td>
</tr>
<tr>
<td>16</td>
<td>S/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>210</td>
<td>35</td>
<td>60</td>
<td>Semi-Stable</td>
</tr>
<tr>
<td>17</td>
<td>S/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>180</td>
<td>37</td>
<td>120</td>
<td>Unstable</td>
</tr>
<tr>
<td>18</td>
<td>Al</td>
<td>DCRP</td>
<td>Argon</td>
<td>195</td>
<td>30</td>
<td>33</td>
<td>Stable</td>
</tr>
<tr>
<td>19</td>
<td>Al</td>
<td>DCRP</td>
<td>Argon</td>
<td>150</td>
<td>33</td>
<td>55</td>
<td>Unstable</td>
</tr>
<tr>
<td>20</td>
<td>Al</td>
<td>DCRP</td>
<td>Helium</td>
<td>200</td>
<td>30</td>
<td>30</td>
<td>Stable</td>
</tr>
<tr>
<td>21</td>
<td>Al</td>
<td>DCRP</td>
<td>Helium</td>
<td>145</td>
<td>33</td>
<td>55</td>
<td>Unstable</td>
</tr>
<tr>
<td>22</td>
<td>Al</td>
<td>DCSP</td>
<td>Argon</td>
<td>205</td>
<td>30</td>
<td>25</td>
<td>Stable</td>
</tr>
<tr>
<td>23</td>
<td>Al</td>
<td>DCSP</td>
<td>Argon</td>
<td>195</td>
<td>31</td>
<td>45</td>
<td>Unstable</td>
</tr>
<tr>
<td>24</td>
<td>Al</td>
<td>DCSP</td>
<td>Helium</td>
<td>185</td>
<td>32</td>
<td>20</td>
<td>Stable</td>
</tr>
<tr>
<td>25</td>
<td>Al</td>
<td>DCSP</td>
<td>Helium</td>
<td>180</td>
<td>32</td>
<td>33</td>
<td>Unstable</td>
</tr>
<tr>
<td>26###</td>
<td>Al</td>
<td>DCRP</td>
<td>Argon</td>
<td>170</td>
<td>31</td>
<td>33</td>
<td>Unstable</td>
</tr>
</tbody>
</table>

**TABLE I. Data for High-Speed Films. (Continued)**
DCSP gas-metal-arcs on carbon steel. Films J - M were of DCSP gas-metal-arcs on stainless steel.

Films N - CC were all of the DCSP gas-tungsten-arc. Arc lengths varied from 1/4" to 3/4"; current varied from 50 to 400 amperes; arc voltage varied from 12 to 38 volts; applied field strengths varied from 0 to 50 gauss. Shielding atmospheres employed were either argon or helium or in the case of films S and T, a mixture of argon and helium.

Films DD - GG were of DCRP gas-metal-arcs on aluminum. Films HH and JJ were of DCSP gas-metal-arcs on aluminum. Films KK - NN were of DCRP gas-metal-arcs on carbon steel using M-2 shielding gas.

Gas-metal-arc parameters covered the full range of welding conditions and particular emphasis was placed on high voltages because these conditions produced the most informative plasma deformations. Currents ranged from 90 to 450 amperes; voltages ranged from 24 to 42 volts; applied field strengths varied from 2 to 200 gauss. Nearly all stainless and carbon steel welds were photographed using 35 cfh of 98% argon + 2% oxygen. However, one series (films F and G) studied the effects of various shielding gases on the DCSP carbon steel gas-metal-arc. Gases employed included; argon, argon + 2% oxygen, argon + 25% CO₂ (C-25), CO₂ and helium. The effect of oxygen additions to all of these gases was also studied in this series.

68
All gas-metal-arcs on aluminum were photographed with argon and helium shielding.

The data collected in this thesis are photographic and are not suited to graphic representation or summarization. Only representative slides, drawings and film footages are included. Sketches from sequences in the high-speed movies and from the still slides are shown in Figs. 15 to 40, and identified in TABLES II, III, and IV. These drawings emphasize the points of interest from the color picture they represent. The drawings are included to supplement the color pictures rather than to replace them.

Frame-by-frame analysis of the high-speed movies has revealed phenomena that were not apparent even when viewing at a reduced speed of 16 fps. Viewing at the normal speed of 24 fps slows down the action by a factor of 160. Approximately 3 minutes are required to view the film exposed in 1 second of arc time. Even at this reduction in speed, much of the dynamic behavior occurs too rapidly for the uninstructed eye to observe.

Presentation of results is divided into four parts. Slides and drawings of the gas-tungsten-arc are presented first. Slides and drawings of the gas-metal-arc follow. Thirdly, Figs. 35 to 40 are included to illustrate sequences of particular interest taken from the high-speed films. Lastly, 620 feet of film have been edited from the
2600 feet exposed, and combined with an introduction and appropriate titles into a movie approximately 30-minutes long entitled "The Gas-Metal-Arc in Transverse Magnetic Fields." It is available through Professor Jackson. The contents of this movie are listed in TABLE V.
<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Slide No.</th>
<th>Anode Material</th>
<th>Electrode Spacing</th>
<th>Shielding Gas</th>
<th>Amperes</th>
<th>Volts</th>
<th>Gauss</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Y-15</td>
<td>S/S</td>
<td>3/8&quot;</td>
<td>Argon</td>
<td>100</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>16</td>
<td>Y-17</td>
<td>S/S</td>
<td>3/8&quot;</td>
<td>Argon</td>
<td>100</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>17</td>
<td>Y-19</td>
<td>S/S</td>
<td>3/8&quot;</td>
<td>Argon</td>
<td>100</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>18</td>
<td>U-17</td>
<td>Al</td>
<td>3/8&quot;</td>
<td>Helium</td>
<td>200</td>
<td>38</td>
<td>14</td>
</tr>
<tr>
<td>19</td>
<td>U-11</td>
<td>Al</td>
<td>3/8&quot;</td>
<td>Helium</td>
<td>50</td>
<td>36</td>
<td>8</td>
</tr>
<tr>
<td>20</td>
<td>N-9</td>
<td>Al</td>
<td>3/8&quot;</td>
<td>Argon</td>
<td>150</td>
<td>13</td>
<td>7</td>
</tr>
<tr>
<td>21</td>
<td>R-10</td>
<td>Al</td>
<td>1/2&quot;</td>
<td>Argon</td>
<td>50</td>
<td>21</td>
<td>7</td>
</tr>
<tr>
<td>22</td>
<td>S-12</td>
<td>Al</td>
<td>1/2&quot;</td>
<td>Argon</td>
<td>100</td>
<td>26</td>
<td>7</td>
</tr>
</tbody>
</table>

**TABLE II. Data for Gas-Tungsten-Arc Slides**
Photograph No. Y-15

I  = 100 amps  
V  = 15 volts  
β  = 10 gauss  
L₀ = 3/8-inch  
Argon Shielding  
S/S Anode

Fig. 15. Gas-Tungsten-Arc; Normal Stable Mode
Photograph No. Y-17

I = 100 amps
V = 17 volts
$\beta$ = 15 gauss
$L_o$ = 3/8-inch
Argon Shielding
S/S Anode

Fig. 16. Gas-Tungsten-Arc; Stable Deflection.
Photograph No. Y-19

I = 100 amps
V = 19 volts
$\beta = 20$ gauss
$L_0 = 3/8$-inch
Argon Shielding
S/S Anode

Fig. 17. Gas-Tungsten-Arc; Semi-Stable Deflection.
Photograph U-17

I = 200 amps
V = 38 volts
β = 14 gauss
L = 3/8-inch
Helium Shielding
Aluminum Anode

Fig. 18. Gas-Tungsten-Arc; Stable Deflection.
Photograph No. U-11

$I = 50$ amps
$V = 36$ volts
$\beta = 8$ gauss
$L_0 = 3/8$-inch
Helium Shielding
Aluminum Anode

Fig. 19. Gas-Tungsten-Arc; Semi-Stable Deflection.
Photograph No. N-9

$I = 150$ amps
$V = 13$ volts
$\beta = 7$ gauss
$L_o = 3/8$-inch
Argon Shielding
Aluminum Anode

Fig. 20. Gas-Tungsten-Arc; Initiating Instability.
Photograph No. R-10

\[ \begin{align*}
I &= 50 \text{ amps} \\
V &= 21 \text{ volts} \\
\beta &= 7 \text{ gauss} \\
L_0 &= 1/2 \text{-inch} \\
\text{Argon Shielding} \\
\text{Aluminum Anode}
\end{align*} \]

Fig. 21. Gas-Tungsten-Arc; Instability.
Photograph No. S-12

$I = 100$ amps
$V = 26$ volts
$\beta = 7$ gauss
$L_0 = 1/2$-inch
Argon Shielding
Aluminum Anode

Fig. 22. Gas-Tungsten-Arc; Approaching Extinction.
<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Slide No.</th>
<th>Electrode Material</th>
<th>Polarity</th>
<th>Shielding Gas</th>
<th>I Amperes</th>
<th>V Volts</th>
<th>β Gauss</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>H-4</td>
<td>M/S</td>
<td>DCSP</td>
<td>M-2</td>
<td>300</td>
<td>32</td>
<td>25</td>
</tr>
<tr>
<td>24</td>
<td>H-7</td>
<td>M/S</td>
<td>DCSP</td>
<td>M-2</td>
<td>300</td>
<td>32</td>
<td>100</td>
</tr>
<tr>
<td>25</td>
<td>H-15</td>
<td>M/S</td>
<td>DCSP</td>
<td>M-2</td>
<td>330</td>
<td>38</td>
<td>5</td>
</tr>
<tr>
<td>26</td>
<td>H-19</td>
<td>M/S</td>
<td>DCSP</td>
<td>M-2</td>
<td>330</td>
<td>38</td>
<td>60</td>
</tr>
<tr>
<td>27</td>
<td>H-20</td>
<td>M/S</td>
<td>DCSP</td>
<td>M-2</td>
<td>330</td>
<td>38</td>
<td>80</td>
</tr>
<tr>
<td>28</td>
<td>H-22</td>
<td>M/S</td>
<td>DCSP</td>
<td>M-2</td>
<td>330</td>
<td>38</td>
<td>100</td>
</tr>
<tr>
<td>29</td>
<td>MM-6</td>
<td>S/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>185</td>
<td>30</td>
<td>75</td>
</tr>
<tr>
<td>30</td>
<td>B-16</td>
<td>M/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>250</td>
<td>32</td>
<td>100</td>
</tr>
<tr>
<td>31</td>
<td>G-6</td>
<td>M/S</td>
<td>DCSP</td>
<td>C-25 &amp; 5% O₂</td>
<td>330</td>
<td>36</td>
<td>100</td>
</tr>
<tr>
<td>32</td>
<td>JJ-12</td>
<td>Al</td>
<td>DCSP</td>
<td>Argon</td>
<td>250</td>
<td>35</td>
<td>17</td>
</tr>
<tr>
<td>33</td>
<td>JJ-17</td>
<td>Al</td>
<td>DCSP</td>
<td>Helium</td>
<td>225</td>
<td>36</td>
<td>17</td>
</tr>
<tr>
<td>34</td>
<td>HH-20</td>
<td>Al</td>
<td>DCSP</td>
<td>Argon</td>
<td>160</td>
<td>34</td>
<td>50</td>
</tr>
</tbody>
</table>

**TABLE III.** Data for Gas-Metal-Arc Slides.
Photograph No. H-4

\[ I = 300 \text{ amps} \]
\[ V = 32 \text{ volts} \]
\[ \beta = 25 \text{ gauss} \]
\[ M/S - \text{DCSP} \]
\[ M-2 \text{ Shielding} \]

Fig. 23. Gas-Metal-Arc; Stable Deflection.
Photograph No. H-7

\[ I = 300 \text{ amps} \]
\[ V = 32 \text{ volts} \]
\[ \beta = 100 \text{ gauss} \]
\[ M/S - DCSP \]
\[ M-2 \text{ Shielding} \]

Fig. 24. Gas-Metal-Arc; Metal Transfer Outside of Plasma.
Photograph No. H-15

I = 330 amps
V = 38 volts
β = 5 gauss
M/S - DCSP
M-2 Shielding

Fig. 25. Gas-Metal-Arc; Normal Undeflected Arc.
Photograph No. H-19

I = 330 amps
V = 38 volts
β = 60 gauss
M/S - DCSP
M-2 Shielding

Fig. 26. Gas-Metal-Arc; Metal-Vapor Stream.
Photograph No. H-20

I = 330 amps
V = 38 volts
β = 80 gauss
M/S - DCSP
M-2 Shielding

Fig. 27. Gas-Metal-Arc; Unstable Deflection.
Photograph No. H-22

I = 330 amps
V = 38 volts
β = 100 gauss
M/S - DCSP
M-2 Shielding

Fig. 28. Gas-Metal-Arc; Impending Extinction.
Photograph No. MM-46

I = 185 amps
V = 35 volts
β = 75 gauss
S/S - DCRP
M-2 Shielding

Fig. 29. Gas-Metal-Arc; Normal Undeflected Arc.
Photograph No. B-16

$I = 250$ amps
$V = 32$ volts
$\beta = 100$ gauss

M/S - DCRP
M-2 Shielding

Fig. 30. Gas-Metal-Arc; Stable Deflection.
Photograph No. G-6

I = 330 amps
V = 36 volts
β = 100 gauss
M/S - DCSP
70% Argon, 25% CO₂, 5% O₂

Fig. 31. Gas-Metal-Arc; Anode Vapor Jet.
Photograph No. JJ-12

I = 250 amps
V = 35 volts
β = 17 gauss
Aluminum - DCSP
Argon Shielding

Fig. 32. Gas-Metal-Arc; Stable Deflection.
Photograph No. JJ-17

$I = 225$ amps
$V = 36$ volts
$\beta = 17$ gauss
Aluminum - DCSP
Helium Shielding

Fig. 33. Gas-Metal-Arc; Unstable Deflection.
Photograph No. HH-20

I = 160 amps
V = 34 volts
β = 50 gauss
Aluminum - DCSP
Argon Shielding

Fig. 34. Gas-Metal-Arc; Impending Extinction.
<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Cine No.</th>
<th>Electrode Material</th>
<th>Polarity</th>
<th>Shielding Gas</th>
<th>I Amperes</th>
<th>V Volts</th>
<th>β Gauss</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>6</td>
<td>M/S</td>
<td>DCRP</td>
<td>Argon</td>
<td>330</td>
<td>34</td>
<td>60</td>
</tr>
<tr>
<td>36</td>
<td>14</td>
<td>M/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>270</td>
<td>34</td>
<td>2</td>
</tr>
<tr>
<td>37</td>
<td>15</td>
<td>M/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>270</td>
<td>34</td>
<td>40</td>
</tr>
<tr>
<td>38</td>
<td>16</td>
<td>S/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>210</td>
<td>35</td>
<td>60</td>
</tr>
<tr>
<td>39</td>
<td>16</td>
<td>S/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>210</td>
<td>35</td>
<td>60</td>
</tr>
<tr>
<td>40</td>
<td>7</td>
<td>S/S</td>
<td>DCRP</td>
<td>M-2</td>
<td>290</td>
<td>36</td>
<td>10</td>
</tr>
</tbody>
</table>

**TABLE IV.** Data for Sketches from High-Speed Films.
A. Stable Deflection

B. Semi-Stable Deflection

C. Instability

D. Extinction

Fig. 35. Gas-Metal-Arc: Transition to Instability Leading to Extinction.
A. Drop Formation

B. Drop Detachment

C. Drop in Transit

D. Drop Striking Weld Pool

Fig. 36. Gas-Metal-Arc: Typical Spray Transfer at High Current Density for 1/16" Diameter Filler Wire.
Fig. 37. Gas-Metal-Arc; Spray Transfer in Magnetic Field Leading to Tumbling Motion of Droplet Transferred Outside the Arc Core.
Fig. 38. Gas-Metal-Arc Pushing Molten Metal Ahead of the Weld Pool.
Fig. 39. Gas-Metal-Arc: Severe Bending of the Electrode Tip in a Strong Magnetic Field.
Fig. 40. Gas-Metal-Arc Spiral Whipping of Filamental Neck Leading to Breakup into Fragmentary Droplets.
### TABLE V. Table of Contents for Movie "The Gas-Metal-Arc in Transverse Magnetic Fields."

**Title:** The Gas-Metal-Arc in Transverse Magnetic Fields.

**Illustration of the Motor Rule for arc deflection.**

**Cine #6:** The Deflected Gas-Metal-Arc on Steel Showing Tail Flames.

<table>
<thead>
<tr>
<th>Carbon-Steel</th>
<th>DCRP</th>
<th>Close-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cine #14</td>
<td>$\beta = 2$ gauss</td>
<td>Undeflected</td>
</tr>
<tr>
<td>Cine #14a</td>
<td>$\beta = 20$ gauss</td>
<td>Stable</td>
</tr>
<tr>
<td>Cine #15</td>
<td>$\beta = 40$ gauss</td>
<td>Semi-Stable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Carbon-Steel</th>
<th>DCSP</th>
<th>Close-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cine #12</td>
<td>$\beta = 2$ gauss</td>
<td>Undeflected</td>
</tr>
<tr>
<td>Cine #13</td>
<td>$\beta = 12$ gauss</td>
<td>Stable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stainless Steel</th>
<th>DCRP</th>
<th>Close-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cine #16</td>
<td>$\beta = 60$ gauss</td>
<td>Semi-Stable</td>
</tr>
<tr>
<td>Cine #17</td>
<td>$\beta = 120$ gauss</td>
<td>Unstable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stainless Steel</th>
<th>DCSP</th>
<th>Close-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cine #7</td>
<td>$\beta = 10$ gauss</td>
<td>Undeflected</td>
</tr>
<tr>
<td>Cine #8</td>
<td>$\beta = 50$ gauss</td>
<td>Unstable</td>
</tr>
</tbody>
</table>

**Cine #26:** The Deflected Gas-Metal-Arc on Aluminum Showing Tail Flames.

<table>
<thead>
<tr>
<th>Aluminum</th>
<th>DCRP</th>
<th>Close-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cine #19</td>
<td>Argon $\beta = 55$</td>
<td>Unstable</td>
</tr>
<tr>
<td>Cine #21</td>
<td>Helium $\beta = 55$</td>
<td>Unstable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aluminum</th>
<th>DCSP</th>
<th>Close-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cine #22</td>
<td>Argon $\beta = 25$</td>
<td>Stable</td>
</tr>
<tr>
<td>Cine #23</td>
<td>Argon $\beta = 45$</td>
<td>Unstable</td>
</tr>
<tr>
<td>Cine #24</td>
<td>Helium $\beta = 20$</td>
<td>Stable</td>
</tr>
<tr>
<td>Cine #25</td>
<td>Helium $\beta = 33$</td>
<td>Unstable</td>
</tr>
</tbody>
</table>
DISCUSSION

INITIAL ARC PHYSICS CONSIDERATIONS

Study of the effects of magnetic fields on welding arcs requires an understanding of what each color and component of the plasma represents. This understanding can be developed by considering four aspects of arc plasma: (1) composition, (2) temperature, (3) color, and (4) streaming. It is first shown that ionization of metal vapors is responsible for current conduction in gas vapor arcs. Saha's equation is then applied to calculate arc temperature. An analogy is drawn between plasma temperature and color to relate the composition and temperature profile of the arc to its visual appearance. Lastly, plasma streaming due to magnetic pumping at the constricted electrode is discussed. Additional information on these four aspects of the arc are included in Appendices B, C, and D.

Thermal Aspects of Metal-Vapor-Arcs

The plasma of a welding arc is visible due to excitation and ionization of gas and vapor atoms. The plasma is heated in the electrode drop regions from which it streams and also by Joule heating resulting from conduction of the arc current. If the plasma is to remain stable, it must stay hot enough to provide ions and electrons by thermal collisions in sufficient quantities to conduct the welding current. Otherwise, radial cooling would extinguish the arc in a
few microseconds. Thermal ionization in arcs is largely dependent upon the effective ionization potential of the arc atmosphere. The temperatures of "clean" arcs free from metal vapor increase as the ionization potential of the atmosphere, $V_i'$, increases. Arcs in helium ($V_i = 24.46$ volts) will be substantially hotter than arcs in argon ($V_i = 15.68$). When considerable vaporization of the electrodes occurs, conduction takes place largely in the vapor of the electrode material. This occurs because metal vapors have ionization potentials much lower than those of inert atmospheres, i.e., $V_i = 5.96$ for iron and $V_i = 7.83$ for aluminum. Metal vapor ionizes more readily than do inert gases. The gas-metal-arc is actually a metal vapor arc whereas the DCSP gas-tungsten-arc is a gas arc in its cathodic portion and a metal vapor arc in its anodic portion. These welding arcs are not clean arcs.

Saha's equation has been useful in determining the temperature necessary to create the ionization ratio, $n_i^2/n$, capable of supporting a given current density. For an ionization ratio of $10^{16}$, a clean arc in argon will have a temperature of $14,000^\circ K$ whereas a gas-metal-arc on steel would have a temperature of only $6,000^\circ K$. Olsen has calculated plasma temperatures ranging from $10,000^\circ$ to $20,000^\circ$ K for clean argon arcs from measurement of spectral line intensities. Webb and Porter have similarly calculated plasma temperatures of $6,000^\circ$ K for the submerged-arc on steel. To date, there are no
publications on the spectrographic determination of temperatures in inert-gas arcs containing significant amounts of metal vapor. However, Olsen\textsuperscript{49} indicated his experience with DCSP gas-tungsten-arcs on molten anodes has shown that the characteristic metal vapor lines dominate spectral emissions. Yenni\textsuperscript{40} has observed radiations from metal vapors in the gas-metal-arc that were so dominant that little else could be determined from spectroscopic analysis. Thus it can be assumed that conduction in gas-metal-arcs is due to metal vapors. The contribution of metal vapors to conduction in the gas-tungsten-arc is less definite. Since the cathode jet tends to suppress metal vapor streams from the anode, conduction via metal vapor is determined by the amount of vapor in the plasma. Webb and Porter\textsuperscript{55} have indicated that the electrode supplies a large fraction of the arc vapor and that the base plate and weld puddle are not greatly vaporized regardless of polarity. This result might be expected in view of the small area of the end of the electrode and the large amount of heat dissipated at its surface. In addition, the typical metal-arc plasma is dominated by streaming from the constriction at the electrode regardless of polarity.

The subject of arc temperature is not simply one of ionization potential. Streaming due to magnetic pumping is the result of a constriction. The fact that a constriction in an arc results in extremely high temperatures is well known and used industrially in the form of
the plasma-arc for cutting, welding and metal spraying. The pumping of cold gas into the arc further constricts the arc reducing the size of the conducting cross-section. The smaller cross-section must have a higher conductivity to support the arc current. Therefore, maximum arc temperature is increased in accordance with Saha's equation.

Color-Temperature Analogy

Color of radiated light is largely determined by the temperature of the radiating medium. Olsen has said that when he looks at the color distribution in an arc he is observing an indication of the temperature profile. Color is identified by wavelength with the visible portion of the spectrum ranging from 4,000 to 7,500 angstroms. Red has long wavelengths while violet has short wavelengths. Quantized light is radiated when an excited atom drops to a lower energy level. Large energy drops produce radiations with long wavelengths and vice versa. In general, three types of spectra will appear: line, band and continuous, all of which depend on the temperature of the emitter. Since red is associated with a smaller energy drop than blue, and because the level of excitation increases with temperature, a crude comparison can be drawn between the various colors appearing in the welding arc. White, which contains the full visible spectrum, is the hottest. Temperatures then decrease as colors fade from violet through blue green yellow and orange to red.
Metal vapor within the arc column is known to radiate a pale blue color\textsuperscript{40, 45, 49} whereas metal vapor outside the arc column typically radiates a red-orange color\textsuperscript{40}. Heavy atoms such as argon or iron contain more probable levels of excitation than the lighter atoms such as helium. In addition, most atoms have characteristic levels of excitation and these will emit strong spectral radiations. Clean arcs in helium may contain only a few hues whereas comparable arcs in argon may appear to have a white core.

It is noted that the human eye does not respond equally to radiant energy of different wavelengths. Maximum response of the eye occurs to green at 5550 Å\textsuperscript{0} and decreases smoothly towards both red and violet. Standard luminosity and relative brightness curves\textsuperscript{41} for the visible spectrum show that greens and yellows will appear brighter even when they are of the same intensity of red or violet.

**Plasma Streaming Resulting From Self Magnetic-Compression**

From Fig. 1, it can be seen that the magnetic field about a conductor is strongest at its surface and rapidly increases with current density. A magnetic pinch effect can be derived from this field geometry suggesting that the resulting forces may be effective in metal transfer. However, calculations indicate that these forces are an order of magnitude too small and they cannot explain acceleration of metal in transit through the plasma. "Although the
pinch effect may contribute to the neck action at an early stage when
the droplet is the fluid end of the electrode, there is no full current
flow in the neck when the droplet is nearing detachment. If there
were, the thin filamentary neck would vaporize in less than \(10^{-4}\)
seconds.\(^{45}\)

More recently, high-velocity gas flows in the arc have been
shown to exert forces capable of detaching the droplets and accelerating
them across the plasma. The terminology of "jets that stream"
from a constriction is descriptive and consistent with most of the
literature.

Jets are due to the interaction of arc current at a constriction
and its own magnetic field resulting in very high compression. A
magnetic pumping action develops as the forced inward motion of
charged particles draws large amounts of colder surrounding gas
into the arc. These gases are accelerated down a pressure gradient
decreasing away from the constriction by an axial component of pinch
resulting in part from the expanding cross-section of the arc column.
The stream is heated by the high current density at the constricted
active spot and also by Joule heating in the conducting stream. A
maximum velocity calculated for the 200 ampere carbon arc of 3.5
\(x 10^4\) cm/sec agrees well with core velocities of \(2 \times 10^4\) cm/sec
observed by Wienecke. Needham, Cooksey and Milner\(^{45}\) have
observed accelerations in the order of 100 times gravity and

106
terminal velocities of $10^3$ cm/sec. for quartz particles dropped near the tapered electrode of an inert-gas arc.

The subjects of magnetic pinch and plasma streaming are discussed in considerable detail in Appendix B.
EXPLANATION OF SLIDES AND HIGH-SPEED MOVIES

The discussion portion of this thesis is qualitative in analysis to emphasize the nature of the phenomena shown in the slides and movies. Consideration is directed to three aspects of inert-gas arc plasmas: namely, (1) plasma composition, (2) plasma temperatures, and (3) plasma jets. Color slides of the gas-tungsten-arc are considered first, and followed by discussion on the gas-metal-arc slides. Discussion of the sketches from the high-speed movies is combined with discussion on the movie proper.

Gas-Tungsten-Arc: Still Photographs and Sketches

Response of the gas-tungsten-arc to applied transverse magnetic fields is shown in the drawings and slides of Figs. 15 through 22. Figs. 15, 16, and 17 are typical of the way deflection develops with increasing applied field strength. Figs. 18 through 22 illustrate varying degrees of instability.

The gas-tungsten-arc in argon is characterized by a white, bell-shaped core. The core is a high temperature plasma jet composed mostly of ionized and excited argon atoms. The jet is a high-velocity gas flow from the constriction at the electrode and streams towards the base plate which is usually the anode. Plasma composition is determined largely by the cathode jet which suppresses most streaming from the anode. There is normally little tendency for
anode streaming to develop due to the large size of the molten puddle as compared to the constriction at the electrode. Metal vapors evaporated from the molten puddle will for the most part be blown aside by the strong cathode stream. Metal vapors, however, do probably contribute to the red and blue hues in the outer plasma sheath. This occurs because stream velocities in the outer portion of the cathode jet are several orders of magnitude less than those in the arc core as shown in Fig. 41.

Radial temperature distributions as determined by Olsen for the clean argon arc are shown in Fig. 42. Maximum temperature is 20,000° K and the isotherms are compressed as current decreases. The arcs in Figs. 15 through 18 are burning at 100 amperes and have core radii varying from 3 mm. to 6 mm. The 10,000° K isotherm in Fig. 42 has a maximum radius of 4 mm. for the 200 ampere arc. The outer sheaths of the arcs shown in Figs. 15 through 18 thus are much cooler and perhaps are lower than 6,000° K. which supports the probability of metal vapor in these regions.

Velocity distributions for the 200-ampere carbon arc shown in Fig. 41 are similar to those in the gas-tungsten-arc. The velocity increases with pressure which in turn increases with current density as shown in Eq. (16) derived by Maecker.

\[ \frac{1}{2} \int P V_{max}^{2} = P_{max} = \frac{1}{j} \frac{j}{C^2} \]  

(16)
Fig. 41. Stream Lines and Velocity Profile of a 200-Ampere Carbon Arc. (A) Map of Stream Lines, (B) Curves of Equal Velocity.
Fig. 42. Radial Temperature Distributions for the 5 mm. Argon Arc.\textsuperscript{54}
For the $I \propto \beta$ relationship used in this thesis, an applied field will exert a force on the arc causing deflection to the left. A deflected arc is the result of a skewed velocity profile in the cathode stream. Increasing amounts of arc deflection, as shown in Figs. 15 through 18, represent increasing amounts of bending of the stream lines. Unstable plasmas usually have stream lines that are reoriented as well as deflected.

Applied fields also distort deflected arc plasmas. Distortion results from an unbalance of the arc stiffness. Arcs possess directional stability, or stiffness, because the arc core is a high-velocity jet. Lesnewich\(^5\) has demonstrated this stiffness for the gas-metal-arc. An applied transverse field disturbs the magnetic pumping action at a constriction by reinforcing the self-field on one side and cancelling it on the other. This results in an arc column with high directional stability on the right and lower velocity streaming on the left.

In Figs. 15 through 18, the right-hand side of the arc maintains the profile of the undeflected arc while the left-hand side takes on a dispersed appearance that is longer, more deflected and more transparent.

Deflection of the main flow of the plasma away from the base plate is accompanied by the appearance of a metal vapor stream from the molten puddle. The stream in its initial stage of formation is
shown in Figs. 17 and 18. The vapor stream appears as a blue tail flame on carbon and stainless steel in argon and as a green tail flame on aluminum in helium. Deflection of the anode vapor stream indicates that current is flowing along its axis.

Deflection of both anode and cathode streams is to the left because current direction is from \(+\) to \(-\) regardless of whether conduction is due to upward mobility of positive ions or downward mobility of electrons. As deflection of the arc increases, the anode and cathode streams become separated and may even become parallel to each other. One wonders where the current makes a U-turn after coming off the electrode with a leftward velocity when it enters the base plate while traveling to the right. One also wonders how the current bridges the gap between parallel electrode streams when no portion of the bright arc cores is connected as is shown in Fig. 27.

To answer the later question, Olsen\(^4^9\) has said that electron conduction can occur through portions of plasma that are not emitting visible radiation. This occurs because conduction depends on sufficient ionization whereas visible radiation is determined by the level of excitation of the atoms in the plasma. Ionization and excitation in this respect are very different.

The answer to the first question lies in the inertia and current density of the plasma stream. A plasma jet acquires much of its velocity at the constriction and is then additionally accelerated while
flowing down the pressure gradient leading away from the constriction. The direction of the jet is thus determined at its point of constriction. Deflection of the jet occurs when the current density is sufficiently high to be affected by the applied field. However, if the current diffuses slowly out of the jet core or if the U-turn is made where two opposing jets intersect over a wide area of contact, the low current density will not approach that of a constriction and the radiating but non-conducting core of the jet will continue to stream on due to its inertia. The visible stream will dissipate soon after it stops conducting because radial heat losses are no longer replaced by Joule heating.

Development of arc instability is shown in Figs. 19 through 22. Instability is characterized by the development of a distinct anode jet and a very long, diffuse flame to the left of the arc that developed from what normally would be the outer sheath of the arc. As field strength is increased, the heat delivered to the anode is decreased due to deflection of the hot cathode stream. Cooling results in constriction of the molten cathode spot leading to streaming. A plasma jet containing large amounts of metal vapor is thus generated at the anode. The size and velocity of this anode jet both increases with the current density at the constriction. In Figs. 19 and 20 the stream is short and wide due to the large anode spot. In Figs. 21 and 22 the constriction is well developed. Fig. 21 is particularly
interesting in that the anode jet has the bell shape normally associated with the cathode jet.

The reduced velocity of the cathode stream and development of an anode stream introduce large amounts of metal vapor into the arc. Whereas the gas-tungsten-arc was originally a gas arc in its cathodic region, it now becomes a metal vapor arc in all but perhaps the core of the cathode jet. Even this is doubtful though since metal vapor abounds in those portions of the arc from which the constriction is pumping. The maximum temperatures are thus reduced by 5,000 - 10,000° K and the temperature distribution is greatly modified. The lower temperatures are apparent in two ways. First, the plasma appears less dense. Secondly, the plasma has larger regions of blue, green and red and the white arc core decreases in size.

In summary, arc extinction develops when applied fields disturb the direction and symmetry of the velocities in the cathode jet. Deflection of the cathode stream results in cooling of the molten puddle leading to an anode constriction from which a jet composed mostly of metal vapor streams. The arc is then transformed to a metal vapor in both its anodic and cathodic regions. The decreased ionization potential results in much lower temperatures. Finally, as shown in the movies and in Fig. 22, the anode spot moves to the left and the arc is extinguished.
Gas-Metal-Arc: Still Photographs and Sketches

Response of the gas-metal-arc to applied transverse magnetic fields is shown in the drawings and slides of Figs. 23 through 34. Figs. 23 through 28 illustrate the development of deflection and instability for DCSP. Figs. 29 and 30 show stable deflection for DCRP. Fig. 31 shows a strong anode jet from the base plate. Figs. 32 through 34 illustrate the development of instability leading to extinction for aluminum.

The gas-metal-arc shown in Fig. 29 has the typical appearance of the arc as it is used in industry. The arc plasma has four components, namely, (1) the white core, (2) a red inner sheath, (3) a blue outer sheath and (4) red and blue tail flames at the base plate. These four components also occur in DCSP spray transfer when 2% oxygen or more is added to the shielding gas as shown in Fig. 25.

The gas-metal-arc is a metal vapor arc in both its anodic and cathodic regions. Saha's equation shows that maximum arc temperatures will be on the order of 6,000° K due to the low ionization potential of metal vapor. The white core of the spray arc plasma is the hottest and therefore conducts most of the current. Due to the high degree of constriction at the electrode, the core is a high velocity jet and will be kept hot by Joule heating. The tendency for the core to remain as a constricted column is particularly noticeable on DCRP. The arc core originates at the end of the electrode rather than at the
highest point of plasma contact with the electrode as illustrated in Figs. 25 through 27. This is most noticeable when using DCSP and M-2 shielding.

The red of the inner sheath is probably due to an emission of excited iron-oxide. Oxygen is supplied in the M-2 shielding gas and at arc temperatures has a very high affinity for iron. This may explain why the inner sheath always originates above the arc core. Since the sheath forms in the upper portions of the arc where current is conducted mainly in the electrode, it will be cooler, as indicated by its red color. If the sheaths about the arc do form in this manner, then they represent stream lines in the velocity profile of the arc. The fact that the tail flames in hot regions removed from gas shielding emit the same red-orange color supports the assumption that the inner core is due to an iron-oxide emission. The color is similar to that emitted by carbon steel at about 2500° F.

The blue outer sheath of the arc is probably metal vapor which is substantially cooler than that in the inner core. However, it is noted that excited atoms of argon will exist throughout the plasma even though conduction occurs by ionization of metal vapor. The emission of light from an excited atom is dependent upon temperature and is independent of conductivity. The white of the arc core is probably due in part to emission of excited argon even though conduction may be entirely due to ionized iron. The same blue shown in the outer
sheath of the arcs in Figs. 25 and 29 is seen streaming directly off metal drops in Figs. 26 and 27 and off the molten weld pools in Fig. 28.

The red and blue tail flames shown in Figs. 25 and 29 are evidence of metal vapor and iron oxide. The structure of the gas-metal-arc is summarized in TABLE VI in terms of composition and temperature.

### TABLE VI. Structure of the Gas-Metal-Arc on Steel.

<table>
<thead>
<tr>
<th>Component</th>
<th>Color</th>
<th>Probable Max. Temperature*</th>
<th>Probable Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc core</td>
<td>blue-white</td>
<td>6,000° K</td>
<td>excited argon + excited and ionized metal vapor</td>
</tr>
<tr>
<td>Inner sheath</td>
<td>red-orange</td>
<td>2,000° K</td>
<td>excited iron-oxide vapor</td>
</tr>
<tr>
<td>Outer sheath</td>
<td>blue</td>
<td>1,000° K</td>
<td>excited and ionized metal vapor</td>
</tr>
<tr>
<td>Tail flames</td>
<td>blue</td>
<td>1,000° K</td>
<td>excited and ionized metal vapor</td>
</tr>
<tr>
<td></td>
<td>red-orange</td>
<td>2,000° K</td>
<td>excited iron-oxide vapor</td>
</tr>
</tbody>
</table>

* See Appendix D

Two per cent oxygen additions to argon as a shielding gas stabilized the tendency for the arc to wander. Arc stiffness is attributed to the formation of high velocity jets\(^1\) but Needham, et. al., have shown that the surface tension of the droplets is related to
transition to spray transfer. It is well known that oxygen will reduce the surface tension in steel and promote better wetting. Thus it is concluded that oxygen additions have several effects which contribute to stabilizing the arc. Oxygen additions stabilized the DCRP arc which was already in the spray transfer mode. Oxygen additions to DCSP arc which was formerly characterized by large uncontrolled globular transfer caused a transition to highly stable axial spray transfer. DCSP arc current was a straight line trace on the Esterline Angus recorder whereas current for even the stable DCRP arc continually fluctuated 3-5 amperes. The DCSP arc responded smoothly to change in wire feed, voltage and slope and stability could be maintained from voltages between 28 and 40 and from currents between 200 and 600 amperes for both carbon and stainless steels.

In addition to arc stability, the DCSP arc in M-2 exhibited two phenomena which were particularly useful in studies of arc magnetics. The plasma core was more transparent and metal transfer could be photographically recorded without under-exposing the outer visible portions of the arc plasma. Secondly, the electrode tapered deep into the arc plasma as can be seen in Fig. 23.

The origin and nature of plasma jets in arcs are discussed in detail in Appendix B, however, much remains to be studied particularly in the gas-metal-arc. Plasma jets in welding arcs assist metal transfer and for the transport of gas through the arc to the
weld metal surface and thus play an important part in mass and heat transfer. They also probably contribute cratering in the weld pool, while the intense jet associated with dissociated cores are at least partly responsible for the action of deep-penetration electrodes, and the ionization core of the deep-penetration toe in inert-gas shielded arc welding. Plasma jets must also be considered in the maintenance of efficient gas shielding at high currents where magnetic pumping would be intense. 46

Needham, et. al., 45 have proposed an explanation of metal transfer caused by plasma jets. "A plasma jet which has a velocity of the order of 10^4 cm/sec. (about 225 mph) is formed wherever an arc is constricted and there is a current density gradient. Plasma jets can originate from either or both electrodes, but with a small diameter electrode the welding arc is mainly constrained by the wire and the main plasma stream operates from the wire to the plate, irrespective of the polarity or electrode material."

Evidence of plasma streaming in gas-metal-arcs originates from studies of drops in flight. Metal vapors stream ahead of the drop in flight rather than trailing the drop as would be the case if the drop were expelled faster than the surrounding plasma. Blue metal vapor can be seen streaming ahead of the drops in Figs. 23 and 26 and is evident throughout the movies. Color enlargements from high-speed movies published by Needham clearly show the
streaming of metal vapor. As the molten drop passes out of the arc zone, it becomes cooler and the trailing stream and accompanying sheath of vapor have a red color. The red vapor trail can be seen in Figs. 24 and 26 through 28. The direction, deflection and dispersion of plasma jets in gas-metal-arcs can be studied from the streaming of visible metal vapor. It may be possible to use this streaming to approximate the velocity of the jets although this is only of relative value since the velocity distribution is severely modified by the applied field.

The velocity distribution shown in Fig. 41 was determined for the carbon arc in air. Arcs in mono-atomic gases such as argon operate at lower current densities due to the absence of a hot dissociated core. Lower current densities result in lower pressures (Eq. (B4)) and hence slower plasma velocities (Eq. (16)). Plasma jets in gas-metal-arc welding are further modified by metal transfer and thus their analysis is complex and to date only indirect.\textsuperscript{45} Velocity distributions for the gas-metal-arc, as is the case with temperature distributions, have yet to be determined.

Needham, et al.,\textsuperscript{45} have used movies taken at 9,000 fps to measure droplet accelerations of $4 \times 10^4$ cm/sec. for the 270 ampere aluminum arc. The accelerating force required is about 100 dynes and is due in part to skin friction and also to pressure drag. Transition from globular to spray transfer occurs over a relatively small
current range because as the globule size decreases, the plasma jet increases and the surface tension forces decrease.

Fig. 31 is a unique picture of a strong anode jet streaming from the base plate of a DCSP gas-metal-arc. The normal cathode jet from the wire is absent due to the very large drop of metal on the end of the wire. The jet exerts a large force on the electrode and appears to be supporting the large metal drop. The abundance of orange flames about the arc is due to 5% O₂ in the arc atmosphere. The dynamic aspects of a jet of this type were captured in Cine #5 for the DCRP arc. The arc is re-established in its normal deflected mode when the drop breaks up into many small droplets which fly away as spatter.

Fig. 32 is typical of the stable deflection in aluminum gas-metal-archs. Large amounts of aluminum oxide formed in the arc region when high currents or high magnetic field strengths were used. The aluminum arc was not transparent and metal transfer within the plasma could not be observed effectively. The gas-metal-archs on aluminum became unstable at lower applied field strengths in both argon and helium than did arcs on stainless and carbon steel. Excellent movies of instabilities of the aluminum arc were obtained showing the development of arc extinction. Fig. 34 shows the arc just before it extinguishes. The arc swirl to be discussed in the next section is indicated by Fig. 34.
Analysis of High-Speed Films

The most interesting and informative portions of the 2600 feet of film shot for this thesis are combined into a 30-minute movie entitled, "The Gas-Metal-Arc in Transverse Magnetic Fields." This movie summarizes the data and, in terms of discussion, speaks louder for itself than could any verbal description. The contents of this movie are organized in TABLE V.

Viewing of this film should be preceded by reading of the previous sections of this discussion. Nomenclature for and identification of components of the arc plasma in terms of their composition and temperature have been developed. The mechanisms of interaction between the applied field and arc current have been explained in terms of plasma velocity distributions. The theory on plasma jets which are responsible for metal transfer have been analyzed in Appendix B and applied in the section on "Gas-Metal-Arc: Slides and Sketches." Titles containing Cine numbers, arc parameters and a drawing of the stable arc configuration representative of that shot, precede each section of film.

Transfer of a droplet the diameter of the filler wire is shown in Fig. 36. This is typical of the stable sequences photographed in this thesis. In the absence of an applied field, the arc column and metal transfer both remain vertical. When a magnetic field is applied, the droplets are often detached with a tumbling motion as shown in
Fig. 37. The manner in which the arc pushes the molten metal in the weld puddle ahead is shown in Fig. 38, but is more evident in the movies. The arc appears to sweep over the puddle surface such that the momentum of the plasma jet from the electrode pushes molten metal ahead of the electrode.

Stable arc deflections are much as would be expected from application of the left-hand rule. Non-stable conditions of arc deflection are dynamic in nature and the action of plasma jets must be thoroughly understood to realize why the arc cores are deflected separately. Two dynamic conditions: arc rotation in a horizontal plane and arc spinning in a vertical plane, occur occasionally as arc instabilities in high applied field strengths that are often part of arc extinction. These phenomena are not presently explained but do occur with increasing frequency as the applied field strength is increased. Verbal descriptions of these phenomena are included in the thesis to supplement the movies and to prepare the viewer for the rapid arc movements.

Occasionally the arc core from the electrode exhibits a rotating motion in the plane of the base plate. Rotation of the arc always occurs in a clockwise direction as viewed from the electrode and for the applied field-current polarity combinations resulting in forward arc deflection used in this thesis. The direction is independent of all arc parameters including polarity and electrode material. When rotation does occur, it is often part of arc extinction. However, very few extinctions are
accompanied by rotation. Rotation may also occur as a momentary instability from which the arc recovers by sweeping back to its deflected position. The arc has not been observed to rotate through more than $90^\circ$ before either extinguishing or restabilizing. However, the whipping rotational motion of a droplet on the end of a filament neck in an applied field indicates that there is directed turbulence within the arc.

The spiral whipping action of a drop is shown in Cine #5 for DCSP on carbon steel and in Cine #7 for DCRP on stainless steel. Rotation at extinction is shown in Cine #16 for DCRP on stainless steel and for DCRP on aluminum in Cine #21.

The arc column frequently spins clockwise as viewed by the camera, in a vertical plane. As with rotation, spinning usually occurs as part of arc extinction but not all extinctions are accompanied by spinning. Spinning occurs more frequently than does rotation and can be seen in nearly every film. Spinning also occurs as a momentary arc instability from which the arc recovers to stable deflection. Unlike rotation, spinning may occur through full $360^\circ$ revolutions and often does so in rapid successions of 2 - 4 revolutions. Spinning looks much like the pinwheel typical of fireworks displays.

Arc instabilities leading to both recovery and to extinction, occur in $1/1000$ to $1/100$ second and are difficult to follow at normal
viewing speeds of 24 fps but are obvious and detailed when viewing the film frame-by-frame.
CONCLUSIONS

The following conclusions are based on the photographic data collected in this thesis and consideration of the nature and effects of plasma streams in welding arcs.

1) Still photography is a useful tool for studying the welding arc. Realistic color can be reproduced with 35 mm slides by using an 85-B color-correction filter. The high intensity of the arc can be compensated for by using slow speed film, numerically high f-stops, and neutral density filters. Determination of the plasma components and metal transfer can be achieved by stopping down three stops further than what is indicated by light meter measurements. Stopping down further than this produces better pictures of metal transfer but at the loss of detail in the outer regions of the plasma.

2) High-speed films, when shot at three or more f-stops down from that indicated by "photo-spot" light meter measurements, reveal metal transfer without the use of backlighting.

3) High-speed films are essential to plasma studies of arc instabilities in applied fields. Instabilities usually progress to extinction in less than 1/100 sec.

4) The DCSP gas-tungsten-arc is a gas arc in its cathodic
regions and a metal vapor arc in its anodic regions. The gas-metal-arc is a metal vapor arc in both its anodic and cathodic regions. The maximum temperature in metal vapor welding arcs is about $6,000^\circ$ K. The maximum temperature in gas arcs in argon is about $20,000^\circ$ K but decreases rapidly with current density and the introduction of small amounts of metal vapor. Conduction in metal vapor arcs is due to ionization of metal vapors. Conduction in gas arcs is due to ionization of the arc atmosphere which in welding arcs is usually argon or helium.

5) Visible radiation from the arc plasma is due to electrons of excited atoms returning to lower energy levels. The color of radiation is dependent upon the magnitude of the energy drop which can be correlated to the temperature of the excited atom. Colors in welding arcs are an indication of temperature. White is hottest followed by blue, green, yellow, and orange to the cooler red hues.

6) Excitation is independent of ionization although both arc temperature dependent. Light from a gas-metal-arc in argon comes from excited atoms of both argon and metal vapor while electrical conductivity is due only to ionization of metal vapors.
7) The ferrous gas-metal-arc has four components:
   a) A blue-white core of ionized and excited metal vapor and excited argon atoms.
   b) A red-orange inner sheath of excited iron-oxide vapors.
   c) A blue outer sheath of excited argon and metal atoms.
   d) Tail flames of blue metal vapor and red iron-oxide vapors.

8) The arc core originates from the end of the electrode whereas the arc sheaths contact the electrode well above the point of drop detachment. This is particularly evident on DCSP using 2% O₂ additions to an argon atmosphere.

9) Ferrous gas-metal-arcs are most amenable to arc magnetic studies when operating on DCSP and in argon + 2% O₂ atmospheres. These arcs are characterized by very stable current traces and large areas of contact between the plasma and the electrode due to the extended deep taper of the electrode tip into the arc.

10) Fleming's left-hand rule is useful in predicting the direction of arc deflection in applied magnetic fields. Explanation of arc deflection and plasma distortion - particularly at high applied field strengths - must consider streaming in the
Arc deflection is the result of a skewed velocity distribution of the stream from the electrode. Unstable plasmas have stream lines that are reoriented in the direction of deflection as well as deflected.

11) Distortion of arc plasmas results from an unbalance in the stiffness of the arc column. Applied fields disturb the magnetic pumping action to produce an arc with high directional stability on one side and lower velocity streaming on the other.

12) Distorted portions of deflected arcs have a dispersed appearance that is larger, more deflected and more transparent than undistorted regions.

13) Deflection of the main plasma stream from the electrode away from the base plate is accompanied by development of a plasma stream from the base plate. Streaming from the base plate occurs because the normal suppressing action of the electrode plasma stream is reduced and because the active spot on the base plate is constricted by cooling which results from decrease in heat transfer to the active spot from the electrode plasma stream.

14) Plasma streams from the base plate conduct current as evidenced by their deflection in magnetic fields. Plasma streams from both electrodes are deflected in the same direction.
indicating that conduction is due to highly mobile electrons which can move against the high-velocity plasma streams, whereas positive ions must move with the streams. It is noted that downward electron motion is equivalent to upward motion of positive ions.

15) Blue metal vapors from the electrode and base plate may become parallel in high-strength applied fields as opposed to their normal co-axial alignment in the absence of magnetic fields. Electron conduction does occur through the region between the visible plasma cores without the emission of visible radiation. This is attributed to low current density over the large area between streams. The inertia of plasma streams causes continuation of their motion even after they stop conducting current. The visible radiation from the core of the stream will disappear soon after it stops conducting because radial heat losses are no longer replaced by Joule heating.

16) The reduced velocity of the stream from the electrode and development to a stream from the base plate introduces large amounts of metal vapor to the gas-tungsten-arc transforming it largely to a metal vapor arc.

17) Arc extinction in strong applied fields occurs as the result of excessive disturbance of the direction and
symmetry of the velocity distribution of the plasma stream from the electrode. Development of a plasma stream from the base plate further deflects the stream from the electrode. Extinction occurs when the plasma streams from the two electrodes are separated so widely that current density between streams becomes low and the plasma cools to the point where it will no longer conduct the arc current.

18) Two forms of plasma instabilities exist that often lead to extinction but do not always occur as the arc extinguishes. Horizontal clockwise (as viewed from the electrode) rotation of the arc through up to 90° occurs in high field strengths as the arc core from the electrode is swept out of its stable forward deflected position. Vertical clockwise (as viewed from the camera) spinning of the arc core from the electrode through several revolutions occurs in high field strengths. Spinning and rotation do not usually occur simultaneously.

19) Very strong forces are exerted on the tip of the electrode when arc spinning begins. The nature of these forces is not known but they are strong enough to bend the end of a 1/16" diameter electrode into a U through a radius of less than 1/4" in a 150 gauss field.
20) Plasma streaming has a large effect on the formation of droplets, on their separation from the electrode and on their transfer across the arc zone. Development of a filamentary tapering neck is more pronounced with DCSP and \( \text{O}_2 \) additions to the argon atmosphere. Break-up of the filamentary neck into fragmentary particles is accompanied by a tumbling action of the detached drop.

21) The blue plasma streaming from a droplet in the arc core is largely metal vapor.

22) The red-orange plasma enclosing a drop separated from the wire above the arc core or enclosing a drop transferred outside the arc core probably is due to iron-oxide.

23) Plasma streams disperse rapidly in the vicinity of the stable arc but persist streaming in the direction of deflection for the deflected and unstable arcs.

24) DCSP using argon + 2% \( \text{O}_2 \) shielding is most amenable to arc magnetic studies of gas-metal-arcs for both stainless and carbon steel.

25) Gas-tungsten-arcs in helium are more readily deflected than in argon due to the lower density of the streaming helium.

26) Gas-metal-arcs on aluminum are less stable in applied fields when using helium shielding than when using argon shielding.
27) Gas-metal-arcs on aluminum are less stable in applied fields than are arcs on stainless or carbon steel of the same current and voltage.

28) Gas-tungsten-arc voltage increases and current decreases as applied field strength is increased, when using a drooping-characteristic power supply.

29) Gas-metal-arc current decreases but voltage remains constant when applied field strength is increased at constant wire feed rate for a constant-potential power supply.


Fig. A-1. Set-up of Electromagnet for Field Measurement and Mapping.
<table>
<thead>
<tr>
<th>Auto-Transformer Setting</th>
<th><strong>$\beta_1$</strong></th>
<th><strong>$\beta_2$</strong></th>
<th><strong>$\beta_3$</strong></th>
<th><strong>$\beta_4$</strong></th>
<th><strong>$\beta_5$</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>18</td>
<td>15</td>
<td>11</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>0.05</td>
<td>27</td>
<td>20</td>
<td>15</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>0.10</td>
<td>33</td>
<td>27</td>
<td>21</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>0.15</td>
<td>45</td>
<td>38</td>
<td>28</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>0.20</td>
<td>56</td>
<td>48</td>
<td>36</td>
<td>22</td>
<td>8</td>
</tr>
<tr>
<td>0.25</td>
<td>67</td>
<td>58</td>
<td>43</td>
<td>26</td>
<td>9</td>
</tr>
<tr>
<td>0.30</td>
<td>79</td>
<td>69</td>
<td>50</td>
<td>32</td>
<td>12</td>
</tr>
<tr>
<td>0.35</td>
<td>90</td>
<td>80</td>
<td>58</td>
<td>37</td>
<td>14</td>
</tr>
<tr>
<td>0.40</td>
<td>105</td>
<td>90</td>
<td>66</td>
<td>41</td>
<td>16</td>
</tr>
<tr>
<td>0.45</td>
<td>115</td>
<td>100</td>
<td>73</td>
<td>46</td>
<td>18</td>
</tr>
<tr>
<td>0.50</td>
<td>128</td>
<td>115</td>
<td>82</td>
<td>51</td>
<td>20</td>
</tr>
<tr>
<td>0.60</td>
<td>150</td>
<td>135</td>
<td>98</td>
<td>62</td>
<td>23</td>
</tr>
<tr>
<td>0.70</td>
<td>175</td>
<td>157</td>
<td>112</td>
<td>70</td>
<td>27</td>
</tr>
<tr>
<td>0.75</td>
<td>188</td>
<td>166</td>
<td>120</td>
<td>75</td>
<td>29</td>
</tr>
<tr>
<td>0.80</td>
<td>200</td>
<td>178</td>
<td>130</td>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td>0.90</td>
<td>228</td>
<td>200</td>
<td>145</td>
<td>88</td>
<td>34</td>
</tr>
<tr>
<td>1.0</td>
<td>245</td>
<td>218</td>
<td>160</td>
<td>98</td>
<td>38</td>
</tr>
</tbody>
</table>

**TABLE A-I.** Data from Measuring Applied Field on 3/8" Thick Carbon Steel.
<table>
<thead>
<tr>
<th>Auto-Transformer Setting</th>
<th>( \beta_1 )</th>
<th>( \beta_2 )</th>
<th>( \beta_3 )</th>
<th>( \beta_4 )</th>
<th>( \beta_5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>.00</td>
<td>18</td>
<td>16</td>
<td>13</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>.05</td>
<td>25</td>
<td>23</td>
<td>19</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>.10</td>
<td>37</td>
<td>32</td>
<td>26</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>.15</td>
<td>47</td>
<td>41</td>
<td>33</td>
<td>27</td>
<td>20</td>
</tr>
<tr>
<td>.20</td>
<td>59</td>
<td>51</td>
<td>41</td>
<td>33</td>
<td>25</td>
</tr>
<tr>
<td>.25</td>
<td>70</td>
<td>63</td>
<td>50</td>
<td>41</td>
<td>30</td>
</tr>
<tr>
<td>.30</td>
<td>82</td>
<td>74</td>
<td>61</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>.35</td>
<td>94</td>
<td>85</td>
<td>70</td>
<td>55</td>
<td>41</td>
</tr>
<tr>
<td>.40</td>
<td>110</td>
<td>96</td>
<td>80</td>
<td>62</td>
<td>48</td>
</tr>
<tr>
<td>.45</td>
<td>118</td>
<td>110</td>
<td>88</td>
<td>70</td>
<td>54</td>
</tr>
<tr>
<td>.50</td>
<td>133</td>
<td>120</td>
<td>98</td>
<td>78</td>
<td>61</td>
</tr>
<tr>
<td>.60</td>
<td>160</td>
<td>145</td>
<td>118</td>
<td>91</td>
<td>70</td>
</tr>
<tr>
<td>.70</td>
<td>182</td>
<td>170</td>
<td>135</td>
<td>110</td>
<td>82</td>
</tr>
<tr>
<td>.75</td>
<td>195</td>
<td>180</td>
<td>145</td>
<td>115</td>
<td>88</td>
</tr>
<tr>
<td>.80</td>
<td>207</td>
<td>190</td>
<td>152</td>
<td>122</td>
<td>94</td>
</tr>
<tr>
<td>.90</td>
<td>230</td>
<td>210</td>
<td>175</td>
<td>138</td>
<td>108</td>
</tr>
<tr>
<td>1.00</td>
<td>250</td>
<td>235</td>
<td>190</td>
<td>150</td>
<td>118</td>
</tr>
</tbody>
</table>

**TABLE A-II.** Data from Measuring Applied Field on 1/4" Thick 308 Stainless Steel.
<table>
<thead>
<tr>
<th>Auto-Transformer Setting</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
<th>$\beta_3$</th>
<th>$\beta_4$</th>
<th>$\beta_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>.00</td>
<td>18</td>
<td>17</td>
<td>15</td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>.05</td>
<td>28</td>
<td>20</td>
<td>18</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>.10</td>
<td>40</td>
<td>25</td>
<td>22</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td>.15</td>
<td>52</td>
<td>40</td>
<td>32</td>
<td>24</td>
<td>19</td>
</tr>
<tr>
<td>.20</td>
<td>70</td>
<td>52</td>
<td>40</td>
<td>29</td>
<td>24</td>
</tr>
<tr>
<td>.25</td>
<td>84</td>
<td>62</td>
<td>48</td>
<td>37</td>
<td>28</td>
</tr>
<tr>
<td>.30</td>
<td>100</td>
<td>75</td>
<td>57</td>
<td>43</td>
<td>33</td>
</tr>
<tr>
<td>.35</td>
<td>118</td>
<td>84</td>
<td>65</td>
<td>49</td>
<td>38</td>
</tr>
<tr>
<td>.40</td>
<td>132</td>
<td>98</td>
<td>75</td>
<td>56</td>
<td>43</td>
</tr>
<tr>
<td>.45</td>
<td>150</td>
<td>110</td>
<td>84</td>
<td>62</td>
<td>50</td>
</tr>
<tr>
<td>.50</td>
<td>165</td>
<td>120</td>
<td>92</td>
<td>69</td>
<td>54</td>
</tr>
<tr>
<td>.60</td>
<td>200</td>
<td>140</td>
<td>112</td>
<td>82</td>
<td>64</td>
</tr>
<tr>
<td>.70</td>
<td>228</td>
<td>160</td>
<td>130</td>
<td>94</td>
<td>75</td>
</tr>
<tr>
<td>.75</td>
<td>240</td>
<td>170</td>
<td>140</td>
<td>102</td>
<td>80</td>
</tr>
<tr>
<td>.80</td>
<td>250</td>
<td>185</td>
<td>145</td>
<td>110</td>
<td>84</td>
</tr>
<tr>
<td>.90</td>
<td>280</td>
<td>205</td>
<td>165</td>
<td>122</td>
<td>94</td>
</tr>
<tr>
<td>1.00</td>
<td>300</td>
<td>225</td>
<td>180</td>
<td>135</td>
<td>118</td>
</tr>
</tbody>
</table>

**TABLE A-III.** Data from Measuring Applied Field on 1/2" Thick 5053-H113 Aluminum.
APPENDIX B

MAGNETIC PINCH AND PLASMA STREAMING

From Fig. 1, it can be seen that the magnetic field is strongest at the circumference of the conductor and rapidly increases in strength with the current density. Herein lies the origin of the well known pinch effect. \(^35, 37, 43, 51\) "As a result of non-parallel current flow within the electrode, the body forces integrate to give a net force of appreciable magnitude on the electrode as a whole. These electromagnetic forces act to depress the surface of the molten electrode near the fringes of the arc impingement zone. For typical high current arcs, the maximum electromagnetic body forces are the same order of magnitude as gravitational body forces. At any point, the force varies as the square of the arc current and inversely as the cube of the effective arc diameter at the electrode surface. The maximum forces occur at the surface well out from the arc axis and are directed at an angle to the surface." \(^37\) Thus the pinch effect has both radial and axial components.

The pinch contraction force acts radially inward independent of current polarity. Serdyuk \(^35\) has determined the pinch pressure at a radius \(r\) inside a conductor of radius \(R\) to be:

\[
F_{mp} = \frac{10.2 m I^2 r^2}{8 \, R^2} \text{ kg/cm}^2
\]  

\hspace{1cm} (B1)
where:

\[ m = \text{magnetic permeability} \]
\[ I = \text{current in the conductor} \]

The pinch pressure for typical arcs calculated by Eq. (B1) is 1 gram/cm\(^2\) within an order of magnitude. The radial pinch force also produces an internal fluid pressure component which gives rise to an axial force. For a complete conductor carrying current I, the component of "balanced" axial thrust, \( P_1 \), is given by Eq. (B2).

\[ P_1 = 50I \quad \text{(B2)} \]

where \( I \) is in amperes, \( P_1 \) will be in dynes.

A conical or bell shaped plasma is typical of welding arcs where one electrode is a thin rod and the other electrode is a plate. When a conductor of circular cross-section is conical and has constant current density at all plane cross-sections, an "unbalanced" axial thrust acts in the direction of current expansion from the smaller cross-section of radius \( R_1 \) to the larger of radius \( R_2 \). The magnitude of this force is given by Eq. (B3).

\[ F_{ap} = k I^2 \log_e (R_2/R_1) \quad \text{(B3)} \]

where the current, \( I \), is in amperes, the force, \( F_{ap} \), will be in dynes when \( k = 10^{-2} \) and in pounds when \( k = 2.25 \times 10^{-8} \).

Several attempts \(^{35, 37}\) have been made to explain metal transfer in welding arcs based on a balance of the surface tension forces (which oppose pinch), of gravitational forces, and of the forces.
stated above which originate from magnetic pinch. Since pinch forces increase with the square of the current, an explanation of the transition to various types of metal transfer, i.e., globular, spray, fingerling and puckering, was logically based on pinch effects. The principal difficulty is that the arc forces so calculated are an order of magnitude smaller than those observed. In addition, pinch forces acting on the molten electrode end cannot explain the observed acceleration of electrically isolated droplets through the column. More recent theories have shown forces of the right magnitude to transfer the metal droplets, could arise from the formation of a "magnetic plasma jet" from the small diameter electrode to the base plate. It is noted that these jets are of a different nature than the electrode vapor jets described by Finkelnberg.

The literature has commonly referred to high-velocity gas flows occurring in arcs as jets that stream from a constriction at an active spot (either anode or cathode) into the arc column. The terms anode and cathode flames have also been used to describe the streaming phenomena. However, the terminology of jets that stream is more descriptive and most consistent with the literature. Therefore the jet terminology will be used in this thesis.

Maeker first proposed the theory to explain plasma jets in 1955. The jets are due to a very high compression of the plasma at the active spots by its own magnetic field. The arc current will
interact with its own magnetic field to produce a force on all charge carriers. Since the current density, \( j \), and its own field, \( H \), are normal to each other, the Lorentz forces (equating) are always directed radially to the axis of the cylindrical arc. In much the same way, parallel elements of current will attract each other. Under the influence of these forces, electrons and ions will move towards the axis of the arc and carry neutral atoms with them by thermal collision. The gradient in the pressure field thus formed will oppose the Lorentz forces. Equilibrium is attained when the increased impacts from within compensate for the Lorentz force field.

Eq. (B4) is cited by Maeccker as describing the pressure gradient in a homogenous arc with current, \( I \), radius \( r_a \), and current density \( j = I/\pi r_a^2 \).

\[
p(r) = \frac{Ij}{c^2}(1 - \frac{r^2}{r_a^2})
\]

(B4)

The maximum pressure will occur at the center and be given by \( \frac{Ij}{c^2} \). Recalling from Fig. 1 that the current density increases as the cross-section decreases leading to very strong radial field strengths and noting that the pressure also increases with current density, one can see that a constriction will tend to maintain itself.

The high pressure at the constriction is partially equalized by flow towards regions of larger cross-section. The change in cross-section results in an axial component of Lorentz force which accelerates the plasma. Thus, any stream line in the vicinity of the con-
striction is about normal to j but is parallel to j in the immediate vicinity of the axis of j where the magnetic field is negligible. "However, let us look only at the radial component of Lorentz force and the accompanying pressure distribution. Along the axis the pressure drops when traveling away from the cathode (constriction). The spreading of the plasma causes a drop in pressure in the opposite direction which is over compensated for by the axial component of the Lorentz force. Without this last force, the pressure gradient along the axis would be equalized by the pressure gradient along the boundary." 52

The fastest streaming occurs along the axis of the arc column resulting in the formation of a core. Constriction of the plasma causes a magnetic pump which accelerates the plasma. "Continuity requires that cold gas be drawn in from surrounding regions. This cold gas stream constrists the cross-section further thus heightening the effect. Cause and effect act together until equilibrium is reached between streaming and steep temperature gradients." 52 The temperature required to heat the incoming gas is reflected in an increase of about 1 volt at the constriction. The high conductivity of the hot stream causes the current fibers to contract. Joule heating compensates for radial heat losses and additionally raises the temperature to form and maintain a visible arc core.
In summary, three conditions are required for the formation of an arc core.

1) Magnetic pumping from a constriction leading to the formation of a plasma stream.

2) Heating of the stream by the high current density at the constriction which is usually an active spot and has the thermal power liberated by the V-I drop of the cathode or anode region.

3) Maintenance of the high temperature in the stream by Joule heating.

Maecker has produced a plasma motion and configuration equivalent to a jet streaming from each of two opposing electrodes. The quantity of gas to produce such jets is much larger than could result from electrode evaporation. The entrainment of gas into the arc column provides a reasonable explanation for the observed jet action. Wilkinson and Milner have shown that, if measured arc pressures at plate electrodes are to be simulated by jet action from the direction of the rod electrode, gas velocities of about \(10^4\) cm/second would be required in the arc column. Values of this magnitude have been observed by Wienecke in the carbon arc.

The pressure at the cathode spot calculated by the hydrodynamic theory of the plasma agrees with manometer measurements and is about 100 mm of water. The reaction on the cathode due to
the stream, about 0.03 pounds, agrees with measurements. Maecker has further shown that any constriction in the plasma will result in an accelerating mechanism effective due to the self-magnetic field.

King and Howes show how the various modes in the welding arc are produced by changes of the plasma stream caused by the formation of high temperature cores in the arc column. In the initial stages of globular transfer, the current density at the wire tip is quite high, but the plasma jet forces are not strong enough to overcome the surface tension of the molten metal. As the current is increased, a critical value is reached where the plasma jet force is just large enough to part off the droplet at its initial small size. Thus the transition from globular to spray transfer will occur over a very small range of power input.

From the above discussion, one can see that the self-magnetic field of the current in the arc plasma affects the plasma configuration, temperature, density, pressure and the mechanism of metal transfer. An externally applied magnetic field modifies the self-magnetic field and also causes motor rule deflection of the arc plasma through interaction of the self and externally applied fields. Thus external fields greatly change the nature and behavior of the arc plasma.
SAHA'S EQUATION

Welding arc plasmas are usually established by an electrical potential between two electrodes at atmospheric pressure. Under these conditions, the electron temperature and gas temperature are essentially the same. M. N. Saha, an astronomer, analyzed thermal ionization to investigate the temperature of the stars. Since welding arcs are also the thermally ionized plasma, Saha's equation is applicable.

In welding arc plasmas the concentration of ions, $n_i$, and electrons, $n_e$, are approximately equal. The concentration of neutral atoms, $n_n$, is equal to the original concentration of atoms, $n$, minus ($n_i + n_e$). The concentrations of $n_n$, $n_i$, and $n_e$ are assumed to be in thermal equilibrium.

Saha's equation for welding arcs is normally given in exponential or logarithmic form.

$$\log_{10} \left( \frac{n_i^2}{n} \right) = -5,050 \left( \frac{V_i}{T} \right) + 1.5 \log_{10} T + 15.385 \quad (C1)$$

where:

$T$ = gas temperature °K

$V_i$ = ionization potential of the arc atmosphere in electron-volts.

151
The ability of plasma to conduct a current is largely dependent upon its degree of ionization and the mobility of charged particles. In welding arcs, the mobility of the electrons is so much higher than that of the positive ions that for practical purposes, all current can be considered to be carried by electrons. It is for this reason that Eq. (C1) is written in terms of electron density.

The electron density can be determined from the current and cross-section of the conductor. Thus, if the ionization potential of the arc plasma is known, the temperature can be calculated. The ionization potentials of elements commonly found in arc atmospheres are given below:

<table>
<thead>
<tr>
<th>Element</th>
<th>Ionization Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon</td>
<td>15.68 volts</td>
</tr>
<tr>
<td>Helium</td>
<td>24.46</td>
</tr>
<tr>
<td>Oxygen</td>
<td>13.55</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>14.48</td>
</tr>
<tr>
<td>Iron</td>
<td>5.96</td>
</tr>
<tr>
<td>Aluminum</td>
<td>7.83</td>
</tr>
<tr>
<td>Tungsten</td>
<td>8.1</td>
</tr>
<tr>
<td>Carbon</td>
<td>11.22</td>
</tr>
<tr>
<td>Titanium</td>
<td>6.81</td>
</tr>
</tbody>
</table>

The curves in Fig. C1 are calculated using Eq. (C1) and ionization potentials of $V_i = 6$, $V_i = 10$ and $V_i = 16$. For equal
conductivities indicated by an ionization ratio of $10^{16}$, an argon arc must be 17,000° K whereas a metal vapor arc is only 6,000° K. The flat slope of these curves for temperatures above 12,000° K is an indication that the arcs in inert atmospheres have temperature profiles covering a wide range to compensate for small changes in current density.

In general, all metals have low ionization potentials as compared to inert gases. This is the reason that metal vapor arcs are much lower temperature arcs than arcs in inert atmospheres.
APPENDIX D

SPECTROGRAPHIC DETERMINATION OF TEMPERATURE

Measurement of temperatures in electric arcs has been accomplished by two techniques. One technique utilizes the spectral analysis of the radiation emitted by the arc to determine temperature. A second technique determines plasma temperatures by measurement of the velocity of a sound wave in the plasma. Discussion of the spectrographic theory follows.

The frequent collisions of particles in the arc plasma promote thermal equilibrium and result in the excitation and ionization of atoms of gases and vapors. When excited, one of the electrons attached to an atom is shifted from one electron orbit to another of higher energy level. Most of these energy levels are highly unstable so the electron immediately drops to a vacant lower level with emission of a photon of energy. The energy of the quantized light emitted determines its wavelength according to Eq. (D1).

\[ E = h\nu = \frac{hc}{\lambda} \]  \hspace{1cm} (D1)

where:

- \( E \) = energy of radiation (ergs)
- \( h \) = Plank's constant \((6.624 \times 10^{-27} \text{ erg-sec.})\)
- \( \nu = c/\lambda \) = frequency of radiation (cps)
- \( c \) = velocity of light \((3 \times 10^{10} \text{ cm/sec})\)
- \( \lambda \) = wavelength (cm.)
It is the analysis of the frequency distribution of this radiation that leads to a temperature measurement.

"The spectrum originating from spontaneous emission by an excited atom of a gas is usually distributed into a number of very narrow, discrete wave length intervals distributed through a broad region of the spectrum."\(^{55}\) The resultant spectrum appears on a spectrogram as a series of narrow lines as shown in Fig. D1. The wavelength of these spectral lines are determined by configuration of the atom and are characteristic of the particular element. "The metallic atoms of large atomic weights have very complex spectra due to the large number of different transitions possible. The particular groups of characteristic wavelengths that appear in the spectrum of an arc depend on plasma composition, temperature and condition of excitation."\(^{55}\)

Since the arc is hottest at its core and is surrounded by concentric shells of cooler plasma and gases, radiation from the hottest arc zone must pass through the cooler gases to the observer. As a result self absorption of some of the spectral lines may occur. Line broadening may also occur. \(^{55}\) Olsen\(^{56}\) has used the optical arrangement shown in Fig. D2 to obtain measurements similar to those shown in Fig. D3.

A brief survey of arc temperature measurements reveal a broad range from 6,000\(^{\circ}\) to 55,000\(^{\circ}\) K. Suits\(^{55}\) determined the
Fig. D1. Optical System for Spectrographic Analysis of the Welding Arc.
Fig. D2. Optical Arrangement Showing the Zonal Division of the Plasma.
Fig. D3. Observed (Left Section) and Cross-Sectional (Right Section) Iso-intensity Contour Maps of the 300-Amp, 5 mm, Atmospheric Argon Arc.
temperature of the bare iron electrode welding arc as 6,000° K using sound waves. Sound waves have also been used to determine temperatures of 14,000° K in the gas-tungsten-arc. Finkelnberg and Maeker have determined temperatures of 6,000° K for the 40 ampere carbon arc while the 200 ampere carbon arc has temperatures of 12,000° K. Olsen has summarized a study of maximum arc temperatures as follows.

<table>
<thead>
<tr>
<th>Type</th>
<th>Temperature (° K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal-vapor-arcs</td>
<td>6,000° K</td>
</tr>
<tr>
<td>Carbon arcs</td>
<td>10 - 35,000° K</td>
</tr>
<tr>
<td>Gas-tungsten-arcs (argon)</td>
<td>10 - 28,000° K</td>
</tr>
<tr>
<td>Restricted 1450 ampere plasma arc</td>
<td>55,000° K</td>
</tr>
</tbody>
</table>