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RESEARCH MEMORANDUM

FREE-FLIGHT PERFORMANCE OF 16-INCH-DIAMETER SUPERSONIC RAM-JET UNITS

II - FIVE UNITS DESIGNED FOR COMBUSTION-CHAMBER-INLET MACH NUMBER OF 0.16 AT FREE-STREAM MACH NUMBER OF 1.60

(UNITS B-1, B-2, B-3, B-4, AND B-5)

By Wesley E. Messing and Scott H. Simpkinson

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
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SUMMARY

The performance of five 16-inch-diameter ram-jet units was determined over a range of free-stream Mach numbers of 0.50 to 1.86 and gas total-temperature ratios between 1.0 and 6.1. Full-scale units were released from an airplane at high altitudes and accelerated to high subsonic and supersonic velocities by the engine thrust and force of gravity. The data for evaluating the performance were obtained from radio-telemetering and radar-tracking equipment.

Time histories of the performance data are presented for each unit; also included are correlations to illustrate the effect of free-stream Mach number and gas total-temperature ratio on diffuser total-pressure recovery, net-thrust coefficient, and external drag coefficient.

Vibratory combustion with a frequency of 12 to 32 cycles per second was found to exist in two of the units employing a ducted-type flame holder. Combustion in two other units that utilized a rake-type flame holder was very smooth. One of these units attained a maximum free-stream Mach number of 1.86 and a net acceleration of 4.2 g's. At the design free-stream Mach number of 1.60, a reduction in the gas total-temperature ratio from 5.0 to 1.0 was accompanied by decreases in diffuser total-pressure recovery of 0.89 to 0.41 and in the net-thrust coefficient of 0.65 to -0.30.

INTRODUCTION

Free-flight investigations are being conducted by the NACA Lewis laboratory on 16-inch-diameter ram-jet units to determine the performance and operational characteristics of ram jets at high subsonic and supersonic velocities. Performance data of the full-scale units operating under actual atmospheric conditions are being obtained over a range of combustion-chamber-inlet velocities and fuel-air ratios. Data are also being obtained throughout the transonic range and under conditions of rapid acceleration with accompanying changes in inlet conditions due to large variations in altitude and Mach number.

The free flights are being conducted off the Virginia coast near the NACA Langley laboratory. The ram-jet units are released from an airplane at high altitudes and accelerated to supersonic velocities by the engine thrust and the force of gravity. In order to obtain data over a range of combustion-chamber-inlet velocities, four ram-jet designs (designated 16-A, 16-B, 16-C, and 16-D) of different inlet and outlet diameters are being used. Several ram-jet units of the same design are being investigated in order to obtain data at different fuel-air ratios. These data are obtained by presetting the fuel regulator at different flow values before each flight. Continuous data records are obtained by radio-telemetering and radar-tracking equipment during the flight.

The results obtained from the first ram-jet unit investigated (designated 16-A-1), are discussed in reference 1. The data obtained from the succeeding four A-type ram-jet units, which were designed for a combustion-chamber-inlet Mach number of 0.12 at a free-stream Mach number of 1.60, are included in reference 2.

Data obtained from the first five B-type ram-jet units, which were designed for higher combustion-chamber velocities (combustion-chamber-inlet Mach number of 0.16 at a free-stream Mach number of 1.60) than the A-type ram jets, are presented herein. Time histories of the performance over a range of free-stream Mach numbers of 0.50 to 1.86 and gas total-temperature ratios between 1.0 and 6.1 are presented, as well as the effects of free-stream Mach number and gas total-temperature ratio on diffuser total-pressure recovery, net-thrust coefficient, and external drag coefficient.

APPARATUS AND PROCEDURE

The B-type ram-jet units investigated are designated 16-B-1, 16-B-2, 16-B-3, 16-B-4, and 16-B-5. A schematic cross-sectional diagram of the ram jets is shown in figure 1. Model B is designed for a combustion-chamber-inlet velocity of 220 feet per second (Mach number, 0.16) at a free-stream Mach number of 1.60 and a gas total-temperature ratio of 5.0. This heat addition is realized at a fuel-air ratio of 0.067 at a combustion efficiency of 80 percent and a pressure altitude of 6000 feet. At this design condition the normal shock is positioned at the diffuser inlet. The outer shell is so located relative to the central body that the oblique shock from the spike intercepts the lip of the outer shell at a free-stream Mach number of 1.80.

The required fuel flow is produced by regulated helium pressure acting on a flexible fuel cell forcing the fuel through various sets of spray nozzles. The fuel used is 73-octane gasoline (AN-F-23a) and is stored in a tank having a capacity of $8\frac{1}{2}$ gallons. The gross weight of each unit is approximately 525 pounds.

A ducted-airfoil-type flame holder with intermediate gutters (fig. 2) was used in units B-1, B-2, and B-3. Units B-4 and B-5 employed the rake-type flame holder shown in figure 3. Magnesium flares were used to provide a continuous ignition source.

The ram-jet units were attached to the underside of the wing of a fighter-type airplane (fig. 4). The units were ignited and released at altitudes of 30,000 to 34,100 feet and free-stream Mach numbers of 0.50 to 0.56. The eight-channel telemetering equipment in the ram-jet unit transmitted sufficient data to evaluate the performance of the ram jet. A time history of the position of the unit relative to the ground during flight was obtained by radar-tracking facilities over a range of free-stream Mach numbers of 0.50 to 1.86 and gas total-temperature ratios of 1.0 to 6.1. A more complete description of the apparatus, the instrumentation, the procedure, the general method of calculation, and the equations used in the performance computations is included in reference 2.

RESULTS AND DISCUSSION

Performance of Ram-Jet Units

A general comparison of the performance of the five B-type ram-jet units is presented in figure 5, which shows the effects of fuel flow and flame-holder design on the free-stream Mach number. The highest free-stream Mach number (1.86) was attained by unit B-5, which employed a rake-type flame holder. Failure of the fuel cell in unit B-1 immediately after launching resulted in a cold run (no combustion). Vibratory and sporadic combustion in units B-2 and B-3 resulted in low values of thrust and relatively low free-stream Mach numbers. No fuel-flow data were obtained from unit B-2 because of the failure of the fuel-flow telemetering channel. The fuel-flow data from unit B-3 indicated that the fuel-air mixture was within the limits of units B-4 and B-5, which had smooth steady combustion. The dashed line in figure 5(b) represents the calculated value of fuel flow necessary to obtain a fuel-air ratio of 0.067 for an assumed combustion efficiency of 60 percent. The vibratory combustion encountered by unit B-3 was therefore not believed to be due to the fuel-air mixture. Inasmuch as the ram-jet units were similar in construction except for the flame-holder designs, the flame holders in units B-2 and B-3 were judged to be the major contributing factors to the rough vibratory combustion.

An example of the vibratory nature of the combustion is shown in the following table:

Ram-jet unit	Time after release (sec)	Free-stream Mach number	Fuel-air ratio[1]	Frequency of combustion (cycles/sec)
B-2	18 to 26	0.72 to 0.91	---------------	20 to 25
B-2	27 to 37	.92 to 1.09	---------------	12 to 26
B-3	20 to 36	.83 to 1.08	0.060 to 0.056	26 to 30
B-3	43 to 45	1.17 to 1.18	.072 to .070	32

[1]Fuel-air ratios calculated from air flows based on assumption that a Mach number of 1 existed at diffuser inlet (shock swallowed).

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A section of the telemeter record is reproduced in figure 6 for comparison of the data obtained from units B-2 and B-4. The vibratory nature of combustion in unit B-2 is clearly shown by the coincidence of pulsations of the accelerometer reading with the vibrations in the pressure measurements, which are shown by the diffuser-inlet static pressure p_2. At 25 to 26 seconds after release, the accelerometer and pressure measurements show a combustion vibration of 25 cycles per second. These measurements compared with unit B-4 at 25 to 26 seconds where the telemeter record shows smooth steady burning without vibration or pulsations. The pulsations of the diffuser-inlet static pressure p_2 of unit B-4 shown in figure 6(b) (21.0 to 23.0 sec) were caused by a slight movement of the normal shock about the static-pressure orifice. As the combustion efficiency improved at 23.5 seconds, the shock moved ahead of the static-pressure orifice and a steady value of diffuser-inlet static pressure was recorded.

Photographic evidence of the visual difference in combustion between units B-2 and B-5 is shown in figure 7. The vibratory burning is obvious for unit B-2 (fig. 7(a)) where the telemeter record showed a frequency of 26 cycles per second. Unit B-5 had smooth steady burning without any apparent pulsations (fig. 7(b)), which was typical of the combustion process throughout the entire flight.

Time histories of the ram-jet-unit performance are presented in figures 8 to 12. In general, these figures include resultant flight conditions, independent test variables, diffuser conditions, combustion-chamber-inlet variables, and performance variables. The solid curves are measured values and the broken lines represent approximated values. The combustion was so vibratory in units B-2 and B-3 that complete time histories of the test data could not be established from the telemeter records.

Unit B-4 encountered a rich blow-out limit at a free-stream Mach number of 1.46 (fig. 11(a)) (33.5 sec after release) as the fuel-air ratio exceeded 0.082 (fig. 11(d)). The telemeter record indicated that the blow-out was sharp and distinct with smooth steady burning prior to the blow-out.

An increase in combustion efficiency occurred with a large increase in combustion-chamber-inlet static pressure and temperature. For example, the combustion efficiency in unit B-5 (fig. 12(e)) increased from 66 percent at 33 seconds to 82 percent at 37 seconds with increases in combustion-chamber-inlet static pressure from 3200 to 6100 pounds per square foot and static temperature increases from 643° to 780° R (fig. 12(d)). This increase in combustion efficiency occurred at approximately constant values of fuel-air ratio (0.053 to 0.057) and combustion-chamber-inlet velocity (205 to 215 ft/sec) (fig. 12(d)). Part of this increase in combustion efficiency may be due to an improvement in fuel pattern and atomization because an additional set of fuel nozzles became operative during this time interval.

Satisfactory combustion was attained by ram-jet units B-4 and B-5, which employed a rake-type flame holder. Unit B-5 (fig. 12) reached a maximum free-stream Mach number of 1.86 (fig. 12(a)) just before blow-out with a net acceleration (excluding gravity) of approximately 4.2 g's, which was based on differentiation of the velocity because no acceleration data were received by the telemetering equipment. A maximum net-thrust coefficient of 0.67 occurred at 36 seconds at a gas total-temperature ratio of 5.0, a combustion efficiency of 82 percent (fig. 12(e)), and a free-stream Mach number of 1.59 (fig. 12(a)).

Diffuser Total-Pressure Recovery

The effect of free-stream Mach number and gas total-temperature ratio on diffuser total-pressure recovery is shown in figure 13. The solid lines are lines of constant gas total-temperature ratio drawn through the collective data points. The broken line represents the transition from shock existing within the diffuser to no shock within the diffuser. In the region below the transition line the shock is swallowed; above the line the shock, if present, is outside the diffuser entrance. The position of this line was determined from data obtained from a flush-wall static orifice $4\frac{1}{8}$ inches inside of the diffuser (station 2 fig. 1) that indicated the presence or absence of shock within the diffuser. The intersection of the gas total-temperature ratio lines with the transition line therefore indicates the heat addition that is necessary to maintain the shock at the inlet for a given free-stream Mach number.

At a constant value of free-stream Mach number, a decrease in gas total-temperature ratio was accompanied by a decrease in total-pressure recovery. This effect was due to the diffuser-outlet conditions of higher velocity, lower static pressure, and a reduction in total pressure necessary for mass continuity accompanying the decrease in heat addition. When sonic or supersonic velocity existed at the diffuser inlet, this reduction in total pressure was made possible by the presence of a normal shock within the diffuser with its accompanying total-pressure loss. For example, at a free-stream Mach number of 1.6 a reduction in gas total-temperature ratio from 5.0 to 1.0 resulted in a decrease in diffuser total-pressure recovery from 0.89 to 0.41.

Thrust Coefficient

The effect of free-stream Mach number and gas total-temperature ratio on the net-thrust coefficient is shown in figure 14. An increase in free-stream Mach number was accompanied by an increase in net-thrust coefficient at a given gas total-temperature ratio. At the design Mach number of 1.6, an increase in gas total-temperature ratio from 1.0 to 5.0 produced an increase in net-thrust coefficient of -0.30 to 0.65.

External Drag Coefficient

The effect of free-stream Mach number and gas total-temperature ratio on the external drag coefficient is shown in figure 15. The minimum-drag curve,as drawn through the collective data points, represents conditions of minimum additive drag and maximum engine air flow when the external flow conditions ahead of the inlet were not altered by variations in heat addition below the critical value. (The term additive drag is fully discussed by Ferri in reference 3.) At the design free-stream Mach number of 1.6, an external drag coefficient of 0.16 was realized as compared to a maximum of approximately 0.26 at a free-stream Mach number of 1.07 and a minimum value of 0.098 at a free-stream Mach number of 0.89.

SUMMARY OF RESULTS

From the data obtained from free-flight investigation of five 16-inch-diameter supersonic ram-jet units over a range of free-stream Mach numbers from 0.50 to 1.86 and gas total-temperature ratios between 1.0 and 6.1, the following results were obtained:

1. Failure of the fuel cell in one of the units, immediately after launching resulted in a cold run. Vibratory burning producing combustion frequencies from 12 to 32 cycles per second was encountered by two ram-jet units employing a ducted-type flame holder. The other two ram-jet units with rake-type flame holders encountered smooth steady burning with resultant high

values of thrust and accelerations. Inasmuch as the fuel-air mixture of one of the units with rough combustion was within the limits of the fuel-air mixtures of the two ram jets with smooth burning, the vibratory burning was attributed to the ducted-type flame-holder design rather than the fuel-air mixture.

2. A sharp, distinct rich blow-out was encountered at a fuel-air ratio of 0.082 with one of the ram-jet units utilizing a rake-type flame holder.

3. A maximum free-stream Mach number of 1.86 was encountered by one of the units with a net acceleration (excluding gravity) of approximately 4.2 g's. A maximum net-thrust coefficient of 0.67 occurred at a gas total-temperature ratio of 5.0, a combustion efficiency of 82 percent, and a free-stream Mach number of 1.59.

4. At the design free-stream Mach number of 1.6, a reduction in gas total-temperature ratio from 5.0 to 1.0 was accompanied by approximate decreases in diffuser total-pressure recovery of 0.89 to 0.41 and net-thrust coefficient of 0.65 to -0.30.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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2. Carlton, William W., and Messing, Wesley E.: Free-Flight Performance of 16-Inch-Diameter Supersonic Ram-Jet Units. I - Four Units Designed for Combustion-Chamber-Inlet Mach Number of 0.12 at Free-Stream Mach Number of 1.6 (Units A-2, A-3, A-4, and A-5). NACA RM E9F22, 1949.

3. Ferri, Antonio, and Nucci, Louis M.: Preliminary Investigation of a New Type of Supersonic Inlet. NACA RM L6J31, 1946.

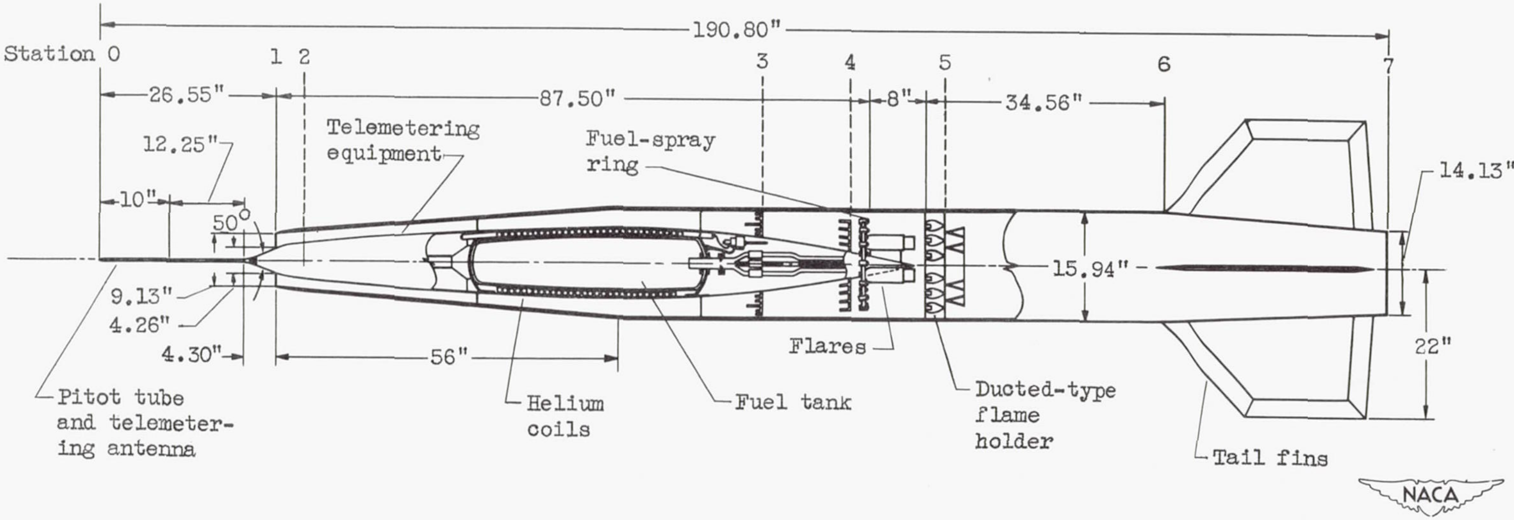
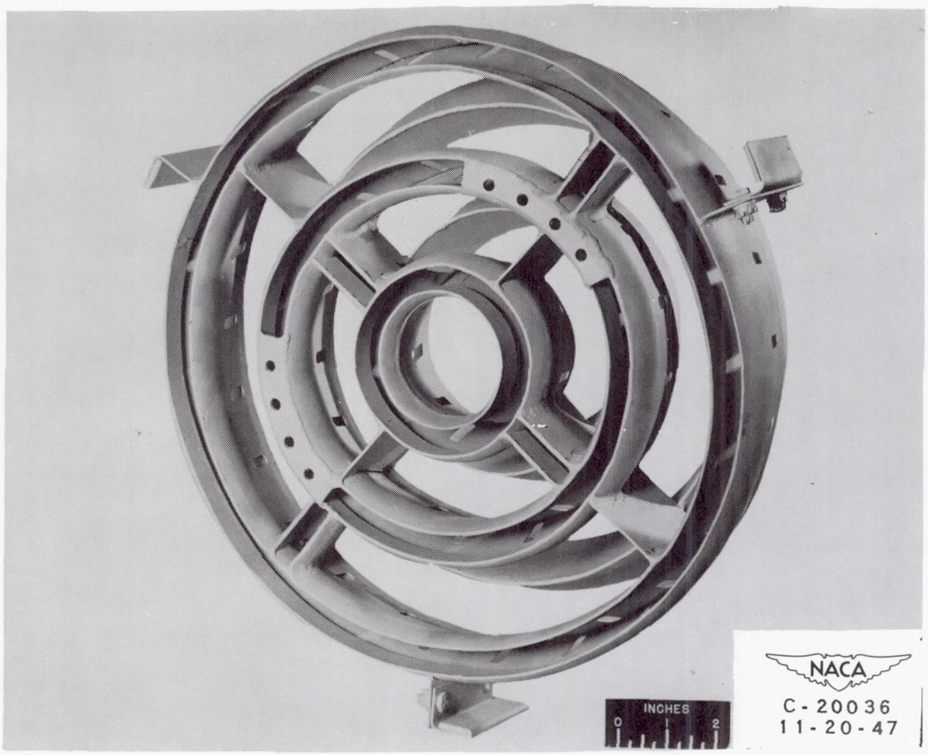
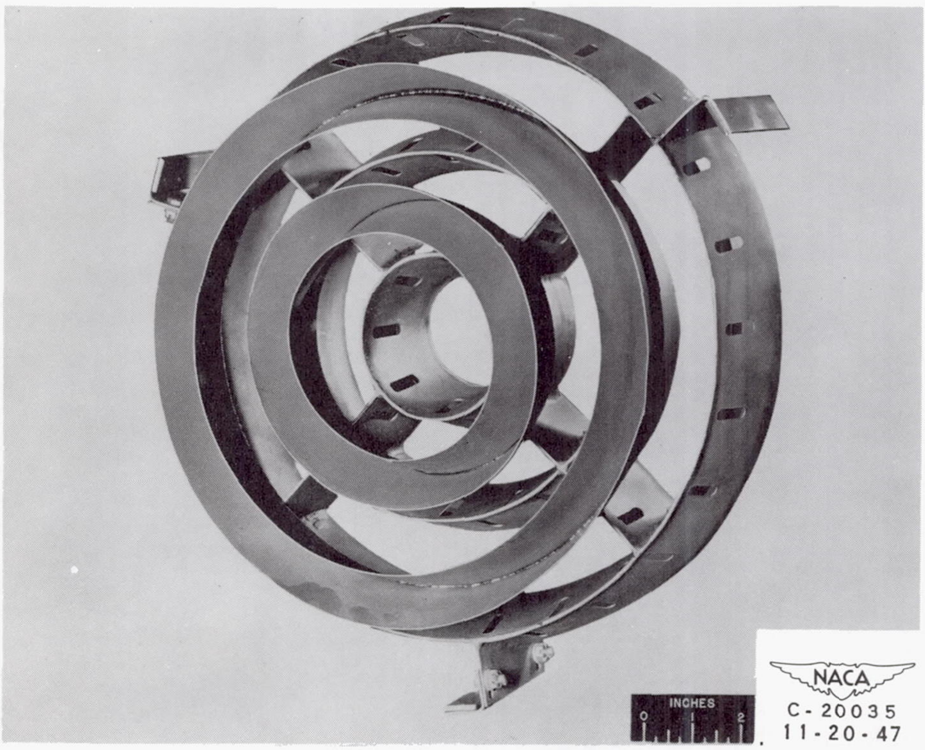


Figure 1. - Schematic cross-sectional diagram of supersonic 16-inch ram-jet unit. (Dimensions given for model B.)

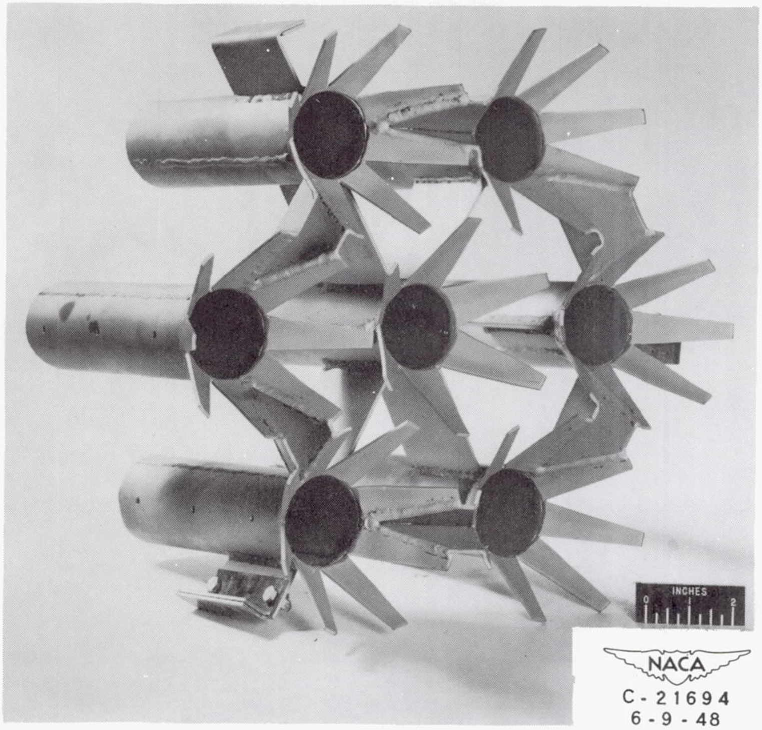


(a) Three-quarter front view.

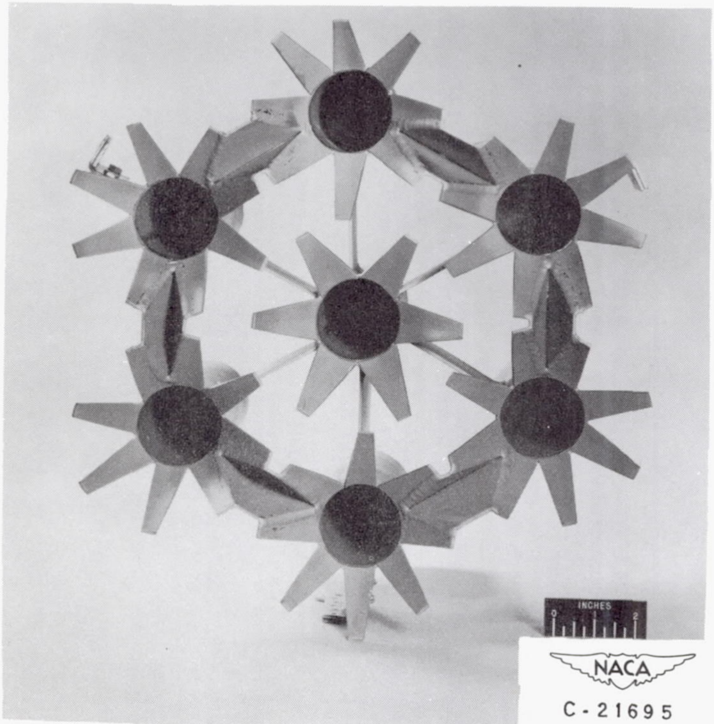


(b) Three-quarter rear view.

Figure 2. - Ducted-type flame holder for supersonic ram-jet units 16-B-1, 16-B-2, and 16-B-3.



(a) Three-quarter rear view.



(b) Rear view.

Figure 3. - Rake-type flame holder for supersonic ram-jet units 16-B-4 and 16-B-5.

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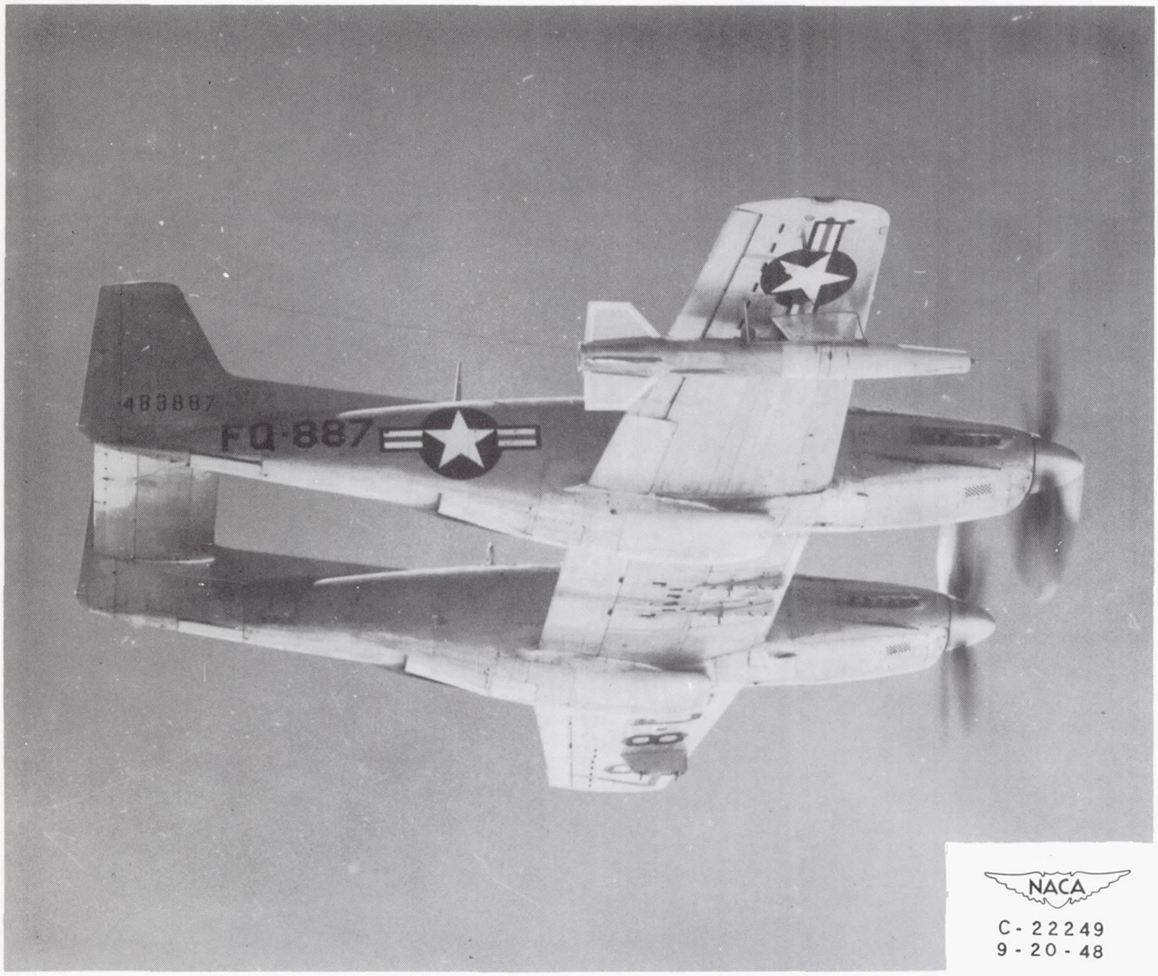
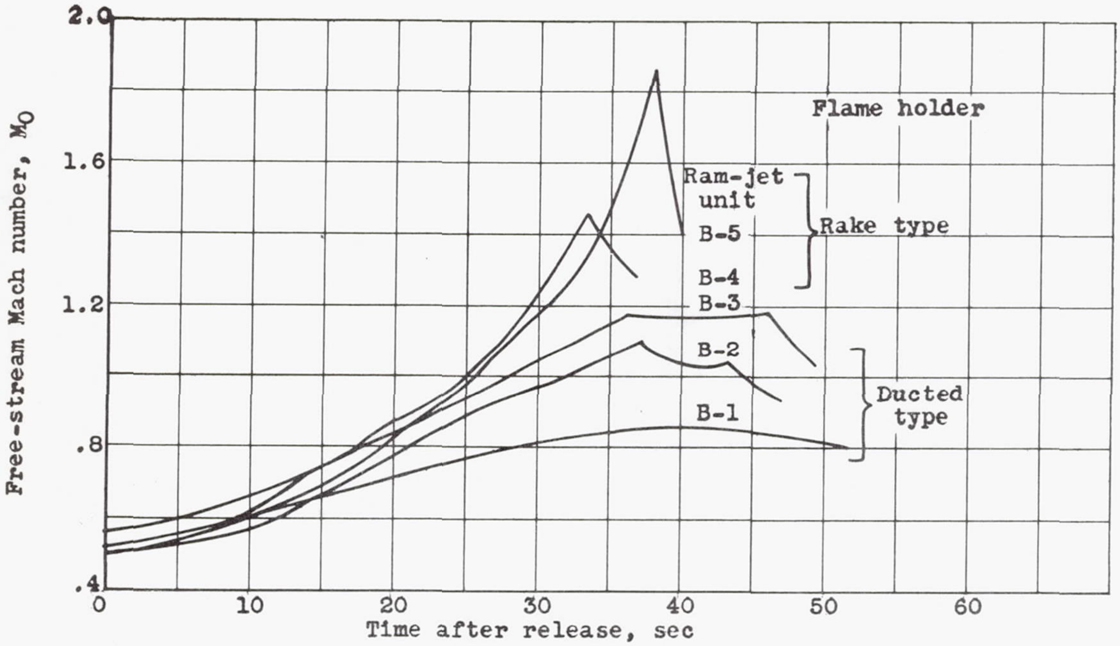
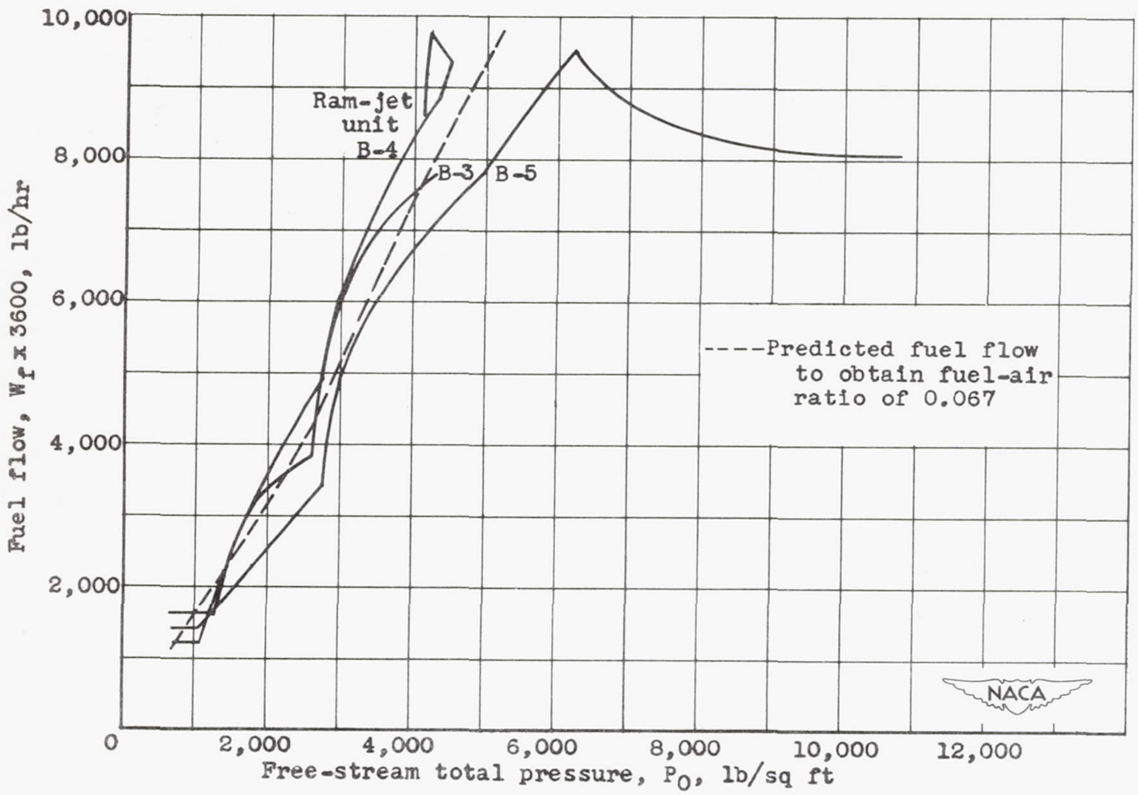


Figure 4. - Supersonic 16-inch ram-jet unit mounted beneath airplane wing.



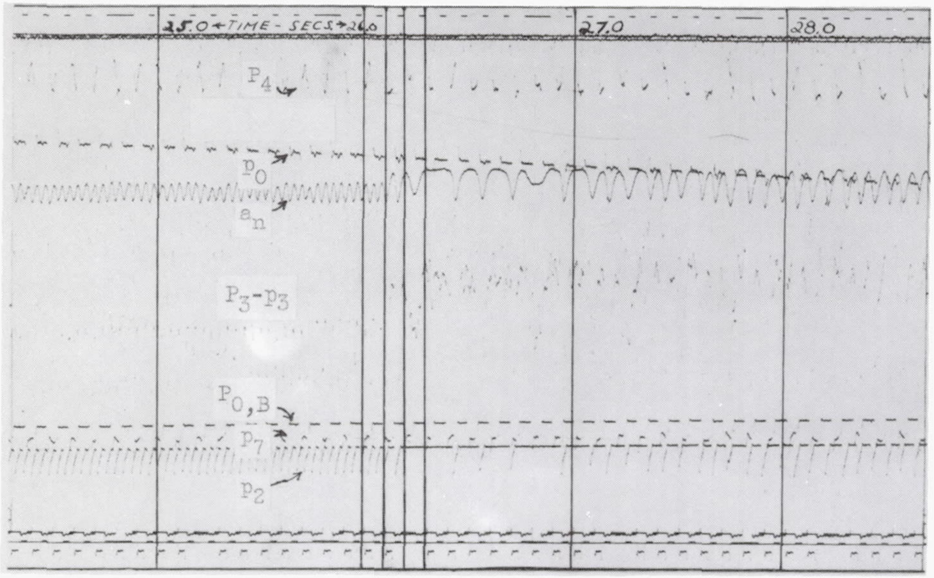
(a) Free-stream Mach number as function of time.



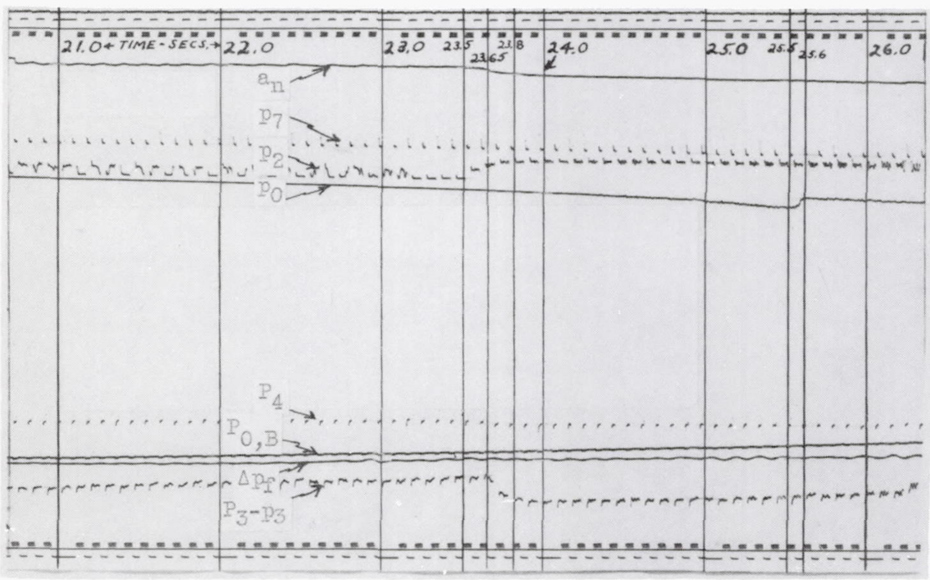
(b) Fuel flow as function of free-stream total pressure.

Figure 5. - Comparison of free-stream Mach number and fuel flow for ram-jet units 16-B-1, 16-B-2, 16-B-3, 16-B-4, and 16-B-5.

a_n	net acceleration	p_0	free-stream static pressure
$P_{0,B}$	total pressure behind shock	p_2	diffuser-inlet static pressure
P_3-p_3	air-flow dynamic pressure	p_7	exit static pressure
P_4	diffuser-outlet total pressure	Δp_f	fuel-orifice pressure drop



(a) Unit 16-B-2 (rough burning).



(b) Unit 16-B-4 (smooth burning).

Figure 6. - Section of telemeter record of data obtained from ram-jet units 16-B-2 and 16-B-4.

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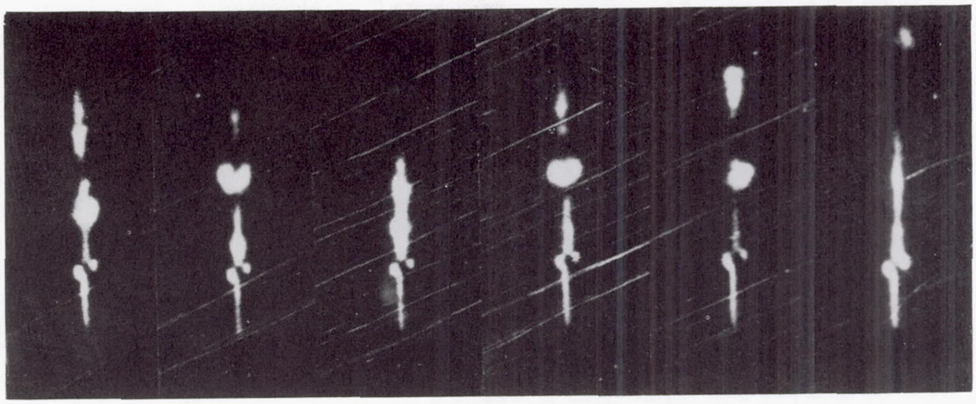
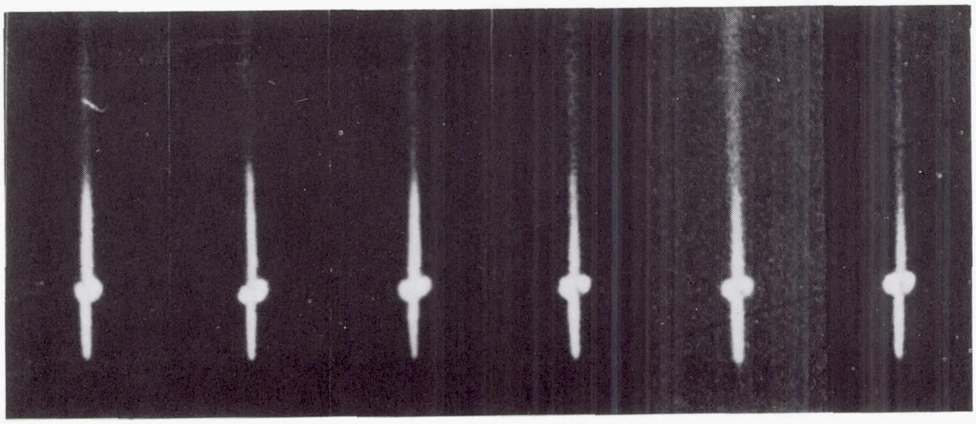


Time after release, sec	35.57	35.78	35.99	36.19	36.39	36.59
Flight Mach number	1.07	1.07	1.07	1.08	1.09	1.09
Frequency of combustion cycles/sec	26	26	26	26	26	26

(a) - Photographic record of combustion that occurred during flight of ram-jet unit 16-B-2.



Time after release, sec	34.96	35.25	35.55	35.85	36.15	36.45
Flight Mach number	1.46	1.50	1.54	1.57	1.61	1.64
Fuel-air ratio	.055	.056	.057	.057	.057	.057

(b) - Photographic record of combustion that occurred during flight of ram-jet unit 16-B-5.

Figure 7. - Photographic record of variation in combustion of ram-jet units 16-B-2 and 16-B-5.

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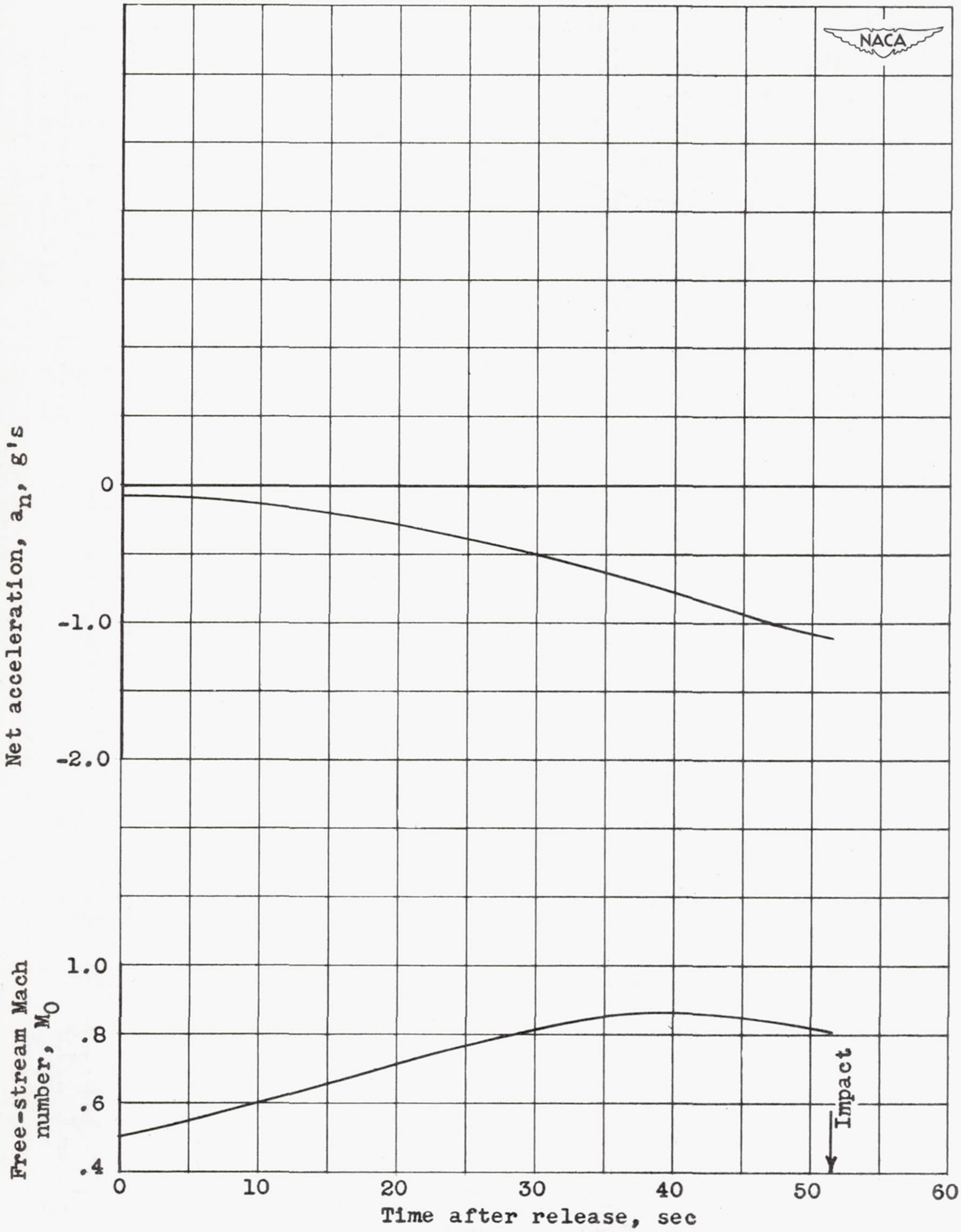
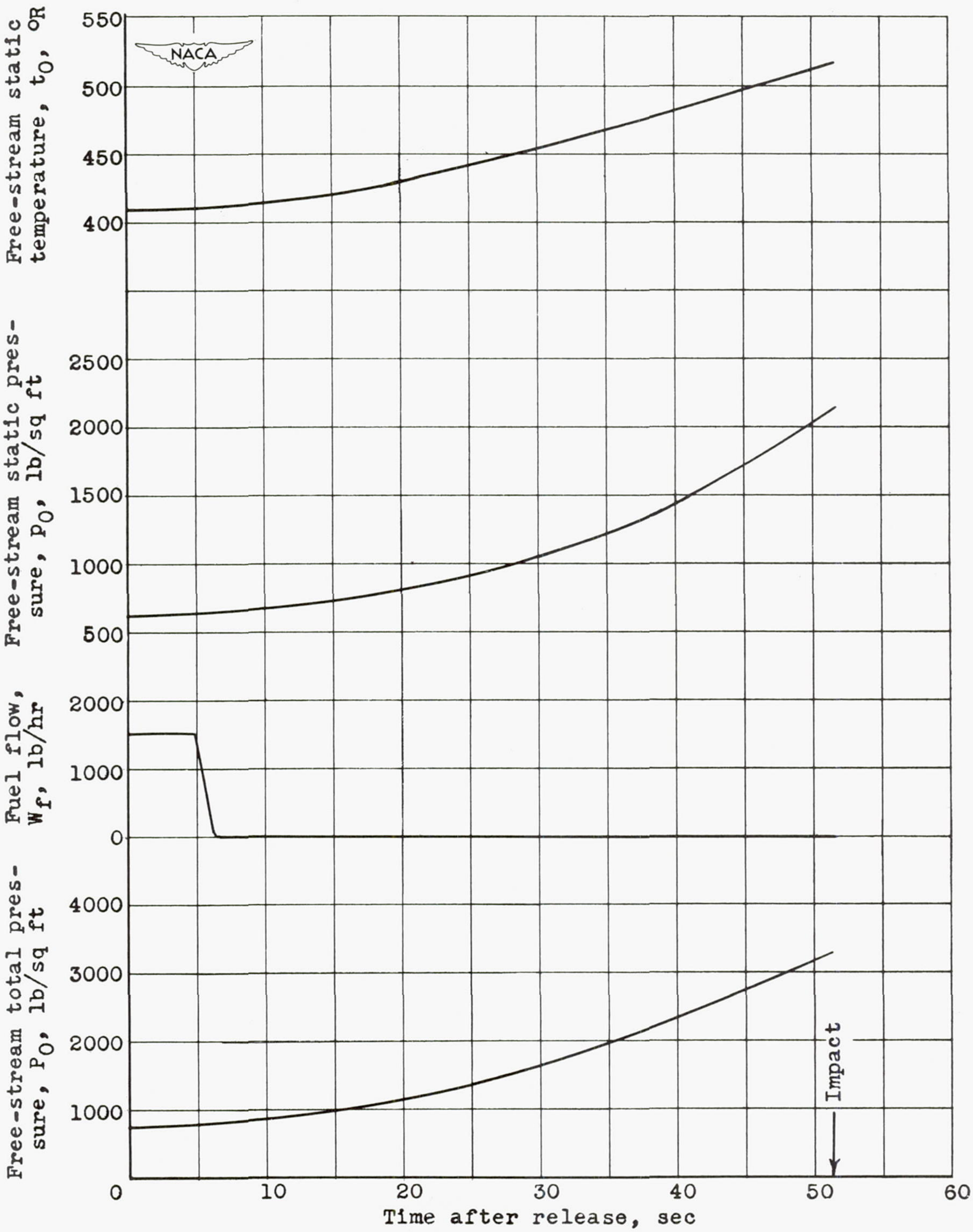


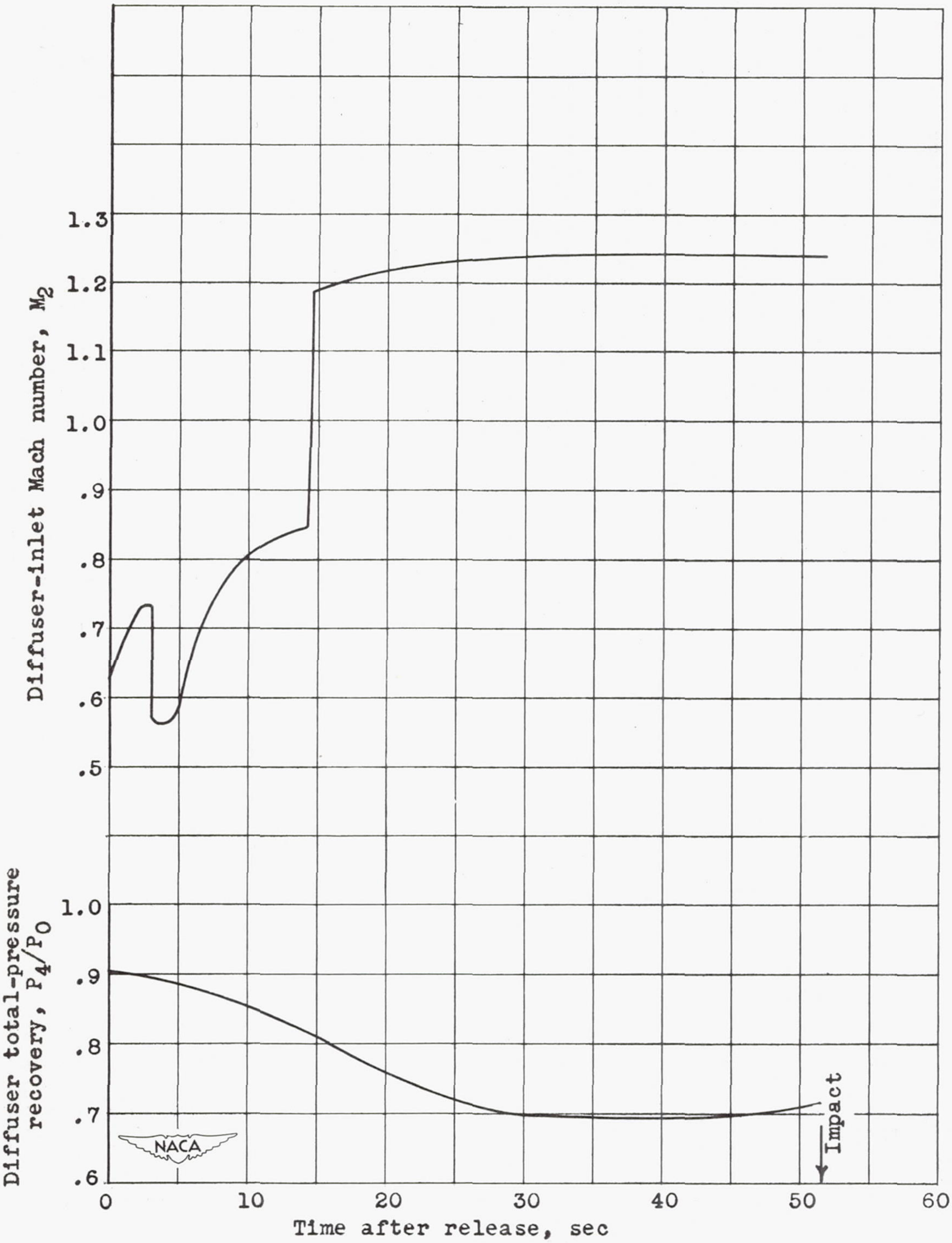
(a) Resultant flight conditions.

Figure 8. - Time history of flight data and performance of ram-jet unit 16-B-1.



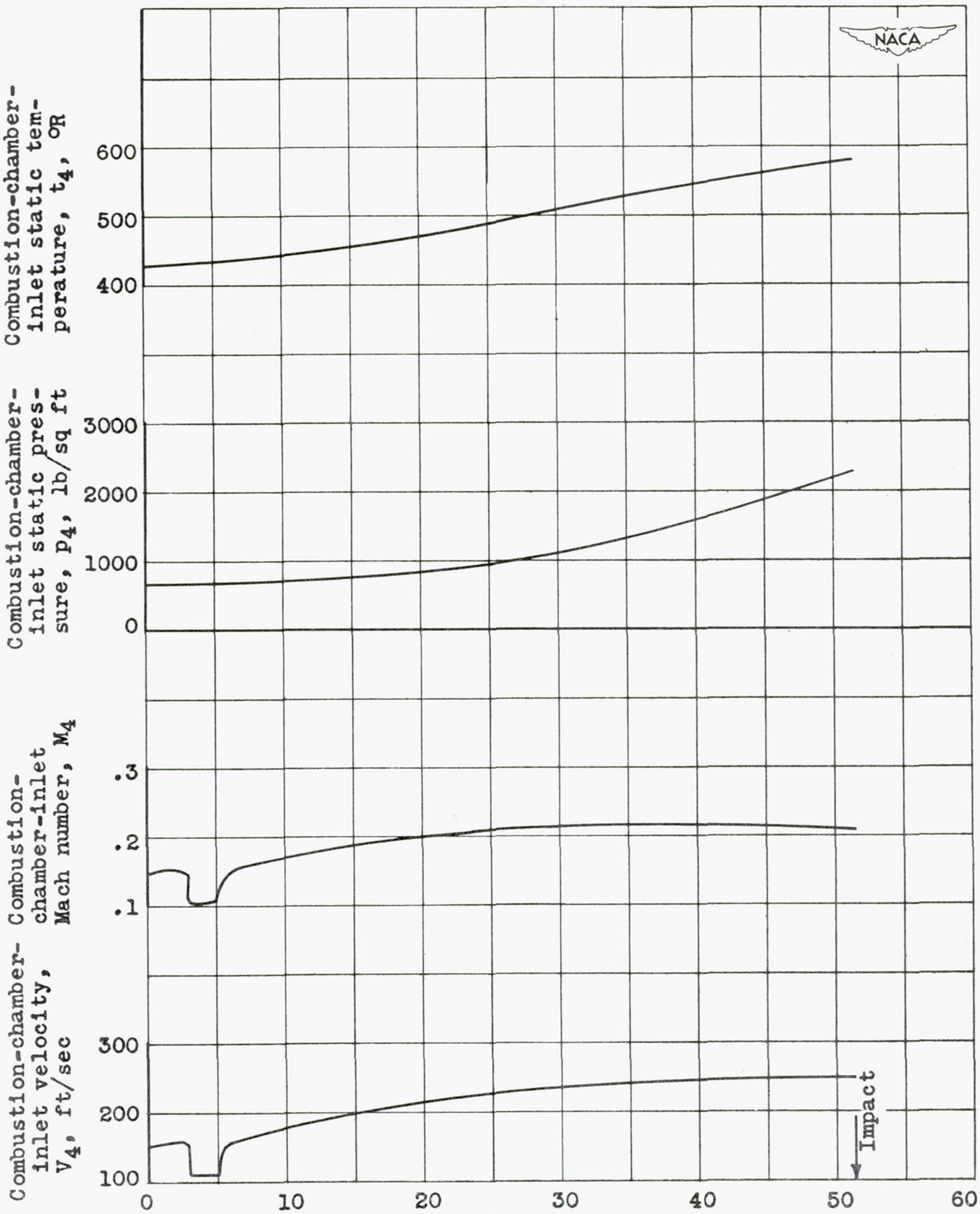
(b) Independent variables.

Figure 8. - Continued. Time history of flight data and performance of ram-jet unit 16-B-1.



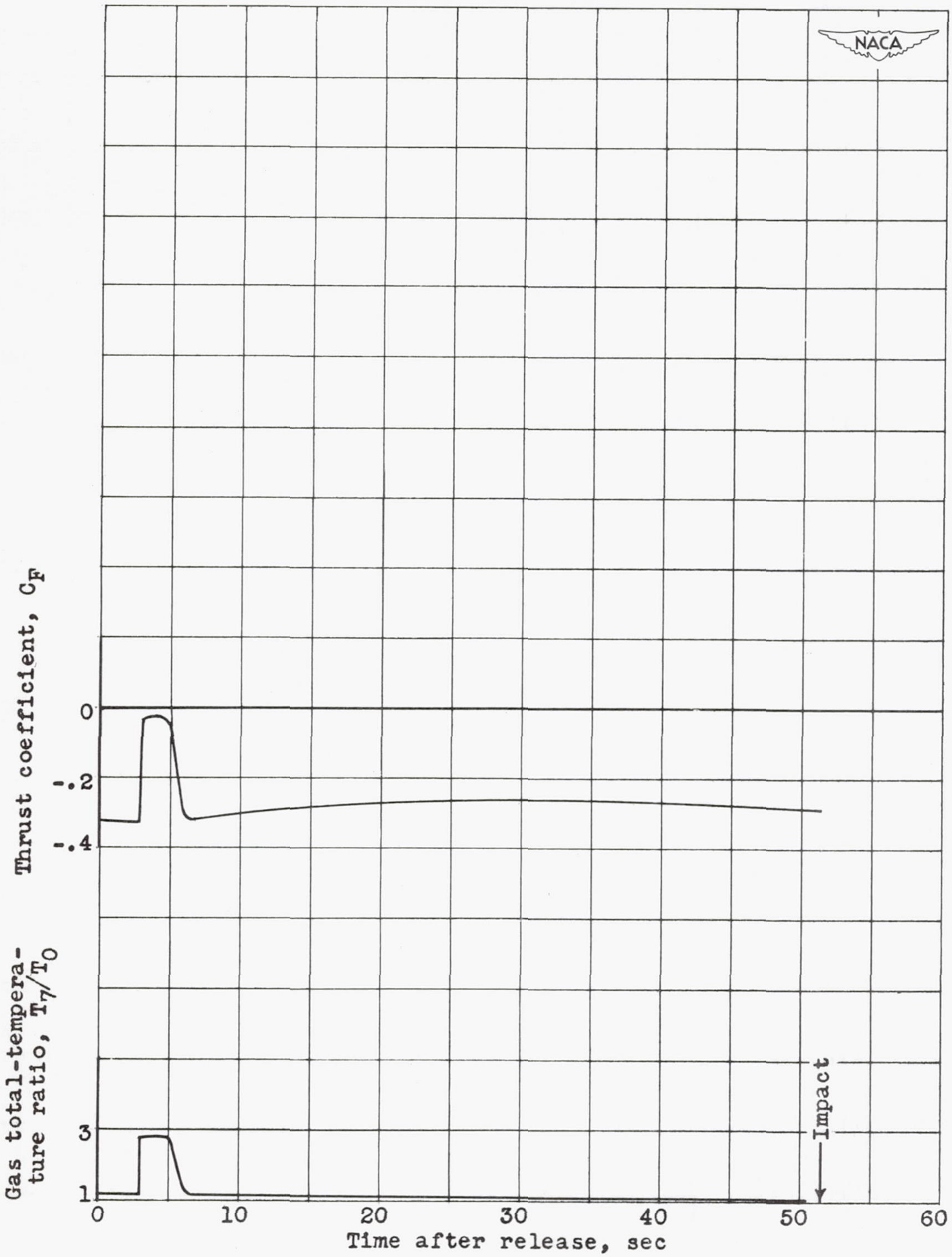
(c) Diffuser variables.

Figure 8. - Continued. Time history of flight data and performance of ram-jet unit 16-B-1.



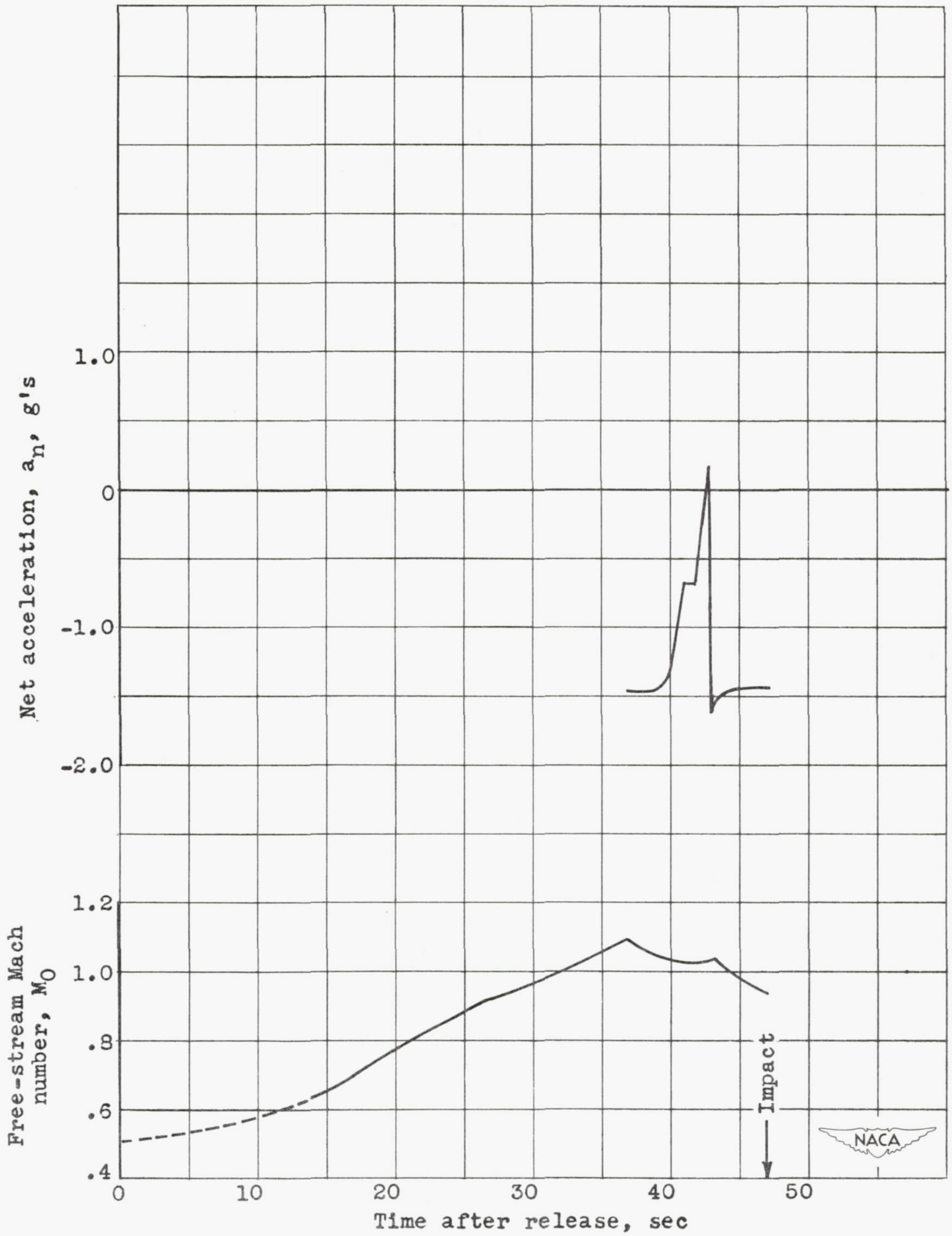
(d) Combustion-chamber-inlet variables.

Figure 8. - Continued. Time history of flight data and performance of ram-jet unit 16-B-1.



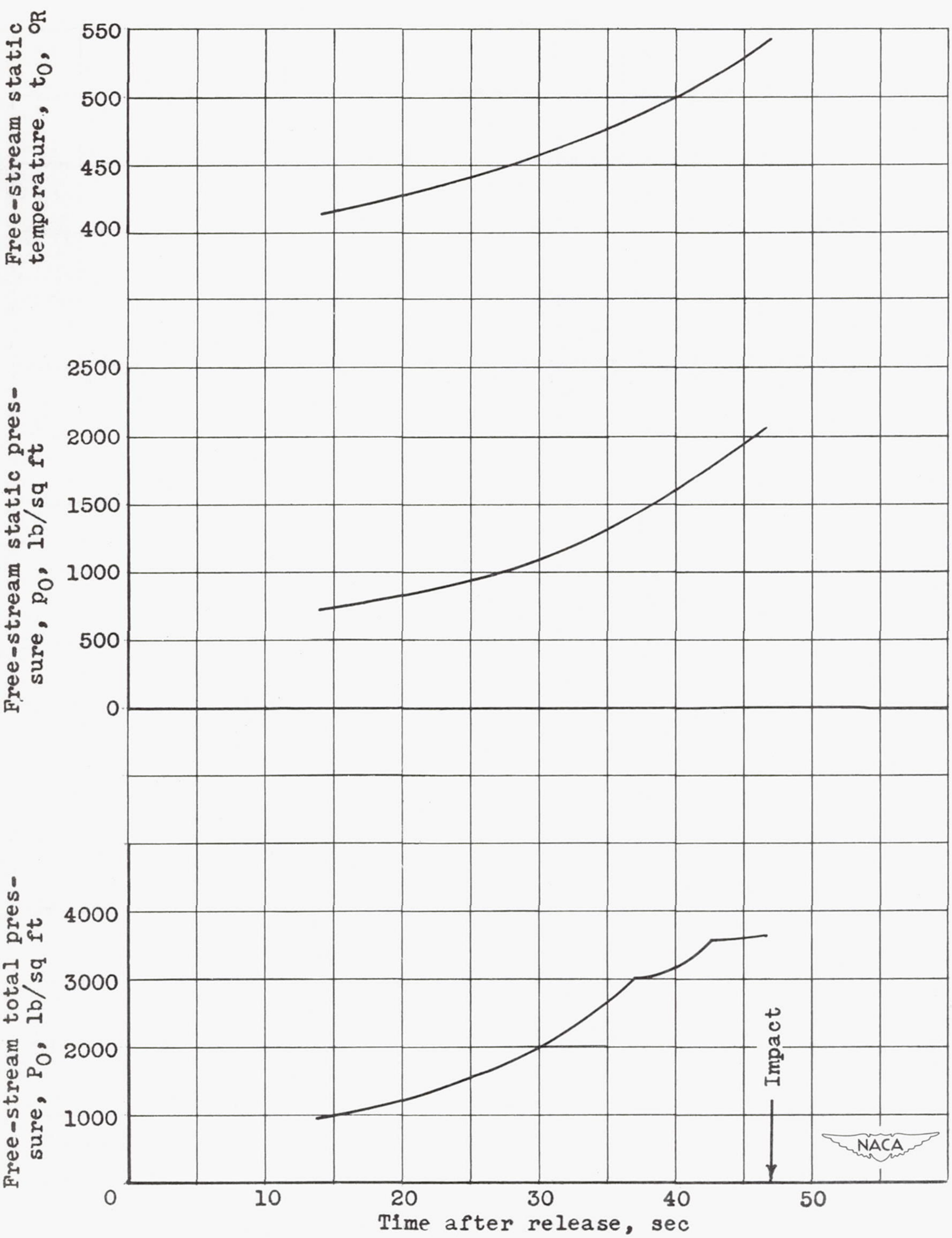
(e) Performance variables.

Figure 8. - Concluded. Time history of flight data and performance of ram-jet unit 16-B-1.



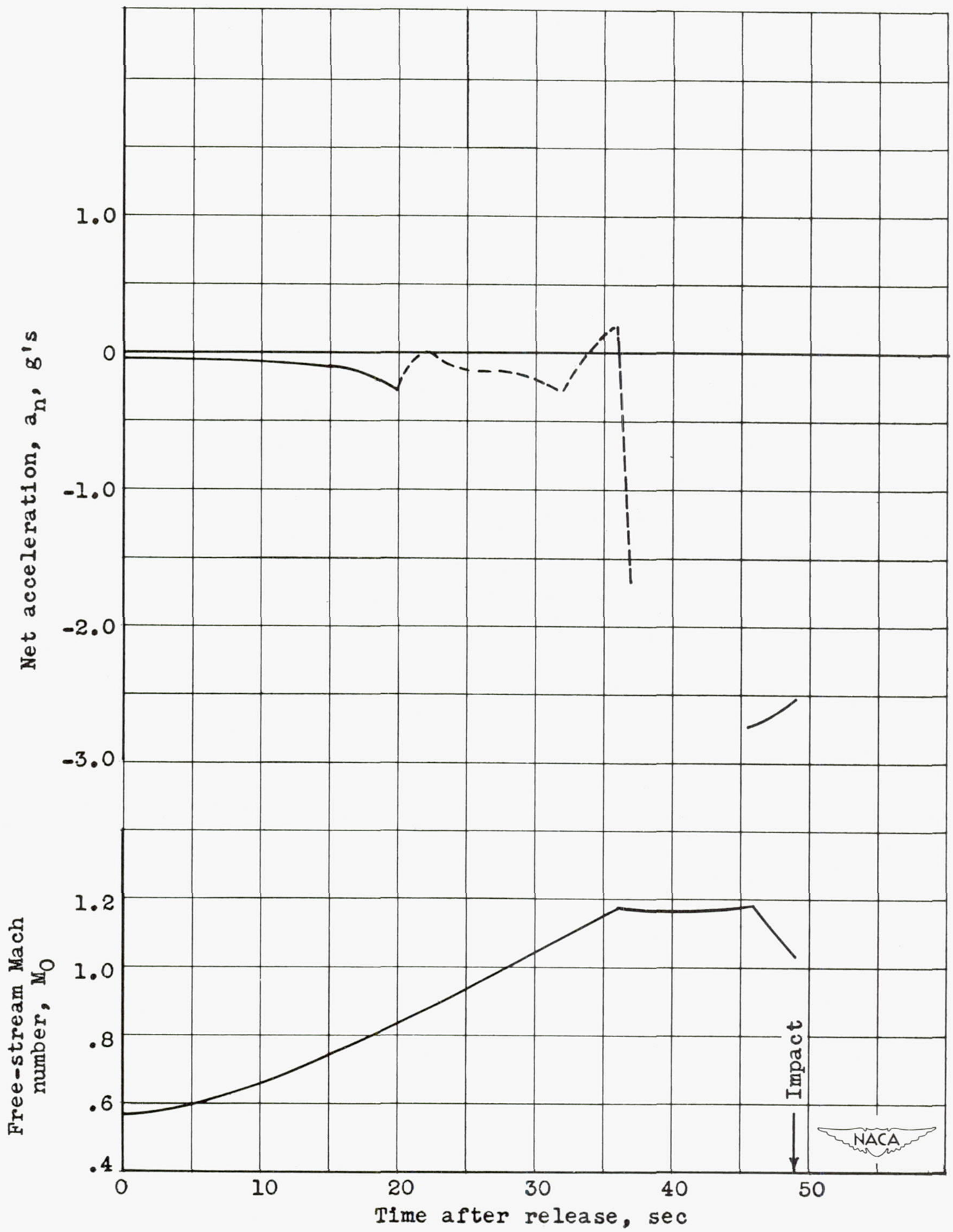
(a) Resultant flight conditions.

Figure 9. - Time history of flight data and performance of ram-jet unit 16-B-2.



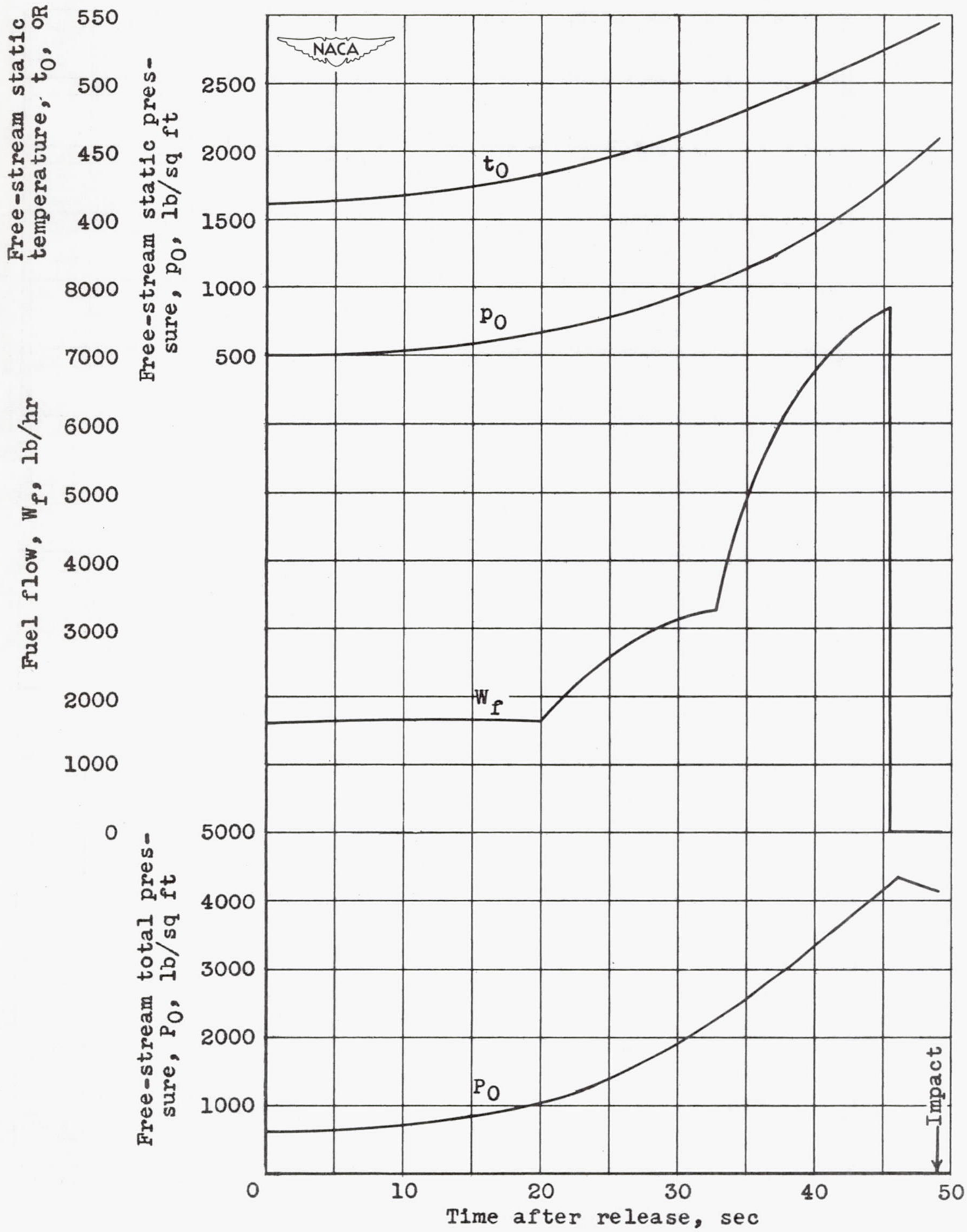
(b) Independent variables.

Figure 9. - Concluded. Time history of flight data and performance of ram-jet unit 16-B-2.



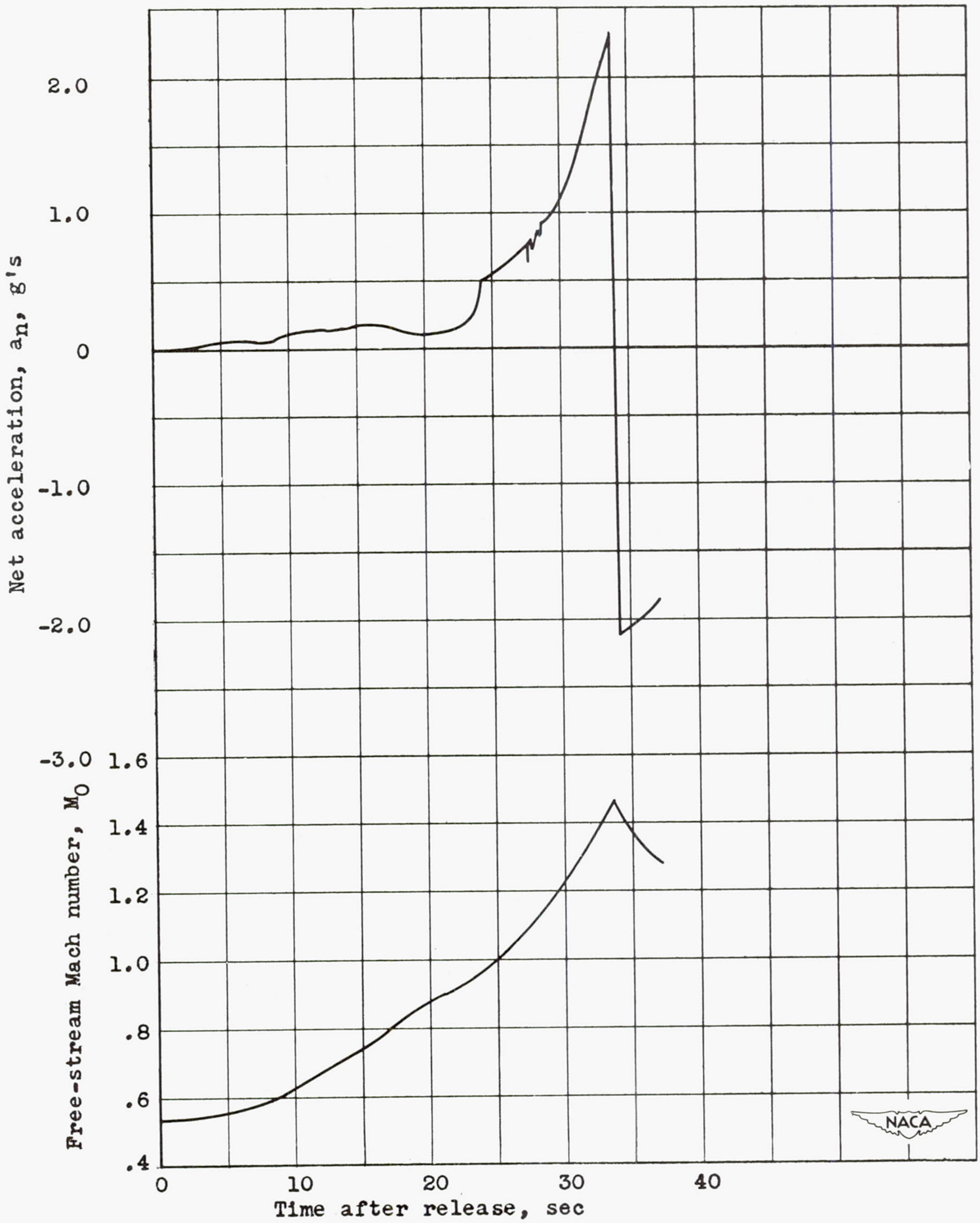
(a) Resultant flight conditions.

Figure 10. - Time history of flight data and performance of ram-jet unit 16-B-3.



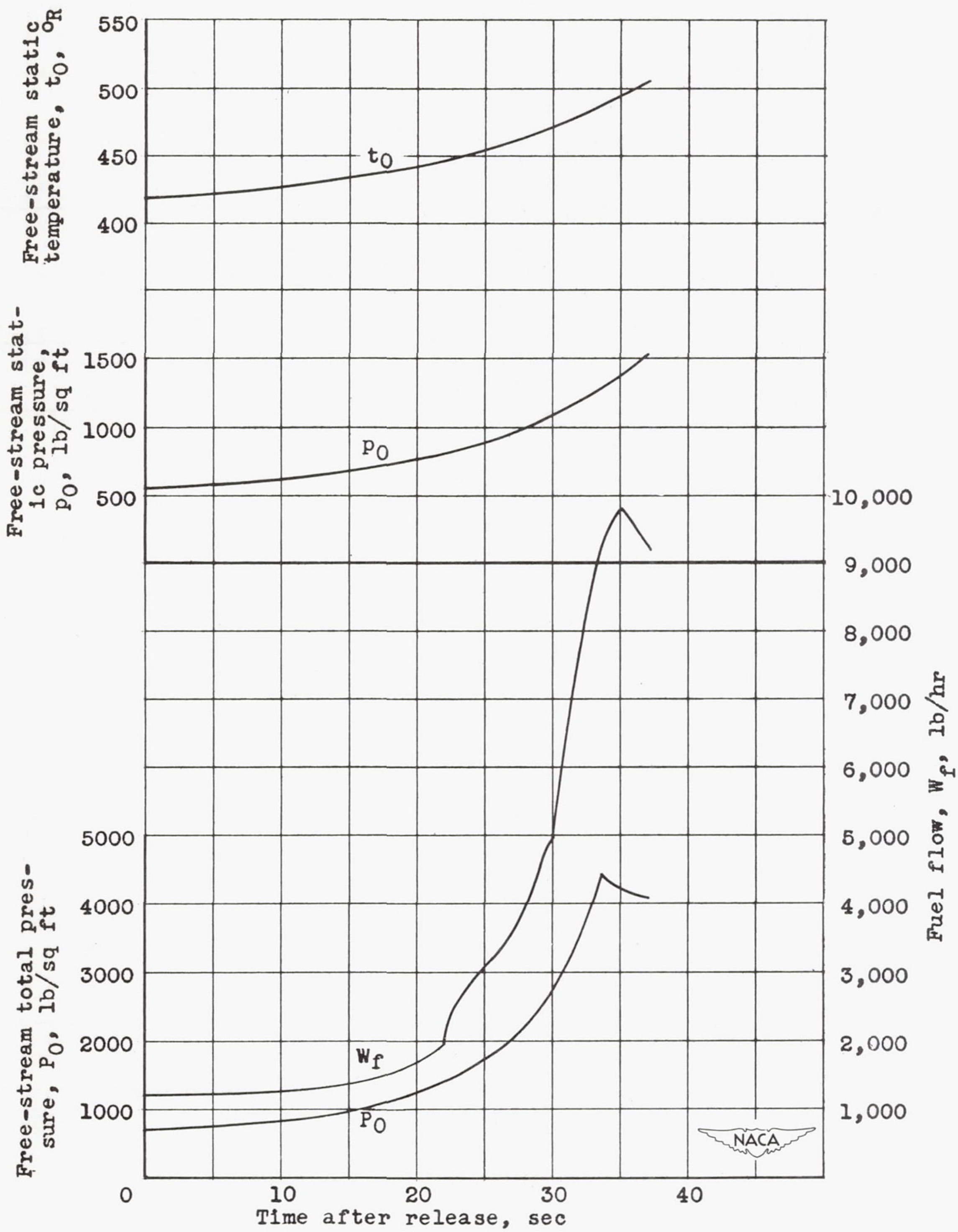
(b) Independent variables.

Figure 10. - Concluded. Time history of flight data and performance of ram-jet unit 16-B-3.



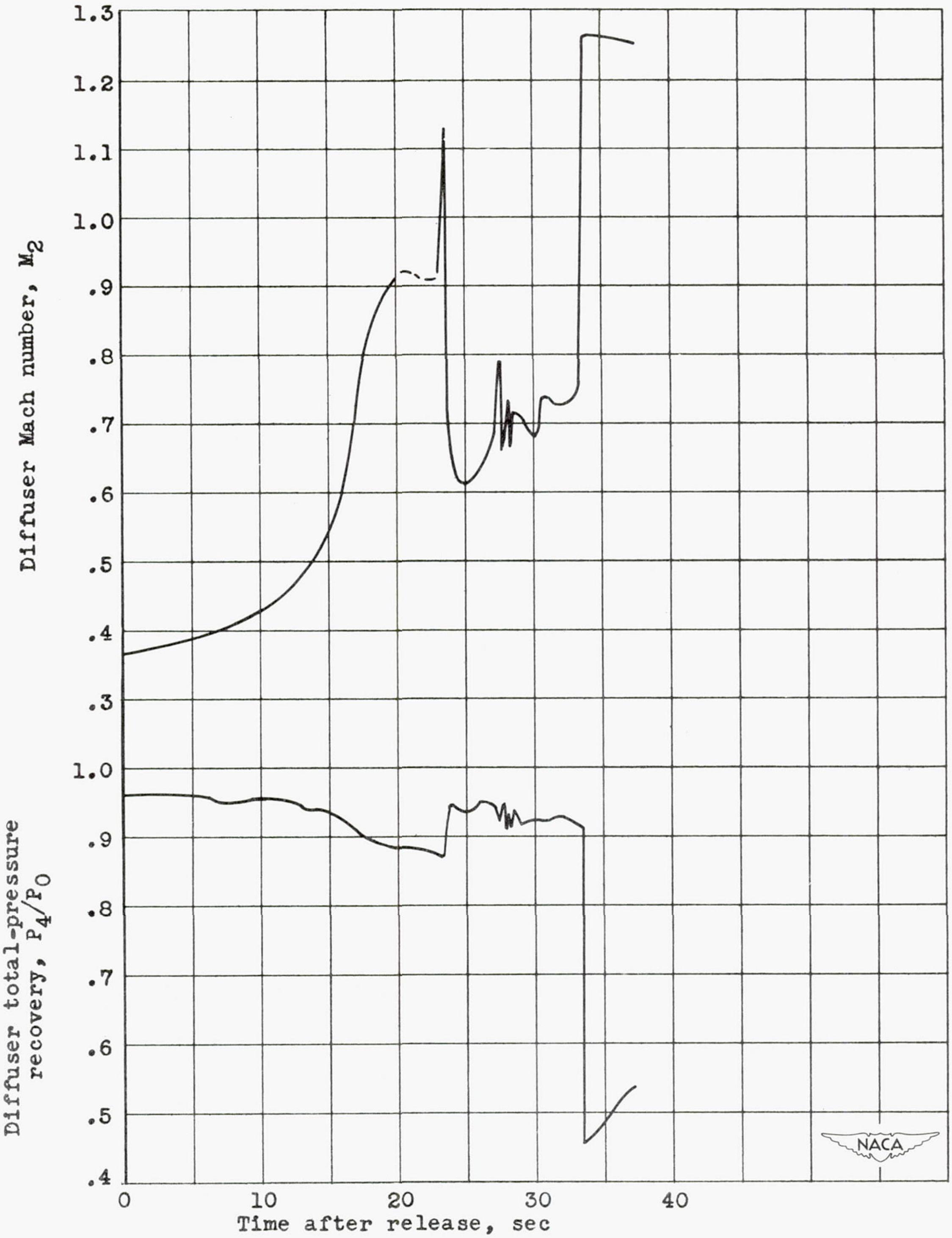
(a) Resultant flight conditions.

Figure 11. - Time history of flight data and performance of ram-jet unit 16-B-4.



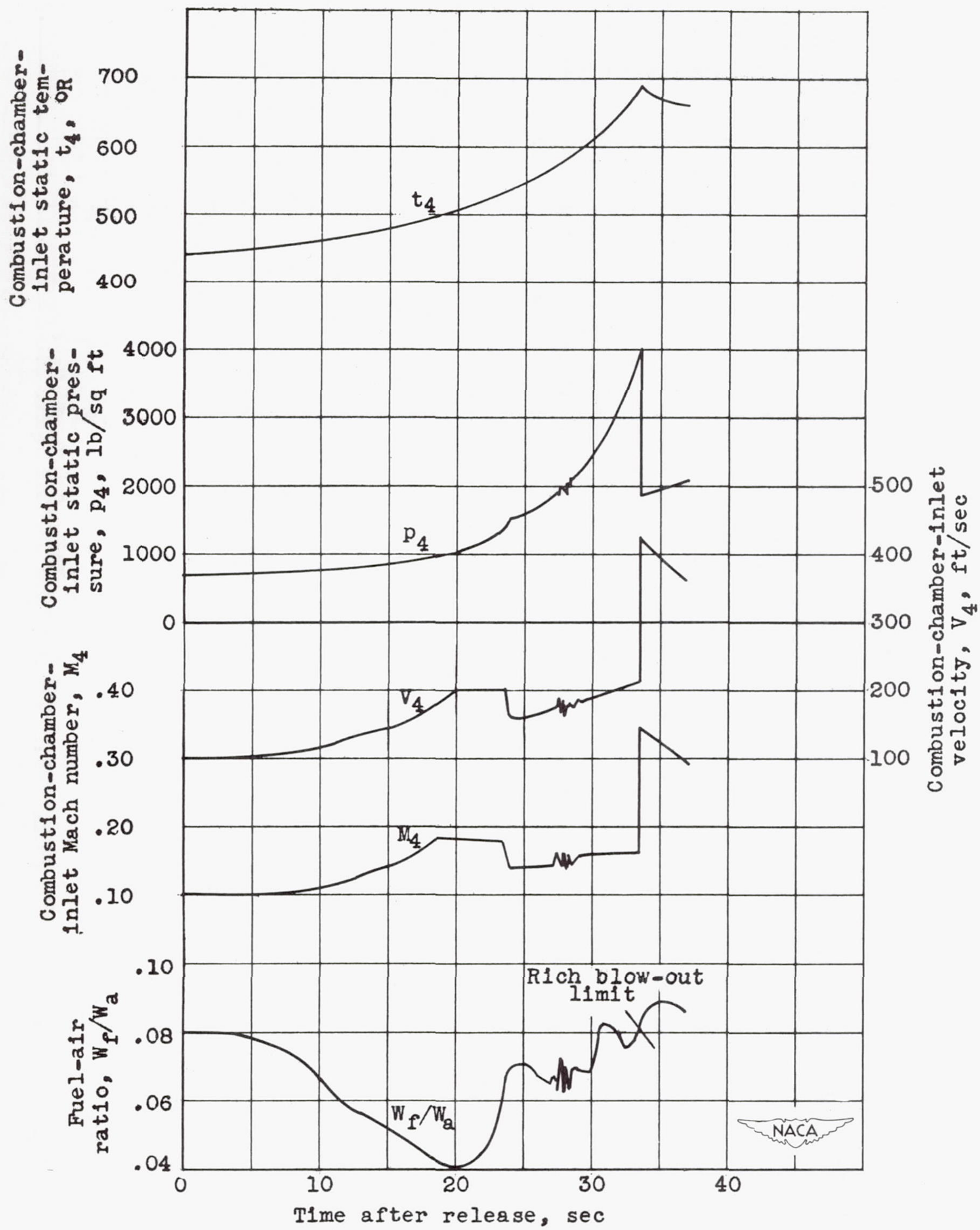
(b) Independent variables.

Figure 11. - Continued. Time history of flight data and performance of ram-jet unit 16-B-4.



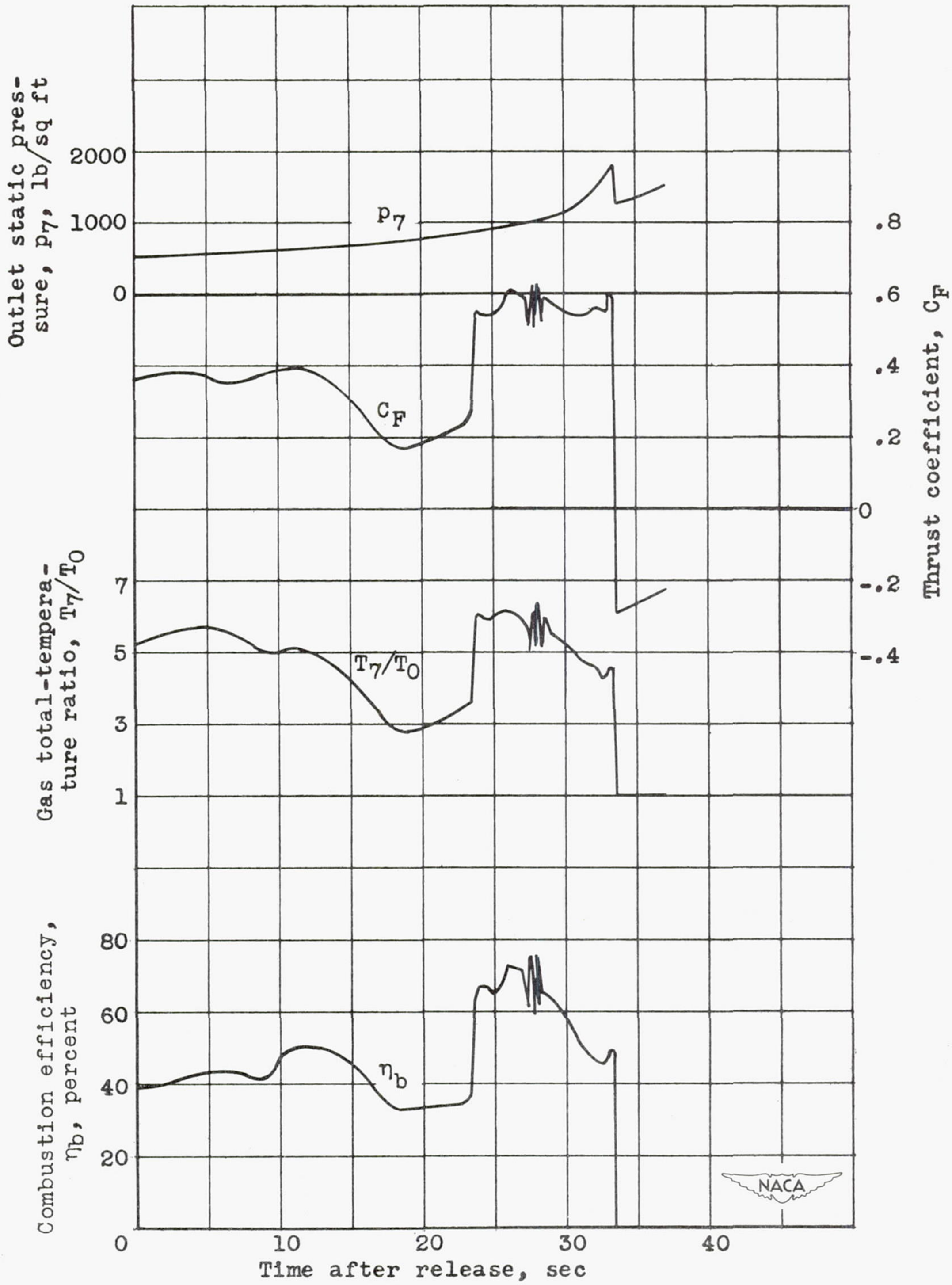
(c) Diffuser variables.

Figure 11. - Continued. Time history of flight data and performance of ram-jet unit 16-B-4.



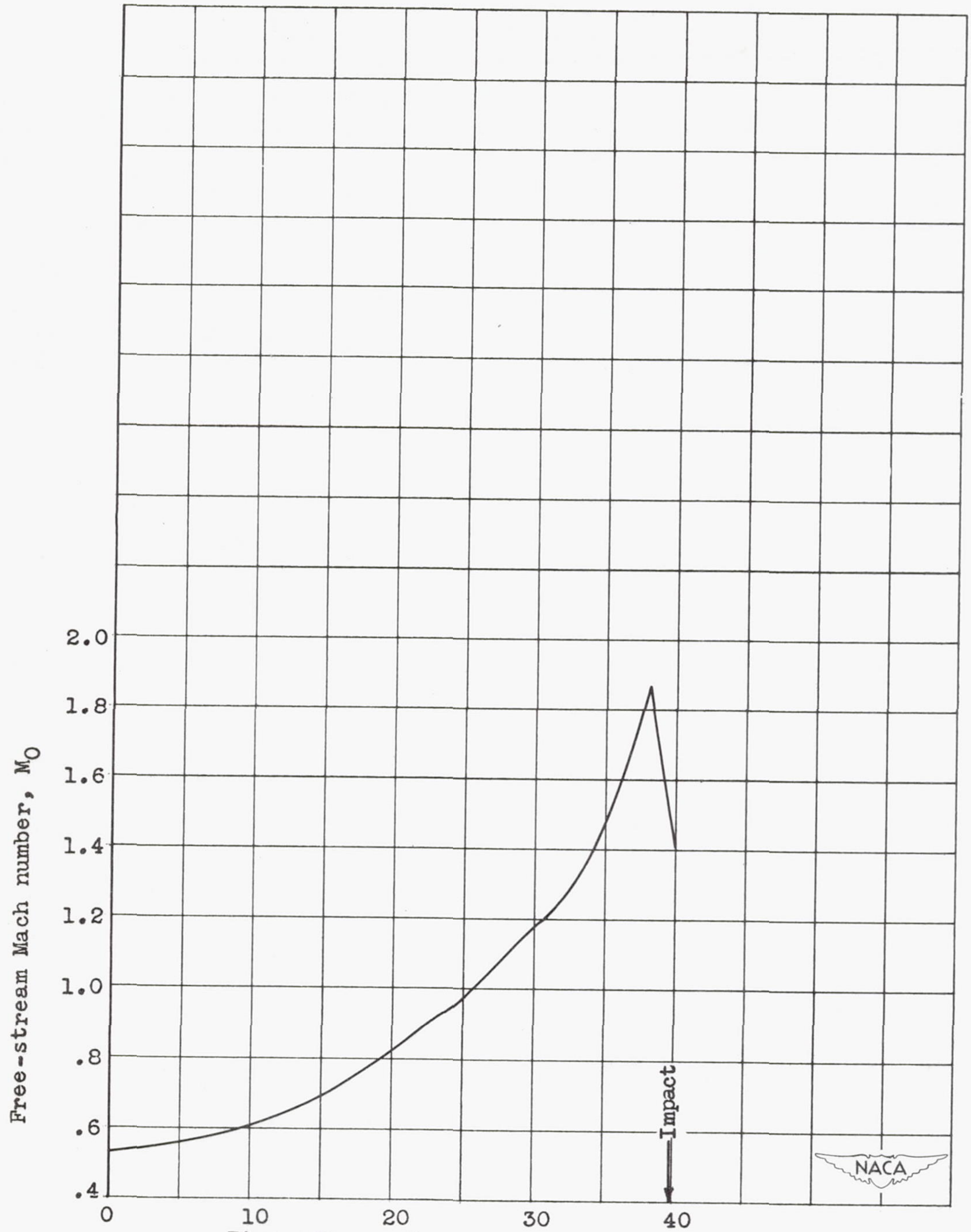
(d) Combustion-chamber-inlet variables.

Figure 11. - Continued. Time history of flight data and performance of ram-jet unit 16-B-4.



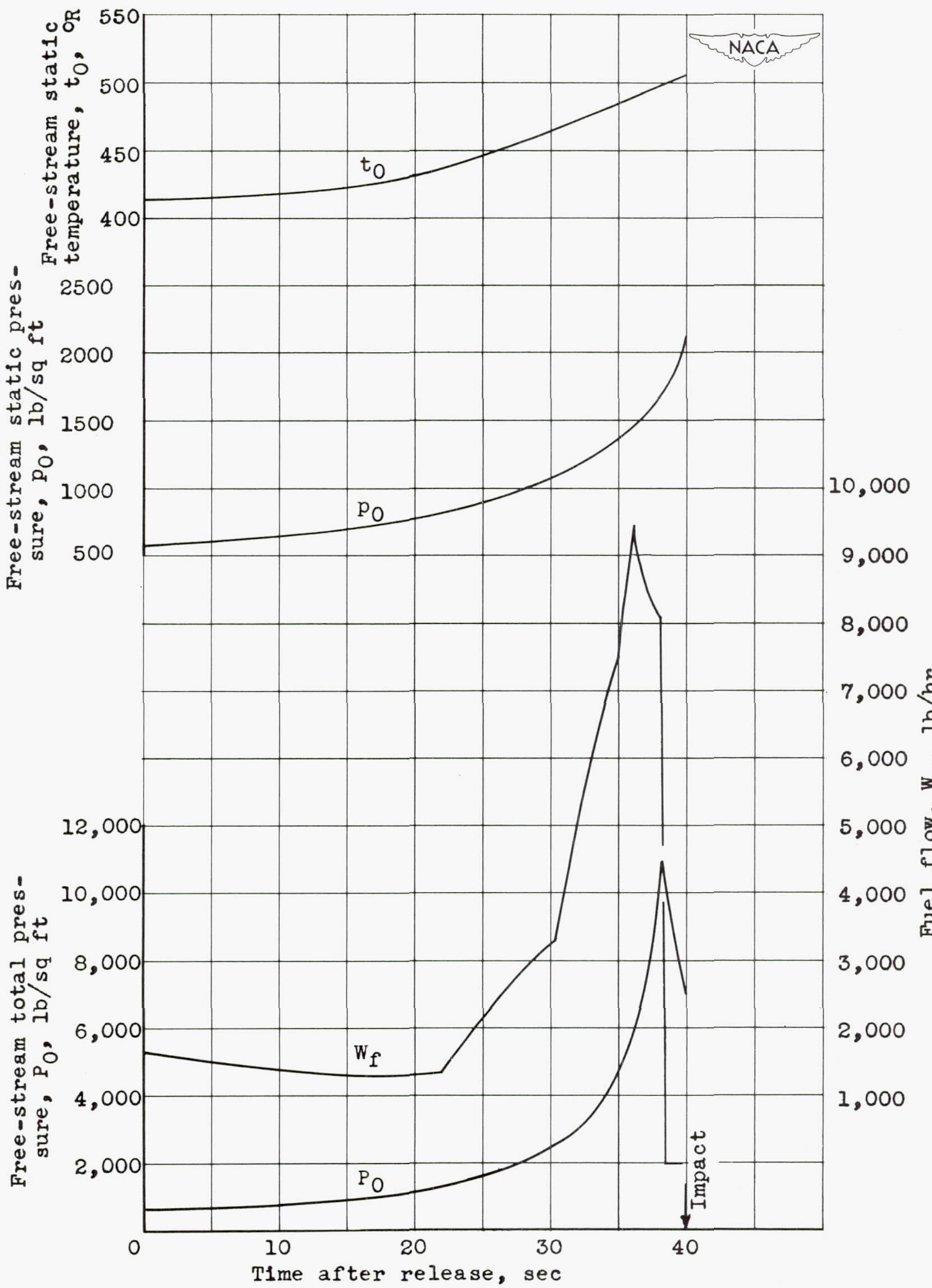
(e) Performance variables.

Figure 11. - Concluded. Time history of flight data and performance of ram-jet unit 16-B-4.



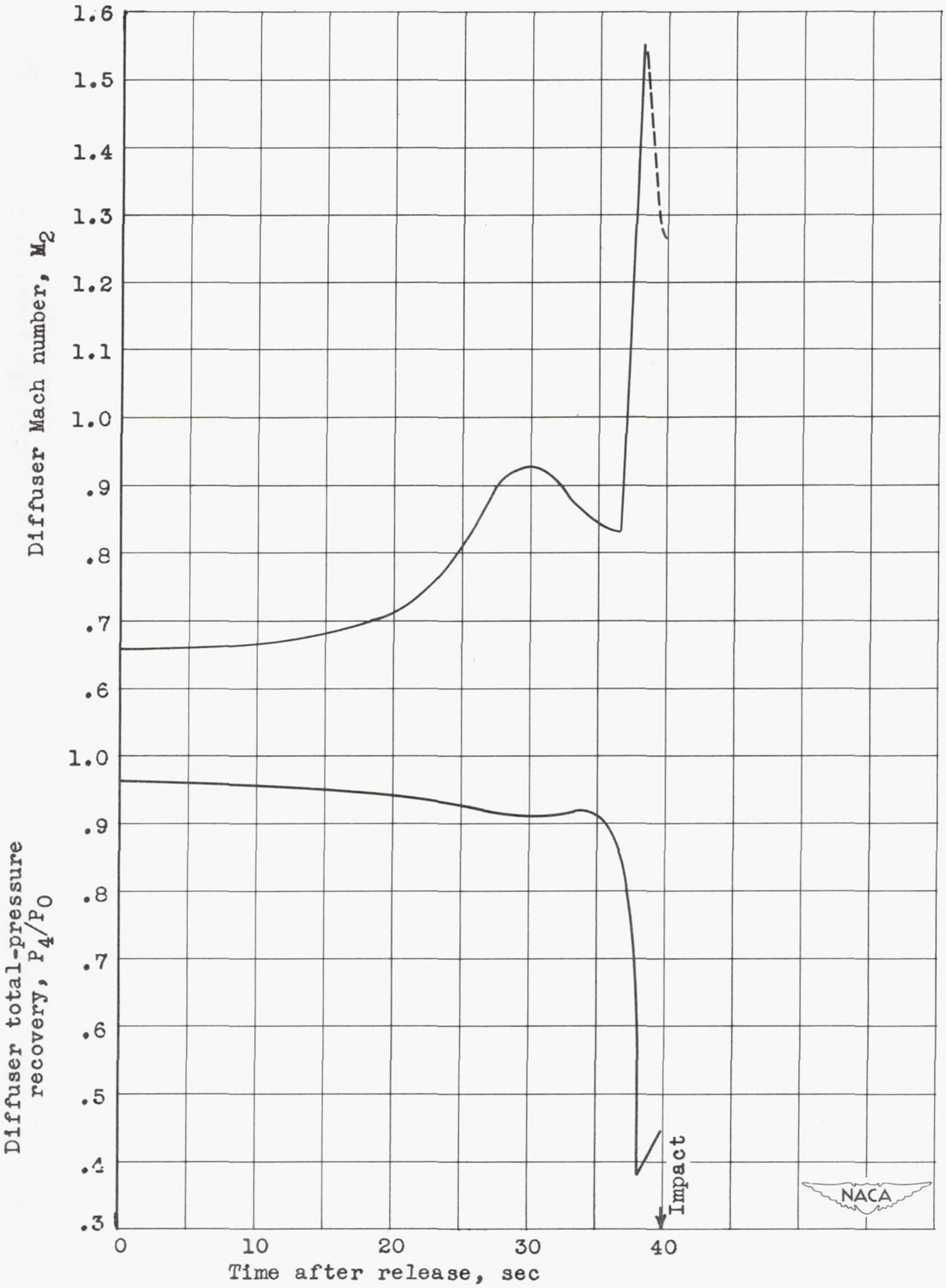
(a) Resultant flight conditions.

Figure 12. - Time history of flight data and performance of ram-jet unit 16-B-5.



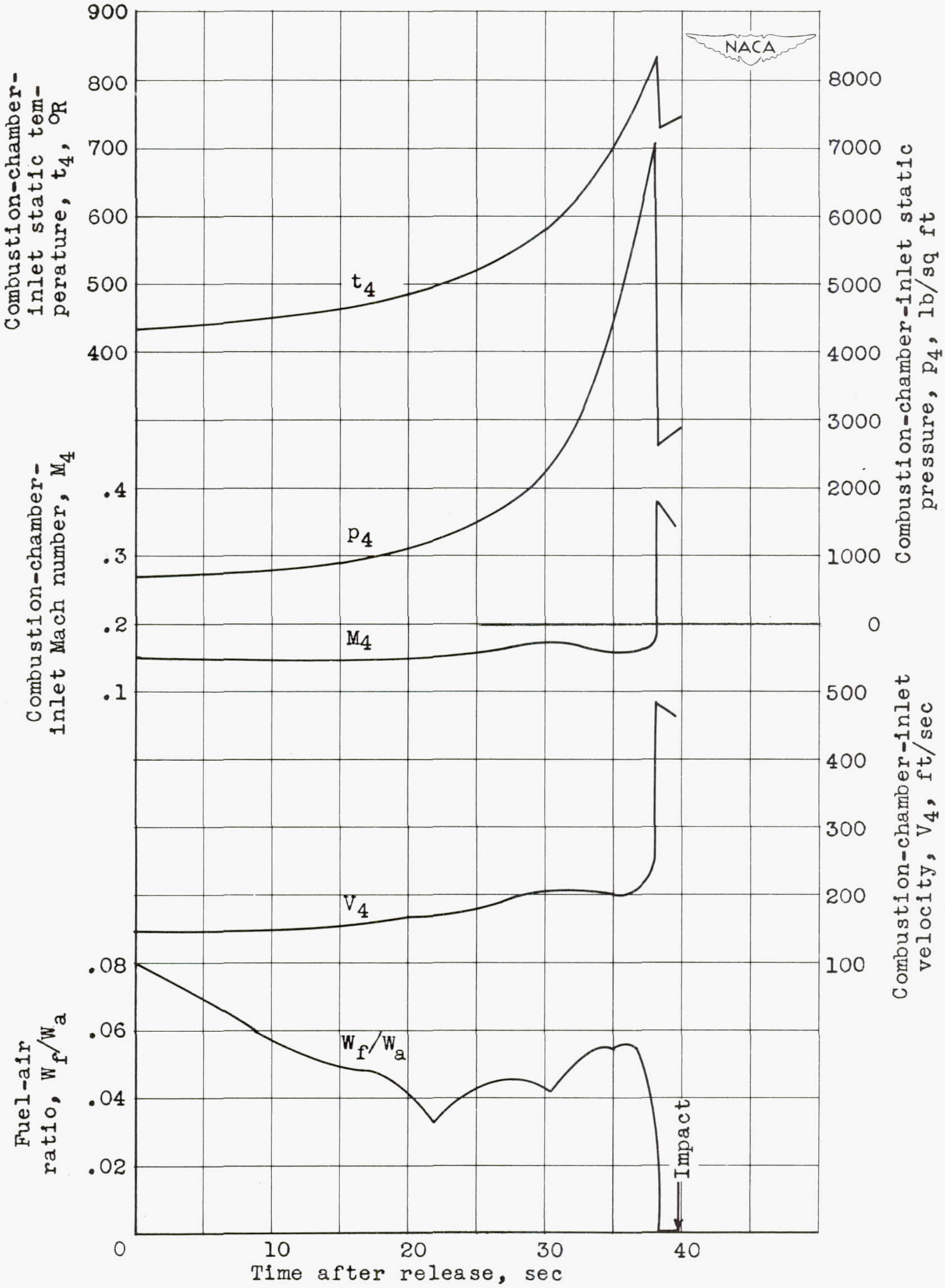
(b) Independent variables.

Figure 12. - Continued. Time history of flight data and performance of ram-jet unit 16-B-5.



(c) Diffuser variables.

Figure 12. - Continued. Time history of flight data and performance of ram-jet unit 16-B-5.



(d) Combustion-chamber-inlet variables.

Figure 12. - Continued. Time history of flight data and performance of ram-jet unit 16-B-5.

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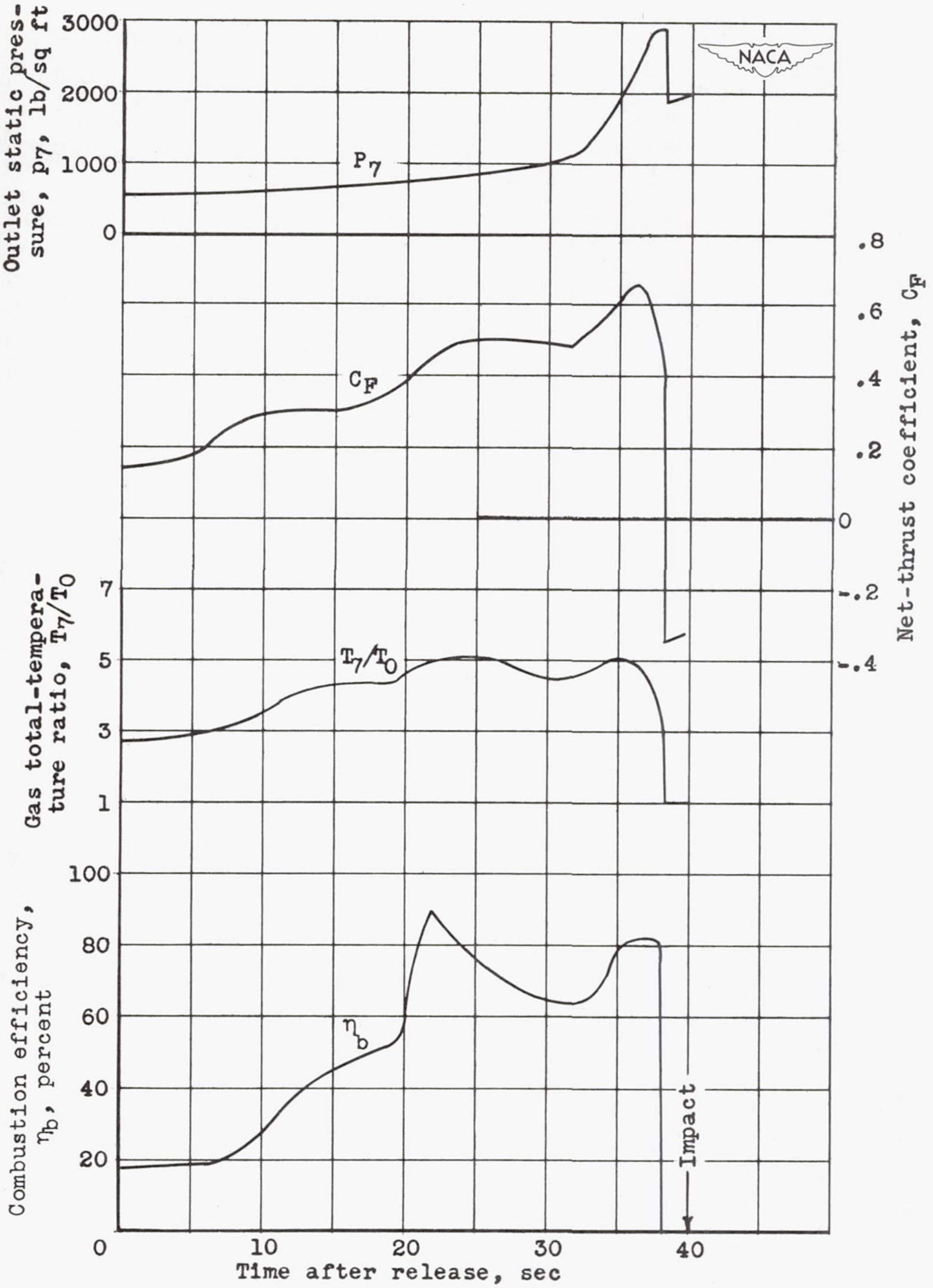

(e) Performance variables.

Figure 12. - Concluded. Time history of flight data and performance of ram-jet unit 16-B-5.

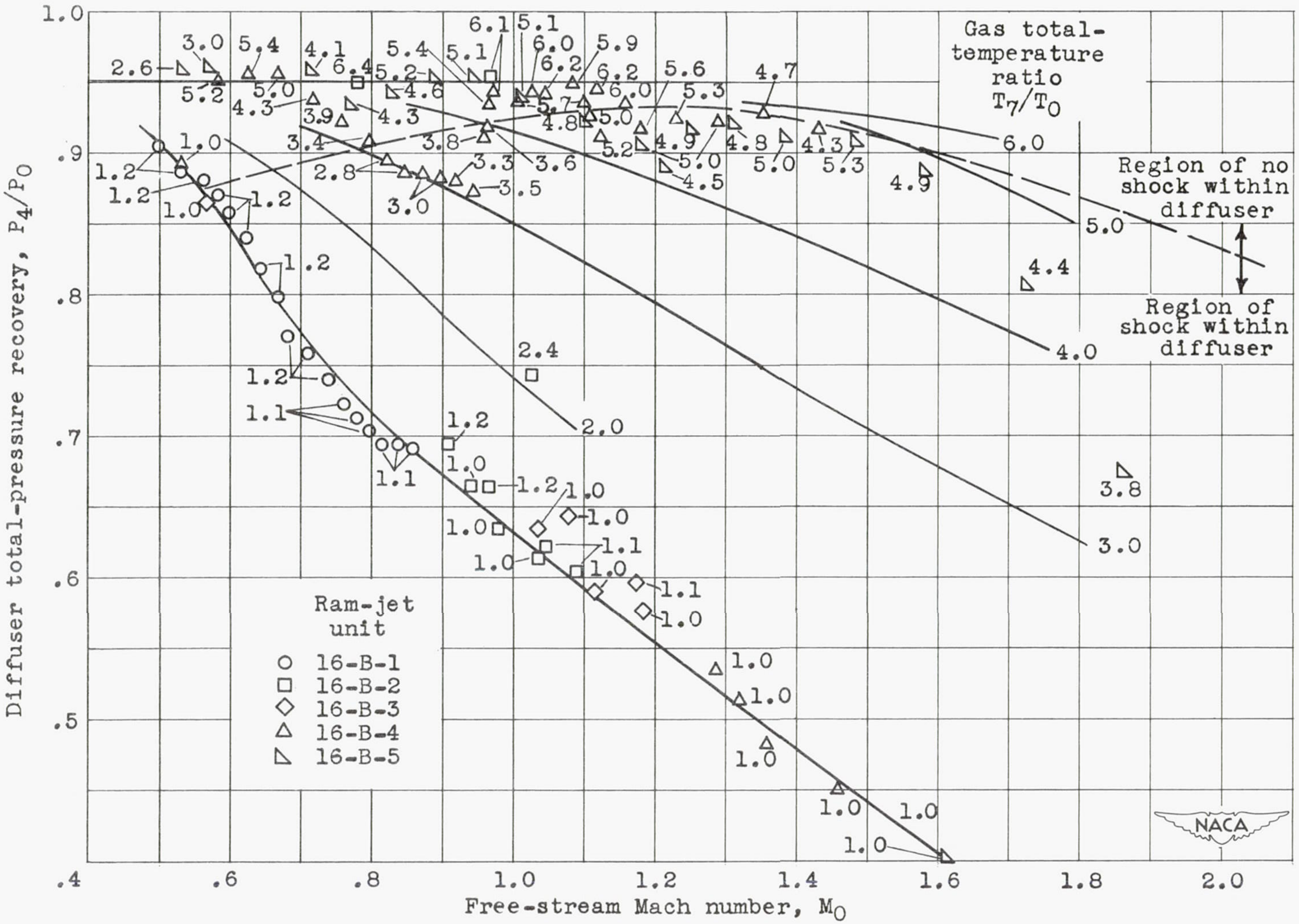

Figure 13. - Diffuser total-pressure recovery as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-B-1, 16-B-2, 16-B-3, 16-B-4, and 16-B-5.

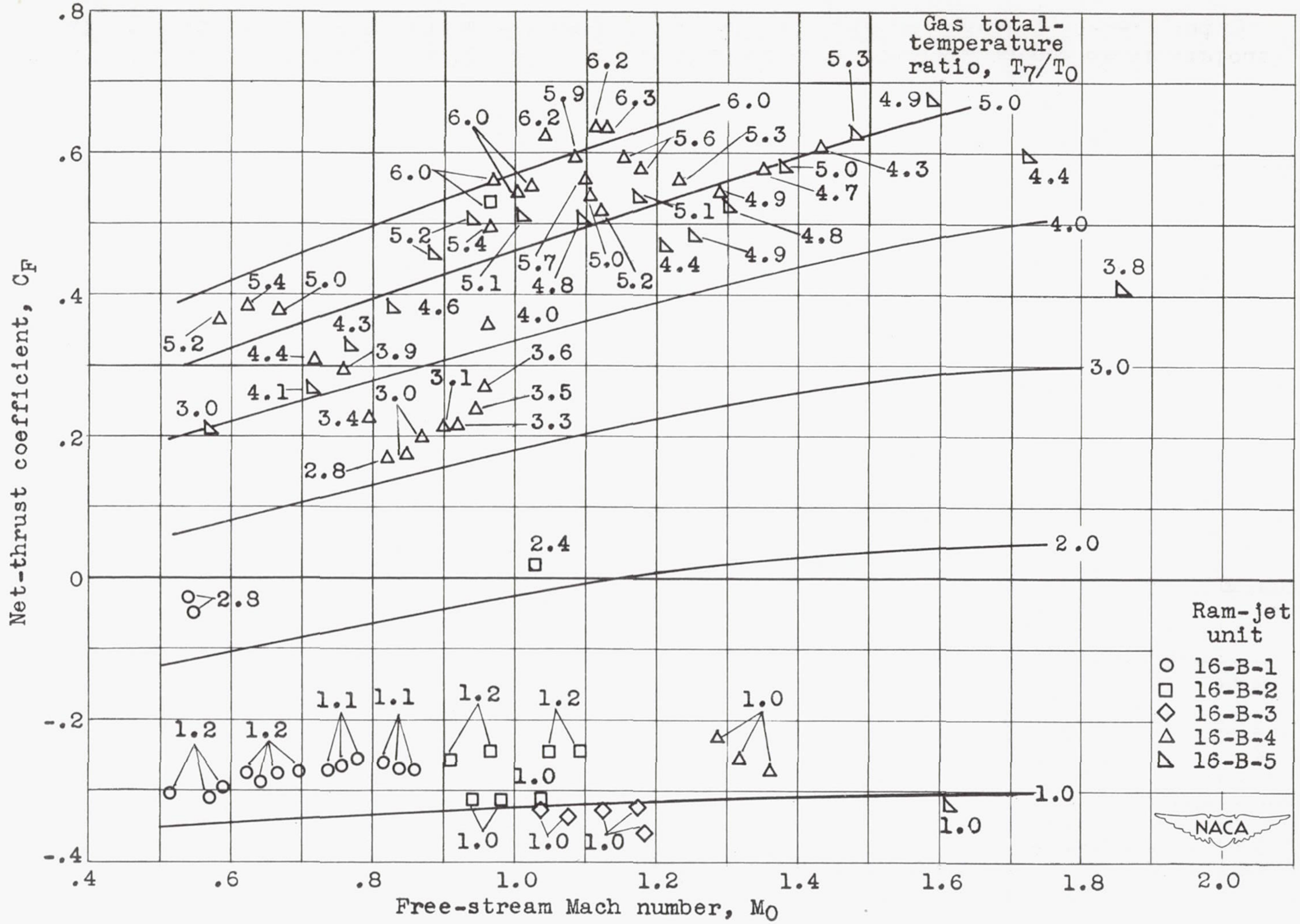

Figure 14. - Net-thrust coefficient as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-B-1, 16-B-2, 16-B-3, 16-B-4, and 16-B-5.

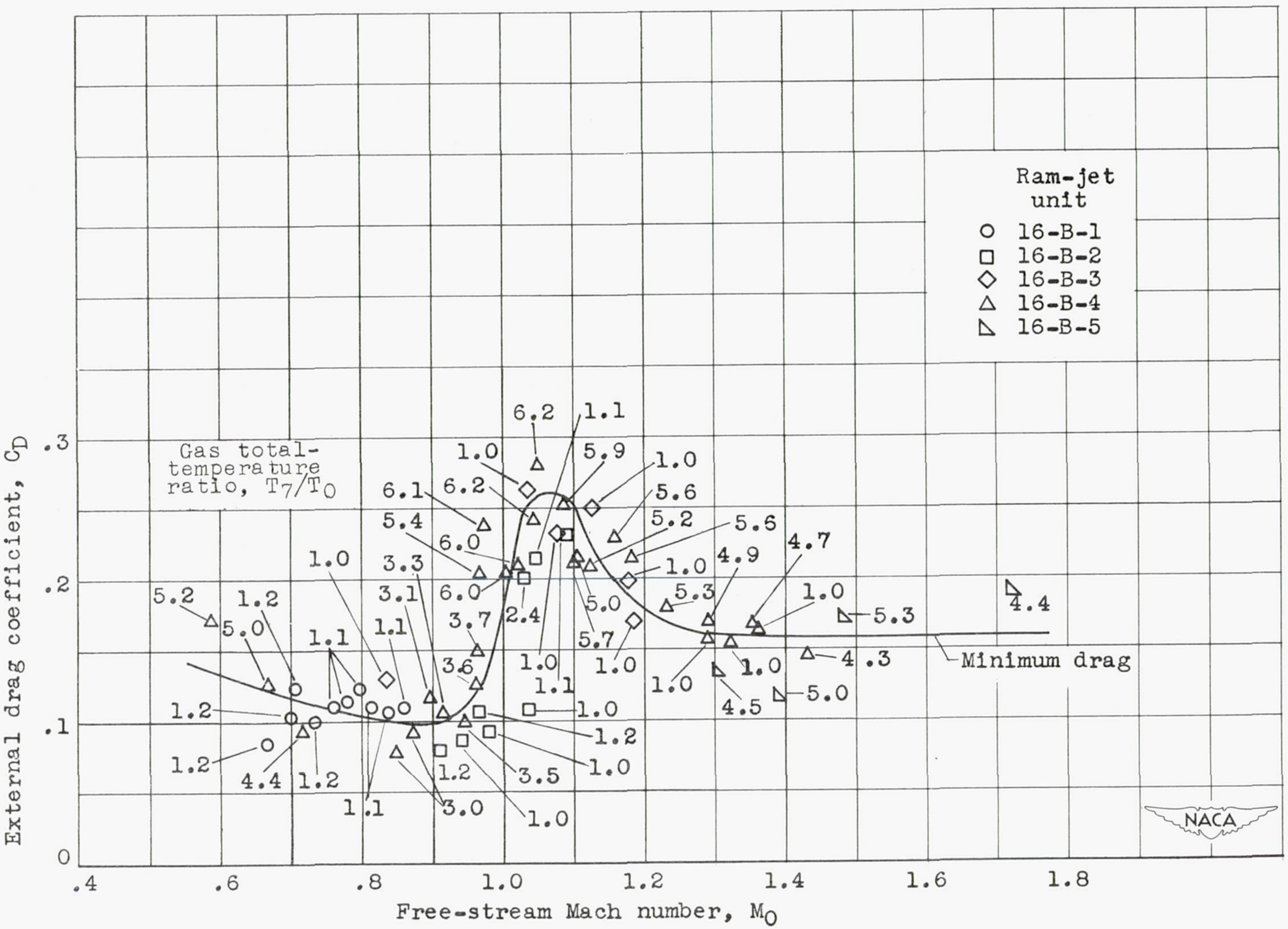

Figure 15. - External drag coefficient as function of free-stream Mach number at various gas total-temperature ratios for ram-jet units 16-B-1, 16-B-2, 16-B-3, 16-B-4, and 16-B-5.

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