The Gas Turbine-Air-Cleaner Dilemma

MARK G. MUND
Senior Engineer,
Donaldson Company, Inc.,
Minneapolis, Minn.

THOMAS E. MURPHY
Associate Professor,
Institute of Technology,
University of Minnesota,
Minneapolis, Minn.
Mem. ASME.

The person confronted with the selection of a gas-turbine air cleaner is faced with a dilemma because the data available to guide his selection are inconsistent and not complete. The need for air cleaners has been established. The level of air-cleaner efficiency required to protect the gas turbine from the effects of dust ingestion has not. This paper reviews the data available and relates it to Donaldson Company experience. Air-cleaner specifications and how they are influenced by gas-turbine needs and experience are discussed. Today's gas-turbine air cleaners and what they will do are reviewed. The paper concludes that it is essential to determine the level of air-cleaner protection required by the various gas turbines and suggests programs to determine it through laboratory and field tests. Further work in air-cleaner and gas-turbine design is suggested to obtain an optimum gas-turbine air cleaner and to obtain long-life gas turbines.


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THE DILEMMA

The man who must select an air cleaner for a gas turbine is faced with a dilemma. Dilemma, according to Webster, implies that all alternatives are unpleasant. Although no longer an alternative, the fact that an air cleaner is necessary at all is unpleasant -- at least to the gas-turbine builders and users. After all, the air cleaner adds nothing to the power output, it does not improve response, nor fuel economy, nor does it reduce weight, space or cost. Its sole job is to keep dust out of the engine. The man faced with selecting an air cleaner -- which he really doesn’t want -- for his gas turbine is "nursing a Monday morning grouch" even before he assembles the meager facts available to help him select the air cleaner.

In this mood, our man faces his dilemma. A portion of his data indicates he needs a highly efficient air cleaner, possibly as efficient as a piston-engine air cleaner. Reviewing his sales brochures, he finds that, even with air cleaners touted to have "High Capacity," the air cleaner he selects will be big ... indeed as big as the vehicle the gas turbine is slated to power.

Browsing further through technical literature, our man uncovers a bright spot. He finds work has been started to develop compact, high-efficiency automatic-cleaning air cleaners. But, these air cleaners won't be available for some time, and he has an application which must be in operation in 2 months.

A little more searching, and our man finds a gas-turbine air cleaner with a reasonable size. He finds still another, and one even smaller. They are self-cleaning. They meet inlet pressure-drop requirements. There is an inconsistency here. The efficiency is somewhat below the efficiency of conventional piston-engine air cleaners. Will this efficiency protect his turbine from erosion -- from damaging deposits?

Here is the dilemma! Our man is confronted with a tough decision. To expedite his installation, should he choose the air cleaner that has not been fully proved? Or should he compromise his installation and select a huge air cleaner with relatively high service requirements and cost?

The solution to our man's dilemma lies buried in the simplicity of a few words -- he must know the actual level of protection required by his gas turbine. Simple statements rarely reveal the complexity of their implications. For example, "let's go to the moon" is also a simple statement. We don't pretend to be able to lift the burden from our friend. We hope this paper will aid in making his job easier.

We will present our experience on gas-turbine air cleaners, relate it to experience of others, discuss what's available today and what is planned for tomorrow, so that the man on the horns of the dilemma will be able to define his problem, take rational action and, thus to make sound gas turbine-air cleaner decisions.

RECENT EXPERIENCE

The damaging effects of dust and other foreign material entering the intake of gas turbines can be divided into the following categories (1): Gross damage, erosion, and deposits.

Let's briefly examine the experience today related to these three problem areas.

Gross Damage

Gross damage to the gas turbine is caused by ingestion of large objects such as nuts, bolts, rocks, rags and lunch buckets. It might seem obvious these items must be kept from entering the inlet of gas turbines. However, the major cause of gas-turbine compressor failures in aircraft is the ingestion of large objects (2). Many papers have been written on the subject of inlet protection for aircraft gas turbines (3,4,5,6). A recent notable example of the effect of gross object ingestion in gas turbines was the experience shared by 19 passengers in a helicopter as they were towed to shore after an emergency landing in New York's Hudson River (7). Pieces of the helicopter cowling broke loose in flight and were ingested into the engine. The resulting power loss forced an emergency landing in the river.

Although prevention of gross object ingestion is a serious, difficult, and possibly controversial problem on aircraft gas turbines, particularly high-performance aircraft, it should be of little concern in ground-operated machines. The only causes for large object ingestion on ground-operated gas turbines, assuming normal precautions are...
taken in the installation design, should be care-
lessness, and poor housekeeping - and these can be
minimized.

Erosion

Erosion of turbine blades is not a problem ex-
clusive to gas turbines. As far back as 1932, the
literature reveals blade erosion was a definite
problem with steam turbines (8). Water droplets,
not dust, were the erosion-causing contaminants.
Although erosion by water droplets is only sig-
nificant over extended periods of time, dust, be-
cause of its hardness and shape, causes much more
serious and accelerated wear. Insight gained from
the 1932 publication should have established long
ago the need for gas-turbine air cleaners.

The need for air cleaners on gas turbines has
now been well established by dust-ingestion tests
in the laboratory and in the field by many people
and agencies, beginning in 1949 (9-18).

Erosion has not been an apparent problem in
the early installations or in many large fixed in-
stallations today because these gas turbines have
been operated in environments relatively free of
hard particulate contaminants. Further, the rela-
tive velocities between the moving parts and the
gas stream in the early turbines was so low that
only the very large particles (which never reached
the inlets) would have had enough momentum to im-
port on the blade surfaces.

The list of the damaging effects caused by
gas-turbine dust ingestion is long and incrimina-
ting. Compressor blades worn to ragged, paper-
thin stubs; diffusers and nozzles in some cases
completely eroded away; elongated and plugged
bleed-air openings and passages; holes eroded
through shrouds; eroded turbine blades; these are
the visible primary effects of erosion. The cor-
responding effect on engine performance and safety
is serious -- significant power reduction, reduced
pressure ratio, increased fuel consumption, in-
creased turbine-inlet temperatures.

Specific conclusions, other than "gas turbines
need air cleaners," drawn from the literature are
in many cases conflicting. Most conflicting are
the conclusions related to the definition of the
dust-particle sizes that cause erosion -- the maxi-
mum dust particle size which can be allowed to
pass the air cleaner. For example, the literature
states that to maintain erosion at an acceptably
low level, an air cleaner must remove all dust
particles over 2 to 3 microns (16) in one case and
100 microns (13) at the other extreme. The lit-
erature further states that the erosion level will
be acceptable if the dust concentration passing
the air cleaner is no more than 0.28 mg/cu ft at the
other extreme (22). One reference says that an
air cleaner efficiency of 90 percent on dust with
a particle-size distribution from 20 to 150 mi-
crons will provide adequate gas-turbine protection
from erosion (15).

We have taken the liberty of summarizing the
following conclusions, weighting the conclusions
of the literature with our experience. This sum-
mary of conclusions agrees generally with most of
the references; however, any specific conclusions
might be challenged:

1 Axial-flow compressors are more sensitive
to erosion than centrifugal compressors.
2 Axial-compressor erosion is most severe at
the rotor-blade tips and stator-blade roots on the
trailing edge in both cases. This does not imply
that the leading edge is free from erosion.
3 As erosion develops, significant loss in
maximum power is experienced with a correspond-
ing increase in fuel consumption and turbine-inlet
temperatures.
4 Total erosion, weight of material lost, is
a direct function of the weight of dust ingested.
To say it another way, rate of erosion is directly
related to dust concentration.
5 A specific weight of dust will cause a
fixed amount of erosion, regardless of the dust
concentration, provided the dust concentration is
not so high as to cause a disturbance in air-flow
characteristics.
6 Erosion increases as dust-particle size,
mass, and hardness increase.
7 It is our belief that erosion not only var-
ies with particle size, but also varies with "ef-
fective" particle size. For example, a test con-
ducted feeding 0 to 5-micron dust to a turbine may
produce erosion, but the majority of the erosion
is likely to have been caused by agglomerates of
fine particles with "effective" diameters greatly
exceeding 5 microns. The agglomerate of fine par-
ticles determines the "effective" diameter causing
the significant erosion. A simple analogy can be
made: You can't knock a man's hat off with a
snowflake but you can with a snowball. Because
of agglomeration, which exists to varying degrees
in nature, fine dust particles (which would nor-
mally pass through some air cleaners) are col-
lected or removed from the air because they are
part of an agglomerate.
8 Since sampling and measuring effective par-
ticle sizes of dust reaching the compressor and
other internal parts of a gas turbine produce re-
sults which are subject to significantly different
interpretations, we cannot define an absolute
dust-particle size which a gas turbine can ingest
without significant erosion, or which the air
cleaner must remove. Actually, if we could, it
Deposits

Possibly the first evidence indicating a need for gas-turbine air cleaners was the occurrence of deposits in gas turbines as far back as the late 1930's. Extensive data have been gathered over the years on the problem of deposits. The problem generally implied with deposits is compressor fouling -- a reduction in compressor efficiency resulting from disturbances in air flow caused by blade deposits (19,20,21). This problem will not, as a rule, cause failure with subsequent long downtime and parts replacement, but it is a serious inconvenience and requires a maintenance operation of washing or scouring the deposits from the blade surfaces.

One source has stated the solution to nondestructive deposits is to accept the deposits and wash the compressor at fixed intervals. The reasoning used to justify this conclusion is that the air cleaner required to remove the depositing contaminants would be large, require extensive attention, and be a major capital investment (24).

Two additional problems have been experienced in the past few years which are a direct result of deposits in gas turbines. The first is corrosion of internal turbine parts resulting from salt deposits experienced in marine installation (22,23). This deposit problem can result in the need for early parts replacement. Frequent engine washing will reduce the corrosion problem. However, in certain applications it is inconvenient and at times impossible to wash the engine.

The second associated problem is plugged air passages by deposits -- specifically, and most critical, the plugging of regenerators, or heat exchanger matrixes (1). As far as we know, only one field experience has been gained on this problem. The exact mechanism causing the deposit formation is not yet fully understood. We do know that the rotating regenerator matrix plugged with dust on the hot gas-inlet surface. The turbine-inlet temperature rose rapidly to well over 2000°F. The gasifier turbine-blade tips were burned off. Some of the conditions under which this failure occurred were unusual. Dust concentrations were extremely high (possibly 250 to 1000 mg/cu ft). The engine was protected by a 90 to 95 percent efficient (ACC test dust) centrifugal separator air cleaner which allowed very fine dust to pass. Only a very light nonrestricting film of dust was found on the cold-air inlet to the regenerator. Questions remaining to be answered are: "Why did the dust deposit on the hot inlet to the regenerator and not on the cold inlet? Is it because the dust particles changed physically in passing through the hot section of the engine, or are the hot-side regenerator entrance conditions more conducive to deposition?"

Although the engine failed in this test as a direct result of dust ingestion, it is of interest to note that the 90 to 95 percent efficient air cleaner did prevent erosion.

What type and size of dust causes deposits in gas turbines? On relatively cold surfaces, such as the compressor blades, contaminants with fine particle size distributions (a MMD of 1 micron or less) will deposit more readily than larger particles. Sticky materials, such as road grime or soot, will also deposit more readily than dry substances. Atmospheres containing oil vapors or exhaust by-products which will coat the surfaces, will accelerate deposition.

Few data are available related to the problem of deposits on hot surfaces. We are quite sure these deposits are inorganic contaminants -- primarily silicates. From the single test experience it appears that fine dust is the culprit. Exactly how fine we cannot say at this time.

It is unlikely hot-surface deposits can be cleaned off, without engine disassembly, by any known washing or cleaning method. It is quite likely failure will occur before the need for cleaning is known.

The problem of erosion and deposits in gas turbines reduces to a dilemma within a dilemma. Fine contaminants form deposits; coarse contaminants do not. In fact, evidence has been obtained indicating that coarse particles in small quantities help keep the deposits from building up through a scouring action (25) and further removal of the coarse particles from a contaminant might even make deposition worse (20). But then, of course, if the large particles are allowed to enter the engine we return to the problem of erosion.

You now have a thumbnail sketch of the experience -- confusing, controversial, and uninterpreted. At this point it is difficult, if not impossible, for our man to select a gas-turbine air cleaner. An off-hand look at the experience to date indicates a need for an air cleaner which will remove all contaminants, regardless of particle size, material, shape or concentration. However, the general conclusion of all the literature is that more experimental work needs to be done.

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2 Stokes Equivalent Mass Median Diameter.
Our dilemma now leads us to examine gas turbine-air cleaner needs and properties in light of the experience gathered to date.

DISCUSSION OF AIR-CLEANER PROPERTIES AND GAS-TURBINE NEEDS

Gas turbine-air cleaner specifications are many. However, one specification, or property, if you will, stands out -- efficiency. Efficiency in one form or another is a measure of the level of engine protection offered by the air cleaner. If the gas-turbine air cleaner does not have an efficiency which will protect the gas turbine, the air cleaner has no reason to exist.

The level of protection provided by an air cleaner is not free of performance penalties. The actual cost of the air cleaner is only a part of the payment for protection. The payment for protection, or efficiency if you prefer, is through the detrimental associated properties of an air cleaner which inevitably accompany efficiency. Efficiency and the associated properties are firmly interrelated. The undesirable associated properties of an air cleaner are (a) pressure losses in the induction system, (b) the space required to install the air cleaner with its accessories, (c) the weight the air cleaner adds to an installation, (d) additional labor and parts required to maintain the air cleaner, (e) initial cash outlay for the air cleaner, and (f) other structural and environmental properties. It is not possible to list these associated properties in order of importance since the particular installation determines their relative importance. For example, weight and pressure losses are of critical importance in a helicopter installation.

The detrimental influence of associated properties is proportional to the level of efficiency offered by the air cleaner. Therefore, it is desirable to specify an efficiency level that protects, but does not overprotect -- an efficiency level that gives protection with a minimum of associated losses.

Efficiency

The air cleaner must provide a level of efficiency which will assure dependable gas-turbine operation, in contaminated environments for an extended period of time. To put meaning in the statement, we must define the word "efficiency."

Air cleaner "efficiency" is simply the percentage of dust, by weight, which an air cleaner removes from the air stream, based on the total weight of dust in the air stream.

Unfortunately, Nature does not allow simple relationships to exist. Experience indicates a relationship between dust-particle size and the degree of erosion (25). Natural contaminants exist in random-particle sizes and shapes. Moreover, air cleaners generally have different levels of effectiveness for different particle sizes (classification). Therefore, it becomes necessary to consider the particle-size efficiency of air cleaners. To help visualize particle-size efficiency consider a chicken-wire fence -- 100 percent efficient on chickens, 0 percent on mice. Air cleaners are much the same, to one degree or another depending on the mechanism of filtration. The particle-size efficiency of an air cleaner becomes important if, for example, the air cleaner removes all dust particles which cause engine damage and allows the particles to pass into the engine which do no damage. Therefore, it is important to include a measure of particle-size efficiency in the specification for gas-turbine air cleaners.

Another consideration which adds complexity to the interpretation of efficiency is particle agglomeration, or flocculation. Current methods and equipment used to measure particle-size distribution measure ultimate particle size, not the "effective" particle size formed by the agglomerates which the air cleaner senses. Therefore, because of the presence of agglomerates, the air cleaner senses more coarse particles. Because of the classification effect, it will be more efficient than might be expected, considering the particle-size-distribution curve of the dust involved and the particle-size efficiency curve of the air cleaner.

The experience to date has substantiated the need for gas-turbine air cleaners. However, the specific data accumulated, although generally enlightening, are of little value when being applied directly to the design of a gas-turbine air cleaner. Only a small amount of information is available on the mechanisms of gas-turbine deposits. Most work has been done on erosion and these data were collected without consideration of dust-particle agglomeration or air-cleaner-classification characteristics.

No information is available in the literature related to regenerator plugging as affected by dust-particle size.

In specifying the efficiency for gas-turbine air cleaners it becomes increasingly apparent that it will be -- economically -- necessary to set different efficiency specifications for different applications and environments. It now appears that the type of gas turbine (simple cycle or complex cycle) and, possibly the make of gas turbine will influence the level of efficiency required. Further, the application and environment will be fac-
tors. For example, consider the air-cleaning needs of an aircraft gas turbine compared to an earth-moving gas turbine, or a mobile installation to a stationary installation.

In attempting to arrive at an efficiency level for gas turbines, consider the following simple approach: First, for practical reasons, the air cleaner cannot be 100 percent efficient and, consequently, some dust will enter the engine. It is likely that the dust which passes any air cleaner will promote either deposits or erosion over an extended period of time. Engine operating life now becomes a factor. If the design life of the turbine, operating in clean air is 5000 hr, then it is not economically reasonable to design an air cleaner with a high efficiency level which would protect the turbine for 10,000 hr in a dusty environment. The extra 5000 hr (which the engine cannot produce) are an unneeded luxury in terms of greatly increased initial costs, service cost, weight, and/or size of the air cleaner. This can be compared to the purchase of a stereo phonograph by a man who is deaf in one ear.

Thus, in establishing efficiency, these factors must be considered, in addition to engine type, application and environment:

1. Particle size efficiency.
2. Overall air-cleaner efficiency.
3. Ambient dust concentration.

The first factors, particle size and overall efficiency can be established as design goals because they are functions of the air cleaner and can be measured in the laboratory. The third factor, dust concentration, cannot be controlled. Regardless of the air-cleaner efficiency (assuming 100 percent is impractical), the concentration of dust passing the air cleaner and entering the engine is a direct function of the ambient concentration. Since field-dust concentrations vary through wide extremes, it is impractical to specify that a gas-turbine air cleaner must reduce the dust concentration to a fixed figure, such as the extremes referred to previously of 0.28 or 5 mg/cu ft., without specifying ambient concentration. If the ambient concentration is specified, in addition to the allowable concentration passing the air cleaner, then we have efficiency and we might as well list it as such. The fourth factor, engine life, must come from the engine manufacturers and from field tests of air cleaners.

These factors, properly weighted, will establish a realistic gas turbine-air cleaner efficiency goal.

How should we measure efficiency in the laboratory? It is not practical at this time to measure and report particle-size efficiency on small particles because of the many problems of feeding dust, the unavailability of quantities of specific particle-size dust, nonstandard methods of measuring particle sizes, problems in taking representative samples and problems in interpretation of results. Therefore, it is our suggestion to adopt a currently available standardized dust, such as Standardized Air Cleaner Coarse Test Dust (see Table 1), to be used in specifying and reporting

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Particle Size Distribution of SAE Standard Air Cleaner Coarse Test Dust as Shown in MIL-A-13488</td>
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<table>
<thead>
<tr>
<th>Particle Diameters, Microns</th>
<th>Percent by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5</td>
<td>12 ± 2%</td>
</tr>
<tr>
<td>5 - 10</td>
<td>12 ± 3%</td>
</tr>
<tr>
<td>10 - 20</td>
<td>14 ± 3%</td>
</tr>
<tr>
<td>20 - 40</td>
<td>23 ± 3%</td>
</tr>
<tr>
<td>40 - 80</td>
<td>30 ± 3%</td>
</tr>
<tr>
<td>80 - 200</td>
<td>9 ± 3%</td>
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</tbody>
</table>

Table 2. The use of coarse dust will give a measure of the efficiency of the gas-turbine air cleaner on dust particles above 200 microns. We suggest Ottawa sand since a specification is available. However, a thorough investigation should be made before a standard is selected.

The question remains: "What efficiency value will provide the level of protection needed by gas turbines?" Even assuming different levels of protection are required for different types of engines, applications, and environments, we cannot, nor can anyone, define unconditionally an absolute...
efficiency level, or levels, that will do the Job.

Our experience, indicates that an air cleaner with an efficiency of 92 percent or more based on AC coarse test dust, will protect all gas turbines, whether they be axial or radial, from significant erosion. Recognize that this is a calculated estimate and must be substantiated by additional field tests. Because of the limited amount of test results on complex-cycle turbines using regenerators or heat exchangers, we cannot, at this time, specify the level of efficiency required which will prevent hot surface deposit formation in these machines. The data gathered so far indicate that the regenerative gas turbine will require either a less efficient air cleaner which would allow the coarse particles to scour the deposits as they form; or, if erosion becomes an overriding factor, which is likely, a highly efficient air cleaner may be required to keep the fine dust out of the engine altogether.

At this point we might digress and look at piston-engine air cleaners. Piston engines have been plagued with dust problems for over half a century. We do not know even today the exact relationship between piston-engine wear and dust. Yet, we are building piston-engine air cleaners which provide excellent engine protection. Piston-engine air cleaners have been developed over the years through extensive laboratory work using standardized dust and relating this laboratory information to actual field operation failure or success, measured by engine wear.

In the final analysis, the required gas turbine-air cleaner efficiency will be determined through field tests of air cleaners with known laboratory performance on known test dusts.

It is important to recognize that the level of efficiency directly influences the nature and degree of undesirability of the associated properties of the air cleaner. For this reason, it is desirable to keep the efficiency at the lowest possible level.

Once the level of efficiency required to protect gas turbines has been established we can concentrate our efforts on minimizing effects of the undesirable associated air-cleaner properties.

Air-Cleaner Pressure Drop

A short few years ago, the allowable pressure drop for gas-turbine air cleaners was on the order of 0.5 in. water. As the need for gas turbine air cleaners became more evident the allowable pressure drop has increased to as high as 10 in. water in one case.

Air-cleaner pressure drop can be directly associated with air-cleaning efficiency. In the case of an inertial or centrifugal separator, the greater the pressure drop the higher or more stable the efficiency and the smaller the size of the air cleaner. In the case of a high-efficiency surface filter, the higher the allowable pressure drop the longer the life, or the smaller the size of the air cleaner. In other words, the higher the allowable pressure drop the better the air-cleaner designer likes it and a better job of filtering can be accomplished. Engine power loss associated with pressure drop is part of the price paid for clean air.

A pressure-drop specification of 4 to 8 in. water maximum is a reasonable air-cleaner design goal for mobile installations in light of current air-cleaner developments, and is consistent with many gas-turbine manufacturers' requirements. Engine manufacturers must set their own maximum allowable pressure drop keeping in mind that very low pressure-drop limits will result in larger air cleaners and/or shorter life, and/or lower efficiency.

The ultimate gas-turbine air cleaner should have a low constant pressure drop -- a pressure drop that does not increase as dust is removed from the intake air. Surface filters increase in pressure drop as dust is collected. If a surface filter is specified for gas-turbine use, care should be taken to (a) over-size the filter to insure a long life, (b) specify a service gage, warning light or alarm to indicate service is required, whether it be cleaning or replacement, at a predetermined pressure drop, or (c) provide a bypass system which allows air to bypass the air cleaner if a critical pressure drop is reached. High-capacity, automatic-cleaning surface filters are in development for gas-turbine use. The pressure drop of these filters will remain relatively constant except in the event of a cleaning-mechanism failure. Then the pressure drop will rise rapidly in dusty environments. Therefore these automatic filters must be equipped with warning devices or by pass systems to prevent excessive inlet-system pressure drops. Excessive inlet pressure drop can conceivably reduce mass flow (particularly on engines not equipped with temperature-sensing fuel controls) where turbine-inlet temperatures increase to the point of turbine-blade destruction.

The simplest way to achieve a nonincreasing, constant pressure drop is to utilize mechanical, inertial or centrifugal air-cleaning mechanisms in the design of the air cleaner, keeping in mind, of course, that the air cleaner must be capable of providing the level of efficiency necessary to protect the gas turbine.

Before we leave pressure drop, here is a brief word on measurement. Pressure drop should be ex-
pressed in terms of total pressure drop (a measure of energy loss), not in terms of static pressure drop which may have a large component of velocity pressure.

**Air-Cleaner Size**

The size of a gas-turbine air cleaner is important to the success of the gas turbine in surface installations. One of the major advantages the gas turbine has over piston engines is its small size. To obtain fuel economy that is competitive with piston engines, regenerators are being used which decrease the size advantage of the gas turbine. Now, if the air cleaner is large, which is conceivable if a very high efficiency is necessary, the required installation space for a gas-turbine power package could be as large or, possibly, larger than the piston engine with its radiator and other accessories.

The fact that gas-turbine engines demand as much as 10 times more air than piston engines of equivalent power output makes the job of designing small gas-turbine air cleaners even more difficult. This is true particularly if the air cleaner must operate at less than half the pressure drop of piston engines and if it becomes necessary to provide gas turbine-air cleaner efficiencies equivalent to those of piston-engine air cleaners.

It is important to recognize that air-cleaner size is related to its efficiency, pressure drop, weight, service, and initial cost. Therefore, we find again a need to establish the minimum air-cleaner efficiency which will provide engine protection yet not increase the size, pressure drop and cost to unnecessarily high values.

Since gas turbine-air cleaner size cannot be fixed in absolute terms, a number of years ago we set a flow-index goal of 2500 cfm/cu ft of air-cleaner volume at a pressure drop of 4 in. water. This index is still appropriate and provides an acceptable air-cleaner size.

**Air-Cleaner Weight**

Small size infers a low weight. Weight can be minimized through the selection of light materials such as plastics, aluminum, and magnesium.

Here again, the required level of efficiency plays an important role. If the efficiency required is determined to be high, the air cleaner will probably become heavier.

**Air-Cleaner Service Requirements**

Air-cleaner service implies expense in labor, parts replacement and required service frequency which, in turn, is related to dust capacity. The gas-turbine air cleaner should require minimum service. Minimum service can be obtained through automatic-cleaning units. This approach implies unlimited dust capacity with a minimum service cost. Another factor which makes automatic-cleaning units necessary for gas turbines, particularly those operating in dusty environments, is that the space necessary for storage of collected dust is eliminated. This significantly reduces space needed for installation.

Exceptions to the need for automatic-cleaning air cleaners are gas turbines operating in normally low-dust environments such as aircraft, standby generator sets, or pipeline pumps in green environments.

Maintenance costs are generally proportional to the complexity of the equipment. Thus, it is desirable to have gas-turbine air cleaners with few, if any, moving parts.

**Initial Cost**

In our way of life and order of things, sooner or later all things are reduced to value, and value is ultimately expressed in terms of dollars and cents. We cannot talk of specific costs because we do not know the specifications required for the ultimate gas-turbine air cleaner. The price for this gas-turbine air cleaner will depend upon requirements. If a relatively simple cyclone separator will meet the performance requirements, the price will be low. If it is found high efficiency is necessary and automatic-cleaning is a must, then the price will be considerably higher.

**Reliability**

Gas-turbine air cleaners must be reliable. Reliability is related to complexity. If it becomes necessary to have moving parts in the air cleaner to achieve efficiency or life, the reliability of the air cleaner will be reduced -- another reason for determining the minimum requirements for gas-turbine air cleaners.

**Durability**

Durability in itself is not a problem peculiar to gas-turbine air cleaners. To be sure, the gas-turbine air cleaner must be rugged. Resistance to vibration, shock, corrosion, heat, cold, manhandling and the like can be adequately designed into the unit using currently well established engineering techniques.

WHAT'S AVAILABLE IN GAS-TURBINE AIR CLEANERS TODAY

In light of the meager and, at times, conflicting experience, and the fact that ultimate gas turbine-air cleaner requirements are yet to be determined, our man in the dilemma has quite a
choice of air cleaners. At least three manufacturers advertise gas-turbine air cleaners, including Donaldson Company, Inc. At first thought this may appear to be unusual. This is a healthy state of affairs, providing the man in the dilemma knows the stage of development. The air cleaners of today will provide the necessary experience to enable us to design the ultimate gas-turbine air cleaner of tomorrow.

The gas-turbine air cleaners available can be divided into two groups. The first group contains air cleaners for large permanent gas-turbine installations, such as electric generating plants, processing plants, and large pumping-station installations. These air cleaners are large, bulky, and require considerable maintenance and replacement parts. Many of these air cleaners include evaporation units to reduce high ambient temperatures and, thus, maintain power. These large air cleaners have done an acceptable job of intake-air filtration in the relatively light dust concentrations of fixed installations. However, it was not practical, because of design and performance limitations, to scale these air cleaners down in size and adapt them to mobile gas-turbine installations.

Thus, the advent of the second group -- high-capacity, gas-turbine air cleaners. These smaller air cleaners fall into two categories; (a) separators, and (b) surface filters.

The separators have efficiencies (on AC coarse test dust) from 85 to 95 percent. This type of device can be further classified as inertial-vane type separators, now produced by two companies, and high-capacity, multiple-cyclone tube separators, such as Strata Panels produced by the company of the first author.

Since we do not manufacture the vane-type inertial separator, we can only submit our experience with the cyclone separator.

In engine dust-ingestion tests in the laboratory, the Strata Panel separator has shown a capability of preventing significant erosion in a 1000-hp axial-flow, simple-cycle gas turbine. Short-duration field tests have also shown this capability. Regenerative turbines may require a somewhat higher efficiency (above 95 percent on AC coarse dust) than the Strata Panel offers.

Fig. 1 is an example of a Strata Panel air cleaner designed for field tests with an air flow of 16,400 cfm. The pressure drop across the unit at this air flow is 4 to 5 in. water. The nominal size of the unit shown is 52 in. x 40 in. x 7 in. plus space for the scavenging blowers. For more details on the performance and size of Strata Panels see reference (1).

The second category of high-capacity, gas-turbine air cleaners available today are bonded extended-area paper panel filters. The Donaldson Duralife Panel, an example of the extended-area panel filter is a cleanable surface filter. The pressure drop of this filter increases as dust is collected. Consequently it is not ideally suited for extremely dusty conditions unless a large space is available for the air cleaner. Air cleaners of this design have been used extensively on aircraft and pipeline pumping stations. Fig. 2 is a photograph of a successful installation of a five-panel (24 x 24 x 2 in. each) Duralife Panel air cleaner on a Halliburton Company oil well-fracturing rig powered by a 1000-hp gas turbine having a nominal air demand of 10,000 cfm.

This filter offers an efficiency of 99.5 percent which we are confident will provide adequate protection for any type of gas turbine including regenerative machines. Additional details of this Panel are also contained in reference (1).

These air cleaners we have discussed are available now. Through field testing, using a properly planned program, the ultimate gas-turbine air cleaner will be developed in the shortest period of time.

WHAT MUST BE DONE FOR TOMORROW

To lift our man from his dilemma tomorrow, there are a number of things we must do today. The first and most important is to "determine the level of protection required by gas turbines whether they be axial, centrifugal, simple cycle
Fig. 2 Halliburton Company oil-well fracturing rig. The 1000-hp gas turbine powering the fracturing pump is protected by Duralife panel filters. Panels are arranged in the form of a cube visible behind the truck cab.

or complex cycle". Next we must determine a laboratory measure of air-cleaner efficiency which will provide the level of protection required. Then we must develop an air cleaner to provide this efficiency with minimum and acceptable detrimental affects from the associated air-cleaner properties.

These are ambitious goals, but they must be accomplished in a short period of time. It is essential that the optimum gas-turbine air cleaner be developed soon because power-plant technology is increasing at an exponential rate. In not too many years the gas turbine may face replacement with newer forms of power, such as fuel cells, solar, or atomic power. We must find the way to make the gas turbine live in dust or it may lose its place in line.

We suggest the following programs be used to come up with the answer in the shortest period of time.

**Field Tests**

Field tests of available gas-turbine air cleaners should continue to be made on gas turbines operating in dusty environments. Special installations of gas turbines need not be made solely for the purpose of air-cleaner tests, although they would be desirable. If a gas turbine is slated for a dusty operation, air-cleaner tests can be run at little extra cost. However, to gain significant data from these tests it is important that the tests be planned and instrumented properly. A small amount of additional gas-turbine operation and inspection is required to obtain useful data.

When a test of this nature appears to be in the making, it is desirable to call the air-cleaner engineer early in the planning stage. His suggestions may save time later, insure an optimum installation of his air cleaner, and a maximum return of usable data.

From these field tests we can learn how well an air cleaner with a given laboratory performance, will protect the gas turbine from the ravages of dust by inspecting the gas turbine before and after the test. Additional information can be obtained from these tests on the ambient dust concentration and particle-size distribution of the dust.

**Laboratory Dust-Ingestion Tests**

A number of laboratory dust-ingestion tests have been run on gas turbines. The results of these tests have provided an insight to the problems of gas-turbine dust ingestion. However, we feel much more can be learned through additional tests of this type by including air cleaners with known performance in the test program and by using the experience gained in the tests to date to plan a more strategic program. These tests might be run by the military, gas-turbine manufacturers, air-cleaner manufacturers, or some combination of these three.

Laboratory ingestion tests on regenerative
turbines are particularly important at this time because of the lack of useful information available for developing the air-cleaner requirements for this type of gas turbine.

One possible approach to reducing the cost of laboratory ingestion tests is for gas-turbine manufacturers to make obsolete or outdated prototype engines available for this purpose.

**Air-Cleaner Development**

During the period of time gas turbine-air cleaner requirements are being established and confirmed, manufacturers can be furthering the state of air-cleaner development.

For example, the Donaldson Company has extensive research and development programs under way on a number of promising high-efficiency, minimum-service gas-turbine air cleaners to meet the need should one or more of the various types of gas turbines require a highly efficient air cleaner.

**Gas-Turbine Design**

Gas-turbine designers are to be commended for their dedication in overcoming the problems obstructing the progress of the gas turbine. Their efforts have been primarily aimed at performance improvement in terms of power, fuel economy, weight, and size. Faced with yet another obstruction, they must take a look at gas-turbine design from the standpoint of ingesting dust. The following suggestions may not be altogether practical, but they are worth considering.

**Compressor Design.** It is quite possible erosion can be significantly reduced by small blading modifications. Indeed, it may be worthwhile to accept slightly lower compressor efficiency in return for less sensitivity to erosion and the knowledge that the machine will live longer in dusty environments (20).

**Regenerator Design.** Regenerator design might also be considered. A slightly less efficient or slightly larger regenerator, less susceptible to deposits, may represent a small price to pay for the use of a low-cost, small, less efficient air cleaner. Indeed the result may be a smaller overall power package even including a larger regenerator. Another consideration is to design regenerators to be removed easily for cleaning or replacement.

**Gas-Turbine Installation Design.** In the design of a gas-turbine installation the following considerations must be kept in mind:

(a) Selection of the location of the air inlet in areas of minimum dust concentrations, away from exhaust stacks and air-cleaner dust outlets, is of prime importance, second only to the selection of the air cleaner itself.

(b) Allocate space for the air-intake system early in the design of a gas-turbine-powered machine. This will save the cost of a specially designed complex air-inlet system including the air cleaner. In addition it will aid in obtaining the lowest achievable intake-pressure drop and optimum air-cleaning system.

(c) Consider combining the air cleaner with the intake silencer. This will save space and money.
REFERENCES


15. Personal correspondence with the Rover Company Ltd., England.


