ADVANCED SUPERSONIC TECHNOLOGY STUDY

ENGINE PROGRAM SUMMARY

SUPERSONIC PROPULSION - 1971 to 1976

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SUMMARY

Sustained supersonic rruise propulsion systems for military applications have been developed by General Electric since the early 1950's. The J79-5 in the Mach 2 B-58; YJ93 in the Mach 3.0 B-70 and the current F101 in the B-1, are all examples of military propulsion systems and airplanes operated at sustained supersonic cruise speeds.

The Mach 2.7 B2707 transport powered by GE4 turbojet engines was the only non-military, sustained supersonic cruise vehicle intended for commercial passenger service. The cancellation of the B2707 and GE4 programs in 1971 ended hardware development effort.

In 1972 NASA initiated study programs to identify the required propulsion system and airplane technology necessary for an environmentally acceptable supersonic cruise vehicle. The Advanced Supersonic Propulsion System Technology Studies at General Electric screened conventional turbojets, mixed flow and duct burning turbofans and variable cycle engines. This resulted in the selection of a Variable Cycle Engine (VCE) concept that provides high airflow for low take off noise levels, using a coannular acoustic exhaust nozzle, and a cruise airflow matched to the airplane inlet flow schedule. This VCE has been refined and its mechanical design simplified to improve reliability and maintainability. Technology predicted to be available for start of development in 1985 is incorporated in the engine, as well as commercial life requirements the same as used in the GE4 turbojets. The propulsion system technology has improved to the point that definition of a second generation supersonic cruise aircraft propulsion system much improved from the 1971 GE4 turbojet is now possible.

SYMBOLS

Values are given in both SI and U.S. Customary Units.

A/B	afterburner
M	flight Mach number

T/O	takeoff
VCE	variable cycle engine
SFC	specific fuel consumption
CO	oxides of carbon
HC	hydrocarbon
NO_X	oxides of nitrogen

DISCUSSION

The GE4 development program, up until its cancellation in 1971, had accumulated 1800 engine test hours on ten nameplate engines, with over 200 hours of simulated altitude operation at Mach 2.7 inlet conditions. Table I shows the GE4/J5 test engine cycle, and figures 1 and 2 show test engines prior to installation in the test cell and on test at the Peebles Test Center.

A cross section of the GE4/J5 engine is shown on figure 3. The engine is a single rotor afterburning turbojet with eleven turbomachinery stages, and uses a two stage ejector nozzle (TSEN) to pump secondary air for nacelle cooling. The GE4/J5 engine was designed for afterburning takeoff and supersonic cruise at Mach 2.7 using partial afterburning. The afterburning takeoff resulted in noise levels of approximately 120 EPNdb.

The environmental impact of the GE4/J5 afterburning turbojet in the B2707 airplane, noise levels, emissions, etc. became a major problem during the development program. Extensive studies resulted in the selection of the GE4/J6H dry turbojet for the production engine configuration (see table II). The GE4/J6H was designed to come close to FAR 36 takeoff noise by providing a high takeoff airflow of 408 kg/sec (900 lbs/sec) at an exhaust velocity of 762 m/sec (2500 ft/sec) to meet the required takeoff thrust. Figure 4 shows a cross section of the GE4/J6H, which is similar to the GE4/J5P, that is, basic engine scaled up in airflow and increased turbine temperature, with a new annular plug exhaust system with a retractable 10 PNdb chute type mechanical jet noise suppressor, (see figure 5), and no afterburner system. The large airflow size provided the thrust required for dry power climb and acceleration and supersonic cruise, but the large engine size and weight reduced the range of the B2707 airplane.

At this point in the development of the engine and airplane, the program was cancelled.

In 1972, the National Aeronautics and Space Administration (NASA) sponsored study efforts by aircraft and engine manufacturers to identify needed technology for supersonic cruise vehicles aimed at the start of full scale development in the 1980-1985 time period. Under contracts from NASA Lewis

Research Center, General Electric has conducted Advanced Supersonic Propulsion System Technology Studies (AST). These studies have screened conventional and variable cycle concepts and combined features of both types into a variable cycle engine that has characteristics suited for sustained supersonic cruise, while also providing inlet flow matching capability over a wide range of airflows. The AST VCE is basically a low bypass ratio (0.35) dual rotor turbofan engine with a low temperature augmentor, designed for dry power supersonic cruise, using the afterburner for transonic climb and acceleration only. At takeoff conditions (see table III) the bypass ratio is almost twice the supersonic cruise level with airflow to provide acceptable FAR 36 noise levels and thrust. Figure 6 shows a schematic of the double bypass VCE concept. The basic differences between the VCE and a conventional turbofan engine are the separation of the fan into two blocks with an outer bypass duct between the fan blocks, and the normal bypass duct after the second fan block. For the low noise takeoff mode the front block of the fan is set at its maximum flow configuration. The second fan block is operated to tailor the jet exhaust velocity and flow to produce the desired thrust/noise relationships for takeoff. During subsonic cruise operation the front fan block is set to provide the best match between inlet spillage and internal performance. In this mode the second fan block is set to provide the proper cruise thrust. The inlet airflow can be maintained down to the required subsonic cruise thrust requirement, which practically eliminates inlet spillage drag, and because of the high flow also reduces the afterbody drag. The effect of the increased bypass ratio and reduction of installation drag decreases the installed specific fuel consumption (SFC) by about 15%.

In the climb/acceleration and supersonic cruise modes, the front block fan is set to meet the aircraft inlet flow supply, and the rear block fan and high pressure compressor are set to pass all of the front block fan flow, and the engine operates the same as the nominal 0.35 bypass ratio turbofan engine. An advantage of the split fan configuration, beyond its inlet matching capability, is that for high takeoff airflow, only the front block fan and low pressure turbine are affected, and a large weight saving is realized over the weight of a conventional turbofan engine sized for the same takeoff airflow and noise level.

A major effort has been made to simplify the engine and exhaust system to reduce cost and weight and increase reliability. The cycle was established for dry (non afterburning) takeoff and supersonic cruise, and to require only two turbine stages. The choice of mixed flow eliminates the need for a sophisticated high performance duct burner and requires only a very simple climb acceleration low temperature rise augmentor. The low bypass ratio mixed flow selection for supersonic operation also assures inlet compatibility. The introduction of the annular jet noise suppression concept on the VCE resulted in a simpler, lighter weight exhaust system with fewer movable parts and actuation systems. These and other improvements have resulted in a lighter, more reliable engine than the GE4 turbojets. A continuing effort on weight, cost reduction and increased reliability through simpler design will show further improvements in the future.

To compare the propulsion system advances from the GE4/J6H of 1971 to the

VCE of 1976, figure 7 compares the subsonic and supersonic fuel consumption and engine weight for the engines sized for the same takeoff noise level. The engines are installed in a Mach 2.4 cruise airplane of 1976 technology so that airplane characteristics are the same. The VCE has about 9% lower M2.4 fuel consumption than the GE4/J6H; about 22% lower subsonic (M0.95) cruise performance and a 25% lower weight. These differences can be attributed to:

Supersonic SFC

- Smaller VCE cruise airflow size - matched to aircraft
- Higher turbine temperature
- Improved component efficiencies and cooling technology

Subsonic SFC

- Cycle selection - higher bypass and cycle pressure ratio (M2.4 vs. M2.7)
- VCE features - minimum installation drag - inlet flow matching
- Smaller VCE cruise airflow size
- Improved component efficiencies

Engine Weight

- High flowed front block fan
- VCE bypass ratio
- Advanced nozzle concepts
- Advanced materials
- Higher turbine temperature

Figure 8 shows installation type outlines of the GE4/J5, GE4/J6H and the GE21/J11B3 VCE. It is apparent that the engine volume required to produce the required airflow has been greatly reduced. The reduction in cruise Mach number from M2.7 to M2.4 has eliminated the requirement to package the engine accessories for cooling. The smaller engine volume and the smaller advanced technology accessories should result in a smaller, lighter and lower drag nacelle.

The effect of the performance and weight advantages of the VCE can be seen in figure 9, which compares all supersonic cruise range at Mach 2.4 with engine takeoff airflow size. With both engines sized for FAR 36 noise levels, the VCE is much better matched to the airplane requirements, and operates at close to its optimum range. The GE4/J6H is not well matched, and its range is much lower than its optimum. Performance differences would account for about a 741 km (400 n.m.) range difference if both engines were sized to the optimum but the actual range difference is about 1296 km (700 n.m.) when sized at approximately the same takeoff airflow and FAR 36 noise level.

The VCE also offers even more advantages when subsonic cruise requirements are added, since the VCE reduces the subsonic installation drag and gives much better installed performance.

The VCE shows the potential of providing viable supersonic cruise range while also meeting takeoff and landing noise requirements with its high takeoff airflow capability and the annular acoustic plug nozzle. Another environmental consideration which had a major impact on the GE4/J6H and B2707 airplane is exhaust emissions around the airport and at high altitude supersonic cruise.

Figure 10 compares the emission levels of the 1971 GE4/J6H with the 1976 VCE. Major reductions in airport emission levels have been achieved; in fact, the VCE is predicted to meet the recently issued 1984 EPA Proposed Standards. Large reductions have been made in the altitude cruise NO_X emissions, but major combustor improvements must be made to approach the suggested Climatic Impact Assessment Program (CIAP) NO_X emission target of 3 g/kg fuel.

The double bypass VCE concept will require some real advancements over today's technology levels. Some of these are unique to the VCE, and others will apply to both military and commercial engines developed in the 1980-1990 time period.

The VCE concepts and features that provide performance advantages, such as inlet matching capability, reduction in installation drags, high takeoff airflow, can be demonstrated in a test bed engine program in the 1978-1980 time period. Other high payoff technology such as high turbine temperatures and improvements in component efficiencies must be demonstrated, and some programs are already underway which should contribute. A major technology item which impacts the VCE is the annular acoustic plug nozzle system. Static model testing has shown the potential for meeting noise requirements with the annular plug nozzle, but unknowns such as in flight effects, full scale test noise measurements, static and in flight at the high exhaust velocities required, may show the need for a back-up system with a 5-10 PNdb mechanical jet noise suppressor.

Commercial experience to date has shown the major impact of hot parts life on operating costs, and we are planning 100-200°C (200-400°F) higher turbine temperature than current commercial engines.

The cost of a supersonic propulsion system will be high. A major effort is required to reduce this cost by use of better, simpler designs, advanced materials and fewer parts.

The flexibility of the variable cycle engine introduces another dimension in engine control complexity. The number of control parameters is more than doubled over a conventional cycle engine. The use of a full authority digital electronic control (FADEC), integrated with the aircraft control system, will be a requirement. Programs are now underway on these types of engine control systems, but the AST VCE will have unique control requirements to fully exploit its flexibility of operation.

The current NASA Lewis Research Center Experimental Clean Combustor Program (ECCP) is showing the potential for solving the airport emission problem. The AST VCE uses the double annular combustor developed in this program and meets the proposed 1984 EPA standards. The high altitude cruise NO_X emissions require a new combustor technology to meet CIAP targets. These combustors will require major research and development effort to achieve a practical design which meets the engine operating requirements, and both airport and altitude cruise emission levels.

The major question, not yet answered is, if all of these technology goals are attained, can we have a commercial supersonic cruise vehicle which will make money for the airlines?

The answer to this question will require a continuing major effort to refine the variable cycle engine, and match the airplane and propulsion system in an integrated economically viable commercial transport.

TABLE I.- GE4/J5 M2.7 TURBOJET RESULTS

• Thrust, N (lb)	311,360	(70,000)
• Airflow, kg/sec (lb/sec)	290	(640)
• Pressure Ratio	12.5	
• Turbine Rotor-In Temp., °C (°F)	1260	(2300)
• A/B Temperature, °C (°F)	1693	(3080)

TABLE II.- GE4/J6H M2.7 TURBOJET

• Thrust, N (lb)	328,722	(73,900)
• Airflow, kg/sec (lb/sec)	408	(900)
• Pressure Ratio	12.4	
• Turbine Rotor-In Temp., °C (°F)	1383	(2520)

TABLE III.- AST-VCE M2.4

• Airflow at T/O, kg/sec (lb/sec)	380	(840)
• Bypass at T/O	0.8	
• Pressure Ratio	17.3	
• Turbine Rotor-In Temp., ^{0}C (^{0}F)	1538	(2800)
• A/B Temperature, ^{0}C (^{0}F)	1038	(1900)

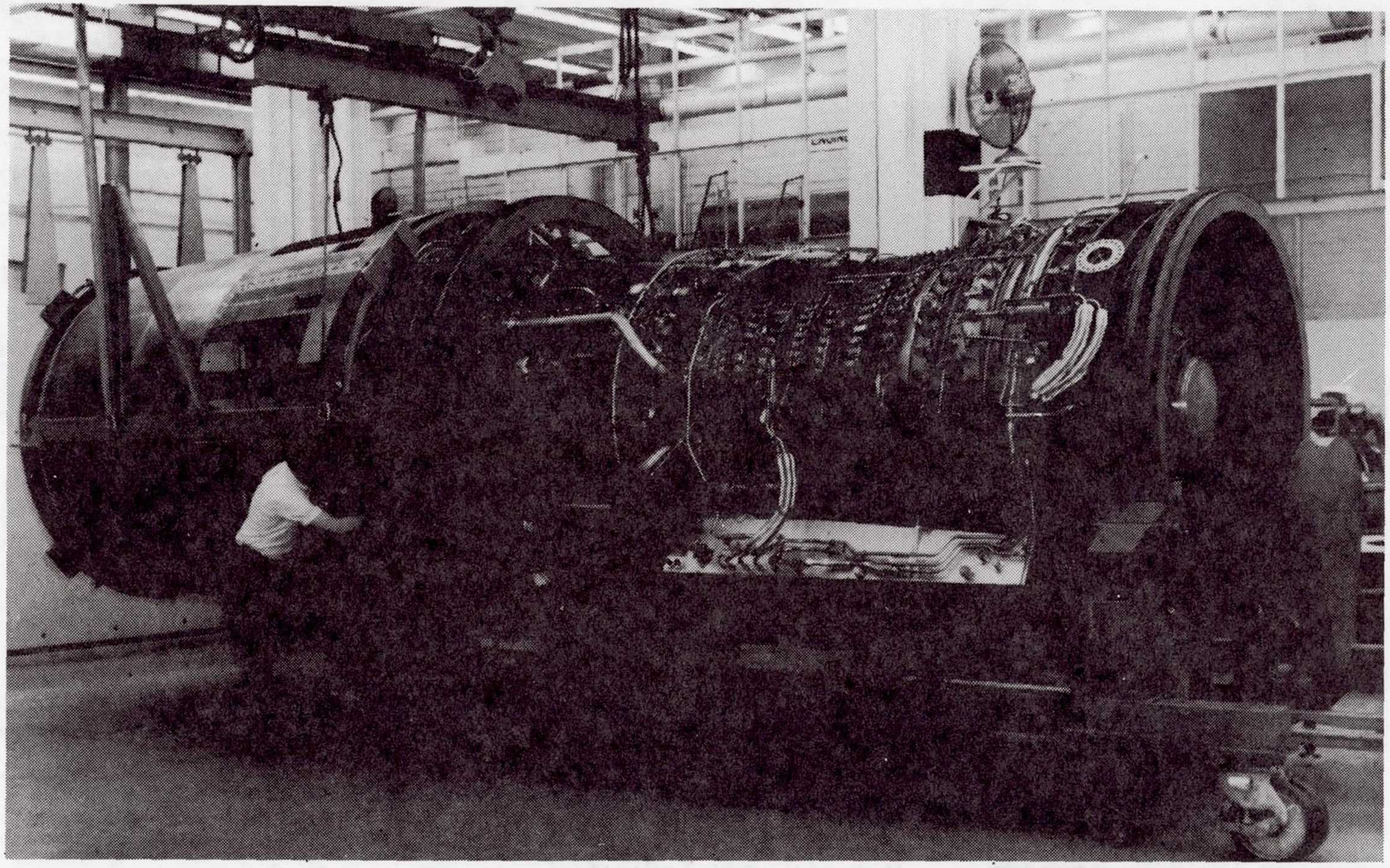

Figure 1.- GE4/J5 test engine.

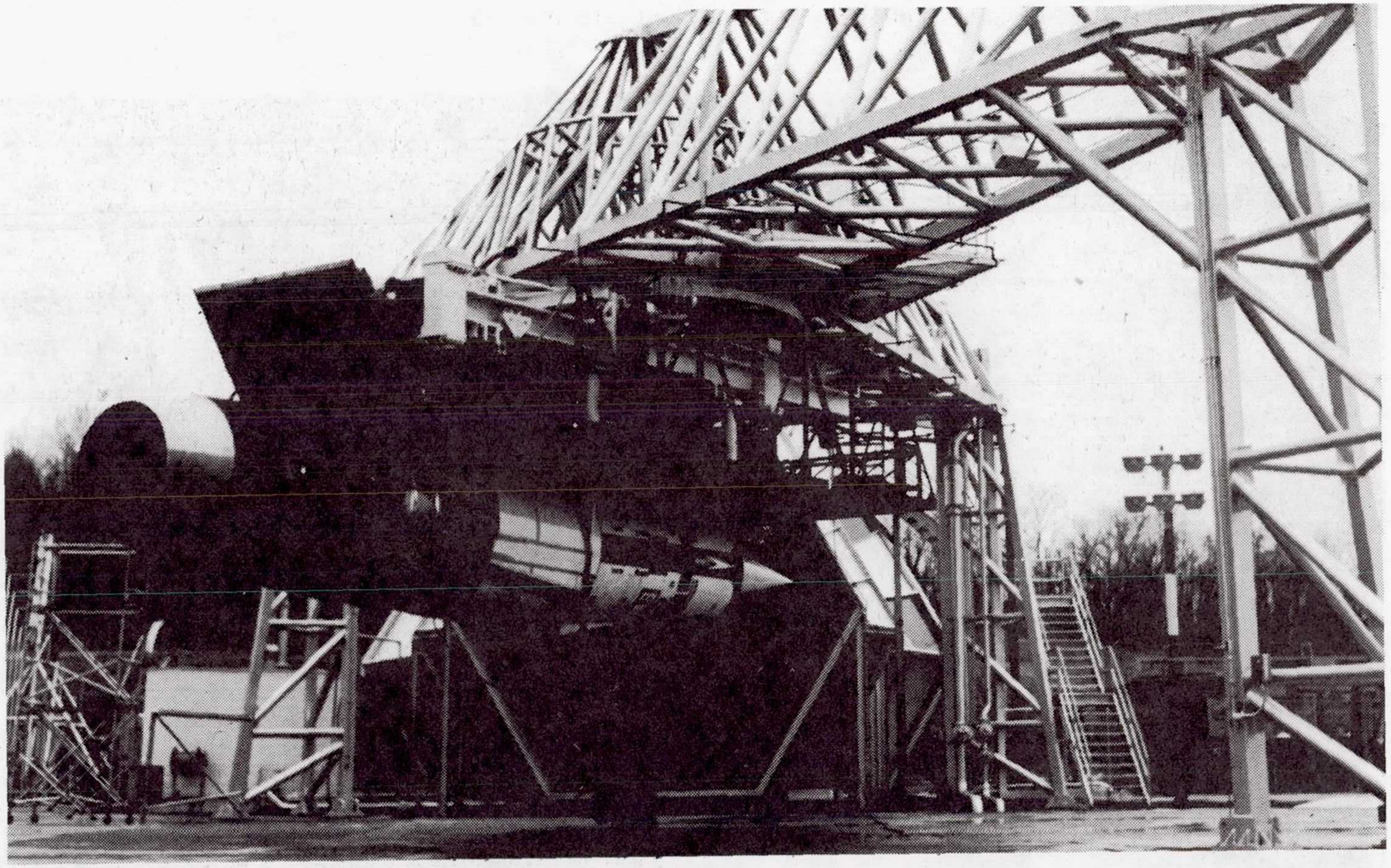

Figure 2.- GE4/J5 at Peebles test site.

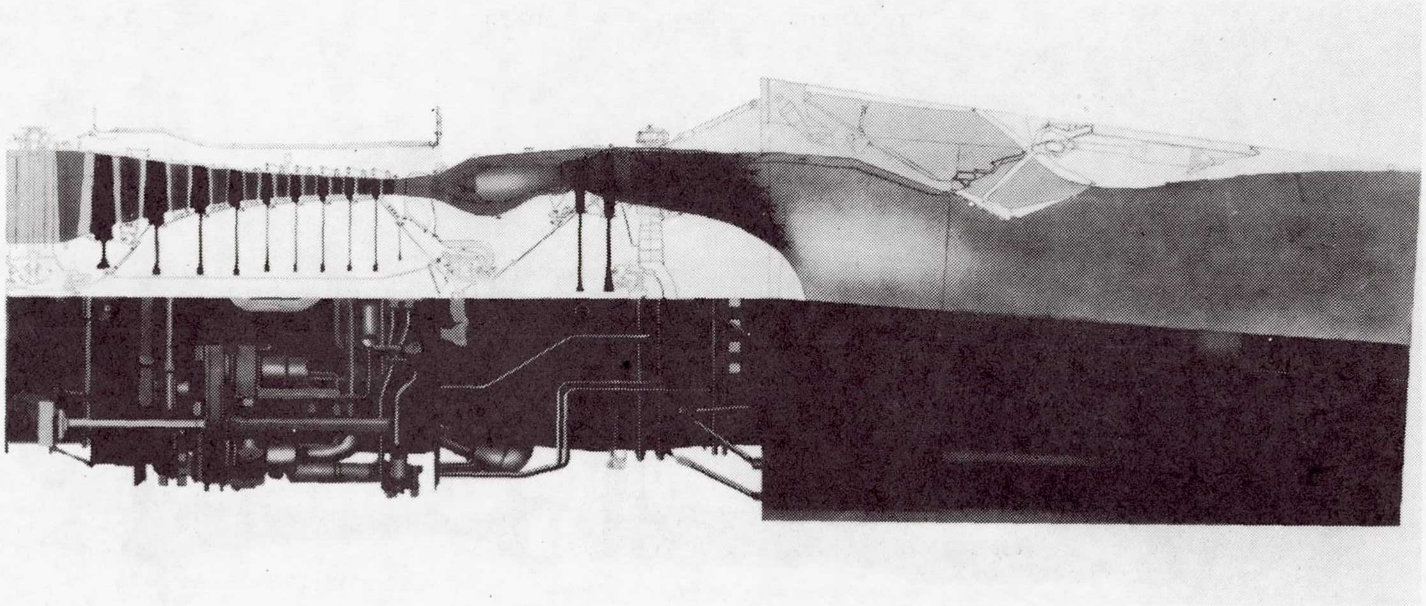

Figure 3.- GE4/J5 M2.7 turbojet.

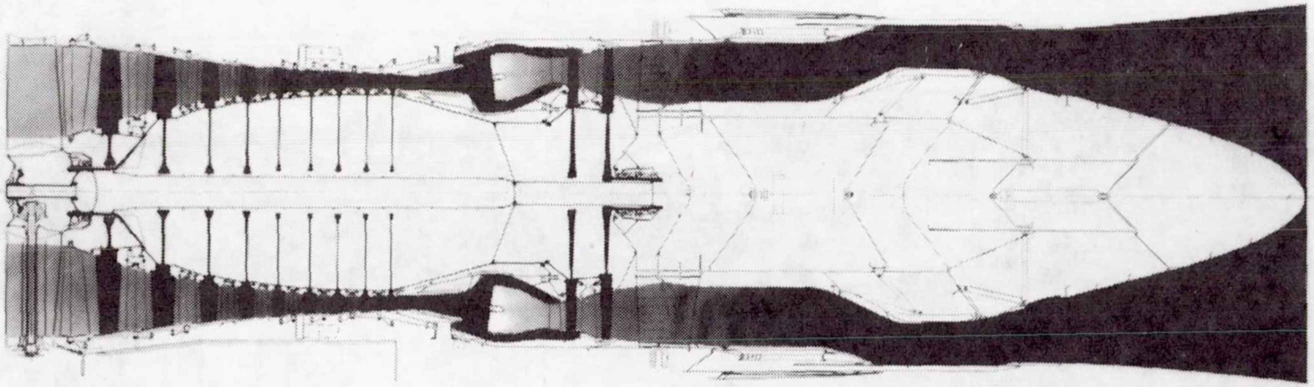

Figure 4.- GE4/J6H turbojet.

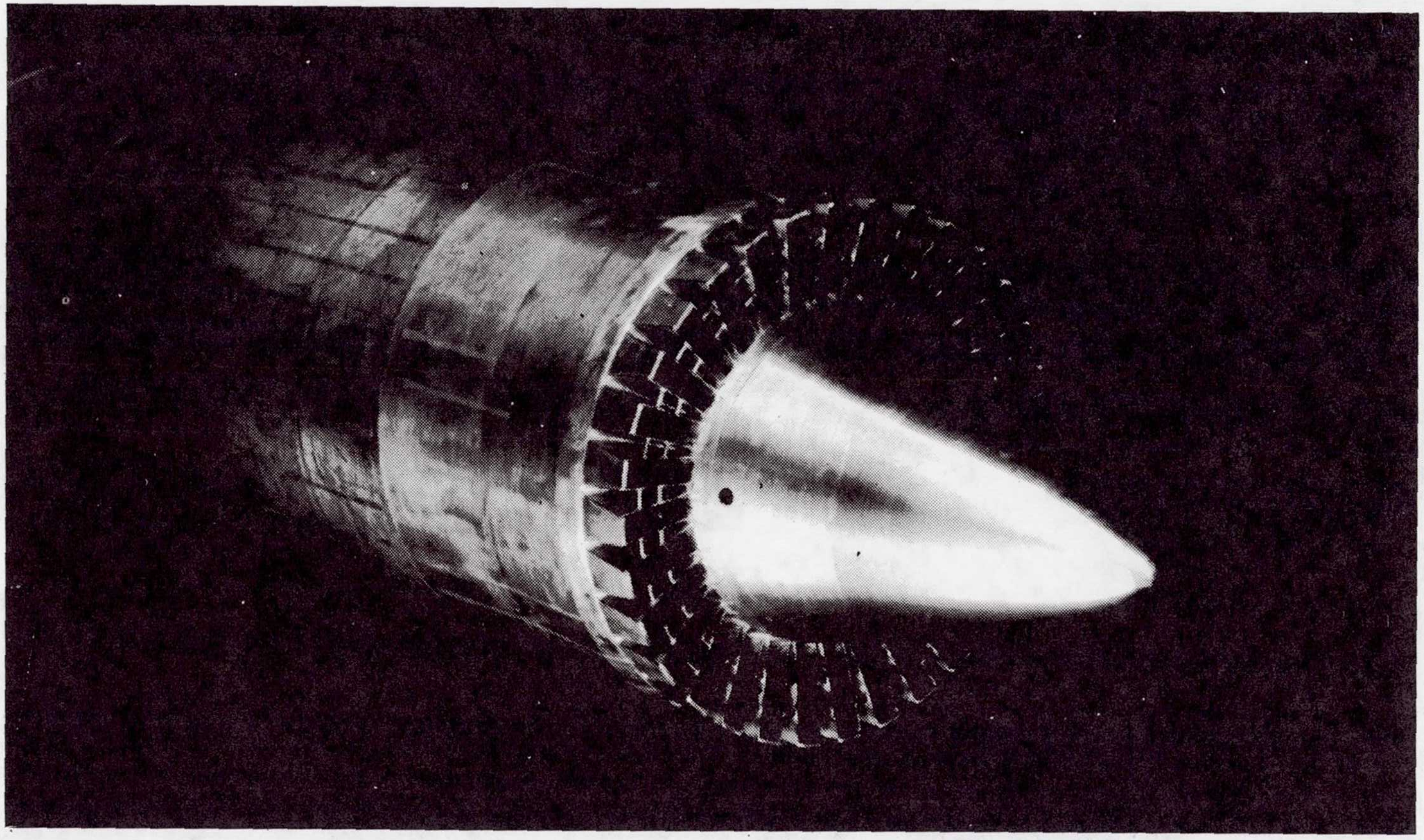

Figure 5.- GE4/J6H suppressor model — 32 chutes.

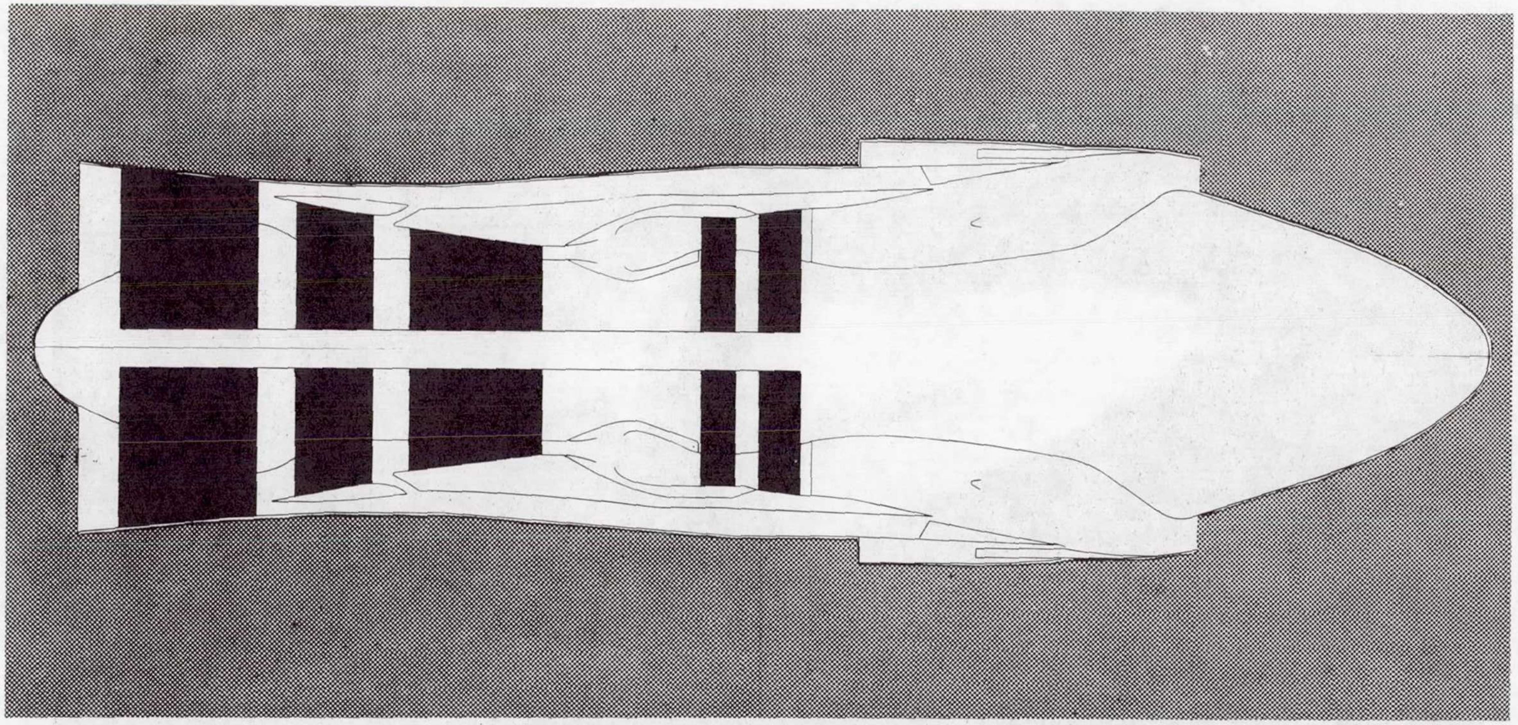

Figure 6.- AST-VCE.

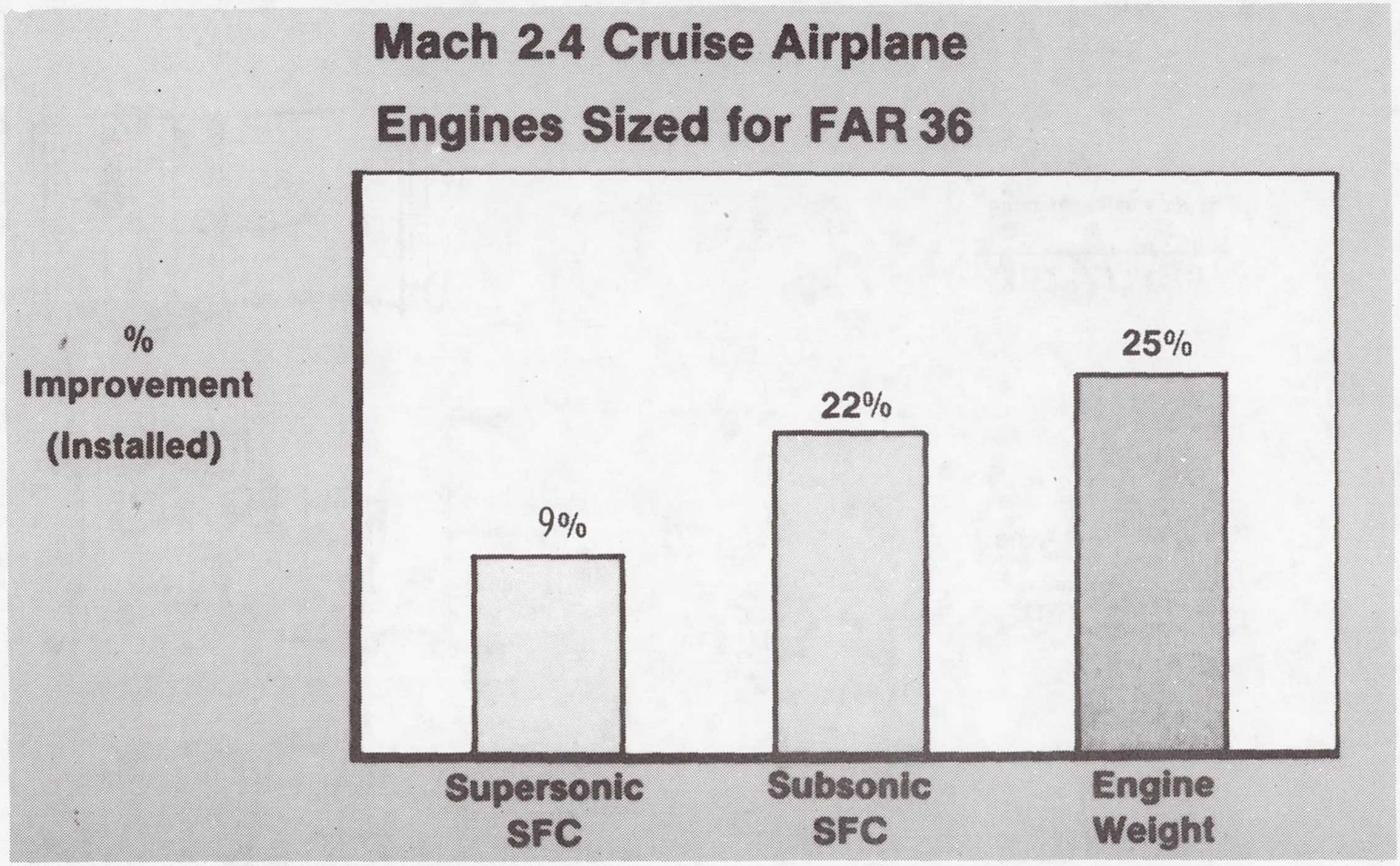

Figure 7.- Comparison of AST-VCE and GE4/J6.

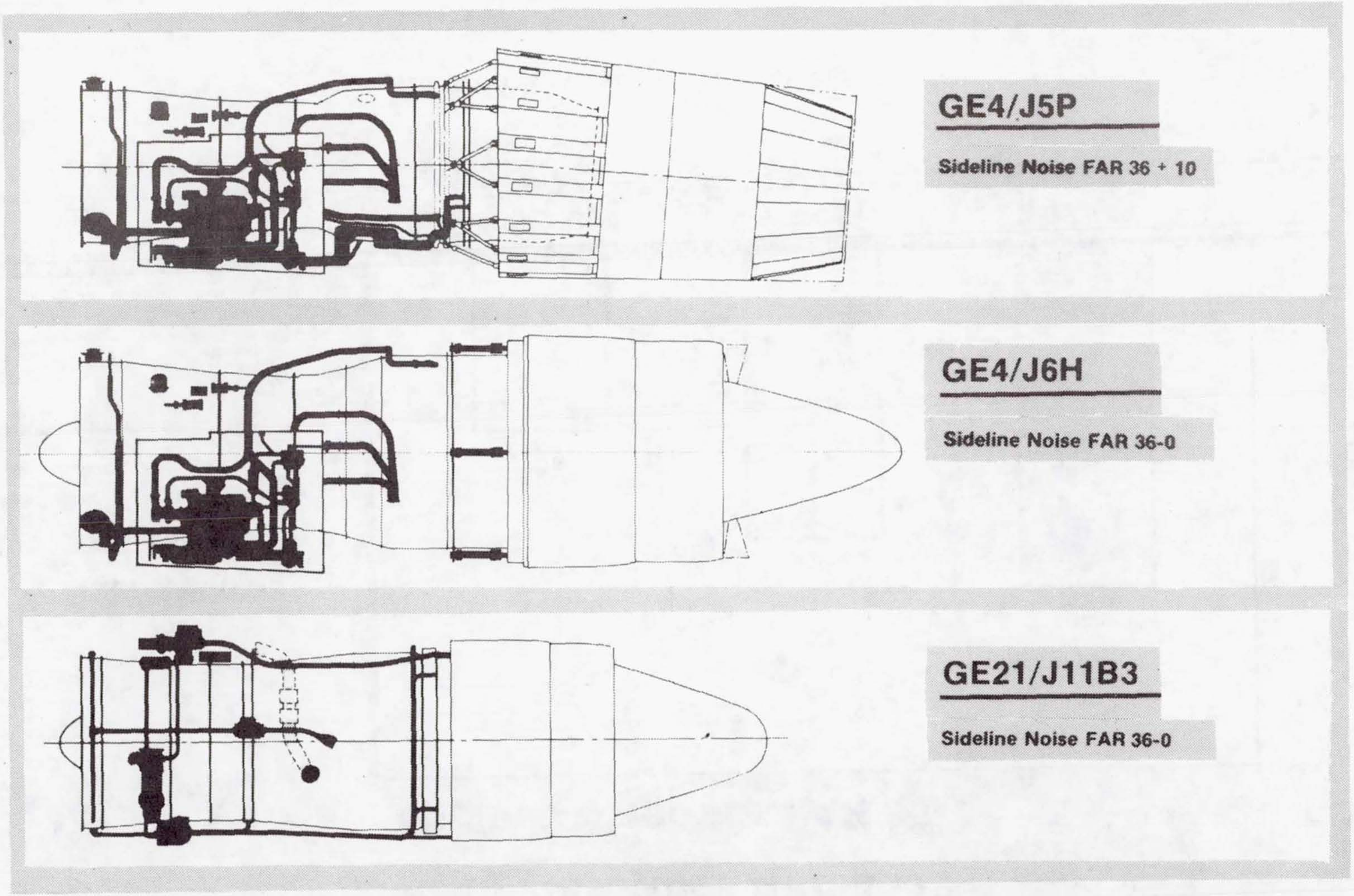

Figure 8.- Engine installation comparison.

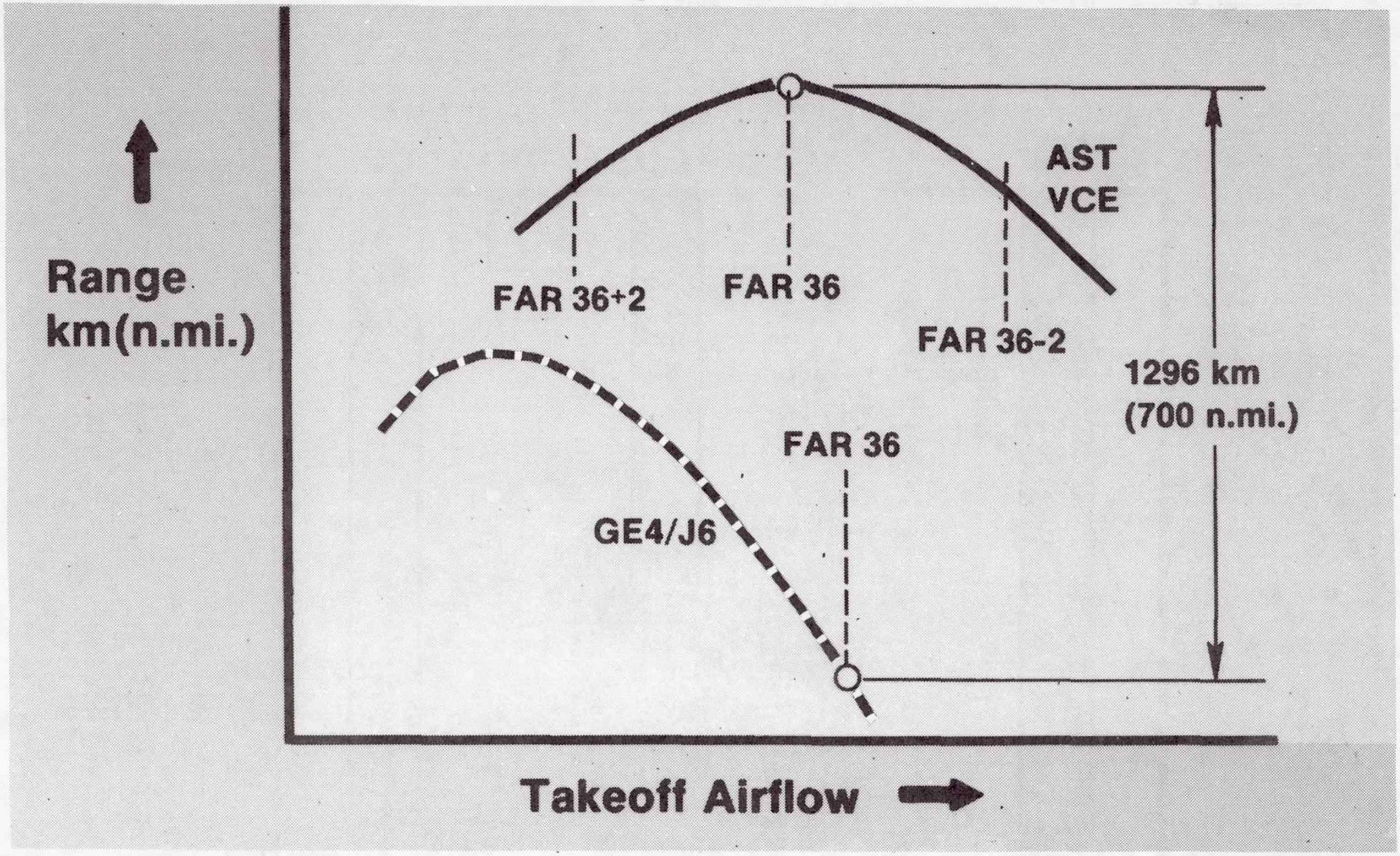

Figure 9.- VCE range improvement.

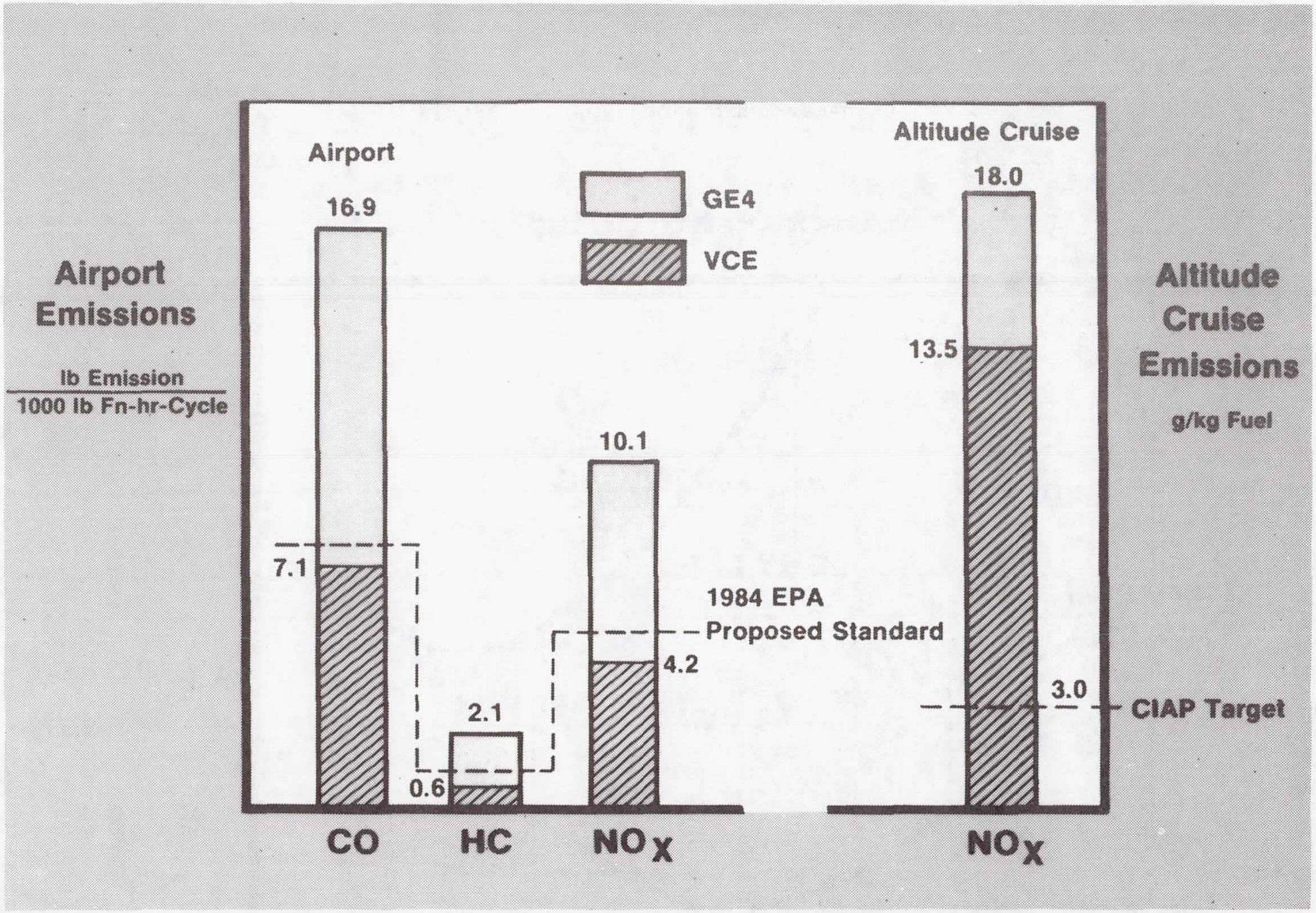

Figure 10.- Emission levels. (To convert from $\frac{\text{lb}}{\text{1000 lb-Fn-hr-cycle}}$ to $\frac{\text{kg}}{\text{kN-Fn-hr-cycle}}$, multiply by 9.807, where Fn is engine net thrust.)