1.3.3
Partial Oxidation Gas Turbine (POGT) Cycles

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1.3.3-1 Introduction

There are two main features that distinguish a Partial Oxidatation Gas Turbine from a conventional gas turbine. These are associated with the design arrangement and the thermodynamic processes used in operation. A primary design differentiating feature of the POGT when compared to a conventional gas turbine is that POGT utilizes a non-catalytic partial oxidation reactor (POR) in place of a normal combustor. An important secondary distinction is that a much smaller compressor is required, one that typically supplies less than half of the air flow required in a conventional gas turbine. From an operational and thermodynamic point of view the key distinguishing feature is that the working fluid provided by the POR (a secondary fuel gas) has a much higher specific heat than lean complete combustion products and more energy per unit mass of fluid can be extracted by the POGT expander than is the conventional case. (This is why the POGT uses a smaller compressor than a conventional gas turbine.)

A POR operates at fuel rich conditions typically at equivalence ratios on the order of 2.5, and virtually any hydrocarbon fuel can be combusted. Because of these fuel rich conditions, incomplete combustion products are used as the hot section working fluid. A POGT thus produces two products: power and a secondary fuel that usually is a hydrogen rich gas. This specific feature creates a great opportunity to provide high efficiencies and ultra-low emissions (single digit NOx and CO levels) when the secondary fuel is burned in a bottoming cycle. When compared to the equivalent standard gas turbine bottoming cycle combination, the POGT provides an increase of about 10 percent points in system efficiency.

The overall efficiency of a POGT two-staged power system is typically high and can approach 70% depending on the POGT operating conditions and the chosen bottoming cycle. In figure 1 a generic arrangement of a two-stage or air-staged reheat power system with a POGT as a topping cycle is shown. The bottoming cycle can be either a low pressure (or vacuum) combustion turbine, or an internal combustion engine, or a solid oxide fuel cell, or any combination of them. In addition, the POGT can be used as the driver for cogeneration systems. In such cogeneration systems the bottoming cycle can be a fuel-fired boiler, an absorption chiller, or an industrial furnace. The POGT is ideally suited for the co-production of power and either hydrogen, or synthesis gas (syngas), or chemicals. Some of the important applications are described below.

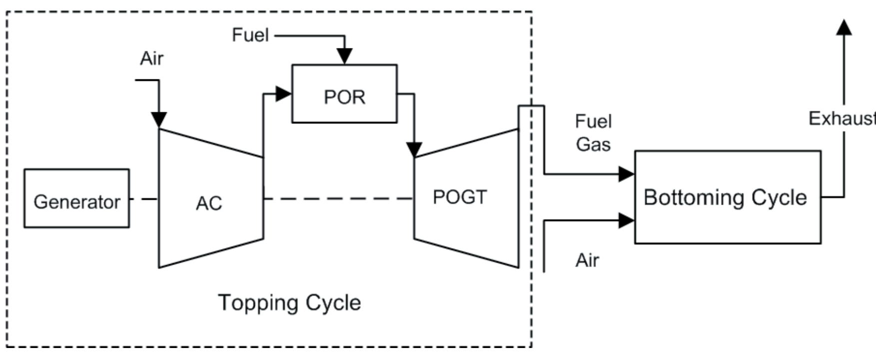

Fig. 1. Generic Schematic of POGT System

1.3.3-2 Background

Research and development (R&D) into the application of POGT concepts for power generation was first performed by the Institute of High Temperature (IVTAN) in the former Soviet Union in the late 1950s[1]. The result of this R&D was the demonstration of a working POGT. In one published application by IVTAN[2], residual fuel oil is partially combusted to produce high-pressure steam and fuel gas, which is then cooled and cleaned to remove ash and sulfur compounds. The steam and purified fuel gas are then used for power generation. A 1970 patent for a POGT by Jacques Ribesse of the JARIX company in Brussels, Belgium, was followed by a technical paper in 1971[3], and a second paper describing further improvements in 1991[4], which described the gas turbine, air compressor, catalytic partial oxidation reactor (POR), and expansion turbine. Partial or total combustion of the combustible gas (leaving the POR) and passing through the expansion turbine was accomplished by injecting air into the turbine vanes. This simultaneously accomplished both the needed cooling and, through local combustion, an isothermal expansion[5].

In 1992, IVTAN published a paper describing an innovative combined cycle utilizing a POGT for the repowering of existing natural-gas-fired steam turbine power plants. The retrofit modifications were estimated to improve fuel efficiencies to between 70-80% and reduce NO_x emissions by a factor of 10 or more[6]. Efficiencies are increased mainly because of (1) complete use of the thermal energy of the hot pressurized gasifier product gas supplied by the POGT; (2) reduced air flow requirements typically about 65% of that used for a conventional expansion turbine, (3) larger volumetric gas flow in the turbine (15-20%), taking into account the lower specific mass of the partial oxidation products, (4) higher specific heat of the turbine working fluid, and (5) close to isothermal expansion, allowing a better utilization potential of the heat[7].

Hodrien and Fairbairn in 1993 evaluated the POGT in a report prepared for British Gas as a highly promising cycle with a potential efficiency above 60%[8]. Further study at the University of Leige (Belgium) in collaboration with other European partners, which included preliminary analysis and testing, concluded POGT has good potential for power generation applications and Combined Heat and Power (CHP) applications as well[9].

The Gas Technology Institute (GTI) has been actively working on the POGT concept since 1995. With support from the U.S. Department of Energy (DOE) and Gas Research Institute (GRI), GTI (formerly IGT) teamed up with SWPC (formerly Westinghouse) to perform a system study of POGT applications[10]. The cycles studied included (1) a conventional natural-gas-fired gas turbine with a POGT utilized as a topping cycle, (2) a combined cycle plant joining a POGT with a steam turbine, and (3) a repowering system for coal-fired power plants using a POGT as a topping cycle. In a continuation of this work Westinghouse performed technical feasibility studies and cost analyses of the PO power cycle[11] and concluded that there was potential for significant plant heat rate and cost-of-electricity improvements.

In a recent development effort to demonstrate a POGT for on-site CHP generation, GTI with support from the California Energy Commission (CEC) and GRI, has teamed with Solar Turbines Incorporated (Solar), Tritek Consulting, Alturdyne Incorporated , and the Belcan Corporation to develop, build, and install at GTI a 10-MW_{th} (34 MMBtu/hr) pressurized research non-catalytic POR, intended to replace the combustor of the Solar Spartan T-350 conventional gas turbine modified to operate in a POGT mode.

1.3.3-3 Overview

The POGT has great potential as a driver for a wide range of bottoming cycles for power generation. A POGT can effectively co-produce both power and syngas from which hydrogen can be extracted. It can also be used in a cogeneration mode where the bottoming cycle systems are industrial furnaces, boilers, or absorption chillers.

Depending on the fuel type and if normal ambient air is used (rather than oxygen enriched air) the exit fuel gases from the POGT are essentially low to medium heating value secondary fuels with variable but high hydrogen contents. In general the lower the hydrogen content of the fuel molecule the lower the exhaust gas hydrogen concentrations will be. An increase in hydrogen content can be obtained by adding steam to the POR which through reforming reactions will increase the hydrogen content of the POR exhaust. Typically the POR will operate at temperatures on the order of 2000 to 2400°F thus keeping the maximum turbine inlet temperature to this level and allowing usage of existing and proven fleet of turbine expanders for POGT application. The simultaneous endothermic reforming and exothermic oxidation reactions that occur within the POR tend to thermally balance each other at a particular temperature (depending on the equivalence ratio) thus eliminating any destructive run-away reactions. The POR exhaust gases, which have very high specific heats, provide a significant improvement over air as the working fluid. Expansion of the POR gases over a turbine provides a much greater power extraction per unit mass of working fluid than is possible for the products of lean conventional combustion systems. This working fluid improvement results in the specific power of the POGT proper, being almost twice that of conventional gas turbines. Generally improved specific power provides in turn improved profitability for the manufacturer and lower unit costs for the customer. Higher efficiencies typically improve the customer's profitability. The POGT exhibits both improved specific power and increased efficiencies when compared to conventional gas turbines. This is clearly shown in figure 2 in which a comparison of the POGT with a number of gas turbine cycles is provided.

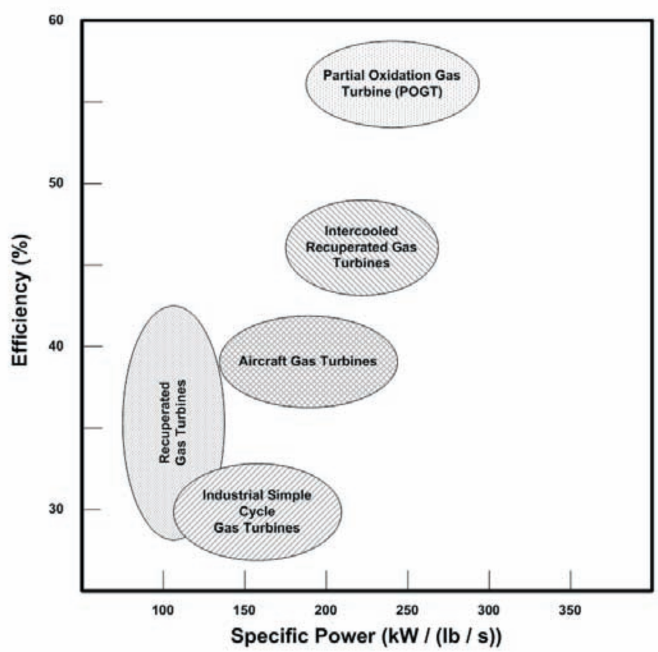

Fig. 2. POGT Cycle Comparisons

1.3.3-4 POGT Applications

This section covers the key applications that are perfectly suited to a POGT. These applications have been divided into power generation, co-production of power and synthesis gas /hydrogen, and cogeneration applications. Each application is covered in details in the following sections.

POGT for Power Generation

The benefits of POGT in power generation systems when compared to those based on a conventional gas turbine are that it provides fundamentally higher energy conversion efficiencies and inherently lower nitrogen oxide (NOx) emissions without any catalytic combustion or post combustion catalytic treatment. Typically in the POGT power generation approaches more of the oxygen in the air is consumed in the staged combustion arrangement than in conventional gas turbine power systems; O_2 in the stack is about 3% for POGT systems vs. 14-16% for conventional systems. This leads to the generally higher conversion efficiencies. The overall combustion system can be regarded as being similar to a rich-lean combustor with an expansion turbine located between the rich and lean sections. The expansion process cools the gases that enter the lean combustion section creating easier premixing and lower flame temperatures than are encountered in a standard rich-lean combustor. It is this critical difference that allows the POGT system to provide NOx emission levels less than 3 parts-per-million, by volume (ppmv), dry (corrected to 15% oxygen). The POGT does require a more advanced control system than a conventional gas turbine primarily for starting and shut-down. In particular if the exhaust fuel gas composition is to be varied then additional control features have to be added to the basic system.

The integration of the POGT with bottoming systems such as a steam based combined cycle is straightforward as is the integration with a fuel cell. Using a gas turbine as a bottoming cycle is more difficult and usually results in either a sub-atmospheric pressure system being employed or forward integration of the gas turbine with the POGT. A steam bottoming cycle involving the return of all of the steam generated (in a fuel fired boiler) to the POGT is shown in figure 3. This is considered to be a steam injected simple cycle. This general approach is similar to steam injected gas turbines and produces a significant increase in power over the non-steam injected case. A combined cycle version of this steam injected POGT is shown in figure 4. In this arrangement the steam produced in the bottoming cycle is split into two streams. One of the streams is injected into the POGT proper and the other is used to drive a steam turbine. This particular approach using steam injection not only increases the power output of the POGT but also increases the hydrogen content of the exhaust secondary fuel gases as mentioned above. The higher hydrogen content provides improved stability for the lean combustion systems that are used to fire the boilers. This improved stability allows the boiler combustion systems to operate at very lean (low NOx emission) conditions. The injected steam not only enters into the POR reforming reactions but is also be used for cooling of the POR and hot-section structures where needed.

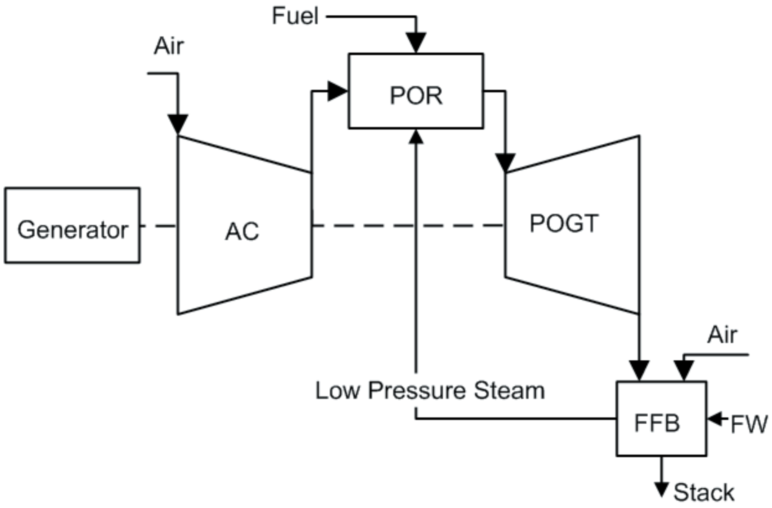

Fig. 3. Steam Injected Simple Cycle POGT

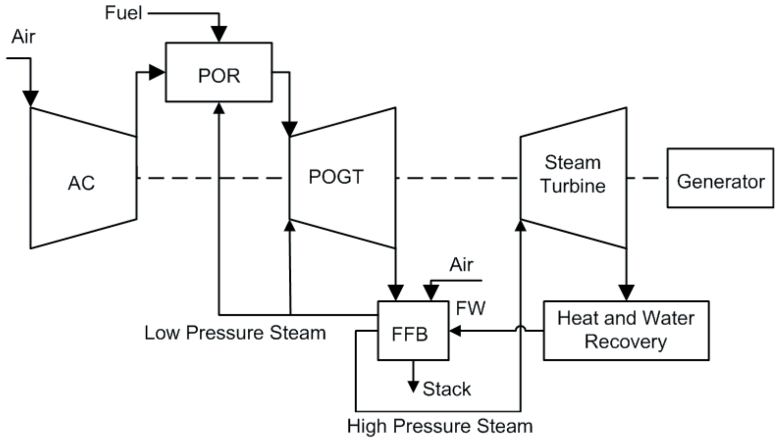

Fig. 4. Steam Injected Combined Cycle POGT

The use of a gas turbine as the bottoming cycle typically involves a much closer integration than say with a fuel cell or boiler. This forward integration results in a configuration that has been termed an Air Staged Reheat (ASR) system. Perhaps the simplest version of an ASR in an all electric power generating system is shown as a schematic in figure 5. In gas turbine terminology this could be a two shaft, single-spool arrangement with a reheat combustor. The POGT turbine provides power to both the low pressure and high pressure compressors while a fired (power) turbine produces the power for export. This configuration has high overall efficiencies because of the higher levels of oxygen consumed in the two stage combustion process when compared to a single combustor arrangement.

The fuel cell integrated as a bottoming cycle with a POGT is shown in figure 6. In this particular version the fuel cell air is provided by an auxiliary fan while the fuel is supplied as the POGT exhaust. This approach of using the POGT exhaust which is a high hydrogen content fuel gas for the fuel cell lends itself well to both the solid oxide and molten carbonate fuel cells. Figure 6 shows an application involving a solid oxide fuel cell. In general the POGT is a better candidate topping cycle to the fuel cell than a conventional gas turbine. The POGT eliminates the need for a reformer and the integration problems that reformers create for fuel cell thermal management, as well as improves start-up and shut-down operation.

POGT for Co-Production of Hydrogen and Power

One of the more promising applications of the POGT is the co-production of hydrogen and electrical power. In figure 7 a POGT system intended for the production of both synthesis gas or hydrogen (from natural gas) together with electrical power is shown. It shares many features with the steam injected systems shown in figures 3 and 4. Instead of reinjecting all of the steam generated into the POR part of the steam produced is reacted with part of the POGT exhaust in a shift reactor to increase the hydrogen content. Part of the exhaust is burned in a boiler to produce the required steam. This particular POGT arrangement is a very effective approach to producing synthesis gas or hydrogen and can be viewed as a "self-powered" reformer when this kind of application is needed.

POGT for Cogeneration with Industrial Furnaces, Boilers or Chillers

The use of POGT systems as the drivers for cogeneration is likely to be very effective primarily because of the use of the POGT exhaust as a fuel. Not only is the exhaust thermal energy made available as in a conventional gas turbine cogeneration system but the fuel when combusted boosts the application

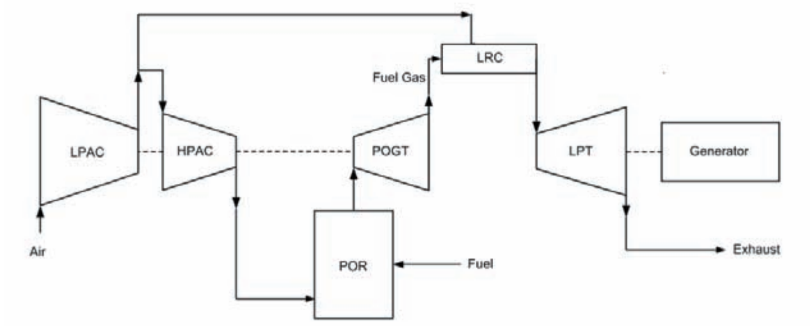

Fig. 5 Integrated Air Staged Reheat POGT

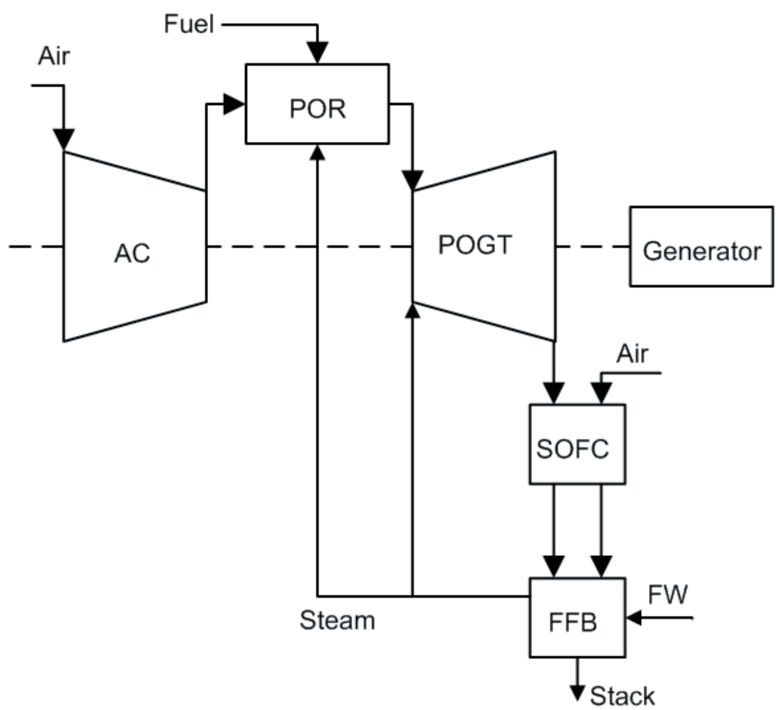

Fig. 6. Hybrid Fuel Cell POGT System

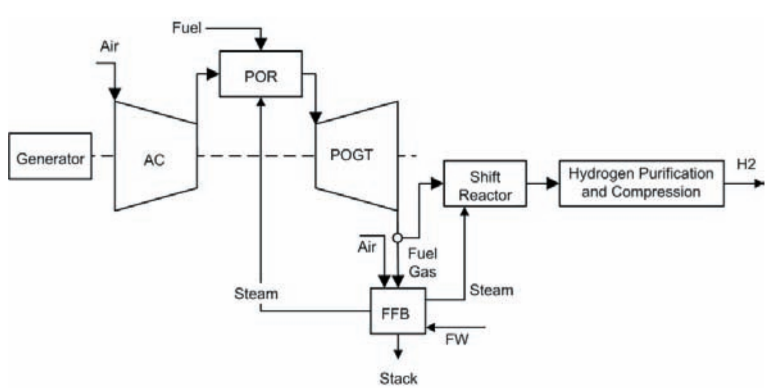

Fig. 7. POGT Co-Production of Power and Hydrogen

temperatures to higher levels. These higher temperatures increase the efficiency of the bottoming cycle. The exhaust which is a low to medium energy gas typically has low flame temperature and thus produces minimal levels of NOx. An arrangement of the POGT with a high temperature furnace (HTF) or an industrial boiler (IB) is shown in figure 8. High temperature steam suitable for process uses or even power generation is typically produced. Furnaces such as those used in steel annealing and reheat, glass melting, or aluminum reclamation are candidates for this approach because the associated processes typically require both electrical power and high temperatures.

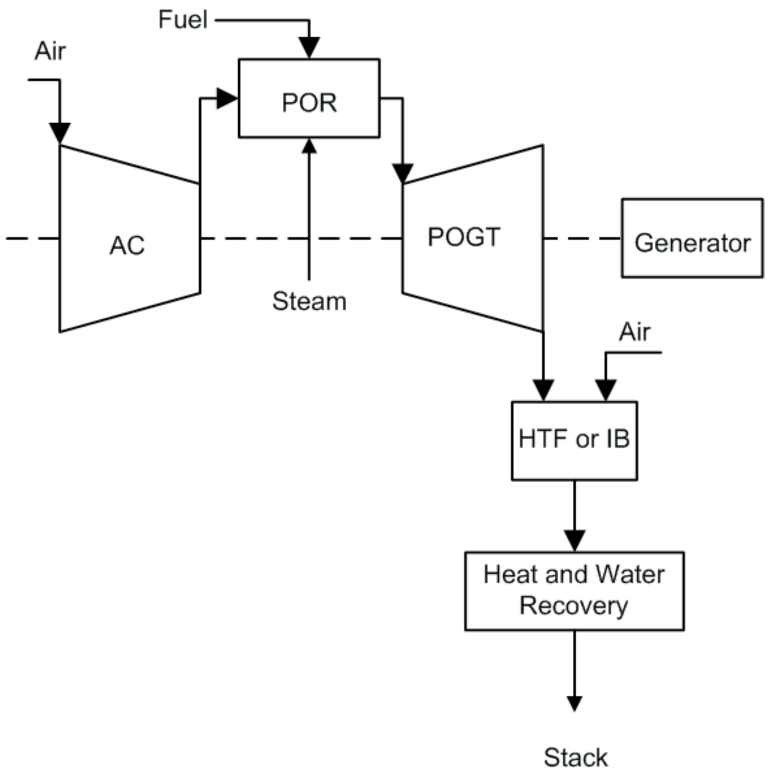

Fig. 8. High Temperature Furnace or Industrial Boiler Cogeneration

1.3.3-5 Conclusions

POGT is a highly flexible device that when integrated with a bottoming cycle can provide significant improvements over conventional gas turbines in both efficiency and gaseous emissions particularly in small megawatt-size power generation systems. The core POGT because of its very high specific power (kW/(lb/s)) should have a lower specific cost ($/kW) than a conventional gas turbine.

Thus the POGT represents a promising type of gas turbine which could be widely used for power generation, cogeneration, and co-production of power and hydrogen, syngas or chemicals. POGT systems efficiency is in the lower fifties for simple cycle systems and the upper sixties for combined cycles. Typically the NOx emission levels are below 3-ppmv without post combustion catalytic treatment. A conventional gas turbine could be converted to a POGT by replacement of the conventional combustor with a POR, and by downsizing the compressor. Modifications to the turbine and the hot section cooling systems could also be needed.

1.3.3-6 Acronyms and Abbreviations

AC	Air Compressor
FFB	Fuel Fired Boiler
HPAC	High-Pressure Air Compressor
HTF	High Temperature Furnace
IB	Industrial Boiler
LPAC	Low -Pressure Air Compressor
LPT	Low-Pressure Turbine
LRC	Lean Reheat Combustor
POR	Partial Oxidation Reactor
POGT	Partial Oxidation Gas Turbine

1.3.3-7 Notes

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BIOGRAPHY

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Dr. Joseph Rabovitser is a director of power generation, at the Gas Technology Institute. Since 1994, he has been involved in the development of the partial oxidation gas turbine (POGT) technology, and currently he is the project manager / principal investigator of the ongoing project "Development of a POGT for Combined Electricity and Hydrogen Enriched Fuel Gas Generation," and he directs several other research programs including development and deployment of high efficiency and ultra-low NOx boilers, burners for gaseous and solid fuels, and novel partial oxidation gas turbine for CHP and multi-stream cogeneration system. Dr. Rabovitser has over 30 years of extensive experience in R&D, engineering, and computer modeling of various power plants equipment. He has over 145 publications, including three books (with co-authors), 44 articles in technical journals and proceeding, and 32 patents.

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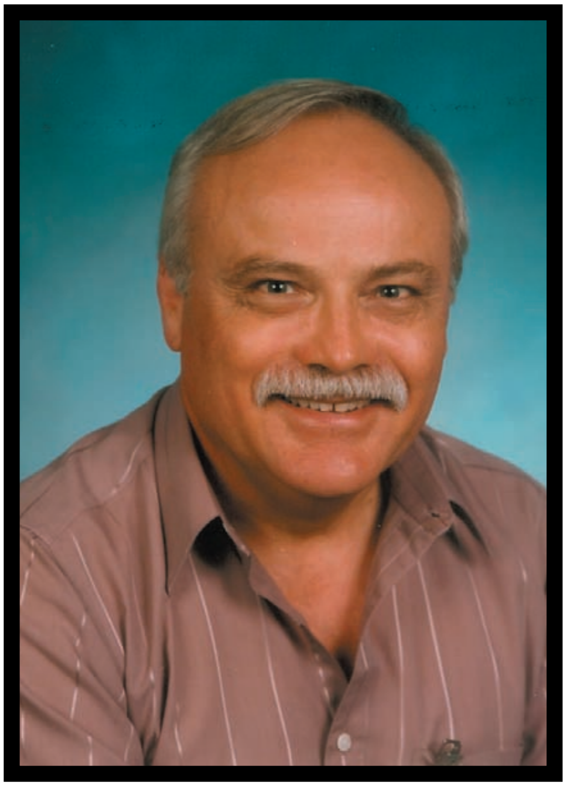
Dr. Serguei Nester is a senior engineer at Gas Technology Institute, Des Plaines, Illinois. He conducts combustion research and development for industrial applications. His responsibilities include CFD modeling, design, development, and testing of novel combustion equipment. Currently Dr. Nester is involved in the development of the Partial Oxidation Gas Turbine (POGT) technology, including Partial Oxidation Reactors, and small and midsize partial oxidation gas turbines, POGT cycle analysis, combinations of POGT with boilers, furnaces and fuel cells, gas turbine/fuel cell hybrids, fundamental studies of partial oxidation of natural gas. Also, he is involved in the development of downstream supplemental firing combustion equipment.



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- Variable power afterburners for the Rolls-Royce Spey-Engined Phantom.
- Hypersonic Ramjet Engine (HRE) for the X-15 (Garrett AiResearch)
- Advanced Turbine Systems (Solar Turbines Incorporated)
- Low NOx Combustion Systems (Several Companies)
- Partial Oxidation Gas Turbine Design (GRI)