1. Final Technical Report

Project Title: Advanced Process Heater for the Steel, Aluminum and Chemical Industries of the Future

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Recipient: STORM Development, LLC
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Working Partners: STORM Development, LLC, Spinworks, LLC, Penn State University – Applied Research and Design Center.

Cost-Sharing Partners: STORM Development, LLC, Spinworks, LLC

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2. Disclosures

There are no limitations on the distribution of this report.

3. Executive Summary

The *Roadmap for Process Heating Technology (March 16, 2001*), identified the following priority R&D needs: "*Improved performance of high temperature materials; improved methods for stabilizing low emission flames; heating technologies that simultaneously reduce emissions, increase efficiency, and increase heat transfer".*

Radiant tubes are used in almost every industry of the future. Examples include *Aluminum* re-heat furnaces; *Steel* strip annealing furnaces, *Petroleum* cracking/ refining furnaces, *Metal Casting*/Heat Treating in atmosphere and fluidized bed furnaces, *Glass* lair annealing furnaces, *Forest Products* infrared paper driers, *Chemical* heat exchangers and immersion heaters, and the indirect grain driers in the *Agriculture* Industry. Several common needs among the industries are evident: (1) Energy Reductions, (2) Productivity Improvements, (3) Zero Emissions, and (4) Increased Component Life.

The Category I award entitled "Proof of Concept of an Advanced Process Heater (APH) for Steel, Aluminum, and Petroleum Industries of the Future" met the technical feasibility goals of: (1) doubling the heat transfer rates (2) improving thermal efficiencies by 20%, (3) improving temperature uniformity by 100^{o}F (38 ^{o}C) and (4) simultaneously reducing NO_x and CO_2 emissions. The APH addresses EERE's primary mission of increasing efficiency/reducing fuel usage in energy intensive industries.

The primary goal of this project was to design, manufacture and test a commercial APH prototype by integrating three components: (1) Helical Heat Exchanger, (2) Shared Wall Radiant U-tube, and (3) Helical Flame Stabilization Element. To accomplish the above, a near net shape powder ceramic Si-SiC low-cost forming process was used to manufacture the components.

The project defined the methods for making an Advanced Process Heater that produced an efficiency between 70% to 80% with temperature uniformities of less than 5^{o}F/ft (9^{o}C/m). Three spin-off products resulted from this project: (1) a low-cost, high-temperature heat exchanger, (2) a new radiant heat transfer system, and (3) a hybrid or integral advanced process heater that incorporates a high surface area ceramic heat exchanger and burner combined with either a metallic or ceramic radiant tube and heat transfer elements.

4. Goals and Accomplishments

Project Goals

The APH design goals were to: (1) operate at a temperature between 1600^{o}F and 2000^{o}F (870^{o}C to 109^{o}C), (2) provide an energy input rating of 100,000 to 175,000 BTU/hr (29 kW to 51 kW), (3) deliver a thermal efficiency between 70% and 85%, (4) produce a heat flux of 75 to 150 BTU/hr-in^2 (34 to 68 kW/m^2), and (5) result in a temperature uniformity of less than 10^{o}F (18^{o}C/m) per foot length of effective radiant tube.

To accomplish the above, it was necessary to integrate the following components into the APH:

> A low-cost, high-temperature compact helical heat exchanger that has a surface area 3 to 5 times larger than current state-of-the-art. This allows the APH to operate at efficiencies approaching 85%, resulting in fuel savings of 25% to 50% over state-of-the-art and basic radiant tube technologies.
>
> An innovative shared-wall high-temperature radiant U-tube that doubles the heat release of current technology. This results in increased furnace productivity. The shared-wall concept minimizes mounting and thermal stresses.
>
> A unique flame stabilization concept that uses a variable helical shape to promote exceptional temperature uniformity and high rates of heat transfer throughout the entire radiant tube.

To support the integration of the above components, a ceramic powder forming method needed to be evaluated for producing low-cost, high-temperature thermal shock resistant components for the APH. To date, the only shapes that have been made using this process are round tubes and the helical shaped SpyroCor^{TM}. The Si-SiC material operates at temperatures up to 2500^{o}F (1343 ^{o}C) with wall thickness of $^1/_8$" to $^1/_4$". The thermal shock rate is 70^{o}F to 1800^{o}F in 3 minutes or 600^{o}F/minute (333^{o}C/minute). Another advantage of the powder forming method is the "green-parts" are "glued or welded or formed homogeneous" to make one piece components prior to vacuum processing at 3000^{o}F (1650^{o}C).

Project Accomplishments

Low-Cost, High-Temperature Heat Exchanger:

An eight-fin helical channel heat exchanger model was used to evaluate the variables of diameter, length, twist rate, number of channels and temperatures on the heat exchanger effectiveness. The Fluent™ computational model, Figure 1, was used to optimize the design to within the following parameters:

(1) preheat air temperature between 900°F and 1200°F (482°C and 649°C),

(2) surface area to volume ratio between 2/in to 3/in (78/m to 118/m),

(3) diameter between 4” to 6” (102 mm to 152 mm) to and effective length of 8” to 12” (203 mm to 305 mm),

(4) overall pressure drop less than 18” water column.

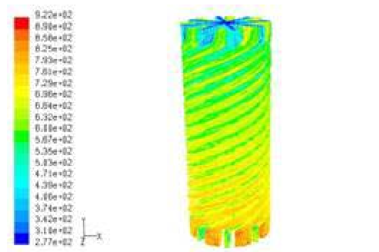

Figure 1: Computational model of an eight-fin helical channel heat exchanger.

Using these design parameters, a powder forming tool, Figure 2, was used to form the ceramic heat exchanger. The outer funnel flows free silicon filler into a forming can which holds the shape in place. The red funnels flow silicon carbide into channels that form the manifold, fluent channels and end caps. The blue funnel is used to flow silicon which will later be infiltrated into the silicon carbide to make a fully dense, heat transfer wall.

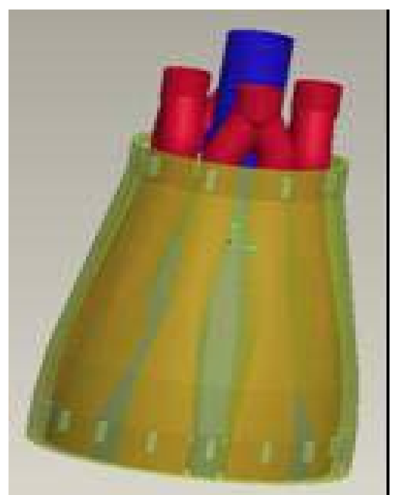

Figure 2: Three-powder heat exchanger forming tool

A fully dense silicon carbide heat exchanger was thermally processed in a vacuum and successfully tested for leakage and wall integrity. Using a high-temperature exhaust gas generator, it was tested with hot gas inlet temperatures up to 2000°F (1093 °C) while generating preheat air temperatures up to 1170°F (632°C). The modeling, tooling, thermal processing, and testing established the methodology for making complex APH components. The final heat exchanger design for the APH would be 4” in (102 mm) diameter, 12” (305 mm) long with 6 fin channels.

Shared-Wall Tube:

(*Please note: pictures of the shared-wall tube cannot be shown at this time due to their proprietary nature.*)

To establish a baseline for design, a 4-1/2" O.D by 96" (114 mm x 2.4 m)effective radiant tube was analyzed using computational modeling and then tested for model validation. The radiant tube temperature profiles, Figure 3, averaged 10^{o}F/ft (18^{o}C/m). These profiles fell to within a 15% bandwidth of a tested radiant tube using an active loading system and thermocouples.

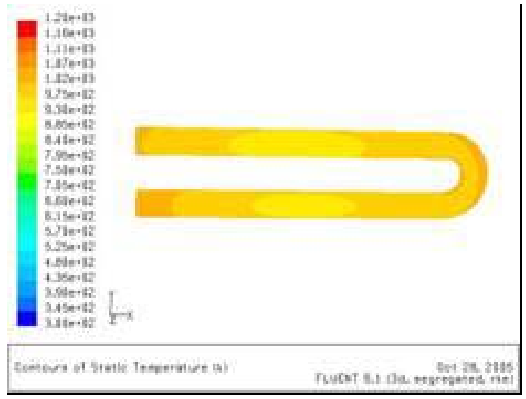

Figure 3: Computational model of a radiant tube

Due to the complex nature of the shared-wall tube and delays in thermal processing equipment, a metallic shared-wall tube was fabricated with a 4" (102 mm) effective diameter and a 72" (1.8m) effective length. The unique feature of the shared-wall tube is that radiation energy exchange is closely coupled between the exhaust leg and the burner leg of the tube. The burner produces non-uniform temperatures along the length of the tube. Typically, a high temperature zone is established near the burner and a cold temperature zone is established near the exhaust. The coupling of the two legs "balances" the temperatures and produces a tube with a more uniform temperature. The metallic shared-wall tube was tested at a temperature of 1800^{o}F (982^{o}C) and produced a temperature uniformity of less than 2^{o}F/ft. (3.6^{o}C/m) as compared to a typical value of 10^{o}F/foot (18^{o}C/m).

Flame Stabilization:

Flame stabilization occurred in three zones: (1) the point where air and gas are introduced to the radiant tube, (2) within the burner leg of the radiant tube, and (3) within the exhaust leg of the radiant tube. A helical shaped ceramic flame holder, shown in Figure 4, was used to establish an initial flame front where the air and gas enter the radiant tube. The design allowed for different tangential velocities to be introduced into the tube. The unique hole design allowed for gas to be introduced with any combination of radial and axial velocities. The design was later used to stage the combustion process for NO_x reduction.

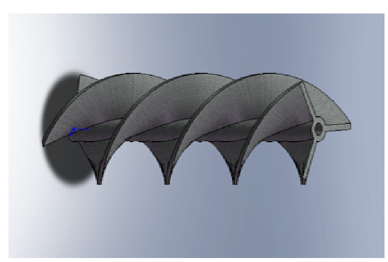

Figure 4: Ceramic helical flame holder and air/gas staging element.

Flame stabilization within the burner leg utilized helical shaped hollow SpyroCor^{TM} radiant heat transfer elements. Helical pitches between 45^o and 90^o (straight) were evaluated for flame stability and temperature uniformity. Pitch rates closer to 90^o produced satisfactory results. However, the close coupling effect of the shared-wall tube reduced the need for utilizing flame stabilization within the burner leg and and exhaust leg. Thus, extension of the flame holder into the radiant tube was used for NO_x reduction.

APH System Integration:

Two APH designs were selected for commercial prototype development. The first design a metallic hybrid, Figure 5, was an integral heat exchanger, burner and flame holder attached to a traditional metallic radiant tube. The second design was an integral “one-piece” ceramic shared-wall tube, heat exchanger, burner, and flame holder, part of which is shown in Figure 6.

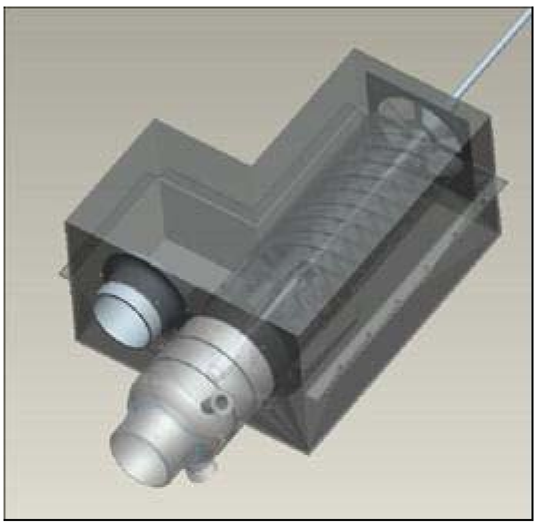

Figure 5: APH metallic hybrid using a 6 fin ceramic heat exchanger element

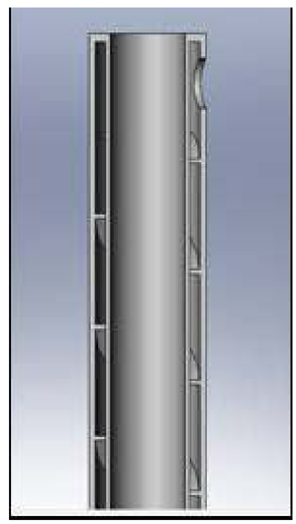

Figure 6: Concentric shared-wall ceramic tube

Initial component integration for both designs produced thermal efficiencies between 72% and 80%, preheat air temperatures between 926^{o}F and 1172^{o}F, and heat fluxes of 100 to 125 BTU/hr-in^2 (45 to 57 W/m^2). The temperature uniformity of the metallic hybrid APH was between 5^{o}F to 8^{o}F per foot (9^{o}C to 14^{o}C per meter) and the temperature uniformity of the integral ceramic APH was less than 3^{o}F/foot (5.5^{o}C/m). Both systems met the project goals.

A demonstration of the APH hybrid was performed at Charter Steel, located in Saukville, Wisconsin. Two commercial prototypes were designed and installed on a batch wire annealing furnace. The units operated at a thermal efficiency of 76%, and resulted in a per tube fuel savings of 42%.

A significant level of process development was performed on the integral ceramic APH. A successful "one-piece" integral greenbody consisting of the shared-wall tube, heat exchanger, burner manifold and burner was successful. Identifying the proper vacuum thermal processing cycle took over 4 months to develop. This resulted in a fully dense integral ceramic APH with a 4" effective diameter and a 72" effective length. The unit was fired for a period of 40 hours, prior to stress concentrations being developed, between the shared-wall and end-cap, resulting in a failed tube.

The component design, modeling, testing, integration, and manufacturing process were identified that produce either a hybrid or integral ceramic APH that meets the project goals. Significant "design for manufacturing" will be required to minimize thermal gradients in the design to eliminate short term failure of the integral APH.

Spinworks, LLC has agreed to commercialize a metallic hybrid APH, a stand-alone heat exchanger, and radiant heat transfer system in 2008. STORM Development, LLC will continue to design the APH to minimize stress concentrations such that an integral unit can be commercialized in 2009 and 2010.

5. Summary of Project Activities

The schedule of project tasks and completion dates are shown in Table 1 below.

Table 1:

Task Schedule

Task Number	Task Description	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	APH Component Design - Using Category I Data	10/31/2005	11/30/2005	12/10/05	100%	Contract Signed Aug-2005
2	APH Component Modeling and Prototyping	11/30/2005	12/31/2005	12/31/05	100%	
3	APH Component Manufacturing	1/31/2006	1/31/2006	3/31/06	100%	
4	APH Component Testing	7/30/2006	7/30/2006	7/30/06	100%	
5	Vacuum Furnace Design and Installation	1/31/2006	Same	7/15/06	100%	Final piece of equipment Apr-2006
6	APH Design for Manufacturing	11/30/2006	Same	9/30/06	100%	
7	Vacuum Furnace Upgrade	1/31/2007	Same	11/30/06	100%	
8	Build APH Commercial Prototype	4/30/2007	Same	4/30/07	100%	
9	Develop "Cost of Manufacturing" and Commercialization Model for APH	7/31/2007	Same	7/31/07	100%	

The primary delay in the project was due to acquisition of a power supply for the high temperature vacuum furnace used to thermally process the ceramic components of the APH. The project was kept on schedule by substituting metallic fabricated components that could be tested under similar conditions as the ceramic counterparts.

A key change in the project scope was in Task 3 where it was originally proposed to use an EDM machine to make tooling. The EDM concept was replaced with tooling made with a plastic, rapid prototype machine.

6. Products and Commercialization

APH Spin-offs:

The Advanced Process Heater Projects resulted in Spinworks, LLC agreeing to commercialize the following products:

1. Low-Cost, High-Temperature Heat Exchanger "HeatCor-451", Figure 7. This patent-pending heat exchanger will produce preheated air temperatures from 451^{o}F to 900^{o}F (232^{o}C to 464^{o}C). Its target application is in strip-steel annealing furnaces. A typical annealing furnace contains 100 radiant tubes with a rating of 50,000,000 BTU/hr and an annual fuel cost of 1.9 million dollars. The unit is designed to work in conjunction with existing combustion systems. The HeatCor-451 combined with the SpyroCor^{TM} Radiant Heat Transfer System (#2) will save approximately 40% of the energy currently being used or 96 million BTU's of energy per year. Demonstrations will occur in the first quarter of 2008.

Figure 7: Low-cost high-temperature ceramic heat exchanger for industrial process heating applications

2. SpyroCor^{TM} Radiant Heat Transfer System (RHTS), Figure 8. This system is a patent-pending system designed to be utilized as a stand-alone system or in combination with the HeatCor-451. The RHTS utilizes a novel ceramic compression system which allows the elements to be mounted in vertical radiant tubes. Typical applications include strip-annealing, wire-annealing, aluminum annealing, and general heat treating. A typical wire annealing furnace is rated at 10,000,000 BTU/hr with an annual fuel cost of $380,000. The RHTS will save approximately 20% of the energy currently being used or 8.1 million BTU's of energy per year. A wire annealing plant will save 100 million BTU's of energy per year. Commercialized in 2006, the RHTS has saved over 15 trillion BTU's of energy.

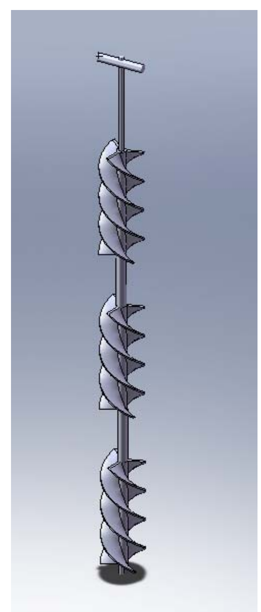

Figure 8: Radiant heat transfer system applied in the exhaust leg of ceramic or metallic radiant tubes

3. HeatCor™-Ready to Fire (RTF), Figure 9, is a hybrid ceramic heat exchanger and burner that can be directly mounted on a metallic radiant tube. When used in conjunction with the RHTS, fuel savings approaching 50% will be achieved. The RTF was demonstrated in 2007 on a wire annealing furnace. Commercialization activities will occur in 2008 and 2009. The RTF, as well as the HeatCor™-451, will be used to open new markets in the Aluminum and Chemical industries. Energy savings of 120 million BTU per installation, per year, are anticipated.

Figure 9: Metallic Hybrid APH system utilizing an integral ceramic heat exchanger and burner.

4. Integral Advanced Process Heater (I-APH) will be a high-surface area, integral shared-wall radiant tube, heat exchanger and burner. The I-APH will approach 60% fuel savings with target markets in the strip and wire annealing, heat treating, chemical, and aluminum industries.

Market Profile:

The APH and spin-off components will first target the market segment of heat treating, where finish machined, or near-finished machined, metal components are placed into furnaces to change their mechanical properties. The second target market segment is aluminum where material is re-heated for preparation in forging. The third target market segment is continuous strip annealing. This last segment is well defined. It consists of approximately 36 companies (primary metals) with large furnaces and a potential of over 900 units per furnace. In total, 250,000 radiant tubes exist in the United States for application of APH. (The above estimates were verified by *Decision Point Report - Radiant Tube Status, Development of Advanced U-Bend Radiant Tubes, Gas Research Institute, Topical Report (April 1991 – August 1992).)*

The table below represents a total U.S. market value of 500 million dollars. The foreign market is estimated at 50% of this, or 250 million dollars.

Market Segments	**Commercial**	**Small, Medium Captives**	**Large Captive**	**Annealing**	**TOTAL**
Number of Customers	1,070	3,000	646	35	4,751
Furnaces/Customer	2	4	6	6	
Radiant Tubes/Furnace	4	12	20	90	
Radiant Tubes in Market	9,630	144,000	77,520	18,900	250,050
Total Flame APH Market Potential	9,630	144,000	77,520	18,900	250,050
Market Value @ $ 2000/APH	$ 19,260,000	$ 288,000,000	$ 155,040,000	$ 37,800,000	$ 500,100,000

In general, radiant tubes are sold independent of the burner and heat exchanger technology. With an average tube life of 5 years, and average retail price of $1,500, the U-tube annual market is 75 million dollars. The U-tube is a commodity high nickel-chrome alloy market that is sold by over a dozen alloy fabricators such as Rolled Alloys, Fab-Alloy, and Hi-Temp. The largest known consumer of U-tubes is General Motors, estimated at 5 million dollars, or 7% of the total market.

An estimated 10% to 20% of the U-tubes have been retro-fitted with plug heat exchangers and burners. Industrial heating equipment suppliers such as Pyronics, Eclipse, Maxon, and Hauck, currently sell to this market. Their total annual sales vary between 5 million and 80 million dollars. The total annual sales of plug heat exchangers and burners is estimated at over 10 million dollars. These are sold to the industrial customer by independent representatives, in-house sales personnel, and buy-resell distributors. Most companies offer a 1-year material defect warranty. Spinworks, LLC offers a 1-year material defect warranty and 100% performance guarantee on its products. To date, no SpyroCor™ has been returned for failure to meet or exceed customer expectations. The same warranty will be extended on the APH and its spin-off components.

Commercialization Plan:

Spinworks, LLC developed a successful sales strategy for the introduction of the SpyroCor™. The same strategy will be used for the APH. This includes direct sales, inside sales, resale to niche markets by its distributor, Avion Manufacturing, manufacturer's representatives (both direct from Spinworks, LLC and under contract with Avion), and OEM sales channels.

Marketing for the proposed APH will include press releases and technical articles to raise awareness in the Steel, Aluminum and Heat Treating industries. The articles will include case studies and success stories. Spinworks, LLC will also maintain a web-based presence (www.spin-works.com) where FAQs, case studies, and news releases will be made available, and e-mail inquiries will allow interaction between potential customers and sales staff.

Market barriers include: (1) proof of savings, (2) unknown impact to existing processes, and (3) ease of retro-fit. Spinworks, LLC is experienced with overcoming all of these barriers. Methods for overcoming these barriers include the offering of trial periods, highlighting detailed case studies, sound customer application engineering, and a credible team with experience.

Commercialization models indicate the ability to penetrate 40% of similar industrial markets within 10-15 years. This represents an annual fuel savings of 102 trillion BTU's of the 256 trillion BTU's of energy per year as analyzed in Table 2 below.

Table 2: Fuel savings analysis of an APH compared to a basic, standard, and "state-of-the-art" radiant tube combustion system

	Basic Unit	Standard	State-of-the-art	**Advanced Process Heater**	
Efficiency	35%	50%	65%	85%	
Radiant tubes/unit	10	10	10	10	
Production rate, lb/hr	8000	8000	8000	8000	
Specific Heat, BTU/lb-F	0.12	0.12	0.12	0.12	
Process Temperature, F	1400	1400	1400	1400	
Net Energy, BTU/hr	1,344,000	1,344,000	1,344,000	1,344,000	
Gross Energy per Unit, BTU/hr	3,840,000	2,688,000	2,067,692	1,581,176	
Annual Operating Hours	6,000	6000	6000	6000	
Annual Energy Use per Unit, million BTUs	23,040	16,128	12,406	9,487	
Annual Energy Use for Market, trillion BTUs	576	403	310	237	
Annual Energy Savings Matrix, trillion BTU's					
Basic Unit vs. Std, S-O-A, APH		173	266	339	
Standard vs. S-O-A, APH			93	166	
State-of-the-art vs. APH				73	
ALL(weighted) vs. APH	60%	25%	15%	256	