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NASA Technical Memorandum 82862

NASA Research in Supersonic Propulsion—A Decade of Progress

(NASA-TM-82862) NASA RESEARCH IN SUPERSONIC PROPULSION: A DECADE OF PROGRESS (NASA) 40 p HC A03/MF A01 CSCL 21E

N82-26300

Unclas

G3/07 28130

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Prepared for the
Eighteenth Joint Propulsion Conference
cosponsored by the AIAA, SAE, and ASME
Cleveland, Ohio, June 21-23, 1982

NASA

E-1230

NASA RESEARCH IN SUPERSONIC PROPULSION - A DECADE OF PROGRESS

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Abstract

At the close of the U.S. attempt in the commercial supersonic transport market in the early 1970's, both the government and aircraft industry recognized that significant technical advancements would be required to make a second generation supersonic aircraft economically viable and environmentally acceptable. Consequently, in 1972, NASA initiated a limited effort to advance supersonic technology. The intent was to identify and investigate areas requiring new and/or improved technology that would lead to substantial improvements in performance. This paper will describe the in-house and contracted efforts of NASA Lewis in the areas of engine selection, testbed experiments, and noise reduction research over the decade from 1972 to the termination of the effort in 1981.

Introduction

In the early 1970's at the close of the U.S. attempt in the commercial supersonic transport market, both the government and aircraft industry recognized that significant technical advancements would be required to make a second generation supersonic aircraft economically viable and environmentally acceptable. Consequently, in 1972, NASA initiated a limited effort to advance supersonic technology. The intent of this effort, the Supersonic Cruise Research (SCR) program, was to identify and investigate areas requiring new and/or improved technology that would lead to substantial improvements in performance.

This was a two-pronged effort involving NASA Langley as the lead center working closely with three airframe contractors (Boeing, Lockheed, and McDonnell Douglas) and NASA Lewis working with two engine contractors (General Electric and Pratt & Whitney).

This paper will describe the in-house and contracted efforts of NASA Lewis in the areas of engine selection, testbed experiments, and noise reduction research over the decade from 1972 to the termination of the effort in 1981. It was recognized at the start of the program that jet noise was expected to be the dominant noise source for an SST, particularly at takeoff and cutback power. Therefore, the suppression of this source of noise would be paramount to the development of a successful airplane. Jet noise can be reduced by lowering jet velocity and raising airflows at takeoff through cycle modifications, by employing mechanical suppressor nozzles, or a combination of these approaches.

At the start of the SCR program, it was recognized that mechanical suppressor nozzles tend to be complex, suffer thrust losses, constrain the engine cycle when deployed and penalize the entire mission as a result of increased nacelle weight and diameter as well as stowage losses. Therefore, emphasis was on the Variable-Cycle Engines (VCE's) and relatively simple and efficient noise suppressors. This then set the stage for the SCR studies.

The Early Years

As previously mentioned, NASA started the SCR program in 1972. The Boeing/General Electric SST effort had been cancelled the previous year. The engine on this aircraft was the GE-4 afterburning turbojet (Fig. 1). Important economic and environmental factors for the aircraft are shown in Fig. 2.

As originally conceived, the SCR Propulsion program was to initially look at a large matrix of engines through contracted efforts with GE and P&W, with a subcontract from P&W to Boeing to perform integration studies. The plan was to narrow the list of candidate engines to one for each company and then build demonstrators of each. There were additional in-house and contracted efforts in the area of noise reduction, inlet stability, and materials. This is shown in Figs. 3 and 4.

During the initial phase of the contracts, 25 engine concepts were evaluated (1973). These engines ranged from conventional concepts to complicated engines with valving, ducting, and other novel approaches. The initial screening reduced the number of engines to ten in the second phase (1974). More detailed analyses were performed on these engines until in 1975, the candidates were reduced to four. These were a conventional non-augmented Low Bypass Engine (LBE) with a mixed flow nozzle and a Variable Stream Control Duct-Burning Turbofan Engine (VSCE) at Pratt & Whitney, and the General Electric Double and Single Bypass Engines (DBE and SBE). These four engines are shown in Figs. 5 and 6. Both the P&W LBE and GE SBE had to be oversized to meet noise requirements or required the installation of a noise suppressor.

The narrowing of the engine concepts to 4 was based on the overall SCR program as shown in Fig. 7. As mentioned earlier, concomitant with the Lewis sponsored propulsion systems studies, Langley had contracted efforts with the three airframers who were supplied data packs of engine performance by P&W and GE. The airframers then evaluated these engines on their airframes. Work was also being done on the problems of emissions and noise. The driving factors in the selection of these engines were the performance of the engines and the noise. It would, therefore, be appropriate at this time to discuss the early noise work that was done.

Early Noise Work

The early noise work focused attention on attempting to develop simple and efficient noise suppression devices suitable for and taking advantage of the unique features of the Variable Cycle Engines. A consideration in going in this direction was that the Department of Transportation (DOT) initiated a substantial effort on high-velocity jet noise suppression in 1972.

But even before this, before the termination of the SST development effort, the Lewis Research Center was already involved in developing the required noise technology. This effort was focused on jet noise for high specific thrust engines similar to the GE-4 and the engines on the Corcorde. In-house studies produced a novel suppressor concept. In 1971, a contract was awarded to Boeing for the development of lined ejector technology through experiments on model and full-scale multitube suppressor nozzles.

In spite of the advances being made on turbojet type suppressors, it appeared that still more innovative concepts would be required to produce an acceptable engine. Therefore, in 1973, Lewis initiated contracts with both P&W and GE to conduct model tests on duct burning turbofan exhaust nozzles, both unsuppressed and with suppressor elements in the outer (high-velocity) stream. This concept appeared attractive, since the high-velocity stream was confined to an annulus (inverted velocity profile, IVP) so that simpler suppressor elements would be required than for a turbojet, which would probably required a full penetration suppressor.

It was acknowledged that effects of flight on noise for even the simplest nozzle geometries were poorly understood. Because of the importance of flight effects on jet noise and the apparent inconsistency between jet noise trends observed in actual flight and in flight simulation experiments, Lewis initiated contract studies with Lockheed-Georgia and Boeing in 1974 on the generation, propagation, and measurement of jet exhaust noise in flight. To minimize cost, much of the experimental noise suppression work was conducted with small-scale model nozzles, which produced significant noise at frequencies up to 100 kHz, a factor of 10 beyond the range where accepted methods were available. Thus, to allow such data to be properly evaluated, Lewis initiated a study in 1975 of high-frequency atmospheric attenuation conducted by the University of Mississippi. The results of this study have been widely used and provided much of the basis for the development of widely accepted standard procedures.

Unsuppressed Coannular Nozzle Results

As mentioned earlier, the inverted-velocity-profile (IVP) exhaust system (Fig. 8) of the duct burning turbofan engine appeared to offer the opportunity to employ relatively simple outer-stream suppressors. However, early testing indicated that even the unsuppressed IVP coannular nozzles offered significant noise reduction benefits. This noise reduction benefit was evaluated differently by different investigators, as illustrated in Fig. 9. In Fig. 9(a), the maximum perceived noise level (PNL), scaled to a common size, and normalized for jet density effects, is plotted against the mass-averaged jet velocity, V_{ma}, and compared with the noise of a conical nozzle having the same thrust and mass-averaged velocity. On this basis, the noise reduction benefit is 3 to 5 PNdB. An alternate comparison is shown in Fig. 9(b), the normalized maximum PNL is plotted against outer-stream velocity, Vj_2, for cases where $Vj_2 \geq 1.5\ Vj_1$ (Vj_1 is the inner-stream velocity). The results are compared with a "synthesized" noise, which is the summation of the noise from a conical nozzle at outer-stream conditions and area and that of a conical nozzle at inner-stream conditions and area. On this basis, the noise benefit of the IVP coannular is 6 to 10 PNdB, with the noise benefit increasing as the outer nozzle inner to outer radius ratio increases. In spite of the slight confusion brought about by the different comparison bases, it was clear that meaningful noise suppression was obtainable with a thrust loss of only 1.5 to 2 percent.

Outer-Stream Suppressor Results

In addition to these unsuppressed baseline coannular nozzles, further experiments were conducted with suppressor elements such as chutes, tubes or convolutions. Lined and unlined ejectors were also evaluated. Results of these studies are shown in Fig. 10 on the same "synthesized" basis as Fig. 9(b). The crosshatched areas represent the outer-stream results, while the dashed lines are reproductions of the synthesized and unsuppressed coannular results of Fig. 9(b). At the higher outer-stream velocities, the suppressed configurations showed an additional noise reduction of 3 to 7 PNdB, but at the expense of relatively large thrust losses (as much as 8 percent greater than the unsuppressed coannular nozzles).

Flight Effects

Although the results discussed so far were quite encouraging, optimism was tempered by the fact that the results were from model-scale static tests. Recognizing the need for an evaluation of flight effects, Lewis initiated simulated-flight tests of unsuppressed IVP coannular nozzles in an anechoic free-jet facility by P&W. Typical results at simulated takeoff conditions are shown in Fig. 11. The variation of overall sound pressure level, OASPL, with outer-stream velocity, V_2, is shown for static and simulated flight ($M_a = 0.3$) conditions for a fixed angle in the aft quadrant ($\theta = 130°$). "Synthesized" levels are also shown for comparison. The difference between the IVP coannular nozzle results and the "synthesized" levels was essentially unchanged from static to flight conditions. Therefore, the noise reduction benefits of IVP coannular nozzles were also shown to occur in flight.

Suppressors

Although the Lewis effort was now focused on the IVP nozzles, suppressors were not being neglected. A major DOT/FAA study (with technical support from NASA Lewis) was conducted on high-velocity jet noise suppression including suppressors for coannular exhausts.

Testbed Engines

At the end of Phase III of the SCR engine studies (1975), the number of candidate engines had been reduced to four. The noise work was now focused on the IVP coannular nozzles although there were concerns about the scalability of the results to full scale engines. The more unconventional GE DBE and P&W VSCE represented relatively quieter engines, even unsuppressed, but required unique and technically challanging components such as the duct burner, IVP nozzles, variable bypass injectors (VABI's), etc. They were chosen as the two engines for the testbed program.

Double Bypass Engine

The NASA testbed engine program at the General Electric Co. was formulated to determine the aeromechanical feasibility of the most critical unique VCE features of a double bypass engine and to verify engine performance and acoustic predictions in a series of limited static engine tests. The double bypass engine concept, shown schematically in Fig. 12, is a turbofan engine in which the fan has been split into two blocks, each with its own bypass duct for better control of the flow over a broad spectrum of operating conditions. The enlarged front block fan is designed to accommodate all the airflow required for takeoff with reduced specific thrust (jet velocity) for low jet noise in the double bypass operating mode. The lower-capacity rear block fan is sized for the nominal single bypass, high specific thrust operating mode needed for transonic and supersonic acceleration and supersonic cruise. A selector valve at the entrance to the outer bypass duct is opened for double bypass operation and closed when conventional single bypass operation is desired. Variable inlet guide vanes (IGV's) control the flow swings into the rear block fan which occur between double and single bypass operation. In double bypass operation, the two bypass streams are merged into a single duct to reduce weight and simplify the exhaust nozzle requirements. This merger is accomplished via the variable area bypass injector (VABI), a translating cylindrical sleeve which varies the discharge area of the inner bypass duct to match its static pressure to that of the outer bypass stream for efficient mixing over a range of double bypass flow conditions. In the low-noise mode, bypass flow is then brought through cross-over struts to the inside of the plug nozzle, as shown in the view above the centerline in Fig. 12. The aft portion of the plug centerbody is translated fore and aft to vary the exit area and thus control the flow of the cold fan stream. The hot turbine discharge gases flow around the nozzle support (cross-over) struts and over the plug crown to surround the cold fan discharge stream to provide an inverted velocity profile for reduced jet noise. In the more conventional single bypass operating mode, shown below the centerline in Fig. 12, all the fan bypass flow goes through the inner bypass duct and is mixed downstream with the turbine discharge gases via the action of drop-chute rear VABI's located between the plug nozzle support struts. As with the forward VABI, the function of the rear VABI is to perform a static pressure balance between the two streams for more efficient mixing. Mixing is desired at flight conditions where jet noise reduction is of no concern in order to provide a uniform exhaust velocity profile for greater propulsive efficiency. To stop the cold flow discharge from the inner plug, the aft portion of the plug centerbody must be translated fully aft in this operating mode.

Another unique feature of the engine concept is the rear block fan drive arrangement. In this engine, the rear block fan is driven by the high-pressure (HP) turbine, as opposed to the conventional low-pressure (LP) turbine drive arrangement for all existing turbofan engines. This unique drive arrangement allows an otherwise under-worked HP turbine to do more work and allows the enlarged front block fan to be driven by a single-stage LP turbine. Reduced turbine cooling also results from the arrangement because of the increased work extraction from the HP turbine stage, which reduces its average metal temperature, as well as that at the LP turbine inlet.

The first NASA-sponsored VCE test occurred in 1978, but drew upon military test experience dating back to 1976, as indicated in Fig. 13. Both the military and NASA programs at GE used YJ101 engine hardware as the basis for the test vehicle, with modifications as appropriate to incorporate VCE features. The YJ101 is a low bypass turbofan previously used in the YF17 flight test program, and served as the prototype for the more refined F404 engine used in the Navy F18 fighter. The availability of the YJ101 hardware greatly reduced the cost of the VCE testbed program to NASA since these engines were military surplus and were furnished at no cost. The combined military and NASA YJ101/VCE experience included over 440 hours of testing, with the NASA test experience alone accounting for over half of this total.

The first YJ101/VCE test shown in Fig. 13 was sponsored by the Air Force and demonstrated the operation of a rear diverter valve with a dual exit exhaust nozzle on an otherwise standard YJ101 engine. The rear valve allowed the engine to operate with the fan and engine exhaust gases either separated or mixed. The second test in this sequence, also sponsored by the Air Force, was the first demonstration of the double bypass concept, with the three-stage YJ101 fan split so that there was one stage in the front section with two stages in the rear (i.e., a 1 x 2 fan split). This engine retained the rear diverter valve so that the inner bypass exhaust flow could either remain separated or be mixed with the primary. Since the outer bypass stream was exhausted separately, a complicated three-exit exhaust nozzle was required. The third VCE test was sponsored by the Navy and was an evaluation of a double bypass system with a 2 x 1 fan split. The rear diverter valve was replaced in this engine with a drop-chute rear VABI for improved mixing. A variable area LP turbine nozzle (VATN) assembly was also substituted for the conventional fixed-geometry stator hardware for additional matching flexibility. The first NASA test configuration, shown schematically in Fig. 14, in addition to the features of the previous Navy vehicle, incorporated a forward VABI to allow the merging of the inner and outer bypass streams into a single bypass duct. This saved weight and greatly simplified the nozzle by permitting a conventional military single-exit configuration to be used with the rear VABI mixing all the bypass flow with the primary.

In the forward VABI test, transitions from single to double bypass operating modes, and vice versa, were successfully demonstrated without any observable aerodynamic instabilities or mechanical problems. Data obtained during this test in June 1978 (Fig. 15) indicate the airflow and sfc advantages of double bypass operation at constant 50-percent thrust throttle conditions. This type of operation is representative of cut-back at the takeoff fly-over noise measuring station or subsonic cruise. Figure 15 shows that a 29 percent increase in airflow is possible in double bypass compared to normal single bypass operation without exceeding the minimum sfc in single bypass. At cutback, this could mean a 6-10 PNdB reduction in jet noise because of the lower jet velocity. At subsonic cruise, the greater mass flow implies reduced throttle-dependent installation drag because the inlet spillage and nozzle boattail are reduced. If less than the full 29-percent increase in airflow is needed in the installed performance optimization, Fig. 15 also shows that uninstalled sfc improvements of up to 5 percent can be obtained in double bypass with at least 13 percent more airflow than best sfc operation in single bypass.

After the completion of the forward VABI test, the engine was then reconfigured as shown in Fig. 16 for an aero/acoustic test which occurred in an outdoor test facility at Edwards AFB, California, in October 1978. This became the fifth test in the YJ101/VCE sequence shown in Fig. 13. To obtain this configuration, the military nozzle and Navy rear VABI were removed and replaced with a coannular plug nozzle with an integrated rear VABI assembly similar to that in the conceptual product VCE shown in Fig. 12. A photograph of this engine on the test stand at Edwards is shown in Fig. 17. A laser velocimeter used to make a plume velocity survey can also be seen to the side of the nozzle in this photograph. In addition to several coannular plug nozzle configurations of different outer radius ratio, a fixed-geometry mixed flow conical nozzle was also used as an acoustic reference. Other than the acoustic evaluation of the coannular plug nozzle system, which will be presented later in this paper, one of the major objectives of this test was to assess the losses in the bypass system from the fan discharge through the nozzle flow-inverting struts. These losses are shown in Fig. 18 for both double and single bypass operation. At the double bypass strut design flow condition, a predicted thrust loss of around 2 percent was expected, but the actual measured loss, as shown, was much less and only slightly greater than that incurred in single bypass where the strut flow was much lower. A pressure loss evaluation of the hot stream from the turbine frame aft also indicated that the low-loss configuration was obtained for this stream, and that no major performance penalties occurred due to the rear VABI or flow around the cold flow inverting system. Comparisons of hot stream loss data were made between the coannular plug configurations and the reference nozzle, both with the rear VABI, and differences were barely detectable. The mixing effectiveness of the new drop chutes - generally above 90 percent - indicating that the ideal thermodynamic thrust gain due to complete mixing was approached.

The Edwards acoustic test VCE was used next in a test of the Navy Full Authority Digital Electronic Control (FADEC), as indicated in the test sequence chart of Fig. 13. The coannular acoustic nozzle, however, was removed and replaced with the conventional single-exit variable area military nozzle. The rationale for using the NASA VCE configuration for this test was that it had more variable geometry features than any other engine and would, therefore, provide a better test of the capability of the new electronic control system. The FADEC test was completed at a GE-Lynn test cell in 1980.

After the completion of the Edwards acoustic test in the fall of 1978, NASA embarked on the construction of a core-driven fan stage (CDFS) testbed configuration which provided a closer aerodynamic and mechanical simulation of the conceptual engine shown in Fig. 12. The rear block fan in the CDFS testbed design was closer coupled space-wise to the HP compressor than in the earlier testbed, and the core drive arrangement, by providing a higher rotational speed, allowed the tip diameter of the fan to be reduced for improved outer bypass duct aerodynamics. A different YJ101 core spool was used so that the required modifications could be made in parallel with the Navy FADEC test. The CDFS modification was such an extensive departure from previous experience that a separate core test was deemed appropriate. The core test configuration, which incorporated the new fan stage as well as the bypass ducting and new forward VABI system, is shown schematically in Fig. 19. Modification of the YJ101 high spool to this new configuration required redesign and relocation of major engine structural frames and a change in the shaft bearing and support arrangement. This core configuration was successfully tested in the summer of 1980 in a GE-Evendale ram test facility which allowed the simulation of the front block fan discharge conditions at the CDFS inlet. A photograph of the core test vehicle being moved into the ram test facility is shown in Fig. 20. During the core test, the engine and fan stage both operated quite well, with very low vibration levels throughout the test. No CDFS blade instabilities were found, and a review of rotor/stator strain gage data showed that stresses were generally only 30 to 50 percent of design. The new forward VABI system, with the flapper-type double bypass selector valves located between the midframe struts, worked quite well in the test. The inner bypass duct, however, seemed to be somewhat undersized and tended to choke and produce a higher-than-expected rear block operating line in single bypass operation. The fan stage aerodynamic performance itself was quite good, with the airflow and stall line both higher than predictions. The unique delta vanes, which were installed on the outer wall ahead of the fixed OGV's in the inner bypass duct (see Fig. 19) also proved to be effective in reducing the incidence angle on the OGV's during low flow operation typical of double bypass conditions. The decision was made to retain these removable delta vanes for the full engine test because of their apparent beneficial effect over a range of operating conditions.

The full engine performance test with the CDFS core was the last test shown in the Fig. 13 sequence and was completed at Edwards AFB in January 1981. The front block fan, VATN, and LP turbine were obtained from the FADEC test engine and combined with the CDFS core from the previous NASA test. A rear VABI from a previous VCE configuration was also used and combined with a standard single-exit YJ101 variable exhaust nozzle. A photograph of this engine on the test stand is shown in Fig. 21. When combined with the coannular plug nozzle for the subsequent acoustic test, as shown schematically in Fig. 22, this testbed engine embodied virtually every feature of the Fig. 12 conceptual engine, with the exception of the enlarged front block fan and the advanced core hot section In the performance test, the engine met its overal pretest performance goals, especially with respect to the matching characteristics of the CDFS compression system. Some core compressor speed/- flow hysteresis was observed during the test, however, and was later attributed to looseness in the HP compressor variable IGV system. A gradual performance loss was also observed over the 43-hour duration of the test and, by a process of elimination, was attributed to a deterioration in the performance of the core turbine. Possibly the most interesting result obtained from the full engine performance test was the airflow extension comparison between double and single bypass operation at a constant 50 percent thrust, as shown in Fig. 23. Double bypass operation provided a 40 percent increase in airflow without any sfc penalty, compared to the single bypass best sfc operating point. The best sfc in double bypass is about 8 percent lower than in single bypass and the airflow is about 19 percent higher. As mentioned previously in connection with the forward VABI test results (Fig. 15), this increase in airflow could reduce throttle-dependent external drag at subsonic cruise conditions. Caution should be exercised, however, in making a direct comparison between the CDFS airflow extension results and those from the forward VABI test. The undersized inner bypass duct and the overworked core turbine in the CDFS engine tend to adversely affect single bypass performance while having little effect on double bypass operation. The double bypass advantage, therefore, may be somewhat overstated in Fig. 23. With a properly designed system, it is expected that the CDFS double bypass advantage would lie somewhere between the results indicated in Figs. 15 and 23.

About 2 hours into the CDFS acoustic test, after the change-over to the nozzle configuration depicted in Fig. 22, a major engine failure occurred. This coannular nozzle had been evaluated previously in the the 1978 Edwards test and was undergoing a recalibration when the failure occurred. An extensive investigation revealed that the first-stage HP compressor blade failure which occurred was precipitated by loose and individually mispositioned HP IGV's which created a source stimulus for the rotor blading. The failure occured at high power during conventional single bypass operation with all variable geometries at their normal settings. The failure was not related to any of the unique VCE features or operating conditions, but was probably caused by a basic deficiency in the YJ101 HP compressor IGV design, which has been corrected in the more mature F404 follow-on engine design. For this reason, it is recommended that any subsequent engine testing of a similar nature should employ the F404.

Plans had been made and hardware had been built for additional acoustic suppression devices, including a multi-element outer stream suppressor (Fig. 24) for the coannular plug nozzle and an add-on acoustically-treated ejector. A boiler-plate hybrid accelerating inlet from a previous DOT/FAA experimental program was also modified for inclusion on the testbed engine in order to address the fan/inlet acoustic interaction problem. Figure 25 shows a schematic of all these components as they would have been assembled on the testbed engine in the planned Edwards acoustics test. These components, however, were never evaluated because of the termination of the test program after the engine failure. A model nozzle acoustic and aeroperformance program has been expanded in the last year to evaluate some of these and other concepts with the potential for additional noise reduction.

Variable Stream Control Engine (VSCE)

Figure 26 is a schematic showing the basic arrangement of the major engine components of the Pratt & Whitney variable stream control engine (VSCE). Also shown is an illustration of the inverted jet velocity profile at takeoff. The engine is a twin-spool configuration similar to a conventional turbofan but with the added feature of a burner in the fan duct. The VSCE derives its name from its ability to independently control the primary and bypass streams. The fan and compressor both have variable geometry components and are driven by advanced technology turbines. The main burner and duct burner both use low-emissions, high-efficiency combustor concepts, based on NASA's Clean Combustor program. The coannular nozzle provides variable throat areas for the core and fan duct flow and also includes an ejector - thrust-reverser system.

The flexibility of this concept to meet the diverse requirements of low jet noise at takeoff and good fuel consumption at cruise can best be illustrated by describing the operation at its three most critical operating conditions: takeoff, subsonic cruise, and supersonic cruise (Fig. 27).

At takeoff, the primary stream is throttled to an intermediate power setting while the duct burner is operated at its maximum design temperature. The independent control of the two streams provides the unique inverted velocity profile that is needed to take advantage of the coannualar nozzle noise benefit. The bypass jet velocity is about 60 to 70 percent higher than the primary jet velocity. This inverted velocity profile provides a significant reduction in takeoff jet noise.

At subsonic cruise, the main burner is throttled to a low temperature and the duct burner is turned off. Variable geometry features are used to "high flow" the engine to match the inlet airflow and thus reduce both the inlet spillage drag and the nozzle boattail drag. The velocity profile is nearly flat, and the engine approaches the performance level of a moderate bypass ratio turbofan engine designed strictly for subsonic operation.

At supersonic cruise, the primary burner temperature is increased relative to takeoff, and the duct burner is operated at part power. The resulting velocity profile again is nearly flat for good propulsive efficiency, and this concept then provides a fuel consumption that approaches that of a turbojet cycle designed exclusively for supersonic cruise.

A comparison of the VSCE with Pratt & Whitney's component testbed configuration is shown in Fig. 28. The NASA component testbed program at Lewis began in 1976 to provide a large-scale evaluation of some of the unique and critical components of the selected VCE concepts. To keep the costs to a minimum, the critical component hardware is applied to existing high-technology engines. In the Pratt & Whitney program, the testbed system is designed to provide a large-scale evaluation of two of the most critical technology components of the VSCE - the low-emissions duct burner and the low-noise coannular nozzle. These components are added at the back of an F-100 engine which is used as a gas generator. The F-100 engine has the best potential to simulate the desired exhaust conditions of the VSCE without any major modifications.

An aero/acoustic design procedure for coannular nozzles was applied to several candidate exhaust systems to identify the most attractive nozzle for the VSCE. A schematic of the selected design is shown in Fig. 29. At supersonic cruise, the nozzle is a conventional convergent-divergent configuration. Two internal clamshells are positioned to provide the initial portion of the expansion surface of the ejector shroud. Variable throat areas are provided for both the primary and fan flows. At low-speed conditions, the nozzle converts to an auxiliary inlet ejector. Actuated inlet flaps are opened to admit external airflow into the shroud. Panels located immediately downstream of the double-hinged doors are translated aft to provide additional area for the ejector, and the internal clamshells are aligned with the inlet flow. Floating tail feathers are aerodynamically positioned to provide the proper exit flow area. The clamshells are also used for thrust reversal by rotating them back to the nozzle centerline. The reversed flow is then expelled through the open inlet doors.

Scale models of this nozzle configuration were tested in the Lewis 8 by 6 Foot Wind Tunnel (Fig. 30) in the Fall of 1978. Thrust performance levels were established for this nozzle design at both subsonic and supersonic speeds. The results of this experimental investigation are shown in Fig. 31. The measured nozzle thrust coefficients are compared to the SCR study goals at three critical flight conditions - takeoff, subsonic cruise, and supersonic cruise. The supersonic cruise point is simulated at Mach 2.0, the highest Mach number available from the wind tunnel. The performance at this flight condition is very good. This is encouraging since this is the most critical operating point for the exhaust system. The low-speed performance was disappointing, especially at subsonic cruise where the measured performance levels are from 5 to 6 counts lower than the study goals. Diagnostic tests of the subsonic cruise configurations showed that the lower performance levels were the result of an aerodynamic flow separation over the inlet doors of the ejector. It was obvious that additional work was required to improve the off-design performance of this ejector nozzle concept.

This concern resulted in a redesign of the nozzle and a follow-on wind tunnel test of an improved nozzle configuration. The aerodynamic redesign requirements were intended to provide improved performance at the critical off-design operating points. This was accomplished by reducing the ejector inlet turning angles, minimizing internal overexpansions and static pressure mismatches, and minimizing core/bypass flow impingement angle. The improved nozzle configuration was design and fabricated and is currently being tested in the Lewis 8-by-6 Foot Wind Tunnel.

An analytical screening study of low emissions, high-performance duct burner concepts in 1976 indicated that a three-stage burner, operating on the vortex burning and mixing concept (vorbix), offered the best configuration for the testbed engine within its risk and schedule constraints. A schematic of the selected configuration is shown in Fig. 32. The requirement that the duct burner be capable of operating smoothly over a wide range of fuel-air ratios leads to the need for a multistage combustor system. The first, or pilot prechamber, stage is sized for stable operation at very low fuel-air ratios to provide a soft light and to minimize disturbances to the fan operation. The combined first two stages (pilot prechamber and pilot secondary) are designed to operate at supersonic cruise, and the third, or high power, stage is designed to operate only during takeoff and transonic climb.

Emissions and performance measurements were obtained for this three-stage vorbix configuration in both a two-dimensional segment rig test in 1978 and in the F100 component testbed engine in 1979. In general, the data from the segment rig test were consistent with the data from the testbed engine, demonstrating the ability of the segment test rig to accurately model the full annular phenomena. Acceptable operating characteristics were demonstrated. Both performance and emissions results were generally better than the program goals.

Emissions measurements from these experimental tests at two simulated flight conditions, takeoff and supersonic cruise, are shown in Fig. 33. The design goals for carbon monoxide (CO) and unburned hydrocarbons (THC) are based on a combustion efficiency of 99 percent. These goals are intended only as a standard for comparison and are not related to any proposed or established regulation for advanced supersonic aircraft. Since the measured combustion efficiencies are very high (near a value of 100 percent), the emissions levels for CO and THC are well below the design goals. The design goal for oxides of nitrogen (NO_x) is the lowest value that can be obtained with this duct burner concept and assumes complete mixing. The measured NO_x emissions levels are quite low and very near the goals at both takeoff and supersonic cruise. It should be pointed out that the duct burner only contributes a small part of the overall engine NO_x emissions when compared to the main burner, as can be seen in Fig. 34.

In Fig. 34 the projected emissions characteristics of the VSCE have been updated to reflect the duct burner emissions measurements from both the segment rig and testbed engine tests. The data used for projecting the emissions of the main burner were based on results from the Clean Combustor program, and the main burner was assumed to be a two-stage vorbix concept. Figure 34 shows the projected emissions levels for both the airport vicinity and at altitude cruise. The shaded area depicts emissions from the main burner, while the unshaded area shows the emissions from the duct burner. The results at the airport indicate that the engine is capable of meeting the 1984 emissions requirement for the class T5 advanced supersonic transport engines. The NO_x emissions at high-altitude cruise are higher than the proposed Climatic Impact Assessment Program (or CIAP) goal of 3.0. Although the requirements of altitude NO_x are not yet established, if they are constrained to this proposed CIAP level, more advanced emissions-reduction technology must be employed to meet the goal. This is particularly true for the main burner, since it produces nearly 90 percent of the total NO_x emissions at altitude cruise.

The VSCE/F100 component testbed program was completed in the Fall of 1980 when the acoustic test was conducted at Boeing's acoustic test site near Boardman, Oregon, Fig. 35. (Results of the acoustic test are discussed later in this paper.) The model nozzle program is continuing with an effort to improve nozzle performance, especially at the off-design conditions where the measured performance to date has been poor.

In summary, the performance and emissions measurements obtained to date from the component testbed program at Pratt & Whitney have been very encouraging. Successful operation of these advanced and unique engine components have removed some of the technical barriers that has previously inhibited the development of an advanced supersonic cruise aircraft.

Testbed Acoustics

The testbed acoustics programs were addressed primarily to the development of prediction procedures and the demonstration of IVP noise benefits at large scale.

IVP Noise Prediction

Since the noise is a complicated function of flow-field and geometric variables, it is necessary to go beyond simple plots such as Fig. 9 to correlate the data. The complexity of the IVP jet noise generation processes is shown in Fig. 36. As many as four noise-generating regions must be considered. It is the differing trends of these different noise sources with operating conditions that leads to the existence of a minimum noise as velocity ratio increases. The low-frequency noise is generated well downstream of the nozzle where the two flows have mixed and can no longer be distinguished; this is termed the merged region. The higher frequency jet mixing noise is generated in the region near the nozzle exit where the individual jets can still be identified; this is termed the premerged region. When either or both streams are supersonic, noise can be generated by turbulent eddies passing through shock waves; thus, we must in general consider inner-stream shock noise and outer-stream shock noise.

Empirical models relating these noise-generating processes to those of a conical nozzle have been developed. Small-scale, plugless, coannular nozzle experimental spectra are compared with predictions in Fig. 37. Sound pressure level is plotted against frequency for an angle of 120°, in the rear quadrant, in Fig. 37(a). For this case both streams are supersonic, so all four noise sources must be considered; but it is the jet mixing noises that dominate at this angle. The shock noise levels contribute somewhat in the high-frequency range but not as much as the premerged mixing noise. Results for the same conditions, but in the forward quadrant at θ = 75°, are shown in Fig. 37(b). It is apparent that shock noise is much more important in the forward quadrant than in the rear quadrant. The inner-stream shock noise dominates the midfrequency range and determines the peak sound pressure level. The outer-stream shock noise controls the high-frequency range. Although the relative contributions of the various sources are different in the forward and rear quadrants, the spectra at both angles are predicted with good accuracy.

Large-Scale Verification of IVP Concept

The acoustic characteristics of IVP coannular nozzles, originally determined from a series of model-scale tests, were first verified on an engine during the NASA-General Electric Double Bypass Engine Testbed acoustic tests. Typical results are shown in Fig. 38 for the VCE testbed coannular plug nozzle as well as for a similar model nozzle at essentially the same conditions, with a mixed jet velocity of about 590 meters per second. For both the engine and the model, the experimental results are scaled up to a typical product-engine size (total exhaust area, 0.90 m^2) at a typical sideline distance (slant range, 731.5 m). The results are also compared with the prediction procedure. Perceived noise is plotted as a function of angle in Fig. 38. The model results are verified by the engine results. The engine results are an average of 0.8 PNdB below the model results, and the standard deviation between the two data sets is 1.5 PNdB. The overall accuracy of the prediction method is also confirmed by the testbed data. The average bias of the prediction with respect to the testbed data is less than 0.1 decibel, and the standard deviation is 1.5 decibel. The predicted contributions of the combined jet mixing noises (merged plus premerged) and the shock noises (from both streams) are also shown. Although the jet mixing noise is most important in this case, the shock noises contribute somewhat in the forward quadrant. Although not shown here, at higher power settings and in flight, the shock noise becomes even more important and contributes significantly to the effective perceived noise level.

Duct-Burner Noise

Tests of the NASA-Pratt & Whitney VSCE testbed not only provided further verification of the IVP noise reduction benefits, but also provided the first opportunity to determine the importance of combustion noise from the duct burner. These tests also provided a large scale evaluation of the influence of the ejector with and without acoustic lining. Experimental data at high fuel-to-air ratio are compared with prediction at angles of 90° and 120° in Fig. 39. Good agreement can be seen in general, and duct burner noise is seen to be significant, though not controlling. The significance of duct burner noise is expected to increase somewhat in flight and also limits the potential benefits of jet noise suppressor nozzles. Ejector results, shown in Fig. 40, indicate that the lined ejector can provide substantial noise reduction, and even the hardwall ejector provides some noise reduction at large angles.

The Later Years

At the same time that the testbed engines and noise experiments were being run, cycle calculations continued on the four "candidate" engines. The two conventional engines were being considered as viable alternatives to the variable cycle engines. Remember, that the experimental programs were looking at the barrier technologies to successful VCE's. In addition, effective low loss suppressors were being developed under the sponsorship of DOT/FAA and NASA. The engine companies were generating data packs for engines tailored to the three different Mach numbers of the three airframers (2.4 Boeing, 2.55 Lockheed, and 2.2 McDonnell Douglas).

P&W was funded in 1977 to do a refined design definition of the VSCE incorporating the latest results from the duct burner and coannular nozzle experiments. It consisted of an updated design of all the major engine components to ensure reasonable engine flowpaths with emphasis on the hot section of the core. The engine went through the preliminary design group and was "weighed" on a component by component basis. This is shown in Fig. 41.

The major changes that occurred were a result of finding that the cooling requirement assumption for the hot section had been overly optimistic.

This caused P&W to reduce the overall engine pressure ratio from 20 to 15 and to put a heat exchanger in the bypass duct to precool the turbine cooling air. Interestingly, this caused a decrease in specific fuel consumption. This updated version of the engine was given the designation VSCE-515 versus the original VSCE-502.

In 1978, the design definition study contract was extended to perform a similar design definition of the LBE and a version of the LBE where a flow inverter was used to take the bypass air into the center of a coannular nozzle and the core air to the outside. This engine (the IFE for Inverted Flow Engine) would, therefore, be expected to have reduced noise because of the inverted velocity profile relative to the mixed flow exhaust of the LBE. Of course, it would be heavier because of the flow inverter. In addition, a design study was done on the VSCE-515 with an outer stream suppressor. The goal was to reach the proposed new noise limit for subsonic aircraft FAR Part 36 (1969) stage 3. Suppressed versions of the LBE and IFE were also studied.

The outer stream suppressor did not appear to significantly benefit the noise obtainable by the VSCE. In order to have a suppressor, the duct burner temperature had to be dropped from 2600° to 2000° F which caused a reduction in the inherent coannular noise benefit of the cycle. The suppressed LBE did benefit while the IFE did not.

As we shall soon see, the original SCR Program goal of finding the best two engines through the process previously illustrated in Fig. 3, instead resulted in expanding the number to where 5 engines still appear to be attractive.

Boeing, under contract to Langley, conceived of a new engine designated the Turbine Bypass Engine (TBE). The TBE as originally conceived was a two spool turbojet where the high-pressure turbine was undersized. Under high-power operating conditions, compressor discharge air (up to 25 percent) was bypassed around the high-pressure turbine and then reintroduced between the two turbines. As the turbine inlet temperature was reduced in throttling back the engine, less and less air was bypassed to maintain constant corrected flow through the HPT. This enabled to turbojet to maintain 100 percent engine speed over a wide range of power settings with significant improvements in uninstalled specific fuel consumption and reduced installation effects by maintaining airflow to reduce inlet spillage and nozzle boattail drags. Boeing subcontracted with P&W to study this engine. Subsequently, it was found that a single spool version of this engine would perform just as well and alleviate the problem of reinjecting the bypass air between the two turbines. The single spool version of this engine is shown in Fig. 42.

The simplicity of the single spool version of the TBE with its ability to maintain airflow at reduced power settings made it very attractive. Being a high specific thrust engine, it would however require some form of a suppressor nozzle. Therefore, Lewis contracted with P&W to do a preliminary design of the TBE in 1980 and compare its performance to that of the other three engines (VSCE, LBE, IFE).

The results of this study are shown in Fig. 43. The TBE is designated the VCE-702. As can be seen from the figure, the unsuppressed VSCE and suppressed VSCE, LBE, and TBE engine are quite competitive at the low noise levels used in this study. The airplane used by P&W in this study was the Langley AST-105 at a Mach number of 2.4. Since the "best engine" might vary from airframe to airframe (and with Mach number), it was decided to have each of the airframers look at these three engines in 1981 and eliminate the IFE. Contracts were being prepared when the SCR Program was cancelled.

We will now discuss the engine studies done by GE in the later years. The reader must be cautioned not to try to compare the performance of P&W and GE engines. The contractors were asked to project engine technology to the late 1980's and the projections are different. Hence, P&W studying the GE cycles would not predict the same performance and vice versa.

The General Electric engines still under consideration at the time of selection of the testbed engine were the DBE and the SBE. In 1977, GE was funded to reoptimize the design parameters of these two engines, with and without suppressors, to try to achieve lower noise levels. They were also to address the major variable cycle components in the DBE, removing them one at a time, to assess which had high payoff and which could be removed to yield a simpler engine.

The major conclusions reached in this study was that the front VABI enabling the engine to have a double bypass was the major payoff item in the DBE. The elimination of the rear VABI and fixing the area of the low pressure turbine had marginal impact. The SBE with full stream suppressor is competitive with the DBE with either a full or outer stream suppressor at low noise levels. This is shown in Fig. 44.

The simplicity of the outer versus full stream suppressor on the DBE led to the conclusion that the outer stream suppressed DBE and full stream suppressed SBE were the two engines that would continue to be considered

Having identified the importance of the various VCE features, it was then decided (in 1979) to try to identify the high payoff technology items between a current technology (1980) and a far term (late 1980's) engine. It would then be possible to recommend the highest priority items to pursue. This was done by taking a current technology engine (designated the V85) and adding new technology in a cumulative manner. Some technologies cannot be added until another has been added first. The results of this study are shown in Fig. 45. The highest payoff by far is for advances in the hot section which if you accumulate the changes for thermal barrier coatings, advanced technology turbines (including reduced cooling), and high turbine inlet temperature account for 11 percent of the 16 percent improvement.

In 1981, GE was asked to look at the sensitivity of the advanced technology DBE to turbine inlet temperature. The cycle parameters were to be reoptimized as temperature changed (bypass ratio, fan pressure ratio, and overall pressure ratio). The results of this study are shown in Fig. 46. Since the cooling requirements are being changed as the turbine temperature is changed, and the cycle parameters have been allowed to reoptimize, the results show that the advanced technology, not the actual temperature level is what is important.

As was the case with P&W, it was planned to have the three airframers look at the latest versions of the DBE and SBE when the SCR effort was terminated.

Results of the testbed program and subsequent analyses indicate that noise levels approaching FAR-36 stage 2 may be attainable by unsuppressed variable cycle engine. However, to achieve noise levels comparable to Stage 3, suppression will be required. Revived interest in high specific thrust engines, such as the Turbine Bypass Engine also necessitates the development of new noise reduction concepts. Several concepts have been proposed, and four of the most promising, currently under investigation, are discussed below.

Later Years Noise Work

Outer Stream Suppressor With Lined Ejector

Model-scale (outer stream suppressor) simulated flight experiments have shown that noise levels on the order of 4 PNdB below the unsuppressed coannular nozzle can be achieved. Furthermore, some of the more recent studies have shown reasonable thrust losses for such devices. The addition of an acoustically-treated ejector (Fig. 47(a) could provide still further noise reductions. The evolution of noise reduction concepts for dual stream nozzles is illustrated in Fig. 47(b). Relative to a reference mixed-flow conical nozzle baseline, the unsuppressed coannular nozzle reduces noise primarily in the middle frequency range. An outer stream suppressor can provide additional noise reduction, mainly by reducing the low frequency noise. The remaining high-frequency noise, from mixing of the individual suppressor element jets, can be reduced with a lined ejector. Aerodynamic and acoustic studies of such concepts at model-scale have been initiated; in addition to ejector lining, acoustic treatment of the plug will be investigated. Addition noise reductions of about 4 PNdB are expected.

Thermal Acoustic Shield

Another concept for reducing high-frequency noise is the thermal acoustic shield, illustrated in Fig. 48(a). The relatively low-velocity, high-temperature, partial annular shielding stream reduces the noise on the shielding side (toward the observer) both by reducing the shear on that side and by redirecting the noise that is generated away from the observer. Typical noise spectra for a subsonic primary jet at three angles $\theta = 45°$ (forward quadrant), $\theta = 90°$ (overhead), and $\theta = 135°$ (aft quadrant) are shown in Fig. 48(b). It can be seen that the partial shield provides high frequency noise reduction at all angles, but the effect is most pronounced in the aft quadrant ($\theta = 135°$). Since it is in the aft quadrant where jet noise peaks, significant peak perceived noise level (PNL) reductions should result. Perceived noise level directivities, scaled up to a nominally full-size engine, for these same conditions, indicate that shielding benefits can be observed at all angles, and the reduction in peak PNL is about 4 PNdB. these promising results indicate that the thermal acoustic shield should be further investigated since the present study was exploratory and the geometry by no means optimized. Lewis has initiated a model-scale contract study by General Electric (with Boeing as subcontractor) of the thermal acoustic shield integrated with several basic nozzle types:

(a) Annular plug (single stream)
(b) Annular plug with suppressor elements
(c) Coannular (dual stream) unsuppressed
(d) Coannular with outer stream suppressor

Convergent-Divergent Nozzle Terminations

Convergent-divergent terminations have been shown to reduce the shock noise of single-stream circular nozzles. Lewis currently is sponsoring tests at GE to determine whether convergent-divergent terminations can be used to reduce the shock noise of single-stream annular plug and suppressor nozzles. This study has been extended to include dual-stream suppressed and unsuppressed configurations (Fig. 49). For unsuppressed nozzles, reducing the shock noise would not significantly reduce the peak noise, but could reduce the EPNL by as much as 2 EPNdB. With suppressors, it is possible that even the peak noise may be reduced.

Vented Plug Nozzle

Another concept which appears attractive for high-specific-thrust engines is the annular plug nozzle with the plug ventilated by ambient air, thereby producing an inverted-velocity-profile coannular nozzle. Boeing has obtained some promising results by simulating the ambient inner flow for this arrangement, termed "Naturally Aspirated Coannular Nozzle" by Boeing. The implementation and a prediction of the potential for this type of concept is illustrated in Fig. 50(a). As the inner (aspirated ambient) flow is increased, the peak noise level is reduced until an essentially asymptotic level is reached. Noise reduction is obtained at middle and high frequency as shown in Fig. 50(b) for conditions near the knee of the PNL reduction versus mass flow ratio curve. The main technical concern with this concept is the ability to obtain sufficient inner mass flow with reasonable performance. A contract has been awarded to Boeing to conduct the needed aerodynamic design and wind-tunnel performance studies.

What Was Accomplished

As was mentioned at the beginning of this paper, the goal of the SCR program was to identify and investigate areas requiring new and/or improved technology that would lead to a second generation supersonic aircraft that was economically viable and environmentally acceptable. A comparison of the noise of this second generation SST to the 1971 SST is shown in Fig. 5. As can be seen, the noise level achievable is over 10 EPNdb quieter and the gross weight has decreased by about 15 percent. The aircraft in fact would be quieter than the vast majority of the subsonic aircraft in operation today.

The key elements in achieving this improved performance in terms of noise were identified as the inverted velocity profile nozzle, light weight efficient (low thrust loss) suppressors, acoustically treated ejectors, and the thermal shield.

A key element identified for improved performance was a low-emissions staged duct burner with excellent combustion and thrust efficiency. It also demonstrated a soft light capability and did not produce screech. Another significant achievement was the forward VABI concept which allowed two bypass streams to be combined. In conjunction with the rear VABI, this combined flow could then be combined with the turbine discharge flow into a single exhaust stream for efficient cruise performance. This greatly simplifies the nozzle requirements and leads to a simple light-weight nozzle for a three flow stream engine.

The variable cycle engine concepts in addition to offering reduced noise showed additional advantages in enhanced airflow extension. This greater airflow capability leads to a reduction in throttle-dependent installation drag at part-throttle subsonic cruise conditions.

Each of the engine companies covered in great detail the advanced technology requirements that they incorporated in their engines. To go into these, component by component, is beyond the scope of this paper. The reader is referred to Refs. 1 and 2 for these details.

In addition, other work in connection with the SCR propulsion program such as on inlets, Boron-Aluminum fan blades, and the supersonic through-flow fan has also not been included in this paper.

The Langley Research Center has published two bibliographies[3,4] of all of The Contractor Final Reports, NASA reports, and society papers and journal articles concerning the SCR program through 1980 (415 in all). It is not known at this time whether another bibliography covering the reports since 1980 will be published.

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2. Hunt, R. B., Owens, R., Carmichael, R., and Stern, A., "Noise and Economic Study for Supersonic Cruise Airplane Research - Phase II - Final Report," United Technologies Corporation, Pratt & Whitney Aircraft Group, Commercial Products Division, East Hartford, CT, PWA-5701-30, 1982. (NASA CR-165613).

3. Hoffman, S., "Bibliography of Supersonic Cruise Aircraft Research (SCAR)," NASA RP-1003, 1977.

4. Hoffman, S., "Bibliography of Supersonic Cruise Research (SCR) Program from 1977 to Mid-1980," NASA RP-1063, 1980.

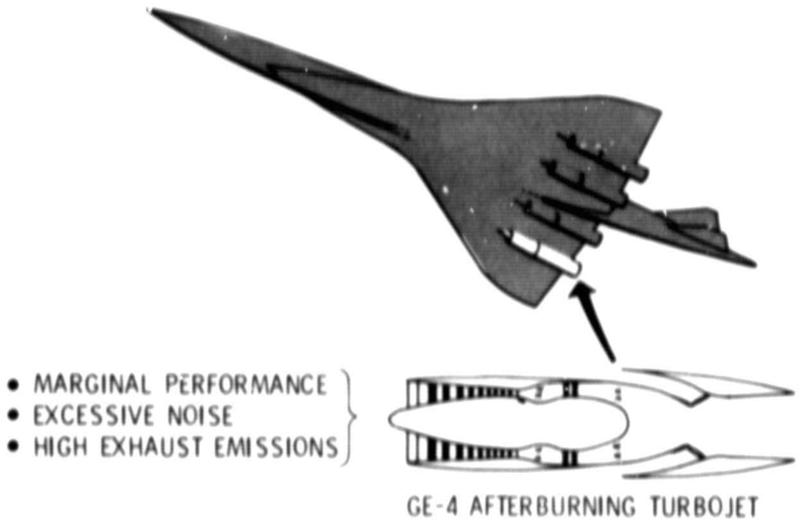


Figure 1. - 1971 propulsion status - U. S. SST.

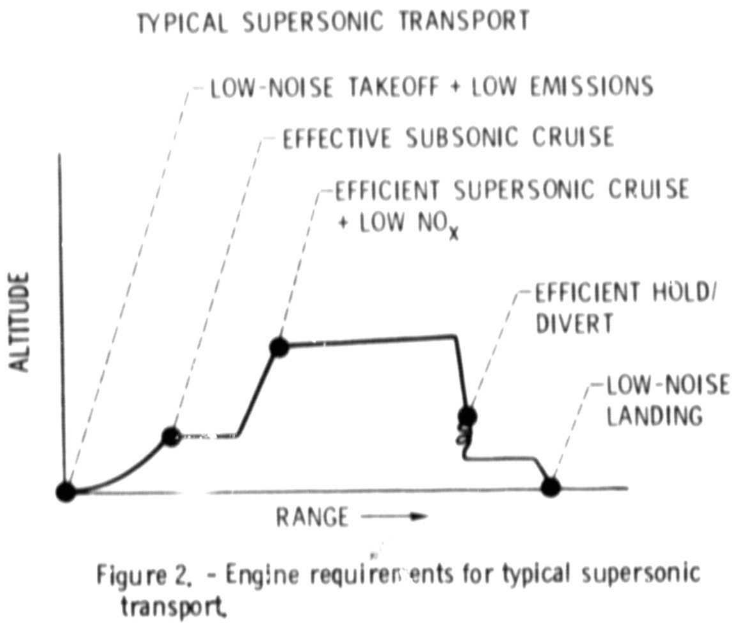


Figure 2. - Engine requirements for typical supersonic transport.

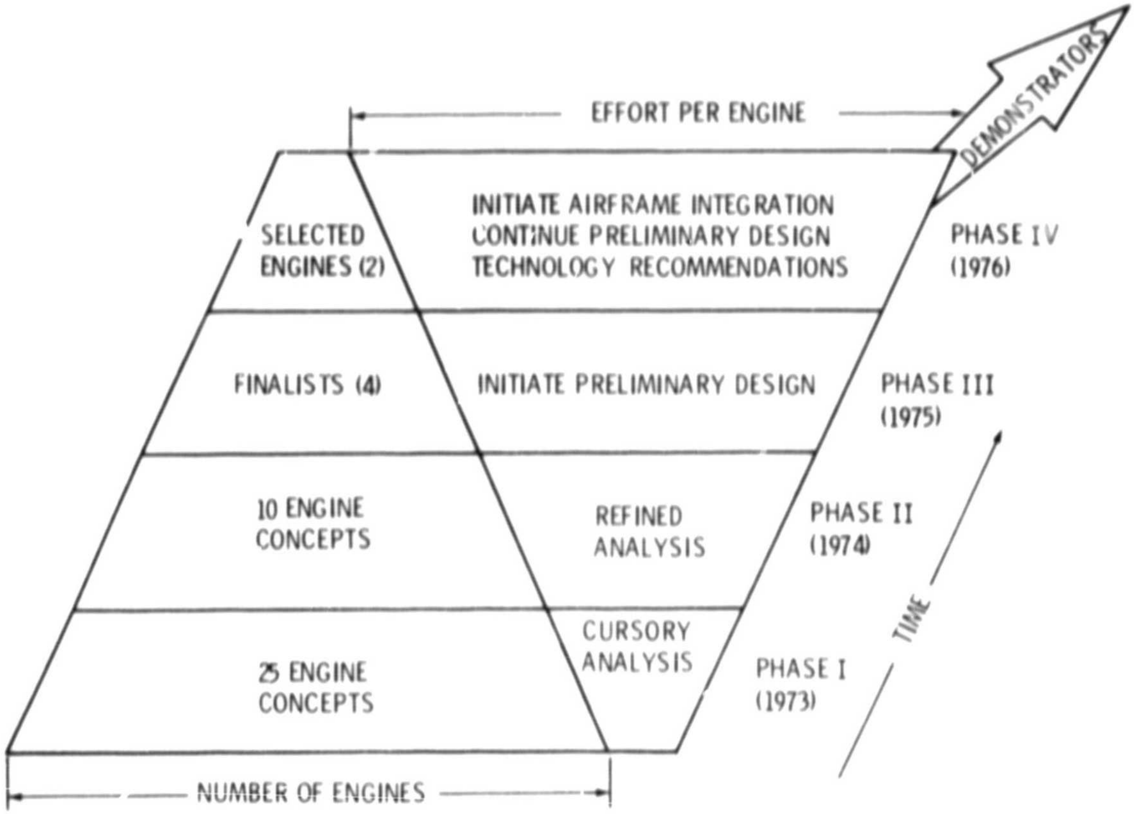


Figure 3. - Evolution of SCAR engine studies.

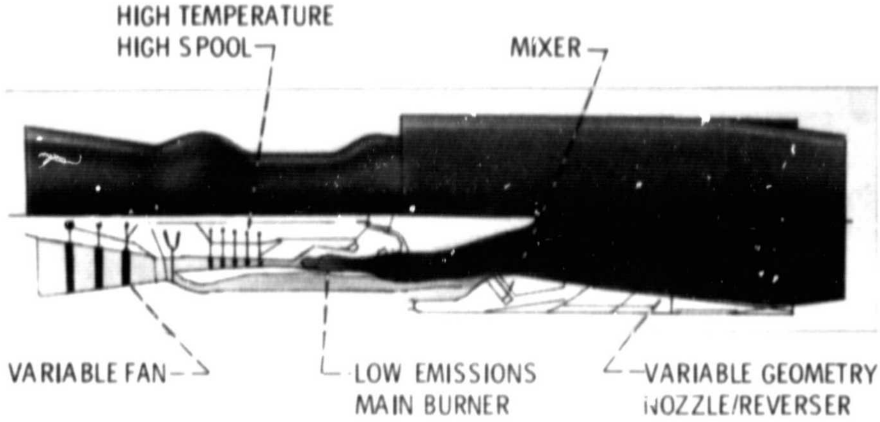
ENGINE STUDIES

- P&W CONTRACTS
- G. E. CONTRACTS
- P&W/BOEING SUBCONTRACT

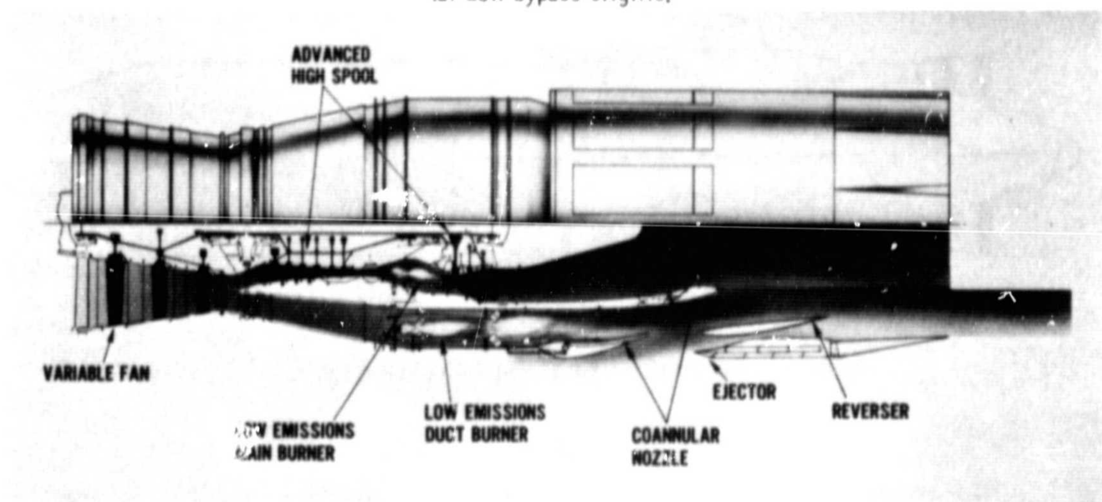
TECHNOLOGY SUBPROGRAMS

- NOISE REDUCTION
- POLLUTION REDUCTION
- INLET STABILITY
- MATERIALS

Figure 4. - The SCAR propulsion program.

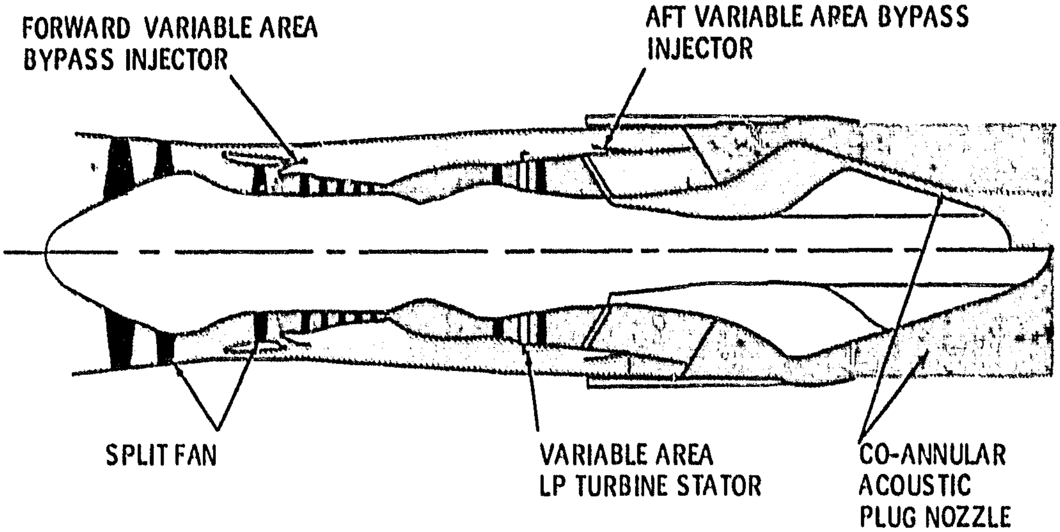


(a) Low bypass engine.

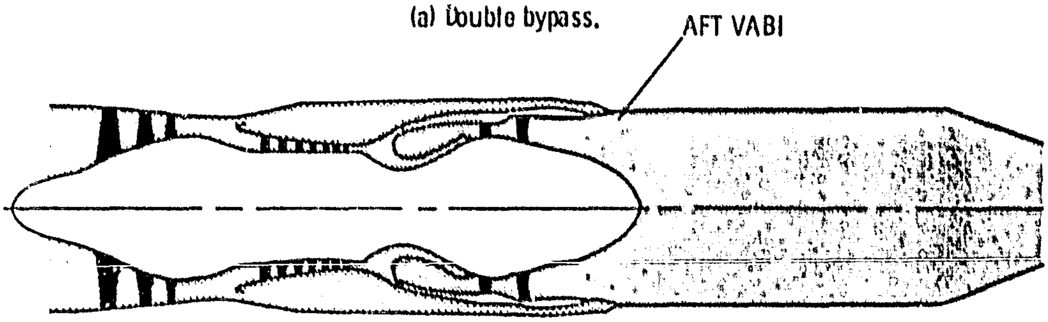


(b) Variable stream control engine.

Figure 5. - Pratt and Whitney variable cycle engines.



(a) Double bypass.



(b) Single bypass.

Figure 6. - General Electric variable cycle engines.

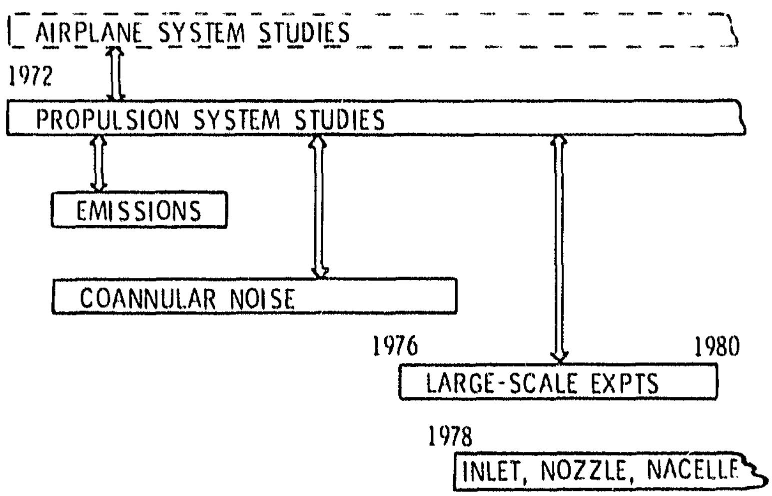


Figure 7. - SCR propulsion program.

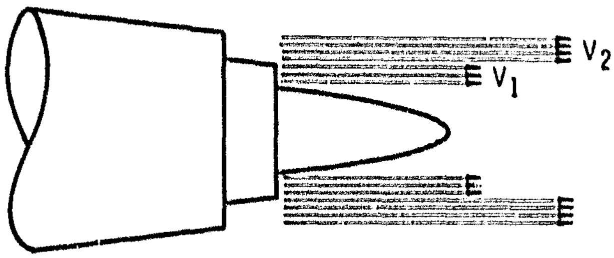
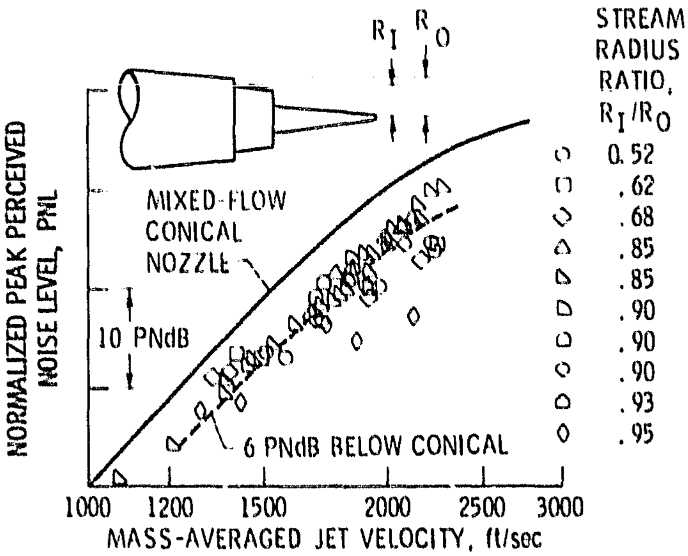
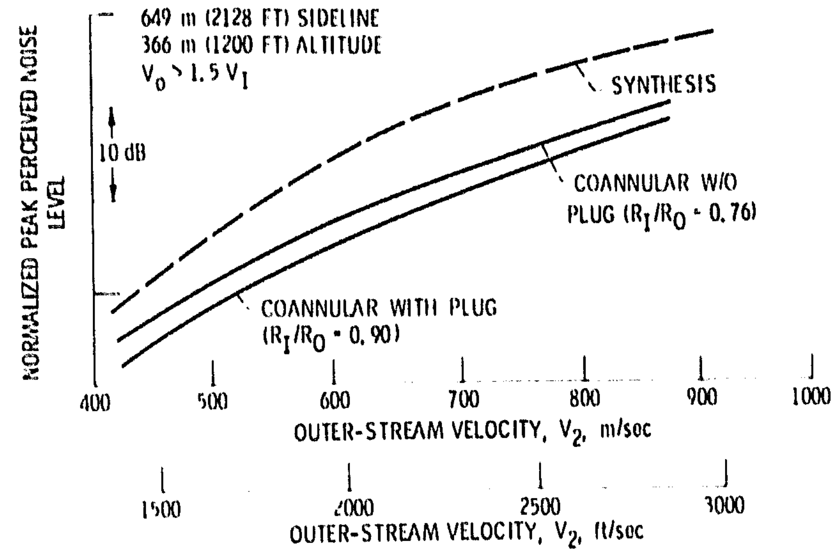


Figure 8. - Flow schematic of inverted-velocity-profile coannular jets.



(a) Mixed-flow (mass-averaged) comparisons.

Figure 9. - Comparison of normalized peak perceived noise level for IVP coannular nozzles with conical reference nozzle as a function of characteristic jet velocity.



(b) "Synthesized" comparisons.

Figure 9. - Concluded.

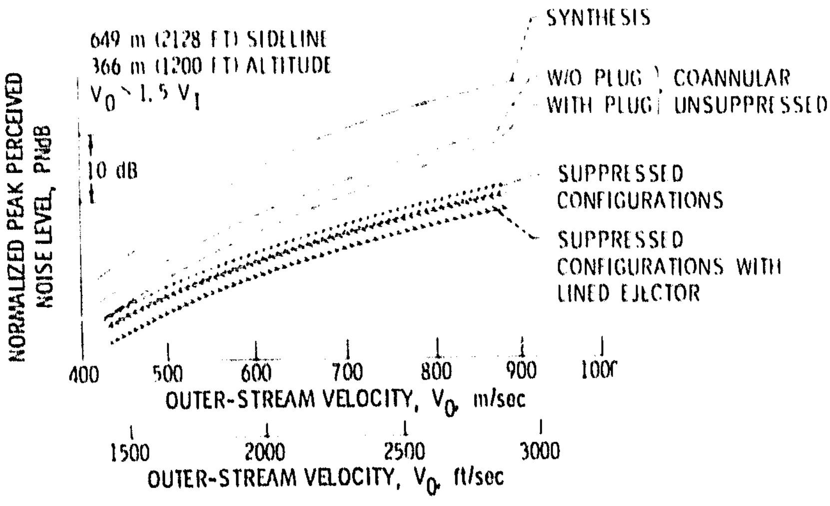


Figure 10. - Peak noise level as function of outer-stream velocity for typical inverted-velocity-profile coannular nozzles. Sideline distance, 649 m (2128 ft); altitude, 366 m (1200 ft); $V_0 \geq 1.5 V_I$.

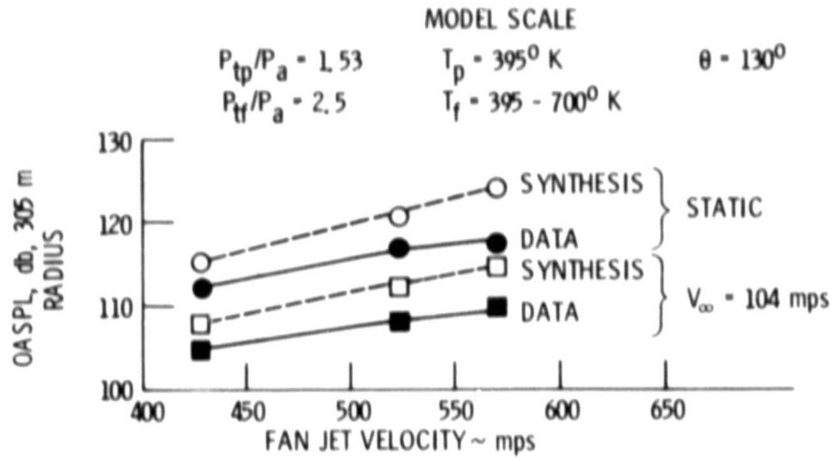


Figure 11. - Effect of take-off speed on OASPL of coannular nozzle.

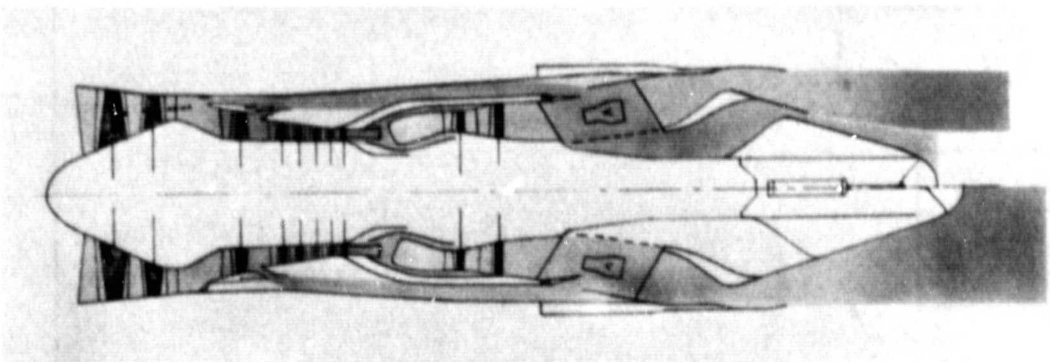


Figure 12. - Double bypass engine.

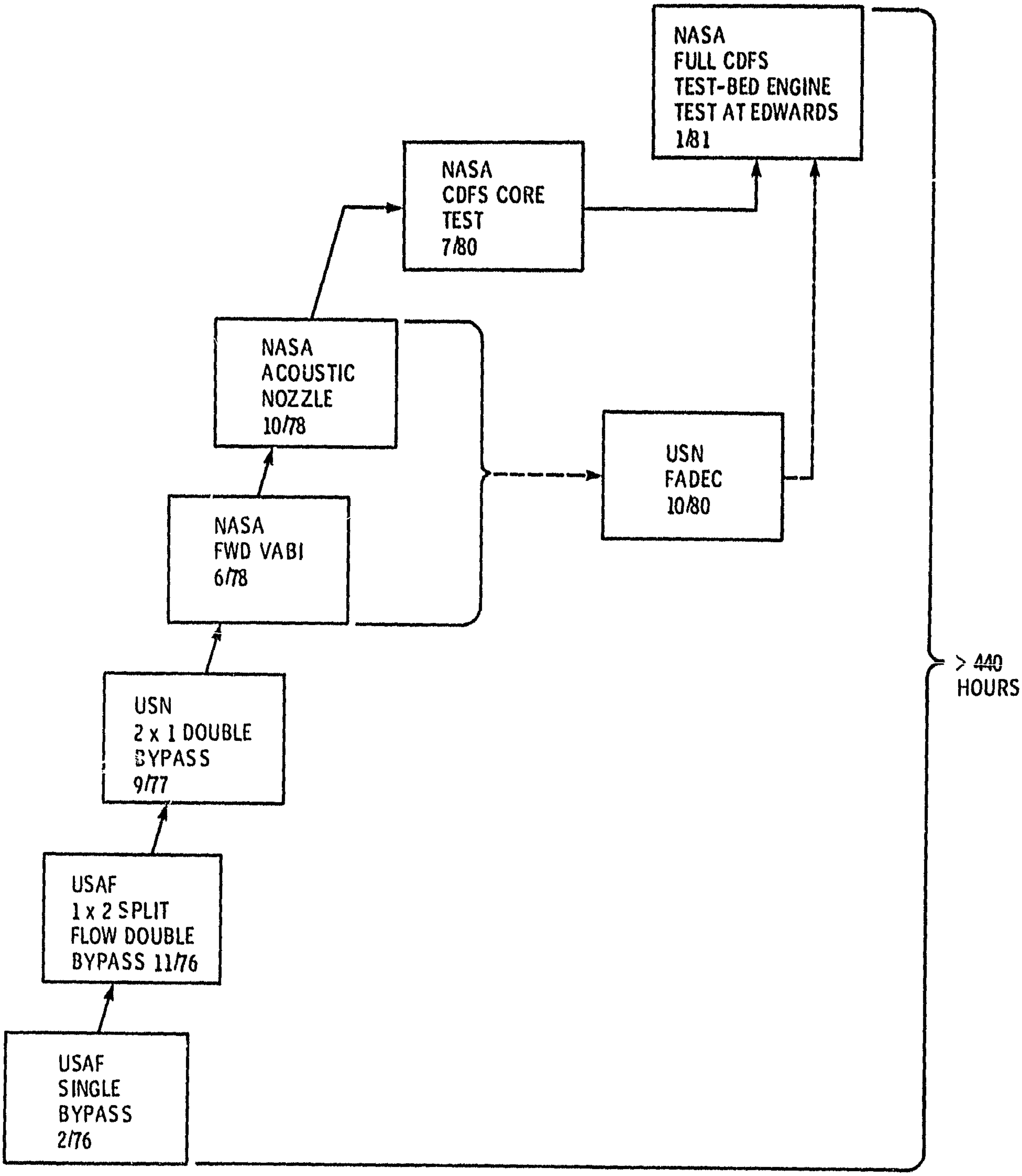


Figure 13. - YJ101 VCE concept demonstrators.

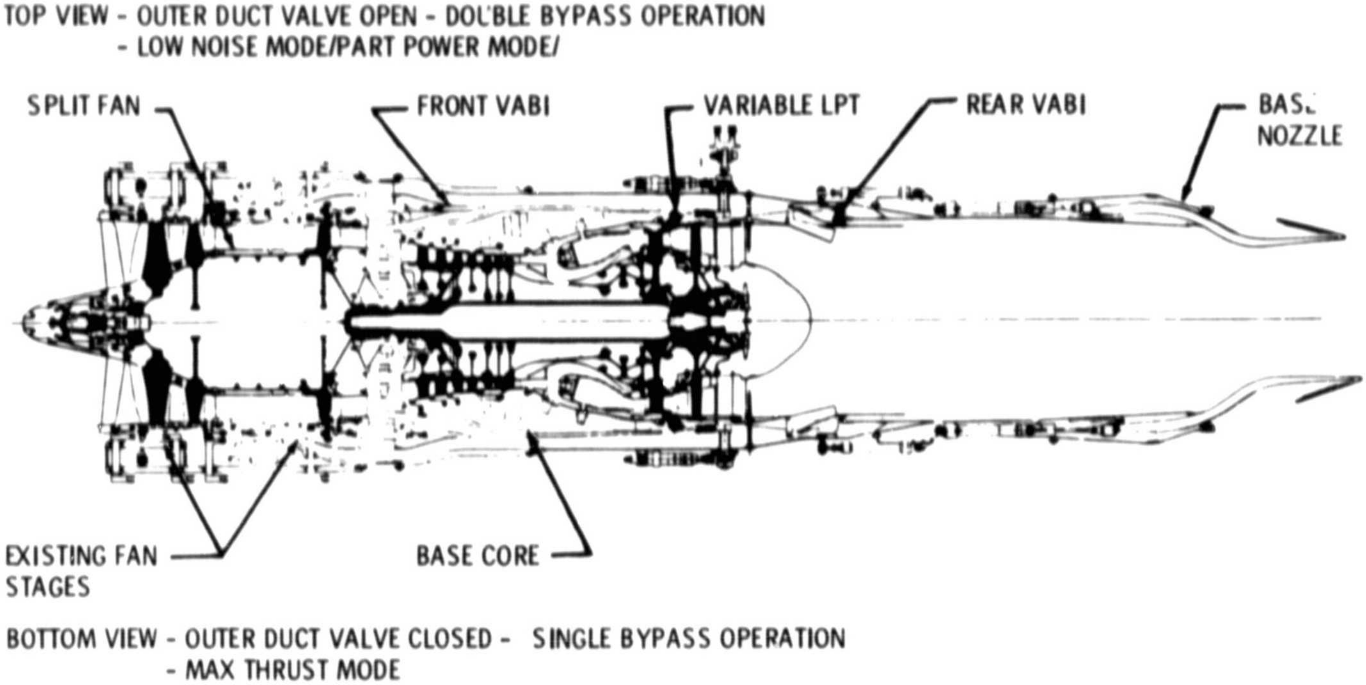


Figure 14. - NASA forward VABI test demo.

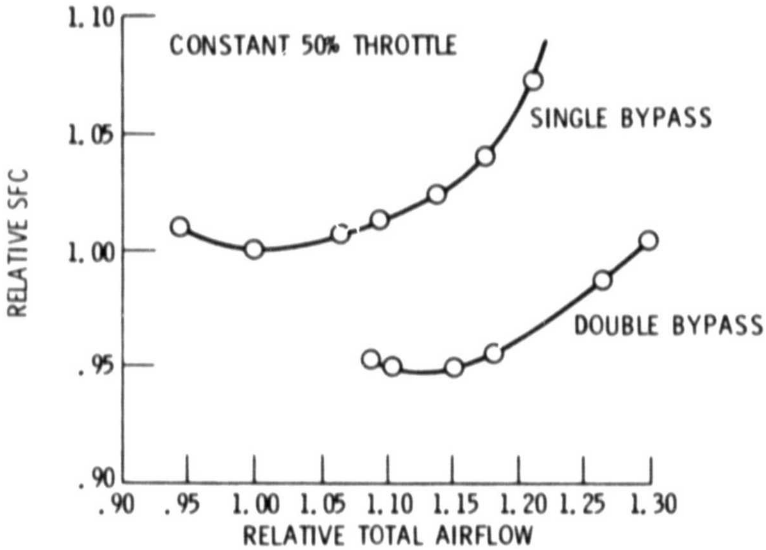


Figure 15. - Forward VABI testbed engine performance data.

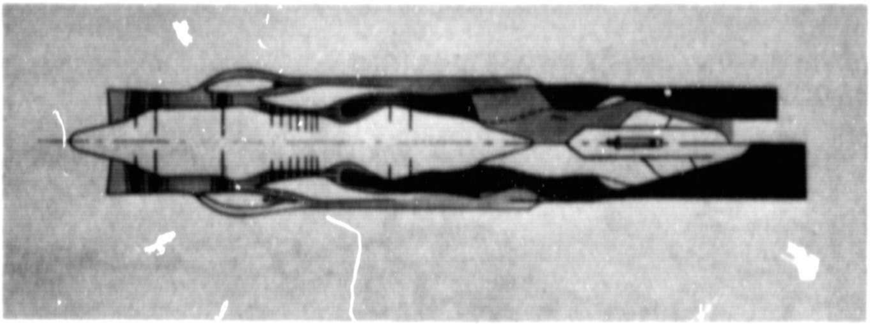


Figure 16. - YJ101 early acoustic testbed engine.

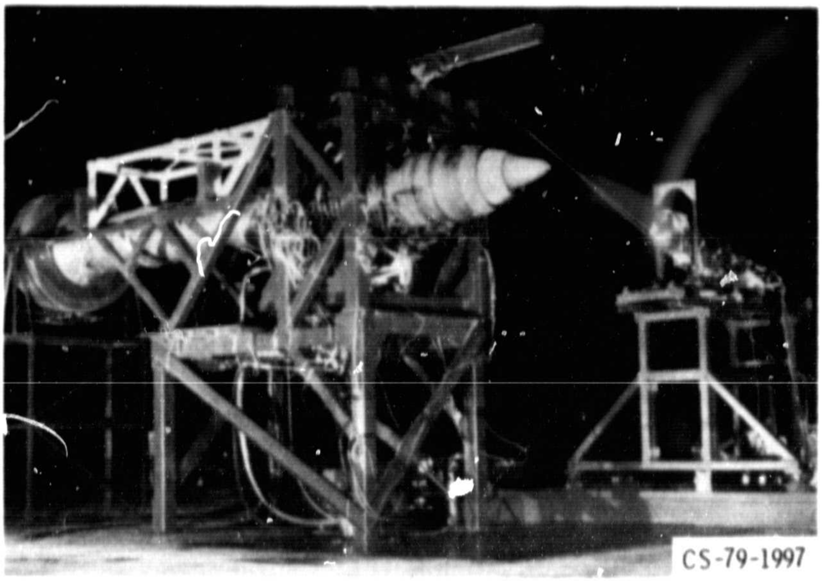


Figure 17. - Coannular noise test of GE engine.

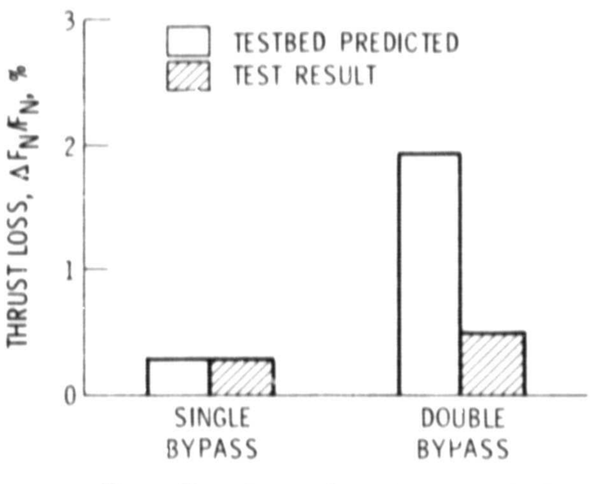


Figure 18. - Coannular noise test of G. E. engine.

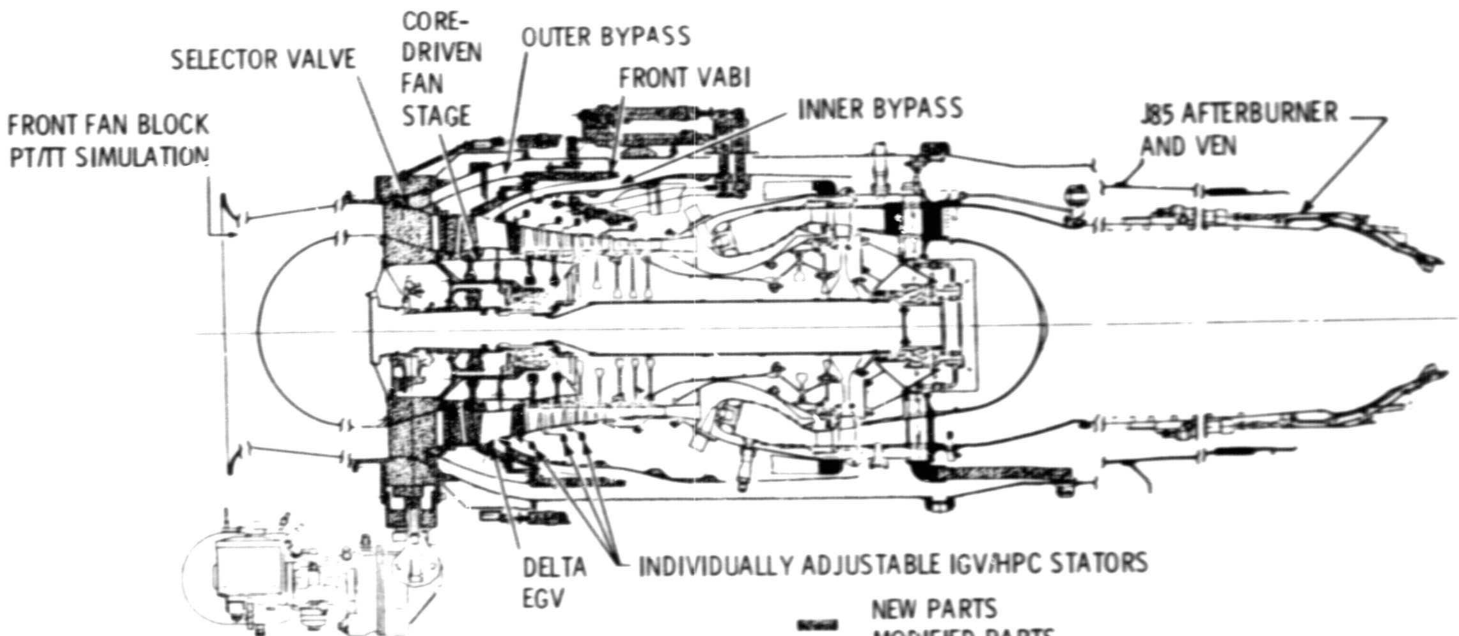


Figure 19. - Core test configuration - VCE test bed engine.

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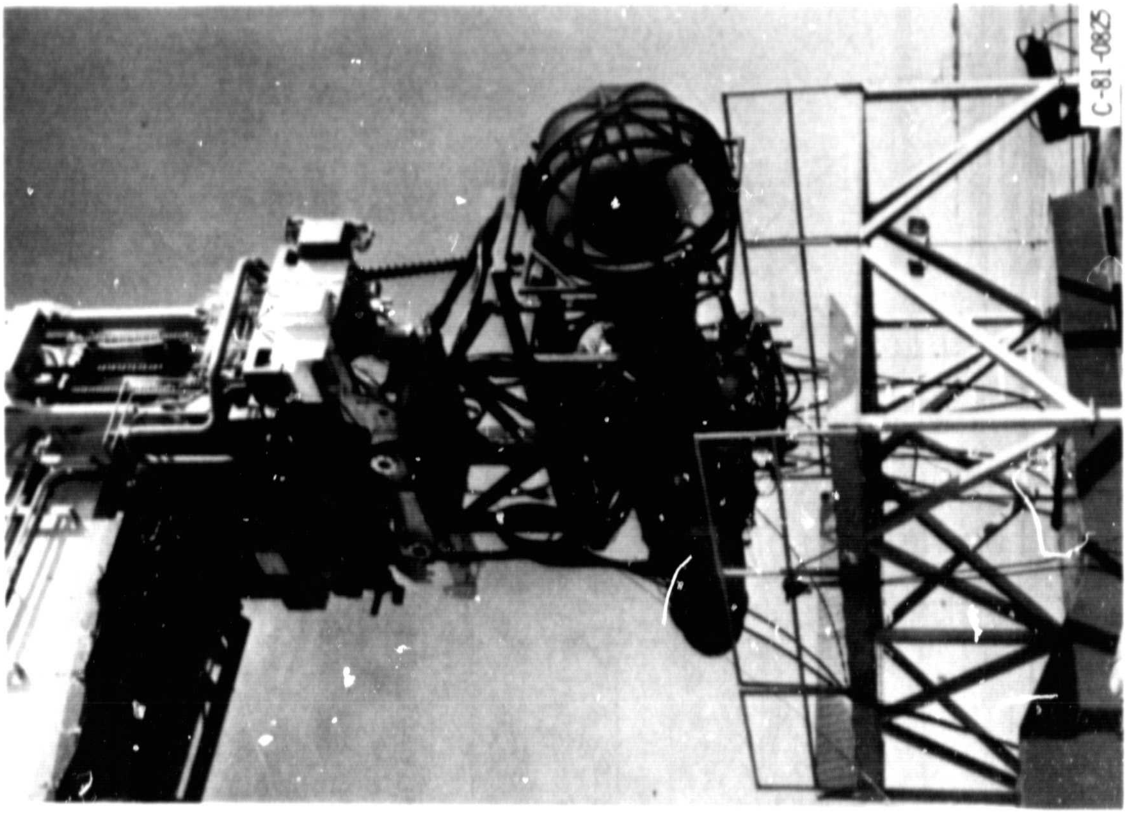

Figure 21. - Full engine performance test at Edwards AFC.

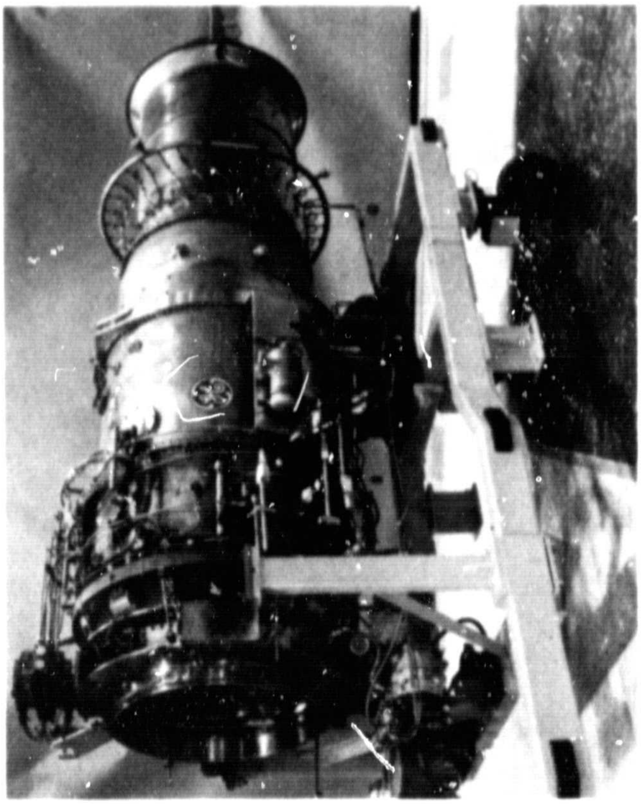

Figure 20. - Core test vehicle in GE ram test facility.

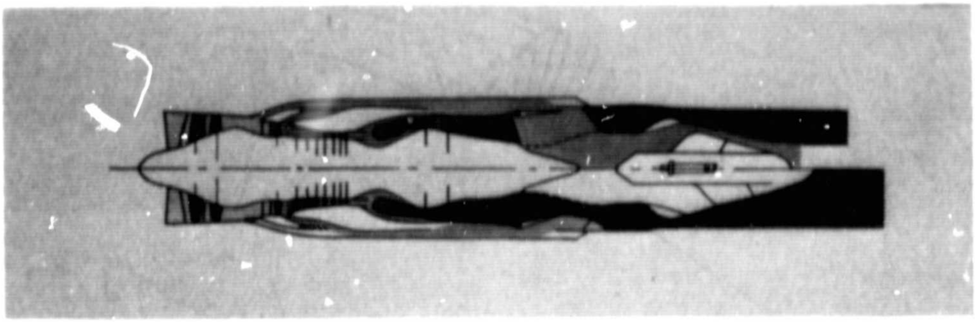

Figure 22. - YJ101/core-driven testbed engine.

DOUBLE BYPASS OPERATION IMPROVES AIRFLOW AND SFC TO PROVIDE BETTER INLET/ENGINE/EXHAUST SYSTEM MATCH FOR MINIMUM SUBSONIC FUEL BURN

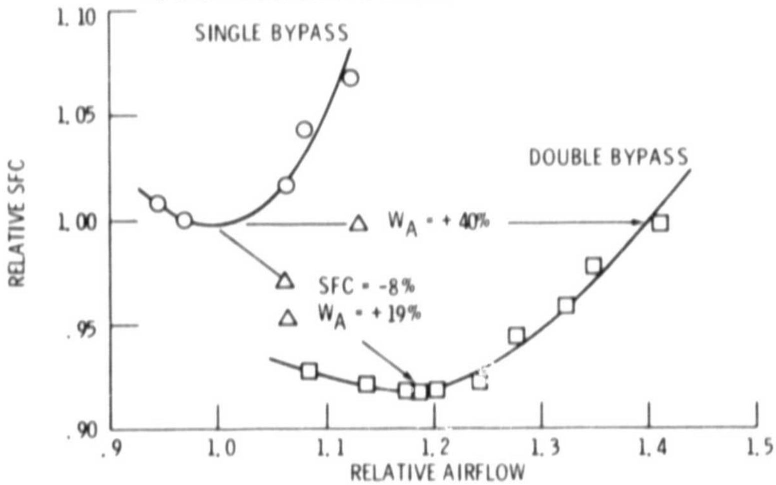

Figure 23. - GE YJ101/CDFS Edwards performance results at 50% thrust.

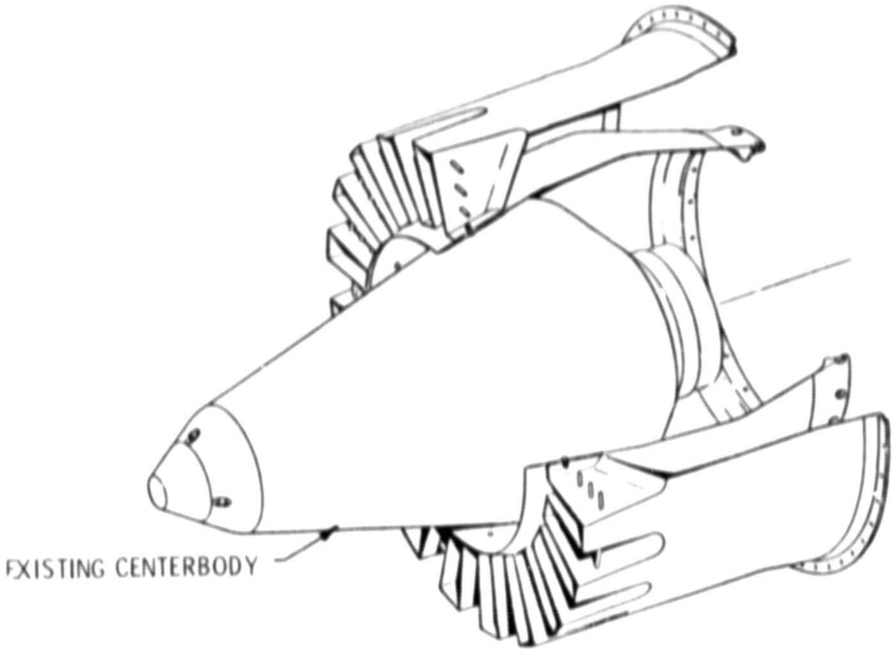

Figure 24. - Twenty-chute suppressor.

Figure 25. - Test bed engine with accelerating inlet and ejector shroud.

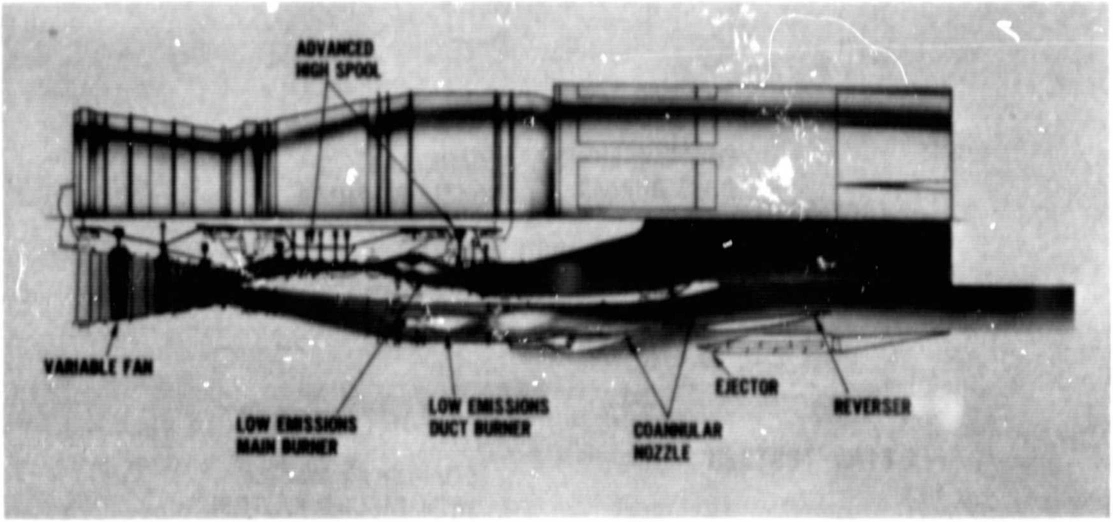

Figure 26. - Variable stream control engine.

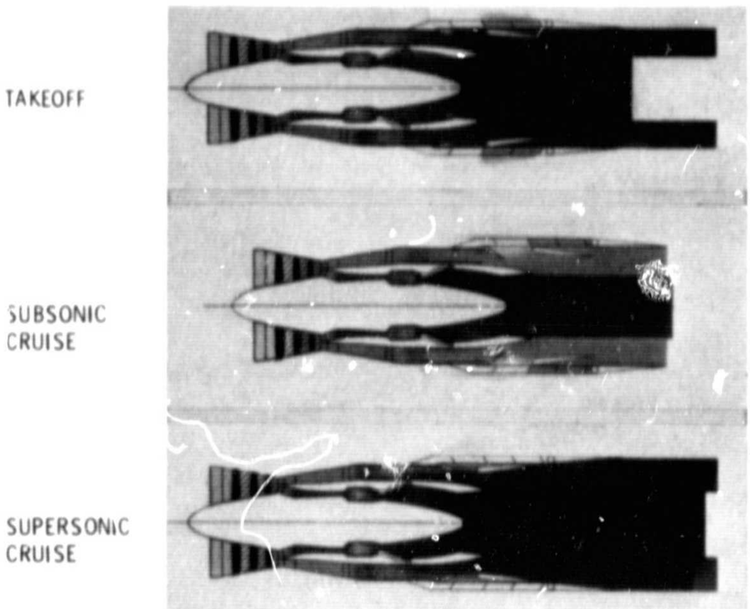

Figure 27. - Takeoff, subsonic cruise and supersonic cruise configurations for Pratt and Whitney variable stream control engine.

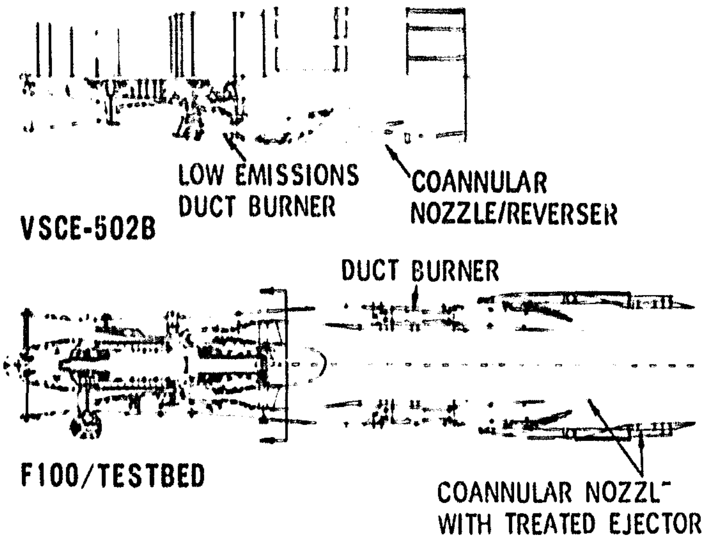

Figure 28. - Comparison of VSCE-502B ano .estbed configuration.

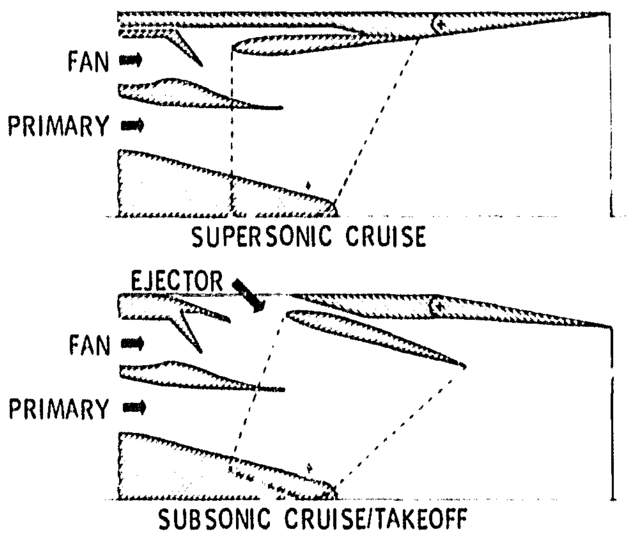

Figure 29. - VSCE - 502B ejector nozzle.

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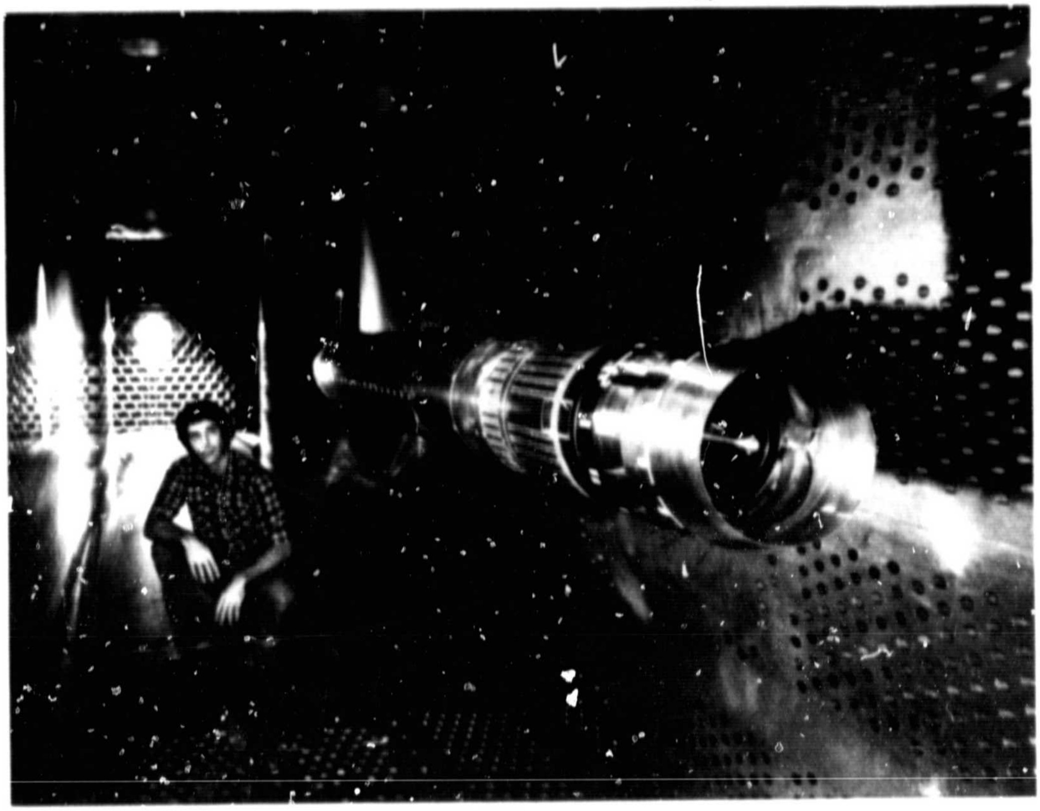

Figure 30. - VSCE-502B nozzle in 8'x6' supersonic wind tunnel.

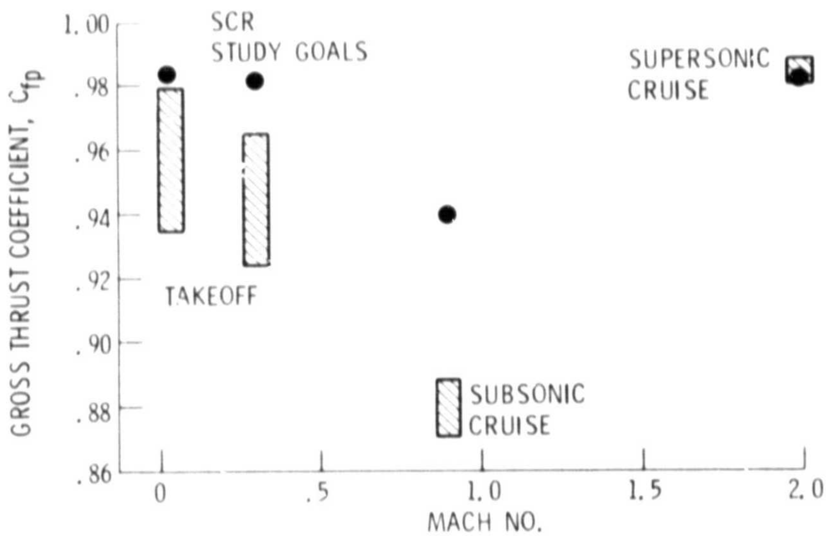

Figure 31. - Pratt and Whitney nozzle thrust performance.

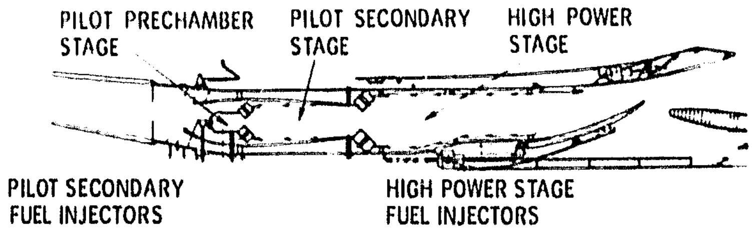

Figure 32. - Pratt and Whitney three-stage vorbix duct burner.

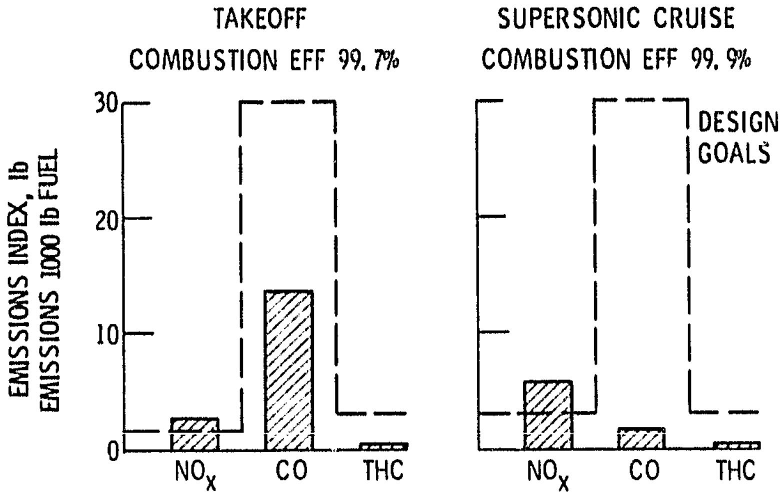

Figure 33. - Measured duct burner emissions.

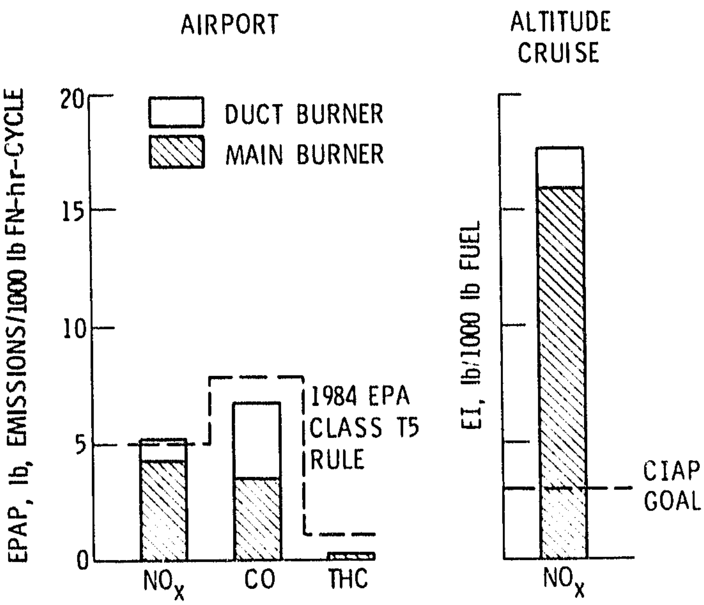

Figure 34. - VSCE-502B exhaust emissions estimates.

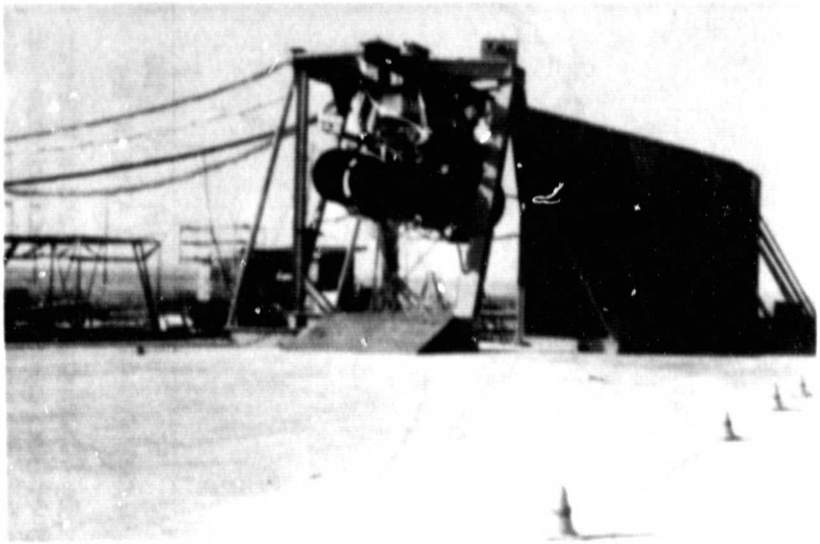

Figure 35. - VCE F100 testbed acoustic program with ejector installed at Boardman, Oregon.

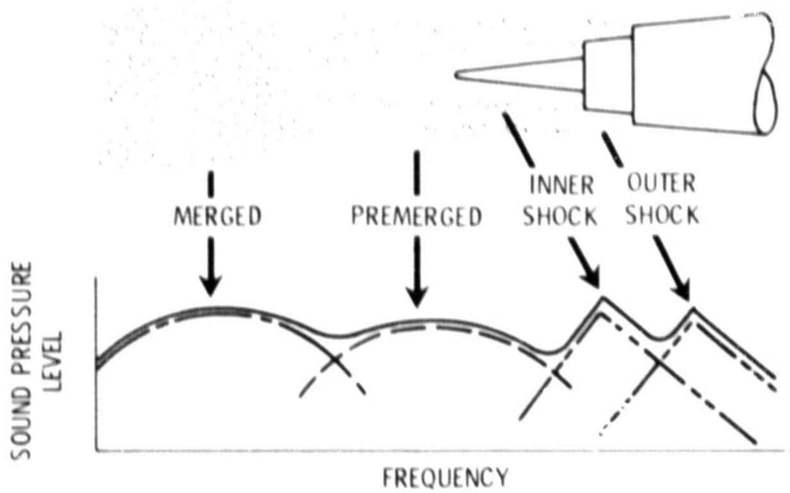

Figure 36. - Inverted-velocity-profile coannular nozzle jet noise sources.

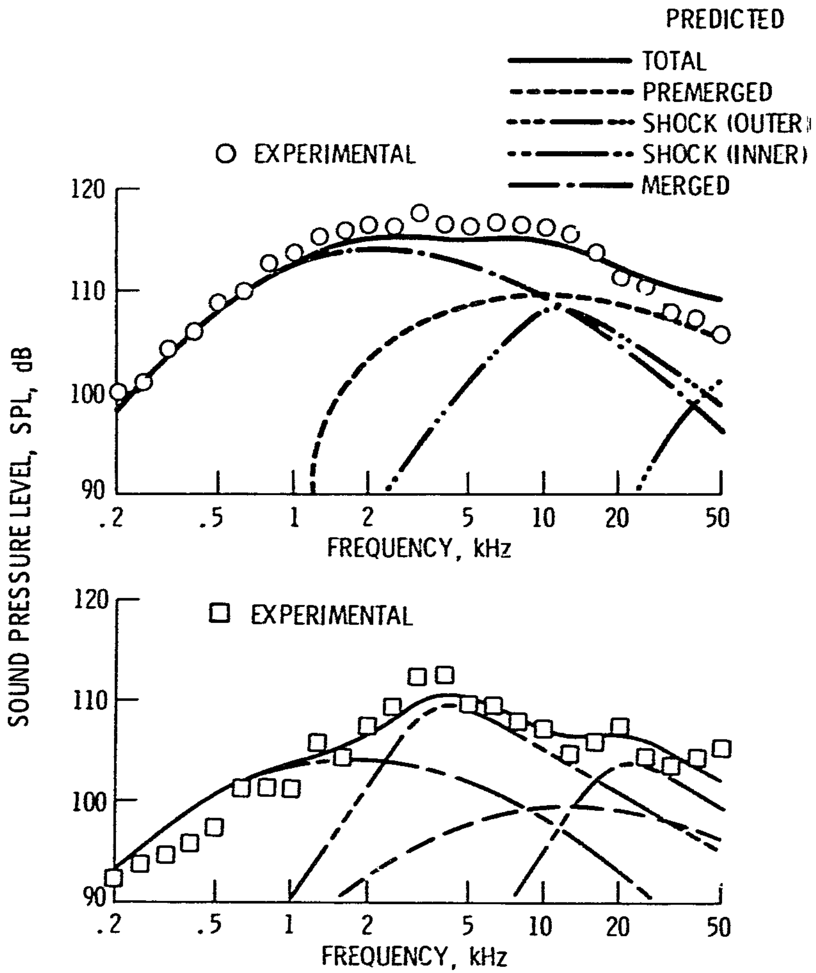

Figure 37. - Comparison of inverted-velocity-profile jet noise prediction with static model experimental data. Plugless co-annular nozzle; mixed-jet velocity, $V_{j,m}$, 652 m/sec; mixed-jet temperature, 922 K; both streams supersonic.

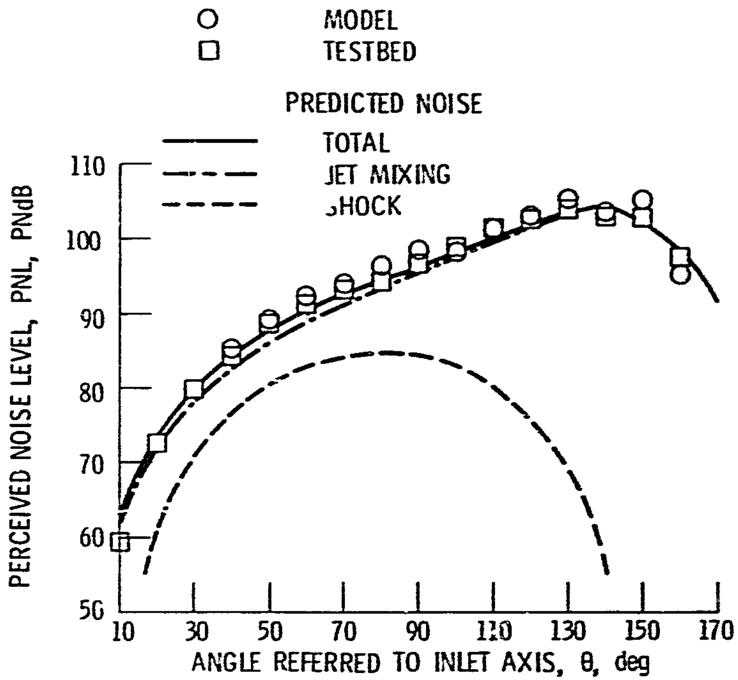

Figure 38. - Comparison of model and variable-cycle-engine-testbed experimental perceived-noise-level directivity with prediction at typical product-engine size (0.903-m^2 exhaust area) and at 731.5-m slant range. Mixed jet velocity, $V_{j,m}$, 590 m/sec; outer-stream radius ratio, R_I/R_O, 0.85.

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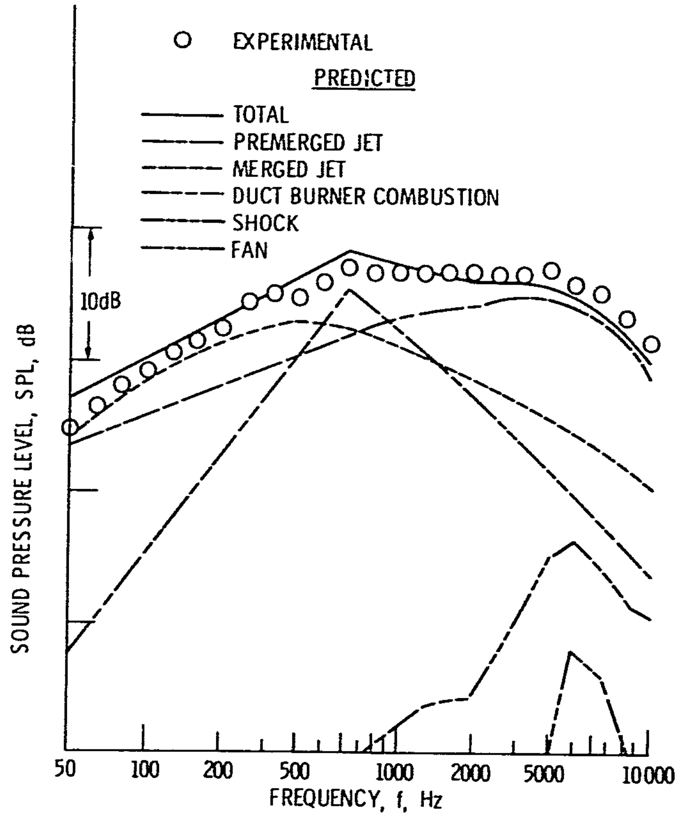
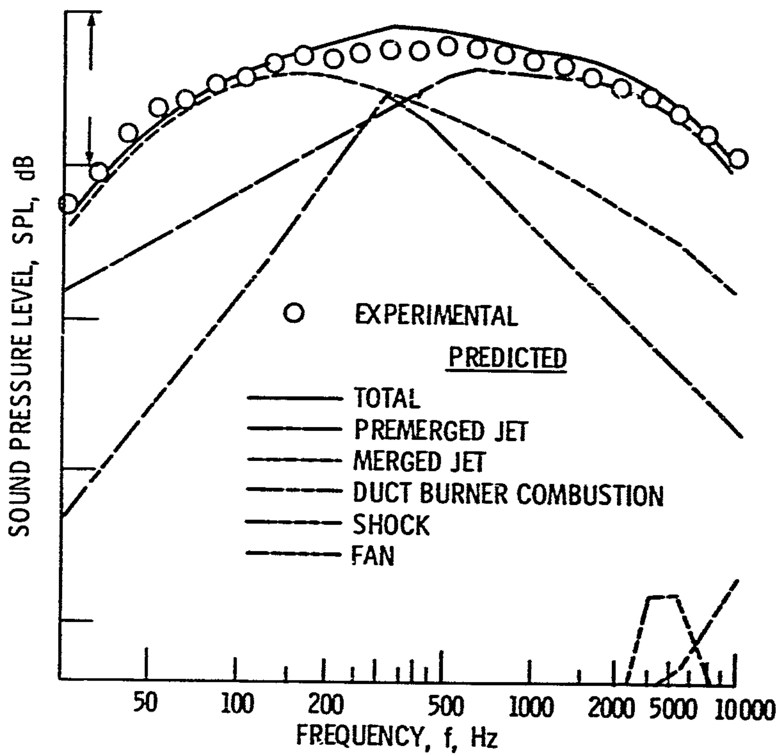


(a) Directivity angle, θ, 90°.

Figure 39. - Comparison of experimental spectra with prediction for NASA/P&W duct-burning turbofan testbed-(without ejector) at takeoff power.



(b) Directivity angle, θ, 120°

Figure 39. - Concluded.

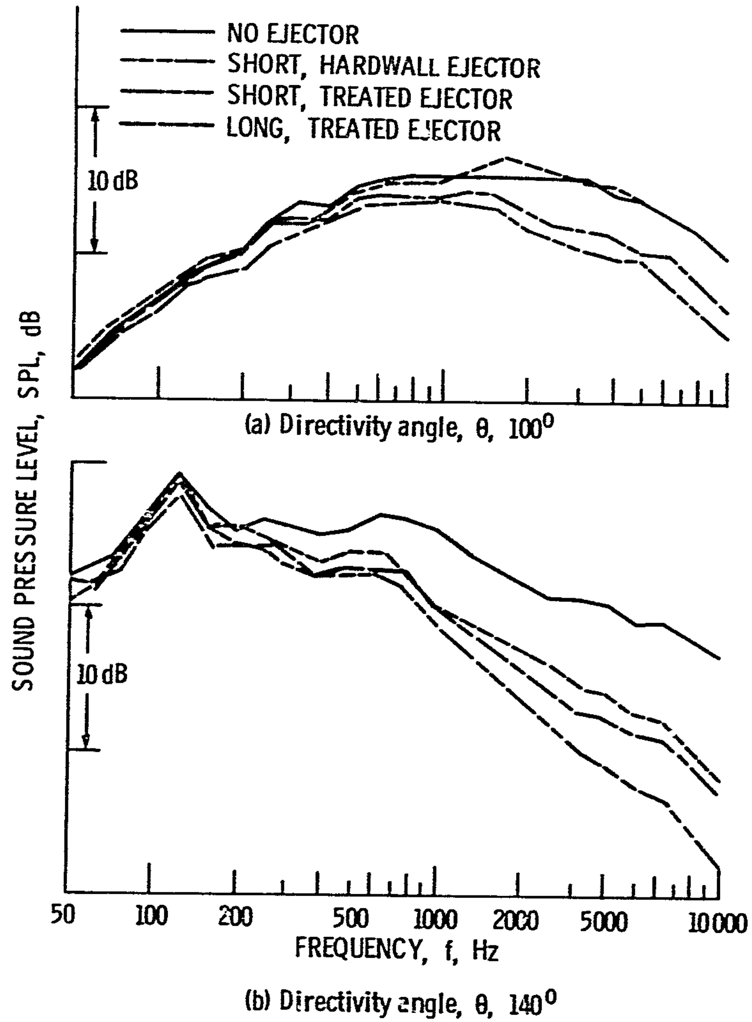


Figure 40. - Effect of ejector configuration on spectra for NASA/P&W duct-burning turbofan testbed at takeoff power.

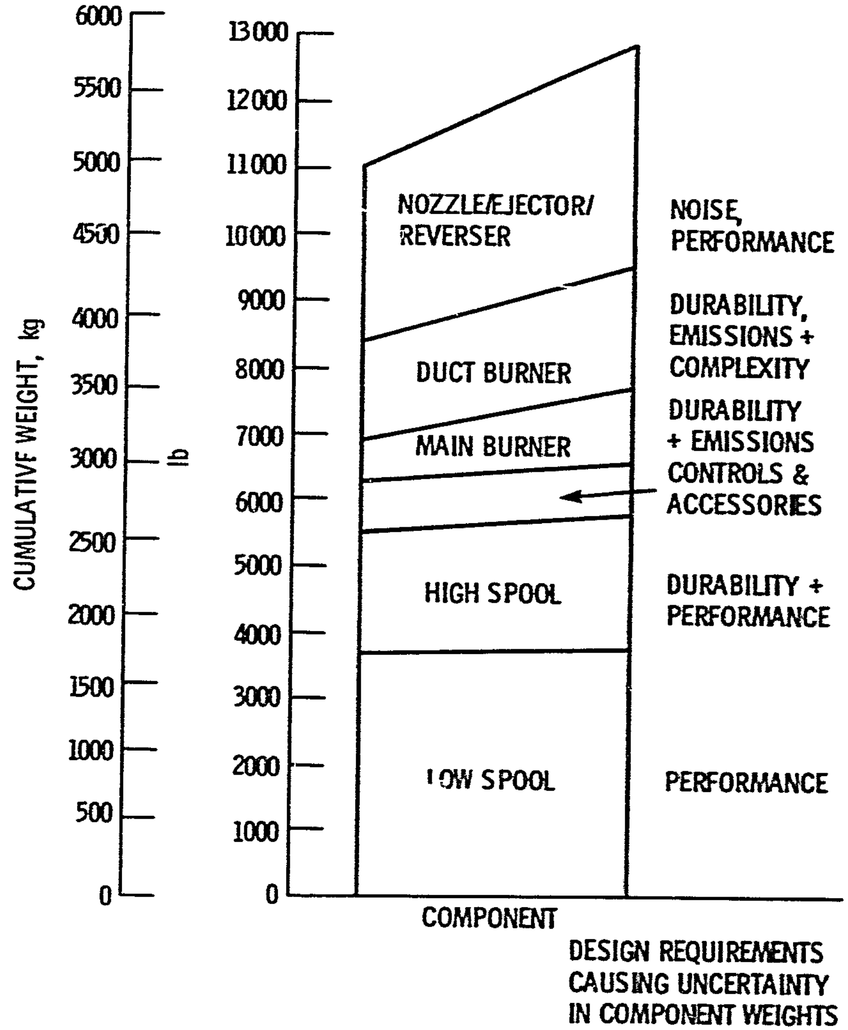


Figure 41. - VSCE-515 weight summary, engine size = 340 kg/sec (750 lb/sec) total airflow.

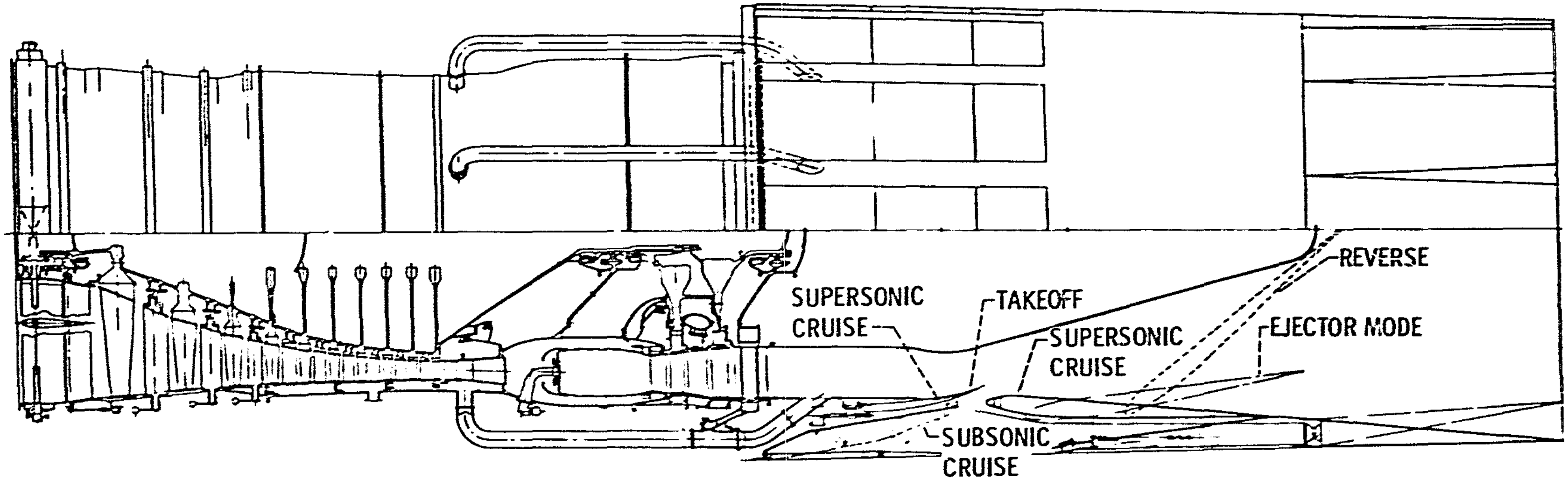


Figure 42. - Turbine bypass engine VCE-702.

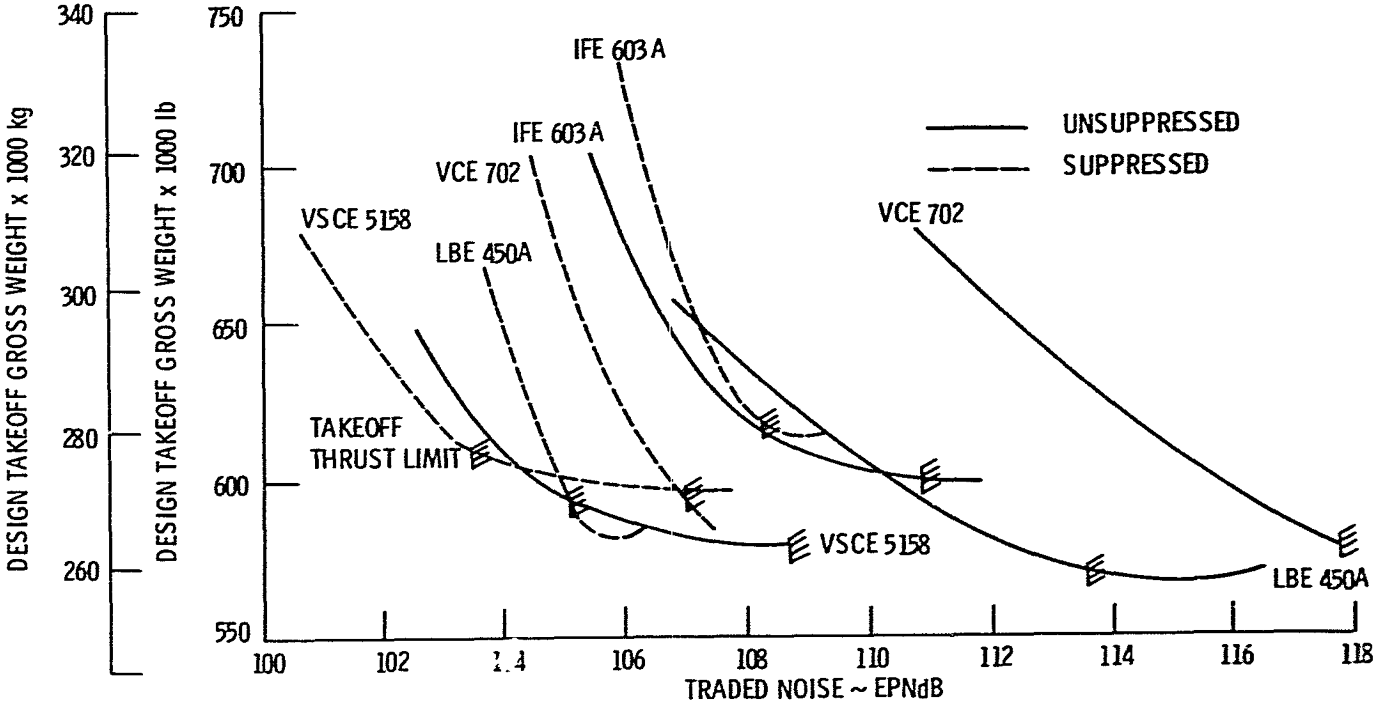


Figure 43. - Effect of traded takeoff noise level on takeoff gross weight for 0.275 thrust-to-weight ratio.

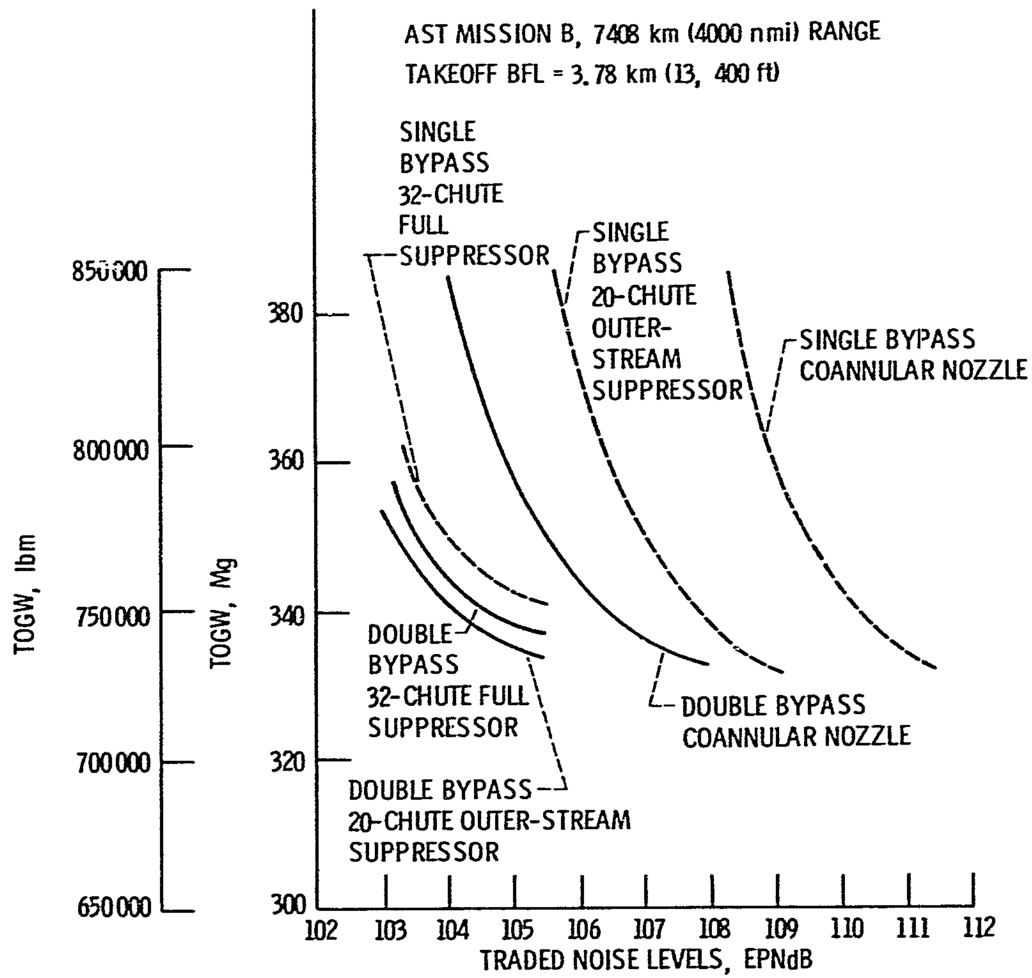


Figure 44. - General Electric Company engines - takeoff gross weight (TOGW) as function of noise level.

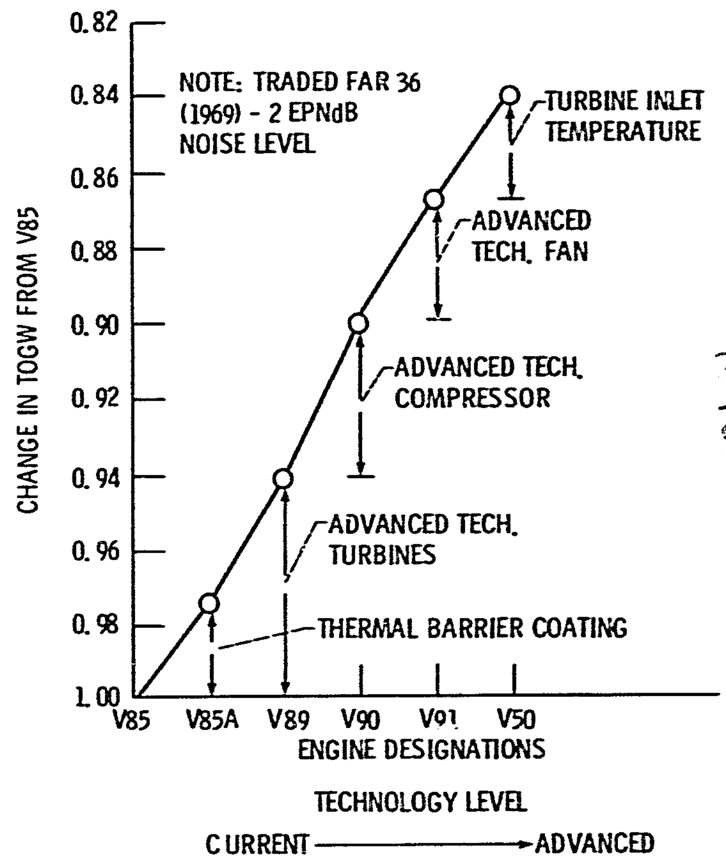


Figure 45. - Change in TOGW for changes in component technology.

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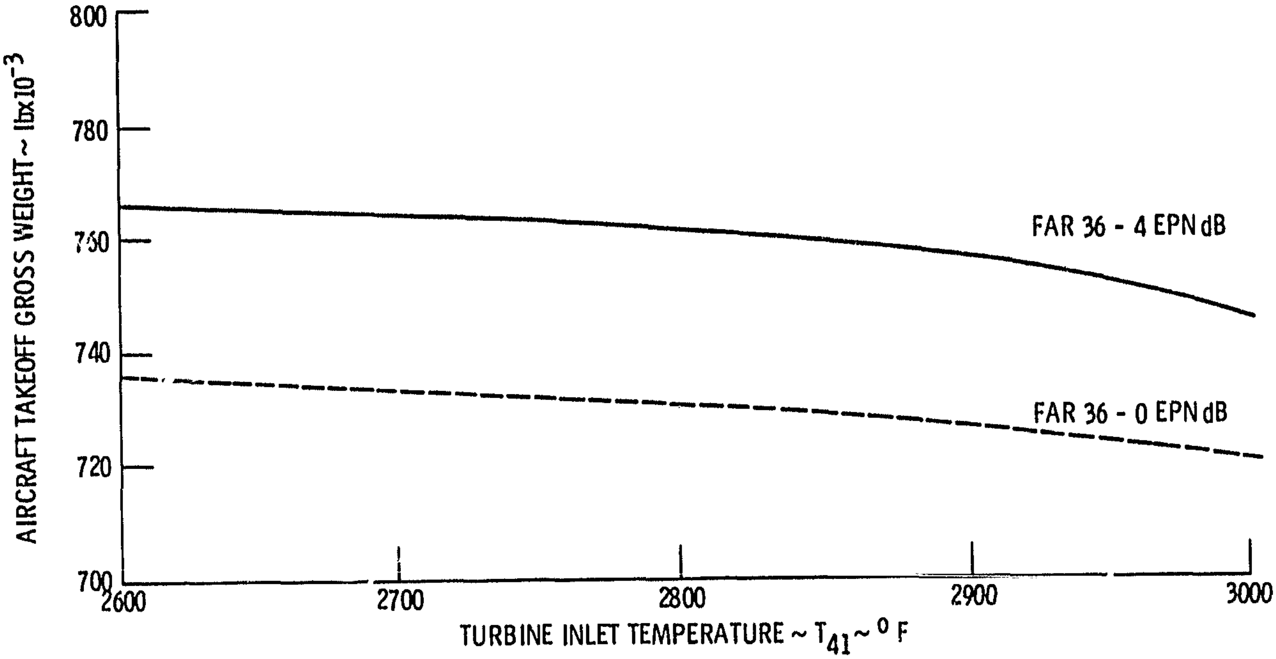
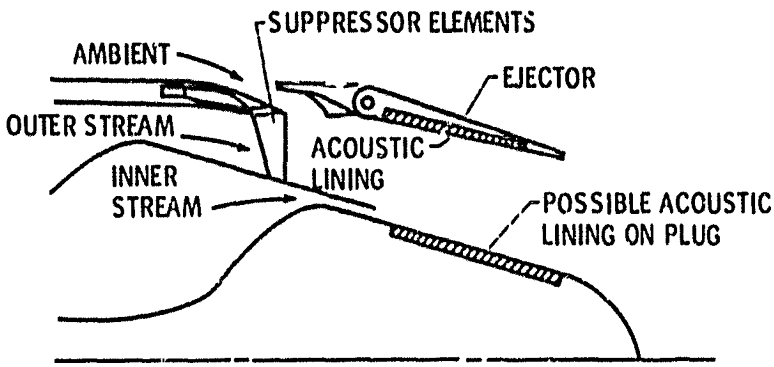
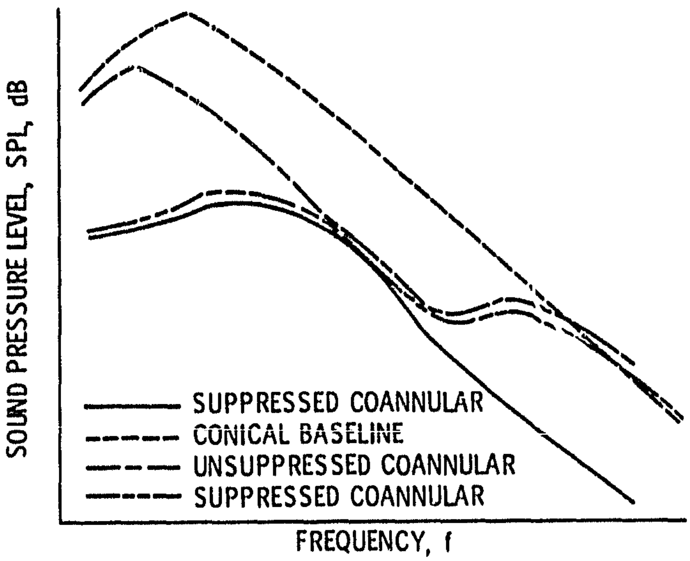


Figure 46. - Variation in TOGW with turbine inlet temperature.

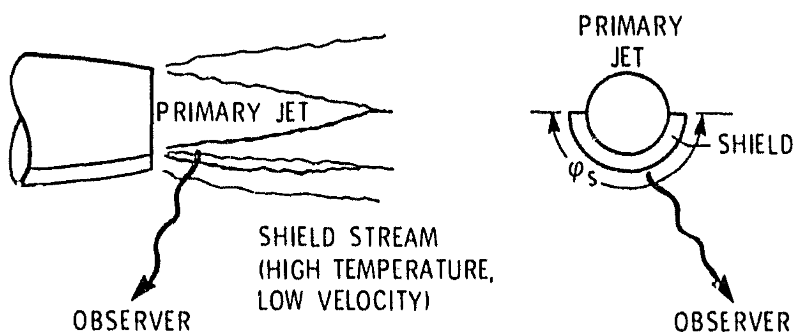


(a) Typical configuration.



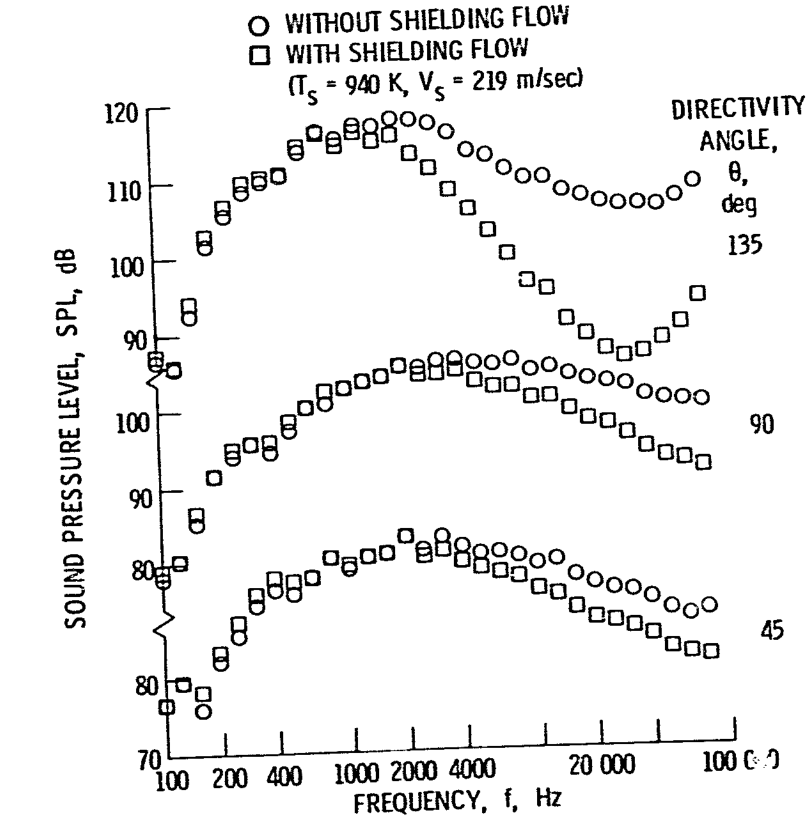
(b) Expected result - spectrum.

Figure 47. - Outer stream suppressor with lined ejector.



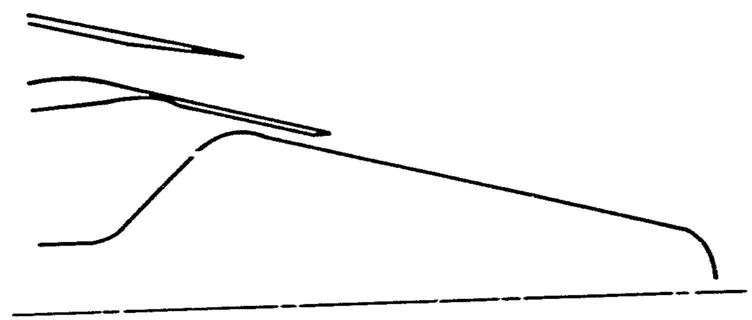
(a) Typical configuration.

Figure 48. - Thermal acoustic shield.

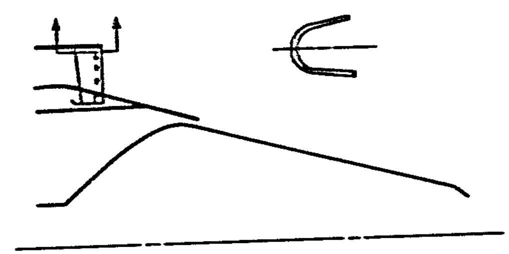


(b) Typical conical nozzle results, jet velocity = 575 m/sec.

Figure 48. - Concluded.

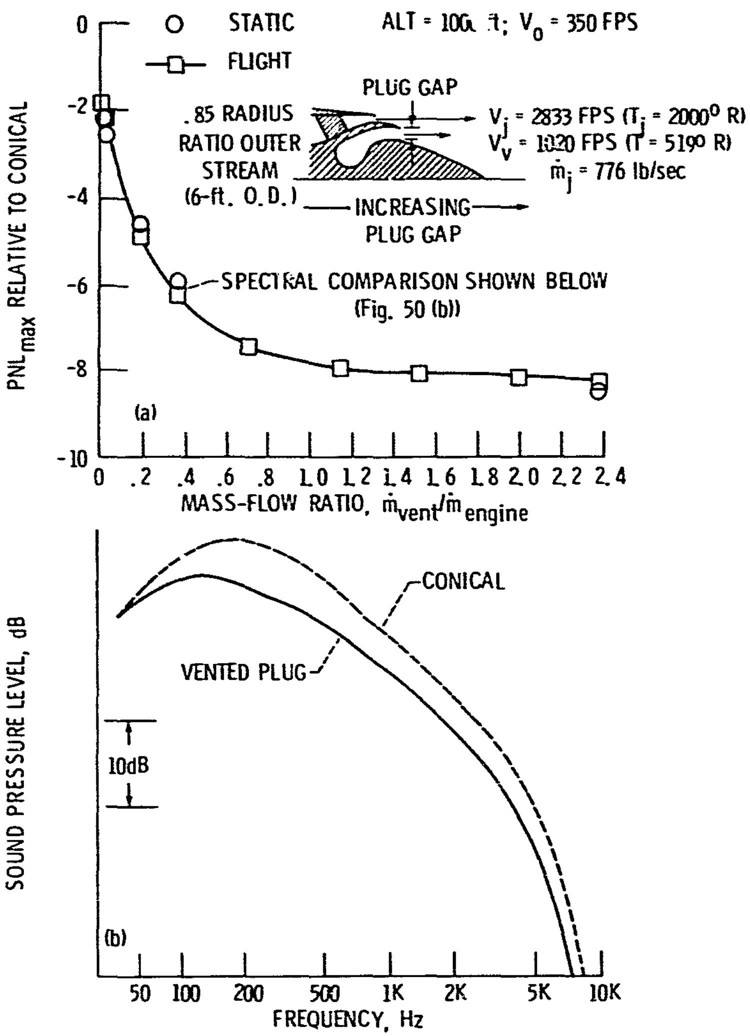


(a) Unsuppressed coannular nozzle.



(b) Outer-stream suppressor.

Figure 49. - Convergent-divergent nozzle terminations for shock noise reduction.



(a) Effect of vent flow on relative peak PNL.

(b) Effect of 0.36 mass-flow ratio venting on spectra at peak PNL angle.

Figure 50. - Vented annular plug nozzle.

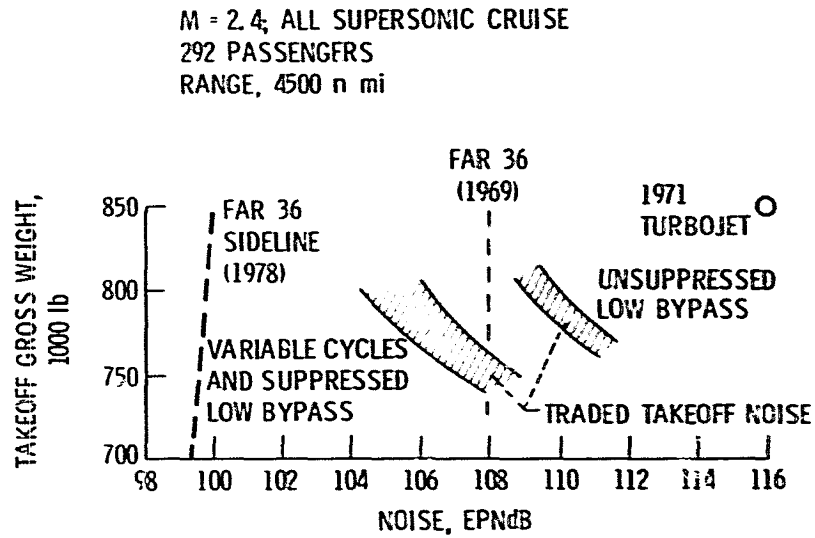


Figure 51. - Where we stood at termination of effort.