"Session 1133"

ACTIVITIES AROUND THE SR-30 MINILAB at PSU

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We build over sand. But we must build as if it were rock
J. L. Borges

Abstract

The installation and operational experience with the SR-30 minilab is described. The minilab is part of an Energy Systems Lab, where students can operate a number of small thermal/vibration demonstrators systems. The SR-30 is an excellent point-demonstrator of the unique capabilities of turbomachines. The turbine installation required some non-permanent building modifications, which are briefly described. The operation has been smooth, except that a fuel leak led to a change in fuel supplier. Whereas well-instrumented systems are necessary for experimental analysis, it was found that student interest and motivation ensue from format-free discussions around design and functional aspects of gas turbines. Hence, along with student-calculated parameters for the SR-30, a brief description of activities leading to free-flowing technical discourse is included. Our experience accommodates the qualitative conclusion that the SR-30 clearly enhances the teaching of gas turbines and thermodynamics.

Introduction

Higher learning in the Engineering endeavor is seldom devoid of the need for experimentation. As Ferguson (1) has unequivocally argued, development of engineers calls for insightful blends of theory and practice. Definition and implementation of experiments that capture an important aspect of science or technology is crucial to the endeavor. Experiments that unleash the imagination and creativity of participants are deemed successful in our scale. The department of Mechanical and Nuclear Engineering at PSU has supported for a few years now a thermal system lab that endeavors to ignite interest and creativity in energy conversion. These creative activities are often called for in the literature, (2, 3, 4) as a component to render engineering education more adaptable and responsive to present needs.

The Energy Systems lab (5) hosts an IC engine, a steam engine, a refrigerator test stand, an IC engine vibration test stand, a mini wind tunnel to visualize separation, a gas turbine display stand, and its latest acquisition, the SR-30. The lab purpose is to illustrate the many aspects (i.e. efficiency, environment, instrumentation, functionality, and integration of many engineering and other disciplines) that lead to an effective conversion technology. The SR-30, however, was acquired with a single purpose in mind, namely the illustration of the high power densities possible with turbomachinery.

The SR-30 is a small thrust demonstration unit, capable of high rotational speeds, (up to 78000 rpm, but possibly higher in our unit), and consequently of high energy densities. Whereas IC engines require in the order of 5 gr. per W of output, gas turbines range in the 0.03 to 0.02 gr/W. These low mass to power ratios have enabled large fast subsonic airliners and supersonic jets, and also have been instrumental for devising efficient (~58%) large-scale cogeneration power plants. Hence, lending practical experience to engineering students in all aspects of gas turbines is important.

The capabilities of the SR-30 as related to the aim of lending a modicum of experience with practical implementations of the Brayton cycle are described in this report. Naturally, the installation and operating experience with the SR-30 are emphasized, , but a additional activities aimed at capturing the essential aspects of aerodynamics, combustion, heat transfer and mechanics invoked by gas turbines are briefly described. In this way, it is hoped that engineering students better understand the achievements and challenges around these remarkable engines.

Purchase and Installation

At the time of purchase (Sp. 1999), the SR-30 was offered in two versions: a thrust demonstration unit with minimal instrumentation, or as a version with more complete instrumentation connected to a PC via a DAS board. The latter unit was deemed as the more appropriate one, for a “turn-key” operation was likely to be more cost effective than a unit needing additional on-site work for enabling cycle analysis.

The installation and site preparation aspects that follow are site-specific. Consequently, the information is not universal, but it offers sufficient generality to warrant a summary presentation. The insightful reader may want to keep in mind that a few years of experience developing teaching stands enables a perspective that the following lines attempt to reflect. The unit was delivered carefully and solidly crated. Older equipment had to be removed to accommodate the minilab, and the installation had to be such as to avoid permanent alterations of the building exterior. Hence, the installation process demanded more planning and energy than that foreseen for a normal lab situation. Besides removal of older equipment, the issues to be resolved in the installation where utilities, exhaust routing and noise levels. Organizational requirements were such that environmental/health regulations had to be satisfied in removing older equipment, a process that called for careful planning and execution. Regarding utilities, compressed air was available in the assigned room, and all that was required was the installation of a filter/moisture separation element, and of a pressure regulator to meet the SR-30 acceptable pressure range. The SR-30 also requires 110 V power, readily available from a wall outlet.

Exhaust routing needed attention considering the position of the lab relative to the fuel depot and other building floors, Fig 1. It was necessary to demonstrate to University regulatory bodies that the exhaust posed no dangers associated with the fuel depot. Ducting the exhaust to the roof (to avoid any exterior modification of the building) required going through two floors and the roof. An existing duct was shown as available in the building layout, but the building had been remodeled during the early 1990s, and the preliminary budget to activate this duct and to connect the SR-30 matched its purchase price and it was in our case, out of the question. The only other possible alternative was to operate the unit discharging through the window.

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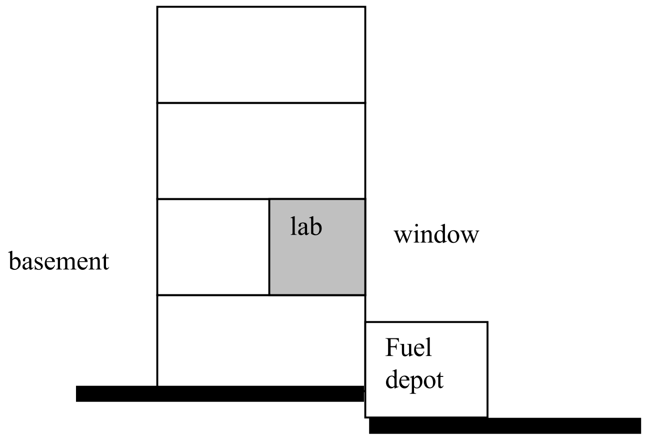

Fig 1. Lab position in first floor of building.

In State College, PA, the weather is erratic. Operating the SR-30 by simply opening the window, although certainly cost effective, would have tied us to the prevalent climatic conditions at the time. Hence, we designed the exhaust system shown in Fig 2. The system directs the jet upwards, and away from the fuel depot, an operation aided by natural convection. In addition, the manufacturer provided us with a chart of centerline exhaust temperature vs. distance for the SR-30 jet. This chart showed that the distance between the exhaust and the roof of the depot is such that the operation of the turbine should be safe for normal conditions.

To avoid a permanent building modification, while allowing operation during all weather conditions, an easily removable window replacement was designed. This consists of Lexan plates with welding clamps attached to them. The clamps are used to secure the plates to the window frame. Two plates are used, to facilitate installation around the exhaust tube. The tube is 9" ID, and it has 2" in the radial direction of refractory insulation. The surface temperature of the exhaust during operation does not exceed 90 F. A 30deg elbow vectors the jet upwards. The exhaust assembly is mounted on a platform with wheels. The exhaust assembly has a slope of 2"/4ft, and a small drain tube at the lowest point. The end exposed to the elements was sealed to prevent insulation deterioration. While not in operation, a cap is used in the inside of the building to prevent drafts originating from the chimney effect.

The issue of noise levels was resolved by obtaining permission from the Environmental Health and Safety group to operate the turbine with an explanatory/warning sign in the hallway. Of course, all operators and students attending the experiment must wear ear protection, with specifications offered in the operating manual of the unit.

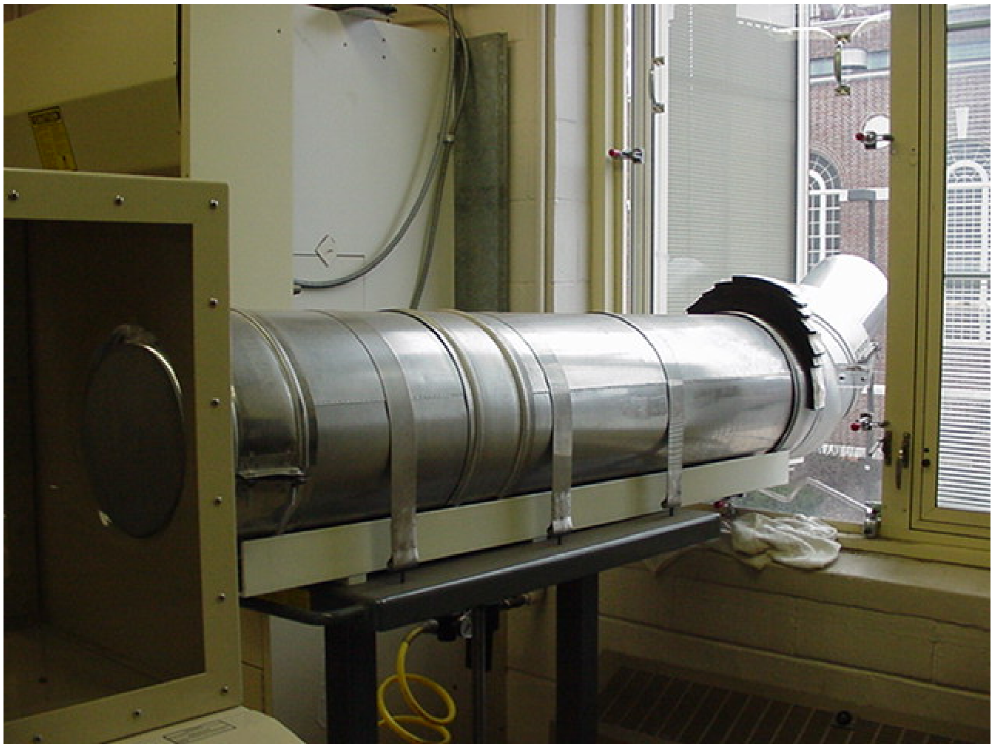

Fig 2. Exhaust tube and Lexan provisional window cover.

Operational Experience

The factory personnel gave a one-day in-site session for start-up and training. This session was productive, and the system was verified to be in good working condition. The installation is such that all one has to do is to roll the minilab into position, remove the exhaust cap, attach compressed air and plug the power cord into a wall outlet, and the system is ready for testing.

The sequence of operation is recorded in a check sheet . The check sheet is laminated, and the operator checks each box as the test unfolds. The starting of the turbine is the most spectacular phase, and it requires a modicum of physical coordination. The compressed air is employed to activate the turbine, and the fuel by is introduced by activating the fuel pump at an instant when operational experience indicates the fuel/air ratio to be favorable for ignition. Fuel pump activation at 9500 rpm is most satisfactory. Upon ignition, flames are visible in the exhaust, and they disappear as the throttle is promptly pushed back to idle. The latter operation must occur swiftly for the internal temperatures to remain within acceptable levels. The operator must monitor the EGT (Exhaust gas temperature), the display of which would turn red at 720 C in the control panel display (First on left in Fig 3)

Table 1. Check sheet.

UPON ARRIVAL		**CHECK**
1	Check compressed air supply pressure-90 to100 psi	
2	Check fuel supply (1 can full at least)	
3	Check fire extinguishers	
BEFORE DAILY START-UP		
4	Open door to 106, place sign on hallway	
5	Align turbine and exhaust tube. Lock casters in place	
6	Connect air and power to unit	
7	Inspect fuel and oil levels	
8	Spin unit by hand to check for free motion	
9	Turn on PC, load settings and name and enable DAS files logging	
OBSERVERS		
10	Advise to stand on sides, not on front	
11	Furnish earplugs, show how to use, do not put on yet.	
START UP		
12	Turn electronic master and let warm up 30" >>red oil light on	
13	Adjust thrust zero	
14	Everyone puts ear plugs on, except operator	
In Operator Panel		
15	Start data login	
16	EGT below 100 C (Green dsp):	
17	Check air pressure, 95 psi before start	
18	Throttle in max, right hand on it all the time.	
19	**Igniter switch on, check ignition, operator puts ear plugs on**	
Using left hand		
20	Air switch on. Watch RPM.	
21	**RPM at 9500; Fuel switch on. If engine does not light, 3-5 sec max., turn off immediately**	
	Using right hand	
22	**Retract throttle to idle.**	
	End Start	
23	Turn ignition off	
24	Turn air off at 45000 RPM	
RUN		
25	Adjust Speed	
26	Monitor DAS	
27	All lights off and EGT dsp yellow, oil press. between 10 and 30 psi, fuel @150 psi.	
SHUT DOWN		
28	Throttle all way back, wait 1'	
29	Fuel off @45000 rpm.	
UPON DEPARTURE		
30	Turn off electronic master and master key	
31	Shut off air supply in wall, disconnect hose at minilab	
32	Move turbine away from duct, and block duct	
33	Bring in sign, lock door.	

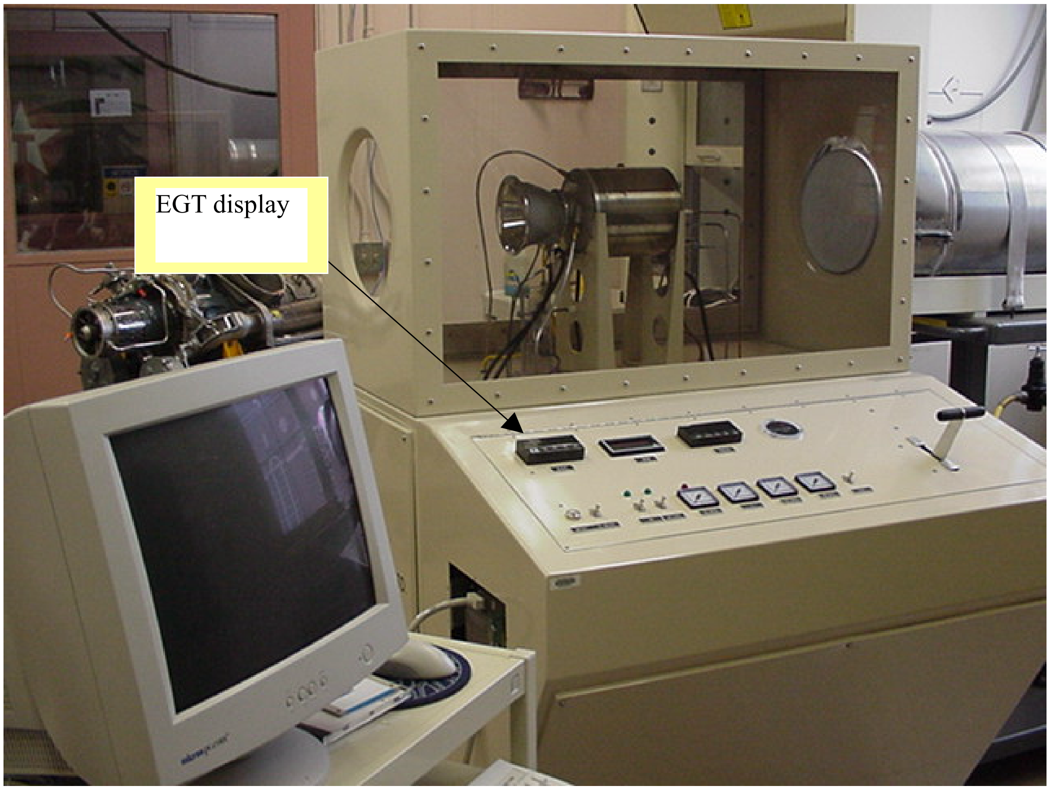

Fig 3. Minilab

Out of about ninety eight starts, only two starts did not result in ignition, requiring the operator to undertake a clearly described procedure in the unit's operational handbook to attain ignition in a subsequent attempt. The unit has operated smoothly, invariably allowing the acquisition of steady-state data.

At about 1 hr of operational time, a fuel leak was detected, enough to pool on the table of the minilab during long runs. Upon consultation with the manufacturer, the turbine was removed from the minilab and sent for repair in a box furnished by the manufacturer to that effect. The manufacturer repaired the sealant of one nozzle, but indicated that the nozzles were partially clogged. An outcome of the manufacturer's communications was switching fuel from domestic kerosene to JP-8 fuel, also labeled jet A-1 fuel. The fuel tank was drained previous arrival of the repaired SR-30. In the process, caked deposits in were detected in the bottom of the tank. Removal was effected by flushing the tank with A-1 fuel repeated times. A new filter was installed, and the unit was reinstalled with telephone assistance from the manufacturer. Since then, the SR-30 has operated reliably for six additional hours.

The Minilab

Whereas simply experimenting with the thrust demonstration capabilities of this small unit constitutes a non-trivial experience for most students, no useful purpose would be served if learning about functional aspects and data analysis was neglected. For developing mechanical engineers, the design, construction and instrumentation of a small machine such as the subject of this report is a source of enlightenment as to the application of the knowledge imparted in a multiplicity of courses. Gas turbine designs, after all, embody principles of fluid flow, thermodynamics, heat transfer, combustion, vibration, fatigue, and lubrication among other disciplines.

Hence, basic principles are emphasized in via two other sessions before running the minilab. Students sign-up for lab sections in groups of four. In the first session, we revise flow around an airfoil. The ideas of Cayley, Lielienthal and the Wright brothers (5) regarding camber and lift are revisited, and the problem of separation is discussed and visualized. In the second session, compressor impellers and blades, and turbine blades are inspected, and principles of blade design are discussed invoking the Mellor charts. Heat transfer issues and materials for the hot section of turbines are visualized and discussed around a twin-spool engine with sections removed to allow for visualization. The rather unique aspect of turbine inlet temperatures in the order of 1650 K, that is, above the working metal temperature, is placed in the context of power to weight ratio. Blades with internal channels and orifices for film cooling are inspected.

The SR-30 is introduced with visual materials furnished by the manufacturer, (Figs 4,5). At this point, the students are familiar with configuration and design challenges of combustion chambers, ignition and nozzles, centrifugal compressors, turbines and exhaust nozzles.

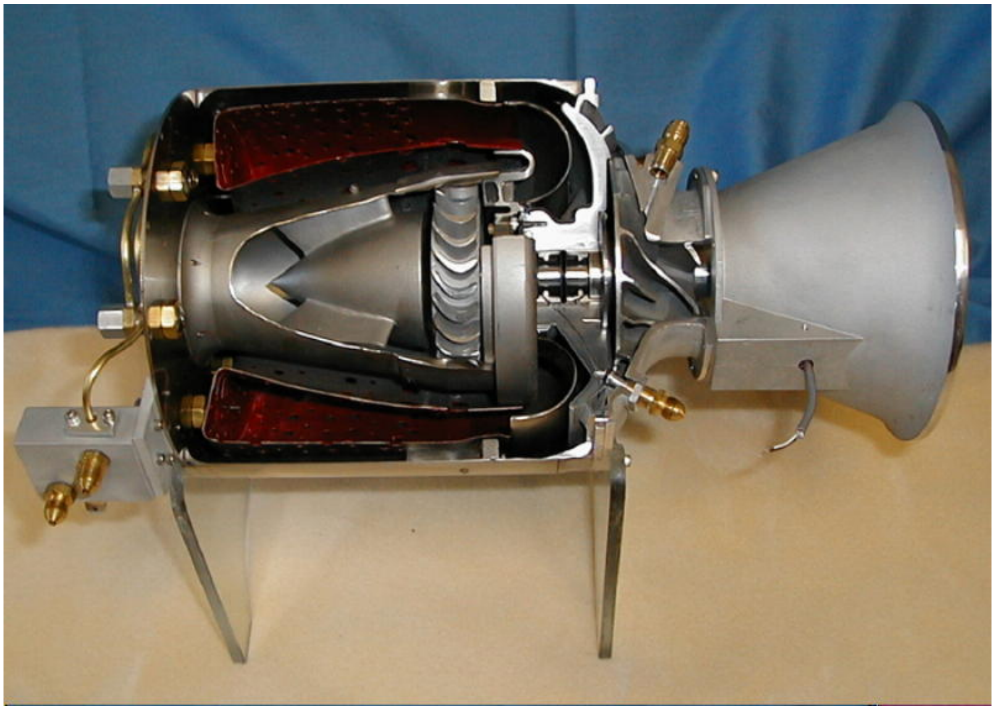

Fig 4. Cutout of SR-30 (Courtesy of Turbine Tech)

Fig 5. Disassembled SR-30 (Courtesy of Turbine Tech)

After the preliminary discussion during which we identify the function of all the SR-30 parts and subsystems, the turbine is started and run. The part identification process and ancillary discussions we found to be most enlightening to all. The students process the data acquired during the steady-state portion of the run at home. The data are normally e-mailed to a team member, and backed-up in a CD-ROM in the SR-30 DAS system.

The DAS system was found to be simple to use and effective. All sensors from the unit are connected to a PC via a DAS board. The user can determine which variables to monitor from the PC screen as the test unfolds by modifying settings of the installed software. Calibration settings can also be readily modified. The stream of data (Table 2) can be used to analyze each run, both regarding transient and steady-state aspects. Data taken when the unit is started allow assessment of internal temperatures during the associated transients .

Table 2. Gas turbine data

Variable	**Compressor**		**Turbine**		**Nozzle**	**Other**
	Inlet	Exit	Inlet	Exit	Exit	
Temperature	•	•	•	•	•	Inlet stagnation
Pressure	• (Dynamic)	• (Static)	• (Static)	• (Static)	•	Inlet stagnation
Flow						Fuel
Rot. Speed						R.P.M.

The data over one minute of steady-state operation (30 points, typically) are averaged to calculate turbine parameters. Parameters defining the turbine operation are calculated using stagnation conditions, which are easily determined with knowledge of air and gas flow and of the cross sections of the turbine. One-dimensional flow is assumed throughout. The cross sections are extracted from a layout furnished by the manufacturer. For instance, the airflow can be computed from the compressor inlet dynamic pressure and temperature, and the stagnation pressure, as follows:

$$amfr = \rho_1 \quad v_1 \quad A_1 \tag{1}$$

$$v_1 = \sqrt{\frac{2 \quad dp}{\rho_1}} \tag{2}$$

$$p_1 = p_o \quad p_1 \tag{3}$$

$$\rho_1 = \frac{R \quad T_1}{p_1} \tag{4}$$

Where,
A: cross sectional area, m^2
amfr: air mass flow rate, kg/s
dp: dynamic pressure, Pa.
p: pressure, Pa.
T: absolute temperature, K
ρ: density, kg/m^3
o: stagnation (subscript)
1: compressor inlet. (subscript)

The gas flow rate is simply given by the sum of the air and fuel flow rates. Determining the speed and stagnation conditions at each section with the data of Table 2 is a simple matter. Isentropic efficiencies are defined, for instance, in ref .7.

An energy balance of the combustion chamber must take into account the enthalpy of fuel, air and gas. In theory, the algebraic sum of the product of the specific enthalpy of each stream multiplied its must flow rate should be equal to zero. In practice, we found that we obtain a value corresponding to a heat loss. This value, divided by the total input fuel enthalpy is reported in Table 3.

Pressure ratios, fuel-air ratios, compressor and turbine efficiencies and heat loss after an energy balance in the combustion chamber are shown in Table 3. Although the uncertainty bands in the variables of Table 3 are noticeable, the trends of higher pressure ratios and efficiencies as the machine approaches full load are well established.

Table 3. Calculated parameters for SR-30.

Rotational Velocity	Pressure ratio	Fuel-air ratio	Compressor isentropic efficiency.	Turbine isentropic efficiency.	Chamber heat loss
(1000 rpm)					% of fuel input
55	1.72	0.0162	0.68	0.75	24.7
55	1.73	0.0160	0.68	0.74	24.7
55	1.72	0.0159	0.64	0.75	25.1
60	1.9	0.0164	0.70	0.73	22.5
60	1.9	0.0165	0.66	0.75	25.9
60	1.89	0.0164	0.67	0.73	25.8
65	2.06	0.0135	0.69	0.75	5.7
71.6	2.33	0.0161	0.64	0.94	5.2
75	2.51	0.0177	0.76	0.91	14.4
75	2.53	0.0178	0.74	0.88	14.5
78	2.61	0.0161	0.75	0.88	5.3

Conclusions

The chief characteristic of gas turbines, i.e. power density, is well illustrated by the SR-30. Instrumented as acquired for our University, the SR-30 can be used to analyze the Brayton cycle and to illustrate the principle of thrust. All relevant state points can easily be calculated. In our approach, format-free discussions regarding the many disciplines that contribute to a gas turbine design lead to motivated students, ready to appraise the SR-30 cycle with experimental data and with subsequent calculation of meaningful cycle parameters.

The SR-30 has been a reliable, effective demonstrator of many aspects of gas turbine design, construction and operation. Additional instrumentation for condition monitoring and more exact fuel and air flow measurements would be helpful. Likewise, we would like to model the simple centrifugal compressor and turbine in CFX, for which it would be useful to have the geometrical parameters of the turbine in suitable software.

Our lab has many types of equipment, some designed and built by students and Faculty or by physical plant personnel, and some purchased outright and either modified or used as acquired. Hence, we have developed over the years certain perspective as to durability and effectiveness of teaching equipment as related to manufacturer support. The success of the SR-30 in our lab is due in no small measure to solid manufacturer support.

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Bio

Horacio Perez-Blanco teaches gas turbines, thermodynamics, vibrations and runs the Thermal Energy Systems lab at Penn State. His research embraces design and control of cogeneration systems, and fluid flow around gas turbines blades. He is also interested in blade heat transfer, and in the measurement of rapidly varying temperatures, such as those arising in IC engines. He is Regional Editor of Applied Thermal Engineering and an ASME fellow.

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