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Use of an Arc Plasma System To Separate Gases

By D. L. Hollis, Jr., B. E. Davis,
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UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	μm	micrometer
atm	atmosphere, standard	pct	percent
C	coulomb	psig	pound per square inch, gauge
°C	degree Celsius	rad/s	radian per second
Hz	hertz	rpm	revolution per minute
in	inch	SLM	standard liter per minute
J/K	joule per kelvin	T	tesla
K	kelvin	V	volt
m	meter	V/m	volt per meter
m/s	meter per second		

USE OF AN ARC PLASMA SYSTEM TO SEPARATE GASES

By D. L. Hollis, Jr.,[1] B. E. Davis,[2] and J. T. McLendon[3]

ABSTRACT

An arc plasma reactor, constructed and used for studying extractive metallurgical processing, was adapted by the U.S. Bureau of Mines to separate gases of different masses by using the high rate of plasma rotation. With argon and helium as input gases, peripheral reactor outlet ports had a measured average increase of about 10 pct in argon concentration relative to helium with the plasma on compared with plasma off for the same gas inlet concentrations in both cases. Approximately the same average increase in argon concentration occurred from the peripheral outlet port compared with a central outlet probe with the plasma on. There was no difference with the plasma off.

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INTRODUCTION

Physical plasmas are more common than some people realize. They are found in nature, such as stellar bodies (of which our sun is one), in ionized gases around the Earth and other planets, and in fact as the majority of galactic matter. Manmade plasmas include the gases of fluorescent light tubes, devices attempting to utilize energy from fusion of light nuclei, hot gases from flue stacks of electrical generating plants made to conduct electricity to gain more energy from the system, and many other uses. Plasmas consist of ions and their electrons. They have to be present, but in addition there are other conditions, such as overall charge neutrality and collective effects, which also have to exist before an ionized gas is truly a plasma. Because of the relatively large energies involved, the corresponding temperatures are very high. The high temperatures provide an attractive environment for some metallurgical processes that otherwise would not be able to occur.

Arc plasmas for extractive metallurgical purposes have been studied for the last few decades (*1-3*).[4] One such system was designed, constructed, and operated at the U.S. Bureau of Mines Tuscaloosa Research Center (*4-5*). A condition for plasma stability that met metallurgical requirements was a rapid rate of plasma rotation (*6*). For the subject system that condition was effected by the action of crossed electric and magnetic fields. The crossed fields caused the arc plasma to rotate rapidly around a central ball-like electrode. It was apparent that the high rotation rate would produce large centrifugal forces that could be utilized in separating heavier gases from lighter ones in the plasma. Mechanical centrifuges have been in operation for many years, and the subject has received considerable investigative attention. An extensive review of much of this work was given by Whitley (*7*) in 1984. Villani (*8*) included centrifuges in his book on Isotope Separation, the subject of which has important ramifications to the nuclear industry. Plasma centrifuges also have been reported in the literature for many years. In addition to initial experimental efforts, supporting theoretical studies have been made (*9*) indicating, among other things, that centrifugal separation is possible with dense (≈1 atm) collision-dominated plasmas. These are conditions similar to what is reported herein. Krishnan (*10-11*) has worked with plasma centrifuges for gaseous isotope separation characterized by low particle density, pulsed operation, and highly ionized plasmas. Simpson (*12-13*) has concentrated on partially ionized quasi-continuous plasma centrifuges, also used for gaseous isotope separation and for studies of unsteady behavior of the plasma centrifuge. This report describes the utilization of a Bureau-designed arc plasma system to concentrate heavier gases through centrifugal effects, thereby demonstrating a method for gas separation based on differing masses (*14*).

ARC PLASMA SYSTEM

In the schematic diagram of figure 1, which is not to scale, the central element of operation is the graphite ball with positive polarity surrounded by the negative graphite outer electrode. The central ball electrode is moved up or down, which varies the gap length between the two electrodes (fig. 2). In figure 2, four different ball locations are indicated, with the ball centered at the throat and at 1/4-in increments below the throat. By moving the ball upward toward the throat, minimum gap separation at the start initiates an arc discharge, which the crossed fields cause to rotate around the ball electrode. The diameters of the ball ($2R_b$) and throat ($2R_t$) are 1-3/4 and 1-7/8 in, respectively. The negative outer electrode tapers outwardly from the throat minimum, inside diameter, so that a greater plasma region is obtained once the discharge occurs and the central ball is moved downward away from the throat. Upward flow of reactor gas causes the plasma to favor the throat region. Graphite erosion due to operational usage takes place almost entirely to the upper half of the central ball electrode; therefore, it is designed to be replaceable by snugly fitting it onto the 1-in-diam graphite rod identified in figure 1 as the graphite stem. The vertical position mechanism moves the stem and central ball up or down by remote control.

For metallurgical purposes, argon was the plasma working gas, but to illustrate gas separation, or concentration, an argon-helium mixture was used. These gases were metered, mixed, and controlled prior to entering the reactor system through the same reactor inlet port. A gas chromatograph (fig. 3) measured relative amounts of argon in a selected gas stream from the reactor. In this case, helium was the chromatograph carrier gas, but the gas roles could be reversed. Normal gas flow rates were approximately 15 SLM. Selected gas outlet streams from the reactor could be taken from the reactor gas outlet port, or from either or both of the gas probes marked C (centerline) and P (periphery) (fig. 1). These outlet

[4]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

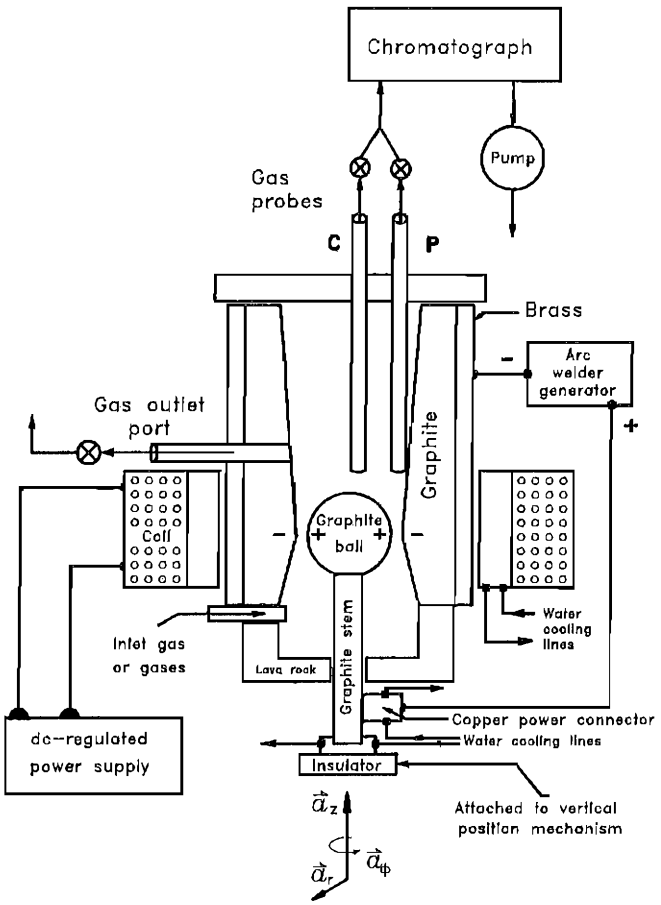

Figure 1.—Schematic of plasma reactor system for gas separation. Cylindrical coordinates for the system are identified with the unit vectors. C and P are ports on the centerline and periphery, respectively.

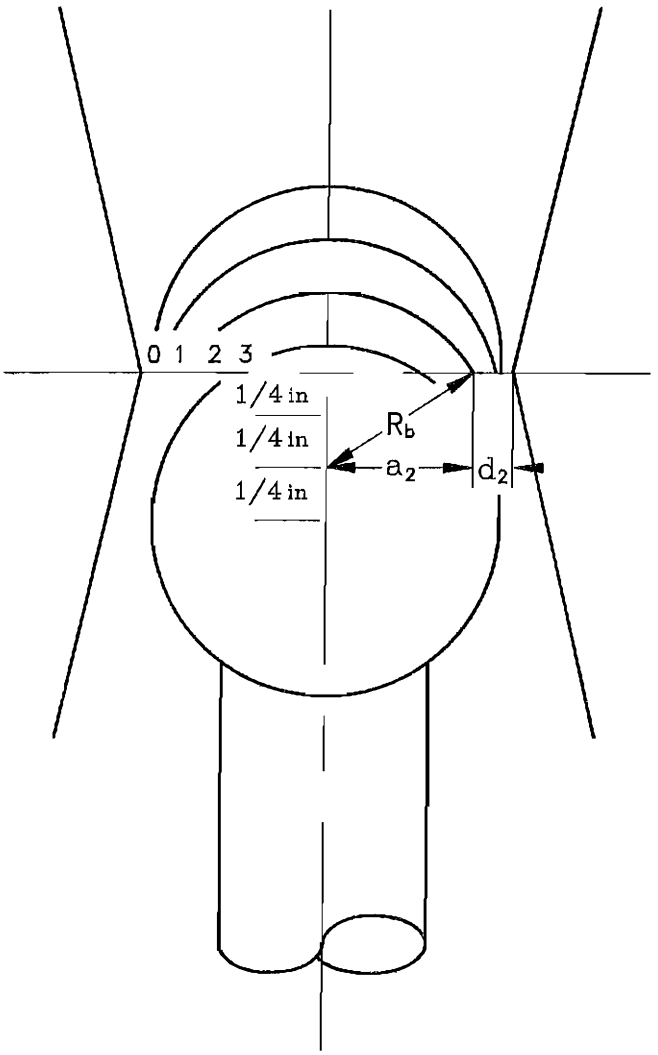

Figure 2.—Side view of central graphite ball electrode and surrounding graphite electrode with four ball positions (0-3). R_b is the ball radius, a_2 is half of the chord at position 2, and d_2 is the gap.

streams are in addition to the main discharge through the reactor top. Figure 3 schematically illustrates the gas flow paths available in the system. Figure 4 shows the actual reactor with one outlet line connected at the top to the C port. Water-cooling lines are connected in a radial direction above the magnetic coil. Another line, in figure 4 at the left, different from the water lines, is attached to the reactor peripheral port as an outlet gas stream.

The main power supply is a Miller[5] model CP/CC-1500 P, direct current arc welder generator. Rated maximum power is 1,500 A at 44 V. Typical plasma operation drew currents of about 600 A at 22 V. Power to the magnetic coil was furnished by a regulated direct current (dc) supply with a variable current output. Coil current of 7 A provided stable plasma conditions with a magnetic induction of 0.0090 T at the throat with no plasma.

[5]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

No attempt is made here to provide a complete description of the plasma; to do so would entail the many and involved collective effects associated with the charged particles. The plasma rotated at a very rapid rate; too fast to be measured by normal photographic means. It rotated in a manner that seemingly agreed with a simple model already reported (*4-5*). The point of interest in this report is the high rotational speed of the plasma, which led to the separation property herein reported. Measured radiations from the plasma were in agreement with the model used to describe the system (*5*). This model was based on single particle dynamics which, indeed, may, in some instances, be overshadowed by the collective regimes that

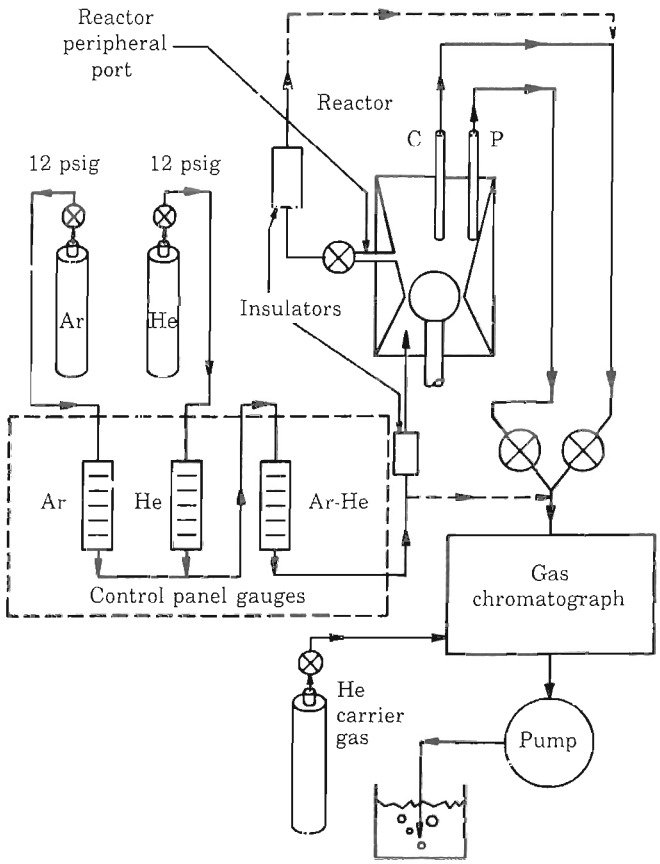

Figure 3.—Detailed schematic of gas flow paths for gas separation.

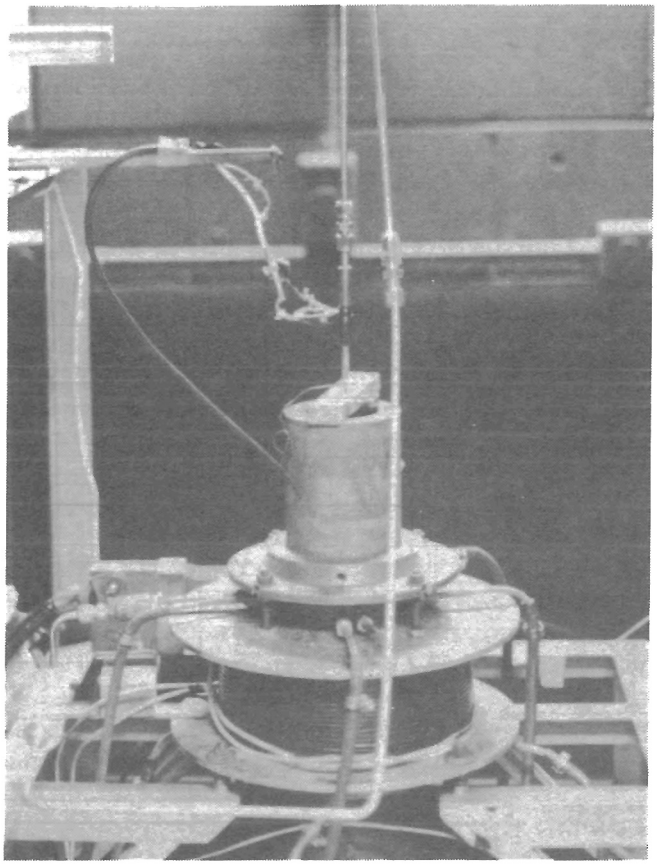

Figure 4.—Plasma reactor. Central outlet probe and peripheral outlet port at far left of reactor.

existed in the plasma. Nonetheless, charged particles will try to follow their individual motions despite collisional effects. Since the plasma was essentially at atmospheric pressure, it was considered to be a thermal reactor with a centerline temperature around 10,000 K (*15-16*). Away from the plasma center, the temperature decreased rapidly to the 2,000° to 2,500° C range in the plasma tail (*2*). Under these conditions, when thermal speeds were small compared with flow speeds, the fluid equations approached the description given by single particle trajectories (*17*).

As indicated in figure 1, the electric field ($\vec{E}$) proceeded from the central positive electrode ball outwardly in the radial direction,

$$\vec{E} \approx (V/d)\,\vec{a}_r, \qquad (1)$$

where $\vec{E}$ = electric field of intensity, V/m,

V = voltage across gap, V,

d = gap length, m,

and $\vec{a}_r$ = unit vector.

Voltage V across the gap of length d was continuously displayed with a voltmeter located in the instrument panel, along with the control panel gages. Current and voltage readings provided good indications of the plasma state. They showed when the plasma was first established, and steady meter values indicated stable conditions. The magnetic coil, prominently visible in figure 4, produced a magnetic flux density, or magnetic induction, directed along the longitudinal axis of the reactor. Figure 1 identifies this direction as $\vec{a}_z$. Maximum value of the induction occurred at the coil center, which was also at the reactor throat. The induction decreased with distance z away from the throat, so that the magnetic induction can be represented as $B(z)\vec{a}_z$. Values of B(z) at different points upward from the throat were measured with a gaussmeter, but the main interest was for maximum values, as determined by coil current, at the throat Magnetic induction is the number of magnetic flux lines per unit area. A particle of charge q and velocity $\vec{v}$ is caused to rotate around its gyrocenter by the second term of the Lorentz force, $q\,\vec{v} \times \vec{B}$. It is conventional to represent a magnetic flux line as passing through such a gyrocenter, and to say that the charged particle is rotating around, and is coupled to, a B-line.

Balance of centrifugal and Lorentz forces results in a gyroradius directly proportional to the particle mass. Consequently, plasma electrons, with masses 1,836 times smaller than the least massive ion, proton, were tightly bound to B-lines. In fact, their uncollided gyroradii were of the order of micrometers, and these were smaller than the gap length, which typically was millimeters in length. On the other hand, the ions (argon and helium) had gyroradii larger than the gap length. These estimates will be substantiated later. According to the simple model previously referenced, the crossed fields cause a drift velocity ($\vec{v}_d$) of the gyrocenters in accordance with

$$\vec{v}_d = \vec{E} \times \vec{B}/B^2 = (E/B)\vec{a}_\phi, \qquad (2)$$

where $\vec{v}_d$ = drift velocity, m/s,

B = magnetic induction, T,

and $\vec{a}_\phi$ = unit vector.

Azimuthal, or ϕ-direction, is denoted by $\vec{a}_\phi$ (fig. 1). This drift velocity is independent of charge and mass, implying that it applies equally to electrons and ions. The very rapid plasma rotation was in the same direction of $\vec{v}_d$, and reversing the direction of $\vec{B}$ reversed the rotation as specified by equation 2. By rotating the initial discharge in the above manner, the charged region was increased from a thin line of ionized particles to a torus-shaped plasma centered around the central ball electrode and extending upward as a spiraling plume into the reactor space above the ball. Upward motion was dictated by the gas flow, which was in that direction.

An estimate of the electric field across a typical gap, of about 1/8 in (or 0.0032 m), with a gap voltage usually around 22 V is

$$\vec{E} \approx (V/d)\vec{a}_r \approx 7(10^3)\vec{a}_r \text{ V/m}. \qquad (3)$$

For a magnetic induction of 0.009 T, the drift velocity approximates to

$$\vec{v}_d \approx (E/B)\vec{a}_\phi \approx 8(10^5)\vec{a}_\phi \text{ m/s}. \qquad (4)$$

Since maximum magnetic induction was used, actual drift velocities were probably larger than this last number. Free electron speed in the gas at atmospheric pressure due to the voltage across the gap was of the order of 1,000 m/s (*18*), and ionic speeds were much less. As previously mentioned, from the balance of centrifugal and Lorentz forces, the gyroradius (R) of charged particles of mass (M) rotating around a B-line is

$$R = Mv/eB, \qquad (5)$$

where M = particle mass, kg,

and e = charge magnitude of electron, C.

With the above electron speeds, its gyroradius was about 1 μm, which as stated earlier, was much less than the gap length. Ionic drift speed was difficult to determine for conditions of this system, and with a much larger mass than electrons, the ion speeds were greatly reduced from those of electrons. Their gyroradii were, therefore, much greater, probably varying from hundredths to tenths of a meter.

Because the speeds in the radial direction were much less than the azimuthal drift speed of the gyrocenters, the charged particles had a good chance of rotating around the central ball at least once before they reached their respective terminal electrodes. If v_d is a good measure of their peripheral speed, the rate of plasma rotation (ν) is

$$\nu = v_d/(2\pi\bar{R}) = (E/B)/(2\pi\bar{R}) \approx V/(2\pi Bd\bar{R}). \qquad (6)$$

where ν = plasma rotation frequency, Hz,

and $\bar{R}$ = average plasma radius, in.

Since the charged particles may have rotated around the central ball electrode in some region above the narrowed throat gap, $\bar{R}$ is an average plasma radius for a given position along the axis. In figure 2, one position is selected to illustrate the determination of $\bar{R}$ as the geometric mean of a_2 and the reactor throat radius R_t. Electrons revolving around their gyrocenters radiate at the cyclotron frequency ν_c,

$$\nu_c = (Be)/(2\pi M). \qquad (7)$$

Plasma rotation frequency also can be expressed in terms of ν_c as

$$\nu = [(eV)/4\pi^2 dM\bar{R})]/\nu_c. \qquad (8)$$

Electrons rotating around the central electrode at the above rate should radiate at that frequency as they do for cyclotron action. Radiations at plasma and electron cyclotron frequencies have been measured (*4-5, 14*) in good agreement with equations 7 and 8. These radiations came from the electrons, and the ions may not have revolved around the central electrode as rapidly as the electrons. The literature (*6*), however, indicates that plasma rotations of at least 60,000 rpm, 1,000 Hz, are needed for metallurgical purposes. Thus, there was sufficient rotary motion to provide centrifugation leading to gas separation. Not only was this true for the plasma proper, but there also was rapid enough rotation in the plasma plume for separation.

CENTRIFUGE SEPARATION

The standard separation factor Q is given (*7-11*) as

$$Q = \exp[(M_2-M_1)\omega^2(r^2-a^2)/(2R_oK)]. \quad (9)$$

where Q = separation factor,

M_i = molecular or atomic weight per mole,

ω = angular rotation rate, rad/s,

r = radial position, m,

a = axial position, m,

and R_o = gas constant.

This factor is defined to be the quotient of the ratios $(n_2/n_1)_r$ to $(n_2/n_1)_o$, for a two component gas, where n_i is the i-th gas concentration and r refers to radial position while o designates the ratio at the axis. Molecular weights per mole of the two gases are M_1 and M_2; r and a are peripheral and axial radii of the centrifuge rotor in meters; K is temperature in kelvin; ω is angular frequency; and R_o is the gas constant, 8,315 J/K-mole.

Although Q was not explicitly measured in this work, equation 9 is pertinent to the study of the subject plasma system. Separation factors as high as 2 have been reported (*10-12*), and a lower limit of 1.1 is reasonable. A parametric examination of Q versus ω, with Q varying over the above range and plasma temperature as a parameter, reveals useful information on plasma rotation. Maximum rotation rate and temperature existed at the plasma center. Away from there, particularly up above the throat region, both ω and K decreased. As a result of the location of the outlet ports, the chromatograph measured gas concentrations at lower angular rates and temperatures than that in the plasma proper. Figure 1 shows an arrangement with one outlet against the reactor wall, r = 7/8 in (0.0222 m), and the other outlet near the center, a = 1/8 in (0.0032 m). The elementary separation factor for this configuration with argon (atomic weight of 40) and helium (atomic weight of 4) is

$$Q = \exp[1.045(10^{-6})\omega^2/K]. \quad (10)$$

A good approximation of the temperature at the probe inlets, located about 1 in above the electrode ball centered at the throat, is 2,273 K. This is based on the observation that the alumina probe tips were close to melting (2,050° C) at operating conditions. Theoretical curves of equation 10 for three different temperatures are plotted in figure 5. The resulting separation factors indicate an enrichment of argon at the peripheral outlet compared with the central outlet. Similar curves are given in figure 6 for just the reactor port configuration. In this case, the separation factor theoretically measures the increase in argon concentration at the peripheral port compared with centerline concentration. The reactor port, too, was at the same level as the above two outlet ports, and here, r = 1 in (0.0254 m), a = 0; thus,

$$Q = \exp[1.4(10^{-6})\omega^2/K]. \quad (11)$$

Four different temperatures are used as parameters in figure 6 for values of Q versus ω from equation 11 for the single reactor port outlet.

EXPERIMENTAL PROCEDURE

Relative argon concentrations with the plasma operating (on) compared with the plasma not operating (off) from different reactor outlets were measured with a Varian series 1420 gas chromatograph using a molecular sieve column. Helium was the carrier gas. A Hewlett-Packard 3390 A Integrator analyzed, displayed, and recorded the data. The integrator system traced a plot of detector response versus time, and it printed numbers representing the area under a sample peak. Detector response actually was voltage as measured by the detector system resulting from the unbalance of a bridge balanced with the carrier gas (helium). The unbalance was due to the presence of the eluted gas (argon) in the constant volume of the detector. Consequently, detector response in the form of numbers, or peak areas, was proportional to the gas mass of the sample to which the detector responded (argon), and it can be considered as an arbitrary measure of argon mass in the fixed detector volume. Figure 3 illustrates the gas flow paths from the reactor to the chromatograph. Two peripheral streams P are shown; one is for the reactor peripheral port and the other is the outer probe located inside the reactor. The C stream refers to centerline, or near centerline, location. By using valves on the "Y" junction leading to the chromatograph (see figure 3) and by proper choice of connections, any one or two of the three streams could be selected for measurements. The same figure shows a small pump that moved the gases through the entire system. All gas lines in the system were

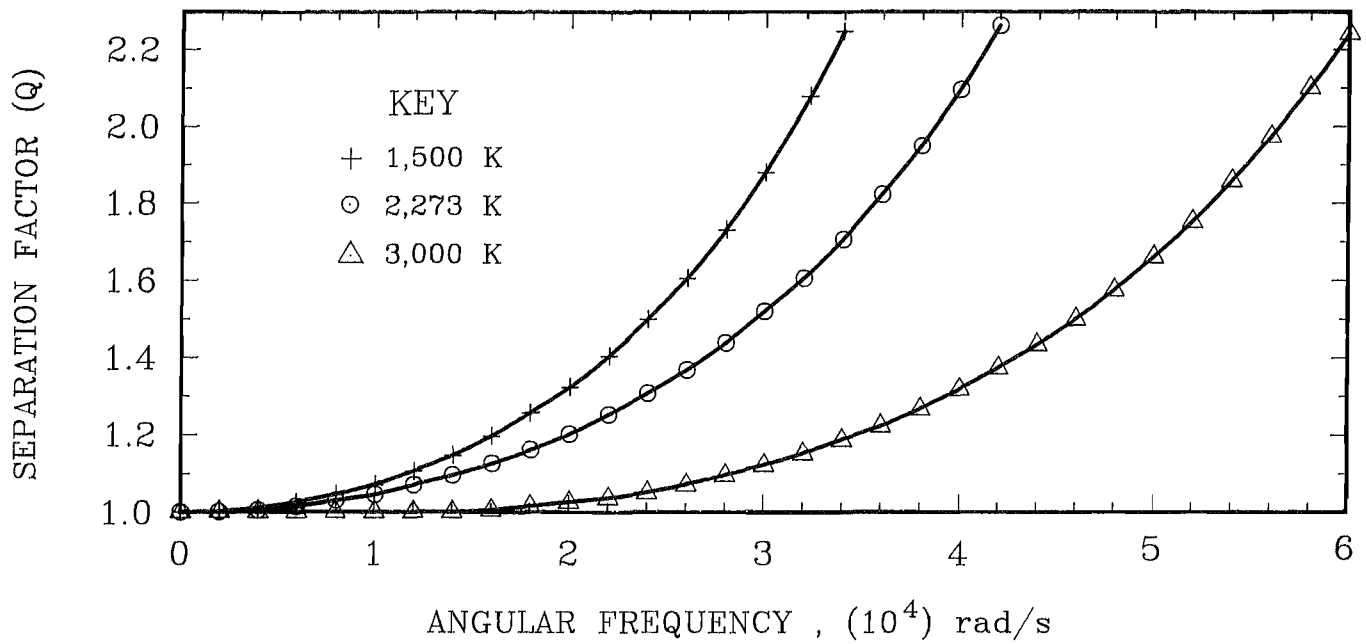

Figure 5.—Separation factor versus angular frequency for two outlet ports based on equation 10.

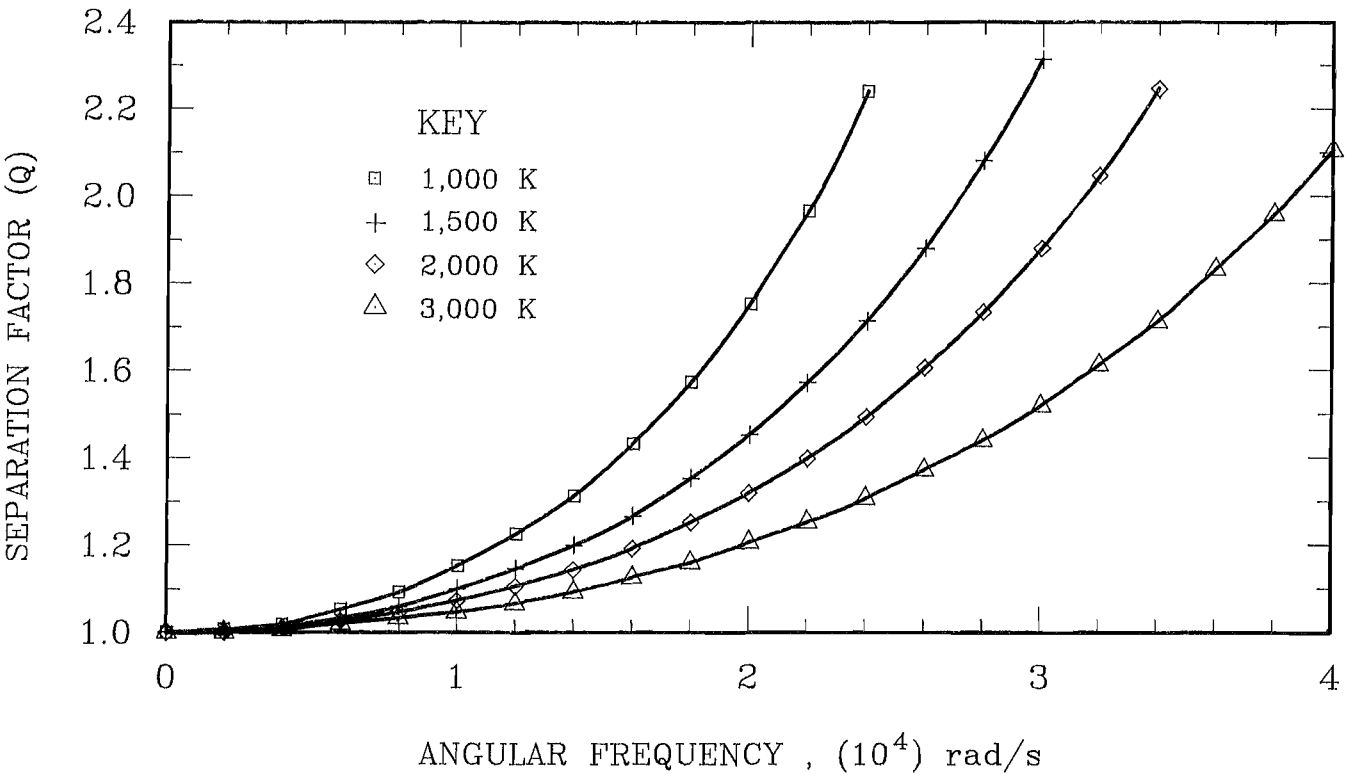

Figure 6.—Separation factor versus angular speed for peripheral port based on equation 11.

stainless steel or copper tubing of 1/4- and 1/8-in ID. Electrical insulation was provided by short, thick acrylic connectors (fig. 3). The same figure indicates a gas control panel, which allowed various flow rate combinations of argon and helium to be fed to the reactor. When the reactor peripheral port was in use, the two alumina probes were removed. The peripheral port was closed when both the alumina probes were used. These outlet ports were in addition to discharge through the reactor top, which was always open.

Normally, helium acted as the carrier gas, and argon was measured by the chromatograph. If there was an air leak, the chromatograph responded to nitrogen, but not to oxygen, for the system in use (*19*). When nitrogen was detected, the leaks were repaired. Because of the centrifugation process the heavier gas, argon, had higher concentrations in the peripheral regions, while helium tended to accumulate at the center. Consequently, the peripheral ports should have had larger chromatograph counts than the centerline counts.

RESULTS AND DISCUSSION

Many different combinations of probe positions with and without the plasma were examined. There were no statistically significant differences in argon concentrations for any probe position when the plasma was off. (Thus, without the rotating plasma, the concentration of argon was uniform at all of the selected locations in the reactor.)

Good statistical data (*20-21*) were obtained from the gas chromatograph readings (six digit numbers for most of the tests, with five digits being the least recorded). In comparing numbers to determine whether one set was significantly different or the same as another set, both f-tests and t-tests were used. For example, chromatograph readings for argon from the P probe were compared with argon readings from the C probe with the plasma off, and these tests indicated that there was no significant difference (see table 1). For these tests, with the plasma off, the calculated f-value from the measured data of 0.142 is much less than the tabulated f-95 value of 7.7086, which indicates that the peripheral and centerline argon counts are the same at the 95 pct confidence level (CL) (*20-21*). Measurements showed a significantly higher argon concentration for the P probe readings with the plasma on than with the plasma off. Table 2 displays one test using the peripheral port with the plasma on and off. Here, the f value of 15.45 calculated from the data is at least three times that for the tabulated f-95 value of 5.1174 indicating that at the 95 pct CL, the argon concentration for the case of the plasma on is greater than that for the plasma off case.

Since the alumina probes were about 1 in above the central electrode and of small size, they probably did not disturb the plasma rotational pattern to any great extent. However, it was found that the more effective method to separate argon from helium in these experiments was to use the peripheral reactor port. The two probes did have the advantage of being used together or singly, and they could be moved vertically as well as radially, which yielded information as to optimum radial locations. They could not, however, be brought any closer to the main plasma than the 1 in distance stated above, or else they would have melted. Furthermore, any closer location would begin to disturb the plasma to an appreciable extent. On the other hand, the peripheral reactor port could be placed closer to the plasma in future systems, and there the separation ability should be greater. Problems of melting would be removed, and the plasma would not be disturbed. The peripheral port also is a simpler system.

Table 1.—Argon concentration in arbitrary mass units at two outlet probes with plasma off

Position	*Detector response*
Periphery	632,830
	637,380
	635,910
Mean	635,373
Centerline	636,510
	635,520
	635,660
Mean	635,897
Grand mean	635,635

Table 2.—Argon concentration in arbitrary mass units at peripheral reactor port with plasma on and off

	Detector response
Plasma on	96,329
	88,910
	89,095
	89,511
	89,226
	84,114
Mean	89,364
Plasma off	80,337
	83,306
	83,533
	84,025
	83,986
Mean	83,037
Grand mean	86,201

Four tests using just the reactor port as the outlet stream to the chromatograph with the plasma on and with the plasma off are displayed in table 3. Tests with 100-pct Ar in the system were completed to be sure that there were no artificial separation tendencies. Different argon and helium flow rates were included to observe any effects that they may have on separation and plasma stability. There appeared to be little influence of different gas flow rates on either separation or stability, but the plasma was easier to start with argon over helium. Increased argon concentration, ΔM in percent, is qualitatively defined as

$$\Delta M \equiv (\bar{P}_{on} - \bar{P}_{off})\ 100\ \text{pct}/\bar{P}_{off}, \qquad (12)$$

where ΔM = increase in Ar concentration average,

$\bar{P}_{on}$ = peripheral counts, plasma on, average,

and $\bar{P}_{off}$ = peripheral counts, plasma off, average.

For each of the four tests in table 3, averages over at least four chromatograph readings were made for argon concentrations from the peripheral port with the plasma on to get $\bar{P}_{on}$. The same procedure was followed to get the average with plasma off, $\bar{P}_{off}$. In all four cases, the f-values calculated from the data were much greater than the tabulated values, indicating that the two averages were different with a 95 pct CL. The maximum argon concentration increase is +18.6 pct, and the minimum concentration increase is +5.9 pct, with an average of +10.3 pct.

Four more tests are shown in table 4 where argon gas separation was demonstrated by measuring argon concentration from the peripheral port compared with argon concentration from an alumina probe placed near the reactor centerline. The plasma was on for all of these tests. These two sets of four tests each were by no means the totality of tests made during this investigation. With the two ports, argon separation is qualitatively defined as

$$\Delta M \equiv (\bar{P} - \bar{C})\ 100\ \text{pct}/\bar{C}, \qquad (13)$$

where $\bar{C}$ = average centerline counts, plasma on.

As before, at least four readings were measured from which the peripheral average $\bar{P}$ was taken, and the same was true for the near centerline average $\bar{C}$. Maximum concentration increase is +22.2 pct, minimum is +3.8, and the average is +10.2 pct.

These experiments revealed useful information about the plasma itself. Estimates of rotation, as reported earlier, were based on radiation measurements due to electron acceleration, which may not necessarily reflect actual plasma rotation. From figure 5, with Q varying from 1.1 to 2, the plasma rotation for the two port system was somewhere in the range of 12,000 to 57,000 rad/s (1,900 to 9,000 Hz). For the single peripheral reactor port configuration, figure 6 indicates that the plasma rotation was in the range of 8,000 to 38,000 rad/s (1,300 to 6,000 Hz). These rotational rates are two to three orders of magnitude less than those predicted in references 4 and 5, but the ports were at least 1 in above the plasma proper where the larger rotational values apply. By placing the peripheral outlet port closer to the main plasma, better estimates of the rotation rates can be obtained. This is one of several desirable projects for future work.

Little was done in this study toward optimization. The plasma reactor was constructed for metallurgical purposes, and first priority was assigned to that objective. Consequently, there is potential for developing the system explicitly for gas separation with even better results than reported here. In addition to locating the outlet ports closer to the plasma proper, different carrier and working gases could be examined. Other designs for the central electrode should be considered, and possibly changes in the magnetic induction might be helpful. All the values reported here are for one stage. There is every reason to believe that more than one stage could be used in series to increase the overall separation. Outlet feedback to the reactor inlet line would also be a feasible enriching feature.

Table 3.—Experimental and computational data for increased argon concentration in arbitrary mass units at peripheral port (P), reactor on versus reactor off

Gas flow rate, SLM		Magnetic field	Av Ar chromatograph reading, reactor		$(\bar{P}_{on} - \bar{P}_{off})/\bar{P}_{off}$,	f-value	
Ar	He	current, A	On ($\bar{P}_{on}$)	Off ($\bar{P}_{off}$)	pct	Calculated	Tabulated[1]
2.5	16.5	7	89,363	83,037	+ 7.6	15.5	5.1174
5	10	7	199,446	168,158	+18.6	309.4	5.3177
14	3.7	7	732,850	692,116	+ 5.9	107.8	5.9874
14	3.7	7	733,416	692,116	+ 6.0	115.9	5.3177

[1]95 confidence level.

NOTE.—All four cases had significant differences between calculated and tabulated f-values.

Table 4.—Experimental and computational data for increased argon concentration in arbitrary mass units at peripheral port (P) compared with concentration at center probe (C), plasma on

Gas flow rate, SLM		Magnetic field	Av Ar chromatograph reading, probe		$\bar{C}$ Probe position	$(\bar{P} - \bar{C})/\bar{C}$, pct	f-value	
Ar	He	current, A	$\bar{P}$	$\bar{C}$			Calculated	Tabulated[1]
14	4	7	702,394	654,013	Center	+ 7.4	10.26	5.9874
14	3.7	7	749,036	695,846	. . do.	+ 7.6	14.44	5.3177
14	3.5	8	769,502	629,506	Middle	+22.2	32.40	5.3177
14	3.8	14	726,377	699,528	Center	+ 3.8	16.90	5.9874

[1]95 confidence level.

NOTE.—All four cases had significant differences between calculated and tabulated f-values.

CONCLUSIONS

The results indicate that the high rate of plasma rotation in the Bureau-designed arc plasma reactor can be utilized in the separation of gases with different masses by using the gases as the plasma fluid. Even with no particular effort for optimization, argon was found to be about 10 pct more concentrated in the peripheral region compared with the central region (with the plasma on).

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APPENDIX.—SYMBOLS USED IN REPORT

$\vec{a}$	unit vector	ΔM	increased argon concentration
$\vec{B}$	magnetic induction, T	P	peripheral argon reading
$\bar{C}$	centerline argon reading	q	charge, C
CL	confidence level	Q	separation factor
d	gap length, m	R	radius, m
dc	direct current	R_o	gas constant
$\vec{E}$	electric field intensity, V/m	$\vec{v}$	velocity, m/s
K	temperature in kelvin	υ	frequency, Hz
M	mass, hg	ω	angular frequency, rad/s