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ELIMINATION OF ENGINE BLEED AIR CONTAMINATION

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ABSTRACT

Air bled from the compressors of some high compression ratio turbojet engines is contaminated because of internal engine oil leakage into the compressor air. External leakage of oil or other fluids wherein such fluids can leak into the engine air inlet can also cause contamination. There are two positive methods of elimination; (1) a catalytic filter which oxidizes the contaminants to carbon dioxide and water; (2) a separate cabin compressor that compresses free stream ram air for cabin air conditioning and pressurization. The method of extracting air from a location in the engine where the compressor air is least contaminated is considered a marginal solution to the contamination problem on some of the present high compression ratio engines. This method of elimination is worthy of consideration providing a marked improvement is realized in the design of those components of the engine that contribute to leakage.

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INTRODUCTION

With the increased thrust of modern turbojet engines, and associated high compression ratios, the compressor bleed air used for aircraft air conditioning is increasingly subject to unacceptable contamination. Under severe conditions the contamination could cause smoke, acrid odors, and eye watering to a degree which would seriously affect the pilot's proper control of the aircraft. As a result of concentrated engineering effort for the past two years to eliminate the contamination, several possible solutions were developed. A few of these have been tested and were found to greatly reduce the concentration of fumes. At present only one of the methods tested eliminates the fumes entirely. All however, require additional operational time in the airplanes before any definite conclusions can be drawn.

CAUSES OF CONTAMINATION

To understand the methods used for elimination, consideration must first be given to the source of the contamination and the process by which the bleed air becomes contaminated. The basic cause has been reasonably well established as leakage of engine oil into the compressor air. In the process of compression the oil and air are heated to temperatures on the order to 700 to 800 deg F. This causes decomposition of the oil and these products are then discharged into the air conditioning system ducting at the engine bleed air ports.

It is practically impossible to determine accurately all the sources of oil leakage. It is believed the compressor bearing seals are the main source of oil leakage, although there are other possible sources of internal leakage.

Malfunctions of equipment or improperly tightened line fittings resulting in engine or hydraulic oil leakage into the engine inlet air stream can produce severe concentrations of fumes depending on the extent of the leaks.

DEVELOPMENT OF ELIMINATION METHODS

The first experiences with the contamination problem were very erratic. The contamination or lack of it varied from flight to flight, from one engine power to another, and from one engine to another even though they were of identical design. One of the most disconcerting situations existed when two airframe manufacturers, each with considerable flight experience on prototypes of the same basic engine, came up with contradicting reports; one had no trouble with fumes whereas the other reported numerous complaints. Though there were differences in the oil systems of the prototypes, this alone did not provide a reasonable explanation.

In attempting to substantiate one of several theories as to how the oil entered the bleed air manifold, one of the airframe manufacturers conducted a test to determine the airflow velocity distribution at the engine compressor discharge. A rake having three total pressure tubes was inserted in a pressure instrumentation port located immediately downstream of the last stage of the compressor. One of the total heads extended almost to the inner surface of the diffuser section, the other to the center, and the third measured pressure near the outer surface of the diffuser. Test data showed a considerably higher air velocity at the outer surface than at the inner surface. The more important result, however, was evident when the probe was removed. The total pressure tube nearest the inner surface of the diffuser was found to be completely clean. The tube at the center was partially gummed up from decomposed oil products, and the tube nearest the outer surface was severely gummed up. Conclusions drawn from this evidence were as follows:

1. Oil leaking from compressor shaft bearing and other seals is picked up by the rotating blade discs and, by centrifugal action, is thrown to the outside of the compressor housing.
2. Though the compressor airflow is essentially axial, the axial velocity is not sufficient to prevent the oil from being centrifuged toward the compressor case.
3. Any bleed air manifolding which selects air at the outer surface of the diffuser is almost certain to collect air containing excessive contamination.

IMPROVEMENTS IN ENGINE AIR EXTRACTION METHODS

Several configurations designed to select air from the diffuser section were then incorporated in various engines and flight tested. Fig. 1 indicates a typical diffuser section between the compressor last stage and the burner section. Configurations tested included bleeding air from the inner surface and outer surface of the diffuser section and at several locations fore and aft in the diffuser.

The configuration shown in Fig. 1 was invariably a stinker, even though the bleed air was forced to turn 180 deg from the normal flow through the diffuser section. It appears that the concentration of oil at the diffuser outer surface may have followed right along the surface and readily turned into the manifold. The first improvement was to bleed air from the inner surface of the diffuser further forward in the diffuser section. Pilot complaints immediately ceased when the cabin air was extracted in this manner. An attempt was also made to bleed the air from the outer surface in the forward portion of the diffuser. Though all evidence previously obtained indicated this would not be satisfactory, early pilot reports stated that the results were identical to the internal bleed.

After a month or two of flying airplanes with this configuration, however, the pilot reports changed radically and stated the fumes were again unbearable. Hence, this arrangement was immediately replaced with an internal bleed and the adverse comments ceased. This matter of getting contradictory reports bears some comment that may be of help in similar situations. Where test data depends entirely on the human sense, it is important for the engineer to establish clearly defined terms to be used by the pilot in making his report. In addition, it must be emphasized that the reports be obtained not only from several pilots, but on all flights and over an extended period of time.

A further attempt was made to bleed air from near the diffuser inner surface but in an area of greater expansion. This was also relatively acceptable from a contamination standpoint. It is to be noted that the word "relatively" is used in regard to the purity of the air as flight tests have shown the internal bleed method still provides air that has a definite pyrolyzed oil odor. The concentration, however, is below the level that creates eye watering and smoke in the cockpit.

FILTER DESIGNS FOR ELIMINATION OF CONTAMINATION

On the assumption (later proved correct) that the engine design changes that could be readily accomplished without a major redesign would not completely solve the contamination problem, a parallel program of filter development was instigated. It should be made clear at this point that the term "filter" is used herein to identify any packed unit which will eliminate contaminating material from the engine bleed air.

In the design of a filter for an aircraft air conditioning system, the selection of the filter media will depend on the temperature, pressure, and humidity conditions of the air at the filter location. A schematic of a typical fighter aircraft air conditioning system is shown in Fig. 2. Locating the filter downstream of the air conditioning equipment presents the most serious problems with very few advantages. Because the refrigeration units are designed to supply air at temperatures well below freezing, the probability of the filter icing is very real. Volume flow and velocity of air through the filter is greatest at this point in the system because the system pressure is low. High velocity is undesirable for two reasons: it reduces the dwell time of the air passing through the filter and thereby minimizes the effectiveness of the filter chemical compounds in eliminating the contamination; the high velocity produces high pressure drop across the filter and the resulting back pressure at the discharge of the refrigeration unit reduces the performance of this unit.

At the location between the refrigeration unit and the heat exchanger the air has a relatively narrow temperature range and, providing a suitable filtering media can be found to eliminate the contamination at these temperatures, this location is well worth consideration.

The upstream location with air temperatures up to 850 deg F presents problems rendering it unusable for any type of filter material other than high temperature particulate and catalytic materials. However, this location is free of icing problems, has relatively low volume flow due to the high pressures, and is least sensitive to pressure losses. Also, if a surface active combustion catalyst is used, the high temperatures at this location are desirable from the chemical reaction standpoint.

To determine the products resulting from decomposition of the synthetic oil, preliminary tests consisted of dropping the oil on a heated plate at 700 deg F and then gathering and condensing the vapors. More extensive tests were conducted using methods for compressing and heating the air-oil mixture to the same conditions that would exist at the last stage of the engine compressor. Tests were also made by operating an actual engine and analyzing for the contaminants in air bled from the compressor. Though detailed chemical analysis of the products of decomposition are available, it will suffice to state that the largest group of noxious compounds were found to be the carbonyls, and that carbonyls include aldehydes, ketones, and organic acids. One of the aldehydes present was formaldehyde. These results, and the typical irritations to the nose and eyes that aldehydes create, coincide with the pilot descriptions of conditions in the airplanes. While this analysis was being accomplished, tests were also being conducted to determine a suitable chemical or compound that would either absorb the objectionable constituents or that would act as a catalyst to oxidize them into carbon dioxide and water.

Activated carbon proved promising at temperatures below 300 deg F. However, during flight conditions when hotter air is supplied to the cockpit or cabin, such as when flying in cold ambient temperatures, the carbon is reactivated, and results in all the absorbed material being driven out of the carbon and directly back into the cabin air supply. This limitation ruled out further investigation of a straight absorption type of filter media.

Effort was then concentrated on finding a catalyst that would convert the contaminants into products which would be acceptable in the air conditioning system. Many surface active combustion catalysts were thoroughly investigated and tested before selecting the one to be used for manufacture of a prototype unit. The fact that the catalyst chosen was effective at temperatures from approximately 300 deg F to 1,000 deg F was an important factor in its selection since this temperature range encompassed the range of compressor bleed air temperatures over the major portion of all flight conditions. It also permitted locating the filter upstream of the air conditioning equipment. For the airplanes then being produced, this was advantageous from an installation and available space standpoint.

Several factors must be considered in designing a catalytic filter for aircraft installations.

1. Selection of Filter Media

The catalyst selection must be based on tests that will determine its ability to purify the air at the temperatures and pressures existing at the selected location in the air conditioning system. It is to be emphasized that the tests must be run using the actual contaminating material, as many catalysts, though capable of converting a variety of contaminants, may be ineffective for a particular contaminant.

2. Dwell Time

Sufficient flow area and depth of the catalyst must be used in the filter pack so that the air velocity through the pack will be slow enough to allow the catalyst to accomplish complete purification. The design flight condition for the unit, therefore, becomes that which produces the greatest volume flow through the filter. Depending on the filter location in the air conditioning system, allowable pressure loss through the filter may dictate an even larger flow area than that required to obtain the minimum allowable dwell time.

3. Filter Case

The case must be carefully designed for stresses produced by the air temperatures and pressures. If the filter location is in the engine compressor bleed duct, it becomes a necessity to have a round case with spherical ends. Otherwise the heavier gauges of materials and stiffening members required to maintain a shape that is other than round usually present a weight penalty that is excessive.

In the catalytic filter developed, the process of decontamination is accomplished by the complete oxidation of the aldehydes and other hydrocarbons into carbon dioxide and water. Since the oxidation process releases heat, excessive contamination from oil seal or oil line failure could cause a hole to be burned through the filter case, if the case material and thickness are not adequate. It is difficult to establish a design condition for this situation since it depends on the location of the oil leak in the engine, the quantity of oil, and the type of airplane and its mission. In a single engine fighter airplane, for example, an oil leak in the engine large enough to cause excessive oxidation and burning in the filter would probably require termination of the mission just as much because of loss of engine lubrication as from failure of the filter case. On a multi-engine airplane, however, the engine bleed air is usually selectable from two or more of the engines. Accordingly, if a large oil leak occurs in one engine, this engine may be shut down and the bleed air for cabin conditioning selected from another engine. Provided the filter case has been designed for at least a short duration of extreme temperatures, the airplane mission need not be aborted.

Particular care must also be given in the internal design of the case to prevent any leakage of air past the filtering media. For the contamination being considered, even a small leak will be evident to the human nose.

4. Filter Pack

Catalysts of the solid type must usually be of a granular form in order to provide a maximum of surface area for the air to contact. The granules must be firmly packed, though not crushed, to reduce attrition losses caused by aircraft vibration and to prevent the air velocity from separating the granules and forming a free path through the media. If the filter media is subject to some wearing, a means must be provided at the discharge of the filter bed to prevent such dust size particles from entering the cabin air supply. Fine fiberglass mats have proven satisfactory for this purpose. The filter pack must be firmly supported within the filter case to prevent vibrations from setting up a resonant condition between the filter pack and the case.

THE SEPARATE COMPRESSOR AS A SOLUTION

This method of eliminating contamination is considered to be the most positive, but as is often the case with the optimum solution to an engineering problem, the separate compressor is the heaviest, most complicated, and the most expensive answer to the problem. For these reasons the project of development of this item was undertaken only to the extent of obtaining preliminary estimates of equipment size, weight, and cost. There are three basic types of compressor systems.

1. Turbocompressors

This method of positively eliminating contamination utilizes a compressor fed by free stream ram air and an air turbine motor using engine bleed air to drive the compressor. For a typical turbo-compressor installation in a bomber having a maximum cabin pressure differential of 7.5 psig, 20 lbs/min compressor bleed air would be required at high altitudes (say 55,000 ft). Such a machine would weigh about 90 lbs and occupy about 2 1/2 cu ft of space. In order to minimize engine bleed, it is felt that a control system allowing for variable turbocompressor rpm operation is desirable. Such a system would control the rpm at the speed dictated by cabin pressure and/or the engine compressor discharge pressure. The control must also regulate the turbocompressor rpm to provide for proper operation of an air cycle refrigeration unit.

2. Boost Compressor System

This system would utilize main engine compressor bleed air obtained from a midstage of the engine compressor with a further boost in pressure achieved with a turbocompressor similar to that described in 1. This system has an advantage over the turbocompressor system in that machine sizes can be reduced due to the lower pressure ratio required in the boost compressor. In the event that compressor discharge temperatures are at such a level that decomposition of engine oil is anticipated, an intercooler could be inserted between the midstage engine bleed port and inlet to the turbocompressor. Such an intercooler would have a dual purpose; namely, (1) reduce discharge temperatures to eliminate any possibility of engine oil decomposition, and (2) compressor size can be further reduced due to the higher inlet density attained with the low discharge temperature from the intercooler. If there is any engine oil leakage upstream of the midstage bleed, however, it is believed that there would be an oil odor carried into the cabin, though it would not be of the irritating type. Such a system would be satisfactory for a military aircraft where a slight odor would be acceptable to the crew. For a commercial airliner, however, even the slightest odor would have to be eliminated.

3. Engine Driven Compressor

For high altitude cruise operation, this system, from a thermodynamic standpoint, is considered best with respect to minimizing engine fuel and/or power penalties. This scheme would probably utilize a constant speed ratio between main engine spool and cabin air compressors. However, it should be realized that at low altitude an excess of compressor air would be available due to the high altitude sizing of the compressor.

Since it is presumed that engine rpm will be essentially constant, this disadvantage could be overcome by inlet throttling or by utilizing a variable speed drive between engine and fresh air compressor. The two preceding schemes would, of course, involve rather complex controls. It should also be realized that aircraft installation problems may be greater with this scheme due to the remote location of the compressor in the engine nacelles plus the problem of obtaining the proper drive pad on the engine.

PERFORMANCE OF FILTER AND INTERNAL BLEED SYSTEMS

Some of the airplanes using engines that are known to produce contaminated bleed air are now in service, and, though the number of them and total flying hours accumulated are not sufficient to draw any final conclusions, sufficient reports have been received to indicate the performance of the filter and inner bleed methods.

It is understood that at least two filter designs have satisfactorily completed laboratory environmental and life tests. The life tests include operation at varying temperatures, pressures, and flows simulating the aircraft operation. It is interesting to note, that, because of the high cost of supplying large quantities of high pressure and temperature air, the test duration was reduced to one tenth of the minimum life established for the particular aircraft installation. To compensate for this, the oil contamination was also increased to ten times that expected in the aircraft. Based on human nose tests of sniffing the air both upstream and downstream of the filter, these particular units appeared to be capable of eliminating all oil odor despite the increased rate of oil injection.

In regard to flight test experience, it is understood that several catalytic type filters have completed at least 100 hrs of satisfactory performance and are still in service. The first filter installations were made in military aircraft, which previously had contaminated air, without thoroughly cleaning the air ducts and air conditioning equipment. This resulted in odors still being evident in the cabin air. After each successive flight, however, the odor gradually reduced until it was no longer perceptible. It is believed that if a properly designed filter is installed with new ducting equipment, or with a thoroughly cleaned system, the contamination will be eliminated from the start.

A system utilizing bleed air from the diffuser inner wall has been installed on a fairly large number of airplanes and considerable flight experience has been accumulated. Engines with this modification do not produce eye watering, irritation of the nose or throat, or any smoke in the cockpit. However, the performance must be termed as marginal in that the oil odor is definitely noticeable.

Where strong complaints of eye watering and nose and throat irritation were reported, investigation of the aircraft provided positive answers to the problem. Loose connections on engine and hydraulic oil lines located in the accessory section on the front of the engine, excessive oil leakage inside the engines, or malfunctioning valves and other components in the oil system were found. After correcting these items, the airplanes were re-flown and were considered acceptable. The few instances where mild nausea and loss of sense of direction have been reported, but with no serious eye-watering or fumes or smoke, have been the most difficult to analyze. In one instance, a very thorough examination of the aircraft revealed no excessive oil leakage or any condition that would be considered other than normal for the airplane. It was determined, however, that the pilots physical condition prior to the flight was below normal and was probably the major factor contributing to his troubles in flight, though the fact that the objectionable odor existed could certainly have caused anxiety and tenseness which then triggered the below normal physical condition. This situation points out the chief problem involved with any decontamination system that does not completely eliminate the oil odor, and that is what may be called the psychological hazard. Dr. George Kitzes of the United States Air Force Aero Medical Laboratory has been studying the effect of contamination on pilots since the problem first presented itself. In a recent paper presented at the annual meeting of the Aero Medical Association, reference (a), Dr. Kitzes states "pollution need not cause injury to health, but, when intolerably annoying and disagreeable, the well being and efficiency of the individual may be affected". We are all blessed with a nose that just doesn't tolerate an obnoxious odor for any length of time without causing mental anxiety and nervous tension. When this tension builds up to a high point, as it will with many normal individuals, most of the symptoms described by pilots can most certainly occur to one degree or another. The modern jet combat airplane is a very complex and costly machine that is flying at velocities in excess of the speed of sound. Considering the resulting demands on pilots who must operate these airplanes in combat conditions, it is the opinion of

many persons who have studied the problem that any contamination or odor cannot be tolerated in military aircraft. This conclusion most certainly applies to aircraft making extended flights of several hours duration.

TOXICITY EVALUATION

When it was first established that the contamination problem existed, tests were immediately started to determine the toxicity effect on small animals. A summary of the results of these tests is also given in Dr. Kitzes' paper, reference (a). Engine oil was dropped into an Inconel tube furnace, heated to 700 deg F, through which air is passed. The resulting fog of air and pyrolyzed oil was then fed into the chamber containing the animals. It was determined that all animals survived when exposed for 7 hrs to oil concentrations of approximately 190 parts per million parts of air. Similar tests were conducted by one of the airframe manufacturers in which excess oil was injected into the inlet of an actual engine. The compressor bleed air was piped through the aircraft air conditioning system and into a cabin occupied by several persons. The results of these tests indicated that approximately 1 to 2 parts per million caused severe eye-watering and irritation to the nose and throat. Considering the large difference between these values (190 ppm and 1 to 2 ppm) it is believed that the concentrations occurring in the aircraft, which are well below the 1 to 2 parts per million figure, are not toxic, and also that there is no cumulative effect as a result of exposure from day to day flying.

CONCLUSIONS

Every effort should be made by the engine manufacturer to minimize or eliminate leakage of engine oil into the compressor air. If this basic cause of contamination can be eliminated, the necessity of adding filters or separate compressors, with their weight and space penalties to an airplane, can also be eliminated.

Where the aircraft designer is faced with the contamination problem, there are two positive methods of elimination, namely the catalytic filter or the separate cabin compressor. The filter is considered preferable because it has no rotating machinery and does not penalize engine performance.

The method of extracting air from a location in the engine where the compressor air is least contaminated is considered a marginal solution to the contamination problem. If a major improvement is made in reducing engine oil leakage, this method of air extraction may be satisfactory for military aircraft, but not for commercial airliners where odor free air is a positive requirement.

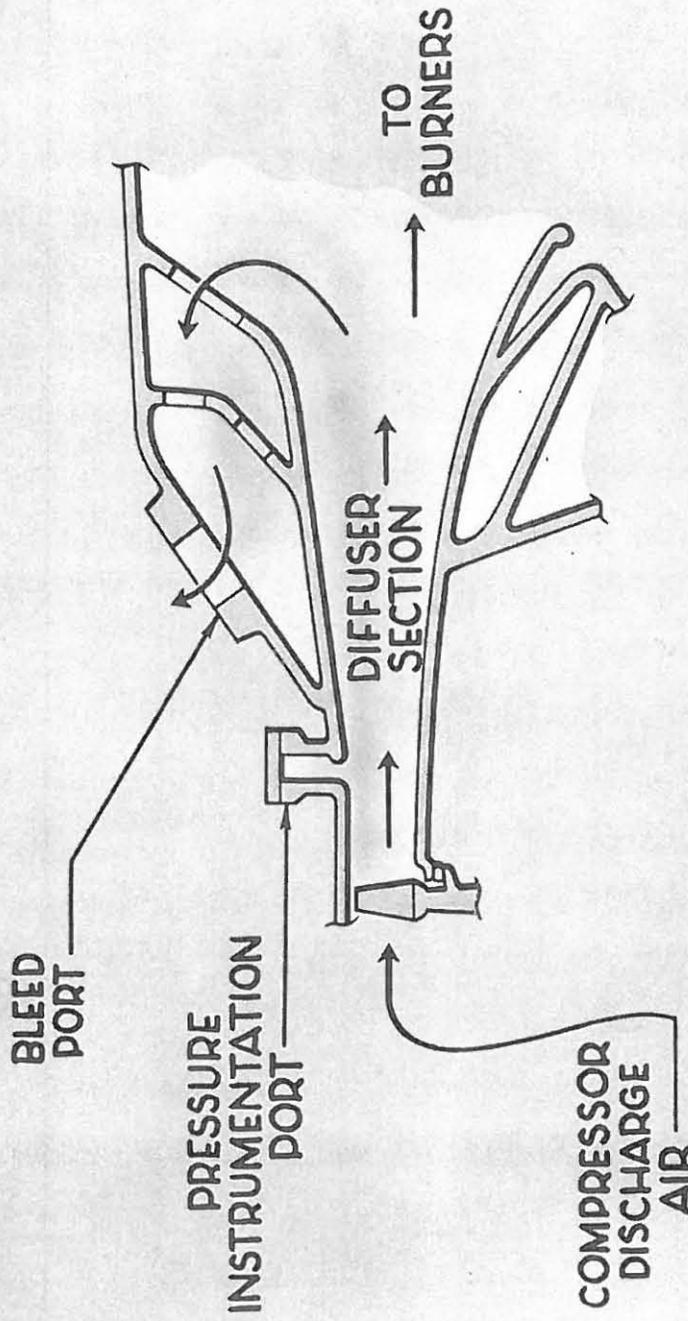
The contamination in our present airplanes is not toxic. If no elimination equipment is installed in the airplane, the contamination can vary from an objectionable odor to a condition that causes eye-watering and irritation to the nose, throat and lungs.

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REFERENCES

- a. George Kitzes, Ph.D., Cabin Air Contamination Problems, paper presented at 26th Annual Meeting of the Aero Medical Assn., Washington, D. C., March 1955.

EARLY PRODUCTION CONFIGURATION



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POSSIBLE FILTER LOCATIONS

