

# NOISE IN AIR TRANSPORT

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## INTRODUCTION

NOISE is of concern to jet aircraft transport operators because of its direct relationship to the comfort, or proficiency, or even the well-being, of the crews and passengers in flight, of the mechanics and personnel on the ground, of passengers and visitors at the airport, and of the neighbors in the community surrounding the airport. It also relates to the durability and functioning of aircraft structures and delicate flight equipment.

For our purposes we might say that noise is sound which, under the circumstances, is unpleasant or inimical to the receiver. Noise usually implies a relatively small, but annoying, diversion and waste of energy. Its contemplation involves problems of physics, physiology and psychology, and it might even be considered to involve philosophy, as in the age-old debate as to whether or not there is any sound (or noise) if there is no one to hear it!

Noise, in our definition, involves three primary elements—the source, the transmission path or medium, and the receiver. Correction or control of noise may involve any or all of these. Obviously reduction of noise at its source is the most rewarding, since it automatically reduces the problems and required corrections of transmission and reception. However, efforts to prevent or reduce the generation of noise at its source are often only partially successful, so all possible recourse must be taken to control, or subdue, noise in transmission and to minimize any unpleasant, or harmful, effects on the receiver.

The degree of unpleasantness, or damage, from noise is a primary function of its intensity—its energy content or noise power, or pressure; and of its quality, which involves its frequency spectrum or composition; and of its duration and frequency of repetition; and to some degree of its rate of onset. Its inherent capacity to annoy is also a function of the background noise level against which it is experienced, and to which the listener may have become accustomed.

This statement emphasizes the inseparable relationship of the physical, physiological and psychological characteristics of noise. The noise problems of jet transport directly concerned with people are truly problems of annoyance, compounded with concern and potential harm.

Principal sources of jet transport noise are the propulsion units, aerodynamic disturbances and auxiliary equipments. Transmission paths may be through the atmosphere, or structures, or combinations of these. The most significant receiver is the human ear, but our concern also involves structures or delicate equipment.

The noise situations of special significance to jet transport are (1) the cockpit and flight crew, (2) the cabin and passengers or cabin crew, (3) the airport ramp and passengers, visitors or service personnel, (4) the more remote airplane maintenance areas and shops and mechanics or other personnel working in those areas, (5) the neighboring airport community and its relation to take-off, landing and run-up operations, and (6) damage to aircraft structure and equipment.

Noise intensities vary all the way from the threshold of audibility to total energy contents and sound pressure levels which can cause physical distress and even destruction of hearing and material. Because of the extreme range of sensitivity of the human ear, sound pressure values are measured on a logarithmic scale in decibels usually referred to a base of 0.0002 dynes per square centimeter, or microbar. The spread of frequencies normally of concern encompasses the range from the minimum to the maximum audible. This range varies greatly with individual hearing characteristics but is usually considered from about 30 to 10,000 cycles per second. The range of frequencies of greatest general interest to the human ear and which is in direct conflict with speech communication is that from 600 to 4800 c/s, the average of the noises experienced in the three octave bands—600–1200, 1200–2400, and 2400–4800 c/s—being considered a measurement of the speech interference level (S.I.L.) characteristic of the noise. This is probably the most significant single characteristic of jet transport noise and the annoyance caused by it.

There are, however, elements of annoyance associated with the startling or fear-producing characteristics associated with the abrupt onset of noise, and there are also factors of irritation in the length of time to which the hearer is exposed and the frequency of repetition of the noise. It is also significant whether the noise is experienced outdoors or indoors, the background noise level against which it is experienced, and the activity of the listener at the time of the experience, particularly if it is normally associated with a quiet and peaceful ambient condition. The situation is also complicated by seasonal factors such as open doors and windows in the summertime.

#### COCKPIT AND FLIGHT CREW

With the customary arrangements or propulsion units buried in the wings or in nacelles or pods, or at aft tail locations, and with the substantial fuselage lengths of modern transport design which place the cockpit well

forward of any propulsion unit location, the sources of noise to be considered in the cockpit are obviously those resulting from aerodynamic sources or from auxiliary equipment operation. Aerodynamic noise may be of two kinds—that originating externally from the turbulent boundary layer and that incident to internal air flow through ventilating ducts and their outlets. The former effect is a function of the forward speed of the airplane and of the boundary layer thickness. These noises generated externally in the turbulent boundary layer and aggravated by any surface irregularities are deterred in transmission through the cockpit walls and windows by the relative stiffness of such cockpit structures. But wherever diaphragm response is present due to lack of rigidity in wall plate areas substantial noise is conveyed to the inside of the cockpit. Internal acoustical treatments will absorb transmitted noise to a substantial degree.

The second significant source of aerodynamic cockpit noise is that incident to internal air flow through ventilating ducts or outlets, or under unusual circumstances, to open cockpit windows. These noises can, of course, be minimized by careful detail design for smooth flow and proper proportioning and by the proper use of acoustical materials and treatments.

A substantial portion of the frequencies inherent in aerodynamic noise in jet transport operating regimes are in the speech interference bands. Consequently, these aspects of cockpit design, both external and internal, merit the most careful attention. These noises can be substantially aggravated as in the case of diaphragm response to aerodynamic boundary layer noise, by the occurrence of vibration which is frequently an annoying accompaniment of noise phenomena, and in many cases becomes a secondary source of noise generation.

The second principal source of annoying cockpit noise is that associated with frequent or continuous auxiliary unit operations, which may vary from low to high frequency and may well be in the speech interference group. Such noises emanate from gears, from valves and from mechanical, electrical, and hydraulic operations of various types. They are normally transmitted through the equipment itself and the structure to which it is attached. There seems little excuse for their existence since their cure is readily susceptible to normal treatments of isolation and insulation of the sources.

One type of cockpit "noise" which has perhaps not been given adequate attention, is that associated with sound characteristics of alarm bells or other alerting devices. I do not know of any studies in this area, but it would seem that there might be beneficial results from an examination of the nature and intensity of alarm noises to produce the maximum alerting effect without undue annoyance or shock. There is also an element of cockpit noise which has not been generally discussed—namely, the soporific effects of a too monotonous steady state noise condition. One of the required conditions of the cockpit atmosphere is the maintenance of a reasonable or even unusual degree of alertness. Monotony of noise

background, just as deficiencies in air conditioning, definitely tends to invoke a physiological and psychological deadening of the senses. We are all familiar with the use of lively music to awaken and alert individuals under many circumstances, including industrial applications. Constructive thought might well be given to ways and means of employing sound in our cockpits to help maintain an atmosphere of relaxed alertness.

#### CABIN AND PASSENGERS OR CABIN CREW

Many of the comments applicable to the cockpit and flight crew apply also to the cabin with its passengers and cabin crew. Physically the location is closer to the normal propulsion unit positions, particularly if they are in or adjacent to the wings. In such cases the rear end of the cabin in flight is frequently subjected to impingement from the noise generating spread of the jet exhaust. The subject of jet exhaust noise will be discussed later, but it is interesting to point out that exposure of the aft end of the cabin to jet exhaust noise is usually in the region of the generation of the lower frequency components of such noise. No effects are noticeable in flight in the cabin from the higher frequency jet intake noises—which will also be referred to later—since these are highly directional and propagate essentially forward.

The cabin in flight is also exposed to the generation and transmission of aerodynamic turbulent boundary layer noise, to noises from poorly designed or acoustically treated ventilating ducts and outlets, to noises originating from improperly isolated or insulated auxiliary units, and, with some arrangements, to noises incident to the opening of wheel wells and the functioning of landing gears during approach and landing, and perhaps to noises from the mechanical operation of controls in flight.

As in the cockpit, the generation and transmission of turbulent boundary layer noise is a function of the forward speed of the airplane and the thickening of the boundary layer as it progresses rearward on the fuselage, and to the stiffness of the wall panels which results in either the suppression of boundary layer noise generation at subsonic speeds with stiff walls or its aggravation by diaphragm response and transmission to the interior of the cabin through non-rigid walls. Whereas the basic structural design and shape do not, of themselves, provide the same degree of wall stiffness to the cabin as is inherent to the cockpit and the nose of the airplane, nevertheless, pressurization is of material benefit in giving a high degree of stiffness to the cabin wall panels, which assists greatly in the suppression of boundary layer noise transmission. Suitable treatments of walls, ceiling and floor with sound absorbing acoustical materials and the usual rigid double glass, small size window constructions which are necessary for adequate protection against decompression failures, are helpful in minimizing noise transmission and encouraging noise absorption.

In general, the rear of the jet cabin is the section most susceptible to annoying steady state noise conditions as a function of the relative disposition to the jet exhaust and its normal spread in flight-developing turbulent lower frequency noise generation and impingement on the side walls of the fuselage. This area of the cabin requires, therefore, extra treatment either to prevent the transmission of the sound, or to deaden it in transmission, or to absorb it locally after transmission. Since the frequencies involved are fairly low, it is costly of structural weight to attempt to provide the extra stiffness and mass in structure to achieve this result, so it appears better to attack the problem by a combination of local structural treatment and the addition of low frequency sound deadening panels combined with sound absorption materials. Any extra stiffness that can be provided in this area by bulkheads is, of course, helpful, provided they do not become of themselves secondary sources of noise generation. Some low frequency sound deadening treatments used in situations of this character—the problem being similar to that which with propeller driven airplanes has sometimes existed in the general vicinity of the propeller plane—have consisted of such materials as lead sheet, steel substitutions for aluminum structures, and acoustical blankets. Recent tests with lighter weight baffles or blankets of steel supported on lead mounts are reported to produce encouraging results.

Brief reference has been made to the noise problem of landing gear extension and functioning, which has become prominent in jet transport arrangements which retract the wheels into openings within the fuselage outline at the root of the wings and beneath the cabin floor. Such openings of large dimension expose, on lowering the wheels, irregular holes which even at approach landing speeds tend to generate a high degree of turbulent noise transmitted directly through the floor structure into the cabin. Aerodynamic treatment of this wheel well opening and the elimination of all unnecessary turbulence-creating pockets or protuberances substantially reduce the basic problem, although the effect is still very evident despite any reasonable amount of floor insulation or stiffening which can be applied. A secondary effect which is unpleasantly transmitted through the floor of the open wheel well into the cabin, is the mechanical noise of brakes, wheels, oleos and linkages, as the gear rolls on the runway. The situation presents a problem which cannot but create some concern on the part of passengers seated adjacent to the cabin areas over the wheel wells.

As in the cockpit, there appears to be some possibility of jet transport cabins, particularly in the forward areas, being almost too quiet, or at least indicating the necessity for more particular local acoustical treatments. The cabin crew is not faced with the problem of monotony, as in the cockpit, since they are expected to move about and perform a diversified series of duties throughout the flight. Furthermore, there is no objection whatsoever if the passengers are in a very quiet atmosphere, since one of the very best ways to pass the time on a trip is to sleep. On the other hand,

unless special local treatments are applied, conversations in a quiet cabin can be very annoying to other passengers. I am sure we have all experienced this in night travel even at present cabin sound levels, where a conversation of thoughtless passengers or cabin attendants can seriously interfere with desired rest. It would seem very desirable to treat jet cabin acoustics in logical groups as conversation units, restraining the noise acoustically as much as reasonably possible within that group. This seems quite possible and eminently desirable.

Another cabin "noise" deficiency, which is all too common, is the poor quality of cabin loud speaker or public address systems. The blame is often laid to the inexperience or inexpertness of the cockpit broadcaster, but equal fault usually lies with the acoustical quality and distribution of the speakers in the cabin. A simple volume control indicator would also be a boon to the transmitter.

#### THE AIRPORT RAMP LOCATION AND PASSENGERS, VISITORS OR SERVICE PERSONNEL ON THE GROUND

This situation deals with the vicinity of the airplane in taxiing and ground handling at the ramp location. The individuals involved in this general area are the passengers, themselves, boarding or leaving the airplane, exposed to noises emanating largely from adjacent gate positions, since the airplane with which they are then associated is quiet and at rest. There are also the mechanics and service personnel working with the airplane who are normally exposed to its noise as it approaches and leaves the ramp positions, and to the noises from adjacent gate positions. During most of the operation of receiving and dispatching the airplane from the ramp the passengers and other personnel are housed within the ramp building and are thus protected from the external noise situation.

Another group of individuals involved are visitors to the airport who are often admitted to a roof-top location over the ramp to watch the airplane operations. Since they have paid admission for this privilege, they are obviously entitled to reasonable protection against any serious annoyance or undue exposure.

The noises and associated exposures in this instance are largely those associated with taxiing to the ramp position at reduced power, restarting the engines, and breaking loose and taxiing away from the ramp position. Under these conditions the seriously annoying noise is not that generated by the jet exhaust but is that which emanates from the jet engine intake generated by the siren action of the early stage compressor blades. This is a relatively high frequency noise of very annoying quality. The intensity of the noise is substantially increased at the break loose thrust required to initiate motion of the airplane from rest.

Additional noise exposures from adjacent gate positions may be due to conventional reciprocating engines, or turbine engine propeller aircraft, or may be those associated with other jet operations. Moreover, the annoying characteristics of the high-frequency intake compressor noise may be aggravated by the jet exhaust blast which is more concentrated and of higher velocity than that normally experienced with propellers under similar conditions. As the airplane turns in maneuvering to and from the ramp position, this jet blast, as well as the highly directional intake noise, sweep the ramp position and give problems of noise irritation and blast annoyance, with its accompanying dust and dirt. Again, this is a minor illustration of the inevitable compounding of noise problems with associated annoyances.

Extensive testing of this situation and the problems incident to it have led to the following conclusions and corrective measures, (1) if the airplane is to be towed into and away from the ramp position to a substantial stand-off location after stopping and before starting the engines, there is obviously no problem except that incident to noise and blast from adjacent gate positions. Such towing, however, is a very slow and expensive operation and seems inconsistent with the speed objectives of jet transport; (2) the airplane may be taxied in, swung around and taxied out under its own power, or part of the operation may be conducted by tow. In any event, the ramp area and personnel working there are subject to the intake noise and blast condition. The adjacent gate positions are also vulnerable to these same phenomena, reduced only by distance attenuation. Deflecting barriers, therefore, must be located between the adjacent gate positions to isolate one from the other and to minimize the noise and blast annoyance between them; and any mechanics, or other personnel, required to work in the area must be provided with adequate ear and eye protection devices, and all equipment used in connection with the airplane handling in that area must be designed to withstand relatively severe blast conditions. The provision of a simple baffle or shelter behind which personnel and equipment can be protected, as needed, seems an essential part of this ramp layout; (3) the passengers who leave or enter the airplane are protected by the deflecting barriers from adjacent noise and blast while outside the ramp building. Within the building simple provisions must be made to guard against the infiltration of high frequency noise, as well as blast and dirt. The windows and doors must be relatively airtight. In fact, the doors leading to the ramp should be either of the sealed rotating type or at least of double vestibule type. This indicates the need for air conditioning of ramp buildings and emphasizes the desirability of an air intake which can be protected against noise and dirt. In consideration of the fuel and exhaust odor problem this filtered intake may better be handled remotely in a protected location.

Tests of the situation have indicated that a sealed ramp building of relatively light construction, that is, the equivalent of 8 in. concrete block

with wooden roof deck, is adequate to deal with the problem. As for the visitors to the airport who have paid admission to watch the ramp and airport operations, and are, therefore, entitled to reasonable protection, it seems that a transparent baffle wall between them and the active airplanes is quite adequate to cope with the problem.

In considering the nature and possible cure of the high frequency intake compressor noise, which is completely subordinate to the jet exhaust noise during high power operations but which is very annoying in taxiing and ramp operations, tests have shown that effective suppression can be had by compressor early stage designs which tend to unload the blades during low power operation. Other suggested solutions have included variable intake duct areas giving a restriction which tends to speed up the intake velocity to Mach 1 thus preventing the forward passage of the noise. Deflector baffles to direct the noise upward have also been proposed. Detuning of intake resonance, particularly with prop jets, has also been used. Most of these solutions are not applicable to flight installations. The compressor design requirements for full power are at variance with the low power unloading concept. The variable intake configuration seems impractical for flight because of design complications, weight and vulnerability to foreign object ingestion. The deflecting baffle is a possible device for static use or test run-up but it seems of little value as a practical arrangement for use in normal operation. We are, therefore, urgently in need of an effective and practical solution for this problem.

Jet engine starting may involve annoying ramp noise if it is accomplished by the use of gas turbine engine driven units for starting air supply. Such gas turbines, of small size and high rotative speeds, are inherently noisy both as to intake and exhaust noises. Some units have recently been installed in light trucks with special provisions for sound suppression, and are stated to give excellent mobility and to be fully adequate with respect to noise reduction. Other types of starters of the electric, hydraulic or self-contained air pressure type do not involve this auxiliary gas turbine noise problem, but may have noise problems of their own requiring careful treatment.

#### MAINTENANCE AND OVERHAUL BASES AND RELATED PERSONNEL

Whereas the jet operations at the ramp are at reduced power with problems primarily related to high frequency intake noises, other maintenance locations on the airport, and the shop overhaul and engine test locations, wherever they may be, are faced with the needs for protection of airport or shop operations and personnel and the community against high power run-up and test procedures. These jet exhaust noises at full power can be harmful to personnel and property and of great annoyance to the airport and adjacent community. It seems common sense, wherever possible, to locate these facilities and operations at reasonable distances



from the built-up communities adjacent to the airport, and from the more sensitive airport activities. However, this is not always possible, and consideration must be given to the establishment of reasonable noise intensities in these sensitive locations on and off the airport at all times and under all conditions. Fortunately, total loss of thrust and the application of relatively large and heavy external devices of various types are fully consistent with these operations. Hence, very practical baffles and sound absorbers can be provided to regulate this noise nuisance to almost any desired extent. The problem, therefore, becomes the design of equipment for such formal run-up and test procedures which is easy to apply and use and which will achieve the desirable noise reduction under the most unfavorable conditions likely to prevail. These results may be substantially influenced by wind conditions, by overcast situations, by the distances involved, and by intervening buildings or baffles, or topography, or ground cover of various characters between the source of the noise and the sensitive location. Some of these are clearly transient conditions. Winds and meteorological conditions normally vary from day to day, and ground cover in the form of crops, which has sometimes been suggested as a noise alleviator, is usually seasonal in character.

The working conditions in the vicinity of engines equipped with good static sound suppression devices are quite acceptable and only require the use by mechanics of normal ear plug or muff devices. There is, however, the occasional need for high output run-up of jet engines under conditions where time does not permit of the application of suppressors, or run-up at an intermediate output adequate to check out certain accessory or instrument characteristics. Under these conditions the mechanics associated with the operation must be fully protected against possible ear damage by the use of the best available protection devices. The effects of the use of such devices have been the subject of study by the armed services, who have to deal with aggravated situations of this nature, including full power operation with and without afterburners, with the close support of mechanics under multiple engine and airplane take-off operations from carriers and air force bases. The hampering effects of the necessary protective devices under such conditions are of concern and may well result in impaired efficiency and proficiency. However, the inevitable ear damage, either temporary or permanent, resulting from too long exposure to jet exhaust noises of too high intensity necessitate the use of the best protective devices despite the depreciating effects. The generally accepted criterion for the onset of temporary or permanent hearing damage is that the noise shall be of such nature and intensity as to be physically painful to endure. A great deal is yet to be learned about this subject but it is generally conceded that damaging results are a function of noise intensity, duration of exposure, frequency of exposure, and recovery time between exposures, with the minimum harmful threshold set at the point of sensible pain.

## THE COMMUNITY NOISE PROBLEM

By far the most critical noise problem with which jet transport is faced is that which concerns the relationship between the community surrounding the airport and the take-off, landing and associated low altitude operations, and the run-up activities on the field. The primary source of noise in this situation is the jet engine exhaust at high power on the ground, and during take-off and initial climb. The intake noise, because of its nature, can become annoying during starting, taxiing and approach operations.

The nature of the community reaction to noise from aircraft relatively low overhead is a compound of fear, irritation and sometimes politically inspired resentment. Fear is invoked by the startling nature of the sudden onset of the noise and by its variable nature under differing altitude, wind, power and meteorological conditions, sometimes giving the impression that the airplane is threatening to the individual or his property. The irritation is primarily due to such interference as the noise may create with the undisturbed conduct of the individual's activities. Such effects are obviously interference with or deterioration of television programs or other annoying distractions from desired activities. Interference with sleep, disturbance to ill or elderly people, or children, are other instances of types of annoying irritation. These conditions are, of course, aggravated during the summer months in temperate climates by the fact that many more activities are conducted out of doors, and when indoors the windows and doors are open. Some study was made of this relationship several years ago by an investigation, under NACA direction, conducted by the National Opinion Research Center of the University of Chicago. The study, at that time, could only consider the reactions of airport neighbors to the operation of conventional propeller driven airplanes. One conclusion was that the neighbors do not grow used to or accept the noise. Continuing studies under Air Force supervision have included a significant number of military jet operations, and while there are ameliorating factors in the military urgency-public necessity relationship, the conclusion has, nevertheless, been that there is a continuing and serious problem of community relations in the generation of noise and supplementary annoyance by the close-in operation of jet aircraft. Since the primary source of this noise is the jet exhaust, it seems obvious that the basic correction should be directed to the suppression, or elimination, of part of that noise. For a given engine the attack on the problem, therefore, has been to provide a noise suppressor attached to the jet exhaust which would achieve a maximum of noise reduction with a minimum sacrifice of take-off thrust or cruising efficiency, or undue weight and maintenance penalties.

A second and very significant factor in the reduction of the noise as received is the attenuating effect of distance created by lateral or vertical separation. This second approach has been in the airport layout and

operational fields, by the arrangement of principally used runway directions leading over unoccupied or zoned areas, and by the use of maximum acceptable take-off rates of climb and landing rates of descent. The use of the so-called "preferential runway" system has been part of this operational effort to achieve maximum distances between the airplane in flight and the neighboring sensitive areas. This involves the acceptance of maximum cross wind components permitting the most frequent take-offs and landings from the runway designed to give minimum neighborhood irritation.

The obviously desirable cure of reducing the noise at its source has led to a most intensive study of the nature of the problem, including the mechanism of jet noise generation and possible ways and means of eliminating or suppressing a substantial part of it. The jet exhaust noises are generated by the turbulent mixing of the high velocity exhaust with the external air, which varies from zero velocity at static condition to a reasonably close approach to jet exhaust velocity at maximum high speed condition. Since, however, we are dealing with the take-off high thrust conditions and the accelerating but relatively slow speeds of initial climb and low altitude operation, we do not enjoy the benefit of the high speed condition with its reduced mixing problem.

In the development of jet exhaust suppressors there is sought the most rapid mixing of the jet exhaust and outside air streams, since if the mixing were achieved instantaneously, turbulence would be nonexistent and the noise would not be created. Another usual objective is an upward shift of spectral frequencies hopefully to move some of the higher frequencies to or beyond the upper limit of audibility, and in any event to profit by the improved attenuation with distance of the higher frequency components. A basic objective of all such designs is, of course, the elimination, absorption or redirection of the noise energy without the accompanying generation of sound.

All of these effects seem to be achieved to some extent in the various designs of noise suppressors which have been proposed. Practical considerations have also been of prime importance in the selection of the designs which have been adopted. These include the weight penalties, the structural and mechanical problems affecting maintenance costs, and, of course, the extremely important characteristics of static thrust reduction, and the creation of internal and external flight drag components.

The development of ground running and test suppression devices based generally upon these same fundamental principles, but able to disregard the importance of size and weight, has shown that a very great degree of noise suppression can be obtained if we can neglect the deterioration or elimination of thrust. Obviously, the thrust and efficiency characteristics are of prime importance in flight articles and, therefore, we have been forced to accept a modest amount of effective noise suppression.

The original work of Greatrex and Lilly in England was directed to the

use of varying numbers, sizes and shapes of internal teeth in the perimeters of exhaust nozzles, later trending toward the use of convoluted shapes, all devoted to the encouragement of prompt mixing, to the generation of more high frequency components and hopefully to the redirection of some noise energy. Their fundamental work has been re-examined and expanded in innumerable researches, and a vast array of jet outlets have been tested, including round, rectangular, oval, convoluted, toothed and multiple pipe exhausts; with and without center plugs for internal smoothing of the flow; and with and without fixed or retractable external sleeves or ejectors.

One of the related problems of these designs has been the necessity of compounding with the suppression device a jet reversing arrangement, either integral with it, or functionally associated in juxtaposition. These reversers are essentially of the target or louvered type, or combinations of both, which by proportionate opening create proportionate percentages of reverse thrust by partial reversal in direction of the jet. Fortunately their use is not required simultaneously with the need for maximum noise suppression, namely during take-off and initial climb, but their intimate design relationship with the suppression arrangement does involve further elements of weight, mechanical complications, potential maintenance costs and the possibility of increased flight drag.

The achieved or promised suppression of the necessarily compromised jet exhaust devices which have been selected to date appears to be in the neighborhood of 6-13 dB overall. The devices selected differ substantially in the compromises of installed weight, mechanical complexity and effects on internal and external flight drag and static thrust. The simplest, lightest and most rugged rather naturally have the least sound suppression effect. This points to the rather distressing conclusion that if our noise generating problem is severe the only known cures are heavy, complex and expensive to operate, and since the future inevitably promises higher jet outputs, our ability to cope with the noise problems of the future cannot be by an extension of established techniques, but must look in other directions for the basic cure.

Most interesting community noise survey studies by Bolt, Beranek and Newman for the Port of New York Authority have been very revealing in emphasizing the nature of one of the fundamental problems of jet noise suppression. Recognizing speech interference and its relationship to normal activities as a most important measure of annoyance, and accepting as a maximum the overall sensible effects, including speech interference characteristics, of the intensity and frequency spectra accompanying the operation of the DC-7 and CONSTELLATION aircraft, the significance of these criteria has been compared to the operation of various jet aircraft equipped with their proposed suppression devices. The specific bases of comparison have been the overall dB levels and the octave sound pressure levels throughout the frequency spectrum, which a receiver experiences on the

ground at a point below the climbing aircraft  $2\frac{1}{2}$ –3 miles from the starting point of take-off. With different take-off weights and wind conditions, and other less important airport variables, and with different regimes of thrust control during and immediately following take-off, the jet thrust outputs and altitudes over the point of measurement vary widely. These factors obviously determine the amount of jet noise generated and transmitted to the ground. The airplane speed is relatively *unimportant* in this situation, except as it affects the time of exposure to high decibel noise conditions. The most critical situation would be, of course, a maximum gross weight take-off under zero wind conditions on a hot day, since the thrust output over the measuring point would be at the attainable maximum and the altitude achieved would be a minimum. Comparisons must, therefore, be made under these least favorable conditions and emphasize the thrust deterioration characteristics of conventional jet engines with temperature. The effects are further aggravated at higher altitude airports. Limiting factors in T.O. flight path noise control are, clearly, a safe margin of climb speed above  $V_2$  (the safe take-off speed consistent with possible engine failure), and a maximum climb angle limited by passenger and cabin crew accommodation. With jets the latter is not the best "rate of climb" since such is achieved at relatively high horizontal speed and hence a relatively low rate of altitude gain with distance. In minimizing T.O. community jet noise, then, we seek an early rapid climb at full thrust, a continuing climb at maximum climb angle and thrust, and a leveling off at reduced thrust and flap angle to gain speed to continue climb to cruise altitude. The early benefit is largely due to the rewards of altitude increase and the later effect is attributable principally to the sound decrease of reduced thrust.

One jet exhaust noise characteristic which mitigates against a favorable comparison is that the noises emanating from a propeller driven airplane, due to the great influence of the propeller noise, peak in the low frequency portion of the spectrum, whereas the unsuppressed jet exhaust has a somewhat flatter spectrum normally peaking somewhat higher than the propeller aircraft. With suppressors the peak may shift further to the right and may exceed the comparable propeller spectrum in the speech interference range. The net result is that for equal overall noise pressure levels the suppressed jet exhaust sound may be more annoying to the listener than is the noise from propeller driven aircraft. The tentative conclusion of investigators of this comparison is that the overall sound pressure level of a suppressed jet exhaust needs to be approximately 5–8 dB lower in order to give the same average speech interference annoyance as that created by a typical propeller driven airplane.

There are supplementary in-flight benefits from the use of noise suppressors in jet operation. Such areas of the jet cabin as may be bathed in noise generating jet exhaust paths are normally subjected to the lower frequency generations. Consequently, in such instances the installation of

noise suppressors with their tendency to shift frequency emphasis to the right permits the easier blocking or absorption of the higher frequency sound, and for the same transmitted cabin noise level in that area, reduces the required weight of structural treatment or insulation. In some aircraft arrangements a supplementary benefit in flight will accrue by the reduction of possible structural damage from high intensity exhaust noise paths—a subject which will be discussed later.

In summary, then it seems that in the present state of the art and with currently planned high subsonic jet transports using conventional jet engines, the use of sound suppressors, effective to the degree attainable without undue sacrifice of weight, maintenance complication, and performance penalties, are obligatory. In addition, airport layouts and operational procedures, emphasizing the benefits of the use of preferential runways and the employment of appropriate power control and climb regimes, are all essential to the achievement of acceptable community noise levels. And with the best we are able to accomplish by these means the results achieved will be marginally acceptable until we are able to devise more efficient and effective sound suppressors or means of reducing jet noise at the source.

#### MATERIAL DAMAGE TO AIRCRAFT STRUCTURE AND EQUIPMENT

The generation, transmission and reception of high intensity noise may be not only damaging to the ear but can produce costly and dangerous results in the failure or malfunctioning of structure and delicate flight equipment. These effects are related to the geometry of jet engine-airplane arrangement. The sources of such high intensity noise are principally the jet exhausts. The structure and equipment susceptible to adverse effects are those located close to the exhaust elements of the powerplant and related by direct material or short distance air transmission, or those areas essentially parallel to and aft of the jet exhausts, which are directly bathed in the high intensity noise generating exhaust jets. Sides of fuselages, under-sides of aft portion of wings, and tail and control surfaces, have all been included in flat plate fatigue failure phenomena associated with such high intensity noise. Resonant response of portions of such surfaces is a prime cause of structural vulnerability. Obvious corrections are either the reduction of the noise intensity at its source inherently, or by suppression, or the detuning of the resonant areas by stiffening, or resonant frequency shift, or by the use of damping, usually by the selection of materials or the use of directly applied acoustical damping treatments.

The principles of insulation, isolation, or detuning by control of resonant frequency characteristics, seem to be the proper corrections of delicate equipment failures due to high intensity noise. One phenomenon not always recognized is that in a noise field vibration can be transmitted

either by direct material path or through the air to resonant sensitive elements or components within a piece of equipment, which by localized failure or malfunctioning, can cause improper operation of the instrument or accessory. There is a substantial need, therefore, for rigorous proof testing of the entire equipment including all its sensitive components throughout the entire spectrum and at the proper noise intensities to be experienced in operation.

These phenomena are, of course, greatly aggravated by the high intensity noises accompanying the use of afterburners and even more so in the operation of highly concentrated thrust, as in rockets—subjects which are under intensive study at the present time, but are not currently of direct concern to air transport.

#### PROPELLER DRIVEN AIRCRAFT

Our subject deals primarily with noise in jet transport—and while there is an unfortunate but growing tendency to consider obsolete and unworthy of comment any problems of propeller operated or reciprocating engine aircraft—our discussion would not seem well rounded without some reference to propeller driven turbine operated transports, of which a substantial number are just coming into commercial operation. The subject of propeller noise generation and control has been under investigation for many years, and the principles are well understood. The noises generated seem to be of two general characteristics—those associated with rotation and blade passage, and those associated with blade vortex generation. The rotational noises are prominently directed to the side, normal to the engine axis, whereas the vortex noises spread essentially aft of the engine-propeller passage. In high power operation, as in take-off and initial climb, the propeller noises normally transcend and blanket the engine exhaust noises whether the exhaust be of a reciprocating engine with its relatively low frequency pulses, or the very reduced jet effect of a gas turbine. Propeller tip speed is the most significant parameter in propeller noise generation. Reductions of such tip speed are unfortunately accompanied by increases of propeller weight and decreases of propeller thrust efficiency, particularly in cruise. As this corrective influence is applied, the relative prominence of exhaust noise becomes evident and ultimately requires the application of exhaust mufflers for effective overall silencing with additional penalties of weight and maintenance cost. Both these corrections have been experimentally applied to a degree far beyond that necessary to produce a satisfactory take-off and in-flight condition with respect to community noise, but the penalties have been so great as to discourage such full application. A sensible reduction of propeller tip speed consistent with reasonable weights, good activity factors, and acceptably high cruise efficiencies, have been the criteria of propeller noise design.

With respect to cabin noise in propeller driven aircraft, as always, the cabin acoustical design features and required insulation will be a function of the sound power field in which the fuselage exterior is bathed. The close location of the propeller tip passages to the side of the fuselage will result in a high intensity of sound field adjacent to the propeller, and a close-in and inadequate isolation or insulation of power plant will result in transmission of noise through structure into the fuselage. The cabin and fuselage in the propeller plane, the nacelles and wing attachment sections are, therefore, the critical areas requiring special treatment. The speed performance of well-designed propeller driven transports is not such as to induce a serious problem of aerodynamic noise.

The noise transmission from close propeller tip passage results in induced diaphragm vibrations of unstiffened fuselage side panels with noise energy regenerated from them to the cabin interior, as well as being transmitted through them and through the structure. Moving the engines and nacelle locations further outboard is somewhat beneficial in reducing the noise field in which the fuselage is bathed. Micro-synchronizing of propeller blade passages is also effective in reducing peak noise intensities. Adequate power plant isolation and reduction of direct noise transmission through structure, are also essential elements in minimizing the noise problem which must be dealt with in the cabin, particularly in the wing and propeller areas. Corrections which have been applied in this section of the cabin include the stiffening of floor and side wall structure by the use of steel elements in lieu of aluminum; the use of low frequency sound deadening panels, sometimes in the form of lead sheet—with supplementary acoustical absorptive materials; the stiffening of panel areas which might act as noise transmitting diaphragms; the use of triple windows as against the normal double safety designs; and the isolation by vibration absorption mountings, of bulkheads which by direct transmission can themselves become radiating sources of vibration and noise. Minor supplementary improvements have been achieved by the use of additional normal acoustical sound absorbing material and treatments in the side walls and ceilings, and by the use of multiple thickness, absorptive type floor coverings. Shock mountings for hat racks, and acoustical treatment of all details in this area are also indicated primarily in the interest of vibration absorption, but in a secondary sense, in the control of noise.

#### AREAS FOR RESEARCH AND DEVELOPMENT IN JET NOISE

We have stated that our most serious noise problem in jet transport is that of community relations, and that its prime cause is the generation of jet exhaust noise, and that our current ability to suppress this in a conventional jet engine without undue sacrifices is substantially limited. We look to the reduction of noise at its source as the most beneficial cure. Since, as Lighthill has pointed out, the jet exhaust noise is a function of the exhaust nozzle area and of approximately the 8th power of the jet velocity, it is



apparent that the most rewarding field of endeavor is in the production of satisfactory thrusts and economies for the varying flight conditions with higher mass flows at lower velocities. This immediately invites consideration of the by-pass or fan principle of jet engine design which analyses have shown to be efficiently suitable to subsonic operation. This is not the place to debate the relative merits of by-pass or fan arrangements. However, it is already clear that appreciable reductions in exhaust jet velocities with enhanced total mass flows producing increased thrusts as required, and substantial improvements in cruising fuel consumptions, with desirably wider latitude of reduced power operations with good consumptions, and accompanied by corresponding reductions in noise generation, are achievable and appropriate for high subsonic jet transport operation. Satisfactory designs of this type show analytical promise of overall noise reductions in the nature of 10 to 15 dB. This benefit is apparently obtained by the abstraction of power from the jet turbine, with reduced jet exhaust temperature and velocity, and its application to driving the fan to produce a low temperature, low velocity, high mass supplementary jet flow; and also by the shrouding of the remaining central exhaust jet with a cylindrical sheath of the intermediate velocity fan air thereby reducing the extreme turbulence of mixing and noise generation.

While this is a very gratifying accomplishment, it does not, in our opinion, eliminate the desirability of the supplementary application of simple noise suppression devices. Not only must we continue to seek full compensation for the increased thrust values of the future, but we must continue to strive for improved comfort achieved by even greater noise reductions, both in relation to community problems and cabin sound levels and structural damage in vulnerable areas. The weight savings in cabin acoustical provisions by such additional suppression, if achieved without severe weight maintenance or flight efficiency penalties, are a compensating reward. We must, therefore, pursue vigorously the development and application of such types of engines which have long been recognized as more suitable to the basic requirements of high subsonic jet transport. If and when we proceed into the supersonic operating regime, we must have solved not only the problems of coping with the jet exhaust noise problems resulting from the greatly increased thrusts required and jet velocities achieved, but we must also be able to handle the aerodynamic noises and most particularly the sonic booms which already threaten undesirable reactions and damage in supersonic operations at altitudes which must be reasonably common to jet transport requirements.

Another area of needed development is that of improved suppressors involving much less serious static thrust loss and flight drag penalties. One approach to this solution has been the use of mechanical sliding sleeves or ejectors which are stated to be effective compensators for static thrust loss and are supplementary mixing devices tending further to reduce maximum noise generation during take-off and low speed opera-

tion. However, they are mechanically complex and heavy requiring retraction in flight in order to reduce external flight drag to a reasonable value.

It is hoped that further development may indicate ways of providing effective light and simple retractable vanes within the exhaust jet stream, which when extended will greatly encourage the noise suppressing mixing but which when retracted will be innocuous in affecting internal drag.

Further investigation of the effects of various shapes of exhaust outlets and their indicated effects in distorting the sound field to minimize vertical noise components, might also be worthwhile. Some work has been accomplished in this field, and the matter is being further pursued.

There is a great need for further investigation of ways and means of controlling compressor inlet noise. The minimum length inlet ducts normally associated with good ram recovery and high intake efficiency do not lend themselves to effective internal acoustical treatments. However, it has been shown that in certain cases of an acoustical relationship between the compressor blade noise and propeller blade passages in prop-jet application, good results have been obtained by the re-design and detuning of the air intake. If other design considerations necessitate the use of a long intake, beneficial results can possibly be obtained by internal acoustical treatment. Variable intake throat dimensions have also been shown to be effective in eliminating compressor noise by speeding up intake velocity to Mach 1—but this does not appear to be a practical airplane equipment solution. Mechanical variation of compressor blade pitch and possibly pitch distribution, are possible solutions for the problem. Another solution which has been mentioned as being applicable to ground run-up is that of a deflector to project the intake noise upward. None of the solutions seems, at the moment, satisfactory or appropriate, and it is, therefore, urged that effort be continued in this area.

It seems possible that the fundamental effects of airplane arrangement on cabin noise and on airplane control and efficiency encourage an increasing trend toward the tail location of power plants as the reliability of jet type engines becomes more and more firmly established. Such arrangements promise substantial weight savings in cabin insulation and almost total elimination of the cabin noise problem.

A further understanding of the nature of the generation and control of boundary layer noise will also be helpful in solving the noise problems and maintaining weight efficiency at ever increasing high speeds. The problem suggests the possible application of boundary layer control principles to fuselage surfaces, which might also be helpful in reducing flight drag and increasing flight efficiency.

Much more understanding is needed in the field of jet exhaust suppressor design. The principles of accelerated mixing and frequency shift are quite understandable in the functioning of most suppressing units. However, the mechanism by which they apparently suppress noise energy is not clearly understood and needs further investigation. It seems unnecessary

to state again that we need jet exhaust suppressing devices which are simple and rugged, light in weight, and which when combined with reversing arrangements are fail-safe in design, and which minimize the static and in-flight internal and external losses.

In the field of noise transmission, as related to the community noise problem, there seems little that can be done other than to recognize the inherent value of separation distance as the principal factor in attenuation. To the extent that permanent building arrangements, baffles and permanent plantings can be effective in intervening between the source and the point of annoyance these devices should be used. It is obvious, of course, that the airport layout should give careful thought to the separation of noise generating locations from both sensitive locations on the airport and in the community.

In the field of noise transmission within the airplane there is still a great opportunity for the development of lightweight durable materials, and arrangements of such materials, which will at minimum weight give maximum noise energy absorption over all significant frequencies.

Many opportunities exist for the further application of available principles of design and materials in isolation and insulation to prevent the transmission of objectionable sounds through metallic and airborne paths to the cabin and cockpit interior. This is largely a problem of good engineering and it seems superfluous to say that any airplane in which there is an annoying sound of a hydraulic pump, valve, landing gear, flap or spoiler operation has not utilized the possibilities of available engineering to isolate or insulate that effect. The same may be said of noisy ventilator outlets, which are still too common.

The acoustical treatment of airplane cabins should isolate logical conversation groups to prevent inter-group annoyance. This problem will become even more significant in jet transport.

As to the third element in our chain of noise effects, namely, the receiver, there is a continuing need for education as a contribution to tolerance. The advantages of high speed air transportation may inevitably entail the acceptance of some noise, and to the extent that conscientious efforts are made to minimize it, the public should be taught to be tolerant. Public relations is, of course, a most important element which requires continuous effort to maintain good relations between either military or civil aviation and the public to which both efforts contribute so greatly. Noise has become one of the important considerations in selecting locations and determining layouts for new airports. The restrictions desirable to apply to zoned areas around the airport sites have been clearly defined. It requires, however, a full understanding on the part of the municipalities and their advisors and the co-operation of the affected authorities controlling zoning in the airport location, to achieve the desired results.

It is also apparent that much more work remains to be done in the efficient and effective protection of individuals against hearing damage

when exposed to high intensity noises. The devices must be so unobjectionable that they will willingly be used. They should be effective in eliminating the hazardous noise elements but in freely admitting, if possible, conversational frequencies, and conveying no sense of restriction or interference with normal activities or comfort.

Further research is necessary in the field of materials and designs to minimize the fatigue effects on structure due to high intensity noise with low weight penalties. Further encouragement should be given to the comprehensive testing of all sensitive flight equipments in noise environments equal in intensity and as broad in frequency spectrum as is the operational situation.

### SUMMARY

We have endeavored to examine the basic problems of noise in relation to jet transport. Objections to aircraft noise and efforts to cope with some elements of it date back at least 40 years. The first attack was on the exhaust noise, later transferred to its combination with propeller noise. The occurrences of such noises, however, were not of great enough intensity or frequency to cause any serious concern for many years. Ultimately, however, the growth of aviation activity, the increase of energy output and the attendant noise generation, the establishment of numerous airports close to large centres of population, and the growth of those centers to surround the airports, have all increasingly aggravated the situation and concern. It can truthfully be said that even without the introduction of jet transport the progressive growth of the problem requires corrective measures. This has already been evidenced in controlled flight patterns and related measures in the New York Metropolitan Area and elsewhere. The introduction of jet transports, however, with the generation of higher noise levels and the change in character of noise has greatly emphasized the problem and made necessary more drastic corrective measures. Our concern is primarily with the community, but is also with the passengers and visitors at the airport, the passengers and crews in flight, the mechanics and other personnel on the ground, and with the airplane itself. The solutions available today are only partial and are marginally satisfactory. Since the future inevitably holds promise of higher jet thrusts and aircraft performances we must vigorously continue the development of ways and means of coping with the ever-growing noise problems, and it is obvious that our great emphasis should be on the reduction of noise at its source.