THE KRISTIAN BIRKELAND LECTURE

THE LEGACY OF BIRKELAND´S PLASMA TORCH

BY
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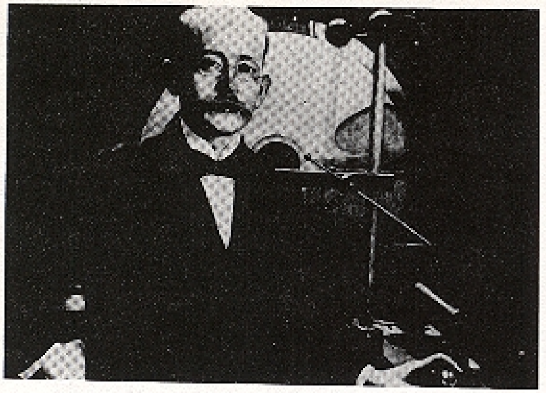

Kristian Olaf Bernhard Birkeland (1867–1917) Norwegian professor in physics. He was originally devoted to mathematics but later became interested in physics. He was appointed professor at 31 years of age and introduced modern physics to Norway.

FOREWORD

In 1867 there was born a man in Norway, who, in his lifetime, brought fame to himself and his country through fundamental, pioneering research in physics, geophysics, technology, and applied physics. His name was Kristian Olaf Bernhard Birkeland.

Birkeland was a most colorful character with a wealth of ideas. He wanted to investigate almost everything in the physical sciences. During the period 1894–1913, while professor at the University of Oslo, he uncovered hidden treasures of knowledge about among other things the earth magnetism and the polar aurora. He also developed advanced theories on solar-terrestrial relationships, comets, Saturn´s rings and cosmology. Birkeland´s discovery of the plasma arc resulted in the development of the Birkeland/Eyde method, the first industrial process for nitrogen-fixation, and in the founding of Norsk Hydro, today a major industrial enterprise, and Norway´s largest company.

Unfortunately, many of Birkeland´s outstanding contributions remained unrecognized up to the space age. As the space around the Earth became more thoroughly surveyed by satellites, there was a change of attitude towards Birkeland´s work to one of admiration and almost total acceptance. In retrospect, it may be stated that Birkeland´s work from 1896–1908 was far ahead of other auroral and geomagnetic research of that time. Only now, in the age of space exploration, can we properly appreciate the prophetic nature of those discoveries.

In order to commemorate Birkeland´s great achievements in both technology, applied physics, and basic research – and in an effort to disseminate Birkeland´s work and ideas more widely disseminated in the international scientific community – the Faculty of Mathematics and Natural Science at the University of Oslo, in cooperation with The Norwegian Academy of Science and Letters, and Norsk Hydro A/S inaugurated in 1986 a lecture series called *The Kristian Birkeland Lectures.*

The organizers were very pleased and honored that Nobelprizewinner, Professor Hannes Alfvén accepted their invitation and gave the first lecture. The second lecture in the series was given by Professor Alexander J. Dessler of Rice University, Houston, who introduced the name Birkeland currents in 1967. The third lecture was given by Professor T.A. Potemra and Professor N. Fukushima.

In 1990 a Nansen/Birkeland Symposium was held in Oslo, with several international leading experts. The proceedings of this symposium were No. 4 in the series of Birkeland Lectures, with Professor J.A. Van Allen of University of Iowa, USA, as invited lecturer. The fifth was the lecture by Director of Geophysical Institute, Alaska, Professor Syun-Ichi Akasofu in 1991, and the sixth lecture in 1992 by Professor W. Ian Axford, Max-Planch Institut für Aeronomie, Germany.

In 1993 the Birkeland lecture was for the first time arranged outside Norway – at the University of Tokyo, and the lecture was given by Professor Takasi Oguti, the first Director of the Solar Terrestial Environment Laboratory of Nagoya University.

Finally, in 1994, the lecture was again arranged in Norway, with Professor Stanley W. H. Conley from Imperial College, England, as invited lecturer.

T. Amundsen *A. Egeland*
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THE LEGACY OF BIRKELAND'S PLASMA TORCH

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Abstract. The year 1996 marks the Centennial Celebration of the founding of Plasma Astrophysics and Cosmology; its origins may be traced to the seminal research first published by Kristian Birkeland in 1896. However, the funding necessary to support Birkeland's world-wide expeditions and laboratory cosmic plasma simulations came from an entirely unexpected event: the shorting-out of his electromagnetic cannon during a demonstration. This simple accident, the 'invention' of the plasma torch, gave birth to founding of Norsk Hydro and also provided the resources for Birkeland to demonstrate the origin of the northern lights and establish the field of experimental astrophysics. The discovery of the torch inspired the use of plasma furnaces to produce nitrogen fertilizer in Norway up to 1940. Today, plasma torches find application in the steel industry, in plasma processing of integrated circuits, parts, and tool hardening. After a gestation period of almost a century, the plasma torch today offers a global solution to the vitrification and storage of radioactive waste.

1 Introduction

The year 1996 marks the Centennial Celebration of the founding of Plasma Astrophysics and Cosmology; its origins may be traced to the seminal research of Kristian Birkeland published in 1896 that began his life–long study of laboratory produced cathodic rays and corpuscles[1] and their analogies to astrophysical and cosmological phenomena. This work was presented in two papers: "Sur un spectre des rayons catodiques" in *Comptes Rendus*, 28 September 1896, and a paper in *Archives des Sciences Physiques et Naturelles*, Geneva, 4th period, vol. I, 1896, that announced his discovery of magneto–cathode rays. It was in this work that, according to Birkeland (1908):

> ...I expressed for the first time my belief that the northern lights are formed by corpuscular rays drawn in from space, and coming from the sun.

In addition to his solving the mystery of the Aurora with his now–famous terrella experiments; electron beams in vacuum from magnetized copper globe cathodes, Birkeland utilized his data to formulate a theory about a plasma–filled universe populated with *systems* of nebula (galaxies).

We quote from Birkeland (1908, Volume 1, Section 131.):

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[1] The term 'plasma' was not to be coined by I. Langmuir until 1923.

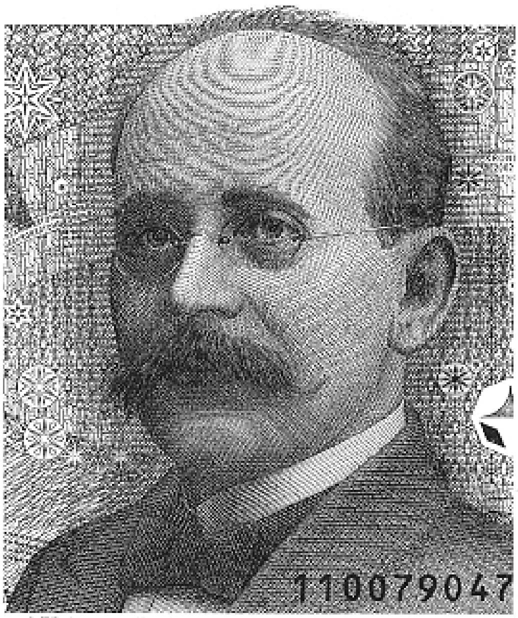

Fig. 1. Engraving of Kristian Birkeland that appears on Norwegian 200 kronor notes.

> **The Worlds in the Universe.** From the conceptions to which our experimental analogies lead us, it is possible to form, in a natural manner an interesting theory of the origin of the worlds. This theory differs from all earlier theories in that it assumes the existence of a universal directing force of electro–magnetic origin in addition to the force of gravitation, in order to explain the formation round the sun of planets, which have almost circular orbits and are almost in the same plane, of moons and rings about the planets, and of spiral and annular nebulæ.

Much of Birkeland's work was rediscovered in the 1980s with renewed interest about the role of large scale magnetic fields and currents in explaining astrophysical, galactic, and cosmological scale phenomena, including the origin and structure or galaxies and the containment of intergalactic gas 'clouds' and filaments, formerly attributed to dark matter gravitational binding energy. It comes as a surprise to most astronomers that as early as 1896 Birkeland and his colleagues took the temperature of the universe to be between 5–6K blackbody[2]:

[2] Birkeland corresponded with his French colleagues, the Guillaume's. Ch.-Ed. Guillaume in the article 'La Température de L'Espace', *La Nature*, vol.24, series 2, pp.210–211, 234 (1896), concludes ...that the radiation of the stars alone would maintain the test particle we suppose might have been placed at different points in the sky at a temperature of $338/60 = 5.6$ abs. $= -207°.4$ centigrade. We must not conclude that the radiation of the stars raises the temperature of the celestial bodies to 5 or 6 degrees. If the star in question already has a temperature that is very different from absolute zero, its loss of

Today, plasma cosmology is a vigorous field of study supported by new observations such as filamentation, large–scale structure, the 2.7K blackbody background, non-Doppler redshifts, the existence of charged particle beam phenomena in cosmic objects, and the morphological observations of the Hubble Space Telescope (Peratt, 1995). This chain of success really started in 1974 when a rocket–launched satellite verified the existence of Birkeland Currents in the earth's magnetosphere/ionosphere (Dessler, 1983).

It is worthwhile to repeat Birkeland's 1908 quote:

> *According to our manner of looking at the matter, every star in the universe would be the seat and field of activity of electric forces of a strength that no one could imagine.*
>
> *We have no certain opinion as to how the assumed enormous electric currents with enormous tension are produced, but it is certainly not in accordance with the principles we employ in technics on the earth at the present time. One may well believe, however, that a knowledge in the future of the electrotechnics of the heavens would be of great practical value to our electrical engineers.*
>
> *It seems to be a natural consequence of our points of view to assume that the whole of space is filled with electrons and flying electric ions of all kinds. We have assumed that each stellar system in evolutions throws off electric corpuscles into space. It does not seem unreasonable therefore to think that the greater part of the material masses in the universe is found, not in the solar systems or nebulæ, but in "empty" space.*

Alfvén and Egeland (1987) have drawn a parallel between Sir Isaac Newton and Kristian Birkeland; the former establishing the law essential to understanding the mechanical forces between neutral matter in the universe, and the latter establishing the law essential to understanding electromagnetic forces in the universe.[3]

Kristian Birkeland was simultaneously a theorist, a laboratory experimentalist, and a field experimentalist. He was one of the few physicists of his time to master Maxwell's electromagnetic theory. In the laboratory, Birkeland was without peer. He could put together laboratory experiments that, at that time were of unprecedented size and complexity, and he could make them work. He pioneered the application of direct, alternating, and pulsed currents and pioneered the observation and photography of arc discharges.

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heat is much greater. We will find the increase of temperature due to the radiation of the stars by calculating the loss using Stefan's law. In this way, we find that for the Earth, the temperature increase due to the radiation of the stars is less than one hundred-thousandth of a degree. Furthermore, this figure should be regarded as an upper limit on the effect we seek to evaluate.

[3] Like Newton (whose work was introduced in France by Voltaire), Birkeland's work suffered a long delay before acceptance.

He also mounted large–scale and widespread field expeditions to gather basic information and quantitative data. These field expeditions included the construction of small but study mountain top observatories in Finnmark (the mountainous region of northern Norway) and the establishment of 'observatories' to measure magnetic needle deflections during a magnetic storm at locations as remote as Novaya Zemlya[4] in the Russian arctic.

Birkeland's central interest was the aurora, but his auroral research expanded into what is now space and cosmic plasma physics. He offered plasma physics explanations of the aurora, as well as a number of other phenomena such as the rings of Saturn, zodiacal light, the formation of comet tails, and even the creation of the solar system (Brekke and Egeland, 1994).

Yet in spite of Birkeland's driving interest in natural phenomena, he invested considerable time and effort in a firearms enterprise, for which he developed the world's first electromagnetic cannon (now sometimes referred to as a rail gun). Later he worked equally hard on the development of a fertilizer manufacturing project (Egeland and Leer, 1986).

2 The Electromagnetic Cannon

One might question Birkeland's interest in guns and fertilizers. They seem inappropriate as focal points for the intellect of someone as absorbed as was Birkeland by this research into the mysteries of the solar system. The answer, is that Birkeland was driven by a need for money to fund his ambitious, expensive research projects (Dessler, 1988). For the first few years of his professorship, he was able to carry out his research with the money provide by the university, the government, and some benefactors. However, as his understanding of the aurora expanded, so did the size, complexity, and cost of his research. Even though he received more support from the Norwegian Government than any other professor for his basic research projects and obtained a significant amount of money from influential business people, he felt it necessary to have more funds to accomplish his research program. For example, his Norwegian Aurora Polaris Expedition of 1902–1903 was budgeted at 68,000 Norwegian kronors, fifteen times his annual salary.

Birkeland turned to the invention and development of armaments as a means of securing his needed research funds because it was the obvious route for quick funding. By the end of the 19th century, technology was increasingly seen as the means of attaining military superiority. For example, the "Dreadnought Race" of that era was a technological battle for naval superiority. The last half of the nineteenth century saw a frantic competition between the British on the one hand and their chief imperial rivals, the French and the Russians on the othera competition in size of guns, thickness

[4] Novya Zemlya served as a Soviet nuclear weapons testing ground during the Cold War.

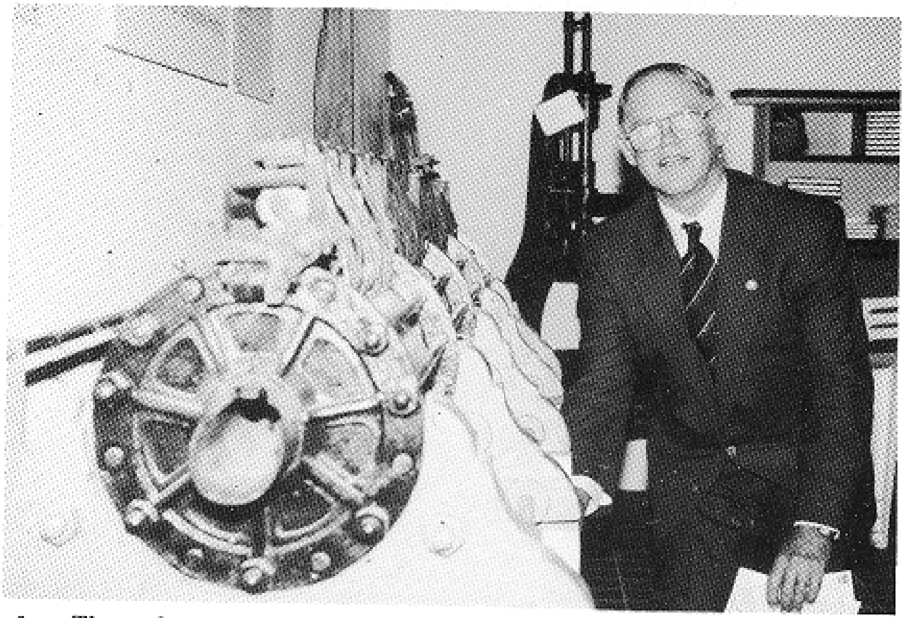

Fig. 2. The author with Birkeland's cannon. It is now displayed at the Norsk Hydro Museuum in Notodden.

of armor, and speed. Technological development in naval warfare looked as if it might provide an advantage sufficient not just to win a battle but to win a war and establish a new kind of political dominance.

Many experts believed that Birkeland's electromagnetic gun would cause a revolution similar to the one brought about by the introduction of gunpowder. In a political climate in which the survival of nations was to be determined by technological prowess, it would be natural for Birkeland to reason that this was the arena in which he could invent a high–technology device that would rapidly earn enough money to support the kind of research program he was determined to pursue.

3 History of Arc Discharges Prior to Birkeland

The history of plasma arc technology is essentially as old as the history of dynamic electricity. Within four years of Alessandro Volta's March 2, 1800 letter to the Royal Society of London describing his battery, Humphrey Davy demonstrated a 40 cm arc from electrodes connected to a 'voltaic pile'.

Experiments and research on electric arcs depended on discharges from batteries and condensers until 1867 when the electric generator was invented. The practical use of arcs for the bulk heating of metals began in 1878 when Sir W. Siemens developed a DC furnace. The Siemens furnace utilized two water–cooled, pencil shaped electrodes to draw the arc; a copper cathode

Fig. 3. Photograph of the King's visit to the 'Admini' at Notodden, Norway, the first of Norsk Hydro's guesthouses. King Haakon (center) is between Kristian Birkeland (left) and Sam Eyde (right).

and a graphite anode, producing enough heat to melt several kilograms of steel and platinum and vaporize copper.

In 1897, the classical experiments of H. Moissan were published on the application of thermal plasmas to metallurgy and high temperature chemistry. In a furnace similar to Siemen's, Moissan attempted to make artificial diamonds. His research included the study of amorphous carbon and graphite as well as diamonds, and the preparation of the metals and carbides of chromium, manganese, molybdenum, tungsten, uranium, vanadium, zirconium, titanium, silicon, aluminum, and calcium carbide. In 1886 he achieved the first isolation of fluorine and in 1906 he was awarded the Nobel prize in chemistry.

In 1901 Marconi demonstrated the practicality of the electric arc discharge for an entirely different application: the production of electromagnetic waves in his transatlantic radio demonstration.

4 Discovery of the Non–transferred Arc or Plasma Torch

The switch from guns to fertilizers was brought about entirely by accident. Birkeland built his first electromagnetic gun in 1900, and he was awarded patents on the device. The Birkeland Firearms Company was formed in 1901, and Birkeland and his investors set out to demonstrate the gun to

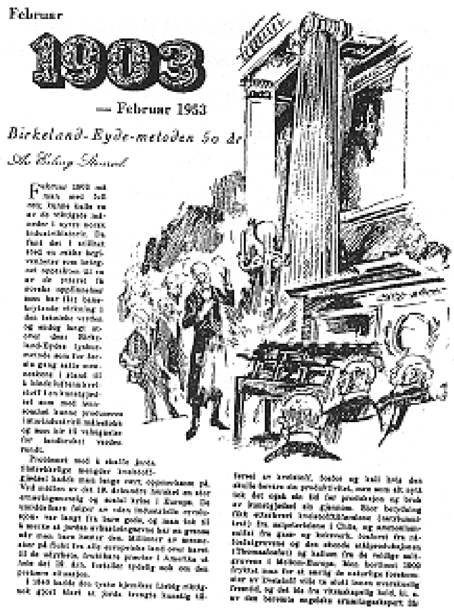
Februar
1903
— Februar 1963
Birkeland-Eyde-metoden 60 år

Fig. 4. A drawing from Birkeland's Gala lecture in the Festival Hall at the University of Oslo on February 6, 1903.

the German and British weapons giants Krupp and Armstrong. There were many successful tests and a successful demonstration of the gun at the Norwegian Academy on March 6, 1902. He then designed a large gun that he calculated should be able to propel a 500 kilogram, 30–cm diameter projectile at speeds up to 500 or 600 kilometers per second with a maximum range of 100 kilometers.

One of Birkeland's supporters, Secretary of Agriculture Knudsen, informed the joint Swedish–Norwegian king, Oscar II, of Birkeland's electromagnetic gun. When the King asked about its maximum range, Knudsen replied: "Birkeland says that projectiles can reach Stockholm" (the King's permanent residence). Noting the King's alarm, Knudsen's quickly added "...and he says that the bullet could go from Oslo to St. Petersburg," a factor of ten greater than Birkeland quoted. The King lightened up considerably (Egeland, 1989).

Needing funds for his 1902–1903 Polaris Expedition, Birkeland arranged a demonstration of his electromagnetic gun at the University of Oslo with the express purpose of selling the Firearms Company.

> *"It was at the University's old banquet hall on February 6, 1903. The cannon was placed in the hall and pointed toward the target which was a three inch thick plank wall of solid wood. I had closed off the space on both sides of the projectile's track, but except for this area the hall was*

full with expectant people. In the first section of seats were representatives from Armstrong and Krupp, the large weapon forgers in Europe. I went through the principles on which the cannon was based, and 'Ladies and Gentlemen,' I said, 'you may calmly be seated. When I pull the switch, you will neither see nor hear anything except the bang of the projectile against the target.' With this I pulled the switch. There was a flash, a deafening and hissing noise, a bright arc of light due to three thousand amperes being short-circuited, and a flame shot out of the mouth of the cannon. Some of the ladies shrieked and a moment later there was panic. It was the most dramatic moment in my life. With this shot, I shot my stock down from a value of 300 to zero. But the projectile hit the bulls eye."

In one brief instant the Plasma Torch was born.

Today, plasma torches[5] are properly classified as either transferred or non–transferred torches. The transferred torches requires an external electrode, which is very often the metallic target to be heated, for example, the molten bath of metal. The transferred plasma torch employs a rear electrode and a collimator. The arc is struck between the rear electrode and the external work–piece and is confined between these two boundaries. In contrast, the non–transferred does not require an external electrode. Non–transferred plasma torches employ two electrodes, a rear electrode and a front electrode that replaces the collimator.

The electrical short in Birkeland's gun was the first demonstration of a non–transferred torch. In terms of plasma physics, this is the more interesting torch configuration. The non–transferred plasma torch is unusual because the plasma flame, a z–pinched column of current–carrying plasma, displays several fundamental magnetohydrodynamic modes, filamentation, and 'flying electric corpuscles of all kinds' away from the electrodes themselves, that is, out of the mouth of a coaxial plasma gun or cannon. This is what Birkeland and his guests observed the night of February 6, 1903.[6] While Birkeland could not have detected it, the kinetics of the particles in his z–pinch are prodigious producers of electromagnetic radiation (Peratt, 1992).

A chance meeting at a dinner party the following week with industrialist/engineer Sam Eyde[7] brought about the first application of the plasma torch. At the turn of the century, Europe used vast quantities of nitrate fer-

[5] We make a distinction between pencil–point electrode heaters or furnaces and the coaxial 'gun–barrel' plasma arc discharge. In this paper the latter is referred to as a 'torch'.

[6] While the non–transferred flame gave Birkeland the inspiration to use electrical energy to produce fertilizer, Birkeland and Eyde actually employed AC furnaces at their plant in Rjukan for this purpose.

[7] Eyde (1866–1940) believed that Norwegian waterfalls could be used to develop that country's economy. He obtained the rights to a number of waterways at an early stage.

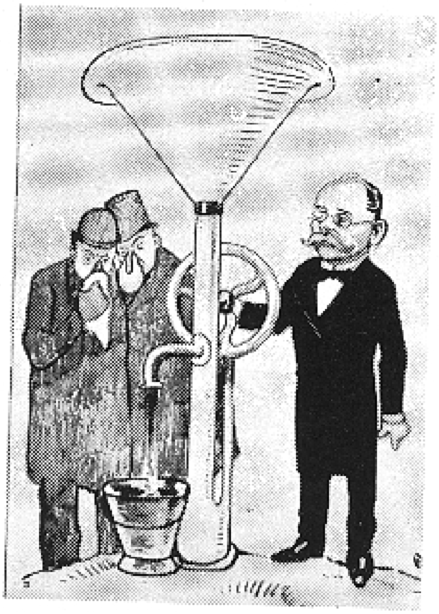

Fig. 5. A contemporary cartoon skeptical of Birkeland's claim that he could make fertilizer from air.

tilizer. However, its principle source, naturally occurring sodium and potassium nitrate from Chile, was being mined to exhaustion. Eyde described a potentially catastrophic shortage of fertilizer. With the memory of the flaming arc still fresh in his mind, Birkeland replied to Eyde, "I have it!" Birkeland said that he could produce artificial fertilizer from air. A contemporary cartoon shows an amused, if not doubtful, view of the Professor's claim that he could make fertilizer. Eyde, however, took Birkeland at his word.

Development of the electromagnetic gun was dropped. By the following Friday Birkeland had filed a patent application for the fixing of atmospheric nitrogen using an electric arc. In actuality, Birkeland did not utilize his pulsed–current, gun–torch to produce nitrogen oxide. Instead, he used far more efficient alternating current plasma furnaces driven by Eyde's generators.

Convinced by Eyde of the practicality of Birkeland's furnace, the noted Swedish capitalist Marcus Wallenberg[8] (1864–1943) provided funds from Stockholm's Bank and obtained further financing from the Bank de Paris. Thus, in a fruitful collaboration between a university professor of physics, an engineer, and a financier, Norsk Hydro was founded in 1905 to provide

The main objective: use of Birkeland's furnace for the production of potassium nitrate fertilizer. He served as the first President of Norsk Hydro from 1905 to 1917.

[8] Wallenberg served as Norsk Hydro Chairman of the Board from 1905 to 1942.

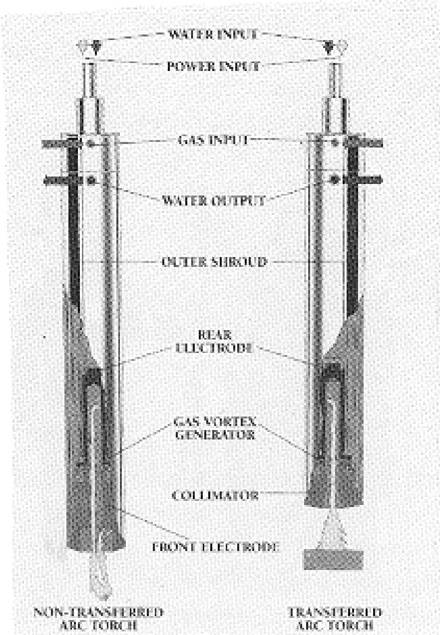

Fig. 6. Non-transferred and transferred DC plasma torches. (Courtesy of D. Cheek, Plasma Energy Corporation, Raleigh, North Carolina).

the hydro–electricity to power Birkeland's plasma furnaces.

Birkeland's research funding problems were over. Between 1911 and 1940 Norsk Hydro generated almost 4 million tons of fertilizer from air, enough to produce 21 million tons of grain in Norway alone (Henriksen, 1994). Birkeland turned his attention back to his space and cosmic studies which he pursued until his death in 1917.

5 The Development of the Modern Plasma Torch

By 1940 Birkeland's furnaces were no longer needed for the production of fertilizer; the Birkeland–Eyde method having been replaced by the more efficient Haber–Bosch process (Storækre, 1980) . However, plasma torches were already finding new applications in the production of acetylene for the European market in Germany and the steel industry. The reason for multiplicity of applications relates directly to the heat generated by the plasma torch.

Since the accidental shorting–out of Birkeland's cannon, the basic design of the gun plasma torch has changed little. It consists of two electrodes: a hollow cylindrical cathode separated by a dielectric from a cylindrical anode nozzle. An inert gas, usually argon with an admixture of hydrogen, flows through the space between the electrodes, where it is ionized to form a plasma. Water circulates through passages in the anode and the cathode to prevent the fierce heat from melting them.

The gun begins operating when a pulse of current creates an arc (an electrically conducting channel in a gas) across the gap between the electrodes. A steady direct current then sustains the arc. As the arc forms, electrons are torn from the atoms of gas; the electrons and the positive ions they leave behind are accelerated toward the anode and the cathode respectively. These rapidly moving particles collide with other, neutral atoms or molecules in the gas, dissociating any molecules into their constituent atoms and ionizing the atoms. In this way the gas within the arc is transformed into a collection of ions and energetic electrons: a plasma.

The stream of gas that flows between the electrodes stretches the arc, so that in its course from one electrode to the other the arc loops out of the nozzle of the gun as a plasma flame. Most of the electric power consumed by the gun, typically from 20,000 kilowatts to twelve megawatts, initially flows into the free electrons in the plasma rather than into the positive ions. In tenuous plasmas, such as the glowing gas in a neon sign, collisions between the energetic electrons and the slow–moving positive ions are rare and little energy is transferred. The positive ions remain sluggish and the plasma, even though it is energetic, stays cool. The plasma of a plasma gun, however, is about 1,000 times denser than the low–pressure plasma in a neon tube. Frequent collisions transfer energy from the electrons to the positive ions, accelerating them until the plasma reaches a kind of equilibrium. The result is a thermal plasma, in which the energy of the electrons has been turned into enthalpy, or heat content.

A high enthalpy is associated with a high temperature; in a plasma gun the temperature can approach 15,000 degrees C. In addition to the enthalpy reflected in its high temperature, the plasma contains enthalpy associated with the ionization of the gas atoms and (a necessary first step for some gases) the dissociation of molecules into their constituent atoms. A plasma of hydrogen, whose molecules must be dissociated into their two atoms before they can be ionized, has a higher enthalpy at a given temperature than a plasma of argon, in which the atoms are independent to start with. Thus hydrogen added to the argon in a plasma gun increases the heat content of the flame, and hence the gun's power and its ability to melt refractory materials.

The high temperature of the plasma generates high pressure, which is supplemented by two effects related to the plasma's electrical conductivity. Near the water–cooled walls of the anode the plasma gives way to a sheath of cooler gas that is not ionized and so is not conductive. The nonconductive layer narrows the plasma channel by forcing toward the center of the orifice the electric field lines that loop through the plasma from electrode to electrode. This so–called thermal pinch effect is supplemented by a magnetic pinch. The electric field threading the jet of plasma is accompanied by a magnetic field, which encircles and constricts the jet. Together these pinch effects increase the pressure, temperature and velocity of the plasma. Depending on the geometry and power of the gun and the flow of gas, the plasma flame can reach supersonic speeds.

6 Plasma Heating

The plasma torch generates its heat in a tiny gaseous arc column of about 1 millimeter diameter or less. The arc column is surrounded by a continuous flow of cold gas which stabilizes the column. The plasma torch transfers its heat to the material being processed via all three modes of heat transfer: conduction, convection, and radiation. The radiative component of heat transfer alone approaches 40–45 percent. The total energy transfer to the material being processed may be in the range of 60–65 percent. The characteristics of the heat by a plasma torch can be tailored to match the requirements of the process. Unlike combustion heating that requires oxygen (or air, which is only part oxygen at 25 percent, and nitrogen at 75 percent), plasma heating can be effected with almost any gas medium. The plasma gas may be argon, helium, hydrogen, methane, nitrogen, etc., or mixtures of these gases. And if desired for chemistry or economic compatibility, air or oxygen may be the choice of plasma gas. But oxygen may be eliminated entirely as a plasma gas when a process demands an oxygen–free environment.

Plasma heat has certain unique and desirable characteristics:

- low mass,
- selectable atmosphere,
- high temperature,
- high heat flux, and is
- simple to operate and employ.

Plasma heat is desirable for use in industrial processes because its high temperature promotes rapid chemical reactions and melts any of the known metals and alloys and other inorganic materials. Today, plasma torch technology is emerging as a viable solution to many environmental problems. The manufacturing and the waste remediating sectors of industry are the obvious present and immediate future beneficiaries of the technology. Today, plasma heaters are employed in steelmaking, refractory metals recycling, ore reduction, powder metal production, composites manufacture, disposal of various solid and liquid waste streams, and recovery and recycling of valuable metals from manufacturing wastes.

7 Plasma Processing

Plasma processing is the art of promoting physical and chemical changes in materials by heating the material with a plasma arc torch. Plasma processing may be used to convert solid materials into liquids and gases, and liquid materials into gases. These physical changes are easy to promote, because of the unique heating characteristics of plasma heaters. Gases may be heated in plasma reactors and dissociated into basic molecules and atoms. Or they may be heated beyond their dissociation temperatures to ionize the atoms and create very reactive ions that promote rapid chemical changes in materials. [Heating materials by combustion heaters cannot dissociate and ionize atoms. The upper temperature limit of combustion heaters is about 2,000 degrees C.]

Plasma processing involves a furnace or reactor to contain the heating process. The electric flame of the plasma torch may be directed at the material being processed or the flame may be directed to a pool of molten material, to which the material being processed is introduced and heated indirectly. When heating gases or particulate materials, the gas or particulates may be introduced directly into the plasma flame (for example, when high temperature is desired), or the plasma flame may be used to heat an intermediate carrier gas, which in turn will heat the gas or particulates. The heat losses from plasma processing includes the heat lost to the cooling water of the plasma torch, heat transferred to effluent gases, and the heat absorbed by the insulating refractories of the furnace or reactor. These losses are approximately: 8–15 percent, 10–29 percent, and 5–10 percent respectively. These losses may be reduced by designing the furnace or reactor to accommodate specifically the use of plasma heating.

Plasma processing has made it possible to create new materials: new metals, new ceramics, composites of different metals, composites of different ceramics, and composites of metals and ceramics. Plasma processing has made it possible to heat and destroy the physical and chemical structure of liquids and gases, a unique heating capability that is exploited in the destruction of harmful and toxic materials. The promise of plasma processing includes the creation of new materials and the safe, final destruction of harmful and toxic materials. Useful materials may be recovered and recycled from the destruction–by–plasma process.

The reasons for which plasma torches have become popular as heaters in processing applications include cost advantages over inefficient fuel–powered combustion heaters, reliability, off–the–shelf availability, and demonstrated productivity.

Plasma heating is almost massless heating, meaning that the plasma heater can deliver heat with very little gas. Combustion heating, on the other hand, requires about a 20 multiple in weight of air to efficiently combust the energy in fossil fuel. The great reduction in weight of material to heat means that higher temperatures are achievable by plasma heaters. And since energy can be delivered by the plasma torch with very little gas, the energy density of the gas is higher. High energy density means high rates of energy transfer to the material being heated. These are the unique heating characteristics of plasma heaters that are attractive to process engineers.

7.1 Characteristics of Modern Plasma Torch Heating Systems

Currently, plasma heating systems are available at power level ranging in size from 100 kilowatts to 8 megawatts. [A trend has been established, however, that indicates the immediate future demand for larger plasma torches of 10 to 20 megawatts.] Today's plasma torches feature water–cooled metallic electrodes and tangential gas injectors. The electrodes and gas injectors are insulated from each other by high–temperature ceramic materials.

The plasma medium in torches have the following characteristics: an arc column of a millimeter or less in diameter conducts electric current of 100 to 10,000 amperes; the arc column length ranges from several centimeters to a meter or more, resulting in arc voltages of 60 to 2,000 volts. The arc column is stabilized by the flow of cold gas. The range of gas flow rate is 5 cubic meters per second to 500 cubic meters per second.

8 Industrial Applications of the Plasma Torch World–Wide

The largest plasma processing facility is located at Marl, in northern Germany. This has 50 non–transferred plasma torches consuming approximately 300 megawatts. The plasma torches heat natural gas round–the clock and produce acetylene for the European market.

The first two commercial plants in Sweden to employ high–power (multi–megawatt) plasma torches developed by the SKF Steel in Hofors were ScanDust at Landskrona and SwedeChrome in Malmö. The plasma facility at Landskrona treats approximately 60,000 tons per year of electric arc furnace (EAF) dust. The facility employs four plasma torches of the non–transferred type. It can treat EAF dust from stainless steel furnaces or from regular carbon steel furnaces. The plant recovers chromium, nickel, manganese, and iron from the stainless dust; primarily iron from the other dust. This plant was the first to demonstrate the inert rendering of industrial toxic waste by plasma heating.

The plant in Malmö processes chromite ore and produces chrome metal for use in making stainless steel. The plant has two furnaces, each heated by four plasma torches. In 1988 ScanArc Plasma Technologies, Hofors, Sweden was founded to carry on SKF's development and implementation of non–transferred DC plasma torches in industrial applications. ScanArc has developed torches rated as high as 8 megawatts which it is applying to processes as diverse as the production of high carbon ferrochromium, dust and ash vitrification, reduction of lumpy ores to prime feed products, smelting, zinc metal production, production of clean fuel gas from coal, solid waste processing, and the liquification of scrap steel (Thörnblom, 1995).

The largest plasma facility for making titanium dioxide pigments from titanium tetra–chloride is located in the United Kingdom. Plasma heaters heat pure oxygen that is reacted with chlorinated titanium feed to produce titanium dioxide. The plasma heating approach makes it possible to recover and recycle the chlorine.

France has three industrial plasma facilities. A Plant in northern France produces ferro–manganese using eight 2 megawatt plasma torches from Aerospatiale. The same plasma torches are used in two plasma–fired cupola furnaces, one at Peugeot's plant in central France to produce special iron for the automotive industry and for the same application at another location. France is conducting tests to evaluate the technical and economic feasibility of disposing of medical wastes by plasma. And in Italy plasma heaters are used to prototype a new process for recovering zinc metal from wastes generated in zinc galvanizing plants.

Canada has a very attractive rate for electricity consumption because of the availability of hydro–electric power. The Aluminum Company of Canada (ALCAN) commissioned last year a plasma–heated process for recovering aluminum metal from aluminum dross. Hydro Quebec operates a one–megawatt portable torch, consisting of three trailer units, for a multiplicity of applications where high temperatures can be transported to site (Figure 7).

In the United States, plasma arc torches first received serious attention from American industry after being used successfully by NASA to duplicate temperatures that space vehicles would encounter on reentry into the atmosphere (i.e., 7,000–9,000 C) (Camacho, 1991). Since then, the plasma torch has been put to use in industrial applications. For example, an aluminum waste–to–metal process, similar to ALCAN, has started operation in West Virginia. In Defiance, Ohio, plasma heaters are used in a plasma–fired cupola. This cupola produces a special grade of iron for the manufacture of automotive engine blocks. The production rate of the cupola is more than 40 tons of iron per hour. The Plant can accept machine shop waste metals, including oily chips and borings. Plasma heaters are also employed in the U.S. to heat liquid metal in ladles and tundishes. This process is being practiced in Holsapple, Pennsylvania, and in Midlothian, Texas. The plasma torch maintains the heat of the liquid metal in the ladle or tundish for vertical and horizontal continuous casters.

In Alabama, plasma heaters are used to process used automobile catalysts to recover platinum group metals. Automobile catalytic converters are made of alumina and platinum catalysts. Both are high melting temperature

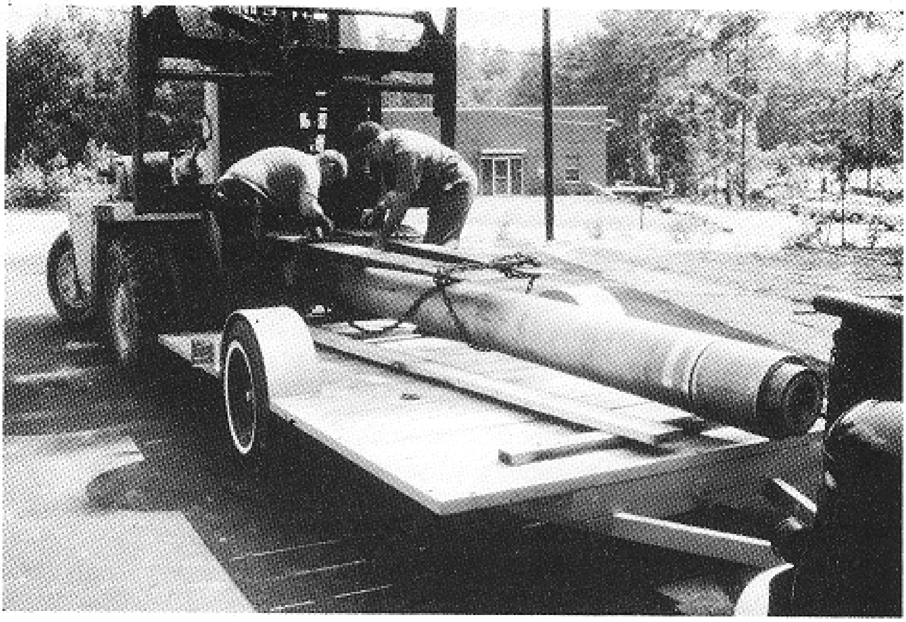

Fig. 7. Portable one-megawatt transportable torch. Not shown are three trailer units for power supply and torch control. (Courtesy of S. Camacho, Plasma Technology Corportion, Raleigh, North Carolina).

materials. The plasma torch melts the alumina and isolates the platinum. In Nevada, Oregon, and Massachusetts, plasma heaters are used to heat, melt, and consolidate titanium scraps. [The conventional technology for titanium scrap consolidation is electron beam. Operating at very low pressures, the electron beam process vaporizes alloying elements such as aluminum and vanadium.] The plasma melting and consolidation process is operated at near atmospheric pressure. At this pressure, the titanium ingots that are formed by plasma melting are cleaner, and the alloying elements are not vaporized during melting and consolidation.

Japan is using plasma heaters to heat molten metals in ladles and tundishes. Japan is prototyping various types of plasma–heated processes, e.g., arc–furnace dust treatment, fly–ash vitrification, large ladle and tundish heating, platinum group metal recovery from automobile catalysts, nuclear waste disposal, liquid waste disposal, titanium metal recovery, and zinc recovery.

Australia and South Africa have plasma–heated furnaces for chrome production, iron production, and manganese production.

Switzerland is commissioning a plant for the disposal of liquid drummed wastes by plasma heating.

The Academy of Sciences in Russia is prototyping plasma processes for chemical synthesis, hazardous waste disposal, surface treatment of metals, plasma deposition, manufacture of composites, volume reduction of trans–uranic, low–level nuclear wastes, and reforming gases into desired compounds. The Kurchatov Institute is investigating the use of plasma torches for the "sarcophagus" transformation of disaster sites such as Chernobyl.

9 Plasma–Spraying of Materials

An entirely new application for the gun plasma torch, plasma–sprayed coating, was accidently discovered when powdered material was fed into the the torch flame (Herman, 1988).

Today, plasma–sprayed metallic coatings protect aircraft turbine blades from highly corrosive environments, and plasma–sprayed ceramics insulate other engine parts from high temperatures. Plasma–sprayed coatings are also found in internal–combustion engines, in power plants, in industrial machinery and in many other areas where technology places extreme demands on materials.

Plasma spraying can melt and apply a variety of materials, including refractory ceramics, at a high rate (in some cases more than 25 kilograms per hour). The technique also carries much less risk of degrading the coating and substrate than many other high–temperature processes do, because the gas in the plasma flame is chemically inert and the target can be kept fairly cool. Integrating plasma torches with computer–aided–design models has led to the rapid prototyping of millimeter dimensioned parts.

9.1 Plasma–Sprayed Coatings

When a powdered coating material is injected into the plasma flame, either within the nozzle or as it emerges from the outer face of the anode, the particles are accelerated and melted by the flame's high temperature, supplemented by heat given off as ions recombine and molecules reassociate on the surface of the particles. The molten droplets are propelled onto the target surface, where they solidify and accumulate to form a thick, tenaciously bonded protective coating.

For the process to succeed, however, a number of sensitively balanced criteria must be satisfied. The particles must take enough heat from the hottest part of the flame, near the anode face, to melt thoroughly, but not so much that they overheat and vaporize. At the same time the droplets cannot dwell and stagnate in the flame; they must be traveling fast enough to flatten and spread out when they strike the target, flowing into crevices and tightly gripping the surface.

A broad array of variables affect particle heating and acceleration. The heat content and velocity of the plasma flame play a critical role; they reflect such characteristics of the gun as its geometry and power level together with the composition and flow rate of the plasma gas. How effectively a given flame melts and accelerates the powder in turn depends on the kind of coating material and the size and shape of the particles. Although not much different from paint spraying, the factors of importance in spraying metals or ceramics include particle size, particle feed rates and angle of injection, and distance of the gun from the target.

The result of this process, repeated many millions of times, is a layer of material that can range in thickness from 10 micrometers to many centimeters, a deposit thick enough to be removed from the substrate and employed as a bulk material. Ordinarily, however, the substrate has been roughened and the coating is firmly anchored to it by mechanical bonding. Other processes that are less well understood can also anchor plasma–sprayed coatings. Some coatings form chemical bonds with their substrates, and metallic coatings can establish a bond as the heat of plasma spraying (the workpiece can reach 200 degrees C unless it is cooled with jets of air) enables atoms of the coating and the substrate to interdiffuse.

9.2 Rapid Prototyping

Rapid protyping is the merging of computer–aided–design models, controllers, lasers, and the gun plasma torch to rapidly fabricate millimeter–dimensioned parts.

The process starts by generating a three–dimensional computer model of the part that is to be manufactured. The model is computationally sliced into two–dimensional layers and each layer forms a pattern that is fed to a computer chip that controls the amount of material that the plasma torch deposits on a substrate. Each new layer is deposited on top of the of the previous layer so that the part grows incrementally from bottom to top (Nickel, 1995).

Fabrication via rapid prototyping employs six production stations:

- A five–axis milling machine to shape the layer and produce sharp edges.

- A low temperature robotic station for the deposition of polymers.

- A high temperature plasma torch robotic station for metallic deposits. The torch may be held horizontally or vertically with respect to the workpiece. If the polarity of the torch is reversed, the substrate may be etched or cleaned. Typical etch times are of the order of 20–50 microseconds.

- A laser deposition station consisting of kilowatt power level Nd:Yag CW laser to inertially force support materials onto the workpiece.

- A shot peener to induce local compressive stresses to compensate the thermal strain induced tensile stresses in the workpiece.

- A cleaning station.

PCB's, hospital waste, plastics, yard wastes, food wastes, tire, panty hose, coal, and wood wastes, are mainly composed or organic compounds. There are more organics known to exist than all other compound combined. Most of these compounds are combinations of carbon with a handful of elements. The most common elements are hydrogen, oxygen, nitrogen, sulfur, phosphorus, and the halogens. Hydrocarbons are made solely from carbon and hydrogen.

At 7,000 C, the plasma torch dissociates these materials into just two products:

- The inorganic melt that becomes a glassy, vitrified rock similar to volcanic obsidian.
- The organic molecules that dissociates into atoms and diatoms (atomic and diatomic structures, approximately 80 percent by volume of hydrogen and carbon monoxide gases, known as "raw" synthesis gas. When scrubbed to leave only hydrogen and carbon monoxide, it is called "pure" synthesis gas.

The synthesis gas is very similar to natural gas. It can be burned, as is natural gas, in a boiler to produce steam to generate electricity or, since it consists of almost two parts of hydrogen to one part of carbon monoxide, it is in ideal proportion to convert to liquid methanol alcohol, using a catalyst and the proper pressure.

10.1 Municipal Solid Waste

Municipal Solid Waste (MSW) is composed primarily of organic materials: table waste, yard waste, wood, paper, cardboard, plastics, and tires. This organic portion consists primarily of combinations of hydrogen, carbon, and oxygen atoms organized and arranged as different molecules. As outlined above, the heat from the plasma torch can dissociate the atoms from each other which can then be reassembled, using catalysts, into completely different products such as methanol, ethanol, and acetic acid. This permits almost 100 percent recycling.[10]

At the same time that organic materials are dissociating, the inorganic materials such as rock, metals, dirt, and other chemicals melt into a glassy slag that can either be poured into molds to produce park benches, fountains, or else tapped to water to produce aggregate for roadways or concrete.

A significant advantage in the large volume reduction effected in the process: the 2 cubic meter volume of one ton of mixed waste becomes 0.03 cubic

[10] Methanol alcohol is produced by converting natural gas CH_4 plus steam, into synthesis gas, a mixture of carbon monoxide and hydrogen gases, $2H_2 = C0$ and reformulating this synthesis gas into methanol alcohol, CH_3OH. Liquid methanol has been produced for thirty years by Lurgi GMBH and, using Lurgi's method, Dupont Chemical produces 810,000 tons of liquid methanol per year in one plant.

TABLE I

Concentration levels in milligrams per liter (mg/l) based on three data sets.

	Data Sets[1] (upper limits)			EPA
	Detroit Edison	Ebara Japan	Silas–Mason	Permissible
Arsenic	0.1	0.01	0.0	5.0
Cadmium	0.02	0.01	0.8	1.0
Lead	0.2	0.5	0.0	5.0
Silver	0.5	–	0.4	5.0
Barium	0.5	–	0.7	100.0
Chromium	0.2	0.2	0.0	5.0
Mercury	0.01	0.001	0.0	0.2
Selenium	0.1	–	0.0	1.0

[1] EP toxicity tests, USEPA procedures and standards.

meter of glassy slag that weighs only 200 kilograms. The 800 kilograms of volatile organics and fixed carbon contents of MSW are converted by plasma pyrolysis into approximately 900 cubic meters of fuel–laden H_2–CO gas mix containing 10^{10} joules of heating value.

The vitrified solid, representing 20 percent of the original MSW weight, is inert and can be returned to the ground. This solid by–product has been analyzed and shown to meet or exceed EPA standards for toxicity leachability (Table I). It may be safely used as construction aggregate or dumped in landfills.

In high–population–density countries, plasma torch refractories for the processing of MSW are already economically feasible. A typical multi–module 12 megawatt MSW plasma torch processing plant may process 1500 tons of waste per day or 495,000 tons per year. Tipping fees, the amount a dump truck pays to unload its waste, generally amount to 45 USD in the eastern United States. Slag sales produce 6 USD per ton at twenty percent of the waste weight. Liquid methanol, amounting to 200 liters per ton of weight, commands a floor price between 0.25 and 0.42 USD per liter.

These revenues must be balanced against the cost of operating a MSW plant. For example, to vitrify the amount of material above, some 600,000 megawatts of power are needed, typically costing 0.034 USD per kilowatt. A figure of merit for the ratio of the production costs to sales income of liquid methanol is 1/20 to 1/24.

10.2 Medical Waste

In the United States, over 12 million kilograms of medial wastes are generated daily by the more than 7,000 hospitals, clinics, medical offices, and research facilities. An estimated 2 million kilograms of the daily wastes are considered infectious and require special handling and disposal procedures. The volume of infectious waste generated on a daily basis is expected to increase at a rate of 3 percent or more through the rest of this decade. The increase is attributed to the growing use of disposables as precautions against exposure to infection diseases such as AIDS. The national average cost of infectious waste disposal was 0.77 USD per kilogram in 1990 and is projected to increase at a rate of ten percent or more through the year 2000.

Currently, approximately eighty percent of the medical wastes are disposed of in on–site incinerators or else are transported to multi–client off–site incinerators. Incineration is not a final disposal method since the residue ash must be buried or otherwise disposed of. Under new regulatory procedures implemented by the United States Environmental Protection Agency, less than twenty percent of medical wastes in the U.S. will be eligible for incineration by the year 2000.

The economics of operating plasma torch refractories for the vitrification of medical waste, or for asbestos containing material wastes, is the same as the MSW plant described above.

11 Vitrification of Radioactive Waste

A problem arousing international concern is the long–term storage and disposal of radioactive wastes. The hazards of radioactive wastes can last for thousands of years. Solving this problem is particularly important because of the dangers of improper storage, both for present and future generations. Therefore, it is necessary that radioactive materials be stored in a compact and stable form.

Plasma torch heating provides a solution for radioactive material storage. For example, radioactive thorium nitrate crystals currently stored by the U.S. Department of Defense can be reduced significantly in volume and transformed into a glassy mass that can be safely confined and placed in long–term storage. While the glassy slag produced by the torch from radioactive feedstock remains radioactive, it has been transformed into a substance that is roughly five times less leachable than bottle glass. The DC plasma torch is only one of several methods currently under investigation to vitrify mixed waste.[11] However, the major attribute of plasma torches are extreme temperatures not approachable by other methods.

One of the most vexing problems for developed nations today is finding

[11] Another method developed by Pacific Northwest Laboratories, Geosafe, involves inserting electrodes into the ground and using three–phase electrical power to heat the contaminated soil. The arc is initiated by placing conductive material called "frits" in trenches between the electrodes. In this way, an underground "furnace" is produced that can melt the soil for several meters below the surface.

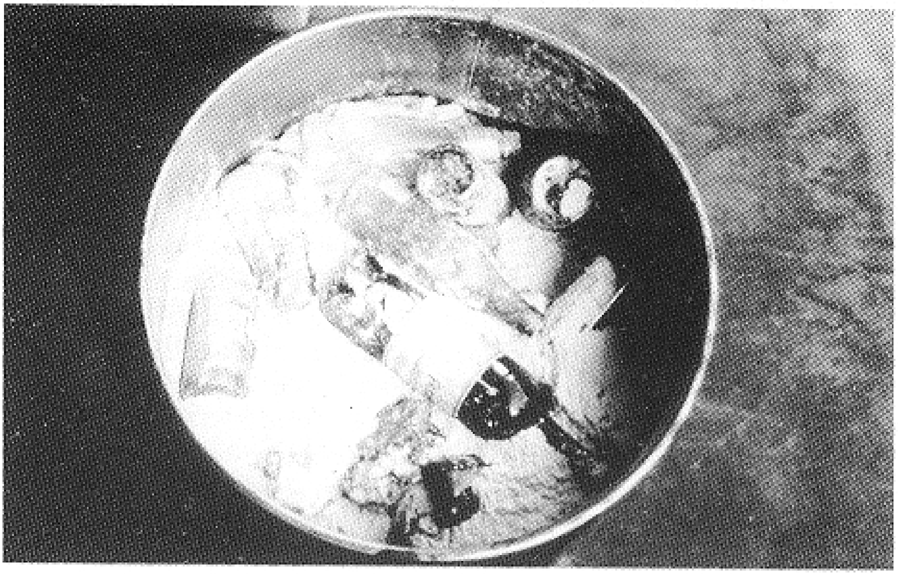

Fig. 8. Drum of heterogeneous debris prepared for the PHP. Photo courtesy of SAIC.

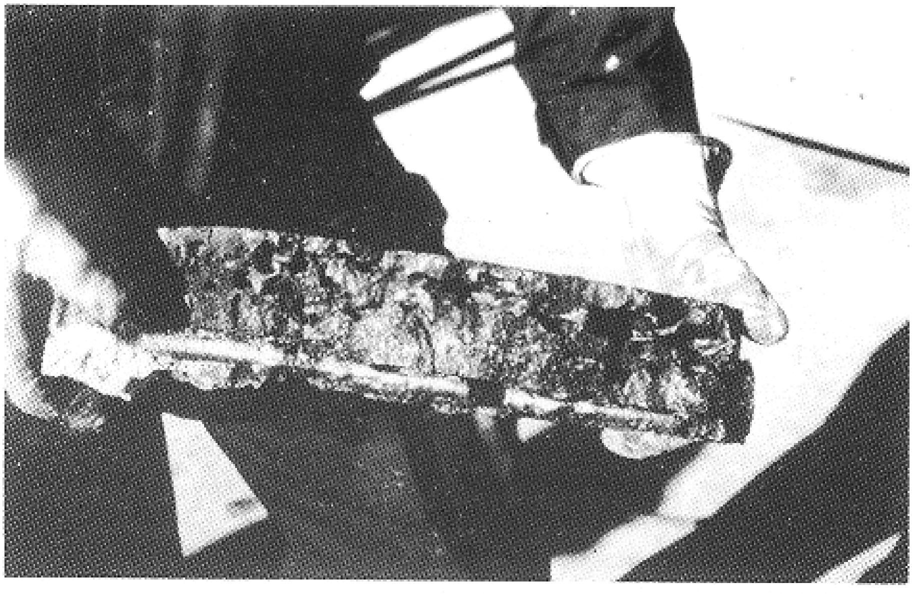

Fig. 9. Hardened slag and metal tapped from the refractory. Note that the slag has pulled away from the metal phase below it. Photo courtesy of SAIC.

With the successful "proof of principle " demonstration of the vitrification of radioactive surrogate material, the next phase of the project is to verify the vitrification of actual low–level radioactive waste. The goal of this project is to place in operation a full–scale system capable of handling one or two 55 gallon (208 liter) drums of mixed waste per hour. The system will employ a 1.2 megawatt DC transferred torch.

11.2 Pocatello, Idaho Demonstration

Another mixed–waste project that also employs a megawatt power DC plasma torch is currently being demonstrated by Lockheed Environmental Science and Technology (LESAT) on Pit 9, a field of mixed waste buried some 2 or 3 meters deep at Pocatello, Idaho. The concept is to straddle the field with tractor/trailer rail tracks upon which a grinder/digger will excavate the mixed waste, separate waste types, and convey the radioactive components to an enclosed plasma torch/refractory unit. After melt, the crucible–hardened glassy slag will be returned to the pit for reburial in non–leachable form along with other chemically cleaned products. The goal of this project is "proof of principle" cleanup demonstration applicable to mixed wastes at all DOE storage sites.

11.3 In–Situ Vitrification of Mixed Contaminated Soils

Low–level radioactive waste accounts for less than 5 percent of the radioactivity, but for more than 98 percent of the volume, of all radioactive wastes from military, government, and industrial sources combined. Currently, Pacific Northwest Laboratories, the Georgia Institute of Technology, Oak Ridge National Laboratory, and the Plasma Technology Corporation of Raleigh, North Carolina are working on a novel disposal process for reducing the volume and vitrifying the radioactive contaminated materials in low–level subsurface waste deposits.

The concept of using plasma arc torches for the vitrification of contaminated sites (mixed waste, buried waste, and landfills) is a promising alternative to several baseline technologies.

The process, called Plasma Remediation of In–Situ Materials (PRISM), stabilizes wastes on–site through melting and subsequent solidification. The process uses a plasma torch placed in a bore hole at a target depth. The arc discharge is struck and as the soil heats and the melt grows, the torch is raised within the borehole so that a cylindrical melt of constant diameter forms from the bottom up. Large sites may be treated by forming contiguous melts, generated at the rate of 10–20 tons per hour.

When the vitrified hole is filled with pyrolyzed and vitrified radioactive wastes, it is capped with clean, non–radioactive soil. The attributes of this technology are that the radioactive waste is vitrified and reduced significantly in volume.

12 Advances in Torch Development

As mentioned, the non–transferred DC gun–type plasma torch differs, in principle, little from the first torch accidentally discovered by Birkeland (and his surprised guests) when his electromagnetic cannon shorted out. However, since that time, significant progress has been made in gun configurations, power capacities, electrode designs, gas injectors, and torch controls for purposes of flame control and stability.

Most torches today are controlled digitally by computer systems. For example, for plasma coatings, the fine degree of flame and feed stock control is handled by automated systems that can intricately manipulate the gun and the workpiece in order to coat complex shapes such as turbine blades. Another development is a gun that has a movable cathode, which makes it possible to adjust the power of the gun by varying the characteristics of the arc instead of by adding a secondary plasma gas. Manufacturers have also introduced mechanisms that feed several different powders into a gun and can gradually substitute one powder for another as the spraying proceeds in order to produce a coating whose composition and properties change across its thickness.

The first significant departure from Birkeland's classic DC gun design is the appearance of radio frequency or induction plasma torches. An induction plasma heater generates its heat by inducing a radio frequency arc discharge in a gas medium. The inductor is often a coil of wire around a glass tube. The arc discharge is established within the glass tube. These RF plasmas do away with electrodes and the possibility of contaminating the coating with material eroded from them (Tuszewski, 1994).

Today, DC plasma torches rated at tens of megawatts are becoming available for specialized applications, especially in the steel industry and in waste treatment. The reverse polarity torch, where the rear electrode is the anode (biased exactly opposite to that Birkeland's torch) produces flame temperatures a few thousand degrees hotter than the classic DC torches.

12.1 Diagnostics

Improved diagnostics, both for torch operation and refractory by–product classification is playing a major role in torch advancement. The Diagnostic Instrumentation and Analysis Laboratory (DIAL) at Mississippi State University, operating with the support of the ALIAS Group[14] and the U.S. Department of Energy, specializing in characterizing the gaseous, aqueous, and material effluent from plasma torch vitrification of solid waste.

These diagnostics include:

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[14] ALIAS Group, Inc., Alexandria, Virginia, is primarily a consulting and research and development enterprise focusing on waste treatment, and signal processing of diagnostics data related to waste off–gas analysis.

magnetohydrodynamic (MHD) codes which average the particle velocities into fluids.

One MHD approach incorporates a non–steady, two–dimensional, composite fluid approach and includes the effects of ohmic heating, finite rate chemistry, thermal conduction, viscosity, and Bremsstrahlung radiation to study the performance of an arcjet in a gun–type plasma torch used for earth–satellite thruster applications (Butler, Kashiwa, and King, 1990). The code, employing both Lagrangian and Eulerian gridding, follows the motion of a propellant gas injected with a strong swirl component of velocity into the arcjet plenum.

The salient features of the simulation are that at some point in the downstream divergent section, the plasma reaches sonic conditions and undergoes a supersonic expansion to ambient space. A DC current passes directly through the propellant between the cathode and the anode nozzle body. The simulation shows that while the arc core is composed principally of ions and electrons, the surrounding gas region contains products of dissociation, ionic recombination, and electronic excitation. The temperatures in the low density core are of the order of 20,000 C, while the bulk or mass averaged temperature ranges from 1,000 to 5,000 C. The arc is stabilized as it passes through the constrictor by both energy (radiation and conduction) and mass transfer (diffusion and convection) to and from the surround gas.

Many of the instabilities observed in the torch flame or z–pinch, are three dimension in nature and await the development of three–dimensional MHD codes. In the meantime, fully three–dimensional particle–in–cell (PIC) codes have been developed to study both the basic MHD instabilities and kinetic effects such as filamentation (Peratt, 1992). Advances in modeling the highly collisional aspects of dense plasmas similar to those found in the plasma torch arc discharge via PIC simulation have been made (Jones *et. al.*, 1995).

13 Conclusions

One may be struck, when reading *The Norwegian Aurora Polaris Expedition 1902–1903* of the frequent switches, paragraph by paragraph, of topics of discharge technology, geophysical phenomena, and cosmic issues. While it appears that Birkeland never returned to research the DC plasma torch,[15] and in fact employed AC furnaces in the Birkeland–Eyde production of nitrogen fertilizer, his dramatic witnessing of the first non–transferred plasma flame is recognizable throughout his book and his view of the universe that, like the flame, consists not of just solar systems or nebulae but of "electrons

[15] Hannes Alfvén was the sole person to carry on Birkeland's auroral research and follow up on the plasma torch discovery. Alfvén's group at the Royal Institute of Technology, Stockholm, developed plasma guns and studied the mechanisms by which the flame, or z–pinch, could be stabilized (Alfvén and Smårs, 1960; Falthämmar, 1961).

and flying electric ions of all kinds" and "electric forces of a strength no one could imagine."

Because of this, Birkeland's geophysical and astronomical theories went very nearly unnoticed. The prevailing astronomical schools could not imagine an energetic universe filled with "electric corpuscles" (plasma) and of electric and magnetic fields, but instead favored a mechanical, clockwork–cosmos in serene, ignorable vacuum in accordance with tradition and in synchronization with the motions of the planets seen through optical telescopes. Birkeland's theories for the Northern Lights and his electromagnetic world–view, that in its modern form has come to be called *the plasma universe* would have to wait acknowledgment for 57 and 77 years after his death, respectively.

Hannes Alfvén often emphasized the "lasting value" of an idea or concept and pointed to Birkeland's auroral theory and its decades long delay before acceptance by the scientific community as a prime example. The measure of Birkeland's accidental discovery is amply demonstrated by the founding of an industrial monolith, Norsk Hydro[16], an entirely new field of science which may be called *experimental astrophysics*, and the first gun plasma torch, the only device known that can produce temperatures equaling those found on the sun, whose legacy may ultimately be the solution of mankind's radioactive waste problem.

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[16] Norsk Hydro is the world's largest manufacturer of magnesium castings and responsible for the operation of the Norwegian shelf North Sea oil reserves.

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