Final Report
DOE Project DE-FG36-04GO14335

1. TITLE PAGE

Project Title: **Versatile and Rapid Plasma Heating Device for Steel and Aluminum**

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Final Report – DOE Project
Versatile and Rapid Plasma Heating Device for Steel and Aluminum

2. EXECUTIVE SUMMARY

The main objective of the research was to enhance steel and aluminum manufacturing with the development of a new plasma RPD device. During the project (1) plasma devices were manufactured (2) testing for the two metals were carried out and (3) market development strategies were explored.

Bayzi Corporation has invented a Rapid Plasma Device (RPD) which produces plasma, comprising of a mixture of ionized gas and free electrons. The ions, when they hit a conducting surface, deposit heat in addition to the convective heat. Two generic models called the RPD-Al and RPD-S have been developed for the aluminum market and the steel market. Aluminum melting rates increased to as high as 12.7 g/s compared to 3 g/s of the current industrial practice. The RPD melting furnace operated at higher energy efficiency of 65% unlike most industrial processes operating in the range of 13 to 50%. The RPD aluminum melting furnace produced environment friendly cleaner melts with less than 1% dross. Dross is the residue in the furnace after the melt is poured out. Cast ingots were extremely clean and shining. Current practices produce dross in the range of 3 to 12%. The RPD furnace uses very low power ~0.2 kWh/Lb to melt aluminum. RPDs operate in one atmosphere using ambient air to produce plasma while the conventional systems use expensive gases like argon, or helium in air-tight chambers. RPDs are easy to operate and do not need intensive capital investment. Narrow beam, as well as wide area plasma have been developed for different applications.

An RPD was developed for thermal treatments of steels. Two different applications have been pursued. Knife edges of the Industrial air-hardening steel were subjected to plasma beam. Hardness, as measured, indicated uniform distribution without any distortion. The biggest advantage with this method is that the whole part need not be heated in a furnace which will lead to oxidation and distortion. No conventional process will offer localized hardening. The RPD has a great potential for heat treating surgical knives and tools. Unavailability of the full amount of the DOE award prevented further development of this exciting technology.

Significant progress was made during the 5th quarter, specially the invention of the wider-area plasma and the resultant benefits in terms of rapid melting of aluminum and thermal treatments of larger size steel parts. Coating of nickel base superalloys was demonstrated (an additional task over that proposed).

Directed low cost surface enhancement of steel and the directed clean low dross energy efficient melting of aluminum are industrial needs that require new technologies. These are large volume markets which can benefit from energy savings. Estimated energy savings are very large, in the order of 3×10^{15} J/year when the equipment is universally used. Compact and directed heating technology/product market in these two sectors could potentially reach over $1B in sales.

The results of the research, presented at the DOE annual Review meeting on Aluminum held at the Oak Ridge National Laboratory during the 4-5 October 2005, were very well received by the delegates and panel reviewers.

3. PROJECT DESCRIPTION

3.1. Original Project Goals and Objectives

To enhance steel and aluminum manufacturing with a development of a new plasma RPD device. During the project:

(i) plasma devices will be manufactured,
(ii) testing for the two metals will be carried out, and
(iii) market development strategies will be pursued.

3.2. Variance from original goals and objectives

None

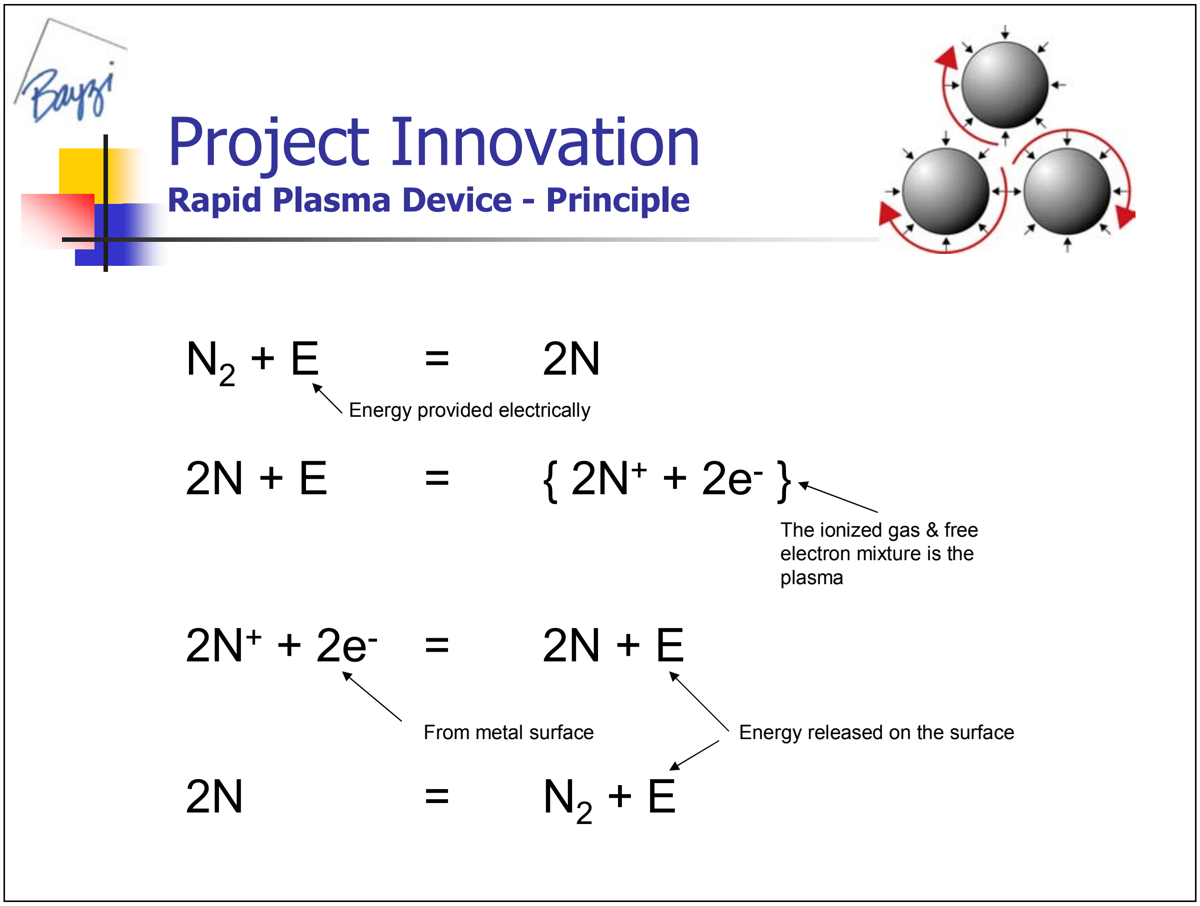
3.3. Discussion of work performed

Eleven project tasks were originally identified to be performed over a period of 8 quarters. Discussion of the task-specific work performed during the 5 quarters is presented in the following paragraphs:

Task (i) Manufacture (& design) of RPD & Controls-Aluminum

Bayzi Corporation has invented a *Rapid Plasma device (RPD)* which produces plasma comprising of a mixture of ionized gas and free electrons. The main objectives in this task were (a) to design and manufacture RPDs and controls, and (b) test them for their full functionality and make them ready for the subsequent tasks of carrying out experiments on melting aluminum.

The basic principle underlying the operation of the RPD is explained in the following illustration Figure 1. The ambient air predominantly consists of nitrogen. Molecular nitrogen disassociates in to atomic nitrogen. Atomic nitrogen disassociates in to ions and electrons. Ions when encounter a metallic surface combine with the electrons forming N and release energy on the surface. On further combination N_2 is formed and release energy on the surface of the metal.



Bayzi

Project Innovation

Rapid Plasma Device - Principle

$$N_2 + E = 2N$$

Energy provided electrically

$$2N + E = \{ 2N^+ + 2e^- \}$$

The ionized gas & free electron mixture is the plasma

$$2N^+ + 2e^- = 2N + E$$

From metal surface

Energy released on the surface

$$2N = N_2 + E$$

Figure 1. Principle underlying the RPD.

The project innovation is different from the previous and current practices. The differences are explained in the following Table 1.

Table 1. Differences between the RPD and current practices

Previous and Current Practices	**Project Innovation**
Aluminum melting is accomplished by using various fuels (natural gas, diesel oil) or electric resistance heating, induction melting, arc melting, plasma arc melting, etc.,	One atmosphere plasma stabilization technology has been invented / discovered.
Conventional plasma	Medium temperature plasma
Helium or argon gases are required for plasma.	Ambient air is used for generating plasma. No need for expensive gases.
Capital investment for RF, microwave with associated health hazards.	No capital investment. Less expensive device.

RPD produced large area plasma source, as shown in the Figure 2, is essential for the rapid melting of aluminum.

Project Innovation

- A Large Area Plasma Source

Figure 2. Large area plasma.

The following were manufactured during the research program:

(a) Three RPDs with 1.5” diameter and 2” x 3” exit nozzles were designed and manufactured for melting aluminum. These devices were capable of operating with ambient air, compressed air, inert gases like nitrogen or argon.

(b) Electronic panel comprising of *silicon controlled rectifier* (SCR), programmable temperature controllers, air speed controllers, and flow meters was designed and manufactured for melting aluminum.

(c) Adaptor for compressed air was manufactured to facilitate easy replacement for use with compressed air or inert gases such as nitrogen or argon. Figure 3 shows the image of RPD with adaptor in position.

Figure 3. RPD

Task (ii) Experiments on Aluminum, Construction of RPD – based unit for melting

A. Experiments on Aluminum

Experimental measurements and computational analysis of heat transfer in atmospheric-pressure, mid-temperature range (1200K-1600K) plasma flow over an aluminum cylinder have been carried out using a RPD. A comparison of transient temperature measurements for the aluminum cylinder under convective un-ionized air flow and those with convective plasma flow shows significantly higher heat transfer from plasma flow compared to air flow under identical temperature and flow conditions. An inverse heat transfer problem is computationally modeled by using available experimental measurements of temperature rise in the cylinder to determine the degree of ionization in the plasma flow. The continuity, momentum, and energy conservation equations as well as conservation equations for electrons and ions, and the Poisson’s equation for self-consistent electric field are solved in the plasma by a finite volume method. The conjugated transient heat transfer in the cylinder and in the plasma is obtained by simultaneous solution of the transient energy conservation equations. It is shown that the enhancement of heat transfer in plasma flow is due to the energy deposited at the solid surface by charged species during recombination reaction at the solid surface. An important finding is that even a small degree of ionization (< 1%) provides significant enhancement in heat transfer. This enhancement in heat transfer can lead to productivity increase in metallurgical applications.

Symbol	Description	Units
D	Diffusivity	m^2/s

e	Electron charge	C
h	Heat transfer coefficient	w/m^{2}K
k	Boltzmann Constant	J/K
m	Mass	kg
N	Number Density	1/m^3
p	Pressure	Pa
Pe	Peclet Number	
Pr	Prandtl Number	
q	Heat Transfer Rate	W
r	Radial coordinate	m
R	Radius	m
Re	Reynolds Number	
Sc	Schmidt Number	
T	Temperature	K
t	Time	s
u	velocity	m/s
V	Voltage	V
x	Axial coordinate	m

Greek Letters

α	Thermal diffusivity	m^2/s
Γ	Flux	1/m^2
β	Ratio of ion to electron diffusivity	
μ	Viscosity	Ns/ m^2
$\mu_{e,i}$	Mobility	m^2/Vs
ρ	Density	kg/ m^3
χ	Thermal conductivity	W/m K

Subscripts

i	Ion
e	electron
w, s	wall
∞	Inlet

Introduction

Flow of plasma, or ionized gas, is used in a variety of materials processing and metallurgical applications including plasma spray coating, arc welding, near net-shape manufacturing, plasma vapor deposition, polymer deposition, and wire bonding in microelectronic chips [1, 2]. Based on the temperature and pressure range, the plasmas used in these applications can be divided in two primary types. First are the systems that use high temperature and atmospheric or near-atmospheric pressure ionized gas, also referred to as thermal plasmas. The condition of Local Thermodynamic Equilibrium (LTE) is reached in thermal Plasma with temperatures around 10000 K and electron densities ranging from 10^{21} to 10^{26} m^{-3}. The high temperatures prevalent in thermal plasmas are useful for heating and melting of ceramic and metallic particles in coating and welding applications and in destruction of bio-hazardous materials. The second type of systems use the low pressures, low temperature plasmas. The operating pressure and gas density are very low. There is a significant difference in electron and heavy particle (neutral and ion) temperature due to weak collision coupling between them. The temperature of ions and neutral particles is typically close to room temperature. The abundance of ionized species in this type of plasma is used to aid in chemical reactions in vapor deposition and polymer processing.

Heat transfer in plasma flow has received much attention in the literature, in the 1960s and 1970s mainly in the context of electrostatic probes and in aerospace applications, whereas in the last thirty years mainly in the context of plasma-aided manufacturing. Available reviews [3, 2] provide detailed discussion of a number of factors that affect the heat transfer to a solid body from plasma. It is noted that the analysis of heat transfer from plasma to a solid surface is significantly more complicated as compared to un-ionized gas flow because it not only involves the hydrodynamic and thermal boundary layers encountered in unionized gas flows, but also electrical effects due to the presence of charged species. This electrical effect arises due to the difference in mobility of ion and electron. The electrons having very high mobility travel faster towards the surface and give rise to a negative potential at the solid surface [4]. This negative potential repels electrons and attracts ions. Subsequently the flow of ions and electrons towards the surface becomes equal and the surface potential remains constant thereafter. The surface potential when both the ion and electron fluxes become equal is called the floating potential. These charged species recombine at the surface and release energy equivalent to their ionization potential to the surface. Therefore the electric field and charged species transport play an important role in determining the heat transport to the surface [2, 3, 5, 6].

Atmospheric pressure, high temperature Thermal Plasmas have been studied extensively. Review [3] and a monograph [1] provide detailed discussion of the work published in literature. Heat and momentum transfer to spherical particles in thermal plasma has been studied extensively for the application of plasma spray coating [7 and references therein]. A unified treatment of heat transfer under continuum and non-continuum conditions has been developed [8]. Correlations for Nusselt number have been proposed for thermal plasma flow over spherical particles [9]. These correlations have been employed by several researchers in computational analysis of plasma spray systems (see for example, Proulx et al., [10]). However these correlations ignore the electrical effects. For plasmas at low pressure, heat transfer to a solid has been investigated applying results from kinetic theory of rarefied gases [11, 12].

Unfortunately, these two extremes (very hot plasmas at atmospheric pressure or cold plasmas at low pressures) are not best suited for metallurgical work. For example, most of the aluminum melting or steel heat treatment is carried out between 600^{o}C and 1200^{o}C. The low pressure plasma possesses very low energy density and can not be used for aluminum melting. The very high temperature thermal plasmas result in significant heat losses and may result in poor efficiencies. Only recently atmospheric pressure convective plasma torches have become available that provides mid temperature range plasma (1200 K – 1600 K) at atmospheric pressure. These plasma torches are being considered for aluminum melting, continuous flow plasma chemical reactors, surface heat treatment and remediation of biohazards and toxic wastes. However, plasma flows under these conditions are not well characterized. To design and improve mid-temperature plasma devices, the ability to predict the plasma flow over a solid body and the concomitant heat transfer, is highly desirable. The results show significant increase in heat transfer with plasma flow. Computational modeling for air flow and plasma flow have been carried out to determine the degree of ionization in the plasma and to analyze the heat transfer phenomena in the two cases.

Experimental measurements:
A schematic of the experimental set up is shown in Figure 4. The set up consists of an insulted cylindrical chamber. An air torch or a plasma torch is connected to the chamber on the left and the high temperature gas enters the chamber through the opening along the centerline of the chamber. A thermocouple is placed at the entrance of the chamber to measure the temperature at the exit of the torch. An aluminum sprue is placed in the chamber with a thermocouple attached to the sprue through a hole drilled from the back of the sprue along its centerline. The thermocouple is at a location, 12mm from the front surface, along the centerline. The K type thermocouple was used which can record temperatures up to 1500 K. The air torch exit temperature was measured with a B type thermocouple. Both the thermocouples were connected to a data acquisition system for transient temperature measurements. An MHI DACs data acquisition system was employed for the thermal measurements and the sampling rate was 1 per second. The mass flow rate was measured at the inlet and the average velocity at the inlet of the insulated chamber was calculated based on the measured temperature.

Temperature measurements were carried out with two identical aluminum sprues of 38.7mm diameter and 39mm length. In the first case, an air torch was used to provide the gas at 1573 K for convectively heating the sprue. Transient temperature measurements were recorded. In the second case, a plasma torch was used. In this case, a weakly ionized gas from the torch provided the convective heating of the sprue. Once again, transient temperature change was measured for the sprue interior. In both cases, identical electric power was supplied to the torch. The sprue heated with the plasma torch resulted in substantially higher heating rate compared to one heated with the air torch. The experimental measurements are discussed later in detail with the computational predictions.

Computational Analysis

A flow of weakly ionized gas consisting of neutrals, ions and electrons over a cylindrical aluminum sprue is considered for the first time. The far field pressure is atmospheric and the flow Reynolds number based on the inlet velocity and sprue diameter is in the laminar range. As the degree of ionization is expected to be small, the overall velocity field can be found from the solution of the continuity, momentum, and energy equations for the neutral gas flow field [13]. The flow was considered to be steady and axi-symmetric, however the temperature field was considered transient due to heating of the sprue. Gas thermo-physical properties were evaluated at the far field temperature. The neutral gas flow in the chamber and conduction in the sprue was computationally modeled by using Fluent 6.2.1 commercial flow/thermal solver. Using Gambit 2.1, a 2-D axi-symmetric mesh was generated using the dimensions given in the experimental set-up. The mesh generated was highly refined in order to facilitate greater accuracy in the numerical solution and to account for steep gradients near the sprue.

Using the velocity field, a computational model was developed to evaluate the electron and ion flux and the self-consistent electric field. A separate program was developed to determine the number density of charged species and the electric field as described below. The charged species flux to the surface was then evaluated and the contribution to heat transfer due to recombination of electron and ions was determined.

Using the following dimensionless quantities: $u^* = u/U_\infty$, $p^* = p/\rho U_\infty^2$, $T^* = T/T_\infty$, and $t^* = tR/U_\infty$,$V^* = eV/(kT_\infty)$, $N^*_{e,i} = N_{e,i}/N_o$, $T^*_{e,i} = T_{e,i}/T_\infty$, $Sc_i = \nu/D_i$, $\beta = D_i/D_e$, $\mathrm{Re} = 2U_\infty R/\nu$, $\Gamma^*_{e,i} = \Gamma_{e,i} eR/(\mu_{e,i} N_o kT_\infty)$, $\mathrm{Pr} = \nu/\alpha$, $\lambda_D = [\varepsilon_0 kT_\infty/(e^2 N_o)]^{1/2}$, $\varepsilon = \lambda_D/R$.

The governing equations in dimensionless form are:

Mass conservation

$$\nabla^* u^* = 0 \tag{1}$$

Momentum conservation

$$u^* \nabla^* u^* = -\nabla^* p^* + \frac{2}{\mathrm{Re}} \nabla^{*2} u^* \tag{2}$$

Energy conservation in the plasma

$$\frac{\partial T^*}{\partial t^*} + u^* \nabla^* T^* = \frac{2}{\mathrm{Re}\,\mathrm{Pr}} \nabla^* (\chi^* \nabla^* T^*) \tag{3}$$

Energy conservation in the sprue

$$\frac{\partial T_s^*}{\partial t^*} = \frac{2(\alpha_s/\alpha)}{\mathrm{Re}\,\mathrm{Pr}} \nabla^* \left(\chi_s^* \nabla^* T_s^* \right) \tag{4}$$

Neglecting production and recombination of the charged species in the bulk of the flow, the conservation equations for the charged species number densities and the governing equation of the self-consistent electric field can be written as follows.

Continuity Equations for electrons

$$\frac{\beta \,\mathrm{Re}\, Sc_i}{2} u^* \nabla^* N_e^* - T_e^* \nabla^{*2} N_e^* + \nabla^* N_e^* \nabla^* V^* = 0 \tag{5}$$

Continuity Equations for ions

$$\frac{\mathrm{Re}\, Sc_i}{2} u^* \nabla^* N_i^* - T_i^* \nabla^{*2} N_i^* - \nabla^* N_i^* \nabla^* V^* = 0 \tag{6}$$

Poisson equation for electric field

$$\varepsilon^2 \nabla^{*2} V^* = \left(N_e^* - N_i^* \right) \tag{7}$$

The ion and electron fluxes are given by

$$\Gamma_e^* = -T_e^* \nabla N_e^* + N_e^* \nabla^* V^* \tag{8}$$

$$\Gamma_i^* = -T_i^* \nabla N_i^* - N_i^* \nabla^* V^*$$

The plasma and air are considered optically thin and the radiation transport is considered between sprue surface and the container wall. Since the gas is at atmospheric pressure, the difference in temperature between the neutral gas and the charged species were assumed to be small throughout the flow domain ($T \approx T_i \approx T_e$).

The flow field for the computational domain is obtained first by solving equations (1) and (2) in FLUENT flow /thermal solver. The SIMPLE algorithm for pressure correction was employed and discretization was carried out using the Power-law method as described in Patankar [14]. An under relaxation technique was used for the momentum equation. The solution of these equations provides the flow field in the entire domain. The equations (3) - (7) are solved to obtain the number density distribution of the ions and electrons and the electric potential in the plasma as well as temperature distributions in the plasma and the sprue. A finite difference method was employed to discretize equations (3) – (7) based on the Alternate Direction Implicit Scheme [14]. A computer program was developed to iteratively solve the resulting tri-diagonal systems of equations using the Thomas algorithm. We expect to have steep gradients in velocity and temperature near the sprue surface. To resolve these steep variations a very fine grid was taken. The convergence criterion was set at 1x 10^{-6} between successive iterations at all points. Thermo-physical properties for charged species were obtained from Refs. [15] and [3]. For the case of heating from un-ionized air flow, the methodology is similar to the one described above, however equations (5) – (7) are not needed.

Boundary Conditions

The governing equations were set to the following boundary conditions. The sprue surface was considered as a perfect sink for the charged species $N_i^* = N_e^* = 0$. The sprue surface was considered at the floating potential so that $\Gamma_e = \Gamma_i$ and the velocity was zero due to the no-slip condition. The heat balance at the surface is $-\chi \frac{\partial T}{\partial n} + q''_{\text{recombination}} + q''_{\text{Radiation}} = -\chi_s \frac{\partial T_s}{\partial n}$. The heat flux deposited at the surface due to charged species recombination is given by $q''_{\text{recombination}} = \Gamma_e V_i$. At the inlet $T_i = T_e = T_\infty$ and the inlet velocity was specified. At the walls of the outer chamber, temperature and electric potential gradients are zero and velocity is zero. At the outlet, the outflow condition of zero gradient of temperature in the axial direction is considered. Zero gage pressure is prescribed at the outlet.

Results and Discussion

In a computational study, it is important to evaluate the effect of grid spacing on the solutions to make sure that the results are grid-independent. The computations were carried out with different grid sizes until the solution was insensitive to the grid size. The node points were doubled until the computed heat transfer coefficient at the sprue surface changed by less than 0.1%. The final grid had 721 points in the axial direction and 193 points in the radial direction.

Heat transfer in air flow

Using this grid, we first considered the flow from an air torch in the analysis. The streamlines for the flow are shown in Figure 5. It is clear from the figure that as the flow goes around the sprue, a re-circulating flow pattern is obtained. Due to the decrease in the cross-sectional area due to the presence of the sprue, the velocity increases as the gas moves along the container walls.

The temperature contours obtained for the flow domain are shown in Figure 6. Most of the region in the upstream of the sprue the temperature is nearly uniform. Due to the re-circulating vortex patterns on the side and on the downstream region from the sprue, colder fluid from the sprue mixes with the hotter fluid away from the sprue. This is evident from the temperature contours. The temperature contours show that the heat transfer rate is at a maximum at the front surface of the sprue and as there is a sharp change in gas temperature near the surface. As the flow proceeds toward the outlet there is a decrease in the heat transfer rate on the top surface of the sprue. This is evident from the temperature contours showing temperature drop over a larger distance compared to the front surface. The heat transfer coefficient was obtained at all points along the surface of the sprue. Then the overall heat transfer coefficient was obtained by an area weighted average taken over the surface of the sprue. The temperature contours in the interior of the sprue showed only a small variation. This is to be expected as due to the high thermal conductivity of aluminum (χ_s = 227 W/m K). The Biot number is very low and temperature distribution is nearly uniform.

Heat Transfer in Plasma Flow

With plasma flow, number densities of charged species and the induced electric field are determined. Figure 7 (a) and (b) show the dimensionless electron and ion density contours, respectively. The motion of the charged species is the net effect of convection, diffusion, and drift under the influence of electric field. Both ion and electron are convected with the same neutral flow. However, electric field has opposite effect on the motion of ions as compared to that of electrons. As the electric potential at the surface is negative, it results in repelling electrons and attracting ions. Not surprisingly, the number densities of electrons are low closer to the surface whereas ion densities are higher near the sprue surface. The recombination reaction of charged species at the surface gives energy equal to the ionization potential to the surface.

Figure 8 shows the transient temperature measurement with the thermocouple placed in the spure interior. The significant increase in the rate of temperature rise indicates higher heat transfer with plasma heating as compared to heating with air flow. To validate our model, we first compared the computational results of temperature rise with the experimental measurements. As seen in the figure, the computational results match well with experimental measurements. Next, to determine the degree of ionization in plasma, a parametric study was conducted by considering different values of inlet ion and electron number densities. The predicted values of the temperature rise with different degree of gas ionization were compared with the experimental measurements of temperature change in the sprue interior with plasma heating. The degree of ionization was obtained as 0.64% and the predicted results for this case are shown in Figure 9.

The influence of ionization on heat transfer enhancement is plotted in Figure 9. The figure shows the enhancement in heat transfer as a ratio of heat transfer due to charged species recombination to convective heat transfer with different degree of ionization. With increase in the degree of ionization the number densities of charged species and hence the flux of charged species to the sprue surface increases. This leads to higher heat transfer to the sprue surface and the enhancement of heat transfer is seen to increase nearly linearly with degree of ionization. It may be noted that the model presented here is restricted to weakly ionized gas and as such the enhancement of heat transfer may not follow the same trend at higher degree of ionization and the results should not be directly extrapolated beyond 1% ionization.

Summary and Conclusions

Transient temperature measurements and computational simulation of convective heating of an aluminum sprue was carried out. Two cases were considered, one with heating by un-ionized air flow and the other with plasma flow. Transient temperature rise in the sprue interior was measured and it showed significant increase in heat transfer with plasma flow compared to air flow under identical temperature and flow conditions. To computationally simulate the process, the flow of continuum, steady, axi-symmetric, laminar, mid-temperature range (1200K – 1600K) plasma flow over a cylinder was modeled using a finite volume method. The continuity, momentum conservation, and energy conservation equations for the flow were solved using commercially available Fluent flow/thermal solver. Using the flow field, a computational model was developed to solve the governing equations for the conservation of electrons and ions and the self- consistent electric field. The governing equations were discretized using a finite volume method and the resulting system of equations was solved by Alternating Direction Implicit scheme. Transient heat transfer to the cylinder was evaluated by considering convective heat transfer from the neutral flow, the energy transport by radiation between the sprue surface and the wall, and the energy deposited by recombination of charged species at the cylinder surface. Results for transient temperature rise in the cylinder with air heating were used to validate our computational model. The degree of ionization present in the plasma flow was determined. The following conclusions can be drawn from this part of the study.

(i) The heat transfer to a solid surface is higher when exposed to the atmospheric, mid-temperature range plasma flow compared to flow of un-ionized air at identical flow and temperature conditions.
(ii) The heat transfer enhancement is due to the ionization energy deposited by charged species due to their recombination at the surface.
(iii) Even a small degree of ionization (less than 1%) can lead to significant enhancement in heat transfer.

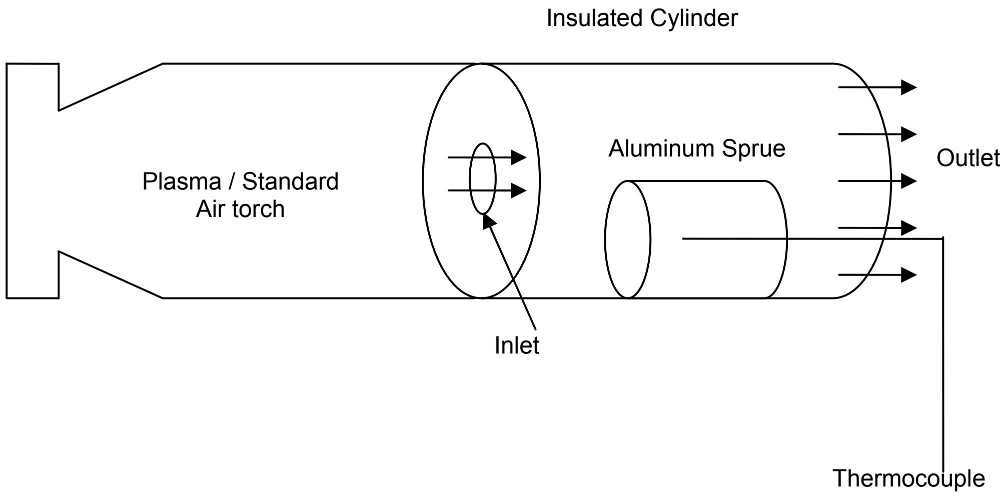


Figure 4. A schematic of the experimental set up.

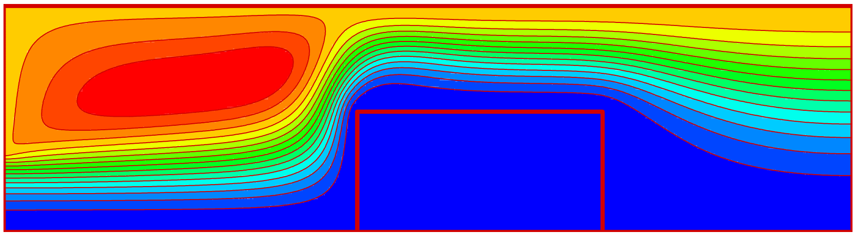


Figure 5. Flow stream lines

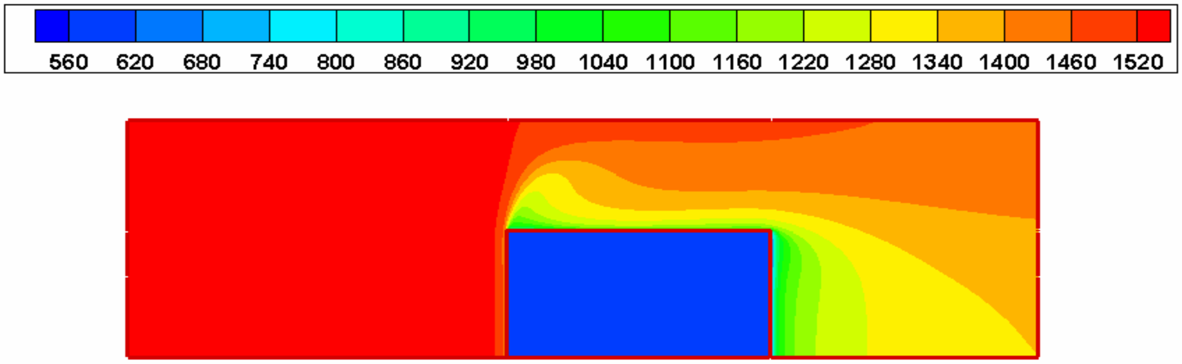
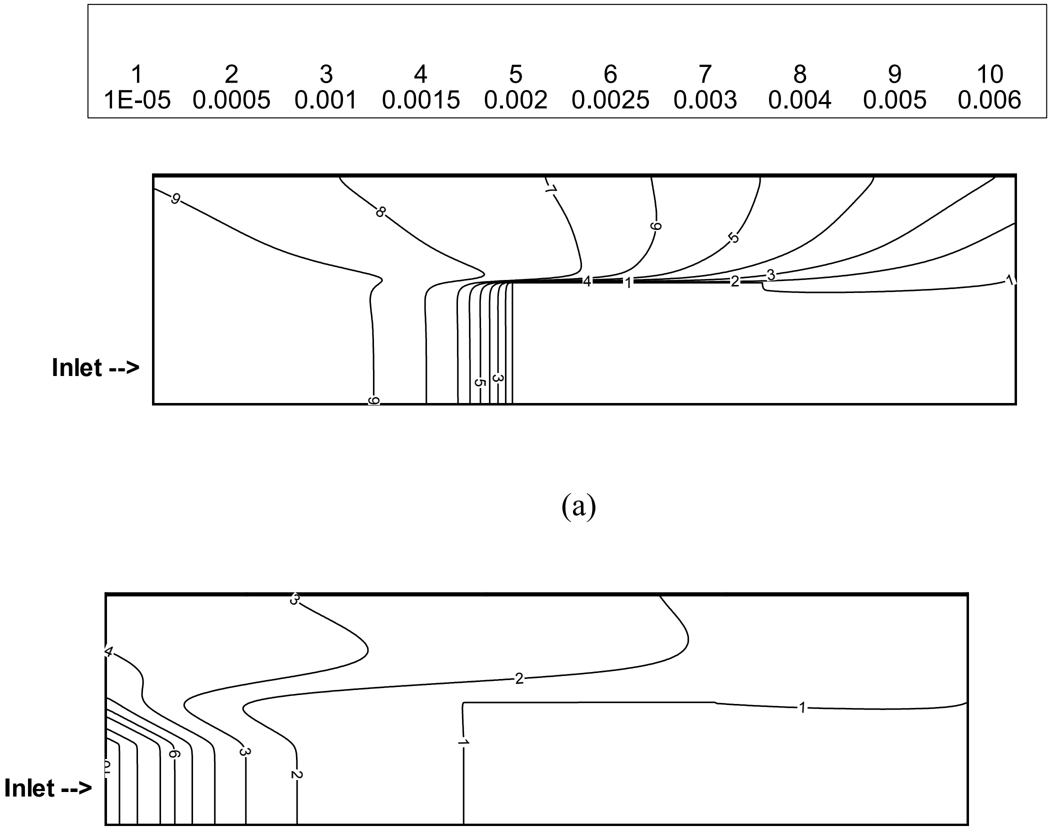


Figure 6. Temperature contours with air torch teaching (K).



(a)

(b)

Figure 7. (a) Dimensionless ion number density contours and (b) Dimensionless electron number density contours

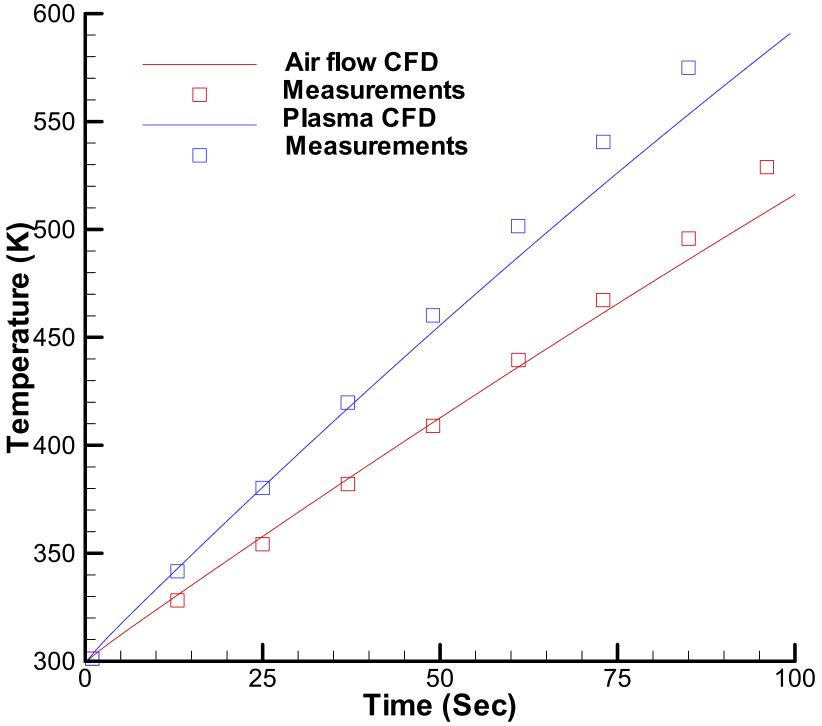


Figure 8. Comparison of computational predictions and experimental measurements of temperature increase in the sprue.

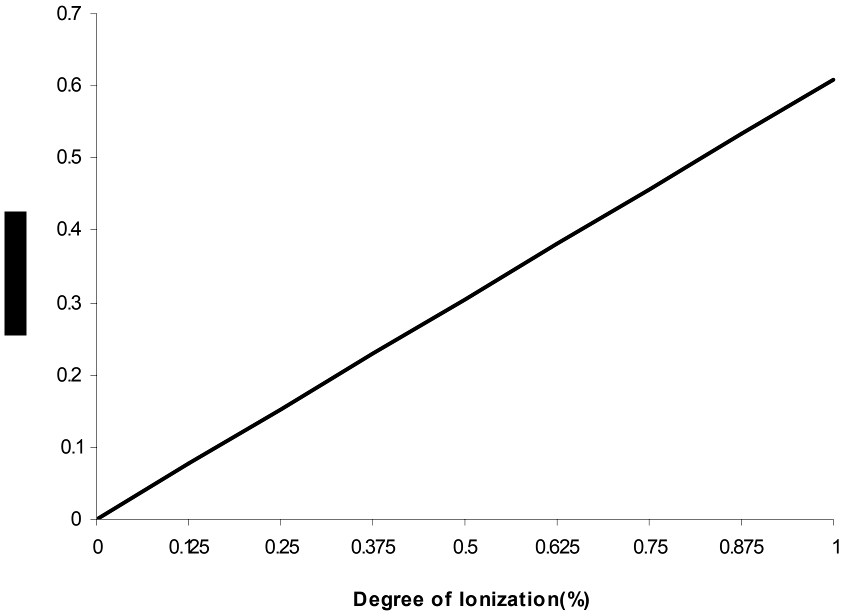


Figure 9. Variation of heat transfer enhancement with degree of ionization

B. Construction of RPD Melting Furnace

A RPD Furnace comprising of thee RPDs has been constructed as shown in Figure 10. The various key steps in the construction are listed below:

(a) Installation of refractory lining and hearth.

Fibrous refractory boards were used for the outer lining. The Fractalin boards were used for hot-face of the furnace lining. Non-wetteble Fractalin boards were used for the hearth. Fractalin glue was applied on the hearth and hot face lining to prevent molten aluminum adhering to the hearth.

(b) Construction of metal pouring spout

Using high temperature Fractalin ceramics, the metal pouring spout was constructed. Fractalin glue was applied for preventing molten aluminum adhering to the spout.

(c) Dross disposal trolley
A dross disposal trolley was fabricated and installed with a capability for making vertical motion, in order to dispose of the left over metal filter. The trolley can be tilted up to 45^0, so that molten droplets if collected can be poured into a crucible.

Project Accomplishments

SIDE VIEW
Concept drawing for Concentrator Aluminum sprue melter

Figure 10. RPD Melting furnace

(d) RPD’s Integrated with the furnace

RPDs have been installed and integrated with the melting furnace such that the hot air plasma will cover the entire hearth surface for efficient melting.

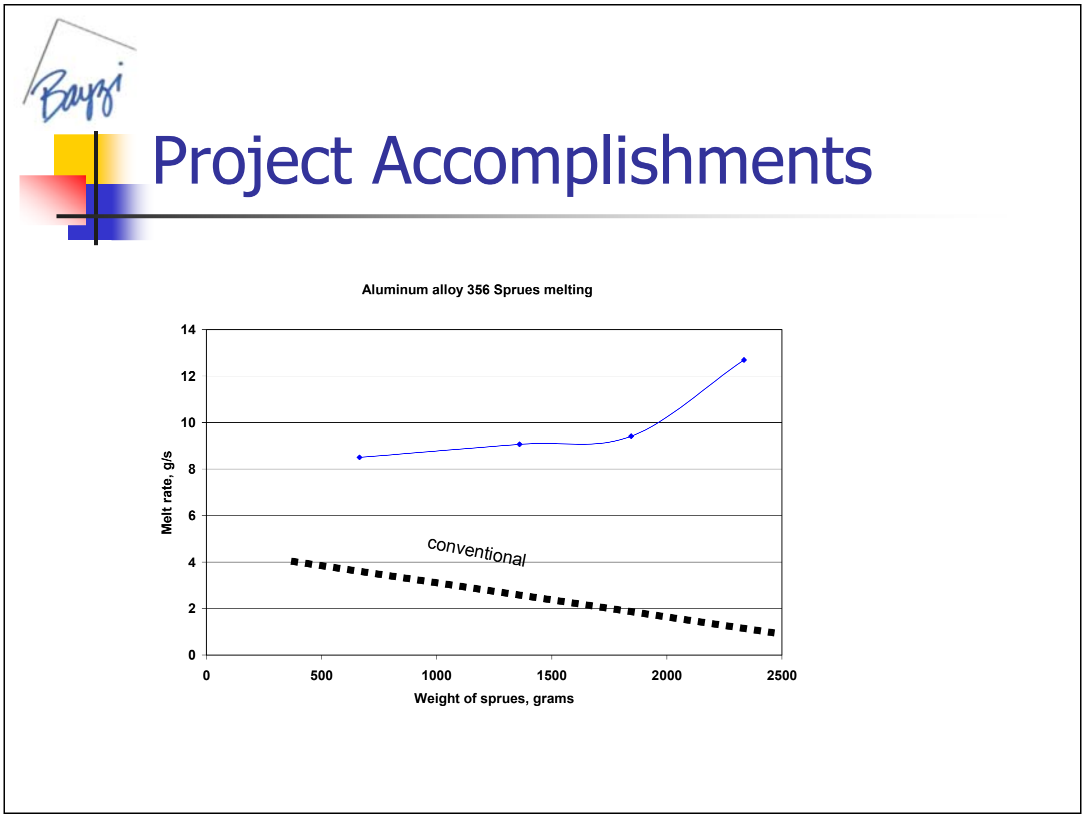
(e) Thermocouples and Electrical panel

Thermocouples were installed for process monitoring and control. Over temperature control thermocouple was also installed. Electrical panel wiring was completed.

(f) All systems have been tested successfully.

(g) Melting rates

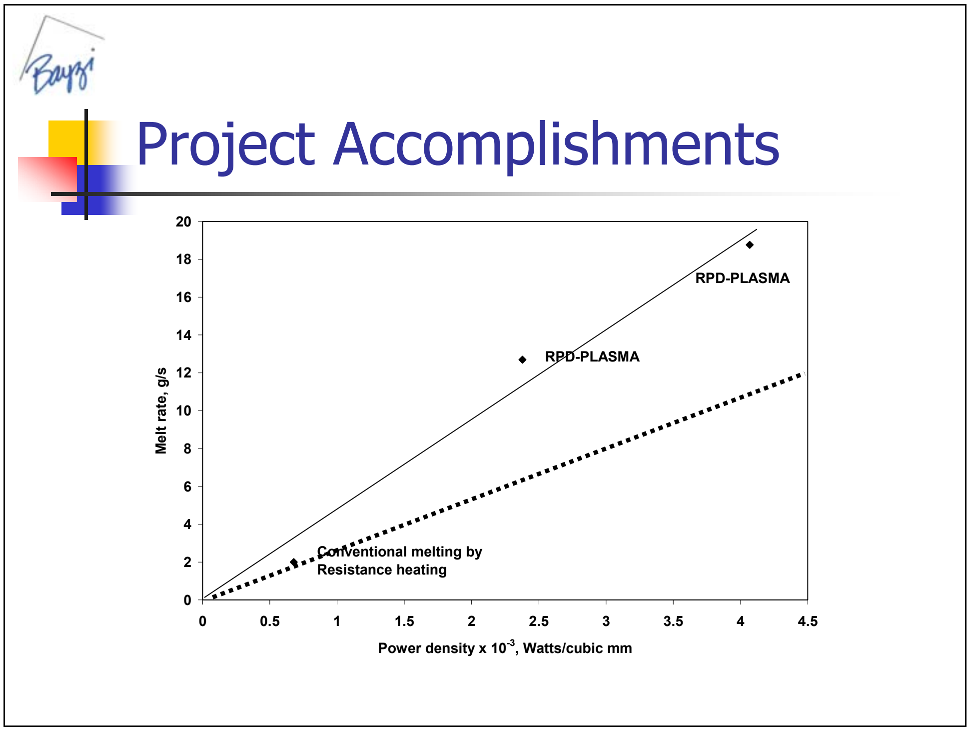
Aluminum alloy 356 sprues were melted. Melt rates for given weight of sprues were experimentally determined and the results are shown in Figure 11. A maximum of 12.7 g/s melt rate was noted for 2300 g charge weight. It is interesting to note that the melt rate increased with weight of the charge, unlike the decreasing melt rates associated with the conventional melting furnaces.



Project Accomplishments

Figure 11. Melt rate versus weight of sprues.

(h) For any given power density value, very high melt rates were obtained with the RPD plasma melting compared to the conventional resistance heating, as shown in the Figure 12.



Project Accomplishments

Figure 12. Melt rate versus power density.

(i) Dross

Two different aluminum alloys (Al 390 and Al 356) and pure aluminum were melted under RPD plasma. Weight of the charge prior to melting and after melting & casting ingots were recorded. Dross is the residue left over in the furnace after the melt is poured out into a mold or crucible. Cast ingots were found to be extremely clean and shining. The same alloy when melted in an electric resistance furnace, invariably associated with gray color oxide layer on the surface. Very low percentage of the charge, 0.3% to 0.9%, resulted in the form of dross, unlike the current industrial practice standing at 3 to 9%. Power utilized for melting was 0.2 kWh/lb. The results are shown in the following Table1

Table 2: Dross

Alloy	Dross Low	Dross High	Number of runs tested
Al 390	0.9%	0.9%	1
Al 356	0.3%	0.8%	10
Al (pure)	0.5%	0.7%	6

(j) Comparison with conventional melting practice is shown in the following Table 3.

Table 3. Comparison

	RPD	Conventional
Energy	0.2 kWh/lb	1.0 kWh/lb
Dross	0.3 to 0.9%	3.0 to 9.0%
Melt rate	12.7 g/s	3 g/s

Aluminum melting rates increased to as high as 12.7 g/s compared to ~3 g/s of the current industrial practice. The RPD melting furnace operated at higher energy efficiency of 65% unlike most industrial processes operating in the range of 13 to 50%. The RPD aluminum melting furnace produced environment-friendly cleaner melts with less than 1% dross. Cast ingots were extremely clean and shining. Current practices produce dross in the range of 3 to 12%. Energy savings and cost savings accrue also due to the less dross generated by the RPD melting. Non-usage of conventional aluminum toxic foundry fluxes attribute to cost savings by the RPD melting. Additional cost savings are realized on account of the non-handling and treatment of flue gases arising due to the usage of toxic fluxes. The RPD furnace uses very low power 0.2kWh/Lb to melt aluminum. RPDs operate in one atmosphere using ambient air to produce plasma while the conventional systems use expensive gases like argon, or helium in air-tight chambers. No need for nitrogen cover. RPDs are easy to operate and do not need intensive capital investment. Narrow beam, as well as wide-area plasma RPD's have been developed for different applications.

(iii) Modifications to RPD-Aluminum

(a) Perforated ceramic paper was found to be efficient in preventing ionic loss on inlet side of the RPD. All RPDs were modified by incorporating the perforated ceramic.

(b) Moldable ceramic was found to be efficient in preventing ionic loss, therefore, all RPDs were incorporated with this modification.

(c) Nozzle optimization- materials:
KVS 124, 144, 164, 175, fractalline and BR were tested. Relevant modifications were made.

Nozzle optimization- Configurations:
9-hole, 7-hole, 3-hole, 1-hole and rectangular openings were tested. Application-specific modifications were incorporated.

Nozzle optimization- Inlet configurations:

Fan blower, adaptor for compressed air or gases, moisture trap were incorporated.

(d) Back pressure development was observed during the plasma melting of aluminum. Instead of a flat surface on the exit refractory, a smooth curvature has been now provided, which has reduced the back pressure significantly and minimized turbulence leading to efficient uniform melting.

(iv) Experiments on steel & analysis of results

(a) RPD device has been designed and manufactured with 2.5” diameter plasma delivery exit for conducting experiments on hardening of steel.

(b) Air -hardening on small portions, ½” x ½”, of the steel knife edge were carried out and hardness measurements were made. Increased hardness was noted. Microstructure did not reveal any quench cracks.

(c) Full size knives were subjected to air-hardening using RPD. Hardness and microstructure was examined. Uniform hardness distribution without any adverse distortions was obtained.

(d) Nozzle optimization.
Several different size nozzles and configurations were made and tested for efficient hardening. 3/8” x 2” and 1.5” diameter exit nozzles were found to be ideal configurations.

(e) Experiments on hardening of commercial steel flat strips were conducted using RPD. Experimental parameters of temperature, flow rate, and speed of hardening were optimized. Hardness measurements on both sides of the flat indicated uniform distribution.

Task (v) Modifications to RPD based on above experiments - steel

(a) Several different materials have been tried on the inlet side of the RPD to prevent ionic loss. Perforated ceramic paper was found to be efficient in preventing ionic loss on the inlet side of the RPD-Steel. RPD-S were incorporated with this modification.

(b) Moldable ceramic was found to be efficient in preventing ionic loss, therefore, RPD-S was incorporated on the periphery of the refractory.

(c) Different exit nozzles with varying size openings and configurations were tested for rapid heating. For wider knife edges rectangular opening was found to be efficient, accordingly, the exit nozzles were modified.

(d) Exit refractory has been modified to deliver a smooth laminar like flow with least back pressure.

(e) An extension to support smooth movement of steel flats for hardening treatment has been developed and incorporated.

(f) A detachable arrangement has been incorporated to allow rapid quenching of hot steel by compressed air jet, independent of RPD.

Task (vi) Testing of RPD on industrial parts & evaluation of properties - Steel

High carbon high chromium steel part of the size 3” x 2” x 1” thick was chosen for testing with the RPD-Steel. The nickel base alloy cold sprayed on steel substrate was subjected to wider area plasma beam. The main emphasis had been to determine (i) the sustainability of the wider area plasma for thermal treatments of steel and (ii) optimization of process parameters. Figure 13 shows wider area plasma in use.

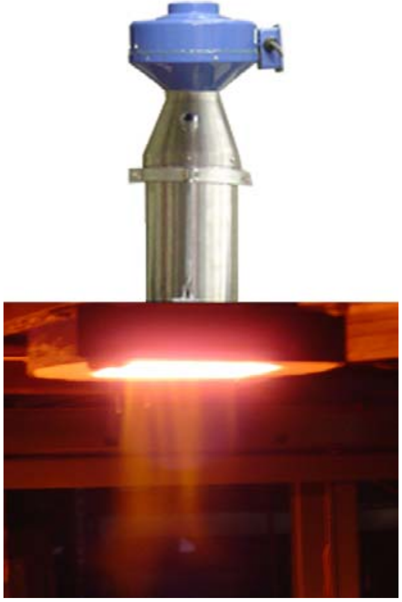


Figure 13. Wider area plasma from RPD.

Using the wider area plasma the thicker cold sprayed nickel base alloy coatings on a steel substrate were thermally fused and formed adherent wear resistant coating. Several experiments were done to optimize the RPD process parameters including plasma temperature, air flow rate, distance from the beam, and shape of the nozzle. Figure 14 shows wider area plasma treated twelve 3”x 2’ x 1” thick steel parts.

Figure 14. Wider area plasma fused coatings on steel substrate

Task (vii) Marketing Research

(a) A new web domain *www.oneatmosphereplasma.com* was obtained and originally planned to integrate t*o* *www.bayzi.com*. The *www.oneatmosphereplasma.com* is under construction.

(b) Aluminum melting commercialization initiated with DOE partner *Vista Ventures*. A preliminary document has been prepared for the aluminum application. Web based marketing collaterals were prepared. More details are provided in section 5.2. Supplemental information.

(c) A 2-page marketing 'tester' prepared with the help of *NEW Horizon Technologies* and circulated to select group of industries.

(d) **Visit to Bayzi by prospective licensee**

A prospective licensee, Berea Industries, LLC., KY, visited Bayzi on 11/15/2005

The following were present during the meeting:

Bayzi	**Visitors**
Dr. Anu Vissa.	Floyd Brown, President Berea Industries, LLC.
G.S.Reddy	James K. O'Donnell, Consultant to management; Engineering-Tech.
Brian	Damon R. Smith, Integrated Solutions; Home Environmental Health & safety
	Rick Richards

Background and Purpose :
James O'Donnell attended the Aluminum review meeting held at ONRL October 5, 2005 and got interested in this new Plasma Aluminum melting technology. Consequently, Damon Smith had contacted Bayzi for an appointment for visiting Bayzi to witness a demo and explore possibilities of using or applying this technology for melting of their scrap. Floyd Brown, James O'Donnell, Damon Smith, and Rick Richards, visited Bayzi on 11/15/05 at 1:30 PM.

Agenda :
- Completion of the *Confidentiality Agreement* documents by the 4 visitors.
- Brief presentation of the Plasma melting device, process and scope of services by Bayzi.
- Demo.
- Discussion.

1. Damon Smith and Rick Richards had questions about how the RPD (Rapid Plasma Device) works and how it was different from the conventional plasma.

They were explained the principle underlying the RPD and how it was different from the conventional plasma.
Benefits, the RPD offers over the conventional are:

(i) Uses ambient air unlike the others using argon gas,

(ii) RPD operates at one atmospheric pressure unlike the others operate invariably at low pressure system with in closed chambers.

(iii) Highly energy efficient over the conventional melting,

(iv) RPD provides neutral atmosphere due to nitrogen ion cover, therefore, least oxidation and less than 1% dross formation, unlike 5 to 15% dross formation by the industry-standard technologies.

2. **The visitors were shown demo of melting of aluminum ingot solid pieces almost without any dross formation using the RPD.**

3. **Visitors were shown and explained about our plasma aluminum melting furnace and its extension.**

4. Floyd Brown brought the following aluminum scrap pieces for melting trials:
   (i) Aluminum can scrap compacted slug:
   The circular disc like slug weighing 301 grams was cut in to two pieces weighing 158.38g, and 142.63 g.

   The piece weighing 158.38 grams was melted and molten metal drained in to crucible. Weight of the solidified cast ingot was 93 grams. Following are the few observations:

   (a) Paint burned off producing intense flame for about 50 seconds.

   (b) The slug got quickly heated up to molten state ~ 2 minutes and the slug opened up, aluminum melt collected at the bottom, slowly drained in to crucible. Because of lack of adequate inclination / slope of the tundish and lack of adequate metallo-static head, the melt drained in to the crucible.
   As soon as the slug gets melted, it needs to be pulled in to the melt by vortex.

   (c) Floyd Brown gave 2 more similar slugs contaminated with paint and another slug without paint contamination for our study.

   (ii) Aluminum can melting :
   Two pieces of aluminum cans were melted by introduction into the plasma stream. The can material melted instantaneously as soon as it was introduced in to the plasma stream. A small droplet of molten aluminum was collected on the tundish surface.

5. The following points emerged during the discussion:
   (i) There is a greater opportunity for melting aluminum canned material which invariably contains 3% paint contamination.

The desired target is to accomplish 95% yield when operated at a rate of 10,000 Lbs/hour.

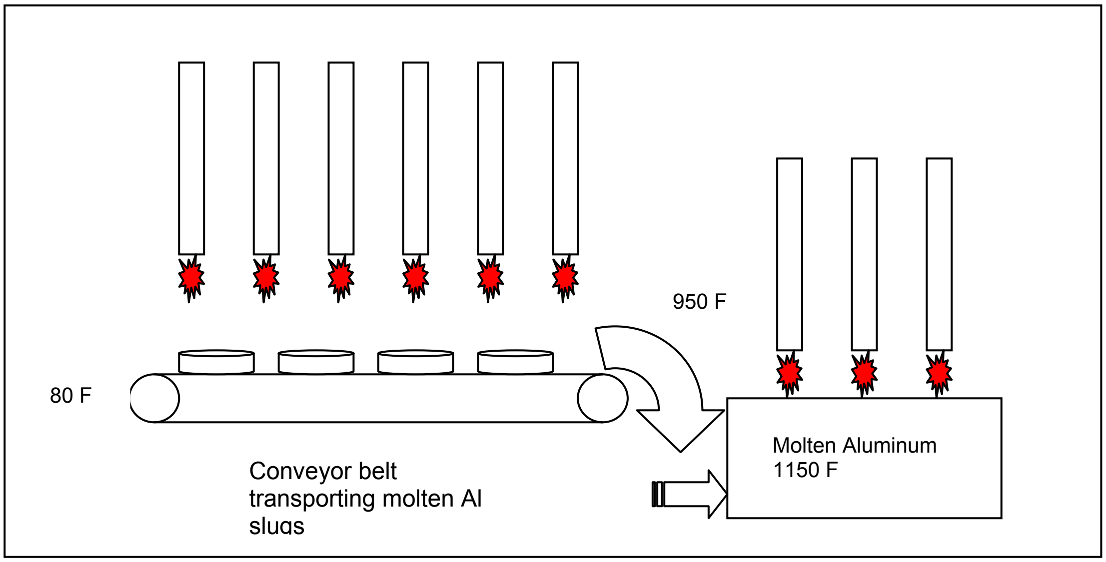


Figure 15. Schematic arrangement showing melting of Aluminum scrap compacts using RPDs.

(ii) The RPD is able to melt the compacted slug rapidly but needs a hybrid type of melting arrangement such that the rapidly melted scrap needs to be pulled in to the molten metal vortex to minimize the oxidation. The conceptual arrangement shown in Figure 15 is contemplated by placing a series of RPDs over belt conveyor in a closed system such that the scrap material placed on the belt is heated instantaneously from 80 F to 950 F, followed by delivering it in to molten bath.

(iii) Dioxins are produced in concentrations when organic material is burned in the presence of chlorine, whether the chlorine is present as chloride ions or organochlorine compounds, so they are produced in many contexts. The commercial melting technologies invariably use hexachloroethane compounds as fluxing material. As stated earlier the RPD melting does not use any fluxing material, in addition, the nature of plasma interactions will produce cleaner metal. However, measurements and or investigations are needed to confirm whether dioxins are nonexistent during the RPD melting process.

(iv) Visitors indicated that they have knowledge but no funds to pursue a joint activity of integrating RPD's in to scrap melting.

(6) See also above for initial licensing marketing trials with a client.

Task (viii) β site testing

The main objective of the following tests at the β site has been many-fold:

- To test the RPDs thoroughly for harsh working conditions to simulate the real world situations by conducting and monitoring the tests constantly.
- To understand the problems associated with the failures, if any, so that they can be fixed with a suitable solution.
- They were tested at 1300 ^{0}C with a plasma flow rate of 14 SCFM.

(a) RPD tested successfully horizontally for 19 days for endurance and reliability evaluation.

(b) RPD tested successfully for 20 days vertically and 45^0 angle for endurance and reliability evaluation.

(c) Three RPDs were tested successfully on the RPD melting furnace.

(d) RPD-Al and RPD-Steel were tested at the β – site during the 5th quarter. The main emphasis has been to determine the sustainability of the wider area plasma for melting as well as thermal treatments of steel. The wider area plasma was found to be efficient for melting aluminum in the RPD furnace. The wide area plasma was also found to be successfully thermally fused and formed adherent wear resistant coating without causing any distortion.

(e) RPD-Al and RPD-S were successfully tested at β site after incorporating the modifications including exit refractory curvature, extension support and rapid external quenching feature.

Task (ix) Sale channel establishment

Significant progress has been made towards the establishment of a sale channel. As a result, prospective customers have approached Bayzi for aluminum melting needs. Most of their questions were answered. One prospective aluminum melting company witnessed the process demonstration and has shown interest in the technology. This interaction prompted further work which is possible direction for the future quarters.

Task (x) Commercialization

Within a short duration RPDs will be ready for commercialization. Bayzi is identifying the target companies processing aluminum and steel. A market assessment report was prepared with the help of New Horizon technologies. The study showed that reaction from aluminum producers was generally positive and some interested entities were identified.

Task (xi) Final Report

Final report completed

3.4 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Conclusions

Versatile and rapid plasma devices for melting of aluminum and hardening of steel have been developed and tested for their intended applications. The device essentially produces plasma comprising of a mixture of ionized gas and free electrons. The heat transfer to a solid surface was found to be higher when exposed to the atmospheric, mid-temperature range plasma flow compared to flow of unionized air at identical flow and temperature conditions. The heat transfer enhancement was due to the ionization energy deposited by charged species due to their recombination at the surface. Even small degree of ionization (less than 1%) can lead to significant heat transfer.

The devices were integrated to a melting furnace and experiments were conducted to determine melt rate, energy efficiency, and dross. Higher aluminum melt rates of 12.7 g/s were obtained, as opposed to ~3 g/s melt rates of conventional melting practice. RPD furnace used very low power 0.2kWh/Lb to melt aluminum. Higher energy efficiency of 65% was realized compared to industrial processes operating in the range of 13 to 50%. Less than 1% dross generated compared to 3 to 12% produced in the current commercial practices. In addition, the conventional toxic fluxes were not required for the RPD furnace to produce cleaner metal. The devices were environment-friendly as no emissions were produced. Cost savings are due to lower power requirement, higher energy efficiency, lower dross, environment friendly, and absence of expenses for handling of toxic fumes.

Knife edges of the air-hardening steel were successfully hardened with uniform distribution of hardness without distortions. The plasma beam allowed thermal treatments over the entire surface of the part as well as selective localized areas of the part. Wide area plasma innovated during this research program allowed melting and solidification of nickel base alloy coatings on large surface areas of the steel part.

RPD has rapidly melted aluminum scrap-compacted slugs. A conceptual hybrid type of melting arrangement has been conceived, so that the rapidly melted scrap is pulled into the molten metal vortex to minimize oxidation and to speed-up production. The additional benefit of overcoming the dioxin problem associated with the commercial melting practice is expected to be realized.

A new website, www.oneatmosphereplasma.com was created. Aluminum melting commercialization was explored with DOE partner *Vista Ventures*. Web-based marketing collaterals were prepared. In addition, a two page marketing ‘tester’ prepared with the help of *New Horizon Technologies* and circulated to select group of companies. A prospective licensee, Berea Industries LLC has shown keen interest in the RPD technology for a new aluminum melting plan.

RECOMMENDATIONS FOR FUTURE WORK

Versatile and rapid plasma heating device for melting of aluminum and treatment of steels will be emerging as a very important device for the future. The main benefits it offered are: (i) rapid melting rates, (ii) cleaner aluminum without dross, (iii) environment friendly, (iv) energy efficient, and does not require any capital investment. Enormous interest from the industry and R&D sectors has been very pleasing. The following recommendations are made.

(a) Build experimental RPD melting furnaces and scale them gradually to industrial quantities.

(b) Expand Aluminum melting experiments to different alloy systems. For example, Al-Si, Al-Si-Mg, Al-Cu-Mg-Zn and other cast alloy systems.

(c) Integrate RPD melting with continuous casting.

(d) Expand Bayzi Corporation interface with the aluminum industry.

(e) Recycling of aluminum scrap by RPD needs immediate attention with regard to the material yield, elimination of dioxin problem.

(f) Additional experiments on processing of steel parts for heat treatment of medical surgical devices and disposal of the used parts by cleaning with plasma.

Many opportunities exist for the RPD in several other metal industries.

4. APPENDICES

Appendix A. Final Task Schedule

Task Number	Task Description	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Manufacture RPD & Controls (design)-Aluminum	04/30/05		05/30/05	100%	Manufacturing of RPDs, Controls competed
2	Experiments on Aluminum, Construction of RPD-based unit for melting	09/30/05	09/30/05	09/30/05	100%	Experiments on Aluminum, construction RPD based unit for melting completed
3	Modifications to RPD-Aluminum	09/30/05	09/30/05	09/30/05	100%	Modifications to RPD-Al completed
4	Experiments on Steel & Analysis of results	09/30/05	07/30/06		57%	Experiments on air hardening steel knives and flats resulted in uniform hardness. Nozzle optimization done.
5	Modifications to RPD based on above experiments – Steel	09/30/05	07/30/06		70%	Several modifications were incorporated
6	Testing of RPD on industrial parts & evaluation of properties - Steel	09/30/05	07/30/06		39%	Coatings were thermally fused and formed adherent wear resistant coating on steel.
7	Marketing Research	09/30/05	06/30/06		54%	A 2 page marketing tester prepared and circulated to industries & feed back obtained.
8.	B site Testing	05/30/06			74%	RPDs were tested
9.	Sale channel establishment	09/30/06			61%	Significant progress was made. Some prospective customers just began to contact.
10.	Commercialization	09/30/06			29%	A comprehensive report was made.
11.	Final report	10/30/06		03/14/06	100%	Final report completed.

Appendix B

Final Spending Schedule

Project Period: 9/30/04 to 12/31/05

Task	**Approved Budget**	**Final Project Expenditures**	
Task 1 Manufacture RPD & Controls (& design)-Aluminum	45,000		45000
Task 2 Experiments on Aluminum, Construction of RPD-based unit for melting	90,000		89,966.75
Task 3 Modifications to RPD – Aluminum	20,000		20,000
Task 4 Experiments on Steel & Analysis of results	90,000		51,000
Task 5 Modifications to RPD based on above experiments - Steel	20,000		14,000
Task 6 Testing of RPD on industrial parts & evaluation of properties - Steel	90,000		35,500
Task 7 Marketing Research	50000		27,000
Task 8 β site Testing	25000		18,500
Task 9 Sale Channel Establishment	25000		15,250
Task 10 Commercialization	45000		12,900
Task 11 Final Report			
Total	500,000		329,116.75
DOE Share	250,000		156,250
Cost Share	250,000		172,866.75

Appendix C
Final Cost Share Contributions

Final Cost Share Contributions

Funding Source	Approved Cost Share		Cumulative to Date	
	Cash	In-Kind	Cash	In-Kind
Q1-MHI Inc.			14891	9750
Q2-MHI Inc			43,535.50	20500
Q3-MHI Inc.			72,484	31,250
Q4-MHI Inc			91,608.50	51,000
Q5-MHI Inc			109,116.75	63,750
Total	150,000	100,000	109,116.75	63,750

Cumulative Cost Share Contributions 172,866.75

Appendix D

Energy Savings Metrics

Here, one unit of the RPD melting furnace, is assumed to produce at a rate of 1000 Lb/hour, 4000 hours per year. The annual production per unit works out to be 4×10^6 Pounds. The RPD melting technology is termed *'Proposed technology'*.

For the purpose of comparison, Electric radiant reverboratory melting furnace technology is termed *'Current Technology'*. The annual production rate per unit of the current technology is also assumed to be 4×10^6 pounds.

An average of 0.6% melt losses due to dross formation based on our results is considered in our calculations for the *Proposed Technology*.

An average of 4% melt losses due to dross formation is considered in our calculations for the *Current Technology*. Usually 3 to 9% melt losses are normal with the current technology.

Gross weight of aluminum required to be melted on account of losses due to dross by the *Proposed Technology* = 4.024×10^6 pounds.

Gross weight of aluminum required to be melted on account of losses due to dross by the *Current Technology* = 4.167×10^6 pounds.

Energy required for melting aluminum by the *Proposed Technology* is 0.20 kWh/Lb.
Annual energy required for melting = 4.0241×10^6 Lb x 0.20 kWh/Lb = 0.8048×10^6 kWh = 0.27468×10^{10} BTU.

Energy required for melting aluminum by the *Current Technology* is 0.25 kWh/Lb.
Annual energy required for melting = 4.167×10^6 Lb x 0.25 kWh/Lb = 1.04175×10^6 kWh = 0.35555×10^{10} BTU.

Energy savings due to the proposed technology = 0.35555×10^{10} BTU – 0.27468×10^{10} BTU = 0.08087×10^{10} BTU.

In 1996 U.S. primary aluminum production was about 3.6 million tons while secondary aluminum recovery was about 3.3 million tons. Number of units required as per the 1996 statistics 3795 units.

It is estimated that the number of units required by 2010 about 4000 units.

Possible energy savings by 2010 = 0.08087×10^{10} BTU x 4000 units = 323.48×10^{10} BTU = 3.2×10^{12} BTU.

Energy savings Metrics

Type of Energy Used	**A**	**B**	**C = A - B**	**D**	**E = C x D**
	Current Technology (Btu /yr /unit)	Proposed Technology (Btu /yr /unit)	Energy Savings (Btu /yr /unit)	Estimated Number of units in U.S. by 2010 (units)	Possible Energy savings by 2010 (Btu / yr)
Electric energy	0.355×10^{10}	0.274×10^{10}	0.081×10^{10}	4000	3.24×10^{12}

1 BTU = 2.93×10^{-4} kWh = 1.055×10^{3} J

5. SUPPLEMENTAL INFORMATION

5.1 References

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5.2. Marketing Teaser

A 2-page marketing ‘teaser’ was prepared with the help of New Horizons Technologies. This is included in this final report as an attachment at the end. The 2-page teaser was circulated to a select group of industry audience. The contacts and company names are included in the attachment. With help of a market analyst, questions and comments were gathered from this group and answers provided.

Changes and revisions to marketing documents are being considered. The next step contemplated was to approach specific companies for licensing possibilities.

The web domain www.One**Atmosphere**Plasma.com was obtained in Quarter 1, and is being integrated into the bayzi.com site. Feedback and questions and answers generated from the circulation of the 2-page teaser were incorporated into the FAQ section and are given in the following 3 pages.

NEW HORIZON
TECHNOLOGIES

P.O. Box 5000
Butte, MT 59702
406.494.4577

Tech Brief (Draft / JL 5/23)

Plasma Aluminum Melting Furnace

Bayzi Corporation, Cincinnati, OH

Overview

Bayzi Corporation of Cincinnati, OH, has developed an improved method of melting and heat treating aluminum, a Plasma Aluminum Melting Furnace. This one-atmosphere, plasma-based aluminum furnace greatly improves upon the energy efficiency of existing designs, with additional benefits in reduced losses from oxidation and contamination. The **Plasma Aluminum Melting Furnace** works on the recently discovered principle of low-ionization melting which imparts heat nearly 60% quicker than conventional high-rate melters, by a 30% increase in the heat transfer coefficient. High melting rates are thus attained with a low foot print of the furnace. Noise and toxic materials normally used as fluxes are eliminated.

Benefits of Plasma Aluminum Melting Furnace

The **Plasma Aluminum Melting Furnace** is the next generation melting furnace, allowing energy consumption rates when melting aluminum as low as 0.198 kWh/lb, compared to induction melting energy rates of 0.345 kWh/lb. This technology allows quick charging, rapid melting, and pouring, plus disposal of dross.

Prototype of the Plasma

This furnace is developed for a variety of melting needs ranging from ingot melting, sprue melting and scrap melting for recycling. Several custom footprints are available. There is no such furnace available elsewhere for aluminum melting. In addition, there is no noise or foul burning gas smell.

Key Characteristics of the Plasma Aluminum Melting Furnace

- **Ingot, sprue and scrap melting**
  The Plasma Aluminum Melting Furnace allows quick charging of ingots, sprues and

scrap for melting and pouring into holding furnace or to ladles for casting parts.

- **Improved Energy Density**
  A typical electric resistance melting furnace will have an energy density concentration of 64,557 BTU/ft3 as opposed to this new plasma furnace with 269,146 BTU/ft3, for equal volume of hot zones. The technology has four times higher energy per unit volume compared to electric resistance furnace, thus making it a unique furnace with highly concentrated power.

- **Excellent Quality of Melting**
  This technology melts at an extremely rapid rate of 13 g/s and allows the molten alloy to drain out quickly leaving the steel filter material behind. Further, the convective plasma provides a protective atmosphere while keeping the thin protective oxide film on the molten surface intact, without causing it to break, preventing formation of dross in the absence of turbulence or agitation. Molten aluminum surrounds itself completely with a thin envelope of oxide film. As long as this oxide layer remains unbroken, the rate at which gas is absorbed by the melt is quite low, and further oxidation is retarded. The dross generated by the **Plasma Aluminum Melting Furnace** is insignificantly low, typically less than 1%, unparalleled to any known industrial melting practice.

For Aluminum, a 23KW system yields:	
Energy to melt	0.2 kilowatt hours per pound
Dross/Total Metal Loss	~0.5%
Melt Rate	~12.7 g/s (compare with 3g/s for conventional) ~1 Ton / day

- **Measured Energy Savings**
  The improvement in energy efficiency over using the Convective Heat Source furnace is calculated to be approximately 73-82%. In addition to this, the **Plasma Aluminum Melting Furnace** offers many other non-measurable savings.

- **No Need for Nitrogen Cover**
  A key non-measurable benefit of using the plasma source is the elimination of nitrogen or toxic flux covers normally used to melt aluminum. The plasma takes air and converts to a nitrogen ion cover.

Aluminum Companies that RPD Melting Technology

Name	Title	Organization/ Company	Address	Website
Michael Skillingberg	VP Technology	**The Aluminum Association**	900 19th St. N.W., Washington, D.C. 20006	http://www.aluminum.org
Rodney Jefferson	Technical Assistant	**The Aluminum Association**	900 19th St. N.W., Washington, D.C. 20006	http://www.aluminum.org
Dr. John A. S. Green	Consultant	**Former Alum. Assoc.**		
Richard Kelly	R&D Director	**The Werner Company**	93 Werner Rd, Greenville, PA 16125	http://www.wernerco.com
Ray Peterson	VP Process Technology	**Aleris International, Inc.**	397 Black Hollow Rd, Rockwood, TN 37854	http://www.aleris.com
Carl Kelley	Director, Engineering and Maintenance	**Superior Aluminum Alloys**	14214 Edgerton Rd., New Haven, IN 46774	http://www.omnisource.com
John Askeland	Operations Manager	**AMPAL, Inc.**	2125 Little Gap Rd., Palmerton, PA 18071	http://www.ampal-inc.com
Chris Devadas	Technical VP	**Hydro Aluminum North America**	801 International Dr., Ste. 201, Linthicum, MD 21090	http://www.hydro.com
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Donald Steward	Program Manager	**Alcoa, Inc.**	100 Technical Drive, Alcoa Center, PA 15069-0001	http://www.alcoa.com
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Wayne Hayden		MMPact Inc		

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ANNOUNCEMENT

UNITED STATES DEPARTMENT OF ENERGY (DOE)
Scientific and Technical Information (STI) For Financial
Assistance Recipients and Non-M&O/M&I Contractors

OMB Control No.
1910-1400

PART I: STI PRODUCT DESCRIPTION
(To be completed by Recipient/Contractor

A. STI Product Identifiers

1. REPORT/PRODUCT NUMBER(s)
None

2. DOE AWARD/CONTRACT NUMBER(s)
DE-FG36-04GO14335

3. OTHER IDENTIFYING NUMBER(s)

B. Recipient/Contractor

Bayzi Corporation

H. Sponsoring DOE Program Office

DOE, Golden Field Office

I. Subject Categories *(list primary one first)*

Rapid Plasma Device, Aluminum melting, energy efficient, low dross, plasma hardening of steel

Keywords

J. Description/Abstract

The main objective of the research was to enhance steel and aluminum manufacturing with the development of a new plasma RPD device. During the project (1) plasma devices were manufactured (2) testing for the two metals were carried out and (3) market development strategies were explored.

Bayzi Corporation has invented a Rapid Plasma Device (RPD) which produces plasma, comprising of a mixture of ionized gas and free electrons. The ions, when they hit a conducting surface, deposit heat in addition to the convective heat. Two generic models called the RPD-Al and RPD-S have been developed for the aluminum market and the steel market. Aluminum melting rates increased to as high as 12.7 g/s compared to 3 g/s of the current industrial practice. The RPD melting furnace operated at higher energy efficiency of 65% unlike most industrial processes operating in the range of 13 to 50%. The RPD aluminum melting furnace produced environment friendly cleaner melts with less than 1% dross. Dross is the residue in the furnace after the melt is poured out. Cast ingots were extremely clean and shining. Current practices produce dross in the range of 3 to 12%. The RPD furnace uses very low power ~0.2 kWh/Lb to melt aluminum. RPDs operate in one atmosphere using ambient air to produce plasma while the conventional systems use expensive gases like argon, or helium in air-tight chambers. RPDs are easy to operate and do not need intensive capital investment. Narrow beam, as well as wide area plasma have been developed for different applications.

An RPD was developed for thermal treatments of steels. Two different applications have been pursued. Industrial air hardening steel knife edges were subjected to plasma beam hardening. Hardness, as measured, indicated uniform distribution without any distortion. The biggest advantage with this method is that the whole part need not be heated in a furnace which will lead to oxidation and distortion. No conventional process will offer localized hardening. The RPD has a great potential for heat treating surgical knives and tools. Unavailability of the full amount of the DOE award prevented further development of this exciting technology.

Significant progress was made during the 5th quarter, specially the invention of the wider-area plasma and the resultant benefits in terms of rapid melting of aluminum and thermal treatments of larger size steel parts. Coating of nickel base superalloys was demonstrated

C. STI Product Title

Versatile and Rapid Plasma Heating Device for Steel and Aluminum

D. Author(s)

Reddy, G.S.

E-mail Address(es):

info@bayzi.com

E. STI Product Issue Date/Date of Publication

(mm/dd/yyyy)

F. STI Product Type *(Select only one)*

☒ 1. TECHNICAL REPORT

☒ *Final* ☐ *Other (specify)*

☐ 2. CONFERENCE PAPER/PROCEEDINGS

Conference Information (title, location, dates)

☐ 3. JOURNAL ARTICLE

a. TYPE: ☐ *Announcement Citation Only*

☐ *Preprint* ☐ *Postprint*

b. JOURNAL NAME

c. VOLUME *d. ISSUE*

e. SERIAL IDENTIFIER (e.g. ISSN or CODEN)

☐ OTHER, SPECIFY

G. STI Product Reporting Period (mm/dd/yyyy)

9/30/2004 *Thru* *12/31/2005*

(an additional task over that proposed).

Directed low cost surface enhancement of steel and the directed clean low dross energy efficient melting of aluminum are industrial needs that require new technologies. These are large volume markets which can benefit from energy savings. Estimated energy savings are very large, in the order of 10^{15} J/year when the equipment is universally used. Compact and directed heating technology/product market in these two sectors could potentially reach over $1B in sales.

The results of the research, presented at the DOE annual Review meeting on Aluminum held at the Oak Ridge National Laboratory during the 4-5 October 2005, were very well received by the delegates and panel reviewers.

Insufficient DOE funds to fully fund the project at the end of the 5th quarter necessitated some key tasks being only partially completed.

K. Intellectual Property/Distribution Limitations

(must select at least one; if uncertain contact your Contracting Officer (CO))

☒ 1. UNLIMITED ANNOUNCEMENT *(available to U.S. and non-U.S. public; the Government assumes no liability for disclosure of such data)*

☐ 2. COPYRIGHTED MATERIAL: *Are there any restrictions based on copyright?* ☐ *Yes* ☐ *No*

If yes, list the restrictions as retained in your contract

☐ 3. PATENTABLE MATERIAL: THERE IS PATENTABLE MATERIAL IN THE DOCUMENT

INVENTION DISLOSURE SUBMITTED TO DOE:

DOE Docket Number: S-

(Sections are marked as restricted distribution pursuant to 35 USC 205)

☐ 4. PROTECTED DATA: ☐ *CRADA* ☐ *Other*

If other, specify

Release date (mm/dd/yyyy)

☐ 5. SMALL BUSINESS INNOVATION RESEARCH (SBIR) DATA

Release date (Required,

(No more than 4 years from date listed in part 1.E above)

☐ 6. SMALL BUSINESS TRANSFER (STTR) DATA

Release date (Required,

No more than 4 years from date listed in part 1.E above)

☐ 7. OFFICE OF NUCLEAR ENERGY APPLIED TECHNOLOGY

L. Recipient/Contractor Point of Contact *Contact for additional information (contact or organization name to be included in published citations and who would receive any external questions about the content of the STI Product or the research contained therein)*

Anu Vissa, COO

Name and/or Position

info@bayzi.com 513-772-0404

E-mail *Phone*

Bayzi Corporation

Organization

DOE F 241.3 *(2-01) p. 2 of 4* **ANNOUNCEMENT**	**UNITED STATES DEPARTMENT OF ENERGY (DOE)** Scientific and Technical Information (STI) For Financial Assistance Recipients and Non-M&O/M&I Contractors	*OMB Control No.* *1910-1400*

PART II: STI PRODUCT MEDIA/FORMAT and LOCATION/TRANSMISSION

(To be completed by Recipient/Contractor)

A. Media/Format Information:

1. MEDIUM OF STI PRODUCT IS:
   ☒ Electronic Document ☐ Computer medium
   ☐ Audiovisual material ☐ Paper ☐ No full-text
2. SIZE OF STI PRODUCT ______
3. SPECIFY FILE FORMAT OF ELECTRONIC DOCUMENT BEING TRANSMITTED, INDICATE:
   ☐ SGML ☐ HTML ☐ XML ☒ PDF Normal ☐ PDF Image
   ☐ WP-Indicate Version *(5.0 or greater)* ______
   Platform/operating system ______
   ☒ MS-Indicate Version *(5.0 or greater)* WORD
   Platform/operating system ______
   ☐ Postscript ______
4. IF COMPUTER MEDIUM OR AUDIOVISUAL
   a. Quantity/type *(specify)* ______
   b. Machine compatibility *(specify)* ______
   c. Other information about product format a user needs to know: ______

B. Transmission Information:

STI PRODUCT IS BEING TRANSMITTED:
☒ 1. Electronic via Elink
☐ 2. Via mail or shipment to address indicated in award document *(Paper products, CD-ROM, diskettes, videocassettes, et.)*

☐ 2a. Information product file name *(of transmitted electronic format)*
Bayzi Final Tech Report

PART III: STI PRODUCT REVIEW/RELEASE INFORMATION

(To be completed by DOE)

A. STI Product Reporting Requirement Review:

☒ 1. THIS DELIVERABLE COMPLETES ALL REQUIRED DELIVERABLES FOR THIS AWARD

☐ 2. THIS DELIVERABLE FULFILLS A TECHNICAL REPORTING REQUIREMENT, BUT SHOULD NOT BE DISSEMINATED BEYOND DOE.

B. DOE Releasing Official

☐ 1. I VERIFY THAT ALL NECESSARY REVIEWS HAVE BEEN COMPLETED AS DESCRIBED IN DOE G 241.1-1A, PART II, SECTION 3.0 AND THAT THE STI PRODUCT SHOULD BE RELEASED IN ACCORDANCE WITH THE INTELLECTUAL PROPERTY/DISTRIBUTION LIMITATION ABOVE.

Released by *(name)* ______

Date ______
(mm/dd/yyyy)

E-mail ______

Phone ______

INSTRUCTIONS

Purpose: DOE F 241.3 provides the Office of Scientific and Technical Information (OSTI) information required to appropriately identify, process, and/or announce and disseminate the results of work funded by the U.S. Department of Energy (DOE). For general information or assistance with this form, contact OSTI at (865) 241-6435, or at the following e-mail address: 241user@adonis.osti.gov.

When to use: Submit this form with each scientific and technical information (STI) Product. Electronic format is the preferred method for submitting the announcement record and STI Product. When submitting electronically, use the electronic version of the form (http://www.osti.gov/elink; discuss with your DOE Contracting Officer).

Describing the data fields: Descriptions of the various DOE F 241.3 data fields, STI Products, format, etc., can be found in ATTACHMENT 3 and other sections of the DOE G 241.1-1A, Guide to the Management of Scientific and Technical Information. Available online at http://www.osti.gov/stip/

DOE Financial Assistance Recipients/Contractors Recipients and Contractors should complete Parts I and II of the form and forward the form along with the STI product to the DOE Contracting Officer who will complete the rest of the form and submit the package to OSTI.

NOTE: Sensitive, proprietary, or other STI Products for which access is restricted by statute or regulation shall not be transmitted via open systems networks (e.g., the Internet) unless authorization and/or encryption has been coordinated with OSTI in advance. This form, unless it in itself is classified, can be transmitted via open systems networks (.e.g, the Internet).

RECORD STATUS - This is a required field. The record status identifies the announcement record or the STI Product as new, or revised. If the record status is not provided, the record is considered "New."

Part I: STI PRODUCT DESCRIPTION (To be completed by Recipient/Contractor)

A. STI PRODUCT IDENTIFIERS.

1. **Report/Product Number(s).** This is a required field. The unique primary report or product number assigned to the STI product. If a report number is not provided, the word "NONE" should be entered.

Following are examples of report number formats for multiple volumes, parts, or revisions:

DOE/ID/13734-2

DOE/NE/01834--1-Pt. 1

More than one report number may be provided. Multiple numbers are separated with a semicolon and a space. When more than one number is entered, the first number, considered the primary number, should identify the submitting organization. All other numbers are considered secondary numbers.

2. DOE Award/Contract Number(s). This is a required field. Enter the DOE award/contract number under which the work was funded. Additional DOE award/contract numbers related to the product may be entered. Multiple numbers are separated with a semicolon and a space. When more than one number is entered, the first number is considered the primary number.

3. Other Identifying Number(s). An additional unique identifying number assigned to the STI product. (e.g., CRADA numbers, Non-DOE contract numbers). More than one other identifying number may be provided. Multiple numbers are separated with a semicolon and a space.

B. RECIPIENT/CONTRACTOR - This is a required field. Provide the name and location of the organization that performed the research or issued the STI product. More than one organization may be provided; separate multiples with a semicolon and a space.

Example: University of Tennessee, Knoxville, TN

C. STI PRODUCT TITLE - This is a required field. Provide the title exactly as given on the product itself, including part, volume, edition, and similar information.

D. AUTHOR(s) - This is a required field. Provide the name of the author (last name first) of the STI product. More than one author may be provided; separate multiple entries with a semicolon and a space. If an author does not exist, the word "None" should be entered.

Examples: Jones, T.M.; Markay, Arthur R. III
Fields, J.M., ed.

Author(s) E-mail Address(es). Provide the e-mail address for each author. Multiples may be provided; they should be listed in the same order as the authors and should be separated by a semicolon and a space.

E. STI PRODUCT ISSUE DATE/DATE OF PUBLICATION - This is a required field. Provide the date when the information product was published or issued.

F. STI PRODUCT TYPE - This is a required field. It should agree with the reporting requirement identifier in the reporting requirements checklist; federal assistance reporting checklist; or in the statement of work if the product is a required deliverable that warrants accountability.

1. **Technical Report**. Identify the type of technical report provided.

2. **Conference Paper.** Provide all available conference information. An agenda alone is not sufficient for announcement.

3. **Journal Article.** Provide all available Journal Article information.

G. STI PRODUCT REPORTING PERIOD. Specify the beginning and ending dates of the period covered by the STI product.

H. SPONSORING DOE PROGRAM OFFICE - Enter the name or acronym of the DOE Program Office (e.g., Office of Science or SC) providing the funding for the work described in the STI product. For projects funded by more than one Program Office, indicate all sources of the DOE funding in descending order of dollar amount of funding appropriated. Separate multiple program offices with a semicolon and a space. If no sponsoring DOE Program Office is provided, "DOE" will be the sponsor.

I. SUBJECT CATEGORIES - Select one or more categories from the list provided. List the primary one first. A list of subject categories is available at (http://www.osti.gov/elink/).

Keywords. Provide terms which describe the content of the publication. More than one term may be entered; separate multiple terms with a semicolon and a space.

J. DESCRIPTION/ABSTRACT - Provide a clear, concise, and publicly releasable English language summary of the information content of the STI product. The abstract length should be no more than 5,000 characters. If you are utilizing paper media, you may provide via attachment.

INSTRUCTIONS

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1. **Unlimited Announcement**. The unrestricted, unlimited distribution of the product (will be made publicly available). The Government assumes no liability for disclosure of such data.

2. **Copyrighted Material**. A copyright restriction on part or all of the contents of the STI product may affect the reproduction and distribution of the product by OSTI. Any restriction must be specified.

3. **Patentable Material**. Provide all applicable patent information.

4-6. No special instructions.

7. Office of Nuclear Energy Applied Technology pursuant to 10 CFR 810.

L. RECIPIENT/CONTRACTOR POINT OF CONTACT. Provide the organization or individual(s) name with corresponding contact information who will be included in the published citation as the point of contact and will respond to external questions about the content of the STI product.

Part II. STI PRODUCT MEDIA/FORMAT AND LOCATION/ TRANSMISSION (To be completed by recipient/contractor)

A. MEDIA/FORMAT INFORMATION

1. **Medium**. This is a required field. Select one of the medium options provided. Note: When announcement record only is submitted, select "No full-text."

2. **Size of STI Product**. Provide the total number of pages or other designation which gives an indication of the size of the information product (e.g., 200 pages; 20 images; 3500 kilobytes; 3-3 1/2 inch diskettes).

3. **File Format**. This is a required field if the STI product is electronic full-text. Select one of the options provided.

4. **If Computer Medium or Audiovisual Material** (do not include software packages).

a. Indicate the quantity and type of medium, e.g., 2 videocassettes, 1 magnetic tape.

b. Indicate the machine with which the medium is compatible, i.e., with which it can be used (e.g., VHS; IBM PC compatible, hard disk, 8 Megs.)

c. Enter any other information which would be helpful to the user of the STI product (e.g., programming language, file format, etc.)

B. LOCATION/TRANSMISSION INFORMATION

STI PRODUCT IS BEING TRANSMITTED:

1. This is a required field. Provide if the full-text STI product is being transmitted electronically. Indicate if product is being transmitted via Internet-accessible system called Elink at https://www.osti.gov/elink/.

2. This is a required field. Provide an electronic copy of the STI product that is being transmitted via other computer-generated medium or other method. Indicate if product is being transmitted via mail or other shipment method (paper products, CD-ROM, diskettes, videocassettes, etc.). Provide information product filename of transmitted electronic format, if applicable.

Part III: STI PRODUCT REVIEW/RELEASE INFORMATION (To be completed by DOE)

A. STI PRODUCT REPORTING REQUIREMENT REVIEW

1. This is a required field if all other required STI products have been received for this award by OSTI and this STI product is the final deliverable required according to the technical information reporting requirement.

2. Indicated if the STI product is not suitable for dissemination beyond DOE based on report type or content, it is being submitted because it fulfills a technical information reporting requirement.

B. RELEASEING OFFICIAL - This is a required field. Provide the name and additional information of the site's individual(s) responsible for the appropriate review and release of the STI product. Do not forward this form or the STI product until after it has been reviewed and released for announcement.

OMB BURDEN DISCLOSURE STATEMENT

Public reporting burden for this collection of information is estimated to average 30 minutes per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to the Office of Information, Records and Resource Management, SO-31, FORS, U.S. Department of Energy, Washington, DC 20585 and to the Office of Management and Budget (OMB), Paperwork Reduction Project (1910-1400), Washington, D.C. 20503.