Thiokol CORPORATION

STRATEGIC OPERATIONS

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Dynamics Analysis

SUBJECT: Predicting Launch Acoustic Environments

Interest from SDC and MDAC coincidentally in the same week on two different systems on predicting launch acoustic environments prompts me to share what I know about the subject. The problem is two-fold, acoustics as a function of motor design and launch pad (launcher) design. The solution is vastly different depending upon which problem is being solved. Obviously, we are more directly involved with the motor design issues but we need to be educated on launch pad design issues also because our equipment is exposed to this environment. However, the motivation for determining launch acoustics has much more to do with payload and launch facility protection.

To give perspective to the design issues involving acoustic environments, a short discussion is informative. First of all, the failure mode driven by acoustic energy is vibration loading of one type or the other. Secondly, all missile vibration is a response to one kind of acoustic energy or the other except for rotating machinery response which is a minor portion to the bulk of a missile structure. The acoustic sources may be loosely listed as follow:

1. Direct External
2. Indirect Reflected External
3. Internal Combustion/Aerodynamics
4. External Aerodynamics

One may argue that these are distinct but in terms of vibration response they all behave the same, i.e., they are dynamic pressure environments. Figure 1 shows in perspective the importance of each environment in terms of structural vibration response. This figure was presented by the writer as part of the 58th Shock and Vibration Symposium in Huntsville. As can be seen, the launch environments are most significant particularly to the base region. However, Max Q environments become more significant at missile stations significantly removed from the base region, i.e., payload. Saturn environments tend to confirm this position as discussed in the attached article. An exception to this recently shown during the Titan launch where the payload was insufficiently protected from the launch environment.

The attached article was written in 1965 when Saturn design was driving launch facility design. The essence of the paper deals with establishing the dependence of source acoustics on motor design. The bottom line is that acoustic intensity is proportional to the exit plane gas velocity cubed. Interestingly, the article concludes that a launch system employing multiple motors in unison develops less apparent sound energy than a single motor of equal thrust. So, if the propulsion designer wishes to modify motor design to lower acoustic intensity during launch, he may change expansion ratio, probably by cutting of the exit cone. Secondly he may choose to change the grain design to lower chamber pressure.

An improperly designed launch pad may completely reverse any advantage the propulsion designer builds into his motor to reduce sound on the pad. For example, berming may reflect a large amount of sound back onto the missile. Large launch structures will also cause the reflected sound to increase significantly. As is discussed in the attached article, the plume is the sound source. The launch pad design optimally will duct the plume away from the missile thus reducing sound levels significantly. Martin Marietta has spent significant effort predicting launch acoustics for the Titan with the objective of modifying the launch pad design. MMA was contracted to develop software to do this. Dr. George Sowers was the principle actor and the final product was GASP computer code. It was used on the Titan launch January 1, 1990 and proved successful.

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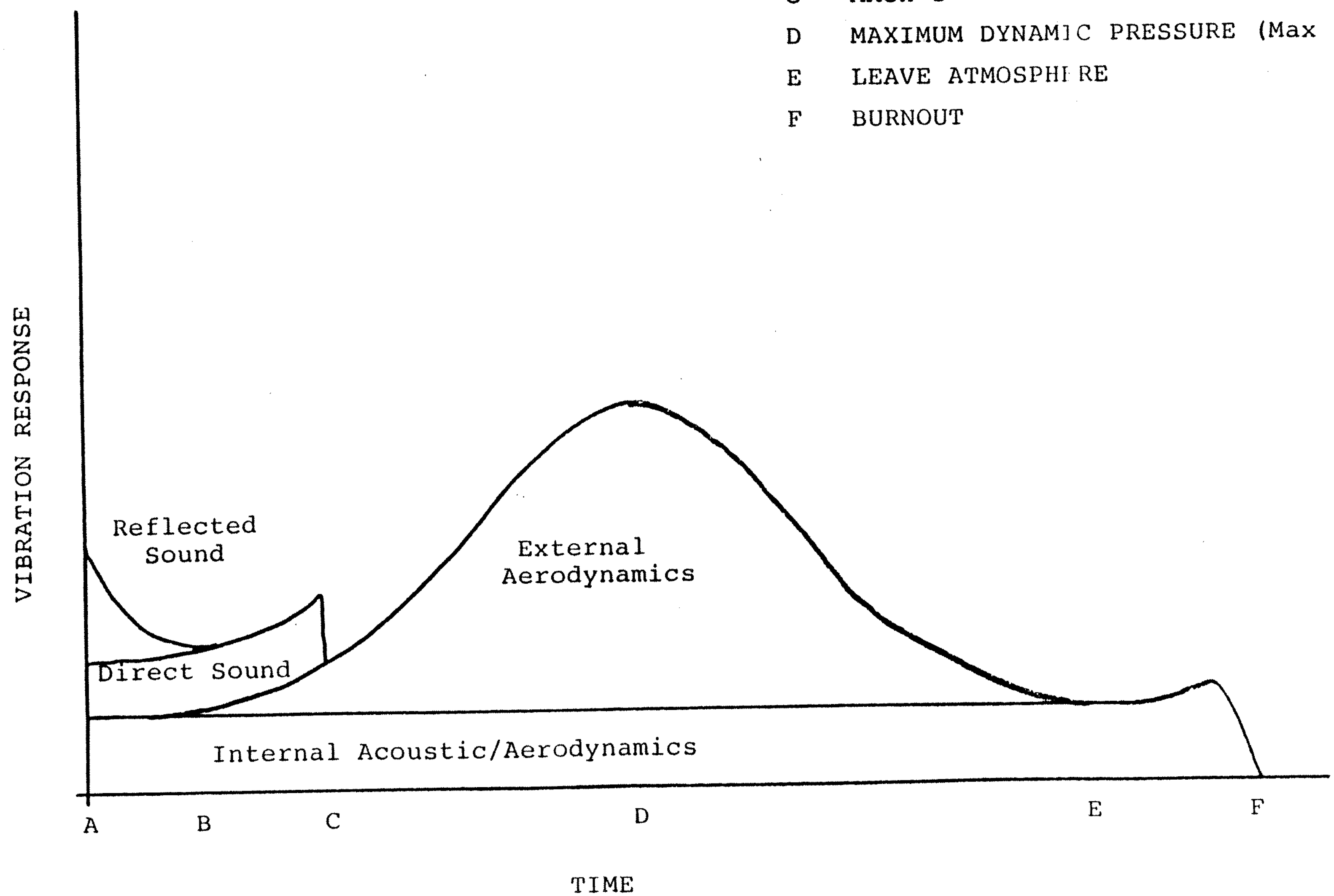
BKA:jac

Attachments

FIGURE 1
FLIGHT VIBRATION RESPONSE CONCEPT

A LAUNCH
B FLY AWAY (1.5 SECONDS)
C MACH 1
D MAXIMUM DYNAMIC PRESSURE (Max Q)
E LEAVE ATMOSPHERE
F BURNOUT



THE NOISE OF ROCKETS

GUY LENEMAN, Vibration, Shock and Acoustics Group, Douglas Aircraft Co.

The problem of acoustic loads from engine exhaust and aerodynamic sources, the main cause of vibration in rockets, gets worse as boosters get larger. As a result, the reduction and control of acoustic noise levels is fast becoming a major constraint in the design of launch facilities and vehicles.

Liquid or solid, some 0.3-0.8 percent of the total power generated by a typical rocket booster is manifest as sound. For a booster of Saturn 5 size, with 7.5 million pounds of thrust, this amounts to about 200 million watts of acoustic power — enough to bring vehicle materials and equipment to the end of their structural lives, to threaten ground support equipment and nearby buildings and rockets, and to constitute a serious physiological hazard including, but not limited by, ear damage.

In fact, rocket noise, acoustically coupled to panels and structures, accounts for the major part of the vibration environment (and the vibration specifications) with which aerospace equipment must contend. When the acoustic coupling is removed or reduced, vibration levels go down almost proportionally. For example, the vibration levels experienced by equipment during ignition and firing of an already spaceborne Agena rocket are only a few percent of the levels measured at the same rocket locations during Agena firings from ground launch pads. The reason: radically reduced (i.e., no acoustical) coupling because of the absence of an atmosphere and the elimination of sound-reflecting launch pad surfaces.

In addition to vibration induced by engine noise at or near liftoff, boundary layer noise from aerodynamic sources often pose a very serious vibration threat to upper rocket stages and to payloads. In some cases, fatigue from this vibration source represents an ultimate design limitation for structures such as spacecraft shields or even the craft themselves. Besides such fatigue effects, the importance of this noise source to spacecraft occupants was dramatically demonstrated in an early Mercury shot: voice-actuated switches were thrown and acoustically induced vibration of men and equipment dangerously interfered with astronaut performance.

Jet aircraft have similar problem

To some extent, vibration from both engine and aerodynamic acoustic sources raises similar structural problems in jet aircraft. Even though the acoustic levels in jets are generally much lower than those in rockets, and although damaging effects such as fatigue are very dependent upon acoustic level, aircraft equipment and personnel must endure the vibration for much longer periods. Acoustic shielding has therefore become an increasingly important design consideration for high performance aircraft.

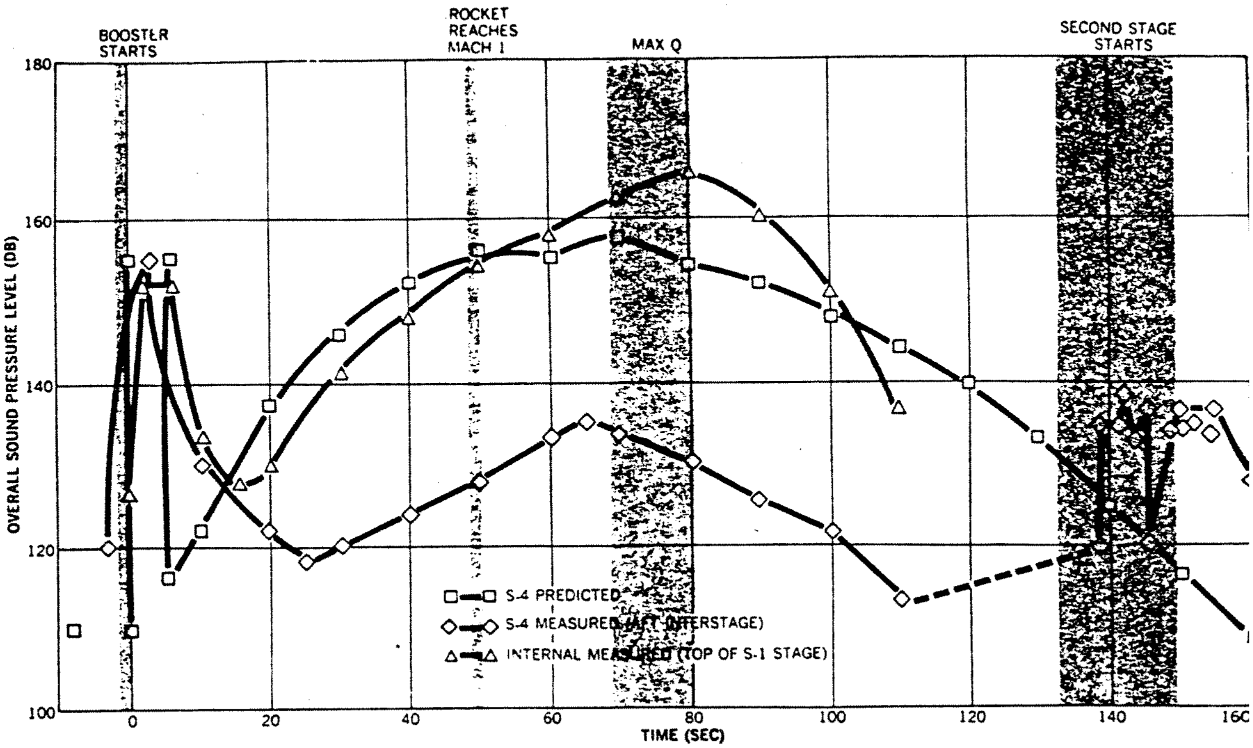
Because both aerodynamic and engine noise effects scale up roughly with vehicle size, the problem has grown from a ground nuisance to serious, and perhaps limiting, dimensions in several advanced programs. Unfortunately, as missions and vehicles get more ambitious, and acoustic environments more severe, it has become increasingly apparent that present techniques, both theoretical and experimental, are inadequate to cope with questions regarding the sonic environment and its effects. Here, as in other areas, it appears ignorance may prove to be the most severe environmental stress of all.

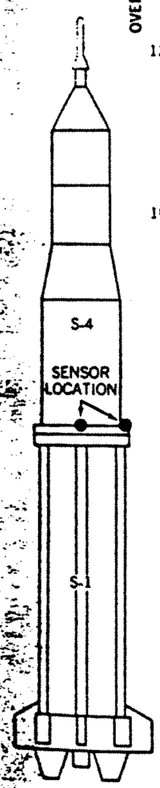
It's not that acoustical problems are new to the industry. Way back in pre-jet days, vibration from the characteristic pulsating noise of propellers was recognized as the source of catastrophic fatigue failures in engine cowlings and similarly exposed aircraft structures. And in the case of helicopters, it was found quite early in the game that unmuffled engine exhausts contribute more to acoustic noise levels than the comparatively slow propellers or rotors.

The physics: complex and incomplete

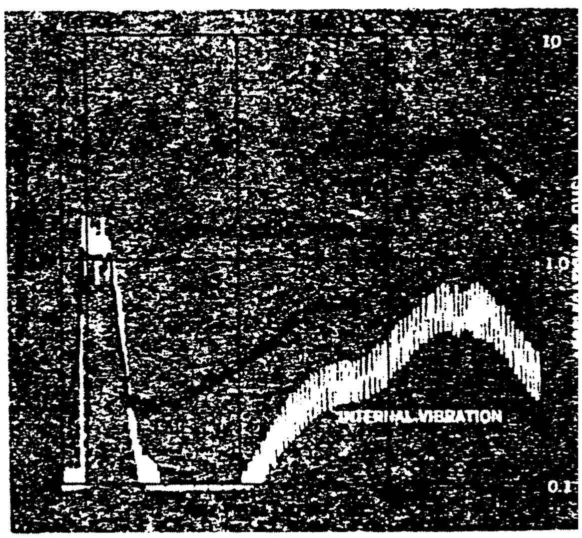
In a very oversimplified way, those unmuffled airplane and helicopter exhaust noises are just different aspects of the same phenomenon which causes the racket of a large booster engine. In all these cases, **the sound is generated by pressure fluctuations within the boundaries of eddies at the shear layers between a high-velocity gas jet and still air.** Of course, in real boosters (and to some extent in turbine and other engines) chamber wall vibrations, unstable combustion and other phenomena contribute to the characteristic exhaust noise of the engine. But for rockets, it's usually safe to neglect those side effects on the assumption that, if they're appreciable acoustically, the engine is probably in deep trouble anyway. This is the working assumption generally made in practical cases.

In principle, once this assumption is made it is possible to predict, from basic physics, the amount of sound generated by a gas stream as it issues from a nozzle. The theoretical basis for such an approach was laid down by M. J. Lighthill in the early 1950s and has been unfolding in further work by Lighthill, his students and their students ever since. It turns out that a cold gas jet exiting with subsonic velocity generates acoustic power proportional to $\rho U^8 d^2/c^5$, where ρ is gas density, U is exhaust velocity, d is the diameter of the exhaust nozzle and c is the velocity of sound in the ambient atmosphere. This expression was used for a while (and still sometimes shows up) to predict the sound levels of rockets. However, this relationship never agreed with measurements of rocket noise; the exhaust gases from rockets have velocities well above Mach 1 — in the range of 6500 to 9000 fps. It wasn't until the early 1960s that theo-





Acoustic histories of booster flights (above) typically show several peaks. The first corresponds to noise from the engine exhaust during liftoff, the second to aerodynamic noise which peaks during the period of maximum dynamic pressure ("max q"). Later noise peaks correspond to separation and startup of second stage. The noise measured internally (lowest curve) is well coupled to lower-frequency exhaust noise, but poorly coupled to high-frequency aerodynamic noise generated later. The data are from the SA-3 and SA-4 flights. Smaller graph shows overall external noise (engine and aerodynamic), measured on the outside of a two-stage Saturn vehicle, and the vibration it caused, measured internally at the gimbal plane of the second-stage engine. Vibration is less well correlated with aerodynamic sound pressure levels than with engine noise, because aerodynamic noise comes from many uncorrelated sources and is less efficiently coupled to the structure. So, though sound pressure is greater during the max-q part of flight than during liftoff, vibration levels are higher during liftoff. Dashed lines on both graphs indicate missing data. Sound power levels in this article are decibels referred to a base of 10^{-13} watts.



retical work by J. E. Ffowcs Williams led to the conclusion that acoustic power for such high-velocity streams is proportional not to U^8, but roughly to U^3.

But $\rho U^3 d^2$ also happens to be proportional to the $\dot{m}$ of the $\frac{1}{2}\dot{m}v^2$ term that represents the thrust available from a rocket engine. And so, the noise coming from the high-velocity exhausts of modern rockets follows thrust in fairly linear fashion. As a result, this relationship between mechanical power and acoustic power is often expressed as a conversion efficiency,

$$\eta = (\text{acoustic power})/(\text{mechanical power})$$

and is plotted for prediction purposes.

Pinning down the conversion efficiency is not simple, for although it tends to follow the U^3 relationship, it still varies somewhat with gas velocity. For engineering purposes, furthermore, specific impuls is a much more readily available characteristic tha exit velocity. Their relationship is simple ($I_{sp} = U/g$ Thus, working rocket-noise curves of the type show on the next page have proved the most hand for predicting overall sound power levels.

But these numbers aren't what we're really afte They just represent the so-called free-field, the start ing point for finding out what the sound will be lik at particular places in and around vehicles. In orde to predict these specifics, it's necessary to take int account not only the effects of atmospheric attenua tion and the dispersion of sound but to determin the frequency spectrum and the directivity patter both near the engine and in the far-field.

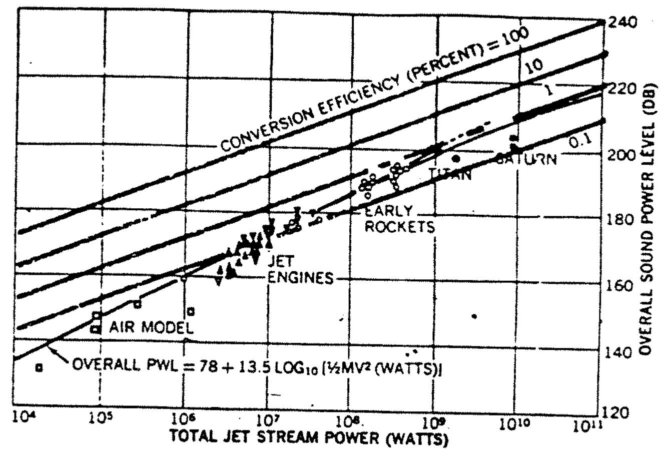
When similar rockets are compared, their soun pressure spectra for corresponding physical locations can be scaled from the dimensions of the engines and the velocities of their exhausts. A common plot for rocket sound spectra is in terms of constant-percentage frequency bands. In these terms, the frequency is scaled inversely proportional to, say, exhaust nozzle diameter. This method of prediction depends upon the similarity of the systems compared; within this constraint, the method works quite well. Just about all healthy engines (i.e., those without resonant death rattles) exhibit spectra that are best described as peaked random noise.

Geometry is all-important

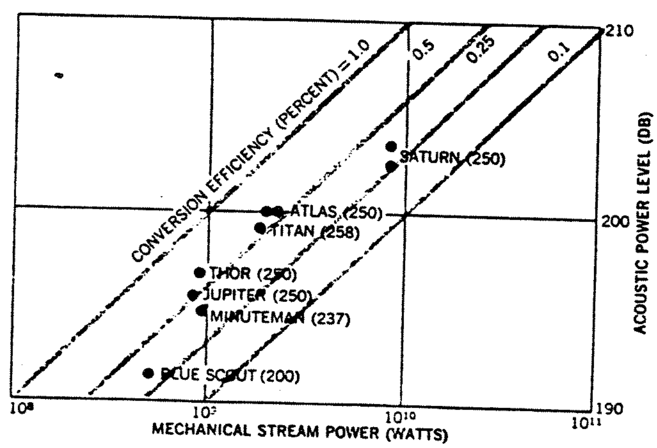
Quite apart from atmospheric absorption and the inverse-square law for attenuation with distance, geometrical effects dominate the acoustic picture, both by their interesting antics and by their significance to equipment and personnel. For example, the engine sound source, from a distance greater than, say, 20 engine-diameters, appears to be a single source slightly downstream from the exhaust nozzle. But in the so-called near-field it appears as a series of sources; within a few nozzle diameters, these noise generators seem to be arranged along the axis of the exhaust plume, with the higher-frequency sources closer to the plane of the nozzle.

Even some distance from the engine, where the virtual noise source is a point, the sound doesn't spread out evenly in all directions. Instead, in this mid-field region, ranging up to several hundred yards, the overall sound level — and each frequency band of it — has a directivity pattern such as the one shown on page 80. For example, for a rocket well above the reach of ground effects, the maximum-intensity lobes are typically some 60 deg off the axis of the jet. That is, it's quieter (albeit hotter, perhaps) to stand directly behind the exhaust than off to the side 60 or 80 deg. Similar phenomena, incidentally, can be observed at and near jet airports. Of course, sound from these lobes, like sound from anywhere else, can be reflected from nearby surfaces to cause damage to still other surfaces and structures, including the vehicle itself. Since directivity patterns vary with frequency, the prediction problem can get very complicated very quickly when a few odd-shaped reflecting surfaces are added to the picture.

The most common reflector of booster acoustics is, of course, the launch pad. Rocket noise reflected from a pad back to the rocket can easily treble the free-field acoustic loads on the vehicle's structure. Studies of various designs have shown, moreover, that the blast deflectors of most launch pads increase the acoustic levels (and the vibration) along the lengths of the vehicles. This is because the geometry of a generally cylindrical exhaust plume is nothing like the directivity pattern of an acoustic field. What deflects a gas stream harmlessly may do just the opposite to the acoustic pressure of an ignition pulse or other exhaust noise.



Sound power from a rocket engine depends mainly on the total mechanical power of an exhaust stream—that is, on gas velocity and specific impulse (mechanical stream power, in watts, equals 21.83 F I_{sp}, where F is thrust in pounds). For low-power jets (characteristically with low jet velocities) the slope of sound versus total power is much steeper (i.e., the conversion efficiency is much higher) than it is for high-power jets. The straight line and the curve drawn through the data points represent two attempts to match data and are not predictions from first principles. Nevertheless, such curves and interpolations are clearly useful for predicting overall sound power levels.



The data points on this graph of engine noise are actually composite points including data from several firings of each type of rocket. The points for any particular specific impulse (the number in parenthesis) tend to fall along the same conversion efficiency (η) line. A probable reason for the anomalously low η of Saturn is the interference effect of using several closely clustered booster engines instead of one large engine or two with wider separation.

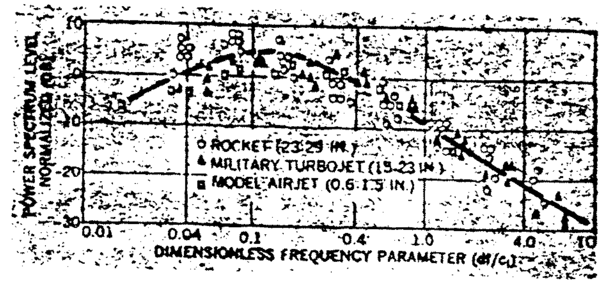
Of all launch pad designs, the common missile silo is probably the hardest on its bird. Measurements from Titan firings have shown dramatic increases (up to 45 db) in noise levels along this rocket, which come from firing the missile from a long tube. Even at that, the type of tube (its ducting to the outside, etc.) makes quite a difference.

Launch pads don't necessarily have to be acoustically deleterious. So far, pads have been designed either ignoring their acoustical characteristics or, if not, for the convenience and protection of pad facilities rather than the vehicle. However, some noise reduction for the vehicle is also possible with improvements in pad design. While these noise reducers only help during the first few seconds of launch, that period (including the ignition pulse) is a very critical time, especially for large vehicles. Though small and medium rockets get away from their pads very quickly after ignition, rockets of the Saturn 5 type will take tens of seconds just to clear their gantries. Considering their need for acoustic protection, it seems about time to design acoustically effective pads.

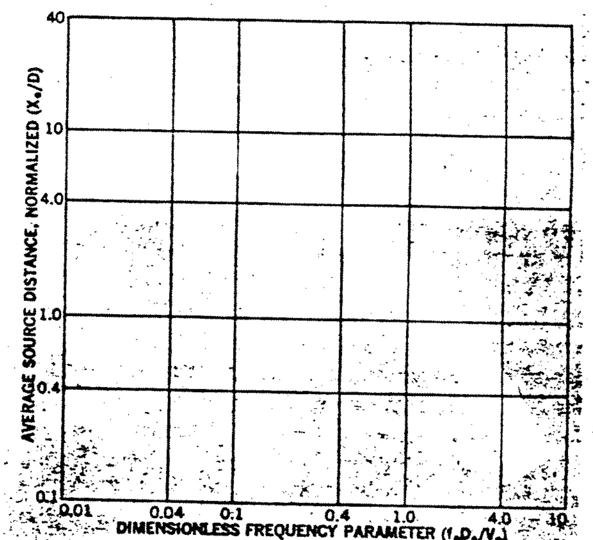
Some preliminary work has already been started along these lines. One approach suggested for Saturn 5 involves mounting the rocket over a large pool of water and circulating the water into the exhaust stream to remove energy from the exhaust gases by using the heat of vaporization of the water; model test results so far have been inconclusive. Other, more conventional schemes involve acoustic baffling in the pad itself. In one design, the rocket is mounted directly above the entrance to a long tunnel so that the effective sound sources in the exhaust stream are well within the tunnel. Sound from these sources is attenuated as it bounces around in the tunnel and moves downstream. At the tunnel exit there is again a stream of gas leaving a port, and it too is a sound generator. However, the geometry is arranged so that the gas moves much more slowly here than it does from the rocket, and so, in accordance with the U^8 dependence of noise level on gas velocity, the noise is much less. A sophistication of this acoustic launch pad is to mount the engine over a concrete slab with a hole to exactly contain the exhaust plume, and to mount a stream diffuser below the hole and coaxial with it. The single long tunnel of before can then be replaced by a system of many tunnels or by a single shorter cavity.

The effects of distance

Beyond the immediate launch area — say, several hundred or a thousand feet away from the source and beyond — sound levels can be expected, by the inverse square law, to attenuate at a rate of 20 db (a power factor of 100) for each decade change in distance. For a rocket such as Saturn 1, this effect of distance reduces the sound pressure levels to about 105 db (the generally accepted threshold of annoyance) at about 50,000 ft. At about 10,000 ft, Saturn 1's 165-170-db near-field level comes out to about 120 db, which is about as loud as a typical jet passing 40 ft overhead. This is the level most state regulations set for requiring earplugs or earmuffs to prevent hearing damage (military safety rules require ear protection beyond 130 db). Even when ear protectors are used, many regulations prohibit human exposures to sounds louder than 150 db, because sounds louder than 150 db can cause surface heating and internal bleeding in animals.



This broad-peaked spectrum is characteristic of rocket engines (having the same general shape for liquid and solid propellants) as well as of turbojets and even airjets. But its frequency range and peak amplitude change from one source to another, depending on the power level (PWL) and the nozzle exit diameter. The ordinate is referred to PWL —10 log$_{10}$ (c_i/d), where c_i is the velocity of sound at nozzle exit (fps) and d is exit diameter (ft).



Low-frequency components of a rocket's exhaust noise appear to originate much farther from the nozzle plane than do high-frequency components. Here, source distance is given in nozzle diameters and frequency in terms of the so-called Strouhal number: frequency times nozzle diameter divided by exhaust gas velocity. At lower frequencies than shown, the curve tends to flatten out.

But Saturn 1 is only a 1.5-million-pound-thrust booster; the corresponding inverse-square law distances for Saturn 5, with its 7.5 million pounds of thrust, work out to 120 db at 25,000 ft and 105 db at 125,000 ft.

Besides the inverse-square attenuation, sound is also attenuated by atmospheric absorption, principally at higher frequencies. By the scaling laws previously mentioned, the peak spectrum of booster noise gets lower as booster size increases. The low frequencies expected from boosters such as Saturn 5 are hardly touched by atmospheric attenuation over such distances.

Complicating this far-field situation still more are the effects of wind gradients and of refraction by temperature inversion layers in the atmosphere near a firing. Such atmospheric effects can focus the sound toward far places to raise sound pressure levels as much as 20 db above what they would otherwise be. During some Saturn 1 firings, for example, parts of Huntsville, Ala., 5-10 miles away from the engine, were subjected to excessive sound pressure levels while people in nearby sections were unaware that a firing was in progress. For this reason, it's now standard practice to take atmospheric soundings before a launch and to then use either manual or computerized ray-plotting techniques to predict possible focusing. Scheduled launches have already been scrubbed on this basis.

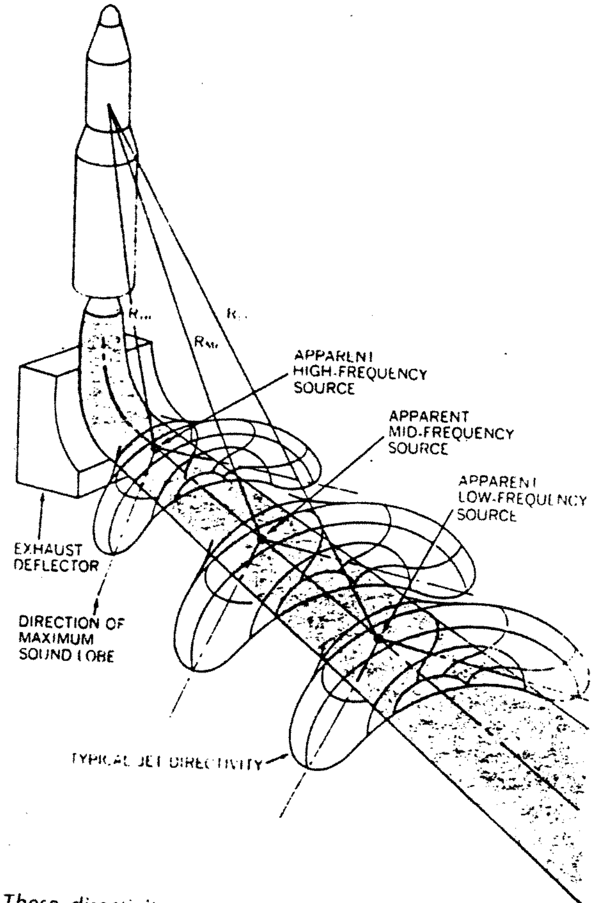
Besides launch pad design, distance and careful scheduling, it's possible to reduce rocket noise by modifying the engine design. This almost always winds up cutting engine thrust. And so it's never done. However, there is one development in boosters that can sometimes help reduce the noise level associated with a particular thrust requirement, and that is the clustering of engines of moderate size, such as is done in the Saturn boosters.

Multi-engine boosters are quieter

The effect on acoustic level of using a cluster of small engines in place of one large one of similar total nozzle exit area is to create interference among the sound-generating boundaries between the jetstreams and the atmosphere. Recent research has shown that this jet-interference effect approaches a maximum noise reduction of 5 db in total sound power level (compared to a single engine of equal thrust) when the area bounding the nozzle exit planes is twice the area of these exit planes. Although it's unlikely that the optimum 5-db reduction can be achieved in clusters that are practical in other respects, some gains are possible this way. The jet-interference effect may, incidentally, account for the unexpectedly low (3 db less than calculated) sound levels measured during Saturn 1 firings.

The use of multiple-engine design for large boosters can also affect a rocket's noise spectrum. Heretofore, such effects have not been taken into account in predictions for acoustic spectra; the present technique is to assume a hypothetical single engine whose total nozzle area equals the total nozzle area of all individual engines. But it looks as though this simplification will have to go when we consider boosters such as a proposed ring of 80 conventional engines mounted concentrically around a plug nozzle to achieve 20 million pounds of thrust or the even further out slot-nozzle designs. And engines using hydrogen as a primary working fluid will certainly also require revisions of the current prediction technology.

Even without these complications, dependence on engine similarity, difficulties in handling geometrical complexities (pad changes, etc.), and other limitations have seriously taxed the present noise prediction methods. This has encouraged most engineers in rocket acoustics to rely heavily on empirical



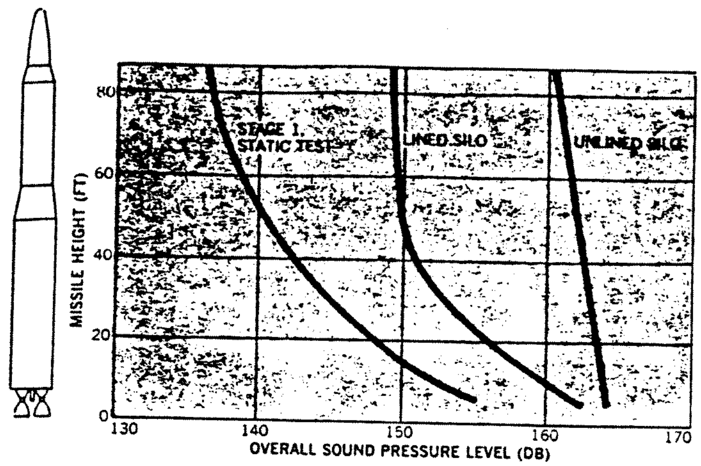
These directivity patterns originate from different torus-shaped sources at various distances along the jetstream from the exhaust plane, and so vary in their effective distances (R_n in the drawing) from any given location on the rocket. This results in slight differences in spectrum shape and peak frequency from location to location. The maximum lobe directions also change slightly with distance along the jetstream, a result of the change in exhaust gas temperature with distance. The presence of an exhaust-stream deflector changes very little except the direction of the stream and the lateral locations of the sources. But that is enough to make profound differences in both the level and the spectrum of engine noise in and around the rocket.

curves and experimentally derived scaling techniques. And that in turn has made us more dependent on field measurements and on testing.

Field instrumentation of rocket acoustics presents some tough problems, partly because of the severe environmental conditions (high temperatures, high static pressures, etc.) involved and partly because definitions must be changed as the instrumentation moves from place to place and level to level.

In the far-field, say, a hundred engine-diameters away from the exhaust, noise is loud but still pretty much the familiar sound of basic physics courses. The apparent sound source is a point, pressure and particle velocity are in phase, and so on. Except for atmospheric and pad effects, the picture is fairly simple, and the levels are within the capabilities of most acoustic test facilities. Although occasional structural damage has been observed in the far-fields of boosters, only very fragile structures having large areas (e.g., large antennas) have been affected and the major concern is for unprotected people.

However, at distances within a couple tens of



Of all launch pad geometries in use, missile silos are among the worst acoustically. In the case of this Titan, engine noise typically falls off rapidly with distance from the exhaust plume—unless the missile is launched from a silo. Even when the silo is lined with acoustically absorbent panels, the facility imposes a 10-15-db acoustic penalty on the upper areas; an unlined silo is 10-15 db worse still.

wavelengths from the noise sources, there are added complications. Second-order effects in the basic sound generation mechanism become significant. Linear extrapolations imply that at the 194-db level the rarefactions of sound waves become absolute vacuums, and that beyond that level there is no physical meaning to sound pressure levels. Actually, these levels introduce nonlinearities called finite-amplitude effects, and those effects show up at the 140-160-db levels common to the mid-field. Structural damage is common in unprotected equipment in this region. Large panels on ground-support trailers have been buckled in acoustic mid-fields; so have silo shelter doors, and so forth.

There are very few test facilities capable of simulating sound of this level, particularly over much of an area. Wright-Patterson AFB has a large, high-intensity siren system (including a special reverberation chamber) under preparation to reach these levels, and Douglas has a facility, suitable for small specimens, which can achieve a maximum overall sound pressure level as high as 170 db by using electro-pneumatic transducers and horns leading to a progressive-wave tube. Acoustic test facilities such as these mark the present boundaries of the available technology as far as level is concerned, and none of these systems is capable of matching the noise spectra of real rockets or their directivity patterns in this mid-field region. Because of its effects on equipment, this part of the overall sound field is receiving a lot of attention from experimenters who have access to adequate test equipment.

But nothing of reasonable size or cost can really make a noise like a rocket — except a rocket. It seems probable that there will be quite a movement to use some of the noise from various test firings in order to test materials and structures and equipment at high acoustic levels, again applying the same scaling techniques common for noise prediction to size and locate the test specimens.

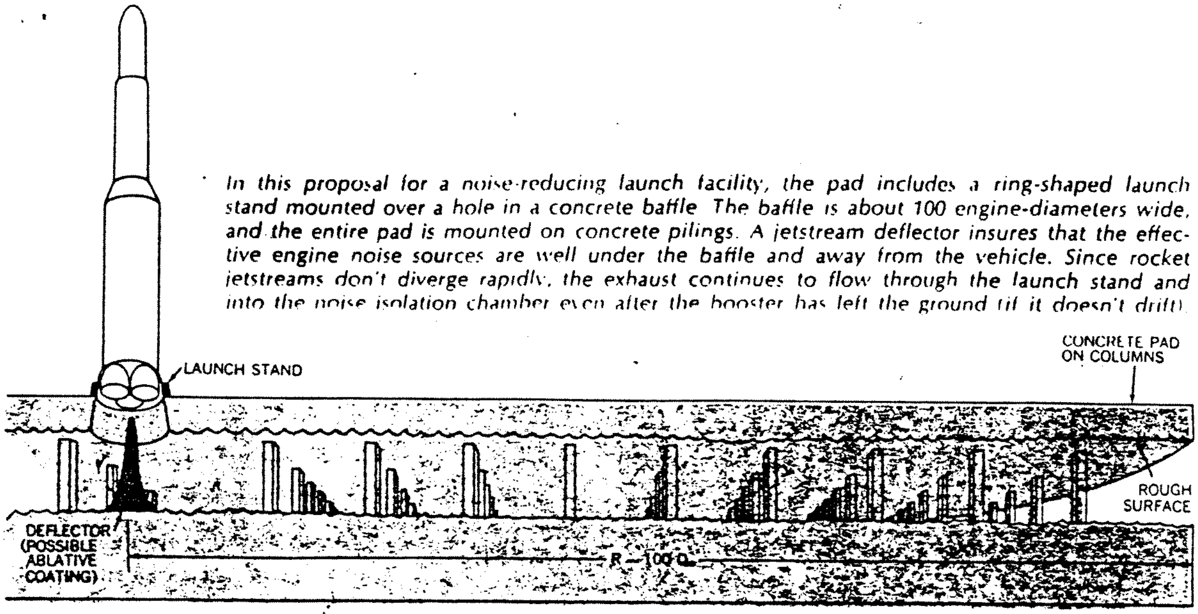
Simulation of the near-field is hardly attempted these days; the near-field (closer than 10 wavelengths or so) of an exhaust noise is an acoustic no-man's land. The field is analytically much more complicated than the sound of the far-field; acoustic pressure is out of phase with velocity, and the source is a continuous chain of sound generators whose frequency varies with position along the chain's length. The levels may well exceed 170 db in some boosters, and will probably be up above 185 for Saturn 5–type boosters. No one who can avoid it subjects anything except heavy structures to this acoustic regime. Trailers and other GSE are ordinarily ensconced safely behind heavy concrete walls, and so there's not too much reason to test GSE to the levels common in the near-field. In fact, the only nonrigid apparatus ordinarily found in the near-field of a large booster is the poor rocket itself. Engine components, booster fins and panel sections a few engine-diameters away from the exhaust plume transform the acoustic energy into the highest and most damaging vibration levels experienced anywhere.

Extrapolations and inferences

Unfortunately, just as these levels get outside the capabilities of present simulation facilities, there's also trouble with the analytic techniques for predicting the vibration response of most real structures to such noise levels. This makes it difficult and problematical to excite the structures directly with shake-tables and other vibration drivers with the idea of using the results to predict what will happen when those structures are exposed to acoustic excitation. However, except for this direct excitation of large structures with vibration test equipment, we are left with extrapolations from the available acoustic test levels and with inferences drawn from previous engine firings.

Damage from acoustically induced (or any other) vibration depends heavily on the level of excitation; in fact, fatigue damage increases exponentially with level. As we move up a rocket, for example, fatigue problems during liftoff decrease. This is because comparatively little acoustic energy is transmitted as vibration along the length of the structure and the sound level drops off with distance from the engine — unless special effects such as reverberation in enclosed launch volumes or peculiar reflections occur.

However, duration of the exposure is also important. Since they take more time to get up and away from a launch area, large boosters are more subject than small rockets to trouble from this source. Flight records show that as a particular location on a Saturn vehicle — say, between the first and second stages — moves away from the pad during launch, it experiences little reduction in sound level during the first few seconds of flight. Then, 5 sec or so after



In this proposal for a noise-reducing launch facility, the pad includes a ring-shaped launch stand mounted over a hole in a concrete baffle. The baffle is about 100 engine-diameters wide, and the entire pad is mounted on concrete pilings. A jetstream deflector insures that the effective engine noise sources are well under the baffle and away from the vehicle. Since rocket jetstreams don't diverge rapidly, the exhaust continues to flow through the launch stand and into the noise isolation chamber even after the booster has left the ground (if it doesn't drift).

the beginning of liftoff, when the rocket has moved about a vehicle length, the sound level drops rapidly — some 12 or 15 db in the next 2 sec. The reason for this sudden decrease (a factor of four or more) in overall sound pressure level is that during this time the effects of reflections from the ground diminish rapidly and the rocket approaches the so-called free-field conditions. From then on, the exhaust noise impinging on the vehicle decreases with increasing altitude as the air density, ρ, goes down. The sound power level also decreases with increasing velocity, according to $\Delta SPL = 20 \log (1-M)$, where M is the vehicle's Mach number. And, of course, when the rocket reaches Mach 1 it leaves its exhaust noise entirely behind.

Aerodynamic noise is even louder

It does not by any means, however, leave behind all of its acoustic problems. With increasing velocity, the eddies created by the turbulent shear layers generate aerodynamic noise which, for large boosters, typically exceeds the noise from the engines. The overall fluctuating pressure level from this source is:

$$\mathrm{OAFPL} = K + 20 \log q$$

Since q, the dynamic pressure, is $\frac{1}{2}\rho v^2$, the noise increases with velocity until the rocket reaches an altitude where the decreasing air density, ρ, becomes dominant. The q, and with it the noise, then falls off until reentry.

The overall fluctuating pressure level (or sound level) reaches its maximum at a very inconvenient time during most present-day missions: max-q generally occurs just after the vehicle has passed Mach 1 and the structures and occupants are recovering from the effects of the buffeting that go with that transition.

The amount of aerodynamic noise generated depends a lot on how aerodynamically clean the external surface has been kept, and this factor shows up in the K of the last equation. A really clean surface might result in a K approaching 87 db (if we follow the present wind-tunnel indications that the fluctuating pressure levels are around 0.9 percent of q). But the K near a protuberance could be around 110 db, a good reason to suspect that things are quieter in a smooth-surfaced Russian rocket than in some of our own necked-down sections and strapped-on afterthoughts.

The frequency of sound from such an aerodynamic source, like the frequency of any other, depends upon the characteristic dimensions of the sound generator — in this case the thickness, δ, of the boundary layer. As a first approximation, the frequency is proportional to v/δ. Because the velocity tends to be high and the turbulent layer small, the frequencies characterizing aerodynamic noise are well up in the kilocycle range.

However, there is no single frequency that characterizes sound from such an aerodynamic source, because the boundary layer isn't the same thickness along its entire length. The δ thickens as it progresses from a leading edge down the flight path, and this range of δs gives rise to a broad spectrum of aerodynamic frequencies, with the highest frequency components dominant near the leading edge of the turbulent layer. Besides this effect, real vehicles tend to have many leading edges on various protruberances, each acting fairly independently of the others. This makes for many such spectra, some important in one place and others important elsewhere.

Of course, this complicates the dynamic analysis enormously, and so statistical approaches are generally applied to such problems. In fact, in questions of the vibration driven by such acoustical sources, where there are not only broad ranges of acoustical frequencies but also very many vibration modes in the structure to consider, statistical methods dominate the field. (Statistical analysis has also moved into the field of engine noise somewhat, even though the engine noise spectrum is peaked.)

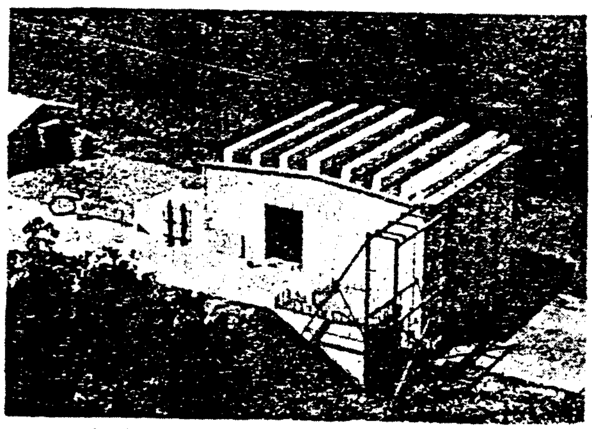
The complicated nature of aerodynamic noise, with its comparatively smooth spectrum, is a boon to the occupants and equipment located up near the source of the cacophony. Because each sound source is, in general, uncorrelated with the others, the net simultaneous forcing function acting on a structure such as a panel is much smaller than the numerical sum of the contributing acoustic forces. The result is a much lower vibration level for the structure than there would be if all the acoustical driving functions were acting in concert. And so, although the aerodynamic noise may be louder than the engine exhaust noise, the vibration levels due to aerodynamic noise are generally lower.

At the reentry phase of a space flight, the returning vehicle is again subjected to aerodynamic noise. This time, because the returning vehicle hits the atmosphere at a very high velocity, the maximum noise level occurs at a much higher altitude and velocity than before. Depending on the reentry trajectory, the levels can be lower (for a low trajectory) or higher than the aerodynamic sound pressure levels encountered during the earlier phase of a flight.

Designing around the problem

There are several ways to minimize these noise problems in future vehicles. Some are just good engineering practice and others are more radical. Perhaps the most important among the former is keeping the entire vehicle as aerodynamically clean as possible. Another is to strengthen structures, particularly panels. (The trouble in the Mercury capsule cited earlier came about because of spacecraft vibration induced aerodynamically; it was finally solved by adding mass to the cabin floor.) And, when power and other considerations allow, it would be nice to pick flight profiles that don't have their maximum-q regions coming out on top of other problems.

Acoustic insulation, such as is used in aircraft, is generally disallowed in spacecraft because of weight. But the ultimate sound insulation for spacecraft is a vacuum, and this solution is being seriously considered in some circles for certain missions.



Among the largest acoustic test facilities built so far, this reverberation chamber at Wyle Laboratories' Huntsville Facility can be driven by two 20-kw, electronically modulated air-jets over a frequency range from below 14 to above 500 cps. The chamber can achieve 155-db overall sound pressure levels throughout the 100,000-cu-ft volume. Electronically shaped spectra from the driver include various combinations of random and sine-wave excitation. Higher intensities—up to OASPLs of 167 db across a test area 8 by 6½ ft—can be obtained in a progressive-wave tube located at the same facility.

Still another possibility is to launch rockets from very high places—that is, from mountains and plateaus 10,000-14,000 ft high. This would have several advantages: a launch from such an altitude results in maximum-q at a lower ρ than a sea-level launch, and ultimately in reduced aerodynamic noise. With lower ρ, there would be lower acoustic power levels at the launch pad. Total energy requirements would also be lower, and, at 14,000 ft or so, the astronauts would already be at about the 7.5 psi proposed for long missions. In any case, significant gains in several areas, including acoustics can be obtained from juggling the few basic parameters, such as ρ, that are available for manipulation.

Besides the possibilities already mentioned here, many others have been proposed, not with acoustics primarily in mind but for other advantages, and several of these are acoustically interesting. The steam catapult is one such case. A rocket launched from a steam catapult would have a significant velocity and altitude before engine ignition, and this could drastically reduce acoustic ground effects as well as extending range. The idea is not too wild; it has been applied successfully for years with smaller vehicles and planes.

More radical proposals than these have been made and studied and flown. But the most general solutions will come from deeper understandings afforded by further instrumentation of the environment and from further study. ■

Selected Bibliography *The richest sources of data on rocket acoustics are publications of NASA, the Air Force and Navy. Some valuable material on vibration induced by acoustic waves appears in C. M. Harris' and C. E. Crede's* Shock and Vibration Handbook *(Vol. III, McGraw-Hill). / The classic review paper on exhaust noise, and the one still most quoted, is Michael J. Lighthill's "Jet Noise"* (AIAA Journal, *July '63). / A very readable and handy (but slightly dated) engineer's introduction to booster noise is "On The Prediction of Acoustic Environments from Rockets," by V. Chobotov and A. Powell (Thompson Ramo Wooldridge paper GM-TR-190). Another good introduction is WADC Technical Report 58-343, "Methods of Space Vehicle Noise Prediction," by Peter A. Franken (available as OTS publication AD 260955). / More up-to-date is S. H. Guest's review, "Acoustic Efficiency Trends for High Thrust Boosters" (NASA TN D-1999, July '64). / An approach to jet noise is summarized by Herbert S. Ribner in his review on fluid dilation theory in* Advances in Applied Mechanics *(Academic Press, '65). / Publications on aerodynamically induced noise are scattered, because much of it is wind tunnel and analytical work, not always considered to be acoustics; indeed, it's just as much aerodynamics. An example of an excellent work of this type is W. W. Willmarth's "Space-Time Correlations and Spectra of Wall Pressure in a Turbulent Boundary Layer" (NASA Memorandum 3-17-59W). / A good and relevant introduction to statistical techniques is Ira Dyer's "Statistical Vibration Analysis"* (International Science & Technology, *Aug. '63). / This whole field is undergoing rapid development, and major international conferences are held annually. The proceedings of the last one, on* Acoustical Fatigue in Aerospace Structures *(held in Dayton, Apr. '64), were recently edited by Walter Trapp and Don Forney, Jr. (Syracuse University Press, '65).*