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Supersonic STOVL Aircraft With Turbine Bypass/Turbo-Compressor Engines

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TURBINE BYPASS/TURBO-COMPRESSOR ENGINES

by

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ABSTRACT

Engine performance and mission studies were performed to compare three propulsion systems for a Mach 2 STOVL fighter. The three propulsion systems are: (1) turbine bypass engine with a turbo-compressor used for STOVL only, (2) turbine bypass engine with a turbo-compressor for both STOVL and thrust during forward flight, and (3) mixed flow afterburning turbofan with a remote burner lift system. In the first system, (1), the main engines have afterburners and the turbo-compressors use afterburning during STOVL. In the second system, (2), the turbine bypass engines are dry and the turbo-compressors have afterburners.

The mission used in the study is a deck launched intercept mission. The aircraft used is the NASA-Langley twin boom concept having a takeoff gross weight of 47000 lbm.

The results of the study indicate that large improvements in combat time (50 to 400 percent) are possible when the turbo-compressors are used for both lift and thrust for forward flight.

NOMENCLATURE

BPR	bypass ratio
CET	combustor exit temperature, °R
F	thrust
FPR	fan pressure ratio
ft	feet
hr	hour
lbf	pounds force
lbm	pounds mass
MAX	maximum
min	minute
n.mi	nautical miles
OPR	engine overall pressure ratio
R	degree Rankine
sec	second
SFC	specific fuel consumption, lbm/hr/lbf
TAUG	augmentor temperature, °R
W	weight, lbm
W _a	engine airflow, lbm/sec
WG	aircraft gross weight, lbm

Subscripts

ENG	engine
MAX	maximum

INTRODUCTION

Providing a short takeoff and vertical landing (STOVL) capability for a supersonic aircraft poses many challenges in propulsion system design. A wide variety of propulsion concepts have been studied for providing jet lift including ejectors, remote burners, and fans and dedicated lift engines¹⁻³. In all of these concepts, the lift system represents a penalty in weight for the rest of the aircraft mission. Also, the aircraft aerodynamics are compromised due to the added volume needed to house the lift system. The tandem fan concept is an approach that is being studied in which the main engine provides both lift and thrust⁴⁻⁵. This concept employs a dual fan arrangement in which the front fan discharge air is diverted downward during vertical operation and converts to a conventional turbofan for forward flight.

The turbojet would be a simple, compact engine for a supersonic STOVL aircraft. An undesirable feature of the turbojet for this application is that hot jet exhaust gas must be ducted to the forward lift system. Another problem is that it is not well suited for aircraft that require wide variations in throttle for extended periods of time and whose missions require significant supersonic and subsonic range capabilities.

A means of adapting the turbojet for these requirements is provided by the turbine bypass engine (TBE). In this concept shown schematically in figure 1, a variable bypass system is employed to improve the turbojet performance for wide variations in throttle settings. The bypass system directs some of the compressor discharge air around the burner and turbine, and reinjects it into the nozzle. At maximum dry power (high turbine inlet temperature) operation the amount of bypass air is at a maximum and at low power the bypass fraction is reduced or the bypass is turned off completely. This concept was first studied by Boeing in their commercial supersonic transport studies. A later study of this concept for a commercial supersonic transport is reported in reference 6.

More recently, the TBE is being studied for military aircraft. The bypass system is an attractive means of powering lift systems for STOVL aircraft. In reference 3, two lift systems powered by the TBE bypass air were studied: a remote burner system and a remote turbo-compressor lift system. The results reported in reference 3 indicate the TBE/turbo-compressor is

an attractive system for STOVL aircraft. The turbo-compressor provides an adequate thrust level for easier airplane thrust balance. It also provides a source of power for the reaction control systems.

An additional feature of the TBE/turbo-compressor that deserves study is the use of the turbo-compressor for both STOVL operation and thrust for the rest of the mission. This would have the advantage of reducing the main TBE engine size. Also, both the single spool TBE and the turbo-compressor are relatively simple turbomachines.

With these motivations, an in-house study has been initiated at NASA-Lewis to quantitatively determine the benefits of extending the turbo-compressor duty to horizontal flight.

In this study, three propulsion systems for STOVL aircraft are being studied: (1) TBE with turbo-compressor for STOVL only, TBE/(TC-STOVL only), (2) TBE with turbo-compressor for both STOVL and cruise, TBE/(TC-STOVL & cruise), and a mixed flow afterburning turbofan with a remote burner (TF/RALS). Engine performance, weight, and mission analysis are being performed for these three concepts. The potential of the engines is assessed in terms of mission radius and combat time. This paper provides some preliminary results of these studies.

DESCRIPTION OF THE ENGINES

Schematics of the three propulsion systems are shown in figure 2. The TBE engine is a single spool turbojet. The turbofan is a mixed flow, two spool engine. The turbo-compressor has an axial-centrifugal fan driven by a two stage axial turbine. The turbine is driven by high pressure compressor bypass air from the TBE engines. The turbo-compressor and the turbofan are equipped with afterburners. In the TBE/(TC-STOVL only) system, the TBE's are equipped with afterburners. In the TBE/(TC-STOVL & cruise) system, the TBE engines are dry.

The TBE/(TC-STOVL only) and the TBE/(TC-STOVL & cruise) propulsion systems and their modes of operation are shown in figures 3 and 4. The modes of operation for the TF/RALS system are the same as for the TBE/(TC-STOVL only) system. As shown in figure 3 for the TBE/(TC-STOVL only) system, the TBE engines are at maximum afterburning power during the takeoff roll, (1), and the turbo-compressors are inoperative. Note that all of the bypass air is directed into the main engine nozzle. At lift-off, (2), the bypass air is directed to the turbo-compressors which operate at maximum afterburner power to provide the pitch-up force for lift-off. The main engine nozzles are directed at a downward angle. Operation of the turbo-compressors would have to be initiated before lift-off to allow time for the turbo-compressors to spool up.

For subsonic cruise, (3), (turbo-compressors inoperative), the TBE engines are throttled back to about 25 percent of maximum dry power and no compressor air is bypassed. During climb and combat, (4), the TBE engines are operated at maximum power and at intermediate afterburning

power for supersonic dash. For the vertical landing, the main engine maximum dry thrust is directed downward at a 90° angle with the turbo-compressor operating at maximum afterburning power.

The various operational modes of the TBE/(TC-STOVL & cruise) are depicted in figure 4. Since the turbo-compressor is used at all times, the bypass air is "on" at all times to power the turbo-compressor. During the takeoff roll, (1), the TBE engines are at maximum power and the turbo-compressor thrust is directed aft at maximum afterburning power. At lift-off, (2), the main engine nozzle is directed at a downward angle. The turbo-compressors are still at maximum afterburning power and the thrust is diverted downward by a ventral nozzle. At subsonic cruise, (3), the TBE engines and the turbo-compressors are throttled back. During climb and combat, the main engines and the turbo-compressors are at maximum power. For vertical landing, (5), the main engine maximum dry thrust is diverted downward and the turbo-compressor maximum afterburning thrust is directed downward by the ventral nozzle.

METHOD OF ANALYSIS

The study reflects differences in engine thrust and SFC, and nacelle and engine weights. Mission performance calculations were made to determine mission radius and combat time for a fixed takeoff weight and payload.

The mission is for a deck launched intercept type aircraft with a Mach 2 supersonic dash capability.

The mission profile is shown in figure 5.

The total radius calculated is the total of climb/acceleration, cruise and letdown ranges. Fuel reserves include an enroute contingency of 5 percent of the mission fuel and provision for a 10 minute loiter.

The airplane used in the study is a twin boom fighter design from NASA-Langley. Two versions of the airplane were studied. In figure 6, the airplane is equipped with the TBE/(TC-STOVL only) engines in which the turbo-compressors are used for lift only. As shown in the figure, the two turbo-compressors are located between the two TBE engines with inlet doors on the top of the fuselage and exhaust doors on the fuselage underside. The airplane used for the TF/RALS is the same as shown in figure 6 with the TBE/(TC-STOVL only) engines replaced by the TF/RALS system. The nacelle weight and volume were adjusted to accommodate differences in engine size. In figure 7 the airplane is equipped with the TBE/(TC-STOVL & cruise) engines in which the turbo-compressors are operated for the entire mission. As shown in the figure, the turbo-compressors are located outboard of the main TBE engines in separate compartments. The nacelle weight and volume were adjusted for the TBE engines and the added volume and weight for the turbo-compressors. These weight penalties were charged to the propulsion system.

Engine cycle and sizing optimization studies have, as yet, not been completed. For the purposes of this preliminary study cycle parameters were selected that would result in representative engines for this application. The engines were sized for a thrust loading (F/WG) of 1.1 which is considered to be a reasonable value of thrust for this mission. The engine characteristics are shown in Table I.

The installed engine performance for the three systems was computed with the engine cycle computer code of reference 7 which performs cycle calculations, design, and off-design on a component by component basis. Installation losses include inlet and nozzle drags.

Baseline engine weights for the turbine bypass engines, the mixed flow turbofan and the turbo-compressor were obtained from the study reported in reference 3. The final report of this study will be available in the near future. The base line engine weights and dimensions were scaled for the engine sizes computed in this study.

RESULTS AND DISCUSSION

Engine Performance and Weight - As mentioned previously, all of the engines are sized for a sea level static thrust to airplane gross weight ratio of 1.1 (51700 lbf). The resulting sea level static engine airflows are shown in Table I. A comparison of the performance of these engines at Mach 0.8 is shown in figure 8. For the combat maneuver, minimum SFC at maximum thrust is a critical element in terms of combat time. As shown in the figure, all three engine have about the same maximum thrust at this flight condition. It should be emphasized that for the TBE/TC-STOVL & cruise) system, the TBE engines are dry and the turbo-compressors are at maximum afterburn. The turbofan and the TBE main engines for the TF/RALS and the TBE/TC-STOVL only) systems are at maximum afterburning power. The maximum power SFC of the turbofan is about 25 percent higher than that of the TBE/TC-STOVL only) and about 35 percent higher than that of the TBE/TC-STOVL & cruise) system. As will be shown later, this has a large impact on the combat time capabilities of these airplanes. As mentioned in the Introduction, one of the attractive features of the TBE is its efficient performance for wide variations in power settings. As seen in figure 8, the TBE engines are operating at 25 percent of maximum dry power for cruise and the turbofan operates at about 38 percent of maximum dry power. The SFC's of the three systems are about the same at this operating condition. The TBE/TC-STOVL & cruise) system SFC is about 3 percent higher than that of the TBE/TC-STOVL only) systems and about 5 percent higher than the TF/RALS system.

Figure 9 shows the Mach 2 engine performance of the three systems. The TF/RALS achieves the highest maximum thrust, but its SFC is 20 percent higher than the TBE systems. At the cruise power setting, the SFC of the TBE/TC-STOVL & cruise) system is about 2 percent higher than that of the TBE/TC-STOVL only) system and 4 percent lower than that of the TF/RALS system.

As also mentioned in the Introduction, another motivation in exploring the TBE/TC systems is the possibility of reducing the overall propulsion system weight. This is accomplished by reducing the size and weight of the main engines having a $F/W_{eng} \sim 8$ and obtaining the additional required thrust from the turbo-compressor having a $F/W_{eng} \sim 18$. As seen in Table I, the sea level static airflow of the TBE/TC-STOVL & cruise) ($W_a = 190$ lbm/sec) is the smallest of the three systems investigated. The reduction in the overall propulsion system weight is shown in figure 10. In this figure, a comparison of the aircraft weight breakdown is shown for the three engine systems. The TBE/TC-STOVL & cruise) propulsion system weight is the lowest of the three systems. It is about 24 percent less than the weight of the TF/RALS and about 40 percent less than the TBE/TC-STOVL only) system. Since the takeoff gross weight is the same for all three airplanes, the TBE/TC-STOVL & cruise) airplane can carry 11 percent more fuel than the TF/RALS airplane and 20 percent more fuel than the TBE/TC-STOVL only) airplane.

Mission Studies It was shown in figures 8 and 9 that the subsonic and supersonic SFC's at the cruise operating points are about the same for all three propulsion systems. The fuel consumed during the cruise parts of the mission, therefore, is about the same for the three systems. The differences between the three systems in terms of mission radius and combat time for this mission are the differences in the amount of fuel available for combat and the maximum power SFC. Figure 11 shows the combat fuel allowance for the three propulsion systems. As mentioned before, figure 10 shows the TBE/TC-STOVL & cruise) propulsion system weight is much less than the other two systems. This results in a much higher combat fuel allowance as shown in figure 11. The combat fuel allowance for TBE/TC-STOVL & cruise) system is 50 percent higher than the other two at a 100 N.Mi radius and 150 percent higher at a 300 N.Mi radius. Even though the TF/RALS total fuel load is somewhat higher than that of the TBE/TC-STOVL only) airplane (figure 10), the combat fuel allowance is about the same because more climb/acceleration fuel is required for the TF/RALS than for the TBE/TC-STOVL only).

Figure 12 compares the combat time and mission radius of the three systems. Since the TBE/TC-STOVL & cruise) system has a better combat SFC (figure 8) and much more fuel available (figure 11) than the other two systems, its combat time capability is much longer. Its combat time is about 50 percent longer for the lower mission radius and 4 times longer at the higher radius. The TBE/TC-STOVL only) system has a 25 percent advantage over the TF/RALS in terms of combat time. This is because the TBE/TC-STOVL only) system has a better combat SFC (figure 8) and the two airplanes have the same combat fuel allowance (figure 11).

CONCLUDING REMARKS

The mission results of this study show that large improvements in combat time (50 to 400 percent) can be achieved by the TBE/turbo-

compressor if the turbo-compressor is used for both STOVL operations and thrust for the rest of the mission. When the turbo-compressor is used for STOVL only, the TBE/turbo-compressor would improve the combat time by about 25 percent compared to a TF/RALS system.

The engine performance studies show that the TBE engines have better combat performance than a mixed flow afterburning turbofan. They have about the same performance during subsonic and supersonic cruise if the engines are sized for high thrust loading (F/WG). For low thrust loading, the TBE engines would have better supersonic cruise performance and about the same subsonic cruise performance as the turbofan.

The preliminary nature of this study necessitated the use of approximate methods especially in estimating the weight of the turbo-compressor and changes to the aircraft structure, weight, and aerodynamics which may be somewhat optimistic. However, considering the large benefits promised by this system, it is believed that these benefits may be reduced somewhat if more exact methods are used, but would still be obtainable.

In addition to the technology advances projected for future engines in materials, cooling, controls, etc., two key technologies unique to the TBE/(TC-STOVL & cruise) system are in the turbine bypass system and the turbo-compressor. The effect of varying airflows on combustor and turbine performance has to be studied. A turbo-compressor such as the one used in this study would be a relatively new concept. Most of the past work on remote fans has been for dedicated lift or auxiliary power. In contrast, this turbo-compressor would be part of the main powerplant operating over a wide range of flight conditions.

Future studies planned for the TBE/turbo-compressor engines include engine cycle optimization; TBE/(TC-STOVL & cruise) systems in which the TBE's are equipped with afterburners and TBE/(TC-STOVL & cruise) systems in which the turbo-compressors are limited to subsonic flight conditions. Additional studies would also include dry turbo-compressors for a cool footprint. This would also alleviate the impact of inlet reingestion on the engine operation since the exhaust gas would be much cooler compared to an afterburning lift system or a dedicated lift engine.

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TABLE I - ENGINE CHARACTERISTICS

Characteristic	TBE/TC STOVL only	TC	TBE/TC STOYL & Cruise	TF/RALS
BPR	0.30	2.0	0.30	1.0
FPR	---	3.0	---	3.5
OPR	20.0	----	20.0	20.0
CET max, R	3500	----	3500	3500
TAUG max, R	3960	3960	- -	3960
F/WENG	^a 8.0	18.0	^b 7.7	^a 8.0
F/WG	^c 1.1	---	^d 1.1	^c 1.1
Wa	230 ←	80	65 →	190

- ^aMain engines afterburning, turbo-compressors not open
- ^bMain engines dry; turbo-compressors afterburning; with main engines afterburning also F/WG=9.0
- ^cMax axial thrust of main engines
- ^dMax axial thrust of main engines and turbo-compressors

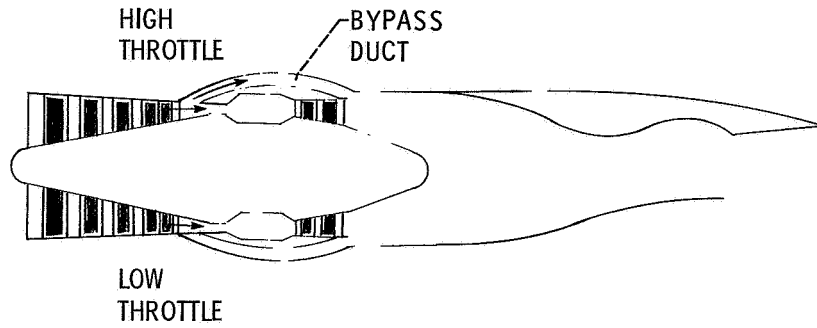


Figure 1. - Turbine bypass engine.

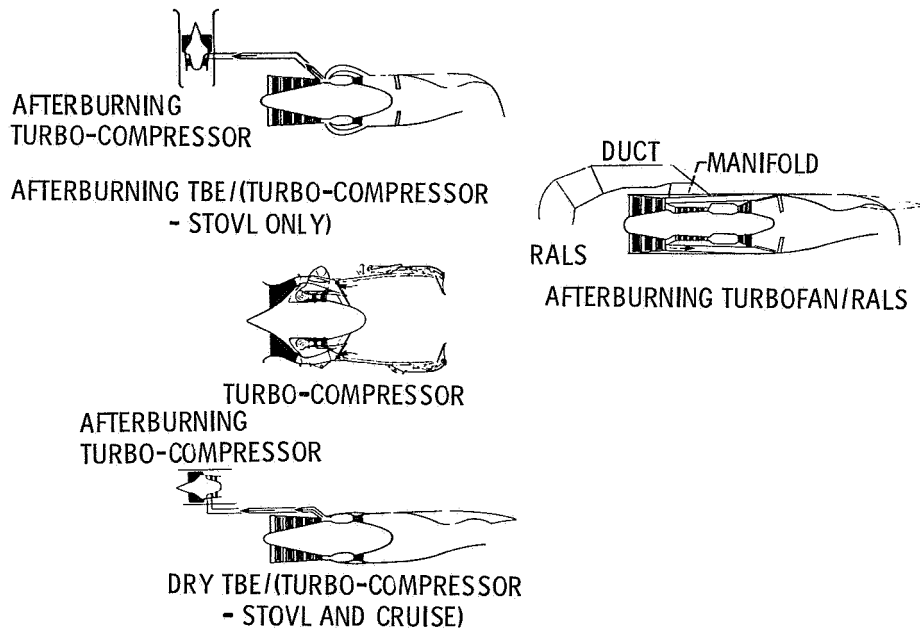


Figure 2. - STOVL propulsion systems.

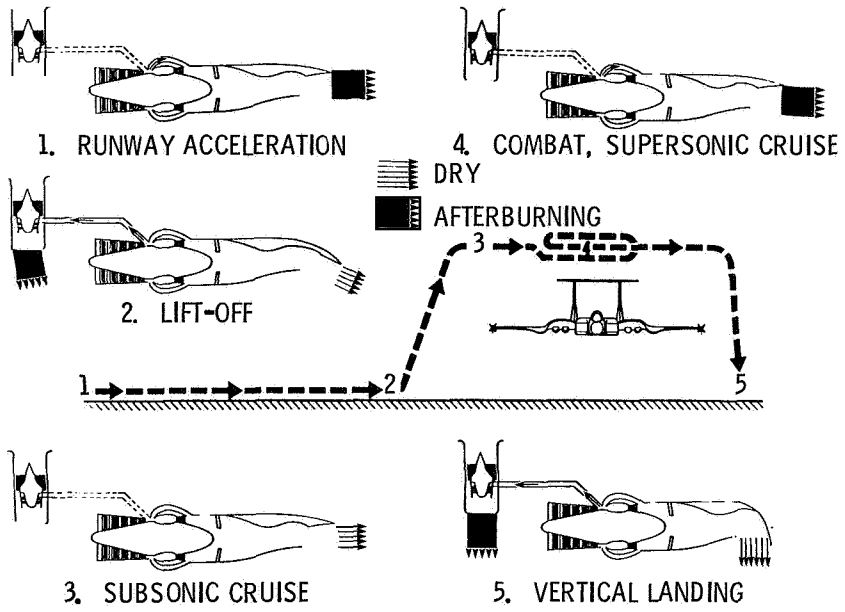


Figure 3. - TBE/turbo-compressor lift engine propulsion modes for super-sonic STOVL.

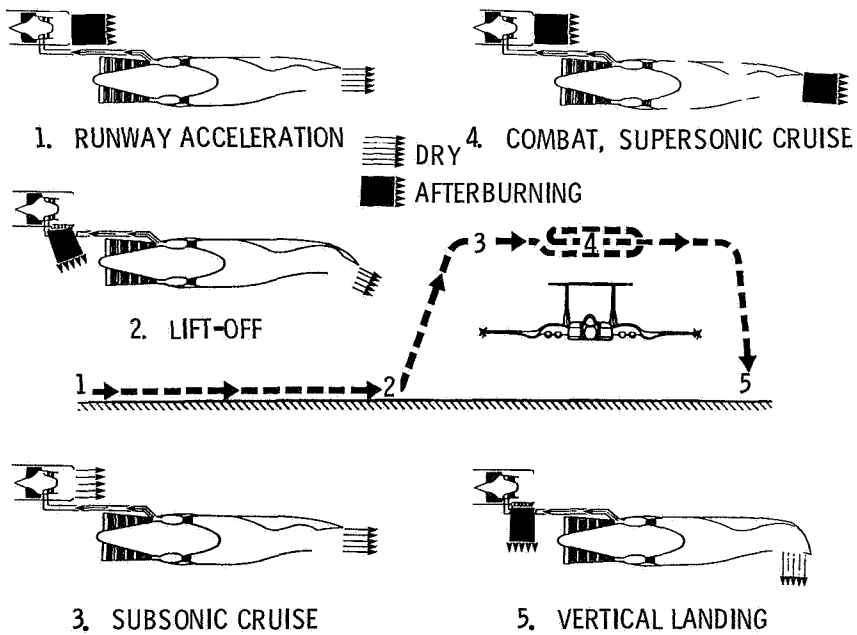
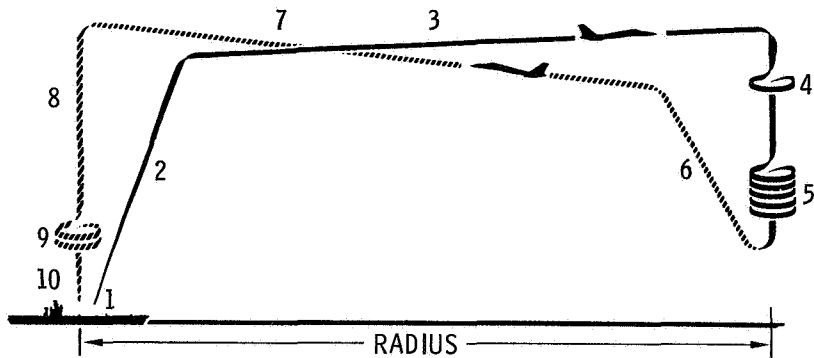


Figure 4. - TBE/turbo-compressor lift and cruise engine propulsion modes for super-sonic STOVL.



1. SHORT TAKEOFF
 2. CLIMB; MAXIMUM POWER
 3. CRUISE; MACH 2; OPTIMUM ALTITUDE
 4. 1/2 TURN; MACH 2; 50 000 ft
 5. COMBAT; MAXIMUM POWER; MACH 0.8; 21 000 ft
 6. CLIMB; MAXIMUM POWER
 7. CRUISE; MACH 0.8; OPTIMUM ALTITUDE
 8. DESCENT
 9. LOITER 10 min; MACH 0.45; 15 000 ft
 10. VERTICAL LAND
- RESERVES - 10 min LOITER AND 5 PERCENT MISSION FUEL
 PAYLOAD - 4600 lbm

Figure 5. - Mission profile.

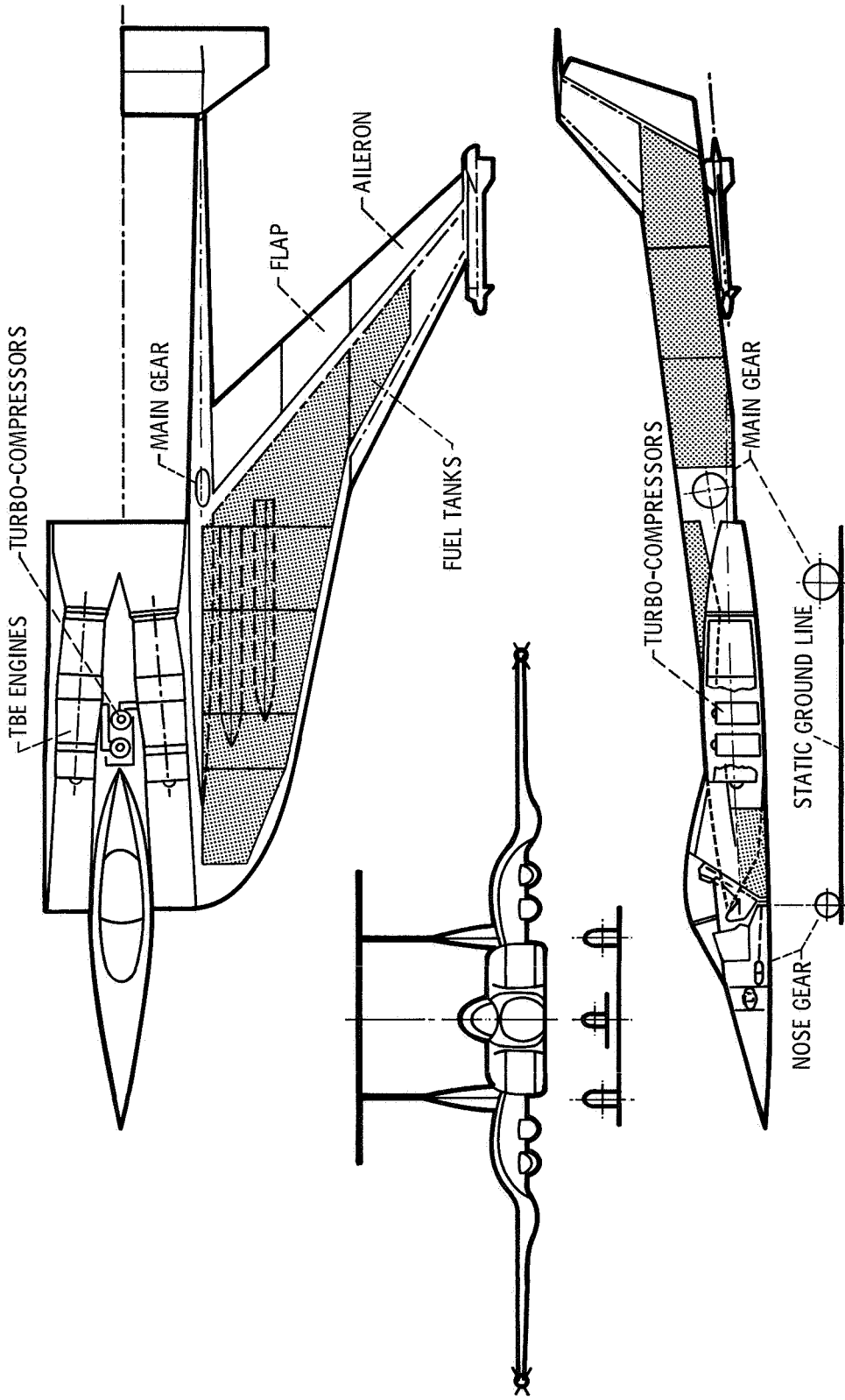


Figure 6. - Twin boom airplane with TBE/turbo-compressor lift engines.

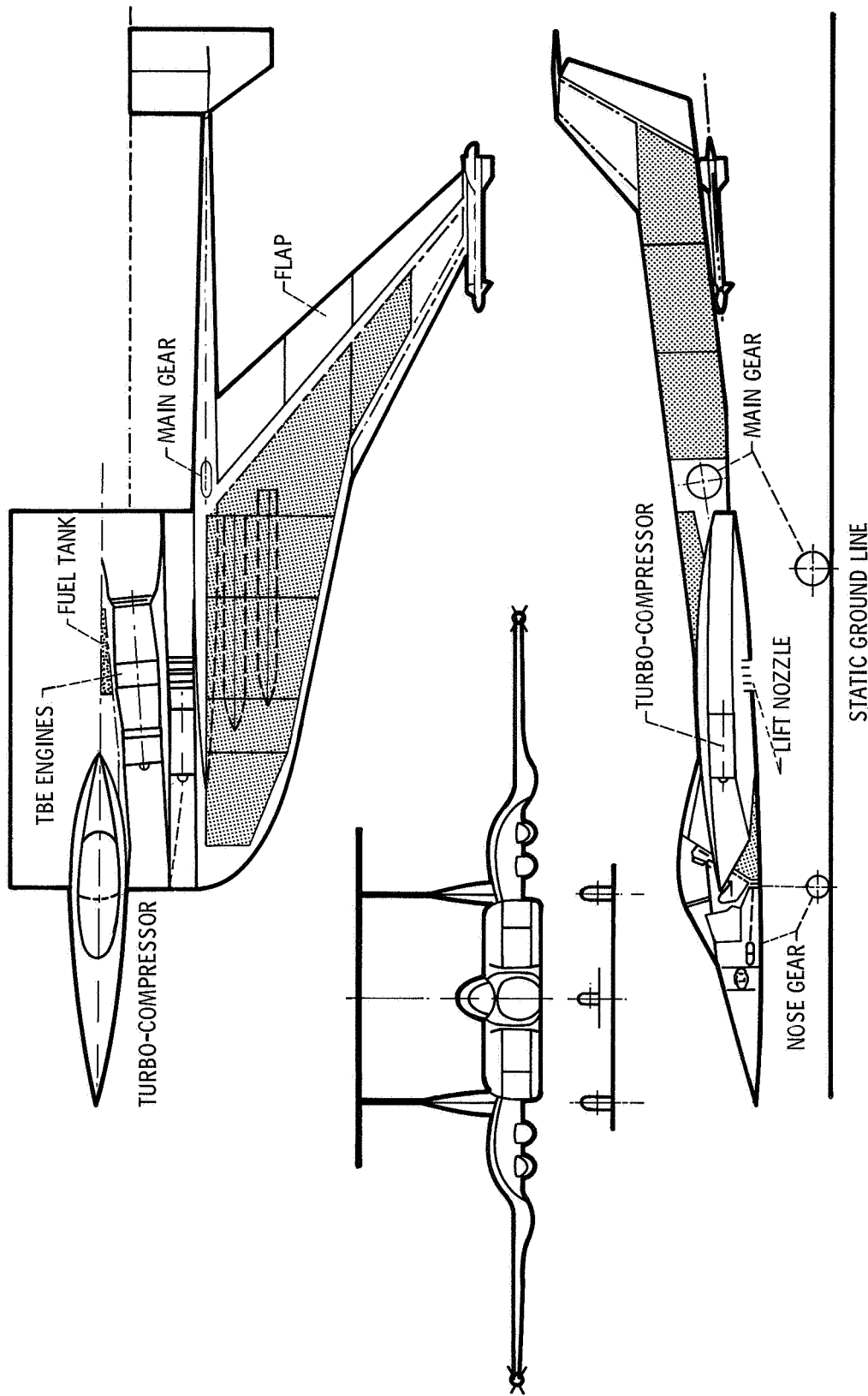


Figure 7. - Twin boom airplane with TBE/turbo-compressor lift and cruise engines.

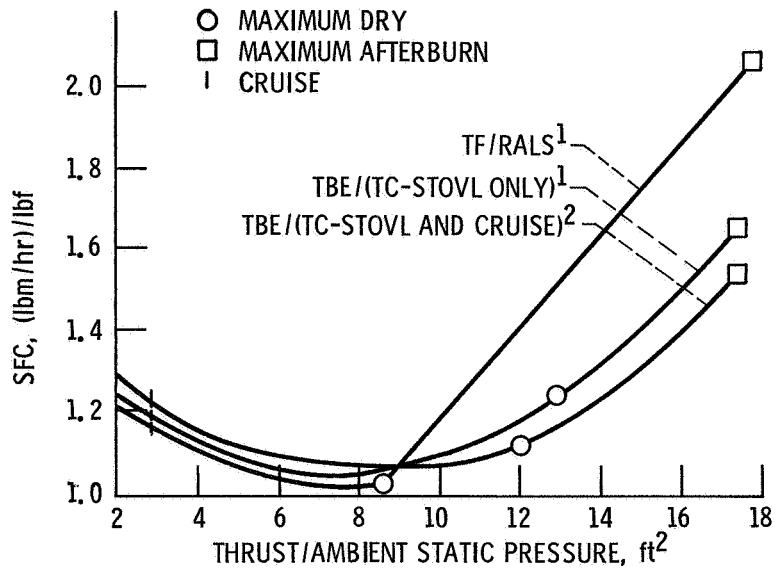


Figure 8. - Engine performance comparisons at Mach 0.8; sea level static thrust/takeoff gross weight, 1.1. Notes: 1. main engine afterburning; 2. main engine dry, turbo-compressor afterburning.

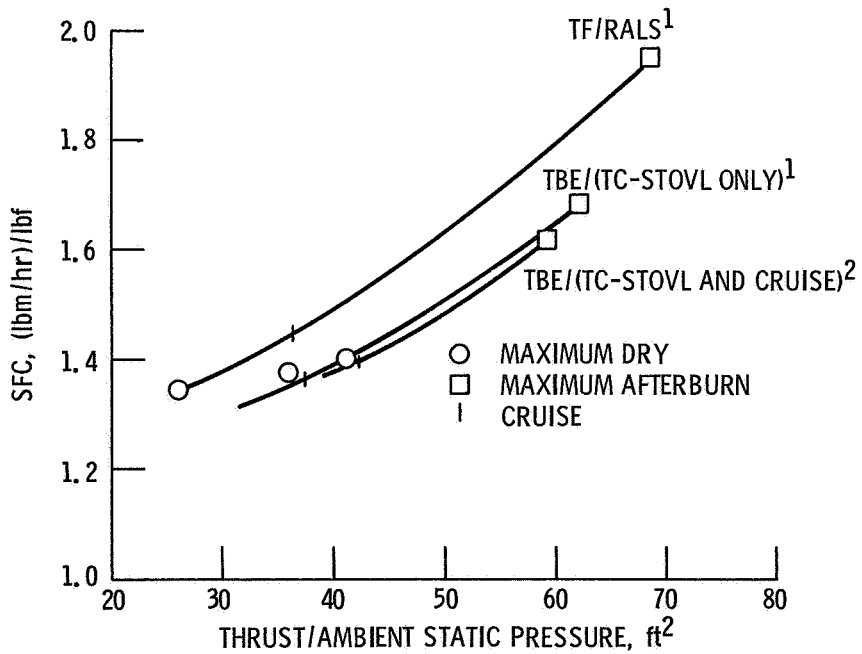


Figure 9. - Engine performance comparisons at Mach 2.0; sea level static thrust/takeoff gross weight, 1.1. Notes: 1. main engine afterburning; 2. main engine dry, turbo-compressor afterburning.

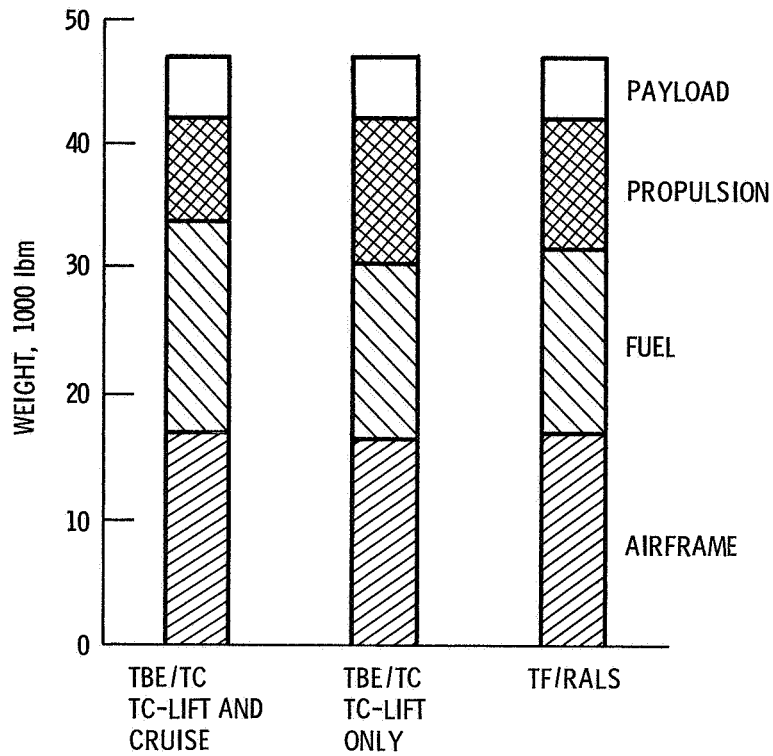


Figure 10. - Aircraft weight breakdown comparisons; takeoff gross weight, 47 000 lbm; sea level static thrust/takeoff gross weight, 1.1.

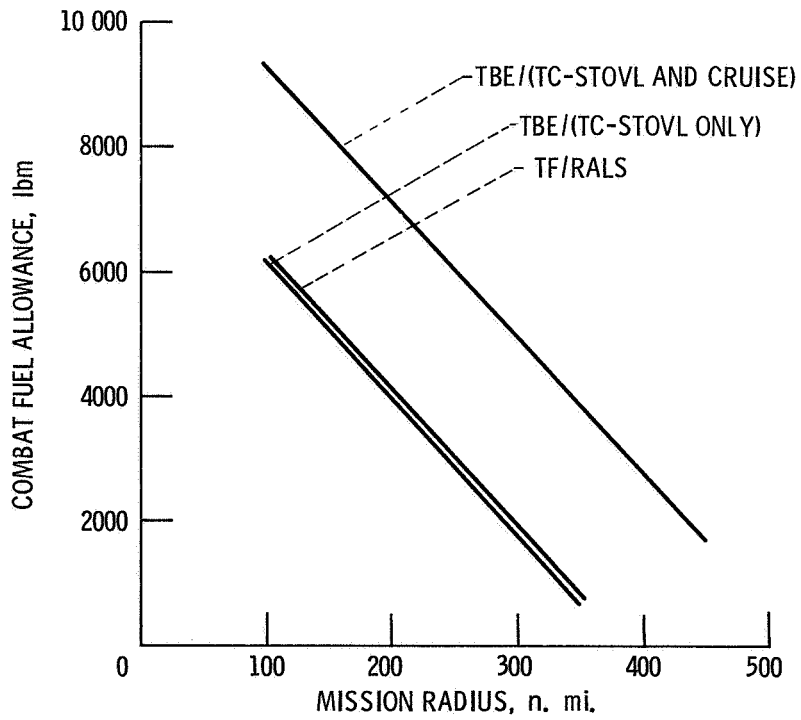


Figure 11. - Comparison of fuel available for combat; take-off gross weight, 47 000 lbm; sea level static thrust/takeoff gross weight, 1.1.

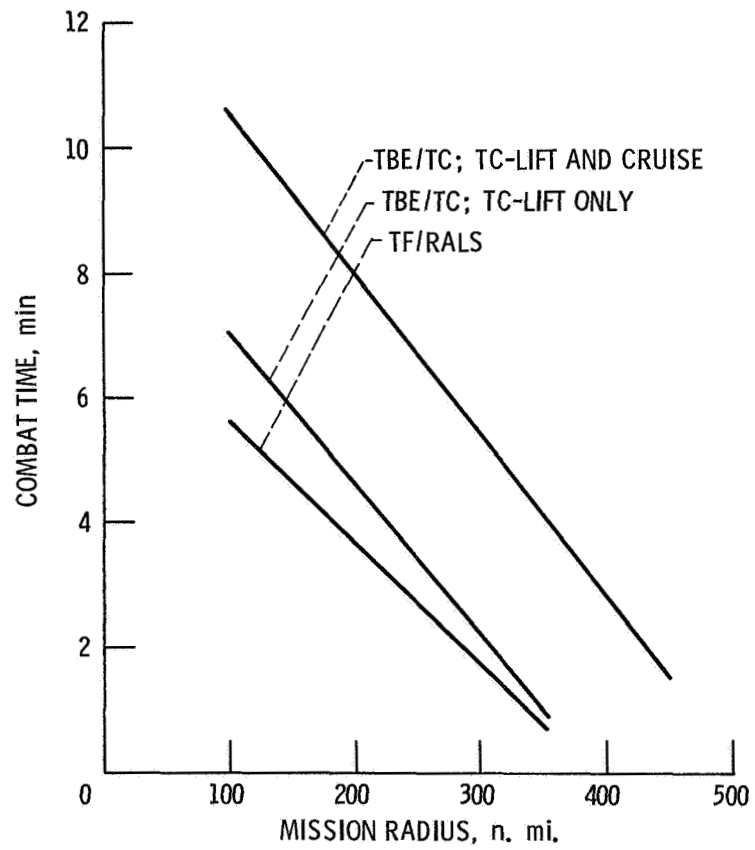


Figure 12. - Combat time versus mission radius; Mach 0.8; 20 000 ft combat; gross weight, 47 000 lbm; sea level static thrust/gross weight, 1.1.

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