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NASA TM X-73524

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(NASA-TM-X-73524) SUPERSONIC VARIABLE-CYCLE
ENGINES (NASA) 11 p HC A02/MF A01 CSCL 21E

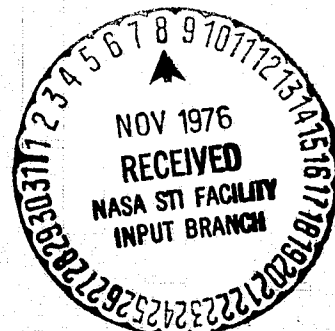
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SUPERSONIC VARIABLE-CYCLE ENGINES

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TECHNICAL PAPER presented at the
Twelfth Propulsion Conference cosponsored by the
American Institute of Aeronautics and Astronautics
and the Society of Automotive Engineers
Palo Alto, California, July 26-29, 1976



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Abstract/Summary

This paper reviews the evolution and current status of selected recent Variable-Cycle Engine (VCE) studies and describes how the results were influenced by airplane requirements. Since future supersonic cruising airplanes must simultaneously meet necessary but essentially contradictory performance regimes and environmental requirements, a VCE should provide a better aircraft performance match at various flight conditions and also satisfy the environmental constraints. Early experience has shown that VCE's can be prohibitively complex, heavy, and expensive unless significant technology advances and clever innovation are realized. The engine/airplane studies described here were, therefore, intended to identify promising VCE concepts, simplify their designs and identify the potential benefits in terms of aircraft performance. This includes range, noise, emissions, and the time and effort it may require to ensure technical readiness of sufficient depth to satisfy reasonable economic, performance, and environmental constraints. A brief overview of closely-related, on-going technology programs in acoustics and exhaust emissions is also presented. It is shown that realistic technology advancements in critical areas combined with well matched aircraft and selected VCE concepts can lead to significantly improved economic and environmental performance relative to first-generation SST predictions.

Introduction

Since the early 1970's, NASA with support from industry contractors has been conducting studies of advanced variable cycle engines (VCE's) and supersonic aircraft as part of the Supersonic Cruise Aircraft Research (SCAR) program. This paper reviews the evolution and current status of recent engine/aircraft study work, conducted jointly by Pratt & Whitney and Boeing under NASA contracts, and describes how the engine concepts have been influenced by airplane requirements.

Future civil or military supersonic cruising aircraft must simultaneously meet severe, essentially contradictory performance, economic and environmental requirements. These, in turn, create difficulties for the propulsion system. In modern multi-mission fighters, for example, the engine size and cycle that are "right" for supersonic combat are very likely to be "wrong" for extended subsonic cruising, and vice-versa. The problem is compounded in civil supersonic airplanes by the need to observe environmental criteria. It is well-remembered that the noise-versus-engine size dilemma contributed heavily to the 1970 SST program cancellation.

How shall we resolve these conflicts? When we examine the engines available today there are a surprisingly small number when we consider U.S. supersonic combat capabilities and the recent advent of foreign SST aircraft; i.e., TU-144 and Concorde. The J58, although capable of sustaining cruise at Mach 3 or above, is a relatively old design, and is not considered suitable when all of the constraints placed on later generation civil aircraft are taken into account. Modern U.S. military engines were essentially designed for sustained subsonic cruise efficiency, with only a high Mach number dash capability; their performance and service life characteristics for supersonic-cruise aircraft would be unsatisfactory. Both the British and the Russians at least have current developmental experience to build upon. The R. R. Olympus-593, for example, could be significantly upgraded by the steps described in Reference 1. In its present form, however, it is subject to many of the same objections that destroyed the U. S. SST program in 1970. It is apparent that we cannot turn to contemporary western engines as powerplants for advanced supersonic cruising aircraft. We evidently need an entirely new class of engines to simultaneously meet the anticipated, conflicting needs.

Taking these factors into account, the NASA Supersonic Cruise Aircraft Research (SCAR) program was instituted in the early 1970's. In contrast to the earlier SST project, the SCAR work is not aimed toward a production airplane, but rather, it is intended to establish a data base of advanced technology to be available for the design of future supersonic cruise aircraft if and when the nation determines it is desirable to build them. The program's elements are relevant in varying degrees to both potential civil and military applications and apply both to the airplane structure and aerodynamics and to the propulsion system; but only the civil-propulsion related aspects will be discussed here.

SCAR is a comparatively small program, but it was designed to cause innovation and it may grow larger. Its leading feature in the propulsion area has been a series of contracted engine studies by General Electric and Pratt & Whitney, with a major subcontract between Pratt & Whitney and Boeing. In this paper we will review only the joint Boeing and Pratt & Whitney activities as an example of the total engine-study effort. In so doing we will trace the evolution of one group of VCE concepts from early ideas (Reference 2) to two well-defined and apparently-attractive Pratt & Whitney engines. (A parallel discussion of VCE evolution at General Electric is being presented in a companion paper, Reference 3). The process of reconciling airplane requirements on the one hand and practical mechanical engineering on the other is described; and it is pointed out that some of the lessons learned apply to more-conventional engines as well as to the complex valved VCE's that were originally of interest. It

is shown that the resulting engines, combined with a well-matched airframe and practical advances in key technology areas, lead to significant performance, economic and environmental improvements compared to the 1970 SST predictions. The technology needs of these engines are reviewed and a brief discussion of related on-going programs and potential future options is also presented.

Lessons Learned in the SST Program

In 1970, the American SST had been penalized by propulsion related environmental and technical/economic difficulties as suggested in Figure 1. The environmental problems centered around noise and emissions, both of which needed to be technically examined in great depth. The takeoff noise problem could be only partially alleviated at the time by using a dry turbojet engine (larger than necessary for best performance) throttled back for takeoff. The resulting effect was increased propulsion pod weight, associated increased drag, and aggravated subsonic fuel consumption due to a larger throttle-back at subsonic cruise. Other technical and economic difficulties were increased by the constraint of noise which introduced poorer than expected specific fuel consumption.

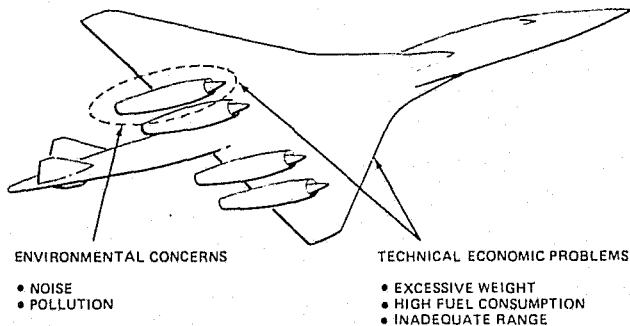


Figure 1. The 1970 U.S. SST Program

The emission characteristics were not examined in great depth at that time, but (as will be discussed later) they would have been unacceptable by current standards.

Subsonic fuel consumption became an important economic issue for several reasons. Because of sonic boom restrictions the SST was limited to over-water supersonic flight, yet many desirable routes include subsonic legs. In addition, the SST was required to fly subsonically to an alternate airfield, when unexpectedly diverted from its original destination by weather or an engine inflight shutdown. It was also required to fly subsonically for one-half hour at the end of the "divert" to represent a typical wait in the holding pattern prior to landing (so as to not require special air traffic control handling). The resulting dry turbojet powered SST required 50,000 lb of fuel for these contingencies in addition to the normal reserve quantity of 6 percent of trip fuel. The poor subsonic performance of the turbojet caused a degradation in total range when the SST was flown subsonically, as shown in Figure 2. Under these conditions, nonstop routes such as New York to Rome or any Pacific routes were not possible to achieve without oversizing the 1970 airplane to an unacceptable degree. It is clear from an economic standpoint that it would be desirable to expand the performance of a second generation commercial transport to encompass more of the city-pairs and hence increase the operational options for the using airlines as shown by the dashed area in Figure 2. To obtain aircraft range as depicted in the dashed area with a reasonably-

sized airplane, improvement in both subsonic and supersonic TSFC must be realized. These requirements have become increasingly emphasized in view of increasing fuel price and the imposition of severe noise and emission requirements. All of these necessary but troublesome factors must be addressed prior to the identification of acceptable aircraft and engine designs.

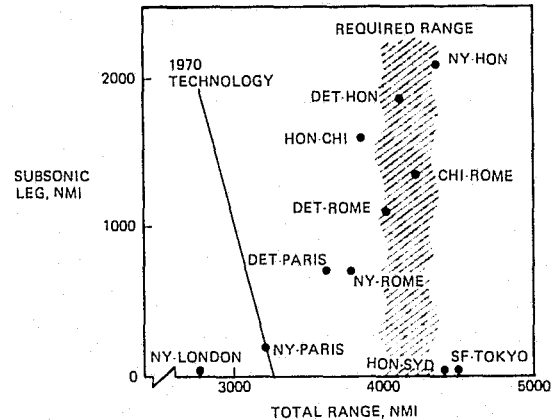


Figure 2. Performance of 2707-300 Relative to Requirement

What have we learned from this experience? The one unmistakable lesson is that any future U. S. civil supersonic airplane will be required to meet stringent and essentially contradictory performance and environmental goals, or else it will never "get off the ground." There may be similar difficulties with future military airplanes also, and we suggested earlier that a new class of engines would be needed to deal effectively with these problems.

There are many ways to build a VCE and some of the early ideas were described in Reference 2. For this discussion, however, a VCE is best defined by what it does rather than how it is built. Functionally, it is an engine which accommodates at least two distinct modes of operation: (1) a high airflow, low jet-velocity mode for low noise takeoff and/or efficient subsonic cruise; and (2) a turbojet-like, higher jet velocity, lower airflow mode for good supersonic cruise.

In more technical terms, the motivation for this "turbofan-convertible-to-turbojet" definition may be understood by reference to Figure 3. There, weight and cruise SFC trends for conventional supersonic engines are presented in terms of bypass ratio. Clearly, both weight and subsonic fuel economy favor a fairly high bypass ratio, about 1.5 (turbofan mode). Supersonic cruise on the other hand calls for a low bypass engine, 0.3 or below when fuel economy is considered, but this is tempered somewhat by the adverse weight trend. With a conventional engine, a compromise bypass ratio (usually in the 0.5 to 1.5 range, depending on the subsonic/supersonic mission mix) must be chosen, which is not really optimum for either requirement. The rationale for a VCE, then, is its potential ability to give us a better compromise. In quantitative terms, Figure 4 illustrates that a 35% subsonic SFC savings was not only highly desirable, but also at least conceptually possible using a once-favored Boeing VCE approach. A significant supersonic SFC savings was also forecast as a realistic goal.

Therefore, according to our definition, a VCE is an engine that *does* the right things. The many attempts that have been made to actually design one may be broadly classified into two generic approaches. One would rely upon valves or equivalent

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means to create two or more discrete flowpaths upon demand within the same engine structure. The alternative would rely primarily upon component variability and spool speed variations to achieve similar results. The joint Pratt & Whitney/Boeing efforts included examples of both of these approaches. We will discuss in the next several sections how the actual VCE concepts have evolved during the NASA SCAR program, driven in part by airplane requirements, in part by practical design simplification, and in part by the influence of major technology results.

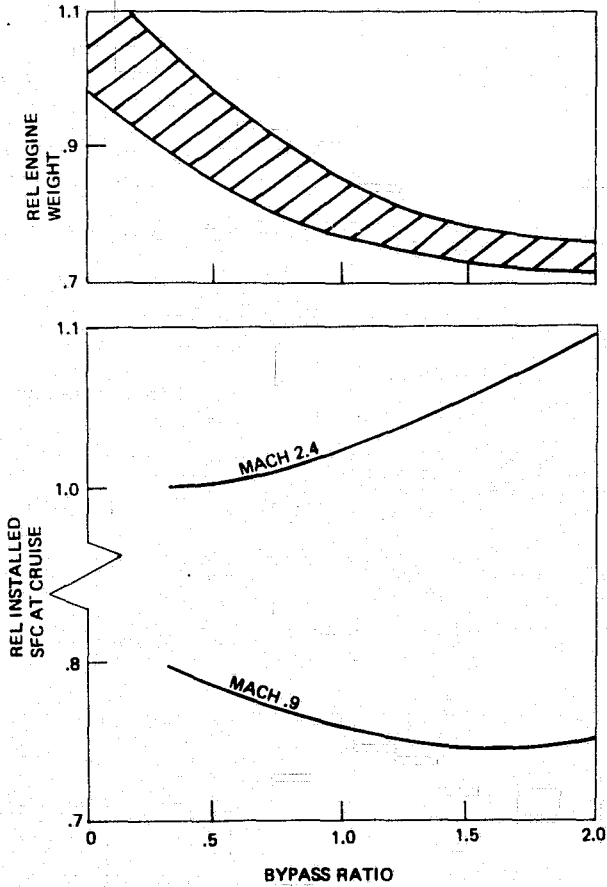


Figure 3. Factors to Consider in Cycle Selection

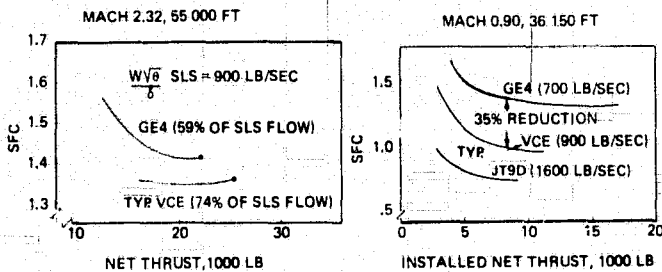


Figure 4. Variable Cycle Engine Cruise Performance Goals

The SCAR Engine Studies

The overall Supersonic Cruise Aircraft Research (SCAR) program was instituted in early 1973 and is expected to continue into the 1980's. A major element is the SCAR propulsion program which was designed to address both performance and environmental problems that came into focus during the SST experience. As shown on Figure 5, it consists of two major, interrelated elements; namely, engine studies and technology

sub-programs. The studies define the objectives and directions of research for the technology sub-programs; results from the latter feed back into the engine studies and regenerate them. The engine studies have been conducted primarily by means of a continuing series of contracts to the Pratt & Whitney Company (Ref. 4 and 5) and the General Electric Company (Ref. 6 and 7), with a major sub-contract between P&W and The Boeing Company (described in Ref. 5 and 8-10). Technology sub-programs involving these contractors as well as others have been launched in the areas of noise abatement (Ref. 11-14), pollution reduction (Ref. 15-17), inlet stability (Ref. 18), and supporting component and material programs (e.g., Ref. 19). Reference 20 provides an overview of the technology programs and Ref. 21 surveys parallel, airplane-related studies and technology programs administered by the NASA Langley Research Center.

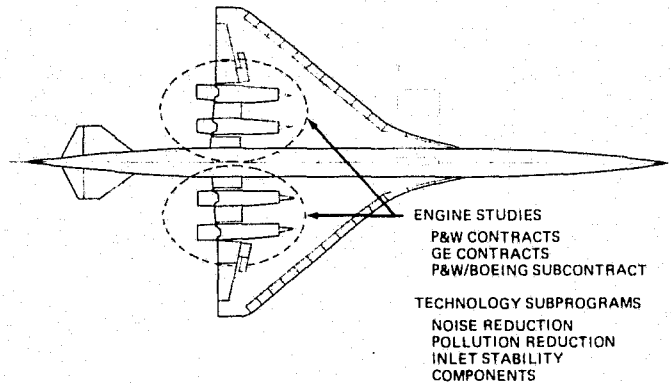


Figure 5. The SCAR Propulsion Program

Because of environmental concerns, results from the noise abatement and pollution reduction technology programs can have an exceptionally large impact on the engine studies. The current SCAR results in both areas will be reviewed at later points in the discussion where their impact on engine concept development is most apparent.

Let us now turn to the engine studies themselves. While both GE and P&WA were involved with these studies, we will concentrate on the P&WA/Boeing studies only for explanatory purposes in this discussion and not to suggest any preference among the competing propulsion systems.

Beginning in 1973, the studies were divided into 4 distinct phases as indicated in Figure 6. Phase I was organized so that

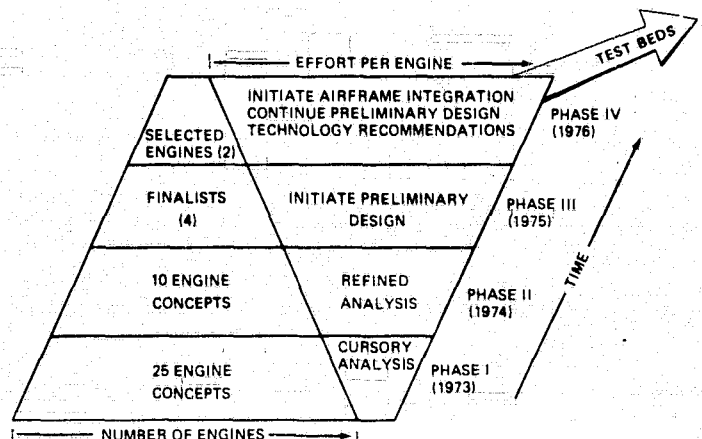


Figure 6. Evolution of SCAR Engine Studies

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no reasonable candidate engines were excluded from consideration. Many engines were studied optimistically but in little depth, References 4 and 6. Only those engines which were obviously unacceptable under the most optimistic assumptions were excluded from further consideration. The deliberate intent was to establish whether any variable cycle engines could stand the test of all the constraints in a closed loop engine/airplane study. After the least promising concepts had been screened out, a smaller number of "survivors" received a more refined analysis in Phase 2 (Ref. 5 and 7). Phase 3 has just recently been completed and is as-yet unpublished. In this phase a greater depth of analysis was accomplished including the start of engine preliminary design activities. Based on the results, we have now identified the two engines which appear to be most promising within the scope of the Pratt & Whitney/Boeing activities addressed in this paper. In Phase 4 we are initiating airframe integration activities, continuing with preliminary design and developing a series of technology recommendations relative to the favored engines. These provide the engine manufacturers with an opportunity to define, for NASA's consideration, what is needed in terms of future technology programs in order to bring these paper engines into being.

engine is now operating at a much higher (up to 2X) airflow than before and without augmentation its jet velocity is significantly decreased. In view of the similarity between this and some of the early Pratt & Whitney concepts and the potential applicability of the novel Boeing valve design, the above-mentioned P&W/Boeing subcontract work was instituted in early 1974. Its objective was to combine the two companies' respective areas of expertise to define an engine concept that would be more useful in the airplane.

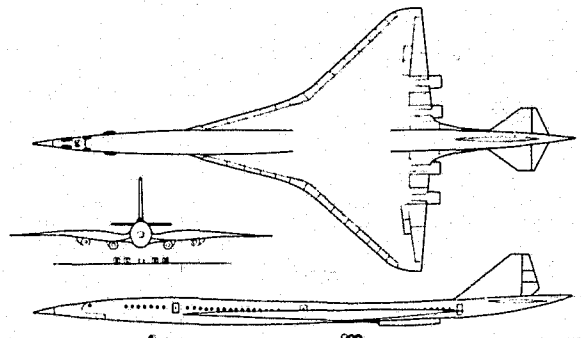


Figure 7. Task XIII Baseline Airplane

Evolution of Valved VCE's

In the early phases of the joint Pratt & Whitney/Boeing efforts, many engine schemes were evaluated in terms of their performance on a baseline Boeing SST design (Figure 7). These were centered around two fundamental and at the outset seemingly different concepts. The first was a duct burning turbofan with considerable component and nozzle variability. It was of interest for its light weight, relative simplicity and ample thrust capability, but was expected to have minimal airflow variation flexibility. The second concept was centered around an airflow inverting valve (AIV) scheme, i.e. Reference 2. This was expected to have the ability for very large airflow variations to match at all flight regimes, at the expense of added complexity and valve weight. It was of particular interest initially because its ability to provide a high airflow, low jet-velocity (and hence low noise) takeoff mode was believed to be an attractive alternative to a mechanical noise suppressor. Since thrust, the product of airflow and jet velocity, is dictated by airplane characteristics and takeoff field length requirements and noise depends primarily on jet velocity alone, the engine's airflow size is the primary variable controlling noise.

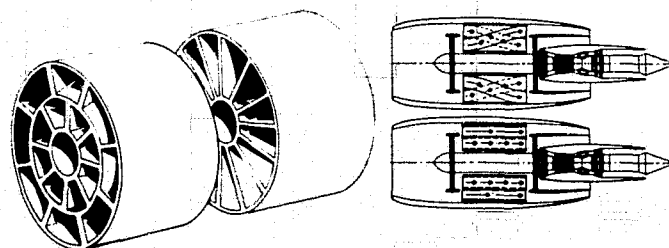


Figure 8. Valve Concept and Series - Parallel Engine

Numerous objections, however, were found upon a closer examination of this early concept. From the engine manufacturer's viewpoint, it developed that the weight and pressure-loss penalties associated with the valve were significantly larger than had been expected. The airplane is very sensitive to these penalties as the following table shows.

Table 1. SST Propulsion System Trade Factors

Item Increased	Change in Total Range on all Supersonic Mission, nmi
1% Supersonic Cruise SFC	- 30
1000-lb OEW (or 250-lb Engine Weight)	- 17
1% Subsonic Cruise SFC	- 5
1% Supersonic Climb Thrust	+ 4
1% Supersonic Climb SFC	- 6
1% POD Drag	- 1
1% Airplane Drag	- 30

The AIV itself and an early VCE concept using it are illustrated in Figure 8. In effect, the valve can transpose the annular positions of two coaxial flow paths by indexing or rotating one-half of a cut cyclinder whose facing ends mate to form the valve plane. Its internal structure and flow path are described in Reference 5. It can be applied to a supersonic engine in various ways. One of the earliest and most obvious was simply to insert the AIV between the fan and compressor of an otherwise-conventional 2-shaft machine. In the "turbojet" mode, the valve is set in its straight-through position. The fan and compressor flow in series, resulting in a two-spool, high overall-pressure-ratio (OPR) turbojet. In the "turbofan" mode, the valve mechanism is moved to the "crossover" position suggested by the upper sketch. Fan air supplied by the normal inlet is bypassed around the compressor and into an auxiliary bypass duct. Meanwhile, additional air from an auxiliary inlet is drawn through a second set of channels in the valve, into the compressor, and hence, through the combustor and turbines. Thus, the

Since the core is de-supercharged in the turbofan (parallel) mode, the OPR is considerably below the optimum value for subsonic cruise. For the same reason a variable (and probably multi-stage)-low-pressure turbine may be needed to provide high relative work extraction in the turbofan mode, and lower extraction in the turbojet mode. From the airframe point of view it was observed that the high-airflow mode for takeoff and subsonic

cruise led to a requirement for an efficient auxiliary inlet. This implied a major design and development task and a significant additional installed-weight penalty (above that required to enclose the engine's greater length and diameter). The closed-off bypass duct also would entail a sizable base or boattail drag penalty during supersonic cruise.

Subsequent efforts were aimed at removing or minimizing some of these complications. Many alternatives involving front valves, rear valves, front and rear valves, and improved valve concepts were evaluated iteratively by Pratt & Whitney and Boeing. Their detailed descriptions may be found in Reference 5 and will not be repeated here. Let it suffice to say that these intermediate concepts, examples of which are illustrated in Figure 9, were generally quite complex. While at first appearing attractive, they generally gave disappointing performance when installed on the baseline SST airplane. Inlet problems and unanticipated engine weight or performance penalties caused reduced aircraft performance relative to a conventional power plant.

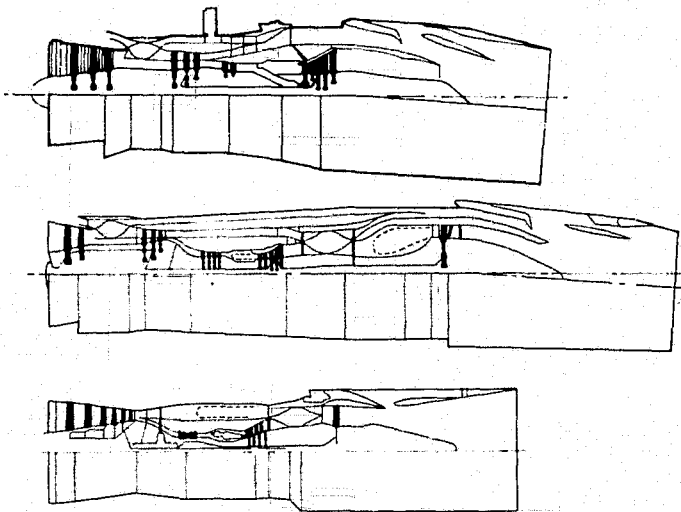


Figure 9. Valved VCE Schemes

The attractive features of the dual and front valve engines (Figure 9) were their ability to obtain increased airflow (about 25%) for takeoff, and to maintain their nominal mode airflow over a wide range of flight conditions. On the other hand, they were 20 to 25% heavier than the duct-burner for the same level of takeoff airflow. This alone was enough to offset their predicted advantages. In addition, the 25% increase in takeoff airflow created a significant engine/inlet matching problem. If sized for the high flow takeoff mode, the baseline axisymmetric inlet is much too large for supersonic cruise and would cause unacceptable installation drags. If sized for supersonic cruise it would starve the engine during its high airflow mode and negate one of its major advantages.

At this point, two alternatives presented themselves. The first was to adopt a different, and possibly novel inlet concept which could more closely follow the engine's inherent airflow schedule. The second was to concentrate efforts on lightweight engines and try to improve their airflow matching to the baseline inlet. The first alternative might have seemed attractive if the engine installations had not already been overweight and unattractive even with matching problems ignored. But as the initial study results developed, the second course was chosen.

Further analysis disclosed that both the inlet matching problem and much of the overweight problem were attributable to the front valve. It was therefore eliminated. This left the rear-valve engine concept and the duct-burner as the sole survivors of the evolutionary process. Both were comparatively simple and lightweight, but as defined in 1974, neither had a truly satisfactory inlet match over the entire flight spectrum. Their supersonic SFC's were still above the goals we illustrated in Figure 4. And the sacrifice of the high-flow takeoff mode meant that the takeoff-noise problem was still unsolved.

It was at this juncture in the studies that two major design and technology developments entered the analysis with a decisive impact. These were the invention by Pratt & Whitney of the unique, "inverted throttle schedule" (ITS), and the so-called "co-annular noise benefit" effect.

The ITS technique allowed the engines to maintain a very satisfactory inlet match over almost the entire subsonic to supersonic flight regime. It also resulted in significant supersonic-SFC improvements. In brief, the primary combustor exit temperature, and hence the core's power level, is scheduled to increase significantly as the airplane accelerates from takeoff to supersonic cruise. This combined with appropriate fan and nozzle geometry variations allows the core to speed up while the fan spool maintains a nearly constant corrected airflow. Consequently the core swallows a larger fraction of the fan flow, i.e. the bypass ratio is decreased. This in turn decreases the need for augmentation and significantly improves the supersonic SFC's—to the point that the goals of Figure 4 were finally met.

This technique is applicable both to the rear valve engine and also to engines of more conventional appearance. In the case of the duct-burner, the supersonic SFC improvement was dramatic and resulted in the two engines finally having very nearly the same cruise performance. Combined with moderate increases in cycle temperatures (made possible by improved cooling techniques), ITS is largely responsible for the airplane performance improvements illustrated in Figure 10.

To summarize Figure 10, the early duct-burners and VCE's were no better than competitive with the GE4, and some of them in fact were worse. The evolutionary process we have described amounted to "fixing" each problem as it was identified. We have

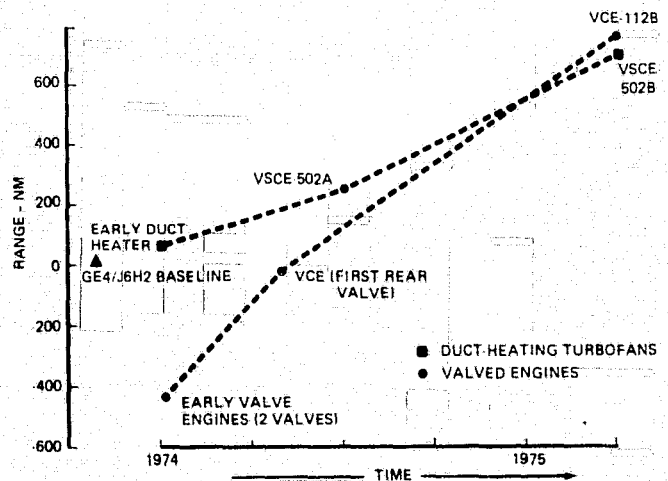


Figure 10. Airplane Range Changes with Engine Concept Improvements

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shown steady progress by this approach over the time span illustrated. At its end-point, both the rear-valve VCE (RV VCE) and the duct-burner (by now termed the Variable Stream Control Engine or VSCE) showed significant improvements over the GE4 baseline. When sized for maximum range, these two engines provide competitive performance levels in the Boeing airplane, essentially within the noise band of the estimating procedures used. This method of sizing however did not consider noise, and the airplanes represented by the two end-points would not necessarily have met FAR 36 without the aid of some form of noise suppression.

The necessary relief was provided by the SCAR noise reduction technology program. This research has led to the "Co-annular Noise Benefit" effect which is considered to be a major "break-through," as illustrated in Figure 11. In brief, small-scale static model test results indicate that: (a) if a two stream coaxial nozzle is so arranged that the high velocity stream is on the outside and the low velocity stream is on the inside; and (b) if in addition the outer nozzle has a high annular radius ratio; then the jet noise is significantly lower than would be classically predicted for an equivalent pair of conventional conical nozzles (having the same individual airflows and velocities as the coaxial streams). This effect was first noted by Pratt & Whitney and was later confirmed by parallel, independent testing at General Electric. It is of the utmost significance for the present VCE concepts since they inherently have a coaxial, high radius ratio two stream nozzle flow configuration.

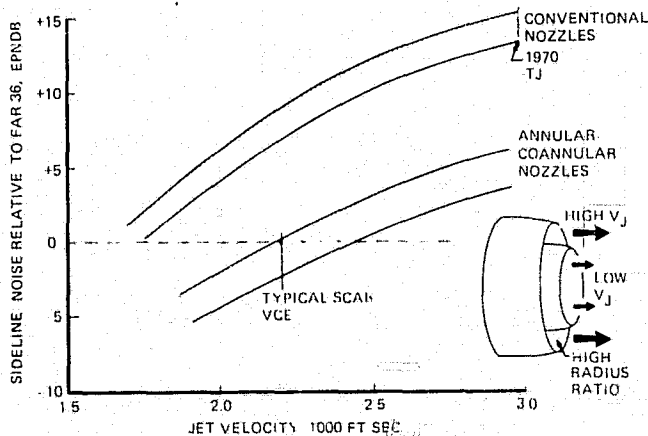


Figure 11. SCAR Co-Annular Noise Benefit

The chart illustrates the sideline noise produced by conventional and co-annular nozzles as a function of jet velocity. Two bands are shown, the upper one for conventional nozzles and the lower one for co-annular nozzles. The 1970 turbojet operated at a relatively high jet velocity and created a noise signature 12 to 15 dB above the FAR 36 requirement. But when a co-annular nozzle is used, the noise signature is immediately decreased by 8 to 10 dB. If this is combined with a variable cycle engine which is capable of taking-off at reduced jet velocities (without otherwise penalizing the airplane), a noise signature well below FAR 36 can be anticipated. The combination of the two concepts, namely, the co-annular nozzle and the two-stream VCE, results in perhaps a 10 to 12 dB lower noise than that of a turbojet with a conventional nozzle. We believe that this will have a decisive impact on the environmental acceptability of any future SST.

The benefit illustrated in Figure 11 was in the beginning described in such terms as "black magic" or "something-for-nothing." We believe however that the test programs mentioned above have been conducted in a sound and scientific manner. Nevertheless, several caveats must be mentioned. Most fundamental is that the results illustrated in Figure 11 were taken at small scale and did not include forward-velocity effects. Testing planned for the fairly near future will remedy these gaps in our knowledge and we are optimistic about the outcome. But 100% confidence is not justified until the tests are complete.

Another caution to be observed is that the benefit does not apply equally or without penalty to all engines. As described in References 11 through 14, the nozzle and engine must meet some very definite conditions involving radius ratios, stream velocities and flow areas. As will be seen later, it is in this area that we finally differentiate between the VSCE and the RVVCE.

Current VCE Candidates

Thus, under the stimuli of airplane requirements, technology advances and practical mechanical design considerations, the valved VCE concept has undergone a significant amount of refinement and simplification. Some of the lessons learned were also of benefit to the "variable-geometry" VCE's. The resulting engines are illustrated in Figures 12 and 13. The Variable Stream Control Engine (VSCE) has a flow path (Figure 12) of a conventional duct heated turbofan. It incorporates the unique "inverted throttle schedule" (discussed in the preceding section) for the main combustion power schedule, together with variable geometry in the fan, compressor and both nozzles to control its operating bypass ratio. Because of these features we have qualified the VSCE as a variable cycle engine while conventional in appearance. It is in fact an attractive example of the "variable-geometry" approach.

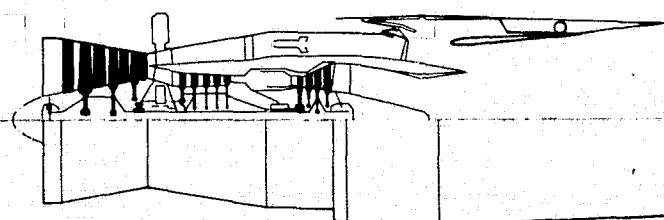


Figure 12. Variable Stream Control Engine

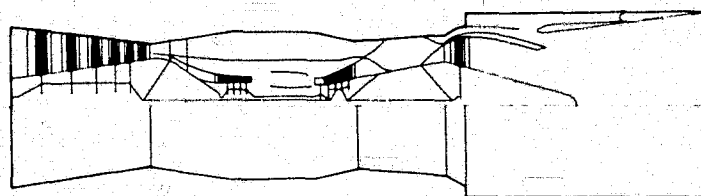


Figure 13. Rear Valve Variable Cycle Engine

Under subsonic cruise conditions the duct burner is not lit. The engine then is precisely a conventional separate flow medium bypass turbofan engine (bypass 1.5) and it provides relatively good subsonic cruise performance.

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For takeoff, acceleration and supersonic cruise, however, additional thrust is required. This is obtained by lighting the duct burner. During supersonic cruise operation the core is speeded up by increasing the temperature in the main combustor and by manipulating the component variable geometry features. Thereby, the bypass ratio is decreased and the need for augmentation is decreased, resulting in specific fuel consumption approaching that of a well designed turbojet engine. For takeoff, the additional noise implied by the duct-burner being lit is offset by the co-annular benefit. As will be seen, this permits us to size the engine for optimum supersonic cruise while still meeting FAR 36 takeoff noise requirements.

The second VCE is the Pratt & Whitney rear-valve engine (RVVCE) depicted in Figure 13. It is an attractive example of the "changing-flow-path" VCE approach, although probably not the end-point of that approach. The engine's flowpath is similar to the VSCE's with the addition of a valve and an additional turbine stage downstream of the normal LPT. The valve is a Pratt and Whitney refinement of the inverting valve which uses flaps rather than a rotating assembly to either mix or cross-over the two flow streams. Depending on the valve's position, either of two distinct flowpaths may be selected.

The cross-over position results in a low bypass mode for transonic and supersonic operation. The fan and duct-burner stream passes through the aft turbine and exits via the central nozzle. Its cycle is that of a 6 OPR turbojet. The core air bypasses the aft turbine and exits through the outer annulus; it has a 25 OPR turbojet cycle.

At Mach 2.4, for example, the fan compresses the inlet air to a relatively high pressure (3.8:1). About 4/5 of the total engine flow is then split off and heated in the duct burner to a temperature level selected for minimum TSFC and minimum cooling air requirements for the aft valve and aft LP turbine. The gas generator airflow, 1/5 of the total flow, continues through the HPC. The primary combustor heats the air to a higher temperature that is more nearly optimum for the higher pressure (10.8:1) stream. The gas generator flow then expands through the high- and low-pressure turbines. The HPT and LPT work is nearly equal to the work of compression on the gas generator stream. The LPT work is adjusted in the engine design to provide a pressure about equal to the fan stream, so that if desired the two streams could exit through a simplified common nozzle (not illustrated). The third turbine provides about 80% of the work of compression of the fan duct airflow.

In this mode, augmentation can be accomplished for little penalty compared to the VSCE because the duct-burner is upstream of a turbine. The resulting "flattened" supersonic throttle curve in turn provides the airplane designer with additional flexibility in sizing the engine.

A reduced-power version of the same mode is used for takeoff. Using the 2-stream exhaust nozzle, a portion of the co-annular benefit is received. But because of the jet noise "floor" due to the large central stream, only a 3-5 dB benefit is expected—compared to 8 dB or more for the VSCE. The impact of this still-unresolved problem is discussed in the next section.

Subsonically, the core stream and the unheated duct stream are mixed and pass through the aft turbine, where they provide about the same corrected flow as the heated duct stream alone.

Since the aft turbine then extracts relatively little power, the engine behaves as if it were a conventional mixed flow turbofan with a bypass of about 2.5.

Airplane Performance Evaluation

The two engine concepts that evolved from the study had, in the limit, essentially equal performance and met the goals we established earlier. By the end of the study, both engines had been integrated into efficiently-shaped low drag pods. A comparison of their installed thrust/SFC characteristics is shown in Figure 14. The supersonic cruise SFC's of 1.35 to 1.4 are very close to what can be attained by an optimum turbojet of equal technology and a substantial improvement over the GE4 (recall Figure 4). The subsonic SFC's were also significantly improved and now approach turbofan performance. The RVVCE was estimated to be 9% lighter than a conventional turbojet.

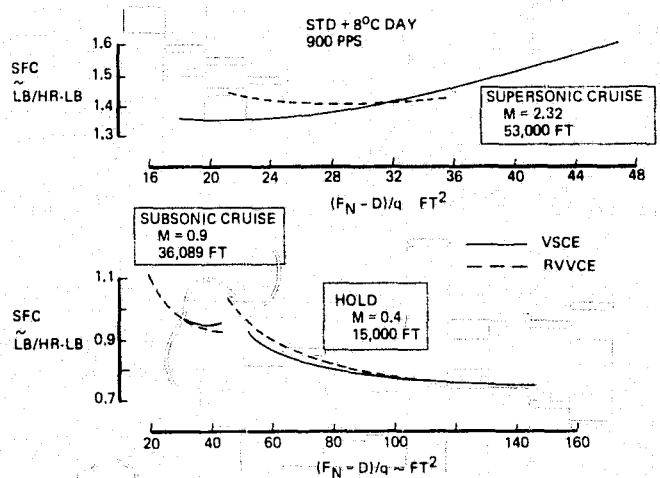


Figure 14. Engine Installed Performance Comparison

By using the trade factors presented in Table 1, we project a 120 nmi. range improvement for weight reduction, 150 nmi. for the supersonic SFC improvement and 170 nmi. for the subsonic SFC, for a total improvement of 440 nmi. There are secondary effects such as integrated climb performance and pod drag reduction which are ignored here but are included in the detailed airplane performance results shown in Figure 15. The total airplane range improvement projected for the 900 lb./sec. VCE then amounts to over 500 nmi. There

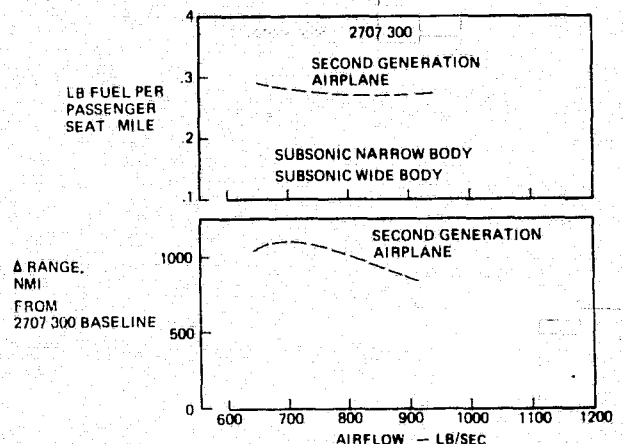


Figure 15. SST Range and Fuel Mileage Comparison

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is also a 20% reduction in fuel burned per scat-mile. The 900 lbs./sec. pod size was selected as a reference because this size was projected to meet sideline jet noise levels that satisfy FAR 36 requirements with an unsuppressed engine (based on calculated noise results using the standard SAE procedure). Ignoring noise for a moment, Figure 15 shows that a further range improvement of up to 1000 nmi. relative to the 1970 baseline could be attained by decreasing the airflow size down to about 700 lb./sec., at which point the absolute maximum range is attained. The primary reason for the range reduction at still smaller engine sizes is supersonic climb thrust margin. As the engine size is reduced, the airplane climb thrust margin reduces, causing the airplane to linger at an inefficient condition around Mach 1.1. Minimum size engines are desirable in the SST for improved balance, lower pod drag, lower cost, lower weight, and better ground clearance which has a significant impact on aircraft gear weight. However, jet noise becomes a problem with the smaller engine because higher power settings, i.e., high jet velocity, are necessary to meet the same takeoff requirements.

The delta-wing airplane equipped with a VCE was found to be limited by supersonic climb thrust and takeoff thrust at a given jet noise level. As we have shown earlier, both VCE's provide essentially the same airplane performance. Any significant departure will come from superior noise characteristics, or the ability to size one engine smaller than the other because of some unique feature. One consideration that has a major impact on the jet noise/engine size question is the coannular noise reduction benefit that has been identified from the previously discussed SCAR technology noise programs. Small size model tests to date argue that the coannular noise reduction may yield up to 10 dB benefit with no thrust penalty if the engine exhaust is configured properly. As previously mentioned, this is of major significance on the VCE concepts since they inherently provide a coaxial, high radius ratio two stream nozzle flow configuration at takeoff. It is at this point, however, that we now find a significant difference in the VSCE and the RVVCE engines.

Figure 16 shows a comparison of the two exhaust streams at equal takeoff thrust. The VSCE with the more conventional duct heater exhaust profile has a larger percentage of the flow in the outer hot stream. Based on the model test data this difference projects jet noise reduction of 8-10 dB while the thinner hot stream of the rear-valve engine results only in 3 to 5 dB reduction. At equal noise therefore the VSCE should be scaled to a smaller size. While at this writing the detailed range differences have not been completed the authors project roughly a 220 nmi. supersonic range difference assuming a 9 dB benefit for the VSCE and a 4 dB benefit for the RVVCE. The expected total benefit is shown schematically in Figure 17. The most recent range-versus-airflow size estimates are presented for the current Boeing airplane and the final Phase III VCE definitions. The performance of the GE4 is shown for comparison. The VSCE, receiving the full co-annular benefit without thrust penalty, is sized the smallest. The GE4, although receiving about the same amount of suppression from a mechanical device, had to be up-sized to make up for the attendant thrust losses. The RVVCE, receiving only 4 dB of the co-annular benefit, must be still-further upsized; it depends more heavily upon increased airflow to meet FAR 36. (Phase III efforts to modify the RVVCE cycle to receive the full co-annular benefit resulted in weight and performance penalties more severe than the degree of up-sizing shown in the figure.) In summary, because of their lower weight and SFC improvements relative to the GE4, combined

with applicable amounts of the co-annular benefit, both VCE's represent a major advance over the 1970 technology turbojet.

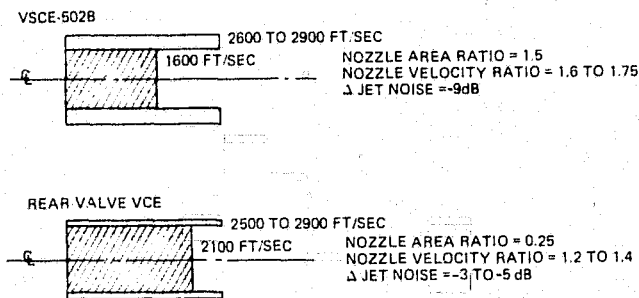


Figure 16. Takeoff Velocity Profile Comparison

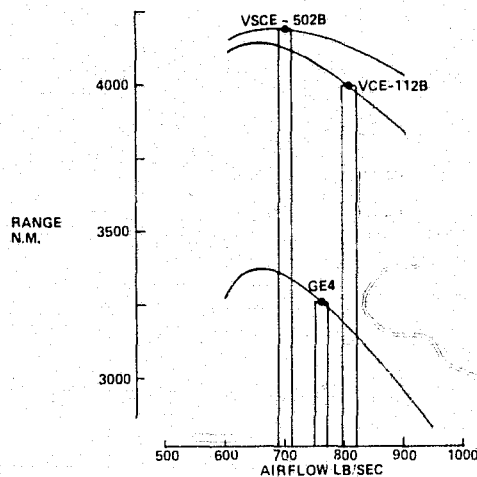


Figure 17. Range Comparison at FAR 36 Sideline Noise and 12,000 Ft. TOFL

We believe that the co-annular noise benefit will be a decisive factor bearing upon the environmental acceptability of any future SST. In addition it now appears to be the primary factor that differentiates between the VSCE and the RVVCE. As mentioned earlier, the second area of environmental concern is exhaust emissions. This is recognized as a potentially serious problem for the present VCE's and all of their competitors. But in contrast to the co-annular benefit, the pollution-reduction program results (while showing significant progress), have not clearly tended to favor one cycle or class of cycles over the others in the area of highest concern.

Both the airport area and high altitude cruise criteria must be satisfied. Cruise NOX emission however is of greatest concern because all of the desirable cycles operate in regimes favoring its formation and the airplane must inherently cruise in the stratosphere. In Figure 18 we illustrate the comparative performance levels of conventional and several advanced primary combustor concepts, over a typical range of combustor inlet air temperature. (This is the primary engine cycle variable affecting NOX generation.) As illustrated by the upper band, a conventional combustor (such as was used by the 1970 SST and is still used today in current airplanes) would present an index of 20-40 gm./kg. of fuel burned. By contrast, Reference 22 has tentatively suggested that an index of 3 gm./kg. may be appropriate, to avoid appreciable stratospheric pollution by a future SST fleet. The clean combustor concepts developed under the SCAR Experimental Clean Combustor Program (ECCP), as illustrated in the

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next band, represent a significant improvement, to about 40 or 50% of the conventional combustor's levels. This represents major progress and could be incorporated in a new engine program starting now. Yet it is still far above the suggested target. Although some minor relief could be had by backing down in cycle temperatures, this results in unacceptable performance penalties without approaching the target very closely. The major hope for the future, therefore, is in the area of advanced combustor technology. Pre-mix and catalytic combustors (e.g. Reference 17) have demonstrated values as low as 1 gm./kg. in small scale, idealized laboratory experiments. But it is clear that a large, lengthy and probably expensive program, including both fundamental research work and applied development, will be required to translate these promising concepts into reality. Assuming that the necessary programs will be forthcoming, we anticipate that values on the order of 25% of the conventional-combustor levels may eventually be attainable in practical engines. It should be recognized, however, that this involves our entering a new and relatively unknown area of technology, and this has yet to be done in a serious way. The above estimates are therefore uncertain, as are the projected requirements; either or both may change significantly in the future.

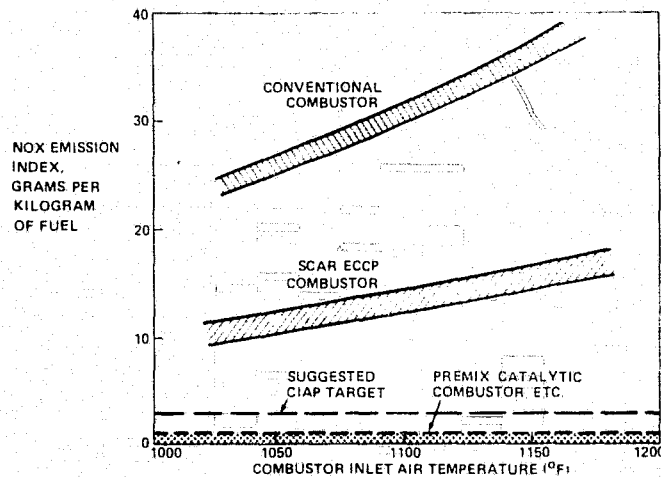


Figure 18. NOX Levels of SCAR Engines

Although NOX emissions are most critical for an SST, the airport-area emissions must also be environmentally acceptable. It is believed that all of the advanced technology primary combustor concepts would be capable of meeting the "proposed" standards for future SST's. This is not clearly the case for augmentors, however, and the search for a locally-acceptable augmentor will again lead us into new areas of technology.

From the foregoing discussion, it is clear cruise NOX generation may be a major unsolved problem for the present VCE candidates and for their competitors as well. On the other hand, it does not appear to differentiate significantly between the two engines, although it will doubtless have some effect on the final choice of cycle temperatures. Both of the engines need clean duct burners, and it is not clear which of the two would represent the greater challenge. In terms of airport-area emissions, the greatest differentiation that we can foresee may be between these engines and their non-augmented competitors.

In conclusion, at the close of the United States SST program, the British/French Concorde and the Russian TU-144 were already ahead of the U.S. airplane in terms of development time. Both have now been refined by an additional 6 years of development effort and operating experience and could presumably serve as a basis for follow-on efforts. We on the other hand elected not only to discontinue the airplane, but also to discontinue a level of technological activity which would have led us to readiness at an identifiable date. This has substantially reduced our immediate options for new programs involving second generation supersonic transports or supersonic military airplanes.

By the SCAR studies, we believe that we are identifying what needs to be done to reverse this trend and develop a viable option which could be exercised when national needs so dictate. We have now completed 3 years of conceptual engine studies, only one portion of which was discussed in this paper. The engines described here, together with other potential P&W offerings and their ingenious and similarly-attractive competitors from GE, represent a major advancement compared to either the 1970 SST engine or early VCE concepts. Their practical realization, however, depends upon some significant technology advancements. Table 2 is a summary of the major technology recommendations that have resulted thus far from SCAR activities.

Table 2. Summary of VCE Technology Program Requirements

- CO-ANNULAR NOZZLES
- CLEAN EFFICIENT DUCT-BURNER
- VARIABLE GEOMETRY FANS
- VARIABLE GEOMETRY TURBINES
- HOT SECTION TECHNOLOGY
MATERIALS & COOLING
CLEAN PRIMARY BURNERS
- INLETS
- ELECTRONIC CONTROLS
- AIRPLANE/ENGINE INTEGRATION

Clearly required are quiet coannular nozzles, underlined on the figure because they are not only critically needed but are unique to this class of engines and not likely to be developed under other programs. In the same category is the low emissions, efficient duct burner which is characteristic of both P&W VCE's. Also needed are flow control valves, variable geometry fans and advanced turbines. Clean primary burners are obviously essential. A major need is for advancements in hot section technology. As previously mentioned, these engines because of supersonic cruise may spend about 80% of their duty cycle at maximum temperature—which is a significant departure in duty cycle demand from current military or commercial engine use. Thus, advanced high temperature materials and cooling techniques are of the greatest importance in these engines. Finally, because of the engine's many adjustable features, there is also a need for advanced digital electronic engine controls.

The airplane manufacturers have also identified their corresponding advanced-technology needs. What is the potential payoff from all these developments? In terms of noise, it is dramatic as Figure 11 has already illustrated. By combining the coannular noise benefit with selected VCE concepts, the noise impact of a second-generation SST would be greatly reduced

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compared to earlier technology airplanes. Smaller but not insignificant improvements are also projected in terms of airplane gross weight. The potential economic benefit is illustrated in Figure 19 where we compare the 1970 SST and the SCAR airplane/engine combinations in terms of their ability to serve important city-pair combinations. The improvement shown is attributable both to general technology advances in the airplane and engines, coupled with the emergence of viable VCE concepts. Clearly, a major improvement in the airplane's ability to serve attractive market areas has been identified on paper.

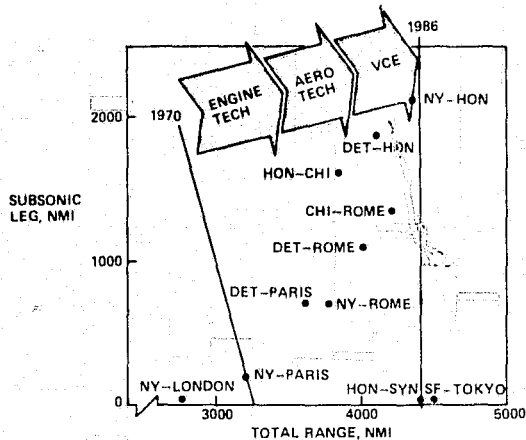


Figure 19: SCAR Technology Payoffs

What is being done to make this happen? In the engine area, NASA has instituted testbed programs with both P&WA and GE. These address the most critical and unique areas identified by the engine companies (underlined on Table 2). Admittedly, there are other needs which are not now being addressed in a serious way. But we believe that as the testbed programs are vigorously pursued to their successful conclusions, the logical next steps will be forthcoming. It should be very desirable to demonstrate that the economic and environmental requirements can in fact be realized through U.S. technology.

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