Model Test and Full-Scale Checkout of Dry-Cooled Jet Runup Sound Suppressors

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Jet aircraft runup sound suppressors featuring complete enclosure of the aircraft, dry cooling of the exhaust sound suppressor (even during afterburner operation), and adaptability to a variety of aircraft types are now employed at a number of U.S. Navy and Air Force airfields. The design, model testing, and full-scale checkout of the existing U.S. Navy hush house is described herein. Also the extension of the hush house concept to unusual aircraft designs and to dry-cooled jet engine test cells is covered.

Nomenclature

AA	= augmenter cross-sectional area, ft^2
AAT	= augmenter throat area, ft^2
DA	= augmenter cross-sectional diameter, ft
DNT	= nozzle throat diameter, ft
f	= noise frequency, Hz
LA	= augmenter length, ft
PWL	= sound power level, dB re 10^{-12} W
SPL	= sound pressure level, dB re 0.0002 mb
TA	= absolute ambient temperature, °R
TTN	= absolute jet total temperature, °R
TWALL	= augmenter wall temperature, °F
VCORE	= augmenter exit core velocity, ft/s
VJET	= jet velocity at nozzle exit, ft/s
WE	= total engine mass flow rate, pps
WIT	= total hush house inlet flow rate, pps
X	= distance from nozzle exit, ft
XN	= distance from nozzle exit to augmenter inlet, ft

Background

As part of the fiscal 1973 Navy Military Construction Program a new air-cooled jet aircraft runup acoustical enclosure (hush house 1) was constructed at the Miramar Naval Air Station, San Diego, Calif. On a limited basis, the Navy had already been building aircraft sound suppression facilities since the early 1960s. The earlier facilities were designed to close-couple the aft end of the aircraft to an acoustically treated exhaust system using doors that sealed around the fuselage. For aircraft with afterburning engines such units used a water-cooled exhaust system.

The NAS Miramar project was originally proposed as such a facility for the swing-wing F-14 aircraft. Because of the difficulty of permitting wing sweep variation with such a suppressor close-coupled to the aircraft, the Navy decided to build a total enclosure or "hush house" around the aircraft. This would provide such additional benefits as accommodation of the other aircraft at the activity, all-weather operation, plus further reductions in external noise, especially just outside the facility.

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The Naval Facilities Engineering Command, which has the responsibility for design and construction of shore facilities for the Navy, assigned the Miramar project to its Southern Division in Charleston, S.C. The initial design effort by the engineering firm engaged by the Southern Division was to design a hush house with a conventional water-cooled exhaust system. However, because of the visible emissions problem with a water-cooled system, a totally air-cooled design concept was sought.

At this point in 1973 a joint Navy-industry team was established to evaluate worldwide the available air-cooled exhaust systems for afterburning jet engines to determine the feasibility of developing an air-cooled hush house for the Navy's F-14 (see Acknowledgments). The team reviewed available literature on air-to-air ejectors and dry-cooled exhaust systems,[1-3] and concluded that a low-pressure-drop exhaust system with a large sound-absorbing augmenter tube could provide sufficient augmentation (pumping) to adequately cool the exhaust of an afterburning jet engine. The team produced a study report recommending a simple dry-cooled exhaust system concept that had already been demonstrated by European hush houses. It was noted in the study report that such a dry-cooled facility would have long-term cost advantages over one with a water-cooled exhaust system.

NAS Miramar F-14 Hush House Design

This new F-14 facility was to feature:

1) Complete enclosure of the aircraft.

2) Dry-cooling of the exhaust even with one TF-30 engine in the afterburner.

3) Easy adaptability to a variety of aircraft types as well as to the F-14.

4) Exterior noise no greater than 85 dBA 250 ft from the engine exhaust plane.

The resulting design, completed in 1974, is illustrated in Fig. 1. An F-14 is shown installed within the enclosure. The significant dimensions are presented in Fig. 1. Of particular note is the 90 ft long exhaust noise suppressor (augmenter) with a clear, 19 ft wide by 11 ft high obround exhaust duct (183 ft^2 open area) followed by a sound absorptive 45 deg ramp. The perforated stainless steel liner forming the augmenter duct is made up of relatively small panels attached to the backup structure in such a way as to allow thermal expansion. The augmenter is made up of nine 10 ft long segments with the perforated liner panels in each segment being surrounded by fiberglass formed into protected pillows encased in wire mesh. A 22 ft diam steel shell surrounds the fiberglass. Another feature of the Navy hush house design is the front air inlet, which can handle the maximum total (engine plus cooling) airflow of 2500 pps with less than a 2 in. H_2O pressure drop. This inlet is formed within the enclosure door structure. Also of interest is the nose wheel elevator that is used to level the aircraft exhaust centerlines before runup. The main gear chocks can be repositioned to accommodate different aircraft treads.

Every part of the basic hush house was designed to control the transmission of noise from the inside of the enclosure to the outside. This involved door seals, acoustic baffles in the main door air inlet, prefabricated enclosure wall and roof panels with a sound-absorbing surface on the inside and a concrete overlay on the exterior to increase transmission loss, adequate sealing of all joints in the enclosure, etc., as well as provision for the sound-absorptive augmenter tube and 45 deg exit ramp. In meeting the 85 dBA at 250 ft exterior noise criteria, this hush house would provide about 5 dBA lower noise than typically experienced with semienclosures that had to seal around the aircraft fuselage. The design of the first Miramar hush house was completed and construction began in 1974.

Model Tests of the F-14 Hush House

After construction had been initiated it was recognized that the Miramar hush house design had been accomplished with inadequate augmenter design information. The augmenter duct cross section (19 ft wide by 11 ft high obround) had been made especially large; yet, with the F-14 having two afterburning engines with centerlines spaced 9 ft apart and angled 1 deg outward, there was some risk of the duct sidewall overheating even without regard to possible aircraft misalignment. Also there remained questions regarding the sound suppression mechanism of such an augmenter. Consequently, the Navy instituted a 1/15 scale model test program aimed at verifying the Miramar augmenter design before completion of construction, at the same time providing design information usable for future hush houses as well as verification of the modeling technique through later comparison with the full-scale hush house checkout results. The test program was designed to determine: 1) jet mixing rate (both free-jet and within an augmenter), 2) augmenter pumping performance, 3) augmenter wall temperature (including the effect of aircraft misalignment), and 4) the exterior noise reduction provided by a sound absorptive augmenter.

The models were constructed with a properly scaled simulation of the full-scale sound-absorptive augmenter packing. Testing was carried out in 1975 using a 1/15 scale hot-jet simulation of the afterburning engine exhaust from an F-14.

To simplify the testing and data analysis somewhat, all of the acoustical measurements were made within reverberant rooms and the data reduced to sound power levels (PWL) of 10^{-12} W. Two reverberant rooms were set up, one surrounding the hot jet and burner (corresponding to a hush house or test cell enclosure), the other surrounding the augmenter (corresponding to the out-of-doors around the hush house) and suitably ventilated to discharge the exhaust flow. A sound-insulating wall separated the two rooms except for the augmenter gas-path opening. The use of the reverberant room method of obtaining acoustic data and the necessary reduction of the data to PWL provided no directivity data. This meant that initial interpretation of the model data to predict full-scale hush house exterior sound pressure levels required judgments as to augmenter exit noise directivity.

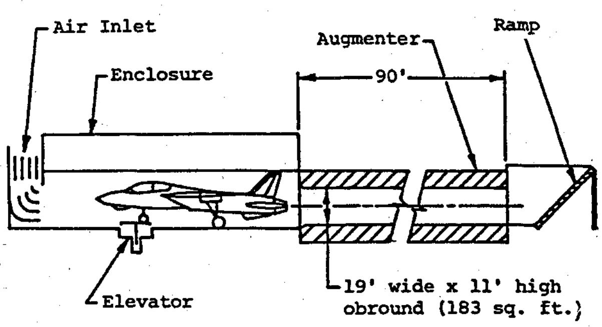

Fig. 1 Miramar hush house side elevation.

The first tests involved the bare-jet simulation of the F-14 engine exhaust. For these tests the augmenter gas-path opening between the two reverberant rooms was sealed around the jet, with the jet directed into the exhaust reverberant room. These tests provided bare-jet PWL spectrum data and, through the use of total pressure and total temperature rakes, jet velocity decay data. Next came tests in which the jet discharged through a hard-walled augmenter (Fig. 2). These tests provided augmenter pumping information for different augmenter diameters, jet decay data with the augmenter surrounding the jet, and acoustical data on hard-walled ejectors of different diameter, length, and subsonic diffuser area ratio. The primary tests were accomplished using a 1/15 scale model of the Miramar hush house augmenter plus exit ramp (Fig. 3). The obround liner with its acoustical packing was properly simulated (Fig. 4) as was the ramp acoustical treatment. Tests made with the scaled Miramar exhaust system provided augmenter pumping data, sidewall temperature data in the air-cooled augmenter, data on jet decay within the lined augmenter model, and, of course, data on the noise reduction afforded by the absorptive augmenter and ramp. These data were obtained for a variety

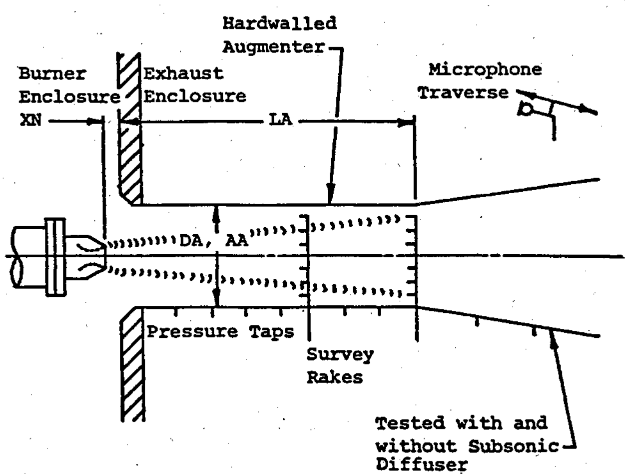

Fig. 2 Hard, round augmenter test setup.

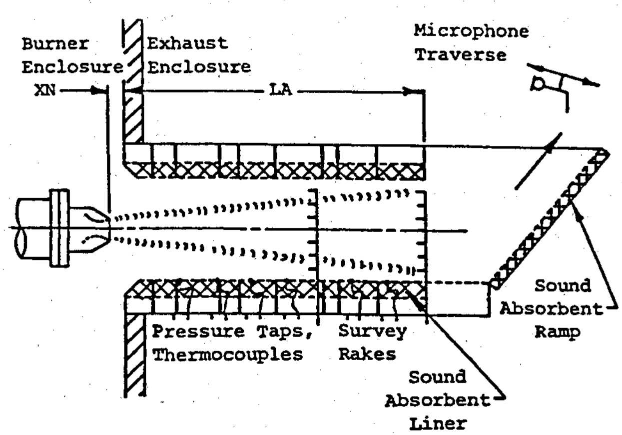

Fig. 3 Absorptive augmenter test setup.

of different test conditions including:

1) Jet total to ambient temperature ratios of 1.0, 4.4, and 6.6.

2) Jet pressure ratios of 2.0 (F-14A) and 3.0 (F-14B).

3) Various jet lateral positions including both centered and F-14 positions.

4) Various jet splay angles including 1 deg corresponding to an aligned F-14.

5) Augmenter lengths of $L/D=4$, 6, and 8, with and without the absorptive ramp.

6) Modifications to the augmenter and ramp acoustic treatment.

Figures 5-8 summarize some of the basic data derived from the tests. Figure 5 presents augmenter pumping data from the model test program (curves) as well as full-scale checkout data (points). The correlation technique was developed during the analysis of full-scale data where it was observed that pumping remained constant during excursions into afterburning thrust for constant engine flow rates. It appears that the nozzle offset and splay associated with an aligned F-14 results in a significant reduction in augmentation (pumping). Both full-scale and extrapolated model-scale augmenter wall temperatures are shown in Fig. 6. The model-scale results predicted that full-scale wall temperatures approaching 1000°F could occur even with a perfectly aligned F-14. This was a surprise (800°F had been the expected maximum wall temperature) and it necessitated a review of the augmenter liner design to make sure that the resulting thermal expansion could be accommodated and that the high-temperature strength of the liner material was adequate (some design changes were included in the hush house 2 at Miramar). Augmenter core velocity data such as shown in Fig. 7 were also obtained. This was useful in the analysis of the acoustic data since a significant portion of the exhaust noise is generated by the flow leaving the augmenter exit (as will be discussed later). The basic noise data obtained with the sound-absorptive augmenter model is shown in Fig. 8. Figure 8 includes the exhaust PWL spectra of both the bare jet and the absorptive augmenter surrounding the jet, thus permitting determination of total augmenter attenuation vs frequency.

A careful analysis of the acoustic data suggested that, from the standpoint of the augmenter and ramp attenuation, the engine could be represented by a sound PWL source at the engine nozzle exhaust plane location. The external noise at any location emanating from the augmenter exit is thus made up of both:

1) Attenuated jet noise that equals the engine source PWL minus the noise absorbed within the enclosure, minus absorptive augmenter attenuation (Fig. 9), minus ramp attenuation (Fig. 10), and with ramp directivity and distance effects accounted for.

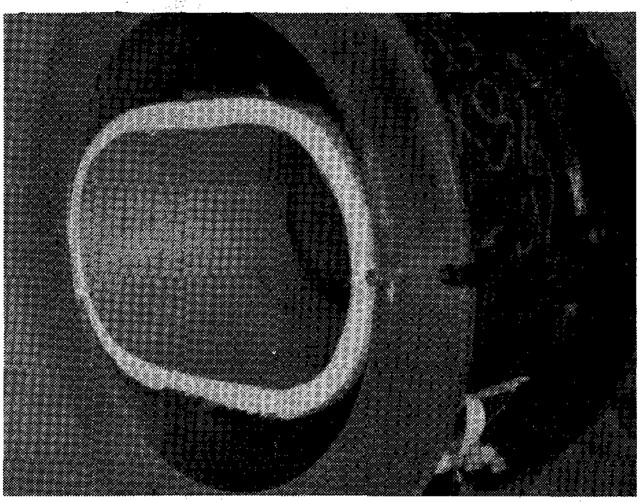

Fig. 4 Model augmenter section with acoustic liner.

2) Noise generated by the flow leaving the augmenter (sometimes referred to as self-noise and consisting of the augmenter exhaust jet mixing noise and edge noise caused by this jet flowing over the edge of the ramp, etc.).

Note that Fig. 9 presents augmenter attenuation obtained with both the modeled jet noise source and a loudspeaker noise source (no flow). The differences in attenuation illustrate the manner in which the velocity and temperature gradients introduced by the jet modify the sound absorption process. With the jet, high-frequency sound is refracted out of the jet and into the absorptive augmenter liner rather than beamed down the tube. On the basis of the model acoustic data, it was expected that the Miramar hush house 1 would meet the 85 dBA at 250 ft noise limit.

Checkout of the Miramar Hush House

The completion of Miramar hush house 1 in 1975 (Figs. 11 and 12) was an opportunity to check out the concept. Full-scale pumping and augmenter wall temperature checkout data appear with the model test trends in Figs. 5 and 6. Acceptable agreement is shown. The high wall temperatures, anticipated

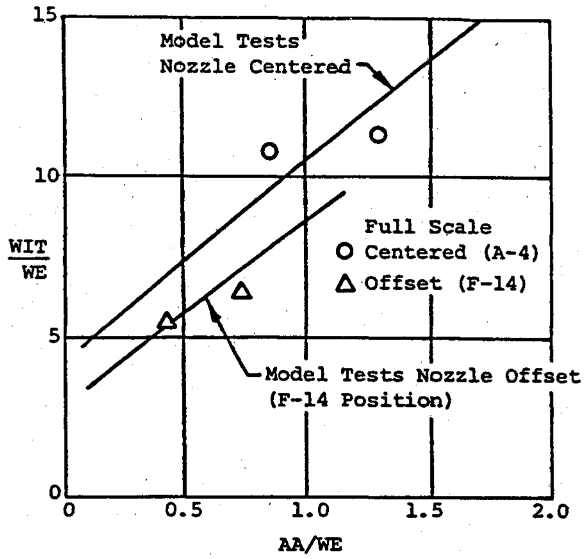

Fig. 5 Augmenter pumping performance.

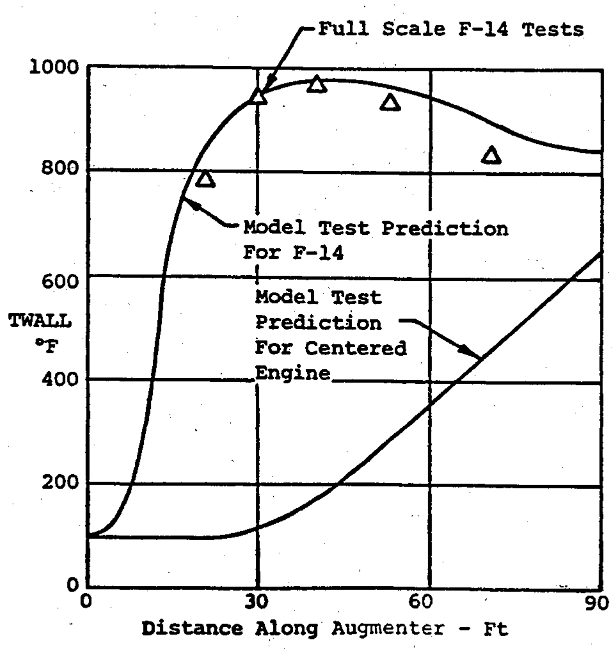

Fig. 6 Augmenter sidewall temperatures.

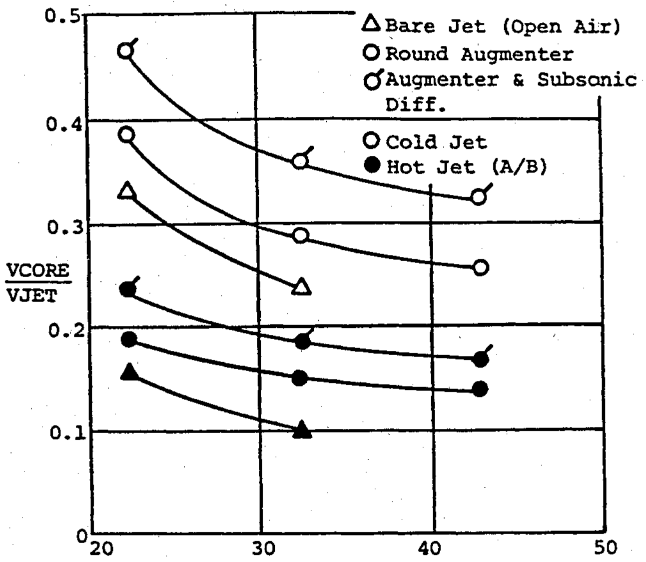

Fig. 7 Augmenter core velocity.

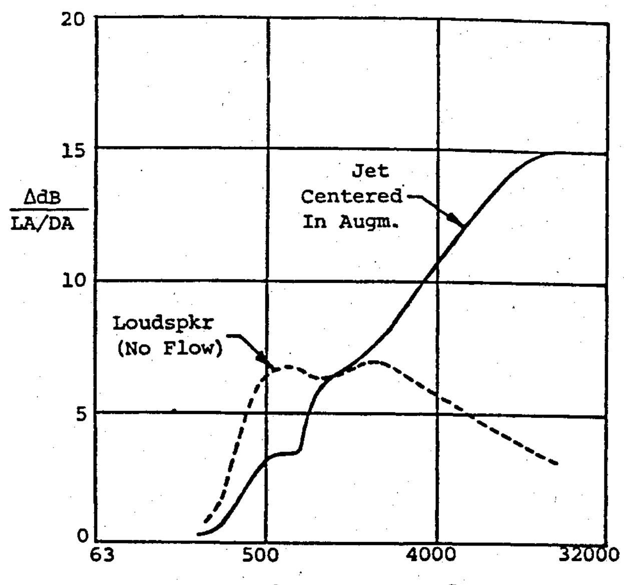

Fig. 9 Augmenter sound absorption.

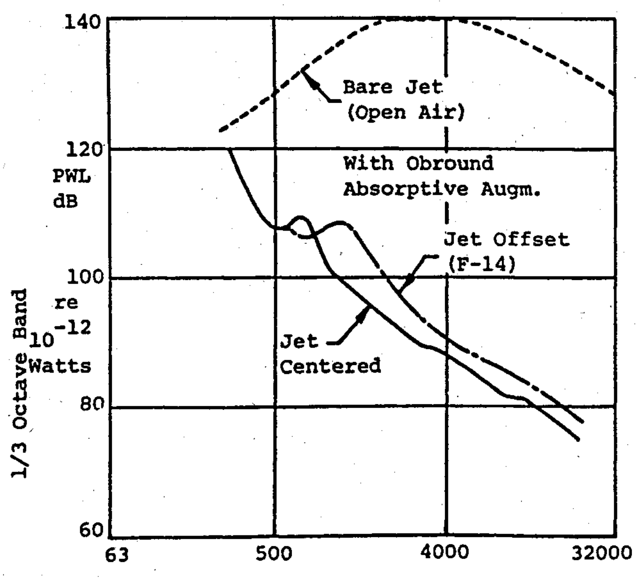

Fig. 8 Exterior sound power levels (model).

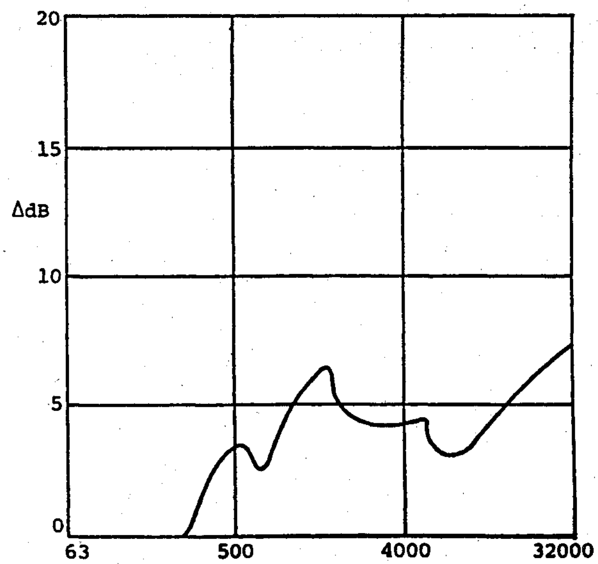

Fig. 10 Ramp sound absorption.

on the basis of the model test results, were indeed experienced with a well-aligned aircraft. In Fig. 13 the measured sound pressure level spectrum at 250 ft (showing compliance with 85 dBA) is compared with predictions made on the basis of the model-scale data. Again agreement is quite good when one realizes that the model scale was 1/15 of full scale. In 1978 a second, basically similar, hush house (Miramar 2) was completed and checked out. One thing that became apparent from the full-scale noise measurements was that noise transmission through the upstream segments of the augmenter shell can contribute significantly to the noise level at 250 ft. It may be necessary to wrap these shell segments to meet lower noise limits.

Hush House Designs for Unusual Aircraft

MCAS El Toro A-6, F-4 Hush House Design

At the same time that the design decisions pertaining to the Miramar 2 hush house were being finalized there was a requirement for a hush house to be located at MCAS El Toro to accommodate the A-4, A-6, and F-4 aircraft. The noise limit was again 85 dBA at 250 ft from the engine exhaust plane and the F-4 with one J-79 engine in afterburner was viewed as the design condition (the A-4 had one and the A-6 two J-52 nonafterburning engines). Because the J-79 engines in an F-4 are smaller than the TF-30 engines in an F-14, the 85 dBA limit could be met with a smaller cross section and shorter augmenter than those required at Miramar for the F-14. A flow pickup problem existed with the A-6, however, since it had engine exhaust centerlines 7 ft apart that were splayed outward 6 deg and in the normal ground attitude the jets were directed downward 12 deg. Cold-flow model-scale tests were used to study flow capture with the A-6. In addition an A-6 was flown to Miramar and adapted to hush house 1. It was found that the flow could be captured by the Miramar augmenter inlet if the A-6 nose wheel was lowered to the maximum extent possible (to level the exhaust jets) and the aircraft moved as far aft as the nose wheel elevator pit would allow. As a consequence the El Toro augmenter was built with a 19 ft wide by 11 ft high obround augmenter entrance (same

Fig. 11 Exterior of Miramar F-14 hush house.

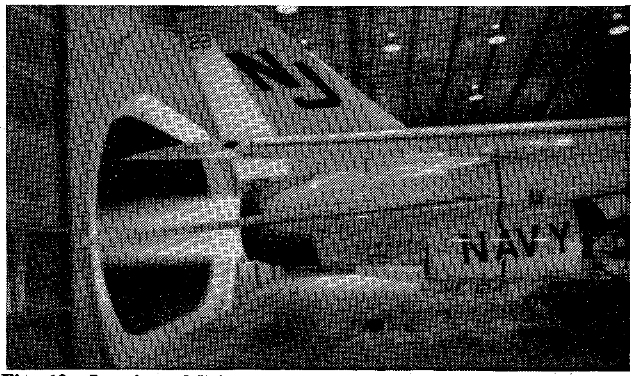

Fig. 12 Interior of Miramar hush house with F-14A in maximum afterburner.

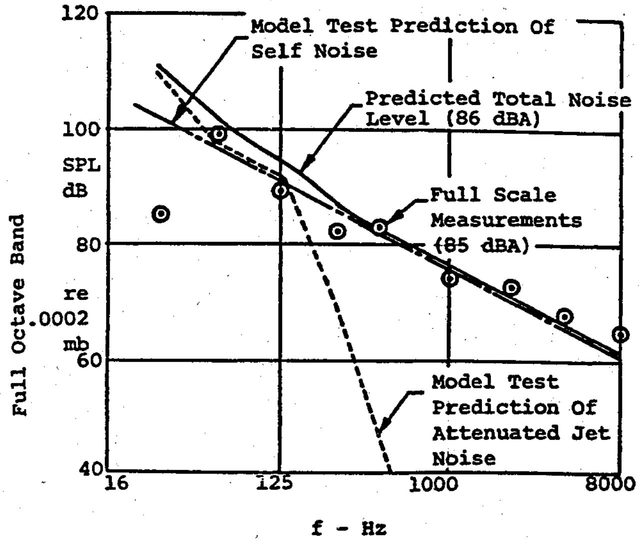

Fig. 13 Hush house exterior noise at 250 ft with F-14A in afterburner.

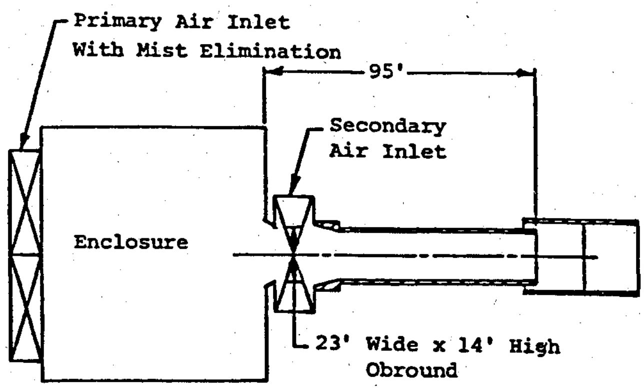

Fig. 14 Patuxent River hush house.

as Miramar) contracting to a 14 ft wide by 9 ft high basic augmenter cross section. The overall El Toro augmenter length is 67 ft. Construction of the El Toro hush house was complete in 1979 and checkout tests were carried out immediately. The maximum external noise level at 250 ft with the F-4 was 84 dBA, which is acceptable. Augmenter maximum wall temperatures were, if anything, cooler than predicted and, at 480°F, much cooler than the Miramar maximum. However, a maximum noise level of 94 dBA was measured straight aft of the augmenter during tests with both A-6 engines at military power. This was unexpected. A possible explanation is that the A-6, with both of its outward splayed engines operating, resulted in an inverted velocity and temperature profile (high at the sides and low in the middle) that trapped noise on the augmenter centerline rather than refracting it into the absorptive lining.

NATC Patuxent River Test and Evaluation Facility

Shortly after the MCAS El Toro hush house requirement surfaced, a need was also expressed for an aircraft test and evaluation facility to be located at the Naval Air Test Center, Patuxent River, Md. The hush houses mentioned earlier had been used primarily for runups related to engine trim. This new facility at NATC was also to be used for testing aircraft operating problems such as those related to landing gear retraction, catapult steam ingestion, etc. It had to accommodate nearly all of the Navy jet aircraft including the F-14A and the S-3A (which has a lateral distance between engine centerlines of almost 16 ft). Since Patuxent River, unlike southern California, experiences its share of rain and cold weather, consideration of the runup crew environment led to specifications for reduced enclosure velocity and mist removal from the enclosure airflow. These specifications necessitated the incorporation of a secondary air inlet above the augmenter entrance. Figure 14 shows the plan layout of the Patuxent River hush house with the secondary air inlet and its 95 ft long augmenter having a 23 ft wide by 14 ft high augmenter entrance to capture the exhaust from the two TF-34 engines on the S-3A. Questions about possible recirculation of secondary inlet flow into the aircraft enclosure prompted a 1/15 scale model test in which the total pressure loss of the demister elements in the door inlet was simulated. No recirculation was found and successful demonstration of S-3A engine exhaust capture was accomplished. This facility is now completed and checkout is scheduled for early 1983.

A Hush House for the VTOL Harrier

Interest in providing a hush house enclosure for the vertical takeoff Harrier aircraft (U.S. Marine Corps AV-8A and 8B) has existed for several years. In 1981 it materialized into the form of a design study and a model test program. The English Harrier aircraft, which embodies a single turbofan engine with vectorable nozzles, is an old aircraft concept, first demonstrated in the late 1950s. Ground runup facilities incorporating trenches alongside the aircraft fuselage with vaned covers to deflect the exhaust flow aft during nozzle vectoring have existed in England since the mid 1960s, with improved facilities being available since the early 1970s. The current change is to incorporate the trench and vane flow capture system into a complete, sound-suppressed aircraft enclosure permitting runup to full power at any nozzle vector angle from 0 to 98.5 deg (maximum) without experiencing significant exhaust gas recirculation within the enclosure. The anticipated enclosure configuration is illustrated in Fig. 15. A 1/15 scale model test of the enclosure, air inlet, jet exhaust flow capture, and exhaust systems has been run to answer questions related to flow capture, air pumping, recirculation within the enclosure, etc. Successful flow capture was demonstrated and, for the normal hush house configuration,

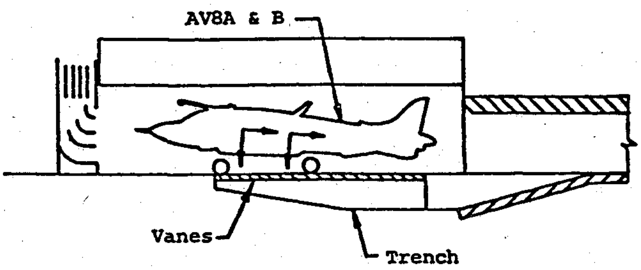

Fig. 15 Harrier hush house.

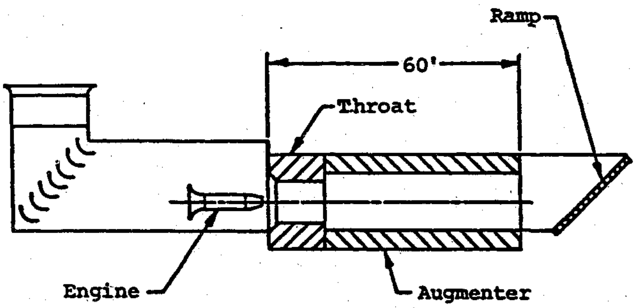

Fig. 16 NAS Dallas test cell.

recirculation (studied with the aid of smokey jet simulation) did not appear to be a problem. Interestingly, full nozzle vectoring did not result in a significant decrease in augmenter pumping (cooling airflow remained at about 3.5 times the engine airflow).

Adapting the Dry-Cooled Augmenter to a Test Cell

Beginning in about 1977 the Navy developed an interest in adapting the dry-cooled augmenter exhaust sound suppressor concept to jet engine test cells. This interest developed partly because the hush house dry-cooled augmenters had demonstrated environmental improvements in that they do not require spray water and usually provide an acceptable exhaust plume opacity.

The application of the dry-cooled augmenter to the test cell where, unlike the hush house case, the exhaust jet would always be accurately centered in the flow pickup offered some opportunities for economy. On the one hand, with a hush house incorporating aircraft with widely spaced, outward splayed exhaust jets, the full augmentation (pumping) is required to cool the augmenter sidewalls. On the other hand, in a test cell with the engine centered, cooling of the augmenter liner does not require the full pumping capability of the augmenter cross section. One can, therefore, incorporate an augmenter throat throttling device and reduce the augmentation, thereby meeting the augmenter exit self-noise limits with a smaller diameter, shorter augmenter. The design of a test cell for the J-79 incorporating a round augmenter cross section is illustrated in Fig. 16. This test cell is complete and is located at NAS in Dallas, Texas.

The Navy's desire to equip themselves with hush house and test cell facilities that are environmentally acceptable has been alluded to before. This primarily means minimizing exhaust plume opacity so that Ringelmann 1.0 is not exceeded (Ringelmann 1.0 corresponds to 20% opacity, Ringelmann 5.0 represents a completely opaque plume). In 1980 the Navy funded a study program aimed at identifying the factors determining plume opacity and defining exhaust system design guidelines that would minimize opacity. The study involved both model tests of test cell exhaust systems and full-scale test cell and hush house exhaust plume observations. The following conclusions were derived from the Navy study observations:

1) Maximum exhaust plume opacity typically occurs during engine runup in maximum nonafterburning thrust.

2) At maximum nonafterburning thrust the open air jet opacity of most engine exhausts is below Ringelmann 1.0 (the exceptions being older J-79s and the TF-41).

3) It does not appear practical to design an exhaust system that exhibits a plume opacity less than that of an open air jet.

4) The jet mixing and deceleration process typical of a low-loss, straight-through augmenter plus ramp yields an exhaust plume opacity only slightly greater than that of an open air jet.

5) The limited dilution and subsequent deceleration typical of older test cell exhaust systems can result in an exhaust plume opacity many times that of an open air jet.

Conclusions

This report shows how model tests have been used to provide design information applicable to dry-cooled test cells and jet aircraft runup facilities and how the model test results have been checked against full-scale results to verify the modeling techniques. Sometimes the model test results have provided forewarning of higher than anticipated wall temperature or other problems for which timely corrections to the design could be made.

For the most part the Navy hush houses have proved to be satisfactory and have contributed an improved operating environment and reduced community noise exposure. Because of the severe jet conditions there remain problems related to aircraft alignment. There are also problems in meeting required construction tolerances. Nevertheless, the existing Miramar hush houses have each handled up to 60 aircraft per month for long periods of time without major downtime.

Acknowledgments

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