NASA Technical Memorandum 88808

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(NASA-TM-88808) A PARAMETRIC STUDY OF A GAS-GENERATOR AIRTURBO RAMJET (ATR) (NASA) 19 p CSCL 21E

N86-31586

Unclas

G3/07 43524

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Prepared for the
22nd Joint Propulsion Conference
cosponsored by the AIAA, ASME, SAE, and ASEE
Huntsville, Alabama, June 16–18, 1986

NASA

E-3156

A PARAMETRIC STUDY OF A GAS-GENERATOR AIRTURBO RAMJET (ATR)

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SUMMARY

Parametric engine performance calculations were carried out for an airturbo ramjet (ATR). A LOX-LH2 rocket-powered turbine powered the compressor. The engine was "flown" over a typical flight path up to Mach 5 to show the effect of engine off-design operation.

The compressor design efficiency, compressor pressure ratio, rocket-turbine efficiency, rocket-turbine inlet temperature, and rocket-chamber pressure were varied to show their effect on engine net thrust and specific impulse at Mach 5 cruise.

Estimates of engine weights as a function of the ratio of compressor air to rocket propellant flow and rocket chamber pressure are also included.

In general, the Mach 5 results indicate that increasing the amount of rocket gas produced increased thrust but decreased the specific impulse. The engine performance was fairly sensitive to rocket-chamber pressure, especially at higher compressor pressure ratios. At higher compressor pressure ratios, the engine thrust was sensitive to turbine inlet temperature. At all compressor pressure ratios, the engine performance was not sensitive to compressor or turbine efficiency.

INTRODUCTION

There is renewed interest in high speed (supersonic and hypersonic) aircrafts (ref. 1); NASA is presently studying possible engine cycles and the corresponding required technology for these cycles. One cycle that is being considered is the airturbo ramjet (ATR) (ref. 2). The ATR has a compressor necessary for thrust at low Mach numbers. The compressor is driven by a turbine supplied with a relatively cool fuel-rich gas from a gas generator. The fuel-rich gas mixes with the compressor discharge air after the turbine and is burned. This combination of turbine, gas generator, and compressor enables this engine to takeoff and accelerate to cruise at Mach 5.

A parametric cycle study of an ATR using a liquid hydrogen-liquid oxygen gas generator was performed to determine the effects of the compressor pressure ratio, compressor efficiency, turbine efficiency, turbine inlet temperature, gas-generator design pressure, and gas-generator mass flow on thrust and specific impulse at Mach 5 cruise. The ranges of these parameters are given in table I. The gas-generator mass flow is not a parameter varied directly, gas-generator mass flow varies to match turbine flow area and the amount of work required to drive the turbine to operate the compressor. The inlet-air mass flow was a constant for all engines at similar flight conditions. The following weights were also estimated for these engines: the compressor weights from the computer code of reference 3 and the rest of the engine components from reference 4.

This paper presents the results of a study to determine the sensitivity of thrust and specific impulse to various engine parameters by varying one parameter while keeping the other parameters constant.

DESCRIPTION OF CYCLE AND GAS GENERATOR

The air entering the engine (fig. 1) is compressed by the compressor and then flows around the outside of the case holding the gearbox, gas generator, and turbine. The gearbox is added to all engines to increase the turbine tip speed to 365.8 m/sec (1200 ft/sec); this increases turbine efficiency, reduces the number of turbine stages and reduces turbine weight. The gas generator produces a very fuel-rich gas, which is expanded through the turbine to power the compressor. After the turbine, the fuel-rich gas mixes with the compressed air stream. Extra hydrogen fuel is then added if necessary for stoichiometric combustion and the mixture is burned. This hot mixture is expanded out the nozzle to produce thrust. Under most operating conditions, extra fuel is not needed because there is sufficient unburned hydrogen present in the gas generator stream; the overall cycle equivalence ratio ϕ (ratio of fuel-to-air actual to fuel-to-air stoichiometric) is already equal to or greater than one.

The fuel-rich gas from the gas generator can be produced in the following ways: the decomposition of a monopropellant, the combustion of a bipropellant stream, or the use of a regenerative expander cycle. Each type of gas generator has different attributes. The first two cycles should have the simplest construction and the lightest weight because they do not need a heat exchanger to heat the gases used to drive the turbine. The gas generator used in this study was a very fuel-rich liquid hydrogen/liquid oxygen combustor. The oxygen to hydrogen ratio is varied in the gas generator to change the turbine inlet temperature.

DESCRIPTION OF THE ENGINE CYCLE SIMULATION

The engine performance is computed with a computer code that performs calculations on a component-by-component basis. The code uses real gas effects (ref. 5) and some assumptions for off-design operation. The inlet performance includes pressure recovery, which is 55 percent for cruise at Mach 5. The compressor operates along an operating line with a 20 percent stall margin. At Mach 5, the compressor runs at 110 percent mechanical speed and 52 percent corrected speed; the compressor pressure ratios at Mach 5 are given in table II. It is understood that this is optimistic operation of the compressor with such high temperatures and stresses, but also an interesting challenge. The gas generator runs very fuel-rich, at a constant temperature; changes in the gas-generator mass flow are directly proportional to changes in the gas-generator pressure. A choked turbine has been assumed, with constant efficiency.

The equations of continuity, momentum, and energy for two ideal streams are solved to model the subsonic co-annular mixing of the gas generator and air streams. A 5 percent pressure loss is assumed in the burner, with extra hydrogen fuel added if necessary for stoichiometric combustion. The combustion gases are expanded through a convergent-divergent nozzle with a variable throat area and a maximum exit area of 1.5 times the Mach 5 inlet capture area. This exit area is sufficient for perfect expansion up to Mach 3.5. At higher Mach numbers, the flow is underexpanded and the actual exit velocity is calculated by using the available exit area. The exit velocity is multiplied by 0.985 to include nozzle losses and used to calculate the gross thrust. Net thrust is gross thrust minus ram drag.

All engines and their components are sized for 22.68 kg/sec (50 lb/sec) airflow at sea level static conditions. The amount of gas-generator mass flow required to drive the turbine at sea level static conditions is used to set the turbine area. Table III shows common conditions used in figures 2 to 12.

RESULTS AND DISCUSSION

The effect of gas-generator mass flow on cruise thrust and specific impulse is shown in figures 2 and 3, respectively. For constant airflow, increasing the gas-generator mass flow increases the thrust but at the same time decreases the specific impulse. The thrust is increased because of two major factors. The first is that the increased total mass flow of the engine increases the thrust. The second factor occurs if the gas-generator mass flow (which is fuel-rich) is large enough such that the overall cycle equivalence ratio is greater than 1.0. When the overall cycle equivalence ratio exceeds 1.0, the specific heat of the exhaust gases is increased by the presence of unburned hydrogen which results in an increase in the nozzle exit velocity and engine thrust. The increase in specific heat more than compensates for the small temperature drop for an overall equivalence ratio greater than 1.0. These two factors have a major effect on the engine operating characteristics as will be seen in the following discussions. The second factor is seen in figure 2 by the change in slope of the thrust curve at higher gas-generator mass flows and is also present as the change in slope of the thrust curve with increasing compressor pressure ratio in later figures. Increasing the gas-generator mass flow decreases the specific impulse because increasing the gas-generator mass flow increases the propellant usage more than the thrust.

The effect of compressor pressure ratio on cruise thrust and specific impulse is shown in figures 4 and 5, respectively. Increasing the compressor pressure ratio significantly increases the thrust but at the same time reduces the specific impulse. This occurs for two reasons. First, increasing the compressor pressure ratio increases the gas-generator mass flow required to power the turbine and has the effects on engine performance as discussed above. Second, the engine mass flow is at a higher pressure entering the nozzle, increasing the exit gas velocity. The change in the slope of the thrust versus compressor pressure ratio line occurs at the point where the overall cycle equivalence ratio exceeds 1.0. At this point, as mentioned previously, the unburned hydrogen present in the exhaust gases further increases the exit velocity and the thrust.

The effect of gas-generator design pressure on cruise thrust and specific impulse is also shown in figures 4 and 5, respectively. Increasing the gas-generator design pressure reduces the thrust at higher compressor pressure ratios, but has little effect on thrust at lower compressor pressure ratios. Increasing the gas-generator design pressure increases the specific impulse. These trends occur because increasing the gas-generator design pressure increases the amount of work available per pound of gas, thereby reducing gas-generator mass flow. At low compressor pressure ratios, where the gas-generator mass flow is a small fraction of the total engine mass flow and the overall cycle equivalence ratio is 1.0, decreasing the gas-generator mass flow has little effect on thrust, but any change in the amount of propellant used is significant to the specific impulse. At higher compressor pressure ratios, the gas-generator mass flow is a larger fraction of the total engine mass flow and the overall cycle equivalence ratio is greater than 1.0. Decreasing the gas-generator mass flow reduces the thrust because of reduced engine mass flow and less unburned hydrogen in the exhaust gases. Increasing the gas-generator design pressure has a progressively smaller effect on engine performance because of the progressively smaller effect on turbine work. Increasing the gas-generator design pressure also increases the number of turbine stages, increasing the total engine length and weight.

The effect of design compressor efficiency on cruise thrust and specific impulse is shown in figures 6 and 7, respectively. Reducing the compressor efficiency from 85 to 80 percent increases the thrust by 2.5 percent, but decreases specific impulse by 3.5 percent at higher compressor pressure ratios and where the gas-generator mass flow is a larger portion of the total engine mass flow. Reducing the compressor efficiency increases turbine work, which increases the gas-generator mass flow thereby resulting in higher exhaust velocity and thrust.

The effect of turbine efficiency on cruise thrust and specific impulse is shown in figures 8 and 9, respectively. At higher compressor pressure ratios, decreasing the turbine efficiency from 80 to 75 percent increases the thrust by 2.2 percent and reduces the specific impulse by 3.6 percent. Reducing the turbine efficiency increases the gas-generator mass flow and therefore increases the thrust but decreases the specific impulse.

The effect of turbine inlet temperature (TIT) on cruise thrust and specific impulse is shown in figures 10 and 11, respectively. Any increase in TIT is achieved by increasing the ratio of oxygen to hydrogen in the very fuel-rich gas-generator mass flow. The ratios of mass flow of oxygen to mass flow of hydrogen used in this study are 1.0, 1.5, and 2.0, which produce gas temperatures of 972, 1407, and 1794 K (1750, 2532, and 3229 °R), respectively. Increasing the TIT increases the available work per pound of gas, requiring less gas-generator mass flow and reduces the amount of unburned hydrogen. The tradeoff between lower thrust and less propellant flow results in the specific impulse being almost unaffected by TIT. Only where the overall cycle equivalence ratio exceeds 1.0, as for the 972 K (1750 °R) case shown in figure 10, does TIT effect thrust because of the presence of unburned hydrogen in the exhaust gases. Increasing the TIT has little effect on the specific impulse because the reduction in gas-generator mass flow is balanced by the amount of extra hydrogen added for stoichiometric combustion.

Engine weights were obtained from the following two sources: (1) the compressors from the computer weight estimation code of reference 3 and (2) the rest of the engine from reference 4, by using their recommendations for selecting other engine component weights. Table IV contains a breakdown of engine component weights. The engine is dominated by the compressor and nozzle; together they comprise approximately 72 to 76 percent of the total engine weight. Any change in the weight of these components would have an effect on the total engine weight. The 6:1 compressor pressure ratio engine was approximately 28 percent heavier than the 2:1 compressor pressure ratio engine.

Figure 12 shows the ratio of sea level static engine thrust to engine weight as a function of the ratio of air mass flow to gas-generator mass flow with lines of constant compressor pressure ratio and gas-generator design pressure. Since the engine weights did not vary much, the trends of the ratio of engine thrust to engine weight follow the same trends as engine thrust with some modification for weight. The lines of constant compressor pressure ratio and gas-generator design pressure are included because these two parameters have the largest effect on thrust.

SUMMARY

A parametric cycle study of an airturbo ramjet (ATR) using a liquid hydrogen/liquid oxygen gas-generator was performed to determine the effects of the compressor pressure ratio, compressor efficiency, turbine efficiency, turbine inlet temperature, gas-generator design pressure, and gas-generator mass flow on thrust and specific impulse at Mach 5 cruise.

The results show that any parameter that changes the gas-generator mass flow changes the thrust and specific impulse. An increase in the gas-generator mass flow increases the total engine mass flow and the fuel used, which increases the thrust but reduces the specific impulse. Increasing the gas-generator mass flow also increases the amount of unburned hydrogen in the exhaust gases, which is a major factor for an increase in thrust. If the overall cycle equivalence ratio is greater than 1.0, the unburned hydrogen in the exhaust gases yields a higher exit velocity. The effect of changing a parameter has a larger effect at higher compressor ratios where the gas-generator mass flow is a larger fraction of the total mass flow. Changes in the compressor pressure ratio or the gas-generator design pressure have the largest effect on engine performance among the parameters varied.

Increasing the compressor pressure ratio, decreasing the gas-generator design pressure, or decreasing the compressor or turbine efficiencies increase the thrust, but at the same time decrease the specific impulse. Increasing the TIT has little effect on specific impulse, but reduces the thrust at higher compressor pressure ratios where increasing the TIT reduces the amount of unburned hydrogen in the exhaust gases.

The compressor and nozzle dominated the weight analysis, weighing more than 70 percent of the total engine weight. Total engine weight only varied 28 percent between the lightest and heaviest engines.

The ATR is a candidate for high-speed flight that removes the turbine from the hot primary stream. The ATR has many different variations for the gas generator, all having different strengths and weaknesses. Further studies are required to determine optimum cycle parameters and to assess the ATR's place and potential in high-speed propulsion.

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TABLE I. - DESIGN POINT ENGINE PARAMETERS

Compressor pressure ratio	2.0 to 6.0
Compressor efficiency, percent	75 to 85
Turbine efficiency, percent	70 to 80
Turbine inlet temperature, K (°R)	972 (1750) to 1794 (3229)
Gas-generator design pressure, atm	20 to 160

TABLE II. - COMPRESSOR PRESSURE RATIOS

Sea level static design	Mach 5 cruise
6.0	1.83
5.0	1.66
4.0	1.50
3.0	1.33
2.0	1.17

TABLE III. - CONDITIONS FOR FIGURES 2 TO 12

Altitude,[a] m (ft)	30,480 (100,000)
Sea level static airflow, kg/sec (lb/sec)	22.7 (50)
Compressor design efficiency,[b] percent	85
Turbine efficiency,[c] percent	80
Turbine inlet temperature,[d] K (°R)	972 (1750)
Gas-generator design pressure,[e] atm	40

[a]Not considered in figure 12.
[b]Compressor design efficiencies of 75, 80, and 85 percent are considered in figures 6 and 7.
[c]Turbine efficiencies of 70, 75, and 80 percent are considered in figures 8 and 9.
[d]Turbine inlet temperatures of 972, 1407, and 1794 K (1750, 2532, and 3229 °R) are considered in figures 10 and 11.
[e]Not considered in figures 2 to 5.

TABLE IV. - ENGINE COMPONENT WEIGHTS

Engine component	Compressor pressure ratio									
	6.0		5.0		4.0		3.0		2.0	
	kg	lb	kg	lb	kg	lb	kg	lb	kg	lb
Compressor	143	315	133	294	123	271	111	245	96	212
Nozzle	122	268	122	268	122	268	122	268	122	268
Engine case	16	35	16	35	16	35	16	35	16	35
Turbine and frame	25	55	23	51	24	52	22	48	20	45
Gearbox	29	65	25	55	20	45	15	32	9	20
Gas generator	2	5	2	5	2	5	2	5	2	4
Duct and main burner	9	20	9	20	9	20	9	20	9	20
Accessories (misc.)	19	42	18	39	16	35	14	31	12	26
Shaft	1	2	1	2	1	2	1	2	1	2
Total	366	807	349	769	333	733	312	686	287	632

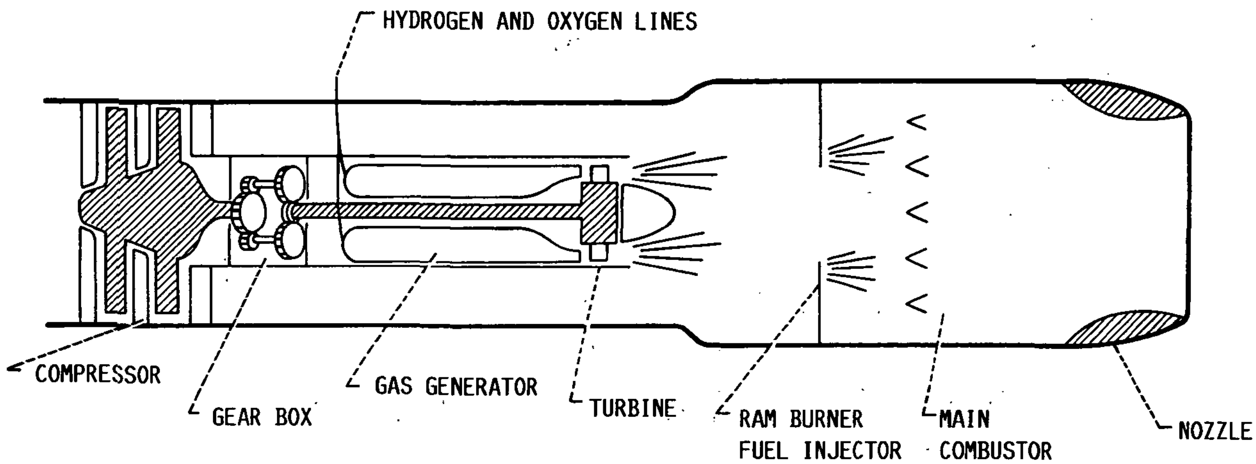

FIGURE 1.- AIRTURBO RAMJET ENGINE CONCEPT.

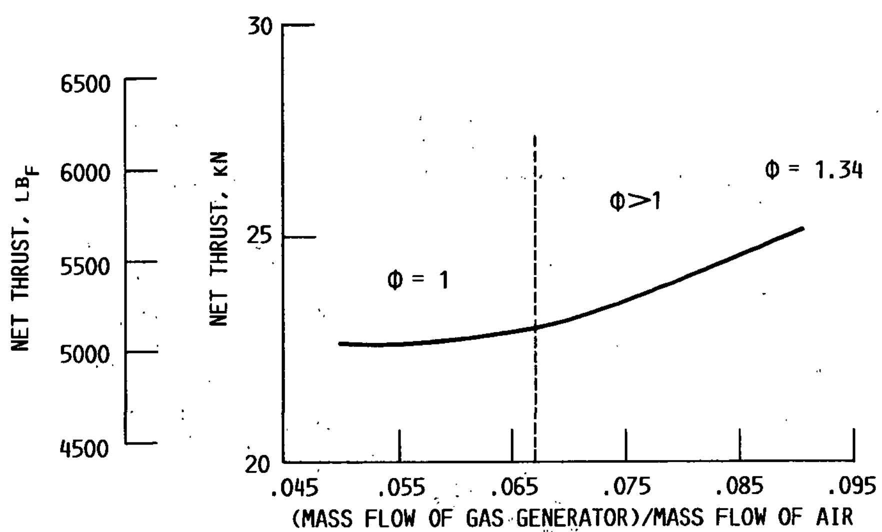

FIGURE 2.- EFFECT OF VARIATION OF GAS-GENERATOR MASS FLOW ON THRUST AT MACH 5; DESIGN COMPRESSOR PRESSURE RATIO, 4.0.

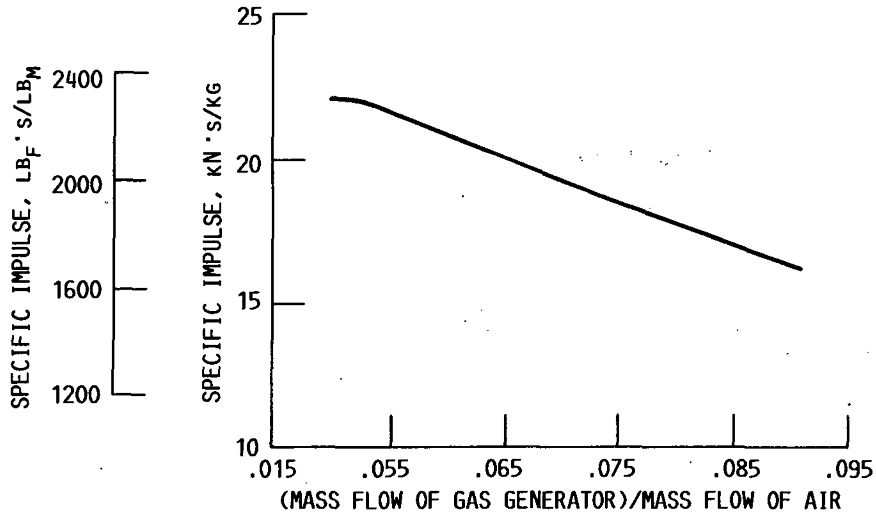

FIGURE 3.- EFFECT OF VARIATION OF GAS-GENERATOR MASS FLOW ON SPECIFIC IMPULSE AT MACH 5; DESIGN COMPRESSOR PRESSURE RATIO, 4.0.

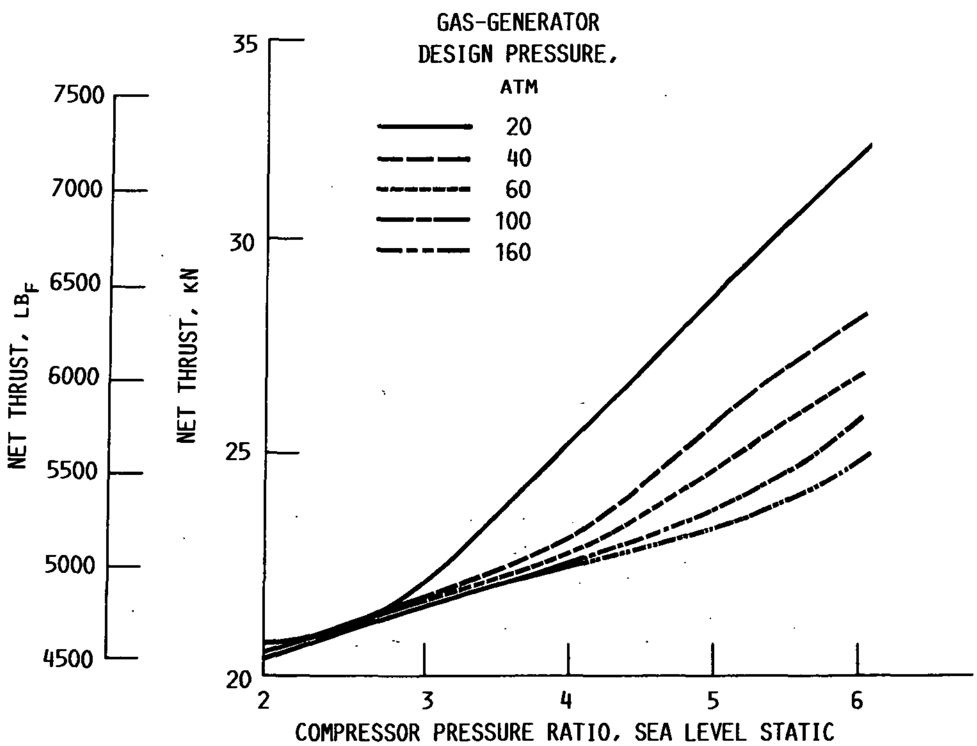

FIGURE 4.- EFFECT OF VARIATION OF COMPRESSOR PRESSURE RATIO AND GAS-GENERATOR DESIGN PRESSURE ON THRUST AT MACH 5.

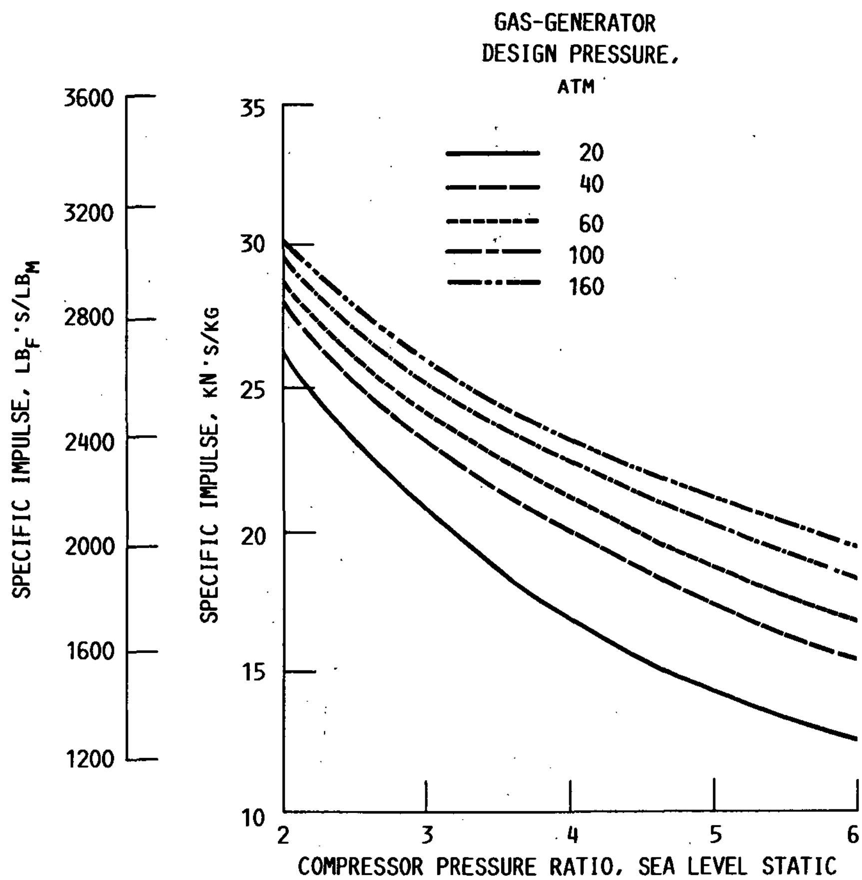

FIGURE 5.- EFFECT OF VARIATION OF COMPRESSOR PRESSURE RATIO AND GAS-GENERATOR DESIGN PRESSURE ON SPECIFIC IMPULSE AT MACH 5.

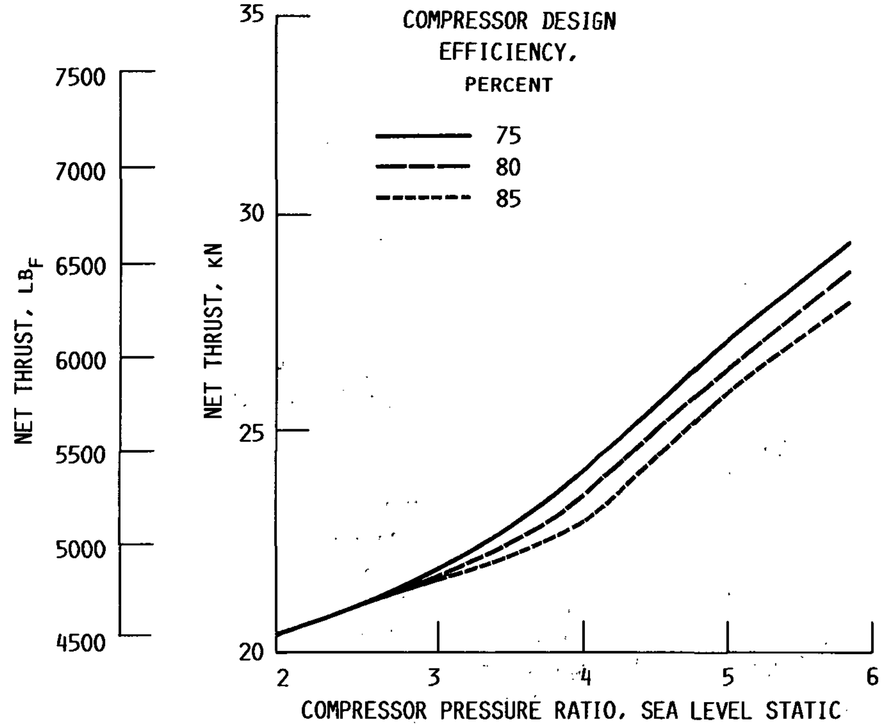

FIGURE 6.- EFFECT OF VARIATION OF COMPRESSOR PRESSURE RATIO AND COMPRESSOR EFFICIENCY ON THRUST AT MACH 5.

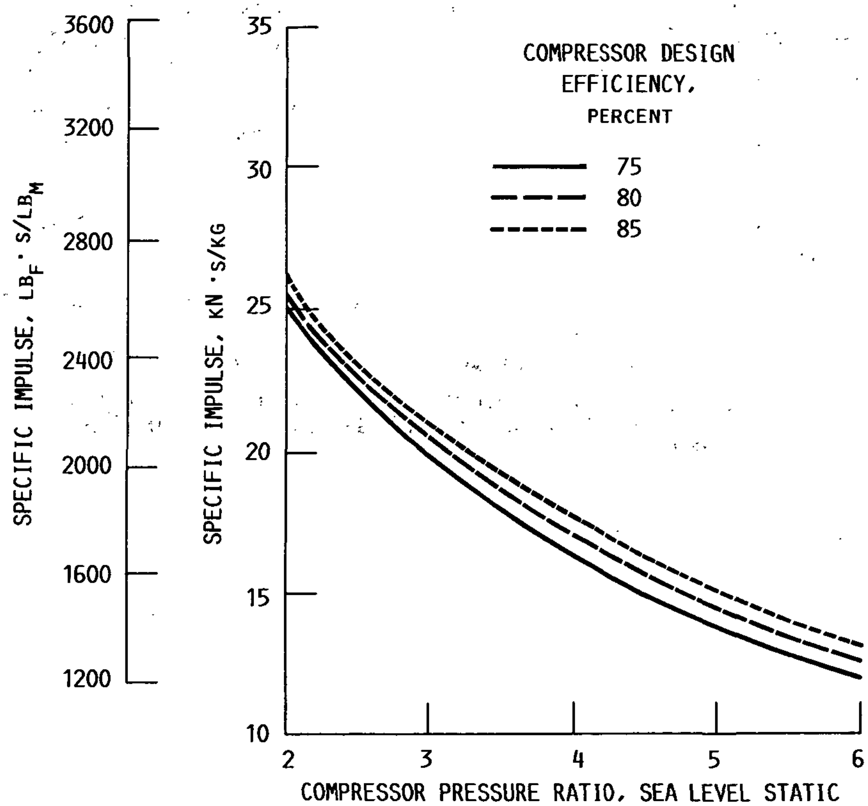

FIGURE 7.- EFFECT OF VARIATION OF COMPRESSOR PRESSURE RATIO AND COMPRESSOR EFFICIENCY OF SPECIFIC IMPULSE AT MACH 5.

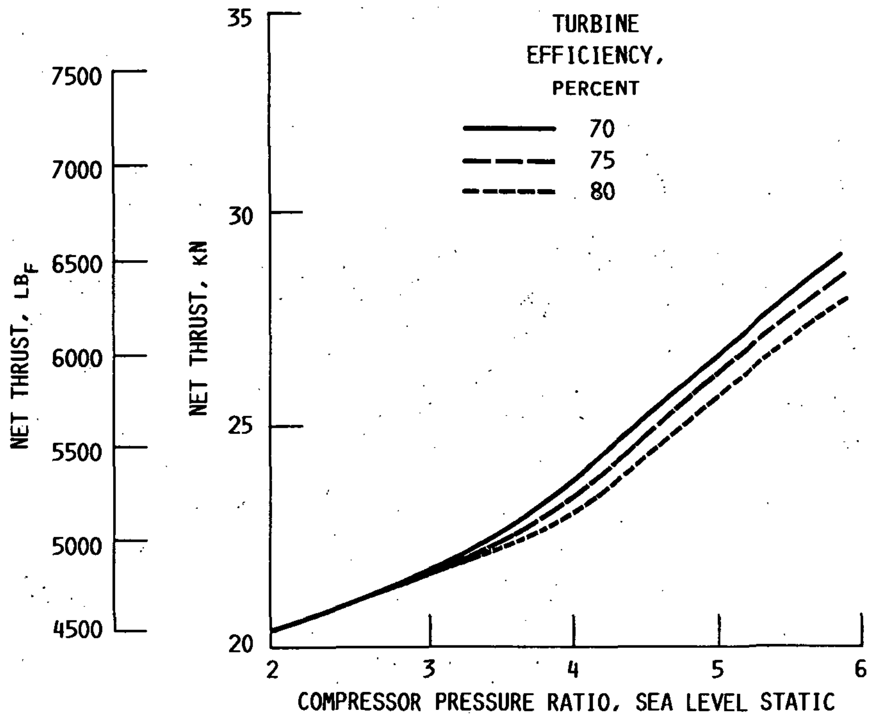

FIGURE 8.- EFFECT OF VARIATION OF COMPRESSOR PRESSURE RATIO AND TURBINE EFFICIENCY ON THRUST AT MACH 5.

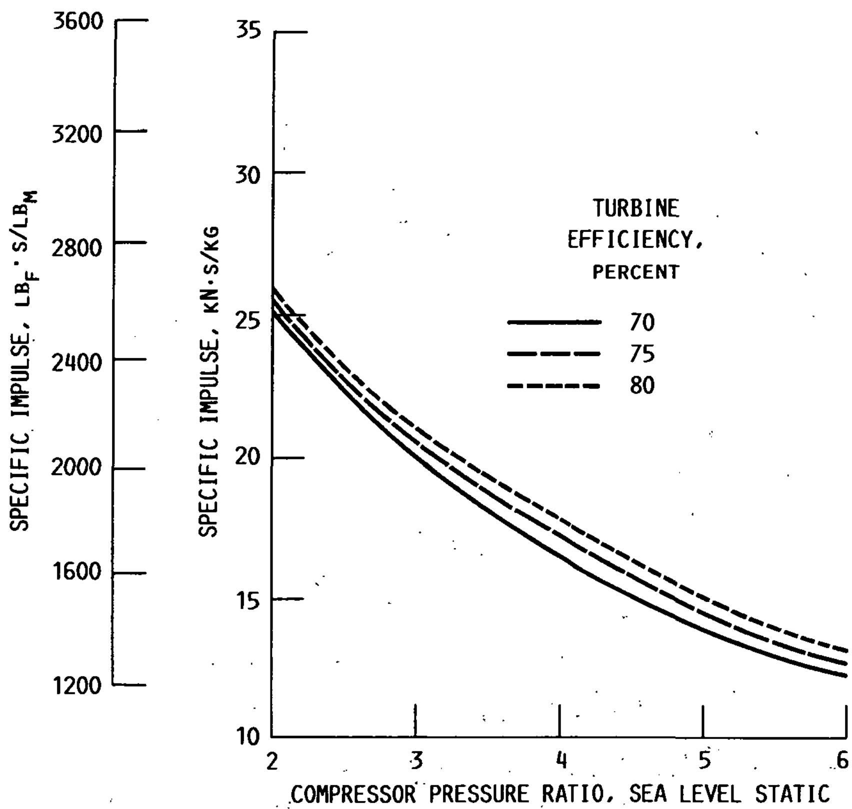

FIGURE 9.- EFFECT OF VARIATION OF COMPRESSOR PRESSURE RATIO AND TURBINE EFFICIENCY ON SPECIFIC IMPULSE AT MACH 5.

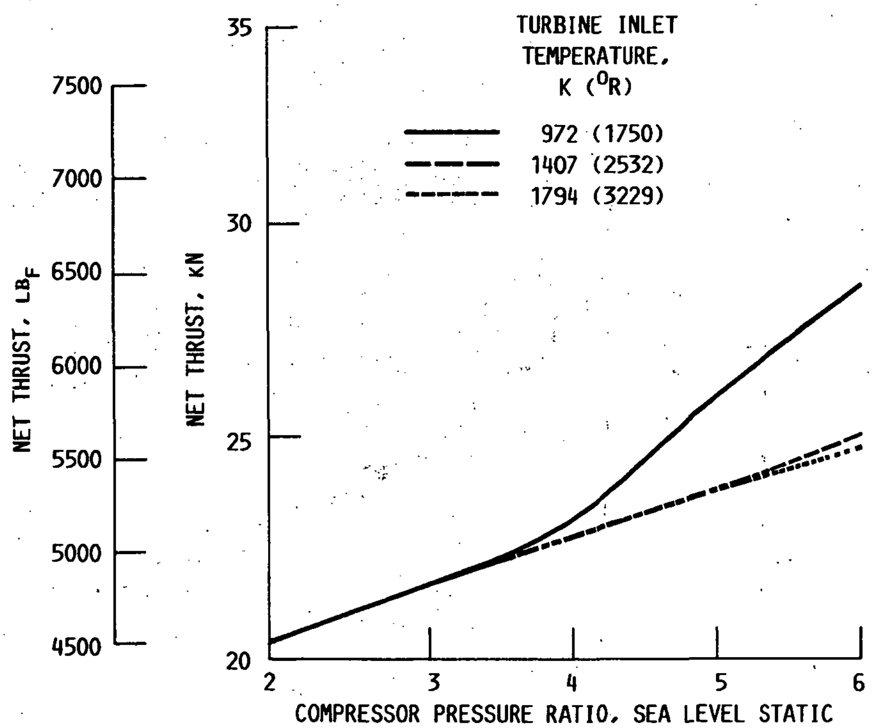

FIGURE 10.- EFFECT OF VARIATION OF COMPRESSOR PRESSURE RATIO AND TURBINE INLET TEMPERATURE ON THRUST AT MACH 5.

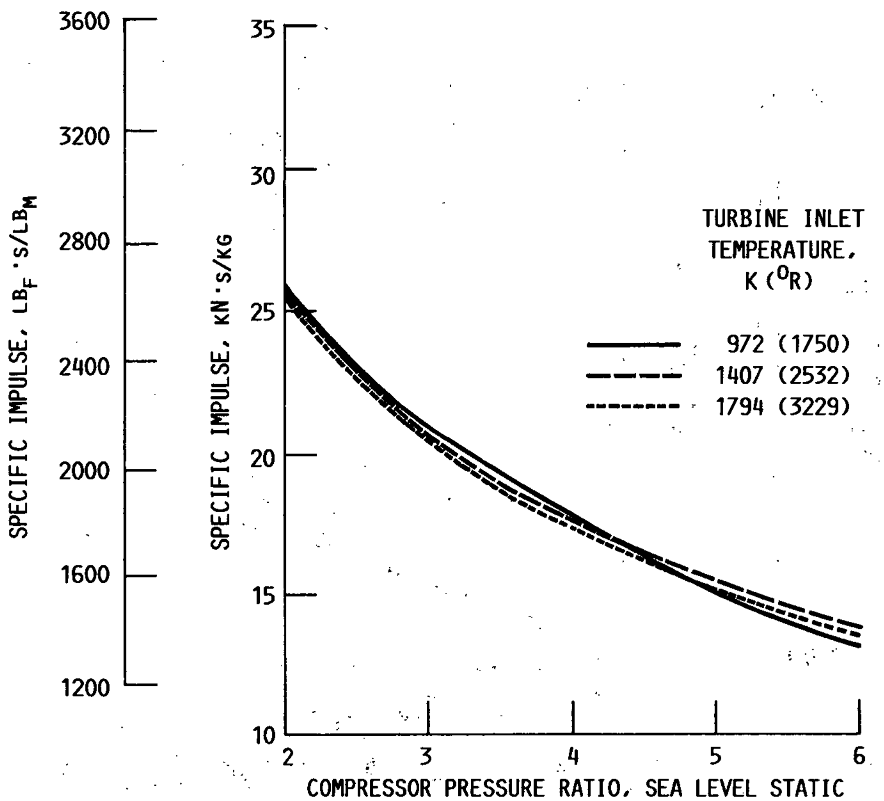

FIGURE 11.- EFFECT OF VARIATION OF COMPRESSOR PRESSURE RATIO AND TURBINE INLET TEMPERATURE ON SPECIFIC IMPULSE AT MACH 5.

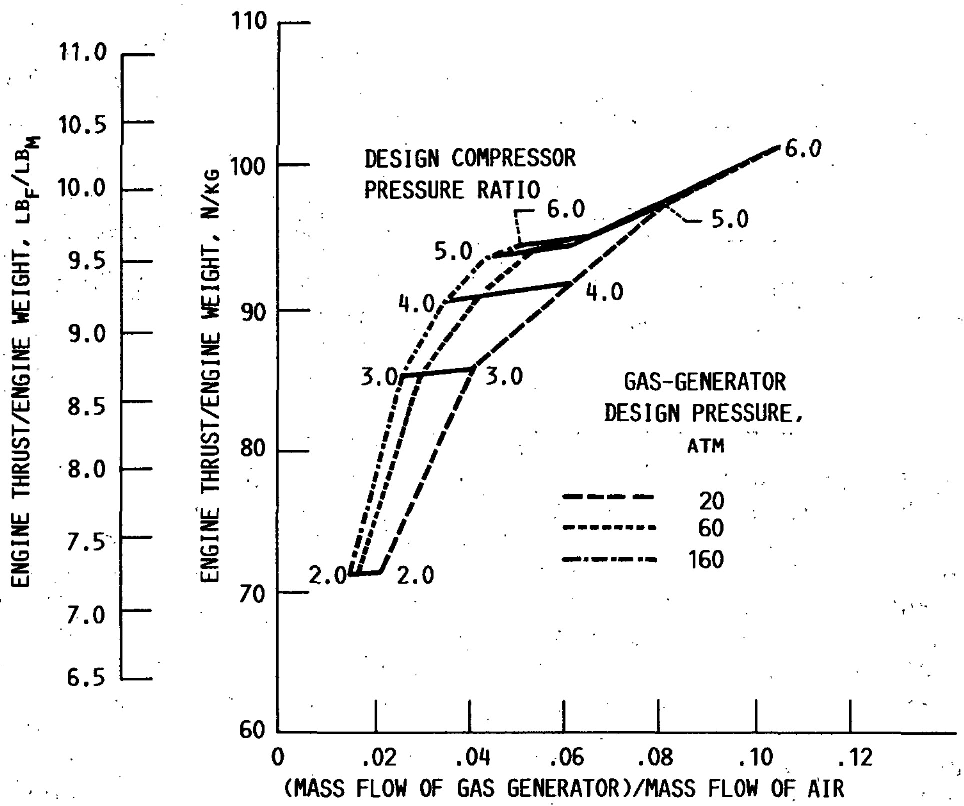

FIGURE 12.- EFFECT OF VARIATION OF THE RATIO OF MASS FLOW OF GAS GENERATOR TO MASS FLOW OF AIR AS COMPARED TO THE RATIO OF SEA LEVEL STATIC ENGINE THRUST TO ENGINE WEIGHT.

1. Report No.
NASA TM-88808

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

A Parametric Study of a Gas-Generator Airturbo Ramjet (ATR)

5. Report Date

6. Performing Organization Code
505-69-41

7. Author(s)
Christopher A. Snyder

8. Performing Organization Report No.
E-3156

10. Work Unit No.

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared for the 22nd Joint Propulsion Conference, cosponsored by the AIAA, ASME, SAE, and ASEE, Huntsville, Alabama, June 16-18, 1986.

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17. Key Words (Suggested by Author(s))
Hypersonic; Supersonic; Airbreathing propulsion; Airturbo ramjet; Airturbo rocket; ATR; Engine weight; Gas generator

18. Distribution Statement
Unclassified - unlimited
STAR Category 07

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of pages

22. Price*

National Aeronautics and
Space Administration

Lewis Research Center
Cleveland, Ohio 44135

Official Business
Penalty for Private Use $300

SECOND CLASS MAIL

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