

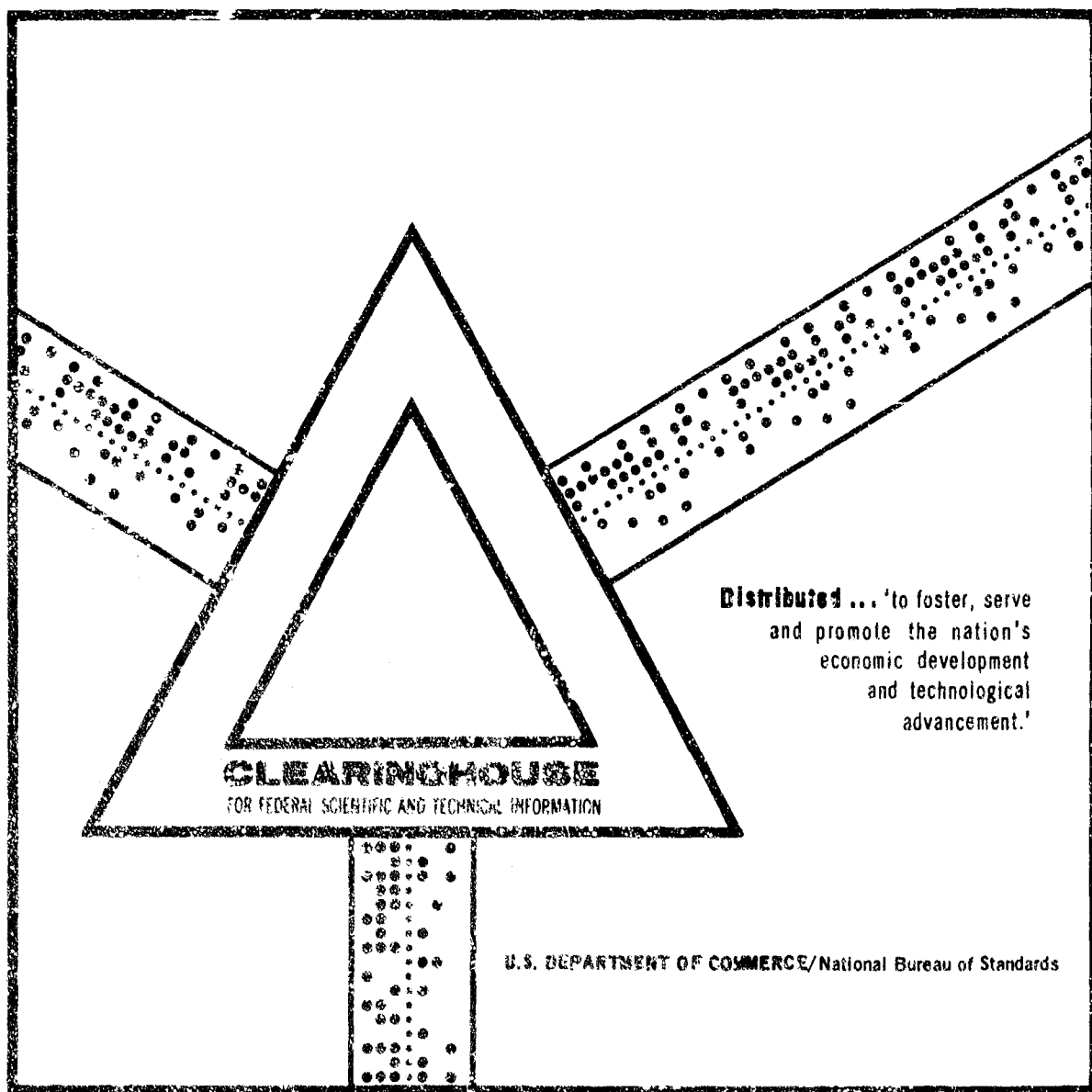
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TECHNICAL EVALUATION REPORT ON AGARD SPECIAL-
ISTS' MEETING ON AIRCRAFT ENGINE NOISE AND SONIC
BOOM

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TECHNICAL EVALUATION REPORT

ON

AGARD SPECIALISTS' MEETING

ON

"AIRCRAFT ENGINE NOISE AND SONIC BOOM"

by W.R. SEARS

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1. INTRODUCTION

This Specialists' Meeting was organized jointly by the Fluid-Dynamics and Propulsion-and-Energetics Panels of AGARD. It was held at the Institut Franco-Allemand de Recherches de Saint-Louis, France, between 27 May and 30 May, 1967. The program committee was chaired by M. l'ing. en chef A. Auriol and consisted of members of both panels.

The purpose of this report is to evaluate and assess the scientific and technical content of the meeting and to draw conclusions that may assist AGARD and those directing research in planning future work and follow-up activities. The author has been able to call upon M. A. Auriol and Prof. J.A. Stakette for assistance in preparing the report, but nevertheless must take full responsibility for opinions expressed.

The meeting was concerned with two related but nevertheless distinct subjects, engine noise and sonic boom, and each session was devoted to one or the other of these subjects, except for Session I, which constituted a survey of the whole situation. We shall, therefore, divide this report into two main sections, rather than attempt a purely chronological report.

Before doing so, however, we should report on the survey paper by Professor Lilley (1)*, which led off the meeting and set the stage for discussions of both noise and sonic boom. This was a review of the physics of noise production and propagation, drawing upon Lighthill's well known formulation of the problem as well as the work of Whitham, Ffowcs Williams, Ribner, and others. The paper made very clear that aerodynamic noise and the sonic boom phenomenon have much in common, to a great extent justifying our treating the two in a single specialists' meeting. Professor Lilley's paper suggests that, except for the important matter of noise due to turbulence the basic physics is mostly in-hand, even though there surely are details that require further study and a host of practical results still to be deduced and confirmed. For the turbulent jet, indeed, fundamental understanding is meager.

II. ENGINE NOISE

A suitable backdrop for the week's discussions of engine noise was provided by Messrs. Hoover and Cochran (2), who set forth the airport noise problem from the standpoint of a regulatory agency, explaining how approach and take-off noise requirements are defined and presenting charts showing noise levels of present aircraft and proposed requirements for the future.

The paper by M. Planko (24) concerning airport noise might also be mentioned at this point. M. Planko reported on airplane flight paths (trajectories) for minimum noise.

A. Fundamental Topics

Session II was devoted almost completely to fundamental problems of aerodynamic noise. In spite of its title, the paper by Dr. Gordon (6) was principally concerned with some basic properties of turbulent-jet noise, especially sound generated by the impingement of the flow on obstacles. This is dipole noise, as contrasted with the quadrupole noise of the turbulence itself, and it has the possibility of becoming a dominant effect, at least in turbofan engines. The experiments reported here did not suggest the presence of significant monopole sound. In discussion it was emphasized that this research is pertinent to real engine noise, since blades and vanes will produce this (dipole) type of sound.

The paper by Mr. Martlew (7) reported on the noise produced in supercritical jets by oscillations of their shock-cell patterns. These experiments were made in the N.G.T.E. anechoic chamber. It becomes clear that these shock cells are an important source of jet noise and that this noise has striking directional properties.

In a related paper in a later session, Wertheim and Woolley (23) presented experimental results of an investigation of a choked air jet in an axisymmetric screech mode. These are detailed, time-resolved measurements of the field near the jet.

Professor Ffowcs Williams' paper (3) was entirely mathematical and concerned the phenomena that are characteristic of a sound field produced by a sound-source (aircraft) in high-speed motion. There arise important directional effects; especially in relation to turbulent-jet noise there are significant effects due to the motion of eddies in the direction opposite to that of the aircraft. Departing from his printed paper, Professor Ffowcs Williams described the use of the shallow-water analogy in turbulent-jet experiments. He states that monopole, dipole, and quadrupole effects are clearly recognized in his experiments.

* Numbers in parentheses refer to papers listed at the end of this report.

M. Thomas reported, in his paper (10), on intriguing experiments concerning the effects of reflection of jet noise from the ground. His analysis of the phenomenon draw upon published theoretical work; the effect of the ground depends upon the frequency, of course, and therefore upon the spectral properties of a real jet. His experiments investigated the effects of jet size (nozzle diameter), index of reflection (for imperfect reflectors), and spectral distribution. The results suggest that the idealizations of point-source and perfect reflector will be adequate for practical purposes.

A detailed effort to relate a series of jet-noise experiments to the theories of Lighthill and Ffowcs Williams was reported by Messrs. Voce and Rush (31). They conclude that the theory, which assumes randomly oriented quadrupoles, can be improved in some respects if an additional distribution of lateral quadrupoles is superimposed. The new theory, however, leaves some details unresolved, and further studies are in progress.

B. Practical Applications.

There were at least two papers that represented attempts to synthesize, from available theories, practical procedures by which the noise properties of real airplanes can be predicted during the process of design. The first of these, by M. Kobrynski (9), sparked some lively discussion, for it followed the theoretical paper by Ffowcs Williams and was concerned with some of the same phenomena. This seemed to be a clash between practical engineers on one hand and scientific investigators on the other. They disagreed as to whether there exists an adequate body of reliable experimental data to permit this kind of prediction. The second paper along similar lines was presented by MM. Hoch and Duponchel (21); it was concerned with the estimation of turbojet noise and consisted principally of a selection of graphs from which, given the design parameters of the engine and the flight speed, the designer should be able to estimate the noise produced.

The paper by Mr. Rekos (33) concerning NASA's "Quiet Engine Program" is somewhat related, for it too attempts to predict turbojet noise and to select engine design parameters to minimize it. It would be interesting to put NASA's engine design through the SNECMA prediction scheme. The Bair, Yasutake, Metzler paper (34) was also related. It recounted the history of the designers' attempts to predict the noise properties of the C5A transport airplane - efforts which seem, in retrospect, not to have been particularly successful.

There were a number of papers devoted to experimental techniques, instrumentation, and facilities in the engine-noise field (18), (22). There were several (17), (19), (35) reporting on devices used to suppress engine noise - most of these were concerned with isolated engines. So far as fan noise is concerned, these suppression techniques seem to be remarkably effective. By contrast, the C5A, mentioned above, may be the archetype of the modern, large airplane whose high-bypass engines have received no sound-alleviation treatment.

C. Conclusions.

The impression received from Professor Lilley's survey, mentioned above, was not contradicted by the papers and discussion of the subsequent sessions. With few exceptions the areas where fundamental physics is lacking are those concerned with turbulent flow. Even if the basic case of the subsonic jet at rest is reasonably well understood, the same cannot be claimed for supersonic jets, especially as they typically involve random dipole effects, oscillating shock cells, and high speeds of flight. Clearly, we are suffering from our incomplete understanding of turbulence itself, and it is commonplace to recommend once again that fundamental studies in that area be encouraged. We must hope that prediction and even alleviation of jet noise will not await full resolution of the mysteries of turbulent flows, but will require only continued research on the particular features that dominate the noise phenomena. But one senses from this specialists' meeting that we are only beginning to know what these are.

There are other aspects of the engine-noise problem that received only brief mention in this meeting but will require the attention of research workers. Among these are improved estimates of the transient loads on the blades of fans and compressors, elucidation of such matters as reflection and refraction of sound - perhaps even generation of sound - at various places in the airplane-plus-engine system, and the whole matter of nonlinear effects. The most basic treatments of the sonic-boom phenomenon have required progress beyond classical linear theory, and it is clear that in some engine-noise problems there are disturbances of sufficient magnitude as to produce analogous effects. The subject of "pseudo-sound" - pressure fluctuations associated with non-propagating disturbance fields - was also not discussed at Saint-Louis, although it is sometimes of major concern in aeronautical engineering.

Experimental results in the aerodynamic-noise area generally agree satisfactorily with theory, but in most cases the measurements are rather global in character, rather than detailed.

III. SONIC BOOM

The background for this part of the meeting was provided by a trio of talks on matters outside the realm of fluid mechanics. The first, by Col. and Mrs. Taylor (2), was a review of the legal picture, a propos the boom, in the U.S.A. The picture is based almost entirely on the history of litigation concerning airplane noise, and involves the delicate balance between legal principles defending air commerce as an essential feature of modern life and opposing doctrines that protect persons from annoyance, harassment, and invasion of privacy. The conclusion can only be that the subject is moot and is non-trivial in the aeronautical world.

Drs. Von Gierke and Nixon's review of the aeromedical aspects (5) was in the same general expository spirit. Even severe sonic booms, reportedly applied, seem not to cause physiological damage to human

subjects, but booms involving maximum overpressures of only 1.0 to 1.6 lb./sq. ft. have been found consistently effective in awaking sleepers. There was considerable discussion, touching, among other matters, on the possible overriding importance of indoor, rather than outdoor, pressure signatures. Thirdly, Dr. Weber (4) reported on detailed measurements of structural response to sonic booms. Excitation of various structural components of instrumented buildings struck by some 25 controlled booms was determined.

A. Fundamental Topics.

In his paper on the sonic boom produced by bodies of revolution (11), Professor Oswatitsch reported on studies based on the method of characteristics and therefore independent of certain approximations frequently introduced in calculating sonic-boom signatures at great distances from the aircraft. He concluded that the familiar asymptotic theories are inadequate in cases involving accelerated flight and/or stratified atmospheres. These conclusions agree with those of other investigators, notably in the U.S.A., where calculation procedures of considerable elaboration are now being used.

The paper of Professor Guiraud (12) introduced the subject of the focusing effect and the related mathematical and physical phenomena, including the so-called "caustic". These occur in a number of practical cases involving linear acceleration, flight-path curvature, and/or atmospheric stratification. He carried over to our field the principles of the theory of so-called "short waves" - also called slowly-varying waves - developed in other fields of physics. The focusing appears as a singularity in the theory, and nonlinear effects become essential. In discussion, Professor Hayes suggested that the phenomenon itself is a linear one, but that a nonlinear theory becomes necessary because of the appearance of shock waves in the interesting cases; the speaker agreed. M. Théry's paper (13) was concerned with the same topic, viz., reflection of the shock wave from the caustic surface, and also from the ground. The approaches of MM. Guiraud and Théry are somewhat different; Théry's calculation reproduced Guiraud's similitude and provided the value of the magnification due to focusing in the supersonic domain. He also provided charts from which the details of reflection from ground can be ascertained.

The paper of Drs. Cheng and Goldburg (16) concerned a particular proposal, made in the U.S.A. about a year earlier, to reduce sonic-boom effects by electrical means. Their analysis confirms that corona discharge ahead of an aircraft might be used to reduce the shock strength, but that the power required would be grossly excessive.

B. Experimental Results and Techniques.

There were three papers reporting explicitly on experience in the comparison of theoretical results with flight results. The first of these (15), by Messrs. Powers, Sands, and Maglieri, was an analysis of the major American overflight programs. Instrumentation has become more and more sophisticated, many experimental data are now available, and many details of the pressure patterns produced by aircraft in steady flight have been compared with theoretical predictions. In general, agreement is remarkably good, and there are few surprises. There are, by now, enough data to support empirical conclusions about statistical variations from still-air theoretical predictions. Further studies of the effects of atmospheric inhomogeneities are still needed. The paper included a few data on structural and seismic effects. Drs. Angell, Herbert, and Hass (26) reported further on the overflight-vs.-theory comparison, namely on the effects of atmospheric properties. The statistical conclusions regarding the effects of atmospheric turbulence seems definitive; the differences noted between stable and unstable atmospheres is striking.

A most interesting and difficult flight investigation was reported by M. Wanner (14), namely observations of one of the focusing phenomena previously discussed by MM. Guiraud and Théry. In these flights the focusing was produced by horizontal turns and by accelerated horizontal flight. It was understandably difficult to produce the desired phenomena at exactly the location of the instrumentation array on the ground; nevertheless, at least 27 good cases were measured. They produced overpressure magnifications (compared to level flight at the same Mach number) varying from 1.4 to 5.1. These are reported to be greater than obtained in certain NASA flight tests. The data are presented in a recent CEV Report. *

Sonic-boom simulation techniques were discussed by Messrs. Warren (28) and Schwartz (29). The former reported principally on techniques using explosives, which have been used with considerable success since about 1961; he also described "Blunderbuss", which involves bursting of a pressurized sphere (or conical segment thereof) and has produced, at model scale, satisfactory N-waves. In response to a query, he stated that rise-time in the N-wave can be controlled so as to simulate an effect of atmospheric turbulence discussed earlier by Dr. Angell. Mr. Schwartz described shock-tube, wind-tunnel, and ballistic-range techniques. There was considerable discussion, following these papers, of simulation of finite rise-times, near-field signatures, very long signatures, and similar practical features.

C. Practical Applications.

The single lecture that was primarily concerned with airplane design and configuration effects on the sonic boom was the one by Messrs. Howell, Sigalla, and Kane (30). In this very informative paper the effects of changes of wing planform, engine location, chordwise lift distribution, and similar features were shown. Some of the unconventional schemes that have been proposed were included in these comparisons. One of these was the electrical "atom forebody" scheme discussed by Cheng and Goldburg (above). Effects on both far- and mid-field signatures were discussed. It is, of course, impressive to see how compensating effects, such as weight penalties, occur and limit the airplane designer's scope as he attacks the sonic-boom problem.

D. Conclusions: Round Table Discussion.

The final session of the meeting consisted of a Round-Table devoted to the topic "Prospects for Sonic-Boom Alleviation". Since its purpose was to summarize and to extract conclusions from the week's discussions of the sonic boom, a report on the Round Table can serve as the basis for the closing remarks of this report. Participants were Professor Hayes, Professor Seebass, M. Vallée, and Mr. Warren, with Professor Sears serving as moderator.

Professor Hayes summarized the present status of the problem from the standpoint of a theorist. He pointed out that the theory is in excellent shape, at least in principle. One needs Whitham's function F , and starts with the lift distribution, which one can calculate; then the theory of geometrical acoustics, with nonlinear distortions accounted for, is a straightforward matter. It can be applied to cases involving focusing. He saw the focusing as a practical problem and proposed on-board computers to lay out trajectories to avoid focusing on the ground at undesirable locations.

He believed that the caustic problem requires more research. There are even possibilities of super-superbooms - cusps in a caustic surface; nothing has been done about this subject. He thought the effects of turbulence should be essentially different for large- and small-scale turbulence, the former producing the statistical deviation from theory mentioned in some of the papers, the latter producing rounding-off of the signatures, finite rise times, etc. Finally, he proposed further studies of the so-called "bangless boom" - signatures free of shocks.

Professor Seebass discussed prospects for alleviation in two categories: aerodynamic and "exotic", the former defined, perhaps, by the constancy of the Bernoulli constant. The exotic schemes must often be discarded because the airplane designer cannot afford much compromise with performance. They compete with alleviation by means of increased altitude, reduced weight, and improved L/D and specific fuel consumption. He remembered that Professor Ferri had suggested making airplanes longer and people smaller.

He discussed the "bangless-boom" possibility, which follows from the discoveries of McLean and Hayes, and emphasized that both front and rear shocks must be considered in exploiting these principles.

M. Vallée returned to the focusing problem. "Focusing factors" as large as 5 were observed in Project Jericho (as reported by M. Wanner (14)), and a project called "Jericho Target" will now explore the subject further - perhaps super-superbooms will be produced. Nevertheless, he did not consider focusing a frightful phenomenon. He was sure that 5 was a kind of maximum value. Furthermore, the focusing usually occurs at moderate Mach number - say 1.2 - where an overpressure of 5 times the steady-flight value is often not so great anyway. The phenomenon is local and we do know how to position it within a few kilometers. He thought Professor Hayes' idea of an on-board computer was reasonable.

Mr. Warren agreed that the real problem still lies in cruising flight. He emphasized the extreme importance of drag in the performance of the airplane; compromises of the order of one percent cannot be tolerated: "one percent in drag is important; ten percent in overpressure is peanuts." He re-emphasized the significance of indoor phenomena in the matter of public acceptance, and stated that these are mostly related to the impulse, rather than the maximum overpressure.

There was lively discussion, limited by lack of time. Professor Hayes cautioned against putting too much faith in two criteria mentioned frequently during the meeting, viz. "PNdb" (perceived noise in decibels) and "focusing ratio". Professor Sears questioned, à propos Professor Hayes' remarks, whether the problem of lift distribution is really in-hand in the required regimes of flight.

So far as sonic-boom phenomena are concerned, then, an overly brief summary of the week's discussion might say, firstly, that the theory is remarkably well developed and successful - really a feat of fluid-mechanical research - but it leads to no panacea; rather, it suggests that major alleviation in practice will not be forthcoming in the foreseeable future. Secondly, that those features of the sonic boom that remain to be elucidated may be somewhat peripheral to the main problem. That the aerodynamicist is still not told precisely what features of the signature are undesirable is probably inherent in the situation, for the answers are at best statistical and at worst ephemeral or subjective. If the answers become available with the passage of time - as, for example, the requirements for gust loads on aircraft became available in the history of aeronautics - the designer is prepared to translate them into configurations. But it is not yet clear whether these can be economically viable airplane configurations.

IV. CONCLUDING REMARKS

The St-Louis meeting surely justified the term "specialists" in its title. One received the impression that all present were truly knowledgeable in this important field of technology and that their expertise spanned a broad range from the highly mathematical to the severely practical. The mixing of propulsion and fluid-dynamics specialists was eminently successful; the dividing line between the categories was never visible. Clearly, much important information was exchanged throughout the meeting.

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9	M. Kobrynski	Détermination du Champ Sonore Produit par l'Evolution des Avions à Réactions
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18	S.N. Suci and W.R. Morgan	Aircraft Engine Noise Measurement Techniques, Facilities and Test Results
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