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TURBINE-ENGINE APPLICATIONS OF THERMOGRAPHIC-PHOSPHOR TEMPERATURE MEASUREMENTS

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EXTENDED ABSTRACT

The thermographic-phosphor (TP) method can measure temperature, heat flux, strain, and other physical quantities remotely in hostile and/or inaccessible environments such as the first-stage turbine components in turbine engines. It is especially useful in situations in which no other known method works well. This paper is a brief review of engine tests that demonstrated the utility of the TP method. For the most part, the results presented here are discussed only qualitatively. The papers in the bibliography describe these and other experiments and results in detail.

The first viewgraph summarizes the many desirable features of the TP method. The second viewgraph describes TPs, and the third summarizes how the TP method works.

To measure single-point temperatures in turbine-engine applications, we use the decay-time method, which depends on the fact that the luminescence following an impulse of ultraviolet excitation decays with a characteristic decay time that is a monotonically decreasing function of temperature over some range of temperatures. The viewgraph is a set of calibration curves showing the behavior of some useful emission lines for ten important TPs. Consider Lu PO_4:Eu as an example. Below the "quenching" temperature near 900 K, the decay time is nearly constant. Above it, the decay time decreases exponentially with the temperature. This strong functional dependence means that one can have a fairly large error in the lifetime measurement, as in environments with poor signal-to-noise ratios (SNRs), yet still obtain high accuracy in the temperature measurement. Our more-recent data up to 1900 K show the same behavior.

Vane Measurements in a Commercial Engine. We used TPs to measure first-stage turbine-vane temperatures in a Pratt & Whitney (P&W) PW2037 engine at P&W, East Hartford, CT. The test affirmatively answered four crucial questions: (1) will the TP coatings survive in an engine environment; (2) can an existing pyrometry probe be modified so that the TP inside the engine can be illuminated by UV and the emitted luminescence be gathered and transmitted by the probe optics; (3) can we detect the luminescence from TP deposited on the first-stage vanes in the presence of a large blackbody background from the burner; and (4), if so, can the luminescence signals be captured with high enough SNR to extract the temperature data?

The viewgraph shows the experiment setup. Other engine-test setups have similar instrumentation. The probe, designed to fit an existing pyrometry port, is required in engine tests. The probe's predetermined

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size and location in the engine place severe constraints on the optics, the experiment geometry, signal levels and SNR, and so on.

The experiment worked so well that we acquired some data for comparison with P&W's thermocouple data. The results show remarkably good agreement.

Measurements in an ATEGG. The maximum surface temperature (≈650°C) of the commercial-engine first-stage components is much lower than that expected in some military engines (≈1200°C). Our next engine tests took place in the more-rigorous military-engine environment

Our first experiment in an advanced turbine-engine gas generator (ATEGG) engine core was to be a durability test of coated blades. The engine core suffered a catastrophic disabling " event" (a separation of the blades from the disk) shortly after being lit, so the TPs saw only a small fraction of their planned operating time. We recovered some of the TP-coated blades from the test. Post-test sectioning and analysis showed that the TP was essentially intact, although it was not possible to determine this quantitatively because of the damage caused to the blades by the event.

We supplied a fully instrumented experiment setup for the second ATEGG test. This engine core also experienced a catastrophic event about 1.4 h after being lit, immediately prior to our scheduled experiments, but we were able nevertheless to get some useful baseline data and solve a number of instrumentation problems that were not apparent in the laboratory.

Four turbine blades were coated on their downstream (cooler, convex) sides with three TPs that covered a broad range of expected temperatures. One vane was coated on its convex downstream side with a medium-temperature-range TP, and another was coated on its hotter concave side with a higher-temperature TP.

We built both a vane probe and a blade probe. Viewgraphs show the experiment layout and the probe designs. The single-optical-fiber vane probe was conceptually similar to that used in the commercial-engine test described above and used the same beamsplitter subassembly. The dual-fiber blade probe viewed the blades at a small angle relative to "edge-on," as shown in the next viewgraph, unlike the perpendicular view of the vanes by the vane probe.

Experiments that use fiber optics and that involve moving test surfaces (such as turbine blades) usually require at least two fibers because of the narrow field-of-view of the fibers. If a single fiber is used on moving parts, the UV-excited spot will move out of the fiber's field of view before any significant signal decay occurs, making a measurement of the decay time impossible. With two fibers, the luminescence-return fiber can often be placed in a good position to view the luminescence decay.

Despite the failure of the core to complete its tests, we obtained valuable information during the windmill tests about the timing and about what we call the moving-blade transfer function. The details on this subject (Noel, *et al.,* 1992) illustrate the fact that, in all experiments involving moving test objects, the observed signal is convolved with a function that results from the test object's motion and the optics. The transfer function varies with the test object's speed and, ideally, the transfer function must be acquired for moving turbine blades at all speeds at room temperature. This obviously cannot be done with the engine lit, but it can be done with the engine windmilling. In addition to some windmilling data, we got one piece of temperature data from a blade at nearly 11000 rpm during a run before the engine core failed, which demonstrates that we can obtain such data. Further, TP signals from a vane were easily measurable with the engine running at 14600 rpm, near its maximum. Blackbody background at that speed was not a problem. Post-test recovery of the blades showed that the TP coatings survived the 1.4 h of lit time.

Measurements on JTDE Vanes. We recently demonstrated that the TP method can measure first-stage vane temperatures in the most-advanced, highest-temperature engines. Because they are immediately adjacent to the burners, the first-stage vanes are subject to the highest-amplitude blackbody backgrounds in the engine. The pressure side of the vanes sees both direct and reflected blackbody background, whereas the suction side primarily sees reflected radiation. We did the experiment in a prototype joint technology development engine (JTDE) at Pratt & Whitney, West Palm Beach, FL. The experiment layout is very similar to that used in the instrumented ATEGG test, but is somewhat simpler schematically because it uses only one probe.

In previous engine tests, the probes often proved to be the weakest component, both optically and in terms of mechanical durability. The optics cannot be optimum because our probe designs are constrained — by the inordinate expense required to modify the engine to accept a developmental diagnostic — to be adapted to existing pyrometer or borescope ports and to existing pyrometer probes. The probes are subject to tight tolerances, close fitting, incompatibility of parts and materials, the need for adjustability because of test uncertainties, and so on, that sometimes suffer in the extreme environment inside the engine. The probe design for the JTDE test incorporated features from previous designs as well as innovations aimed at securing better performance and reliability. It included a custom-designed turning mirror, all UV-grade optical elements, and internal filtering to block intense, short-duration blue light generated in the optical fiber.

Based on laboratory testing, previous usage, and the expected engine temperatures, we deposited a high-temperature TP, YAG:Tb, on the higher-temperature pressure side of one vane and a mediu-temperature TP on the cooler suction side of the adjacent vane. As it turned out, the engine ran cooler than expected, so we could have chosen a more nearly optimal pair. This would have also improved the SNR, because — among other reasons — we could have used a more-efficient operating wavelength for the laser, rather than the 266 nm that was chosen to accommodate the YAG:Tb.

The viewgraph shows the temperature data *vs* normalized fractional rpm. Despite the large error bars, the data appear reasonable, the trends on the independently acquired curves being similar to the extent allowed by the small quantity of data. Note the large difference in temperature of the two vane surfaces at the same rpm. This result is within the bounds of the uncertainty in the theoretical calculation of the temperature.

The TP on the turbine vanes survived more than 51 h of testing. No previous engine test had lasted more than 1.4 h, so we obtained a new durability baseline. Examination showed that the TP had eroded somewhat, but it was not possible to evaluate the fraction of TP remaining quantitatively, because we could not access the vanes.

Temperatures of Ceramic Components in Turbines. TPs appear to offer a good method for temperature measurements in improved-efficiency gas turbines now being developed for use as jet engines, electrical-power generators, and automotive engines that will contain ceramic or ceramic-coated components. Ceramics allow engines to run at much-higher temperatures than the superalloys in today's engines can survive. Some experts concede that pyrometry is not likely to work there for two main reasons. First, pyrometry requires high emissivity, but ceramics have low emissivity. Second, it appears that ceramics become translucent at high temperatures. If so, the pyrometry cannot measure surface temperature because the blackbody radiation from the ceramic, which is what the pyrometry measures, will come from a distribution of points that extends into the body of the material. On the other hand, TP measurements do not depend on the emissivity. They are deposited in thin films directly onto the surface, so measurement of the surface temperature is guaranteed. Finally, recall that TPs are themselves ceramics. This fact has a number of important implications, among them the possibility that TPs can be incorporated into the ceramic components when they are being fabricated, thus forming an integral, permanent temperature diagnostic.

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This presentation is a review of turbine-engine tests that demonstrate the utility of the thermographic-phosphor (TP) method of measuring temperature remotely in difficult and/or adverse environments where no other known method works satisfactorily.

The physical principles behind the method and details on such topics as TP selection,coating methods, etc., are covered thoroughly in the papers cited in the bibliography.

THERMOGRAPHIC-PHOSPHOR TEMPERATURE MEASUREMENT

Thermographic Phosphors (TPs) can measure static, dynamic, or steady-state temperature, heat flux, strain, ...

- at a single point or over an entire surface
- with diffraction-limited resolution
- remotely and nonintrusively
- with exceptionally high background and interference rejection
- over an immense temperature range (0 K to >1900 K established)
- independently of emissivity and geometry
- with high accuracy

The TP method is especially useful in hostile and/or inaccessible environments!

What Are TPs?

TPs are rare-earth-doped (or -activated) ceramics and similar compounds

- Eu, Dy, Tb, Pr, Tm, ...
- Group III metal oxides: Y_2O_3:Eu
- Group III metal oxysulfides: La_2O_2S:Tb
- Orthophosphates: $LuPO_4$:Eu
- Vanadates: YVO4:Dy
- Yttrium aluminum garnet (YAG) : YAG:Dy
- Fluorogermanates: $Mg_4(F)GeO_6$:Mn
- Etc.

PHOSPHOR-SELECTION CRITERIA

- Must be a thermometer in the temperature range of interest
- Must be chemically stable in the expected environment
- Must have enough luminescence amplitude to be detectable in the environment

Results must be reproducible (for example, with temperature cycling)

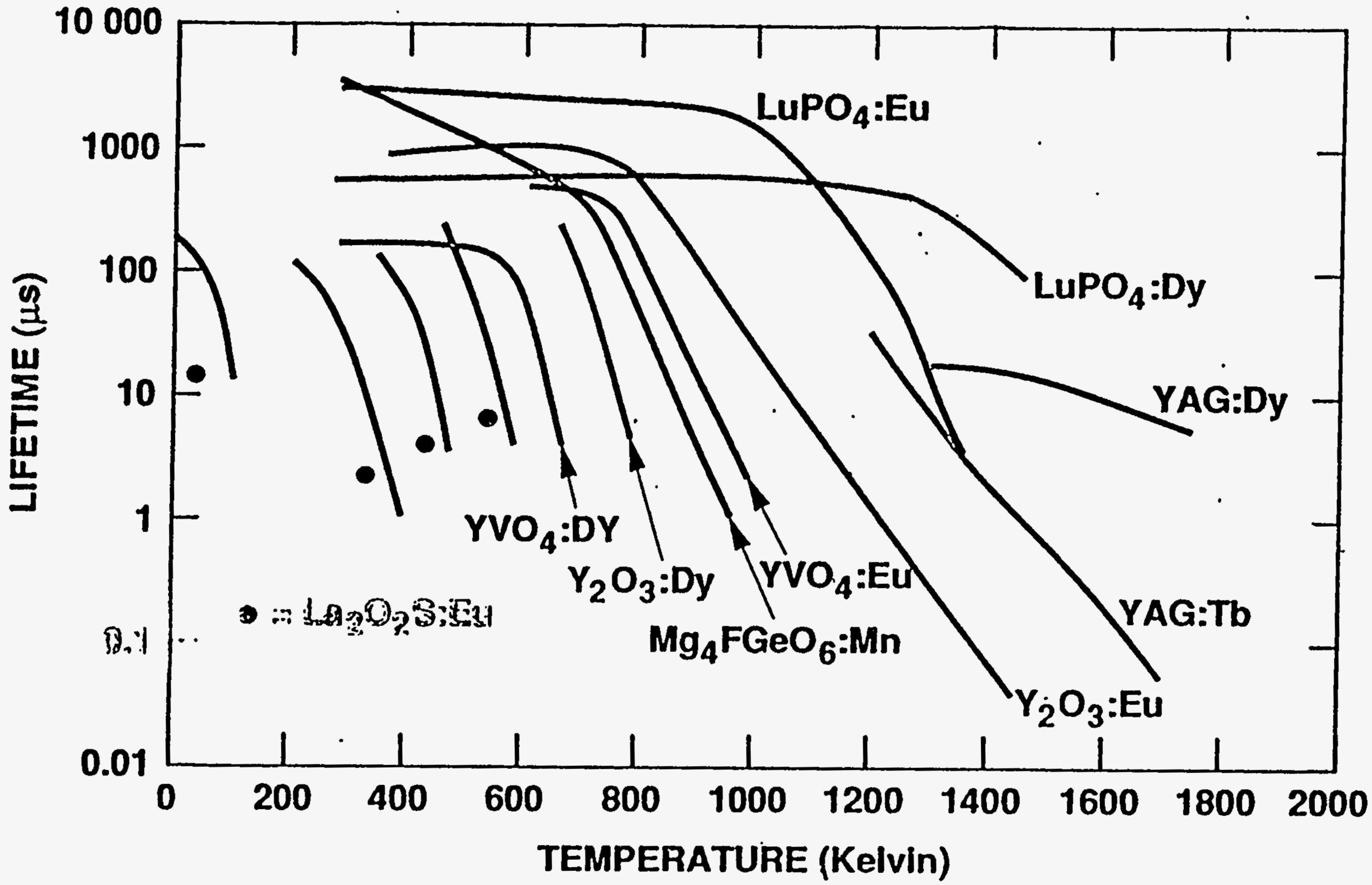
HOW THE TP METHOD WORKS

- Deposit TP on a surface whose temperature is to be measured
- Induce visible fluorescence with an ultraviolet source (laser or lamp)
- Detect desired emission line(s)
- Use decay-time method: measure fluorescence-decay time (pulsed or optically chopped UV source)

or

- Use ratio method: measure amplitudes of two emission lines and take their ratio (cw or dc source)
- Relate observed decay time or amplitude ratio to temperature

Phosphor-Lifetime Temperature Dependence



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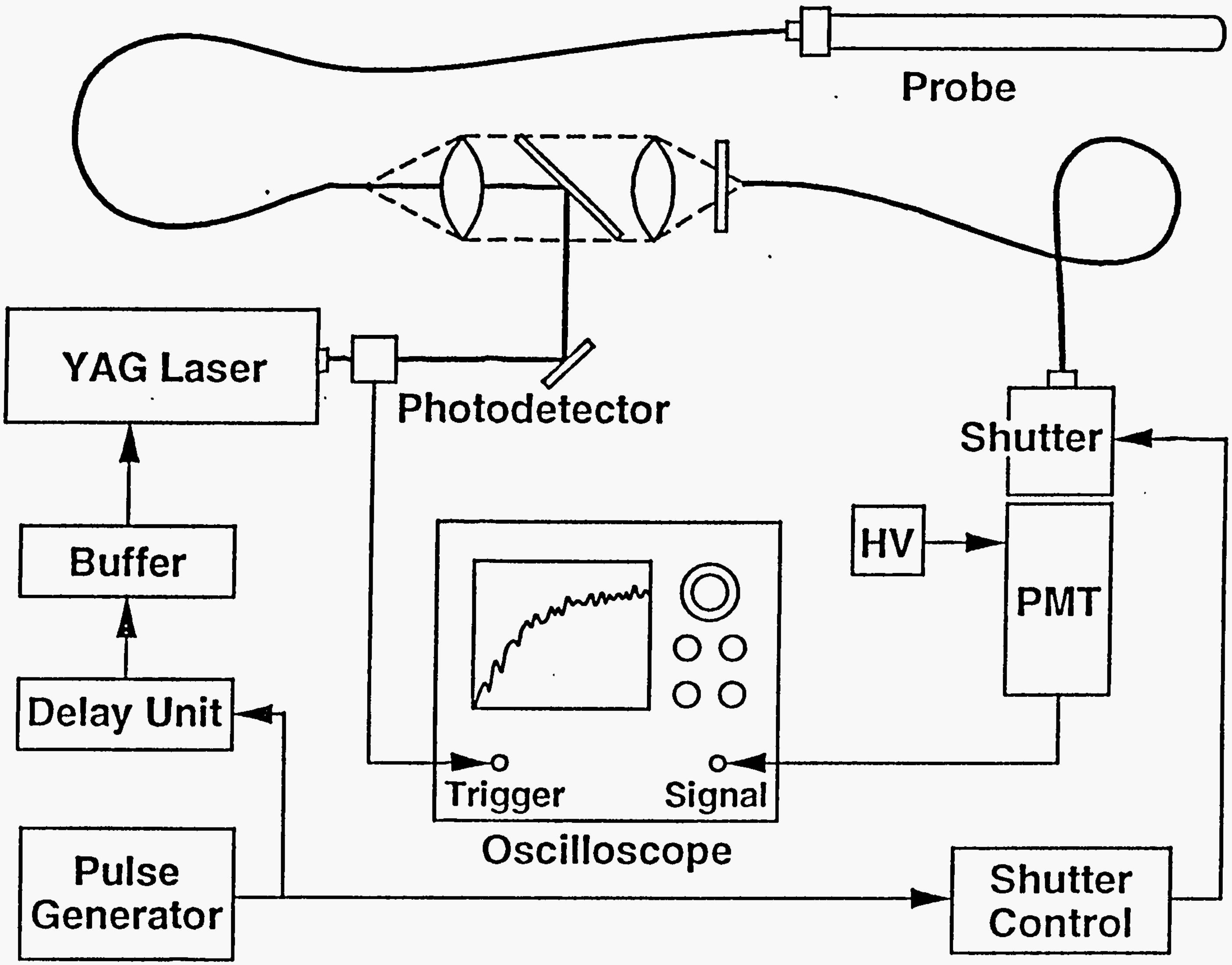
CRUCIAL QUESTIONS ANSWERED BY PW2037 TEST

1. Will the TP coatings survive in an engine environment?

2. Can an existing pyrometry probe be modified so that the TP inside the engine is illuminated by UV and the emitted luminescence is gathered and transmitted by the probe optics?

3. Can we detect the luminescence from TP deposited on the first-stage vanes in the presence of a large blackbody background from the burner?

4. If so, can the luminescence signals be captured with high enough SNR to extract the temperature data?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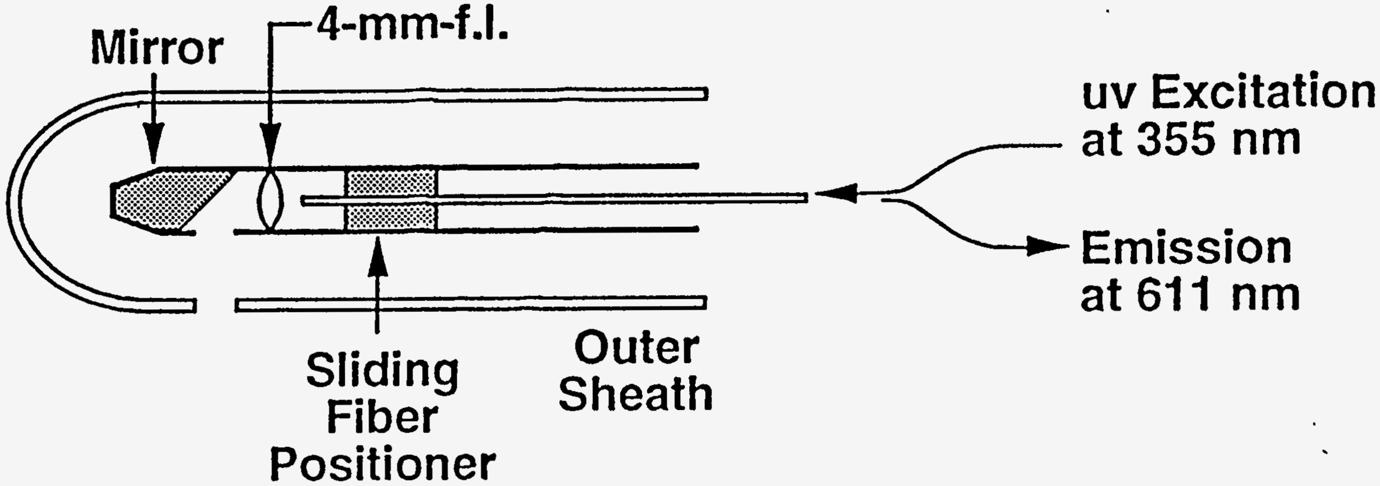
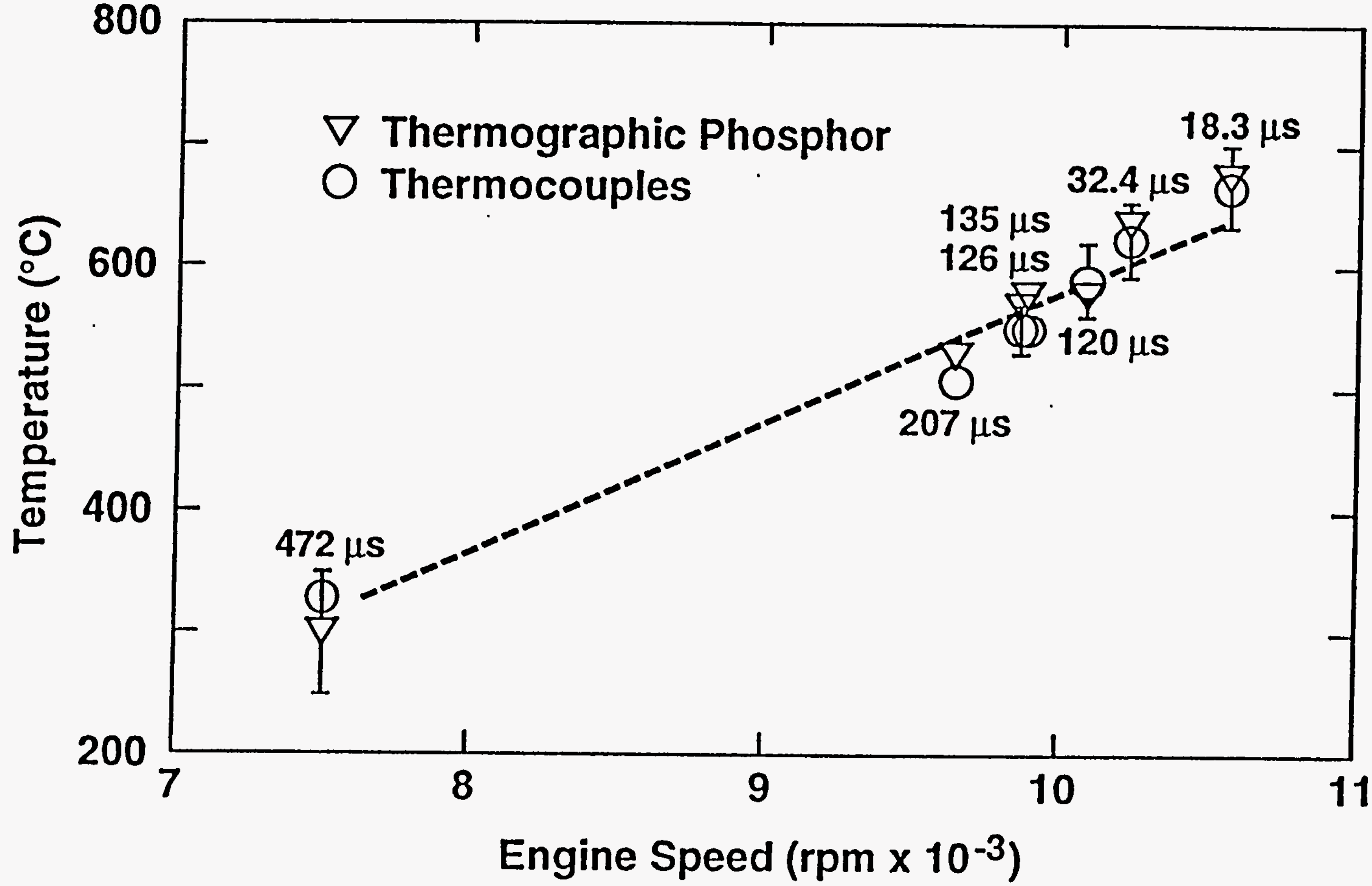
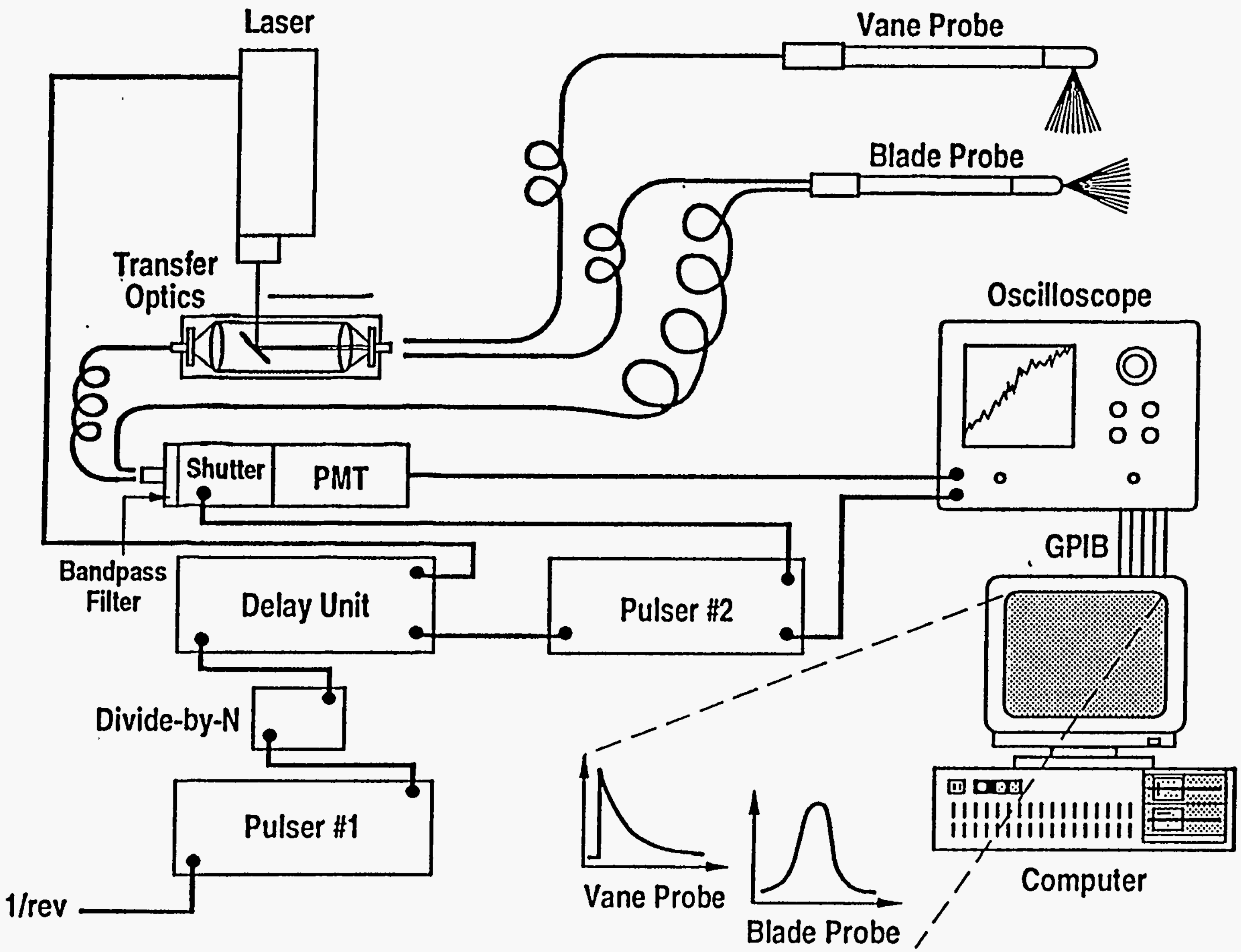
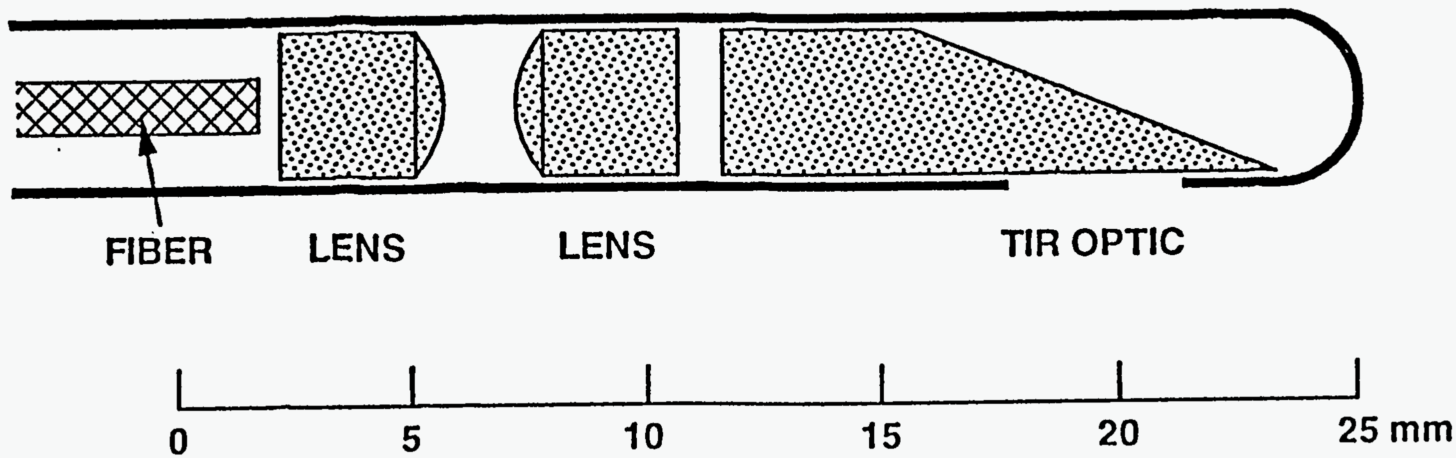
YAG Laser
Photodetector
Shutter
Buffer
HV
PMT
Delay Unit
Trigger
Signal
Oscilloscope
Pulse Generator
Shutter Control


Mirror
4-mm-f.l.
uv Excitation at 355 nm
Emission at 611 nm
Sliding Fiber Positioner
Outer Sheath



Thermographic Phosphor
Thermocouples
472 µs
207 µs
135 µs
126 µs
120 µs
32.4 µs
18.3 µs
Temperature (°C)
800
600
400
200
7
8
9
10
11
Engine Speed (rpm x 10-3)


Laser
Vane Probe
Blade Probe
Transfer Optics
Oscilloscope
Shutter
PMT
GPIB
Bandpass Filter
Delay Unit
Pulser #2
Divide-by-N
Pulser #1
1/rev
Vane Probe
Blade Probe
Computer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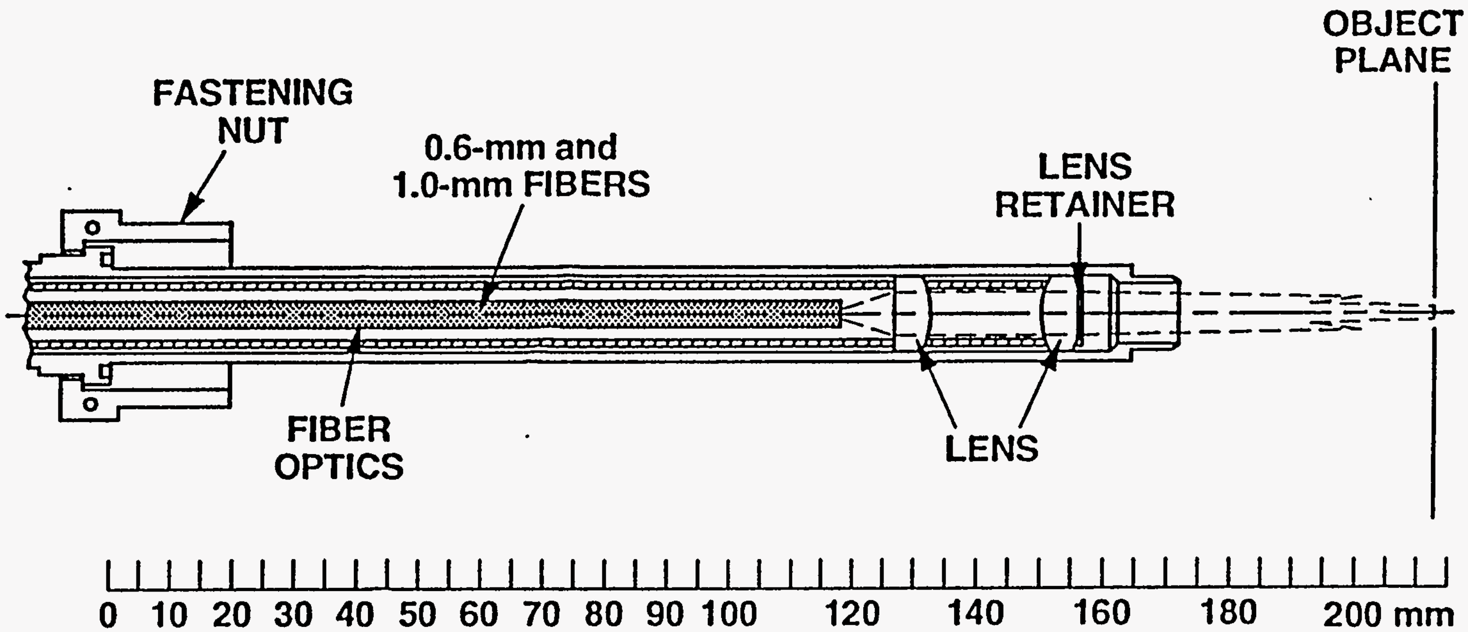
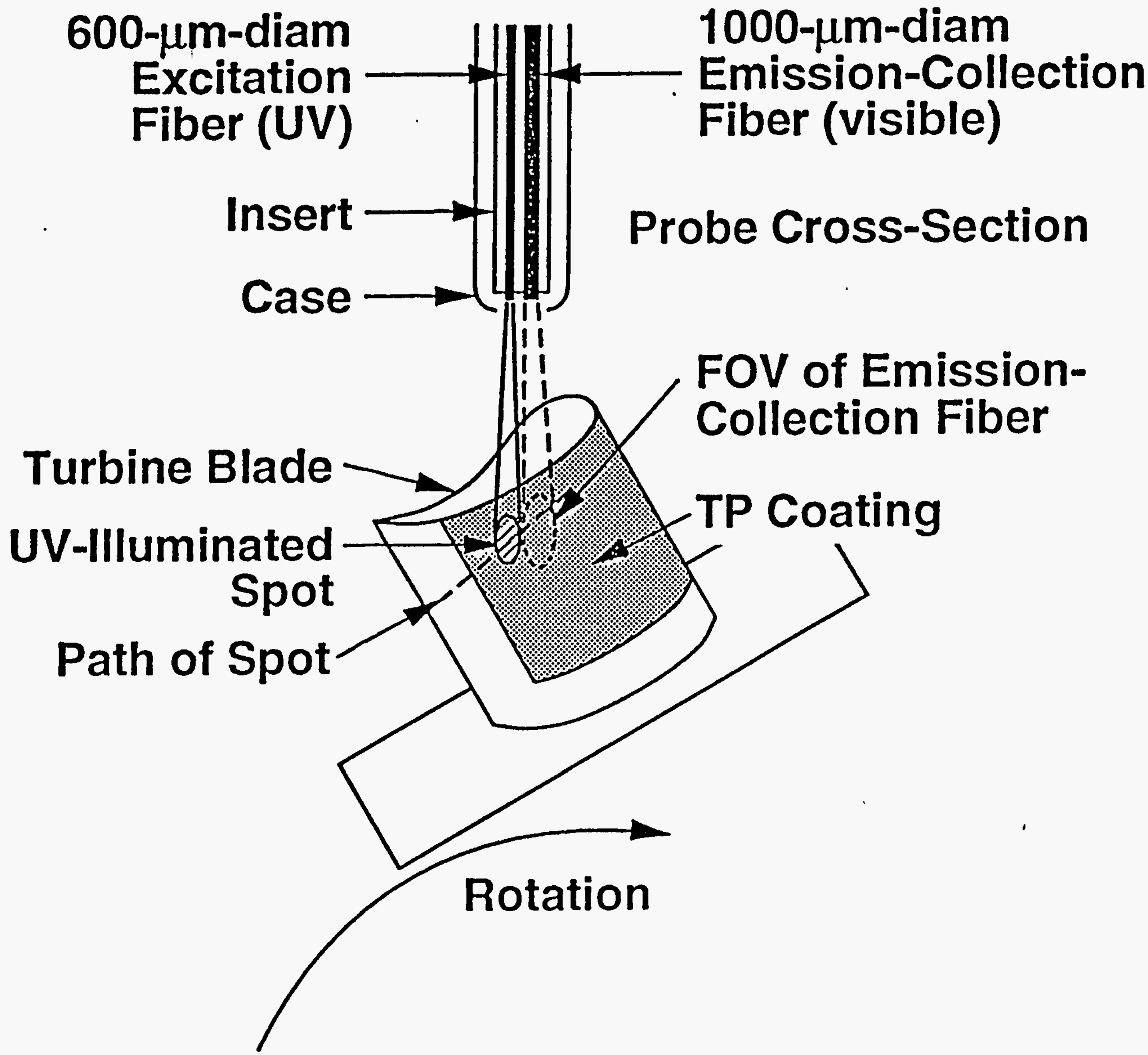
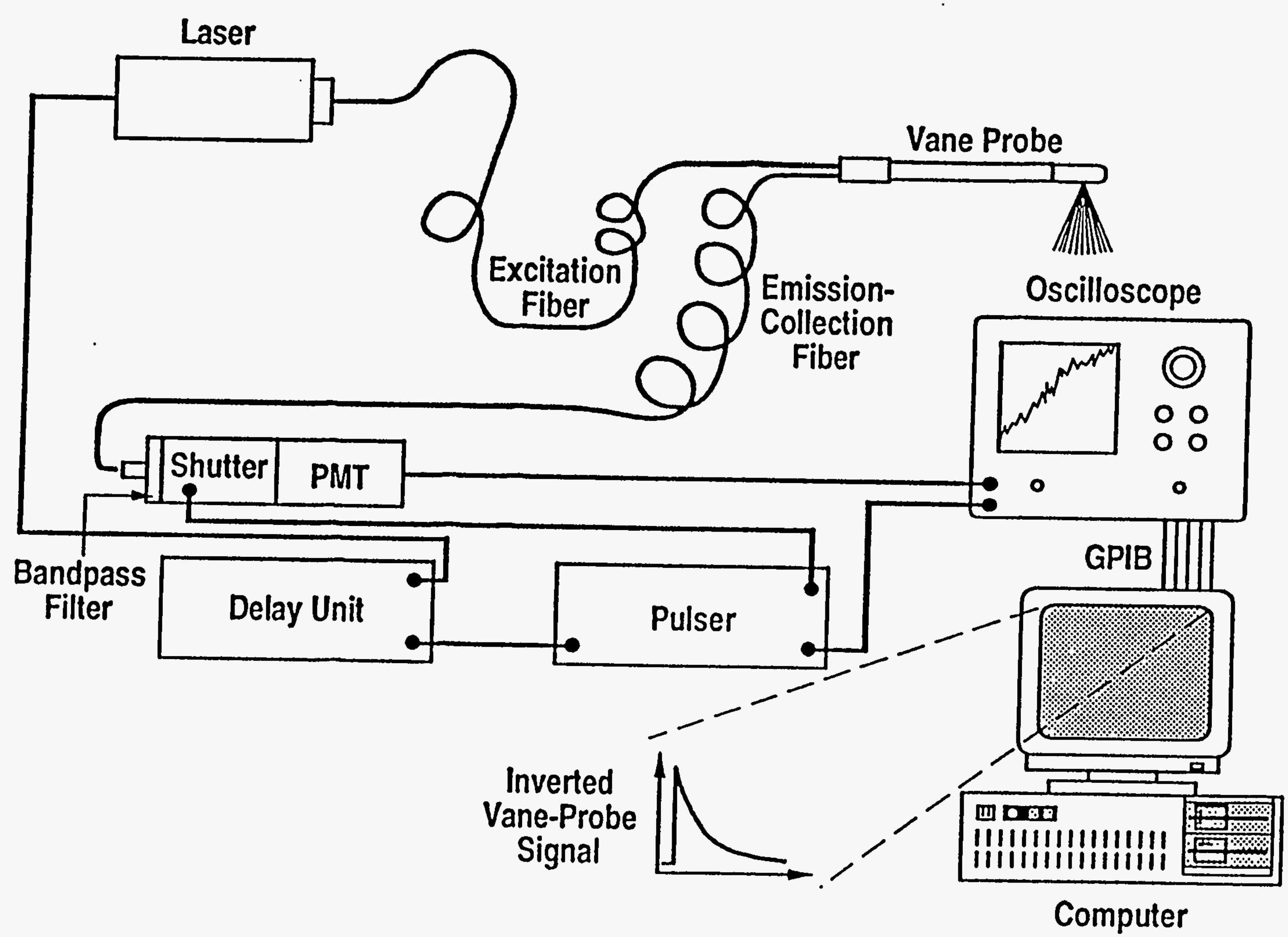
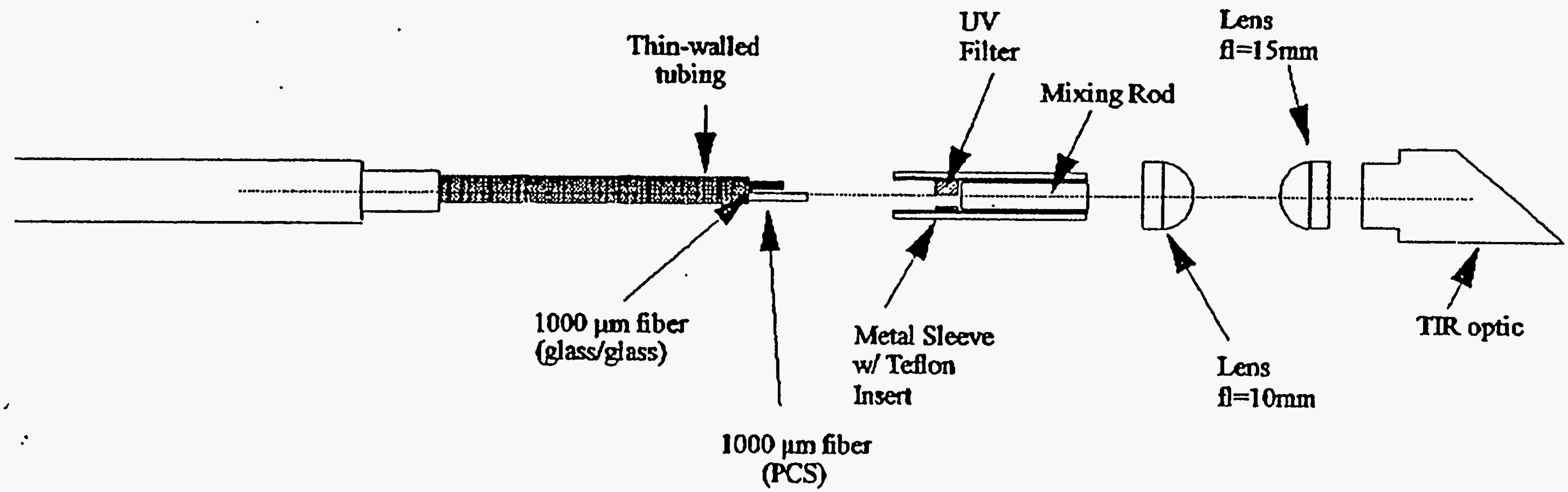
LENS
LENS
TIR OPTIC
0
5
10
15
20
25 mm

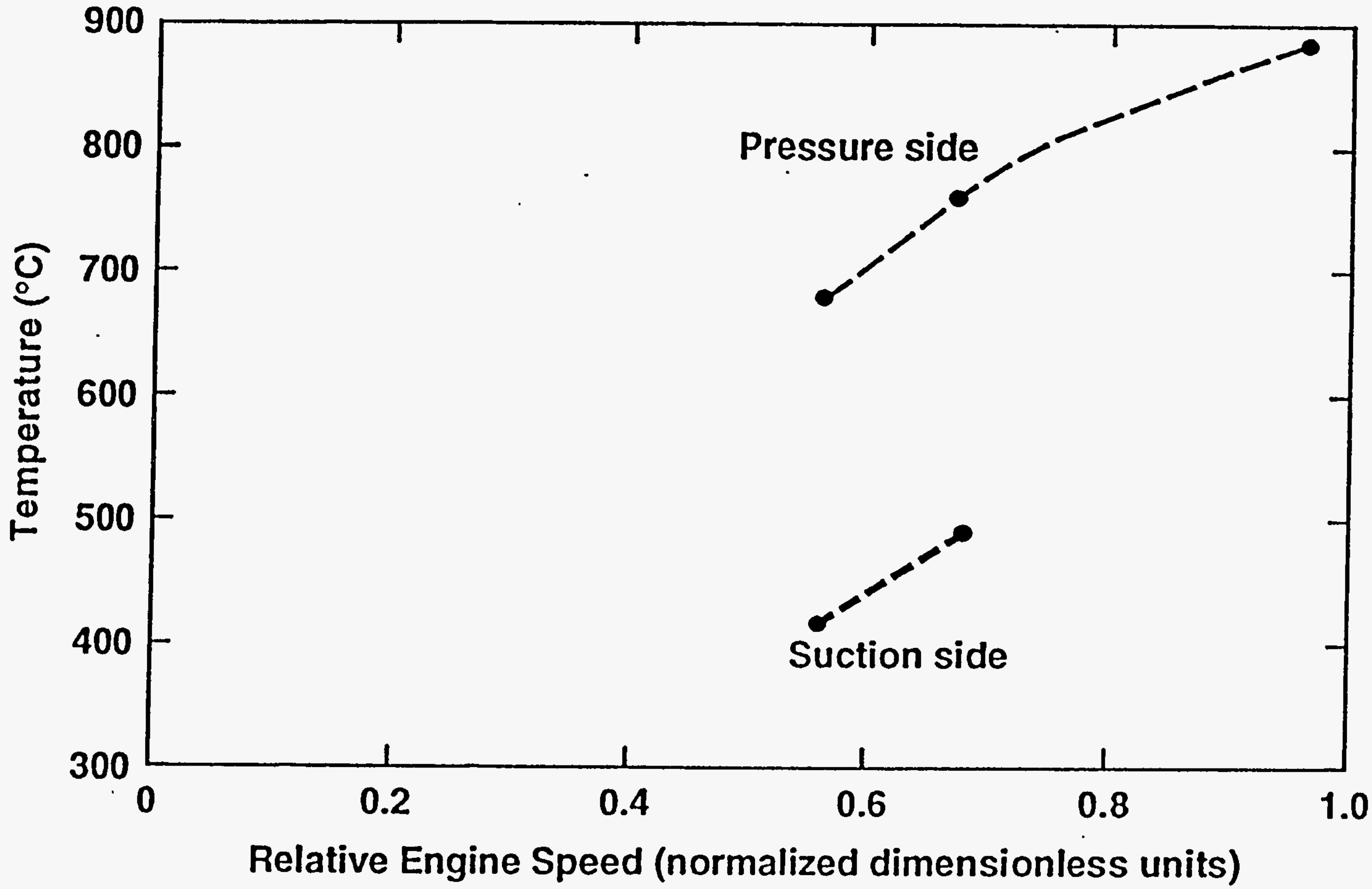

FASTENING NUT
0.6-mm and 1.0-mm FIBERS
LENS RETAINER
OBJECT PLANE
FIBER OPTICS
LENS
0 10 20 30 40 50 60 70 80 90 100 120 140 160 180 200 mm



600-µm-diam
Excitation
Fiber (UV)
1000-µm-diam
Emission-Collection
Fiber (visible)
Insert
Probe Cross-Section
Case
FOV of Emission-
Collection Fiber
Turbine Blade
TP Coating
UV-Illuminated
Spot
Path of Spot
Rotation


Laser
Excitation Fiber
Emission-Collection Fiber
Vane Probe
Oscilloscope
Shutter
PMT
Bandpass Filter
Delay Unit
Pulser
GPIB
Inverted Vane-Probe Signal
Computer


Thin-walled tubing
UV Filter
Mixing Rod
Lens fl=15mm
1000 µm fiber (glass/glass)
1000 µm fiber (PCS)
Metal Sleeve w/ Teflon Insert
Lens fl=10mm
TIR optic


Temperature (°C)
900
800
700
600
500
400
300
Pressure side
Suction side
0
0.2
0.4
0.6
0.8
1.0
Relative Engine Speed (normalized dimensionless units)

TP MEASUREMENTS ON CERAMIC COMPONENTS

The TP method appears to be an excellent method for measuring the temperature of ceramic components

1. Ceramic components have low emissivity; the TP method does not depend on the emissivity.

2. Ceramics may be translucent at high temperatures.

   Equivalent blackbody radiation comes from somewhere inside the material

   Pyrometry will measure that temperature.

   The TP method measures the surface temperature.

3. TPs may be fabricated as part of the material: an integral permanent diagnostic.