NASA MEMO 1-6-59E

NASA

MEMORANDUM

ANALYTICAL INVESTIGATION OF THE SIGNIFICANCE OF TURBINE-INLET TEMPERATURE IN HIGH-ENERGY ROCKET TURBODRIVE APPLICATIONS

By Harold E. Rohlik

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON
February 1959

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MEMORANDUM 1-6-59E

ANALYTICAL INVESTIGATION OF THE SIGNIFICANCE OF TURBINE-INLET TEMPERATURE IN HIGH-ENERGY ROCKET TURBODRIVE APPLICATIONS*

By Harold E. Rohlik

SUMMARY

The effect of turbine-inlet temperature on rocket gross weight was investigated for three high-energy long-range rockets in order to explore the desirability of turbine cooling in rocket turbodrive applications. Temperatures above and below the maximum that is permissible in uncooled turbines were included. Turbine bleed rate and stage number were considered as independent variables.

The gross weight of the hydrogen-reactor system was more sensitive to changes in turbine-inlet temperature than either the hydrogen-oxygen or the hydrogen-fluorine systems. Gross weight of the hydrogen-reactor system could be reduced by 2.6 percent by the use of cooling and a turbine-inlet temperature of 3000° R. The reductions in the first stages of the hydrogen-oxygen and hydrogen-fluorine systems were 0.7 and 0.2 percent, respectively. The effect of turbine-inlet temperature on rocket gross weight was small because the resulting turbine weight and bleed rate variations were small. Since these small gains must be balanced against considerations of greater cost, weight, and complexity as well as lessened reliability with a system utilizing a cooled turbine, none of the systems investigated showed gains warranting the use of turbine cooling.

INTRODUCTION

The gross weight of a rocket with a given payload and a given mission is influenced in two ways by the turbine design selected: (1) the mass of the turbine must be accelerated to the burnout velocity, altitude, and direction and consequently influences the expenditure of the propellant and (2) the turbine bleed rate (that fraction of the propellant used by the turbine) directly influences the effective specific impulse of the total propellant being consumed. These conditions indicate the desirability of low turbine weight and high turbine work per pound of turbine flow.

Turbine specific work (work per pound of flow) increases with increasing inlet temperature for a given pressure ratio so that turbine cooling offers the possibility of savings in rocket gross weight. An investigation of the effect of turbine-inlet temperature on gross weight has been conducted with three high-energy propellant systems: a single-stage rocket utilizing hydrogen with a nuclear-reactor heat source and two-stage chemical systems employing hydrogen-oxygen and hydrogen-fluorine combination. The mission selected for consideration was a simple vertical mission with constant gravity and no air drag that was determined to be the equivalent of a long-range mission. The turbodrive systems considered included a single turbine driving one or two propellant pumps with a small fraction of the propellant flow as its working fluid. Investigation of the effect of turbine-inlet temperature required consideration of variable bleed rate and stage number in the calculation of the gross weight-to-payload ratio. Turbine-inlet temperature was varied through a range above and below the maximum permissible for uncooled blades. Turbine-exhaust thrust recovery was also considered.

This report presents the method employed in the analysis and the results of the analysis in terms of gross weight-to-payload ratio for several turbine-inlet temperatures, turbine stage numbers, and bleed rates.

SYMBOLS

c_p specific heat at constant pressure, Btu/lb/$^{\circ}$R

g acceleration due to gravity, 32.2 ft/sec^2

h altitude at end of powered flight, ft

I specific impulse, sec

n number of turbine stages

P payload, lb

p pressure, lb/sq in abs

$\overline{S}$ structural parameter excluding effect of turbine weight,

$$\overline{S} = \frac{W_e - P - W_T}{W_{pr}}$$

T turbine-inlet temperature, $^{\circ}$R

t duration of powered flight, sec

U turbine blade tip speed, ft/sec

V velocity, ft/sec

W weight, lb

w flow rate, lb/sec

y ratio of turbine flow to pump flow (bleed rate)

ε thrust recovery coefficient, I_T/I_n

λ speed work parameter

ρ blade metal density, lb/cu ft

Subscripts:

av time average

b burnout, end of powered flight

cr critical, corresponding to a flow Mach number of 1.0

e empty

ex turbine exit

g gross

n rocket nozzle

P pump

pr propellant

ref reference

T turbine

V vacuum

x axial component

METHOD OF ANALYSIS

Rocket Requirements and Assumptions

The rocket systems selected for this investigation included a nuclear-powered hydrogen system and two chemical systems utilizing the combination of hydrogen with oxygen and hydrogen with fluorine. A ratio of first-stage gross weight to second-stage gross weight of 5.0 was selected for both chemical rockets (the hydrogen-reactor rocket had only one stage). The effect of turbine-inlet temperature on missile gross weight was investigated in only the first stage of the two-stage systems.

The effect of turbine-inlet temperature was studied by determining the changes in turbine weight and turbine flow rate that were associated with changes in turbine-inlet temperature and turbine stage number. The variations in turbine weight and flow rate affected the gross weights of the rockets for the fixed missions considered so that gross weight could be related to the turbine-inlet temperature and turbine stage number.

The rocket structural and flight parameters corresponding to the mission selected are listed in the following table (the values shown serve as the reference conditions for each system):

Rocket system	Ratio of gross weight to empty weight in first stage, W_g/W_e	Ratio of gross weight to payload in first stage, W_g/P	Ratio of gross weight to payload in second stage, W_g/P	Over-all ratio of gross weight to payload	Duration of powered flight, t, sec	Time-average specific impulse $I_{av,n}$	Bleed rate y	Structural parameter, $\overline{S}$
Hydrogen-reactor	3.70	6.26	----	6.26	309	720	0.03	0.15
Hydrogen-oxygen	[a]4.21	5.0	3.12	15.60	[a]191	[a]340	.02	[a].05
Hydrogen-fluorine	[a]4.32	5.0	2.49	12.45	[a]217	[a]397	.01	[a].04

[a]First stage only.

Equations for simple vertical flight with no air drag and constant gravity were used in order to facilitate the investigation of turbine temperature effect. Equation (1) gives the velocity at the end of powered flight and is a rearranged form of equation (12-18) of reference 1.

$$V_b = I_{av} g \ln \left(\frac{W_g}{W_e} \right)_1 - gt \qquad (1)$$

The turbine flow results in a loss in impulse as shown in the following equation for time-averaged effective specific impulse:

$$I_{av} = I_{av,n} \left[1 - (1 - \varepsilon_{av}) y \right] \qquad (2)$$

where $I_{av,n}$ is the time-averaged specific impulse for full flow through the rocket nozzle, y is the bleed rate as a fraction of the total pump flow, and ε_{av} is the time-averaged ratio of turbine-exhaust specific impulse to rocket-nozzle specific impulse. Calculations were made for $\varepsilon_{av} = 0$ assuming no thrust in the direction of flight and also with the maximum thrust obtainable with a converging nozzle directed for thrust in the direction of flight.

Equation (3) gives the altitude at the end of powered flight and was derived as the time integral of instantaneous velocity expressed as in equation (1).

$$h = t \left(I_{av} g - \frac{V_b + gt}{W_g/W_e - 1} - \frac{1}{2} gt \right) \qquad (3)$$

Values of I_{av}, W_g/W_e, and t from the preceding table were then used to define a vertical mission for each system as an equivalent of the selected mission. Calculated values of velocity and altitude are given in the following table:

System	V_b ft/sec	h, ft
Hydrogen-reactor	19,471	2,044,653
Hydrogen-oxygen	[a]9,273	[a]544,159
Hydrogen-fluorine	[a]11,527	[a]776,860

[a]First stage only.

Relation Between Rocket Characteristics and Turbine Characteristics

The turbine influences the rocket gross weight through the effects of bleed rate and turbine weight, as noted previously. The effect of bleed rate on the ratio of gross weight to empty weight and on burning time may be obtained by first solving equation (2) for effective specific impulse I_{av} and then solving equations (1) and (3) simultaneously for W_g/W_e and t with the fixed values of V and h. The quantities W_g/W_e and t are therefore unique functions of bleed rate y, and may be used to relate structural weight and turbine weight to gross weight for a range of bleed rates.

Weights of the rocket structure and the turbine are related to gross weight and payload in the following equation:

$$W_g = W_T + P + W_{pr} + W_{pr}\overline{S} \tag{4}$$

where the structural parameter $\overline{S}$ is defined as the ratio of empty weight without turbine and payload to the weight of the propellant consumed. Similarly, for the empty weight,

$$W_e = W_T + P + W_{pr}\overline{S} \tag{5}$$

Equations (4) and (5) can be combined and rearranged to provide an expression for the ratio of gross weight to payload where

$$W_g/P = \frac{W_g/W_e}{1 - \left(\overline{S} + \frac{W_T}{w_P}\frac{1}{t}\right)\left(\frac{W_g}{W_e} - 1\right)} \tag{6}$$

Equation (6) then can be solved for a range of turbine weight parameters W_T/w_P with W_g/W_e and t values corresponding to a range of bleed rates y. The ratio of gross weight to payload may then be shown as a function of bleed rate y for several values of the turbine weight parameter as in figure 1 for the hydrogen-reactor system. This figure is representative of the first group of working curves used in the investigation. In the case of the two-stage rockets, equations (1), (2), (3), and (6) were solved for the first stage only. The resulting ratio of gross weight to payload was the ratio of first-stage gross weight to second-stage gross weight. The over-all ratio of gross weight to payload was obtained by multiplying the first-stage gross-to-pay weight ratio by the fixed second-stage gross-to-pay weight ratio.

Effect of Turbine-Inlet Temperature on Turbine Weight and Bleed Rate

Reference 2 describes a method for relating the turbine weight parameter W_T/w_p to the required pump work, blade speed, inlet gas conditions, blade stress, bleed rate, gas properties, and a range of turbine stage number. Included in reference 2 is a set of curves relating turbine efficiency to the speed-work parameter λ and turbine stage number. This information was obtained analytically from velocity-diagram and -loss considerations. The loss coefficients used in the analysis were determined from results of small transonic turbine cold-air tests. The subject investigation utilized these curves with the assumption that the trends with turbine staging and the speed-work parameter are valid with other gaseous working fluids such as hydrogen, steam, and hydrogen fluoride. The levels of efficiency may be somewhat different in these fluids but this would not significantly affect the results of the subject investigation.

The examples described in this report included specification of a single turbine driving one or two propellant pumps with a small fraction of the propellant flow as a working fluid and utilization of thrust from the turbine exhaust in a converging nozzle. Alternate drive systems such as two turbines operating in flow parallel or a turbine operating in a gas other than the propellant could also be investigated in this manner.

Turbine-inlet temperature was varied above and below the maximum value for uncooled turbines, which was defined as 1860° R. The lowest temperature considered was 1500° R and the highest temperature, considered the practical maximum for a cooled turbine, was 3000° R.

Properties of pure gases, hydrogen, steam, and hydrogen fluoride, were taken from reference 3. The gas mixtures in the chemical-rocket turbines were determined by assuming complete combustion in a fuel-rich mixture so that the mixtures always consisted of hydrogen and a single product of combustion.

Values of certain parameters were arbitrarily specified in the solution for the turbine weight parameter, and are as follows:

Blade metal density, ρ, lb/cu ft	494
Untapered centrifugal blade stress, lb/sq in.	40,000
Exit axial critical gas velocity ratio, $(V_x/V_{cr})_{ex}$	0.5
Exit hub-tip radius ratio	0.79
Blade tip speed, U, ft/sec	1400
Turbine-inlet pressure, p, lb/sq in. abs	1100

The use of lighter materials such as aluminum was not considered here.

Pump work was calculated as that required to raise the liquid pressure from a tank storage pressure of 35 pounds per square inch absolute to a pump exit pressure of 1200 pounds per square inch absolute with a pump efficiency of 0.7. This value of pump exit pressure influences the level of bleed rate required for the turbine, but, since it is fixed, not the effect of changes in turbine-inlet temperature.

The results of the calculations outlined previously were used to plot the turbine weight parameter W_T/w_P as a function of bleed rate y over a range of stage numbers and turbine-inlet temperatures. Figure 2 is an example of the results of these calculations and shows the variation in turbine weight parameter with bleed rate and stage number for the hydrogen reactor system with a turbine-inlet temperature of 1860° R.

A single curve was then obtained by reading the lowest value of W_T/w_P from any of the stage-number curves at several values of bleed rate. This curve, the lower envelope of the stage-number curves, represents the lightest turbine for each bleed rate that satisfies the pump work requirements at a particular turbine-inlet temperature. Figure 3 shows curves of this type plotted against bleed rate for each of the turbine-inlet temperatures considered, and is an example of the second set of working curves used in this investigation.

Matching Rocket Systems with Turbine Designs for Minimum Gross Weight

The method used in matching turbine designs with each rocket system may be briefly summarized as follows:

(1) A bleed rate is selected and for each temperature line on the plot of turbine weight parameter against bleed rate a value is read for the turbine weight parameter W_T/w_P, (fig. 3).

(2) The ratio of gross weight to payload is read corresponding to the bleed rate being checked and the turbine weight parameter obtained in step 1 from the appropriate plot of gross-to-pay weight ratio against bleed rate (fig. 1).

(3) Steps 1 and 2 are repeated for several bleed rates and gross-to-pay weight ratio is plotted against turbine-inlet temperature (fig. 4).

RESULTS AND DISCUSSION

Effect of Turbine-Inlet Temperature on Gross Weight

E-173

Without turbine exhaust recovery. - Figure 1 shows gross-to-pay weight ratio of the hydrogen-reactor system plotted against bleed rate for several turbine weight parameter values, and zero turbine-exhaust thrust recovery. Gross weight increases almost linearly with both bleed rate, which reduces effective specific impulse, and with turbine weight, which increases the rocket empty weight.

Figure 2 shows the turbine weight parameter plotted against bleed rate for several turbine stage numbers and a constant value of turbine-inlet temperature for the hydrogen-reactor system. Each stage-number curve shows a decrease in the turbine weight parameter with increasing bleed rate because the required turbine specific work decreases with increasing turbine flow rate. This decrease in required turbine specific work results in a decrease in the required exit flow area because of the smaller pressure ratio required and, consequently, a decrease in the turbine size in the range of bleed rates considered. Each stage-number curve has a minimum bleed rate, which occurs at that value where the required ideal specific work equals the total energy of the turbine-inlet gas. As this bleed-rate limit is approached, the turbine pressure ratio and required exit flow area become infinite. The differences among the limits of the various stage-number curves, then, result from different limiting efficiencies, since the inlet temperature is constant for all curves shown. The variation in turbine efficiency with stage number is taken from reference 2, as noted previously. All turbines considered in the subject investigation were in the low range of the turbine speed-work parameter where turbine efficiency increases with stage number.

CP-2

Figure 4 was plotted with results of the turbine-rocket matching procedure described previously, and shows gross-to-pay weight ratio as a function of turbine-inlet temperature for several values of bleed rate and no turbine-exhaust thrust recovery. Each bleed-rate curve has a relatively flat portion which indicates little change in turbine size, and also a lower temperature limit beyond which the turbine cannot produce the required shaft power. As the temperature is reduced toward this limit the required pressure ratio increases thus increasing the required turbine-exit flow area and turbine size, causing the rocket gross weight to increase. The temperature limit occurs when the required ideal specific work equals the total energy of the turbine-inlet gas. At this point infinite exit flow area and turbine size would be required.

The lower envelopes of the curves of figure 4 (dashed lines) represent the minimum gross weights obtainable at any turbine-inlet temperature between 1500° and 3000° R. The bleed rate decreases with increasing temperature, and it is largely this change in bleed rate that causes the reduction in gross-to-pay weight ratio. Figure 4(a) shows that the bleed rate decreases from 0.030 to 0.017 as the temperature is increased from 1500° to 3000° R. The corresponding values for the turbine weight parameter W_T/w_P are 0.73 and 0.57.

The dashed line of figure 4(a) shows a gross-to-pay weight ratio of 6.192 at a turbine-inlet temperature of 1860° R and 6.030 at 3000° R, a maximum saving of 2.62 percent in gross weight made possible by using a cooled turbine. This gross-weight saving would amount to 811 pounds for a payload of 5000 pounds. It would be offset, however, by the increases in cost and complexity as well as the decreased reliability of a cooled turbine.

The dashed lines of figures 4(b) and (c) show gross-weight savings of much smaller magnitude for the chemical systems. The following table shows the decreases in gross weight for all three systems as the turbine-inlet temperature is increased from 1860° to 3000° R.

System	Decrease in gross weight, percent	Reduction in gross weight for 5000-lb payload, lb
Hydrogen-reactor	2.62	811
Hydrogen-oxygen	.66	510
Hydrogen-fluorine	.24	150

The gross-weight savings shown in this table are not sufficient to warrant the use of turbine cooling in any of the systems investigated.

At this point it may also be noted that the gross-weight savings for the chemical systems are listed for the first stage only and that these figures are valid for the whole rocket only with a constant ratio of gross weight to payload in the second stage. If it is assumed that the second stage utilizes a cooled turbine in the same manner as the first stage, then the savings in over-all gross weight would be nearly double those listed in the table.

Figure 5 shows the sensitivity of gross-weight ratio to changes in turbine-inlet temperatures for the three systems investigated. Changes in temperature have a greater effect on the gross weight of the hydrogen-reactor system for two reasons. First, the pump work required is much higher, approximately 70 Btu per pound compared with 21 for the hydrogen-oxygen system and 9 for the hydrogen-fluorine system and, consequently, a greater bleed rate is required for comparable turbine pressure ratios and efficiencies. This effect causes a greater fraction of specific impulse to be affected by changes in turbine operation. The second reason is the large difference in gas properties between pure hydrogen and the mixtures of gases employed in the chemical-rocket turbines. This is shown in figure 6 where the product of specific heat and temperature (total energy) at the turbine inlet for the three systems is plotted against temperature. The pure hydrogen curve has the greatest slope because of its high specific heat and the fact that specific heat increases with temperature. The gas mixtures used in the chemical-rocket systems have lower specific heats and these decrease with increasing temperature because more oxidant is required in the fuel-rich mixtures in order to produce the higher temperatures.

With turbine-exhaust thrust recovery. - The effect of turbine-exhaust thrust recovery was evaluated by calculating the specific impulses obtainable with a converging nozzle at the turbine operating points associated with turbine-inlet temperatures of 1500°, 1860°, and 3000° R on the dashed lines of figure 4. Specific impulse values were computed for exhaust to a vacuum, and are plotted in figure 7 in terms of the specific impulse ratio. The impulse ratios for all three systems increase with turbine-inlet temperature and lie between 0.35 and 0.61, with maximum values of 0.52, 0.61, and 0.61 for the hydrogen-reactor, hydrogen-oxygen, and hydrogen-fluorine systems, respectively.

The ε values calculated for figure 7 and for sea-level operation were used to determine gross-to-pay weight ratios for the vertical missions used in the investigation. These values for gross-to-pay weight ratio were lower than those determined for $\varepsilon = 0$ because of the higher effective specific impulse values. The effect of turbine-inlet temperature on gross weight was smaller because of the reduced effect of bleed rate on effective specific impulse.

Figure 8 shows the effect of turbine-inlet temperature on gross weight with and without turbine-exhaust thrust recovery. The reference gross weight used in figure 8 was that corresponding to a turbine-inlet temperature of 1860° R without any turbine-exhaust thrust recovery, (as shown in fig. 4). The following table shows the decreases in gross weight made possible by increasing the turbine-inlet temperature from 1860° to 3000° R with turbine-exit thrust recovery. The values shown here correspond to those presented previously for zero thrust recovery.

System	Decrease in gross weight, percent	Reduction in gross weight for 5000-lb payload, percent
Hydrogen-reactor	2.20	660
Hydrogen-oxygen	.13	100
Hydrogen-fluorine	.19	115

The changes noted in gross-weight savings from the values shown previously for $\varepsilon = 0$ are small, and these values indicate the same conclusion. Savings in gross weight made possible through the use of turbine cooling are very small, and must be balanced against considerations of cost, complexity, and reliability.

It may be noted that recovering thrust from turbine exhaust gas with a constant turbine-inlet temperature of 1860° R is more effective in reducing gross weight than is increasing the turbine temperature from 1860° to 3000° R with no thrust recovery.

Effect of Turbine Stage Number

Information calculated to determine the effect of turbine-inlet temperature on gross weight was also used to determine the effect of turbine stage number on rocket gross weight at two turbine-inlet temperatures. This information is presented to illustrate the interdependence of stage number and turbine-inlet temperature and how they affect rocket gross weight.

Figure 9 shows the effect of staging for all three systems at a turbine-inlet temperature of 1860° R. This figure shows that the hydrogen-reactor system requires the largest number of turbine stages in order to obtain gross weight near the minimum and also that the hydrogen-reactor system is most sensitive to changes in turbine stage number. The reason for this is the previously noted fact that the pump work requirements are greater for the hydrogen-reactor system requiring a greater bleed rate and thus providing a greater fraction of the specific impulse which is affected by turbine operating characteristics.

The hydrogen-reactor requires a ten-stage turbine to achieve gross weight near the minimum, while the hydrogen-oxygen and hydrogen-fluorine systems require seven and four stages, respectively. These stage numbers were selected as the minimums required to keep gross weight within 0.25 percent of the lowest value shown.

The lower envelopes of the groups of curves shown in figure 9 were used to show the effects of stage number and temperature on gross weight for the three systems. A stage number of 12 was arbitrarily selected in order to present these curves in ratio form for comparison.

Figure 10 shows the gross-weight ratio plotted against turbine stage number for each rocket system at two temperatures, 1860° and 3000° R. The reference gross weight used in the gross-weight ratio is that corresponding to 12 stages at a turbine-inlet temperature of 1860° R. The hydrogen-reactor is again most sensitive to changes in turbine characteristics with a relatively large range in gross weight (6 percent) resulting from the ranges in stage number and turbine temperature shown (fig. 10). The hydrogen-oxygen system (fig. 10(b)) shows a gross-weight range of 4 percent while the hydrogen-fluorine system gross weight (fig. 10(c)) varies through only $2\frac{1}{2}$ percent. The effect of stage number on gross weight is about the same at both temperatures (1860° and 3000° R) for each system.

SUMMARY OF RESULTS

The effect of turbine-inlet temperature on the weight characteristics of three high-energy propellant rockets has been investigated analytically and the major results may be summarized as follows:

1. The hydrogen-reactor system was more sensitive to changes in turbine-inlet temperature than either the hydrogen-oxygen or the hydrogen-fluorine systems. The reasons for this were the higher pump work (which required higher bleed rates), the higher specific heat of the turbine inlet gas, and the fact that the specific heat of pure hydrogen increases with temperature while the specific heat of the combustion products in the chemical-system turbines decreased because of the changing ratio of oxidant flow to fuel flow.

2. The study of the three systems showed that no system indicated sufficient decreases in rocket gross weight to warrant consideration of turbine cooling in achieving high turbine-inlet temperatures. The hydrogen-reactor system showed a possible decrease of 2.62 percent in gross weight while the hydrogen-oxygen and hydrogen-fluorine systems showed decreases of 0.66 and 0.24 percent, respectively, with zero turbine-exhaust thrust recovery.

3. The recovery of thrust obtainable from turbine exhaust gas through a converging nozzle increased with increasing temperature in all three systems considered. Maximum values of the ratio of turbine-exhaust specific impulse to rocket-nozzle specific impulse were 0.52 for the hydrogen-reactor system, 0.61 for the hydrogen-oxygen system, and 0.61 for the hydrogen-fluorine system. Consideration of turbine-exhaust

thrust recovery indicated appreciable savings in gross weight at all temperature levels considered but did not materially influence the effect of changes in turbine-inlet temperature.

4. The hydrogen-reactor system requires the largest number of turbine stages in order to obtain gross weight near the minimum and also is most sensitive to changes in turbine stage number, the reason being the higher pump-work and bleed-rate requirements. Stage numbers required for near minimum gross weight were ten for the hydrogen-reactor system, seven for hydrogen-oxygen, and four for hydrogen-fluorine. This was true at both turbine-inlet temperatures examined, 1860° and 3000° R.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, October 8, 1958

REFERENCES

1. Sutton, George P.: Rocket Propulsion Elements. Second ed., John Wiley & Sons, Inc., 1956.

2. Stewart, Warner L., Evans, David G., and Whitney, Warren J.: A Method for Determining Turbine Design Characteristics for Rocket Turbodrive Applications. NACA RM E57K25a, 1958.

3. Huff, Vearl N., Gordon, Sanford, and Morrell, Virginia E.: General Method and Thermodynamic Tables for Computation of Equilibrium Composition and Temperature of Chemical Reactions. NACA Rep. 1037, 1951. (Supersedes NACA TN's 2113 and 2161.)

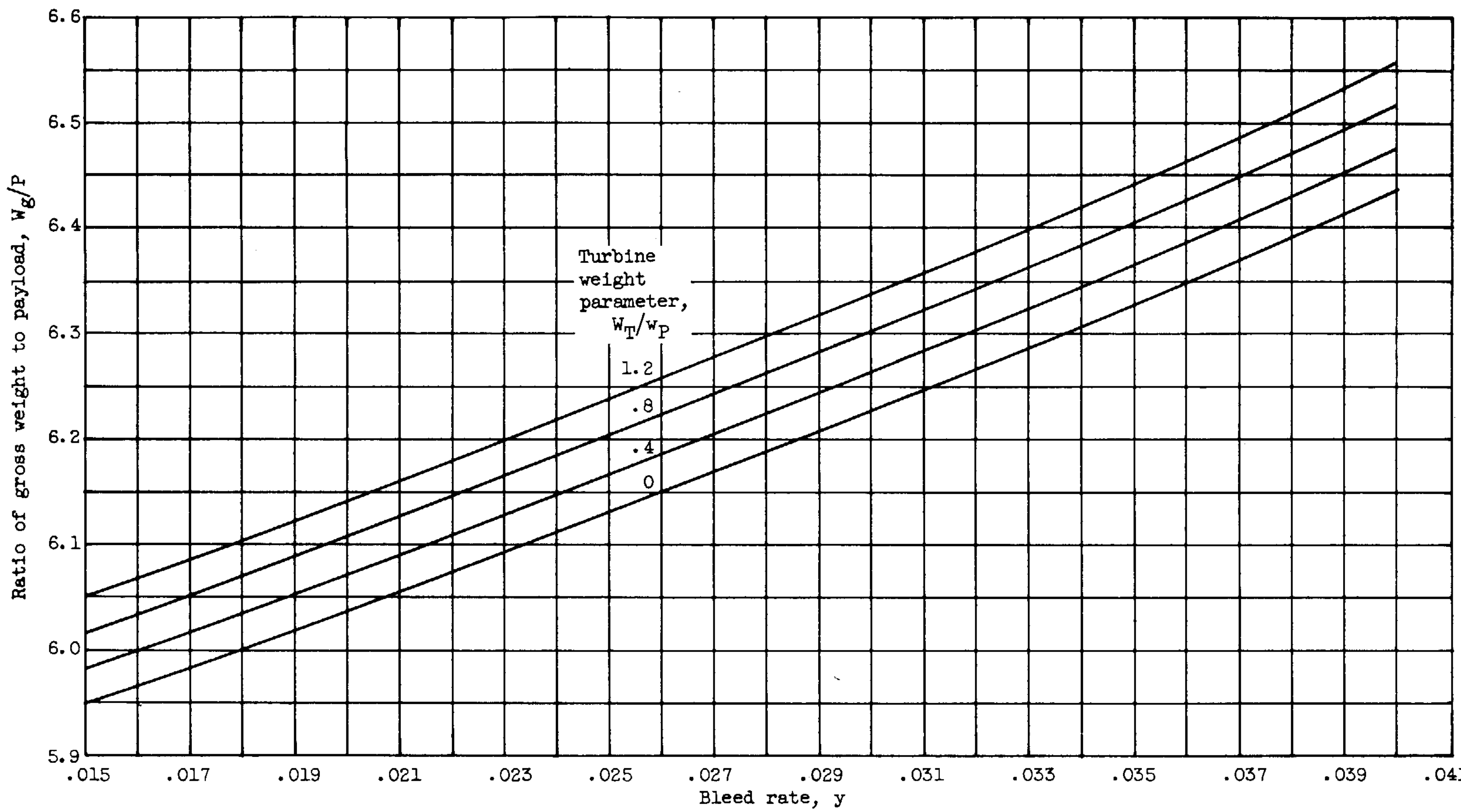


Figure 1. - Effect of bleed rate and turbine weight parameter on gross-to-pay weight ratio for hydrogen-reactor rocket. No thrust recovery.

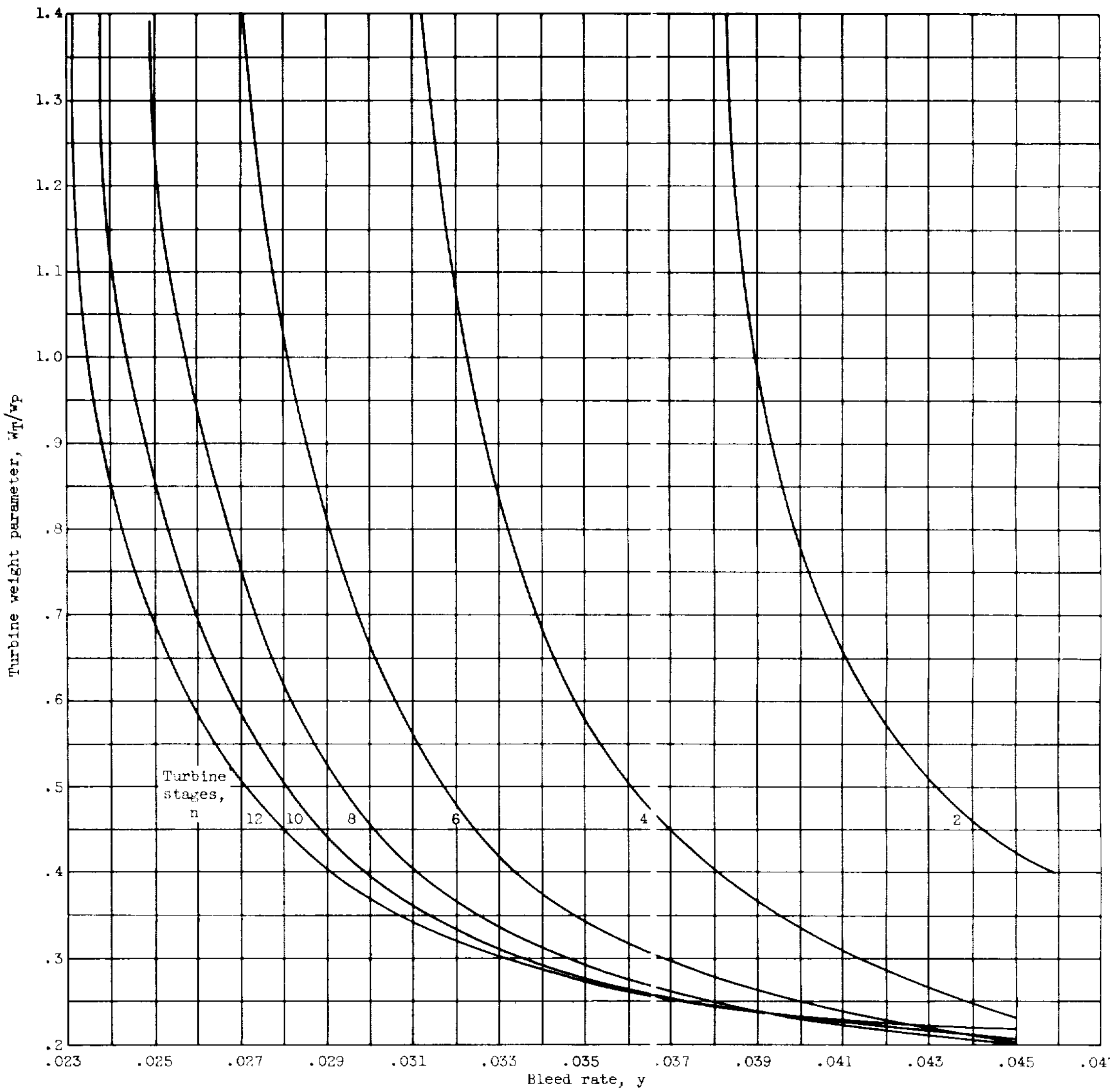


Figure 2. - Variation in turbine weight parameter with bleed rate and turbine stage number for hydrogen-reactor system. Turbine-inlet temperature, T, 1860° R.

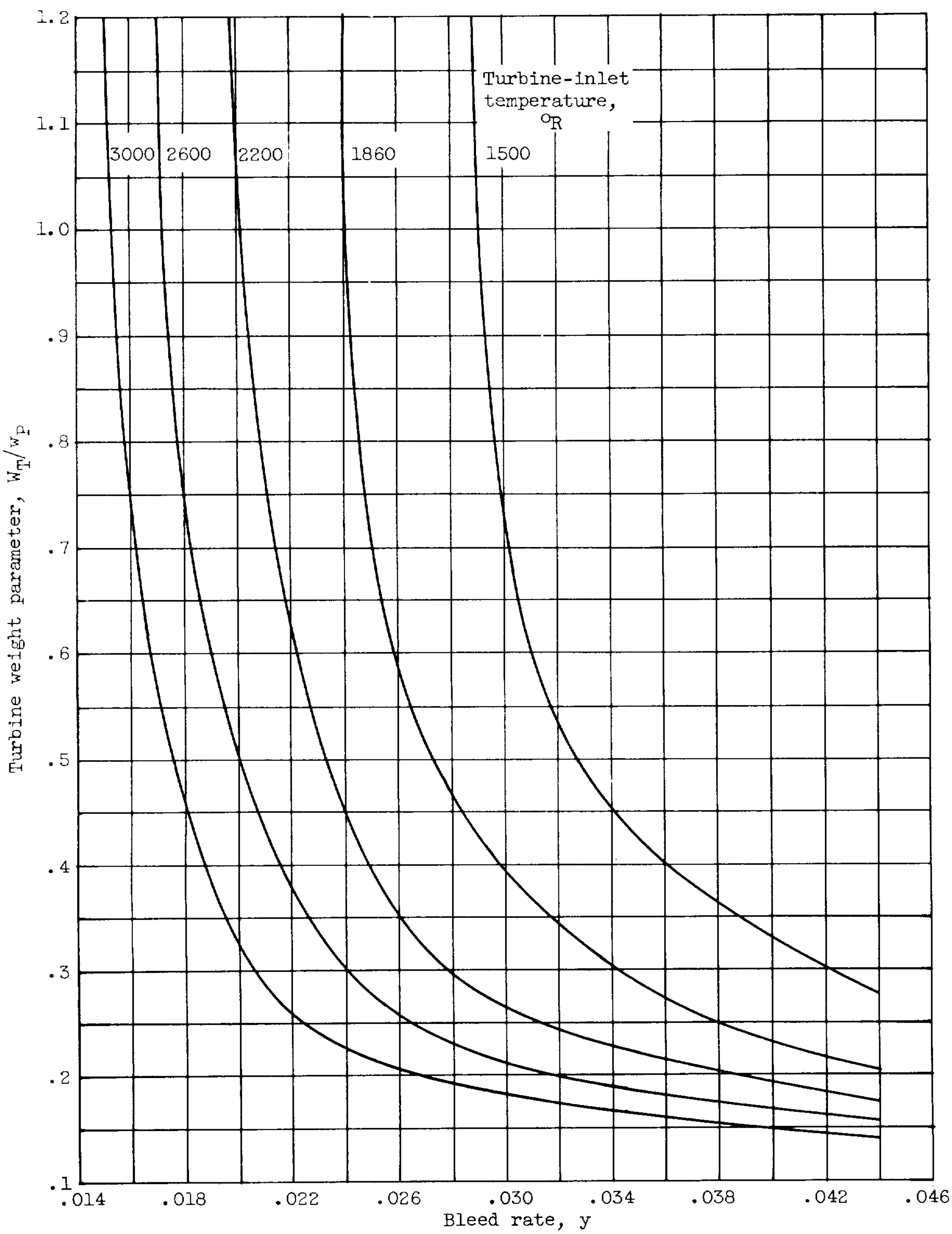
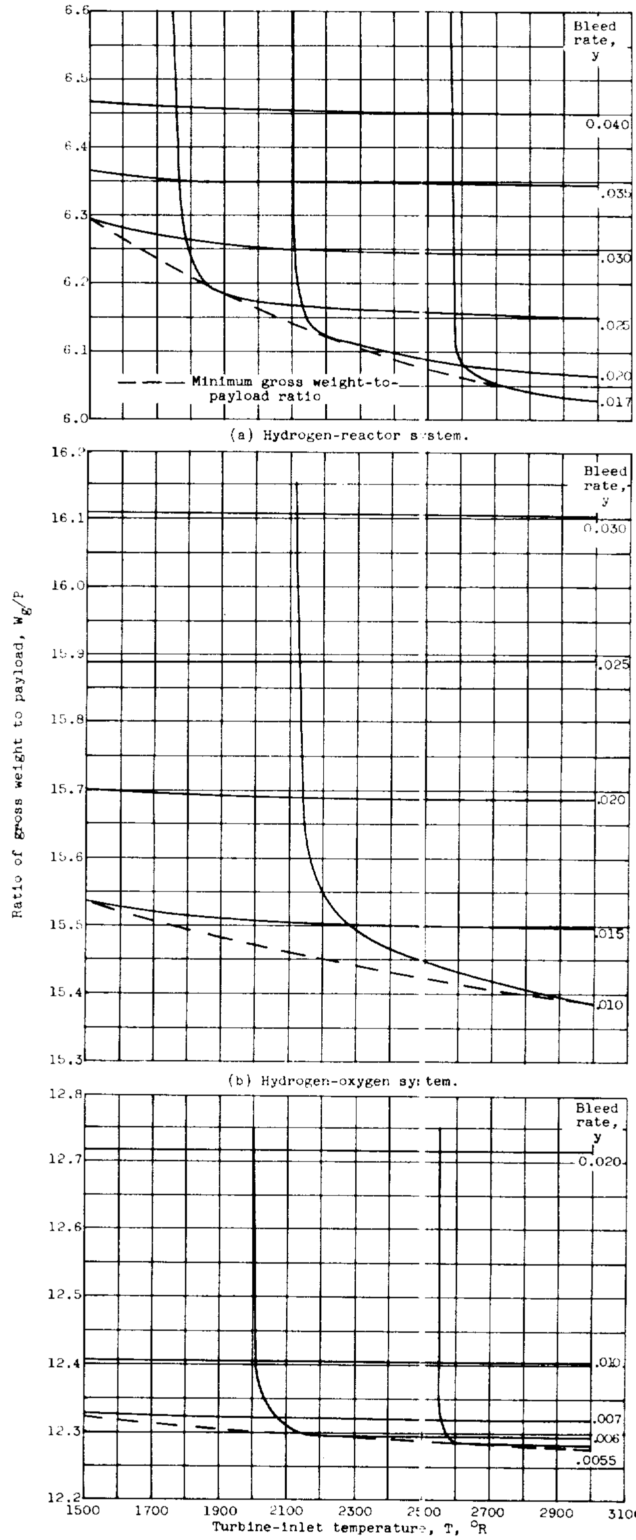


Figure 3. - Variation in turbine weight parameter with turbine-inlet temperature and bleed rate for hydrogen-reactor system.



(c) Hydrogen-fluorine system.

Figure 4. - Effect of turbine-inlet temperature and bleed rate on rocket gross weight. No thrust recovery.

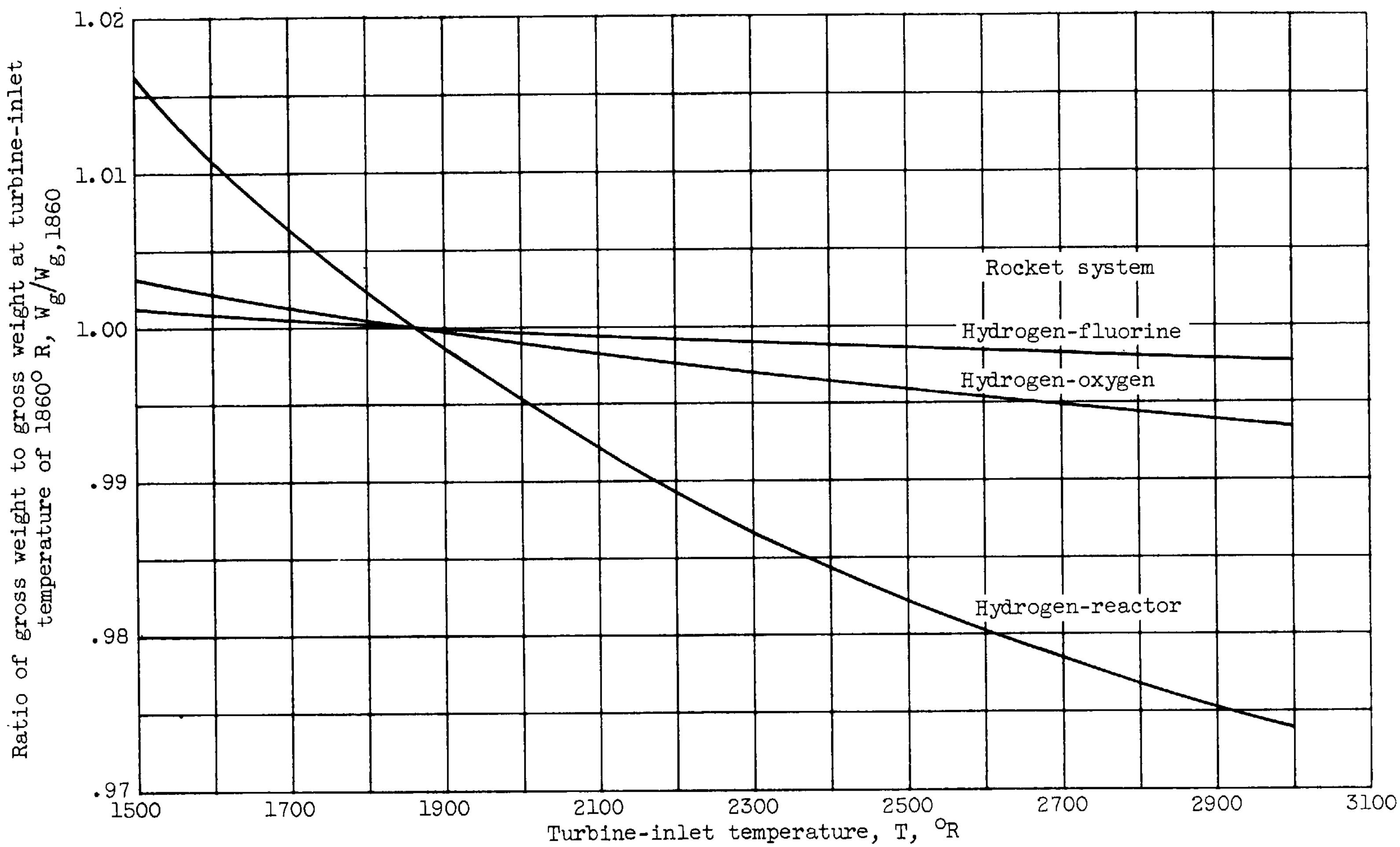


Figure 5. - Effect of turbine-inlet temperature on gross weight ratio. No thrust recovery.

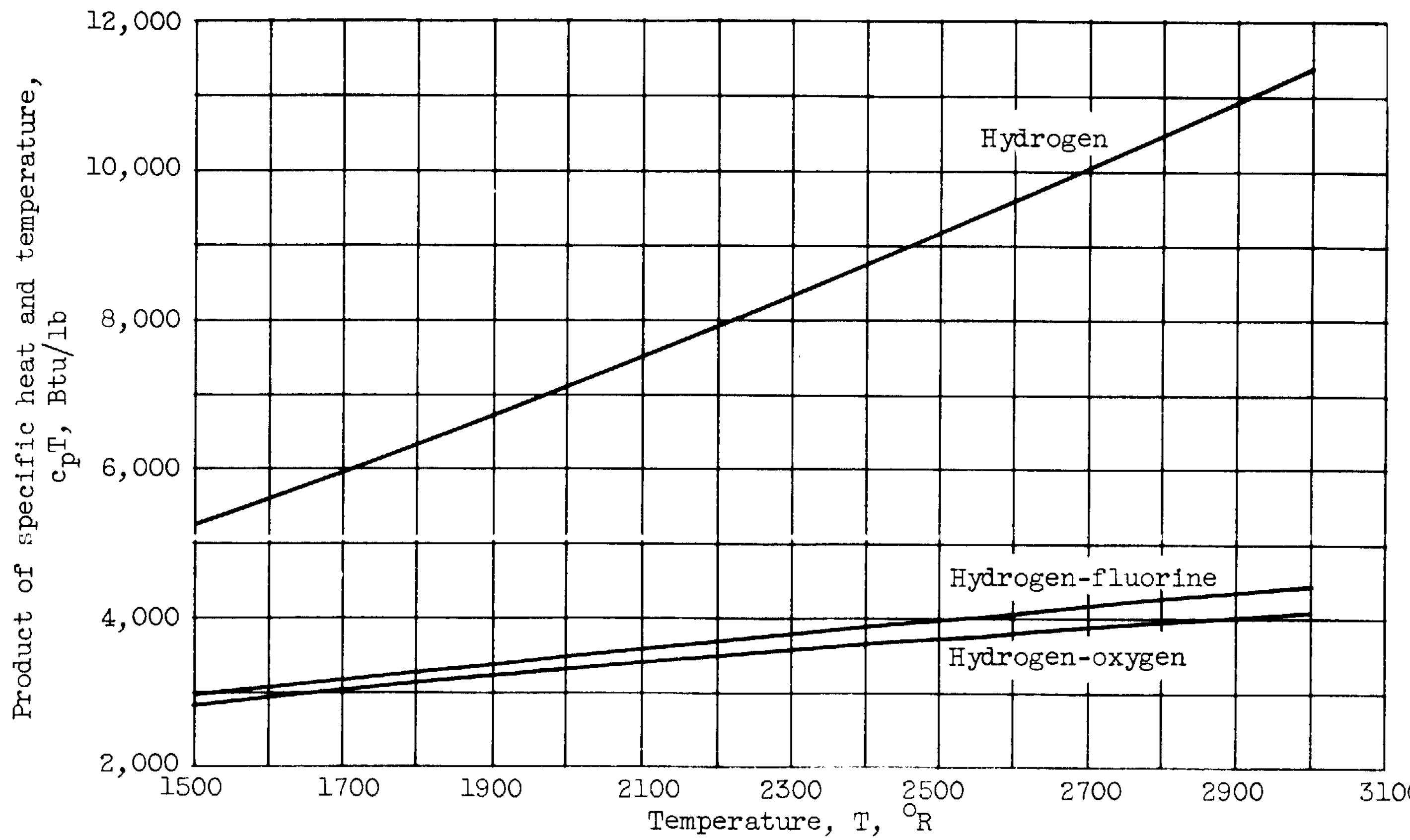


Figure 6. - Effect of temperature on turbine-inlet gas properties.

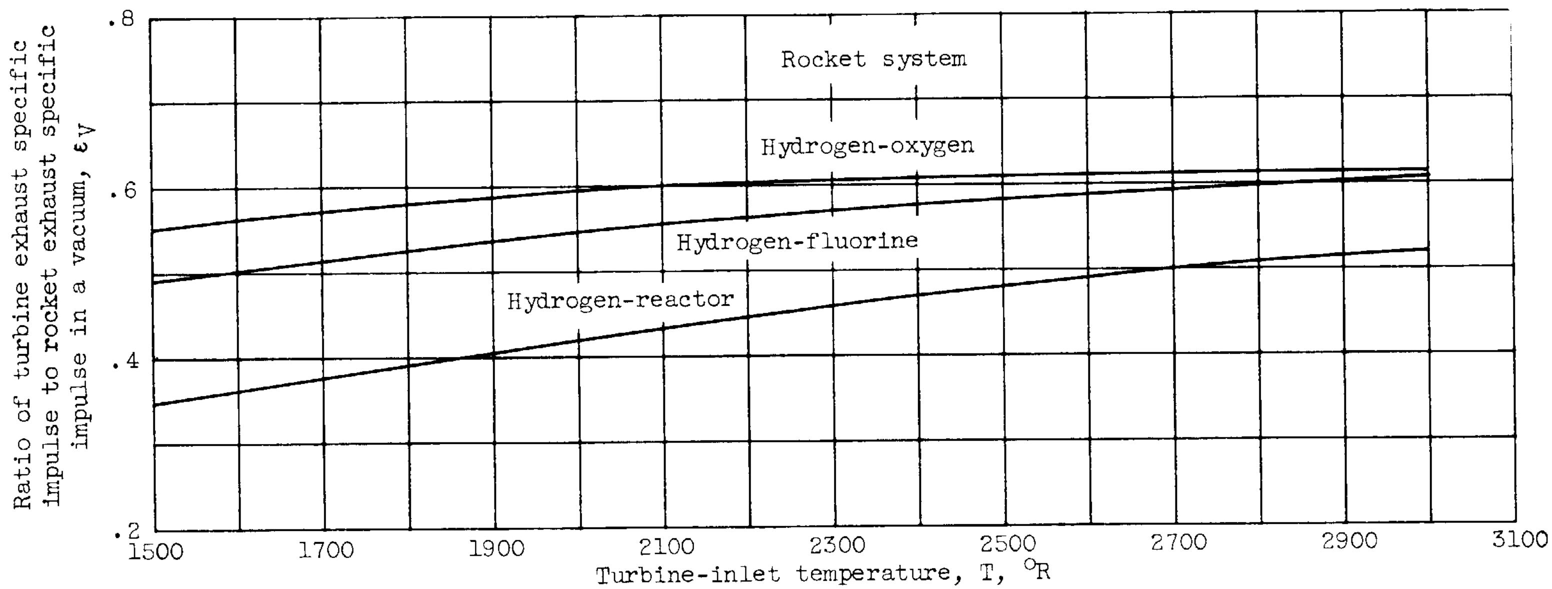
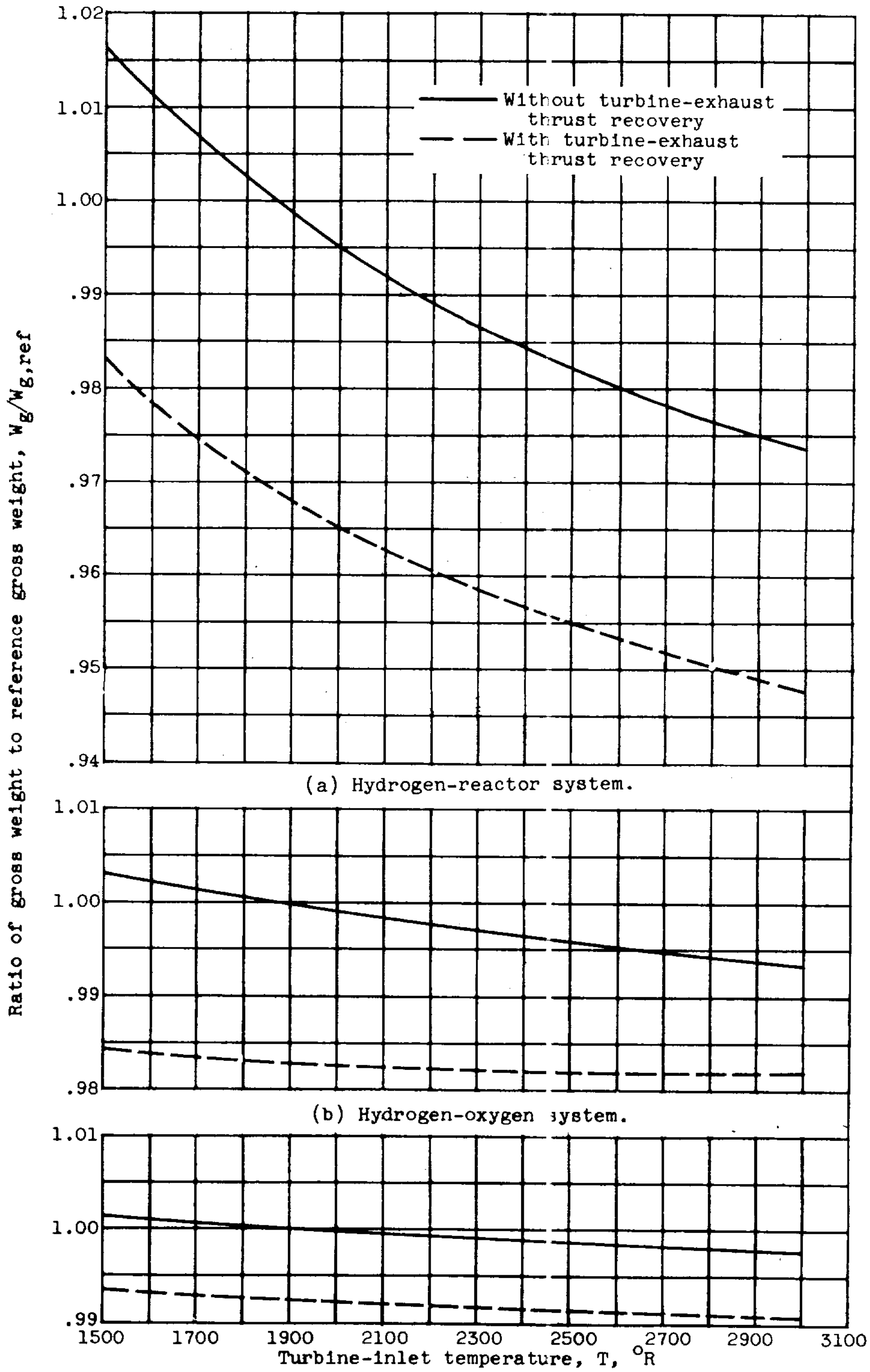


Figure 7. - Effect of turbine-inlet temperature on turbine-exhaust thrust recovery in a vacuum for turbine operation corresponding to minimum gross weight-to-payload ratio.

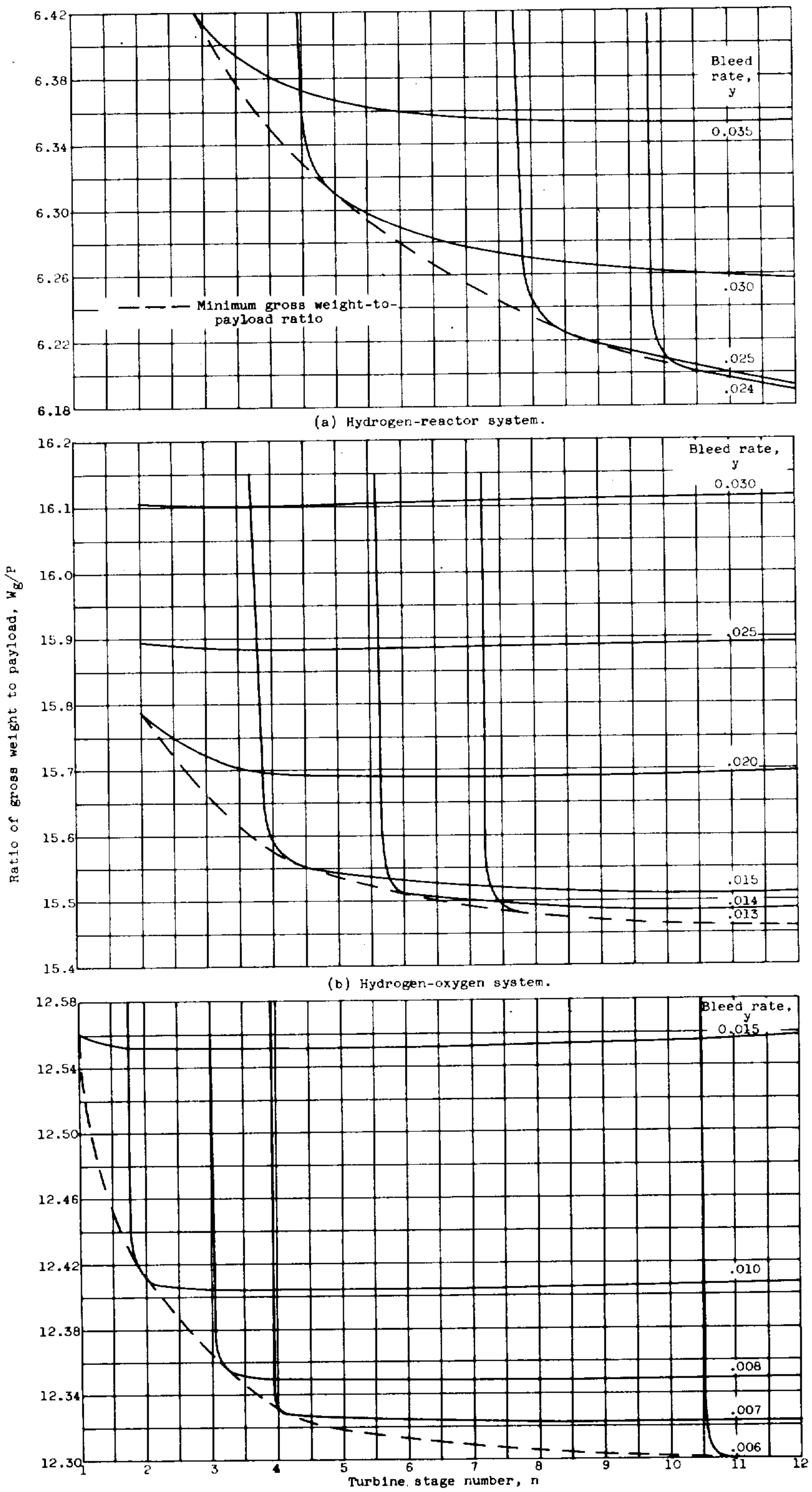


(a) Hydrogen-reactor system.

(b) Hydrogen-oxygen system.

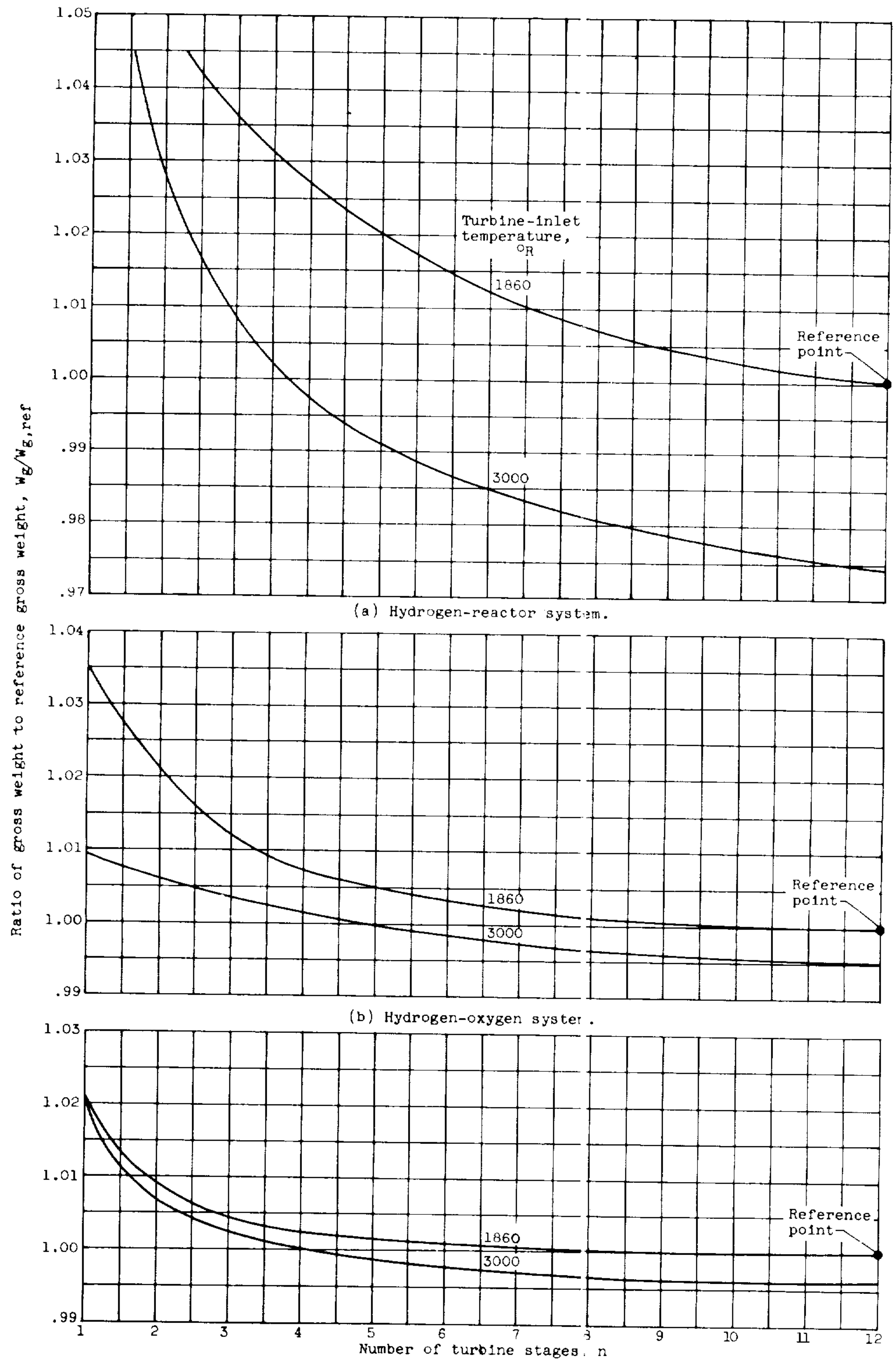
(c) Hydrogen-fluorine system.

Figure 8. - Effect of turbine-inlet temperature on gross weight ratio with and without turbine-exhaust thrust recovery.



(c) Hydrogen-fluorine system.

Figure 9. - Effects of turbine stage number and bleed rate on rocket gross weight-to-payload ratio. Turbine-inlet temperature, 1860° R; no thrust recovery.



(c) Hydrogen-fluorine system.

Figure 10. - Effects of turbine stage number and turbine-inlet temperature on rocket gross weight. No thrust recovery.