# Detecting Abnormal Turbine Engine Deterioration Using Electrostatic Methods

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**A method of detecting abnormal turbine engine deterioration has been developed and tested. The method observes pulse electrostatic signals in the exhaust which have been determined to originate from component rubbing, chaffing, erosion, and burning (i.e., various forms of deterioration). The normal (healthy engine) deterioration rate is first studied as a function of engine cycling and power. This deterioration rate is then normalized with an engine power and an engine cycling parameter. Tenfold increases in the normalized deterioration rate are then used as an indication of impending component failure. Experience shows that about two out of three turbine engine gas-path failures can be predicted four or more hours ahead of time by this method. The false alarm rate is estimated to be about 5%.**

## Introduction

### Early History

IN 1970, an Air Force Institute of Technology (AFIT) student discovered that some jet engine gas-path failures are preceded by an increase in electrical activity in the jet exhaust gases. At first the electrical activity was thought to be simply individual charged particles striking the electrostatic probe.[1] Particle ingestions and simulated particle generating distresses did not, however, make the same signals that had originally been interpreted as individual particles and engine data taking was terminated. Finally, Sajben, Peng, and Shaeffer[2] determined that the signals were actually Trichel pulses (a form of repetitive corona discharge) from high potential pockets of excess charge. However, they could find no definite physical process linking the pockets of charge and engine distress; they found only that there was definite statistical evidence that pockets of charge did precede some engine failures.

### Recent History

Since the charged pocket interpretation was set forth, controlled high-speed rub and burn experiments have been performed by AFIT students both in the laboratory and on a small jet engine.[3-5] It has been found that the signals are generated when thousands of tiny metal particles (5-100$\mu$) are separated from internal engine component surfaces in "bunches" as rubs and burns occur, forming a pocket of excess charge. The number and size of these charged pockets (pulses 5-30 ms wide) has been found to follow a trend during normal engine running which parallels the expected physical deterioration rate of engine gas-path parts. In addition, a method of normalizing the data using the average dc level in the exhaust[6] (which is a function of turbine inlet temperature and mass flow rate) and the time rate of change of rpm squared has been developed. The result is a 10-channel digital trending system[7] (2 channels of predicted deterioration and 8 channels of measured/analyzed electrostatic activity) which results in a nearly constant digital electrostatic output independent of engine power setting, inlet temperature, and cycling rate. Increases in the output on any electrostatic channel indicates gas-path distress or impending component failure. It is suspected that signatures will be unique as to engine section, such as compressor, combustor, and turbine, but this can only be verified by accumulating large amounts of statistical data.

It has been concluded that an electrostatic system can function (at least on the ground) as an overall gas-path deterioration monitor and condition indicator and has the potential of becoming a diagnostic tool capable of isolating the engine section which is undergoing accelerated deterioration.

### Current Activities

A joint Air Force/Navy program is well underway to develop/apply the method in-flight to the A-7D&E (TF 41 engine). Results to data indicate that the method requires no additional compensation for flight use.

This paper discusses the method in general, which is basically a three-step process of selecting sensors and quantifying the signals observed by these sensors, normalizing the data, and establishing warning criteria. Estimates of the potential of the method will then be presented based on 25 actual case histories with electostatic probes in operation, and an engineering analysis of 358 engine teardown inspections. A recent case history will then be presented as an illustation of this method.

## Electrostatic Method

The basic method involves placing electrostatic sensors in the jet exhaust, electronically quantifying the signals observed to these sensors, and then normalizing and trending the number, size, and polarity of these signals which, when they exceed a warning level, indicate an impending failure.

### Sensors and Quantifying Electronics

A number of sensors can be used; for example, a single insulated rod could be used or an insulated surface could be placed on an existing strut or pressure probe. The principal requirement is to have an insulated metal surface in the engine exhaust.

Two sensors have been developed for the TF 41 engine application (see Fig. 1) in an attempt to examine the failure signaturing capabilities of the method. These consist of a semicontinuous electrostatic surface (called a ring probe) and a triangular wire (called a grid probe) placed in the exhaust. The ring probe is constructed from standard 1/16-in.-thick printed-circuitboard material which is bolted and epoxied in the tailpipe. The three segments shown in Fig. 1 are externally wired together to form a nearly continuous ring which every pocket of charge must pass through in exiting the engine. The

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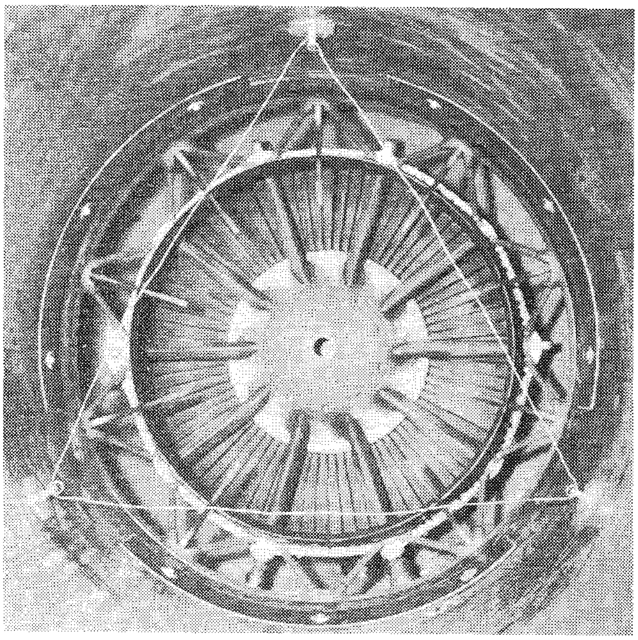

Fig. 1 Ring and grid probes in TF41 exhaust.

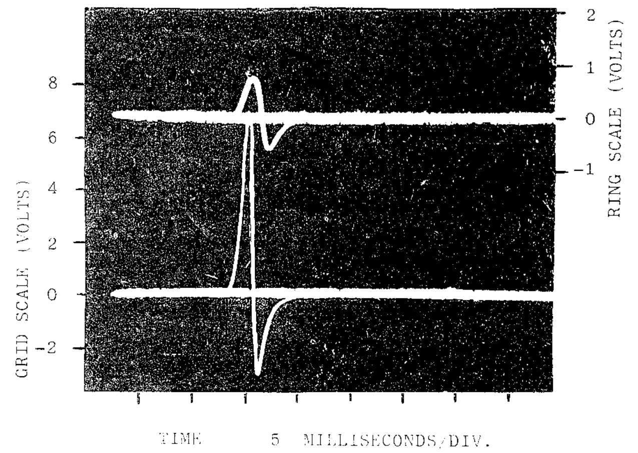


Fig. 2 Typical pocket pulses observed on ring and grid probes during snap deceleration (known HPT-1 rub).

grid probe, which is 10 in. downstream from the ring probe, is made of 3/32-in. Hastalloy-X wire strung through three insulated eyelets bolted in the tailpipe wall. The triangular shape was selected because it gives a reasonable average of the exhaust with minimum complexity and also has a low drag. A typical pocket signal, as observed with these sensors, is shown in Fig. 2.

The signals from the sensors are counted (the polarity and number above a preset threshold) and sized (the polarity and area above a preset threshold) in an analog signal processor (see Fig. 3). Additional details of the electronics may be found in Ref. 7. The counting thresholds are normally set at a factor of two times the maximum noise level. This system has eight digital outputs from the analog signal processor. They are:

| | | | |
|---|---|---|---|
| Ring outputs: | + pulse count | Grid outputs: | + pulse count |
| | − pulse count | | − pulse count |
| | + area count | | + area count |
| | − area count | | − area count |

These eight channels are used experimentally in an attempt to signature failures. The five failures observed to date with this signaturing system have had a unique distribution of counts.

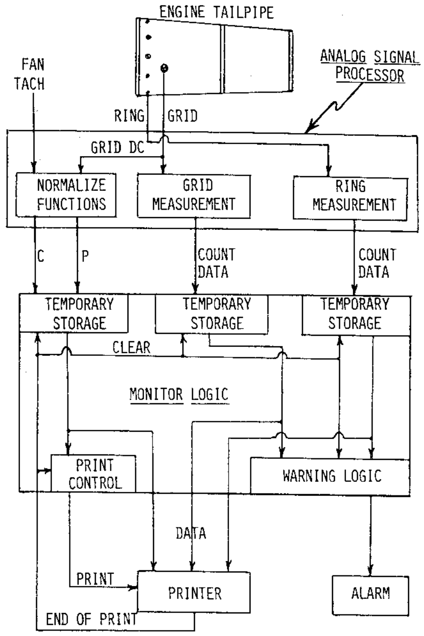


Fig. 3 Block diagram of deterioration monitor.

**Normalizing the Data**

In general, the number of pockets observed in the exhaust varies with both engine power $P$ and engine cycling $C$. In addition, there may be some unique flight factors $F$. The only unique flight factor anticipated is the run-in phenomena expected for a new engine/airframe. We anticipate excess rubbing caused in the first few flights from aerodynamic, acceleration, and gyroscopic loads as well as initial seal "rub-in." The flight tests on an older A-7E at Patuxent River Naval Air Station have shown no unique flight factors. In practice, the procedure simply involves studying the number of pockets as a function of power, cycling, and flight operating for a few hundred hours on a healthy engine and then curve-fitting the count data. The process is described mathematically by the equation

$$R = \frac{\text{observed pulse count}}{K_1 \times P + K_2 \times C + K_3 \times F} \tag{1}$$

where $R$ is the normalized count ratio and the constants ($K_1$, $K_2$, $K_3$) and functions ($P$, $C$, $F$) are determined from empirical observations of a healthy engine over a variety of operating conditions. The power function $P$ could be derived from thrust, burner pressure, time at temperature, or even possibly fuel flow. The cycling function $C$ may not be required for bomber, transport, or airline operations since little cycling occurs. In fighter operations, a rate of change function is recommended.

For the TF 41, a convenient power function has been the dc current in the exhaust. Figure 4 shows a plot of the dc current as a function of turbine inlet temperature (approximate thrust is also shown). It is a rapidly increasing function of temperature and is close to zero until the temperature reaches about 1750°F (about 9000 lb of thrust). This power function may be useful for any engine with a turbine inlet temperature of 1800°F or more. Figure 5 shows that for steady power operation, the pulse count rate varies linearly with the dc current. It also shows that for rapid engine cycling the count rate is higher than expected from the mean dc current (or engine power). This illustrates the need for a cycling factor $C$ to normalize the count rate data. The cycling function used for the TF 41 is the time deriative of the fan rpm squared.

It has been found convenient to perform the division indicated by Eq. (1) by accumulating digital pulses proportional to the power function $P$ and cycling function $C$ until they reach a fixed total (see Fig. 3, monitor logic). In other words,

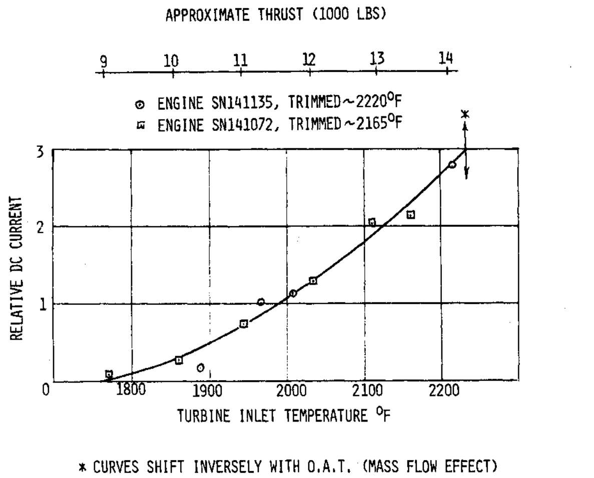


**Fig. 4 Relative dc current vs turbine inlet temperature for two differently trimmed TF41 engines at an outside air temperature of ~86°F.**

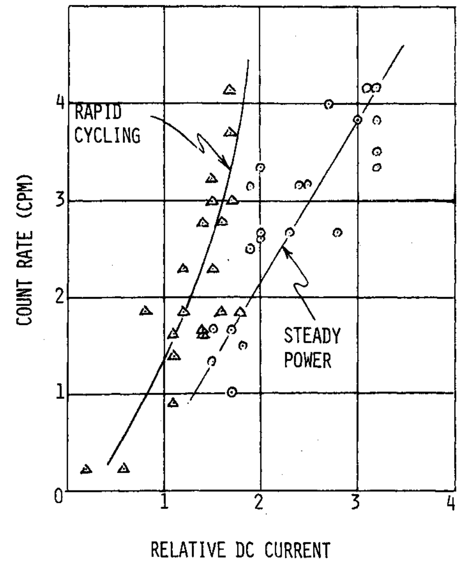


**Fig. 5 Pulse count vs relative dc current for steady power and rapid cycling.**

if the numerator (actual sensor pulse count) is checked when the denominator (predicted pulse count) reaches a fixed level, this is equivalent to counting both for a fixed period of time and then performing the division. The process of checking the actual pulse count at fixed predicted pulse counts leads to better counting statistics. It has the disadvantage that samples may be unequally spaced in time.

#### Warning Criteria

Having selected a set of sensors, quantified the signals to the sensors, and normalized power and cycling effects, warning criteria must then be established. In order to establish warning criteria, actual failures must be observed and only experience can lead to a valid set of criteria. Our experience from 11,000 h of test-stand operations where 25 actual failures or severe distresses requiring attention have occurred has led to the following set of warning criteria:

1) If $R \geq 10$ for three samples in a row, give warning.

2) If $R \geq 50$ for any single sample, give warning.

3) If any significant count occurs at idle, give warning. The sampling method we use produces a sample about once every 5 min at steady high power.

## Failure Prediction Capabilities

The electrostatic method is unique in that it is the only known method of monitoring gas-path debris in real time. In an attempt to estimate the ultimate potential of this debris-monitoring concept, a survey[8] was made of nearly 360 failure cases from overhaul teardown reports. Engineering judgments were made as to the timeliness of particle emission as an indicator of impending failure. It was found necessary to divide failures into actual failures, which would result in loss of power and an inflight shutdown (76 cases), and "potential failures," which consisted of broken and burned components requiring repair or replacement. For "potential failures," severity of the failures had not yet progressed to the point where an inflight shutdown or loss of power would occur (282 cases). Four categories of engineering judgment were used:

1) Certain. There is definite evidence to indicate particle emission was both timely and of sufficient quantity to be detectable.

2) Possible. There is evidence to indicate particle emission prior to failure, but the quantity is in doubt.

3) Indeterminant. There is not enough evidence to make a reliable engineering judgment.

4) Definitely not. There is definite evidence that particle emission was not timely or did not occur.

Table 1 summarizes the study results along with our actual experience of observing 25 failures with an electrostatic system in operation. The actual electrostatic probe prediction capabilities agree reasonably well with what was projected, except in the turbine section. It seems to be performing slightly better in the turbine section than the original projections. The statistics of having observed only 25 actual failures makes any detailed comparison difficult. When one considers only the overall record for failures and assumes that one-half of the "indeterminant" cases would have been predicted, an overall capability of about 59% is projected. This is not far from the observed 72% capability. It is probably more realistic to say that both the projected and observed capability are approximately two out of three.

**Table 1 Comparison of the projected and actual prediction capabilities of a real-time engine gas-path debris monitor**

| | Projections for potential failures, % | | Projections for potential failures, % | | |
|---|---|---|---|---|---|
| Engine section | Indeterminant | Possible or certain | Indeterminant | Possible or certain | Observed/predicted failures |
| Fan | 1 | 12 | 0 | 25 | 0/0 = ? |
| Compressor | 6 | 70 | 20 | 43 | 2/4 = 50% |
| Combustor | 8 | 92 | 32 | 63 | 6/7 = 86% |
| Turbine | 17 | 31 | 11 | 61 | 9/11 = 82% |
| A/B nozzle | 3 | 37 | 0 | 25 | 1/3 = 33% [a] |
| Overall | ... | ... | ... | ... | 18/25 = 72% |

[a] These are failures in the exhaust system; probes are not used in the A/B.

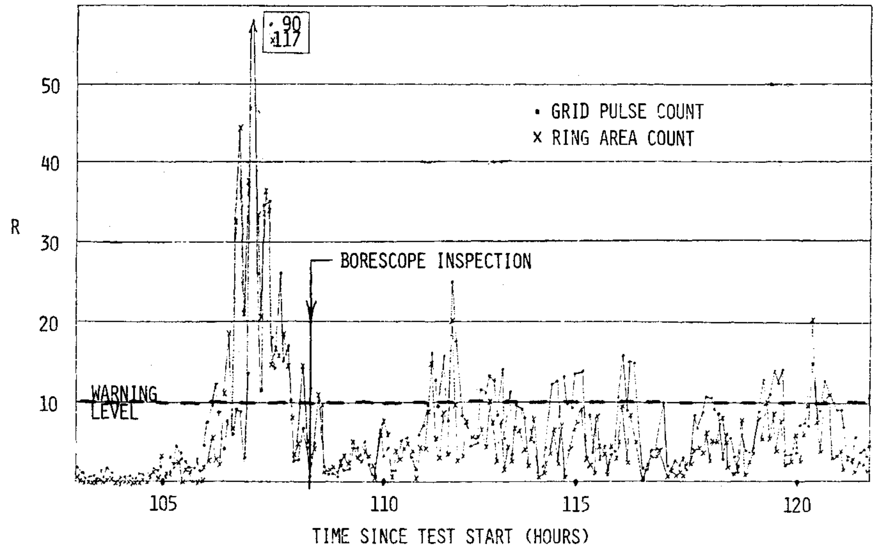


**Fig. 6 Normalized count $R$ vs time during recent case history.**

There have been three false alarms, all of which occurred early in the program. Two of these are suspected to have been from stray pickup, and this problem has been solved by recent improvements in electronics. The third was chaffing combustor cans where large quantities of debris were exiting the engine and the system was responding correctly; however, this excessive chaffing could have continued for hundreds of hours before an actual failure. We, therefore, call this a false alarm. Discounting the two suspected cases of stray pickup, the false alarm rate is estimated to be one out of nineteen total alarms, or about 5%.

## Recent Case History

Most of the failure predictions discussed in the last section were "after the fact" correlations. As a final proof test, the complete normalizing and trending system was assembled by Baker[7] and placed in operation on a TF 41 undergoing endurance testing. During the test, a normalized count history as shown in Fig. 6 was observed. For the first 105 h, $R$ never exceeded 4. A warning was issued, the engine run was stopped, and a borescope inspection (mainly of the high turbine) was performed. No damage was found. Because the rate remained high, we persisted in maintaining that, upon teardown, significant damage would be found in the engine. The teardown, occurring after Baker's thesis had been defended and published, revealed that one combustor can airscoop had broken into three separate pieces and five others had large cracks.

## Summary

A simple electrostatic method of reliably predicting two out of three gas-path failures has been developed. The method is now ready for application and both the Air Force and the Navy are involved in applying the method as a new tool in engine health monitoring. The method is capable of predicting a large class of failures previously thought to be unpredictable, as well as nearly all of those which are predictable by more standard gas-path trending methods.

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