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Project title "Plasma-Based Coal Gasification Technology"

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Lead Organization: International Plasma Technology Center

International Plasma Technology Center, Corp. (IPTC) proposes a project - entitled Plasma-Based Coal Gasification Technology - to model, develop, build and test a small scale prototype of a coal gasification module based on a recently developed and patented new generation of high power plasma torches with virtually unlimited lifetime. The objective is to produce, depending on the operational mode, either (1) high temperature products of a plasma assisted clean coal combustion process for coal-boiler start up and continuous flame stabilization with significant efficiency increase, elimination of the need for any supplemental fuel, and dramatic emissions reduction (NO_x reduction by a factor of 2 to 3), or (2) high hydrogen-yield syngas ($CO + H_2$), which could be used for power and heat generation, as well as an intermediate product to feed an indirect liquefaction technology, followed by the well-known and well-developed Fisher-Tropsch process for synthetic liquid fuel production. In the case of a redox-cycle catalyst application, pure hydrogen could be produced (without CO or CO_2 products – a CO_x-free option) for further super-high efficiency power generation based on a combined Fuel Cell + Gas Turbine + Steam Turbine cycle as shown in Fig.1. Additionally, under a CO_2 sequestration option,

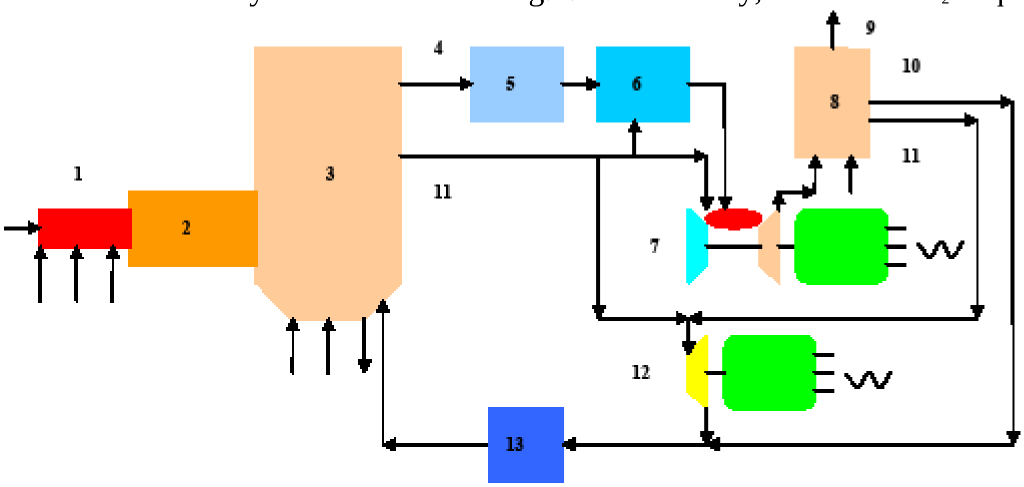


Fig.1. Scheme of the prospective co-generation power plant based on complete plasma coal gasification: 1 – plasma torch; 2 - plasma muffle; 3 – modified boiler- last stage gasifier; 4 – synthesis gas; 5 – gas clean up and compression module; 6 – optional catalyst; 7 – STIG cycle gas turbine gen set; 8 – heat recovery boiler with contact type heat exchanger; 9 – exhaust gases 65ºC; 10 – water; 11 – steam; 12 – steam turbine gen set; 13 - condenser.

captured CO_2 could be used as a feed gas for plasma generation, coal powder transport, and gasification for pure hydrogen production.

Our proposed research and development plan has the following unique and innovative features:

- Employment of a recently-developed and patented, new generation of high power plasma torches with virtually unlimited lifetime (due to electrodeless design) and high efficiency (due to the application of solid state power supplies, and reverse vortex plasma stabilization). Total plasma generation efficiency (ratio of plasma power to that consumed by the electrical power supply) is over 70% and in the case of steam coal gasification, it can reach ~ 90%;
- Plasma coal gasification provides significant advantages in comparison to the state-of-art approach of high temperature (over 4,000°C) processing, as well as high reactivity

(dramatic reduction of the activation energy in comparison with fossil fuel flames) which leads to simple and reliable process initiation (decreased ignition delay time), dramatic reduction of processing time, and corresponding decreases in volume and weight of the gasifier, and the possibility to use steam and oxygen as oxidants;

- Presently-developed plasma torches can be scaled up from an achieved 300 kW power level to 10 MW per unit and use a variety of plasma-sustaining gases, including air, oxygen, CO, CO_2, water-steam, and blends;
- Syngas production with volumetric hydrogen yield of 54-60%, depending on feedstock composition and oxidant; or hydrogen production and power generation;
- The process is amenable to multi-feedstock operation, including in-situ materials such as scrap tires, used motor oils, petro-coke, biomass, municipal solid waste (MSW), etc.;
- Mobile design for remote-site power and heat supply;
- Possible combination with a variety of power generation units, such as boilers, gas turbines, and IC engines.

Identification and Significance of the Problem or Opportunity, and Technical Approach

Since the 1950s, plasma-related processing has been a promising tool to enable and speed up numerous processes and technologies, but with the major disadvantages of existing high-power devices, such as limited lifetime because of electrode erosion or melting. This problem was successfully solved by IPTC, which recently introduced to the market its 50-150-300 kW hybrid plasma torches, with the main focus on coal and waste gasification, electronic grade silicon production, materials modification, nano-powder production, and related applications.

Precise analyses of coal gasification technologies and preliminary modeling of plasma-based coal gasifiers [1-3, 6] have lead to ideas for pilot plant development, a schematic of which is shown in Fig.2. This concept was discussed during a Coal Gasification Meeting and Open Discussion within the 5th International Workshop and Exhibition on Plasma Assisted Combustion, which was held 15-18 September, 2009 in Alexandria, VA, and initially at the Applied Plasma Technologies -Turkish Coal Enterprises meeting on 18-19 June, 2009 in Ankara. Going forward on this program plan was supported by over 30 world-leading scientists in the field of plasma assisted combustion and was suggested for funding, implementation, and experimental operation to potential customers, initially in the USA, India, and Turkey.

A suggested pilot plant will be based on a 50-100 kW hybrid plasma torch (10) with optional plasma gases - such as air, oxygen, and water-steam - and a downstream gasification chamber (13). Feeding of coal will be provided in the form of a variable- composition coal slurry and coal dust (air/coal mixture). Conditioned syngas is produced after cooling in a heat exchanger (15), and also by means of a double-stage ash separation process in a cyclone filter (19) with further compression in a compressor 22 [4].

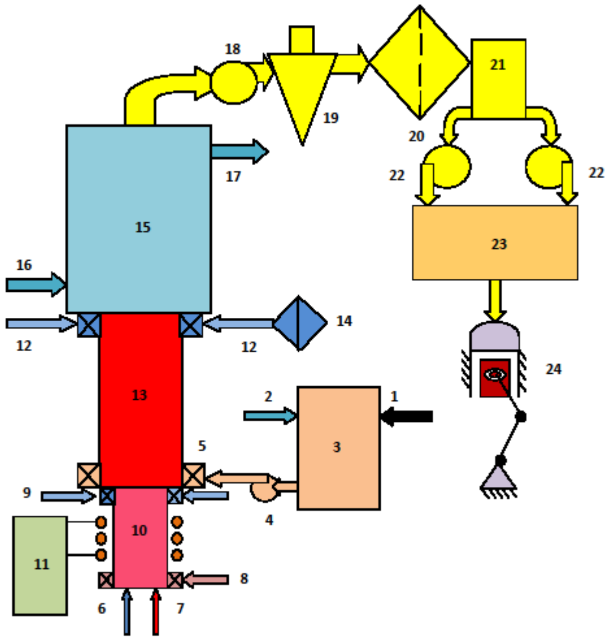


Fig.2. Coal gasification pilot plant: 1 – coal dust; 2 - water; 3 – slurry tank; 4 – slurry pump; 5 – slurry feeder; 6 – plasma torch cooling water input; 7 – igniter; 8 – start up gas; 9 – plasma gas (air or oxygen); 10 – plasma torch; 11 – plasma torch power supply; 12 – oxidant (O2); 13 – triple vortex gasification chamber; 14 – oxygen separation unit; 15 - synthesis gas cooler – water/steam boiler; 16 – water input; 17 – hot water or steam output; 18 – fan; 19 – cyclone filter; 20 – fine particle filter; 21 – syngas control and distribution unit; 22 – synthesis gas compressors; 23 – syngas storage tank; 24 – power generation unit , optionally IC engine, turbine or boiler.

For high power applications, like industrial scale coal gasification plants, the gasifier could consist of several horizontally oriented pre-gasification modules based on 100-1,000 kW plasma torches and two to three stage downstream reactors all connected to the vertical final stage as shown in Fig.3. Such a scheme allows power flexibility by simple variation of the number of modules (like cylinders in an IC engine and combustor cans in a gas turbine); cost reduction by application of well-developed standard modules; significant footprint reduction by using vertical final stages; possible application of existing boilers for the final stage, which could combine several functions such as (i) coal, steam, and oxygen feeding, (ii) steam generation, and (iii) ash removal; total gasification process residence time increase, which might reach 1-1.5 seconds depending on many factors; could be an option for existing coal fired power station retrofits to transform them from a low efficient steam cycle to a much more efficient combined cycle (gas turbine + steam heat recovery) or gas turbine + fuel cell.

As the first stage on the three year way to such a plant development, we envision a time scale of 24 months for the investigation and development of key elements according to the scheme in Fig.4, which demonstrates a new vision of a known muffle approach. Such a new muffle or plasma based pre-gasifier with relatively low plasma power gradually increases the initial plasma power of 100-300 kW to 1-5 MW of thermal power on the output of the pre-gasifier due to power release of burned and partially gasified coal at stages 2 and 3 for further complete coal gasification within stage 4. Due to the plasma properties at temperatures over 4,000C and its influence on solid fuel ignition [3,5,6] the plasma significantly decreases the ignition power threshold – by a factor of 10, in comparison to a conventional oil or gas flame. Moreover, the coal particles experience a thermal shock at the thermal plasma plume, which dramatically reduces the ignition time delay. In contrast, non-thermal plasma devices cannot provide effective processing of solid state matter but can suffice for gas-phase matter. This is a key reason for choosing a ‘hot’ or thermal-plasma torch.

So, according to [6], for a one-stage plasma coal gasification system with steam as an oxidant, we can expect 94-96% coal conversion into syngas within 0.3-0.4 seconds with power consumption of 1.5-2.0 kWh per kg of coal. Our suggestions for further investigations and development point to staged plasma gasification, which promises 95-99% conversion, 1 to 1.6 seconds residence time, and power consumption of 0.03-0.05 kWh per kg of coal.

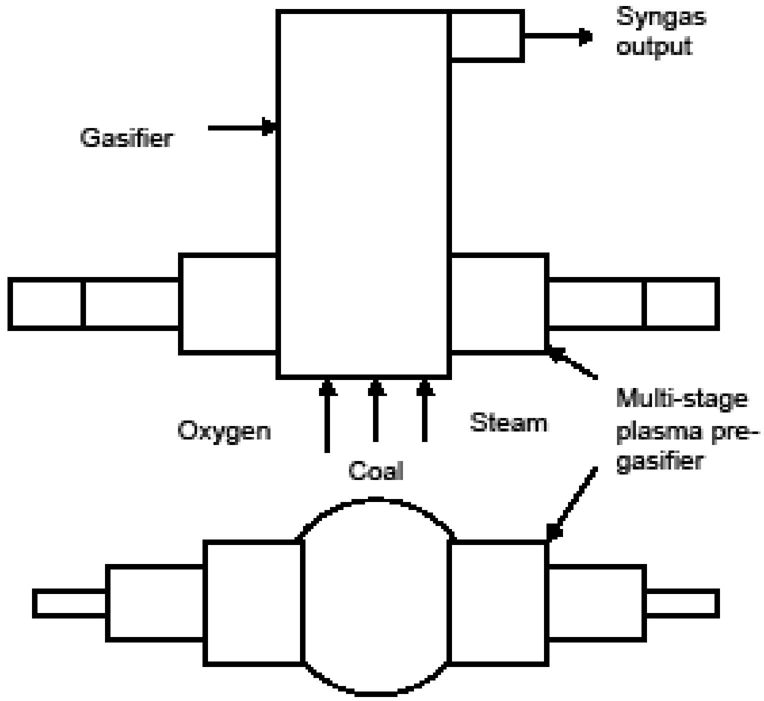


Fig.3. General scheme of a gasifier with a variable number of plasma pre-gasification units for total thermal power 5-40 MW.

Example: We have suggested a baseline design concept for a South African 200 MW coal power plant gasifier, which has flexible design and a variable number of plasma based pre-gasification units, for example from 1 to 6. Each pre-gasifier also could have variable capacity depending on the plasma torch power – from 30 kW to 300, 500, or 1,000 kW. This allows significant thermal power variations at the output. A basic gasification process with oxygen and steam as oxidizers provides the highest caloric value of the generated syngas and could be improved in the future by adding an optional catalyst (redox cycle) to generate almost pure hydrogen (up to 98% by volume).

An initial project along these lines would be based on 50-100 kW plasma torches with near unlimited lifetime, eight gasifiers with four pre-gasification units per gasifier. Such gasifier units will have a variable number of pre-gasification modules, similar to internal combustion engine cylinders, working on one final gasification chamber. Below in Fig. 4 is an optional scheme of the pre-gasifier or burner.

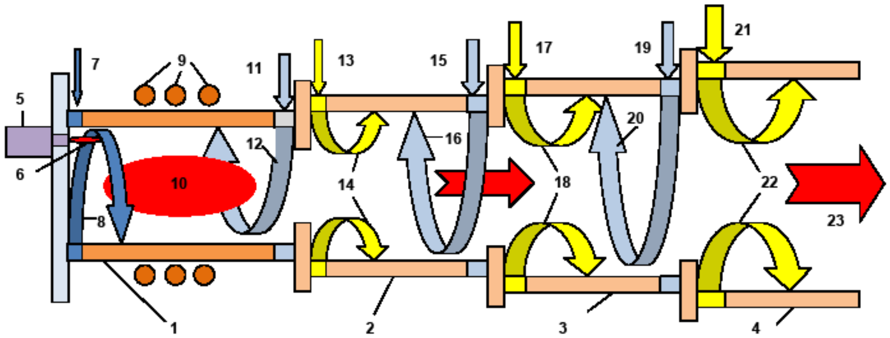
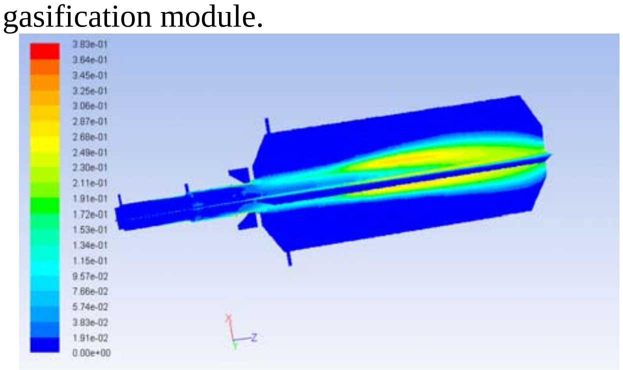


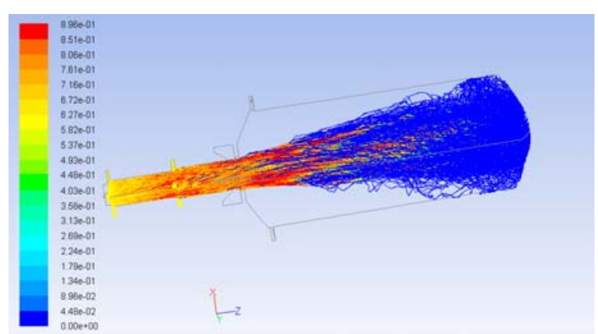
Fig.4. Plasma assisted coal burner/gasifier scheme (US Patent 7,452,513 B2): 1 – plasma generation module, 2,3,4 – stages of the combustion/ partial gasification module, 5 – starting torch, 6 – starting torch plume, 7 – starting gas, 8 - starting gas vortex, 9 – inductor, 10 – plasmoid, 11 – main plasma gas (air, oxygen, blends), 12 – main gas reverse vortex, 13 – feedstock 1 fraction 1, 14 - feedstock 1 flow,15 - feedstock 2 (optionally water steam), 16 – feedstock 2 vortex, 17 – feedstock 1 fraction 2, 18 – feedstock 1 flow, 19 – feedstock 2 fraction 2, 20 – feedstock 1 fraction 3, 22 – feedstock 1 fraction 3 flow, 23 – high temperature exhaust gases/ products of coal dust partial gasification.

Preliminary plasma coal gasification modeling using 3D CFD (Computational Fluid Dynamic) calculations of flow dynamics have already been conducted [14, 16-17]. For the modeling of physical and chemical processes inside the plasma gasifier, a generalized method has been used, based on numerical solution of the combined conservation and transport equations for a turbulent-flow, chemically reacting system. The coupled discrete phase model has been used for definition of the trajectory of a discrete phase by integrating the force balance of the coal particles.

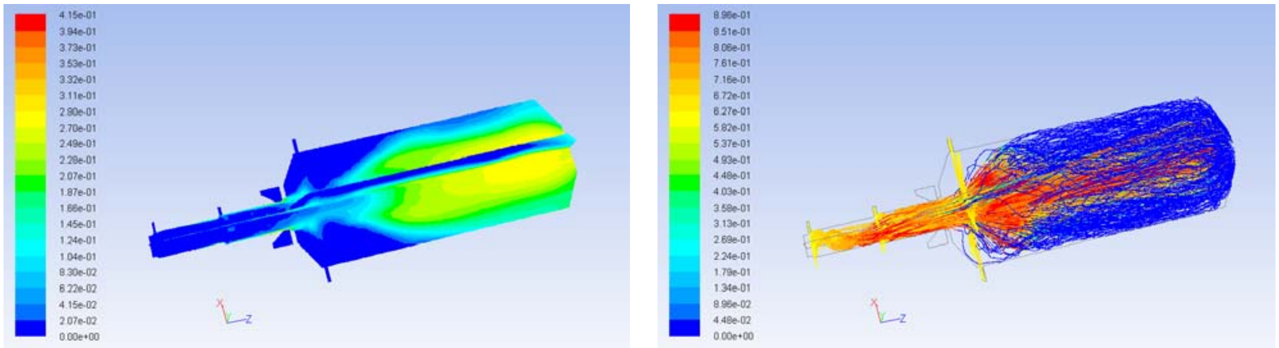
The gasification system has two sections: a plasma pre-gasification or combustion module and a gasification module. Each module can be accordingly divided into 2 or 3 stages. Plasma-process air is injected through the cylindrical duct. Two air-coal streams are injected in series into the plasma for initial heating, devolatilization, and combustion (partial oxidation). Next, a portion of the air-coal mixture (or pure air) is supplied into the gasification module through a special swirler to guarantee stable combustion (partial oxidation) of the previously-processed plasma-air-coal mixture. Steam and coal are injected in a radial direction for the production of gasification products, including a mixture of carbon monoxide and molecular hydrogen (i.e., syngas).

Contour plots of CO mass fraction and particles, colored by particle char fraction, for two and three coal injections are shown in Fig. 5. Case *a)* corresponds to partial oxidation of coal in the plasma pre-gasification module, and case *b)* corresponds to coal-steam gasification in the gasification module.





a)



b)

Fig. 5. Contour plots of CO mass fraction and particle traces, colored by particle char fraction:
a – two coal injection; *b* – three coal injection

These calculations have demonstrated that CFD codes/models can be used for prediction and parameter optimization of plasma coal gasifiers. Further improvements of computational procedures are linked, first of all, with development of more detailed kinetic schemes of coal (with different fractional composition) combustion and gasification, amelioration of devolatilization mechanisms, and taking into account radiation heat transfer. Special attention is necessary to verify the proposed chemical and physical mechanisms, which requires conducting coordinated experimental and theoretical investigations.

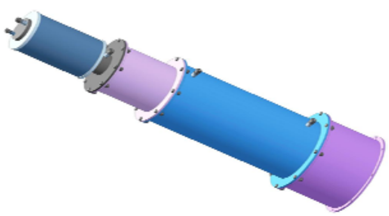


Fig.6. Expected appearance of the three-stage gasification chamber with a plasma torch

Anticipated Public Benefits

Our suggested plasma coal gasification technology will lead to new product development, mainly: (1) plasma coal burners for coal fired boilers and (2) plasma coal gasifiers.

The first product envisioned would implement a two-stage process of plasma enhanced thermal activation and processing of coal dust or slurry into synthesis gas (mainly CO and H_2) and heated coal particles with energy consumption of 0.1 – 0.5 kWh/ kg. This is partial coal gasification and so-named Coal 1 project.

The main applications for the above technology are many types of coal fired boilers, cement kilns, as well as other coal and solid fuel burners. The advantages of this product in comparison to conventional coal burners are as follows:

- Unlimited number of start ups, including cold state;
- Elimination of supplemental fuel;

- Multi-mode operation (ignition – complete coal combustion with the boiler refractory heating up by the products of clean coal combustion, and flame control – partial gasification and heating up of coal dust before injection into the boiler);
- Reduction of unburned carbon, C_xH_y and NO_x (by 70%);
- Increased boiler efficiency;
- Smokeless operation;
- Multi-fuel operation;
- Return on investment from 8 to 24 months;
- Estimated market value $1 to 2 billion for US only.

A second envisioned product would implement a three-stage process of plasma enhanced thermal activation and processing with energy consumption of 0.03 – 0.05 kWh/ kg. This is complete coal gasification system and so-named Coal 2 project. Applications for this technology include coal conversion into syngas for electricity, heat, hydrogen and synthetic liquid fuel production. The expected market for this technology is initially envisioned to be small to mid-size gasification units, both mobile and stationary, as well as universal multi-feedstock gasification plants. Initial customers are expected to be coal mines, power generation companies, and fuel gas production companies.

The advantages of this product in comparison to conventional coal gasifiers are as follows:

- Fast start up;
- No need for any supplemental fuel;
- Wider turn down ratio;
- Total estimated thermal efficiency of up to 85% in the case of steam or hot water production;
- Flexible feedstock operation (petro-coke, used oil, etc.);
- Steam-coal gasification for higher hydrogen yield;
- Mobile to mid-scale units for remote operation;
- Opportunity to install near coal mines to avoid transportation of coal;
- Estimated market value $5 to 10 billion, US only.

Related Research or R&D

The first know tests of a plasma torch for coal ignition was performed by P.R. Blackburn, as described under United States Patent 4089628, and assigned to Union Carbide, Inc. But this work was not further developed and commercialized.

Plasma thermal coal preparation for combustion and so named "allo-auto thermal technology" have been suggested and investigated by Professor Messerle from the former Soviet Union (now Kazakhstan) at the end of the 1980s [3,6,7]. He and his team used 60-200 kW DC torches with air as a plasma gas for partial coal dust gasification. The results demonstrated significant advantages of this approach, which resulted in dramatic increases, by factors 3 to 6 for reduction of the heat source power in the case of plasma application in comparison with oil and gas flames, due to higher plasma product temperature, reaction activity (high electron density), and observed effect of coal particle thermal explosions with further active species formation (ions, atoms, radicals) and ions in the gas. The limitations of DC torches did not allow development of industrial prototypes.

The project proposal PI, Dr. Matveev, is in close cooperation with Professor's Messerle team. Within the last three years, we were working on further improvements of a plasma thermal coal gasification process and published two fundamental manuscripts [1,2] and delivered several presentations to the International Workshop and Exhibition on Plasma Assisted Combustion (IWEPAC) in 2007-2010 [8,10,11,15,16] on this subject

There are several known attempts in Russia, Ukraine, and China to utilize different plasma sources, mainly lab-scale microwave and DC, but just for research purposes [13, 14].

China widely uses 100 kW DC plasma torches (copy of the Messerle first generation plasma ignition system) from the early 2000s for coal fired boiler ignition (over 400 systems in operation according to oral statements of industrial representatives), but not for gasification because of limited lifetime and absence of their own alternative plasma sources.

This proposed project is an attempt to solve the problem of energy-efficient, compact plasma coal gasification hardware/processes, with further liquefaction into liquid fuels, hydrogen production or highly-efficient and clean direct heat and power production based on the knowledge and expertise of the involved field-leading scientists by utilizing a new generation of plasma sources with virtually unlimited life time and in close cooperation with research institutions and industry partners who are interested in final product commercialization.

Principal Investigator and other Key Personnel

The IPTC key personnel include: Dr. Igor Matveev, PI; Ms. Svetlana Matveeva, Chief Designer, Mr. Eveginy Kirchuk, Engineer, and Dr. Louis Rosocha, Sr. Scientist. Dr. Matveev will serve as PI and perform overall supervision of project work, participate in equipment design, test conduction, data analysis, and reporting.

Dr. Igor Matveev, IPTC President, proposed project PI: From 1977-2009, 32 years of gas turbine engineering experience; two decades with military aircraft and related gas turbines; 30 years experience in plasma assisted combustion, including igniters, plasma pilots, plasma fuel nozzles, reverse vortex combustors; founded US company in 2003 for R&D, design, marketing and production of plasma sources and plasma based technologies for coal and waste gasification, materials modification, other products for industrial and military uses. Currently in operation worldwide over 1,200 plasma systems developed under his supervision. He holds basic patent and three pending patents on a hybrid torch, reactor, and pilot plant.

Will be responsible in the project management, strategic planning, work distribution, gasifier scheme and parameters definition, tests planning, negotiations with vendors and suppliers, reports development, relationship with the project officer. Level of involvement – over 60% of the annual time budget within the entire project duration.

Svetlana Matveeva, Chief Designer, APT: From 1977-2009, 32 years experience with modeling, engineering, and design (including CAD) related to turbine engines and plasma sources, plasma ignition systems, plasma nozzle, high power plasma torches, gasifiers. Will be responsible in design of all critical parts as torch and gasifier, merging them with a heat exchanger, filter, compressor, gas engine, positioning on a frame, and after tests improvements. Level of involvement – over 75% of the annual time budget within the project time frame.

Dr. Louis A. Rosocha, APT Senior Scientist: received the Ph.D. degree in physics with a minor in chemistry from the University of Wisconsin, Madison, in 1979. From 1978 to 1981, he was with the National Research Group of Madison, WI and, from 1981 to 2008, a Technical Staff Member and Manager at the Los Alamos National Laboratory (LANL). Over the course of his career, he has worked on plasma chemistry, large inertial fusion gas laser systems, relativistic electron beam sources, pulsed power, and non-thermal plasma processing. Dr. Rosocha is the author of five chapters in books, has published about 100 articles in professional journals and conference proceedings, and made dozens of presentations at conferences, including at least ten plenary lectures/invited papers. He has five patents to his credit, with two more applications in progress. He organized the 1st International Workshop on Plasma Assisted Combustion in 2003, co-organized the second event in 2006, and served on the steering committee in 2007 - 2010. In addition, Dr. Rosocha has served on many international advisory and organizing committees for technical conferences. He is also a guest editor for IEEE Transactions on Plasma Science's special issue on Plasma Assisted Combustion, published on a yearly basis since 2006. He has also received two Distinguished Performance Awards at LANL during his career. His current R&D interests are focused on two of the most important problems of our time, namely, CO_2 sequestration/global warming and national energy security (improving combustion, the efficiency of engines/fuels, and the conversion of trash into 'green' energy). Dr. Rosocha is presently a member of the American Physical Society and the IEEE. He has previously been a member of the International Ozone Association, Sigma Pi Sigma, and Phi Beta Kappa.

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In addition, the following intellectual property resources are available to the proposed project: The proposed project efforts will be based on the intellectual property of Dr. Igor Matveev, protected by:

1. US Patent 7,452,513 B2 "Triple Helical Flow Vortex Reactor," issued Nov.18, 2008.
2. European Patent Application No. 07735540.2, Publication No.2081674 – Triple helical flow vortex reactor.
3. US Patent Application US 2008/0245749 A1 "Powerplant and Method Using a Triple Helical Vortex Reactor," Publication Date Oct. 9, 2008.
4. US Patent Application US 2009/0050713 A1 "Triple Helical Flow Vortex Improvements," Publication Date Feb. 26, 2009.
5. US Patent Application US 2010/12/756,303 "Triple Helical Flow Vortex Improvements," Filing Date Apr. 08, 2010.
6. Submitted to the European Patent Office application based on the US Patent Application US 2008/0245749 A1, no number.

Also available to the project is IPTC's contribution of:

- Prototypes of the 50 kW and 150 kW hybrid plasma torches (see Figs.7 & 8);
- License-free utilization of the IPTC patents and IP rights;
- Involvement of highly-knowledgeable plasma and coal specialists in an advisory capacity.

Fig.7. Power supply.

Fig.8. Plasma torch in operation.