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SUMMARY

Three turbopump feed systems were analyzed for possible use in a high-chamber-pressure hydrogen-oxygen rocket engine. The feed systems studied were the bleed, hot topping, and a combination of these two called a pressure-staged system. In the pressure-staged system, the hydrogen is pressurized in two stages by two separate turbopumps that utilize both bleed and topping turbines. The engine systems analyzed had a combustion chamber oxidant-fuel ratio of 7.0, chamber pressures from 1000 to 4000 pounds per square inch absolute, turbine inlet temperatures of 1400° and 1800° R, and turbine-exhaust thrust-recovery factors of 0 and 0.5.

The analysis showed that the bleed rate of the bleed system, with two-stage turbines at an inlet temperature of 1800° R, increased approximately 1.7 percent for each increase in chamber pressure of 1000 pounds per square inch. The attendant loss in engine specific impulse is dependent on the amount of thrust recovered from the turbine exhaust gases. Even small specific-impulse losses, however, required significant increases in the amount of vehicle propellant tankage when compared with a rocket engine having zero bleed rate.

The hot-topping system had no specific-impulse loss, and therefore, for a specified engine thrust and burning time, resulted in the minimum amount of vehicle propellant tankage of any of the feed systems analyzed. For any given chamber pressure, however, this system had the highest feed-system pressures. The differences in feed-system pressures of the three feed systems were small at a chamber pressure of 1000 pounds per square inch absolute but became considerable at higher chamber pressures. The analysis also indicated that the feasibility of the hot-topping system is dependent on a sufficiently high turbine inlet temperature.

The pressure-staged system represents a compromise between the lower engine pressures of the bleed system and the higher specific impulse of the topping system. Dividing the total hydrogen-pump power requirement equally between the bleed and topping turbopumps reduced the specific-impulse losses to about one-half of the corresponding bleed-system values and increased the maximum feed-system pressure only moderately.

INTRODUCTION

Employing a high chamber pressure in hydrogen-oxygen rocket engines results in a number of engine performance improvements. Increases in the combustion chamber pressure permit greater expansion and larger nozzle area ratios, resulting in (1) increased specific impulse at sea level and (2) increased vacuum specific impulse for a nozzle of limited exit diameter. In addition, the engine size may be reduced.

Hydrogen-oxygen rocket performance studies (e. g. , ref. 1) have indicated a theoretical sea-level specific-impulse increase of 9 to 11 percent for engines utilizing optimum area ratio nozzles by increasing the chamber pressure from 1000 to 4000 pounds per square inch absolute. For the same range of chamber pressure, specific-impulse gains of 4 to 5 percent would be realized for engines operating in a vacuum by decreasing the throat area of a nozzle with a limited exit diameter. These performance gains make the high-chamber-pressure engine attractive provided a workable design of such an engine is possible.

One particularly difficult engineering problem that the high-pressure engine presents is finding a suitable propellant feed system. An associated problem is the need to minimize engine specific-impulse losses. Three propellant feed systems considered for this purpose are (1) the bleed or gas-generator system, (2) the hot-topping or staged-combustion system, and (3) a combination of these two herein called a pressure-staged system.

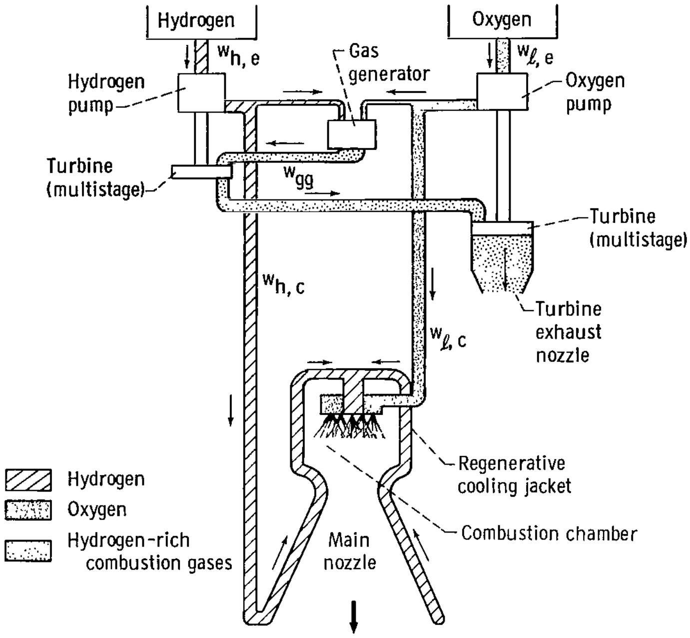
An analysis of each of these feed systems was made to determine the effect of chamber pressure on bleed rate, engine specific impulse, relative propellant tankage volume, and maximum system pressure. The investigation did not include such turbopump design details as pump hydrodynamics, turbine aerodynamics, or mechanical design.

A thrust-chamber oxidant-fuel mixture ratio of 7. 0 was selected for the particular hydrogen-oxygen rocket engine studied. The independent variables considered were (1) chamber pressures from 1000 to 4000 pounds per square inch absolute, (2) turbine inlet temperatures of 1400° and 1800° R, and (3) turbine-exhaust thrust-recovery factors of 0 and 0. 5. The results are not dependent on rocket size or propellant flow rates.

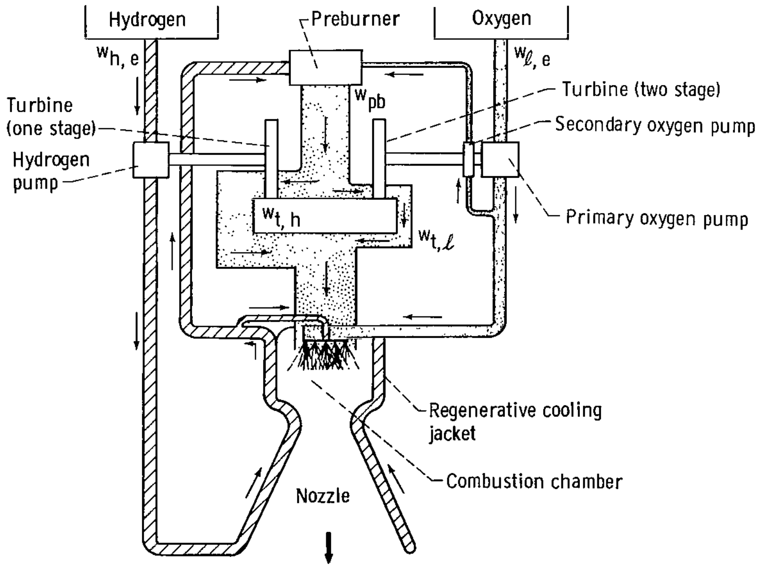
DESCRIPTION OF PROPELLANT FEED SYSTEMS

Bleed System

The concept of the bleed system used herein is illustrated in figure 1(a). In this system, hydrogen and oxygen are pumped from the propellant tanks and pressurized by two separately driven pumps to a level equal to the sum of the chamber pressure and the



(a) Bleed system.



(b) Hot-topping system.

Figure 1. - Schematic drawings of bleed and hot-topping feed systems.

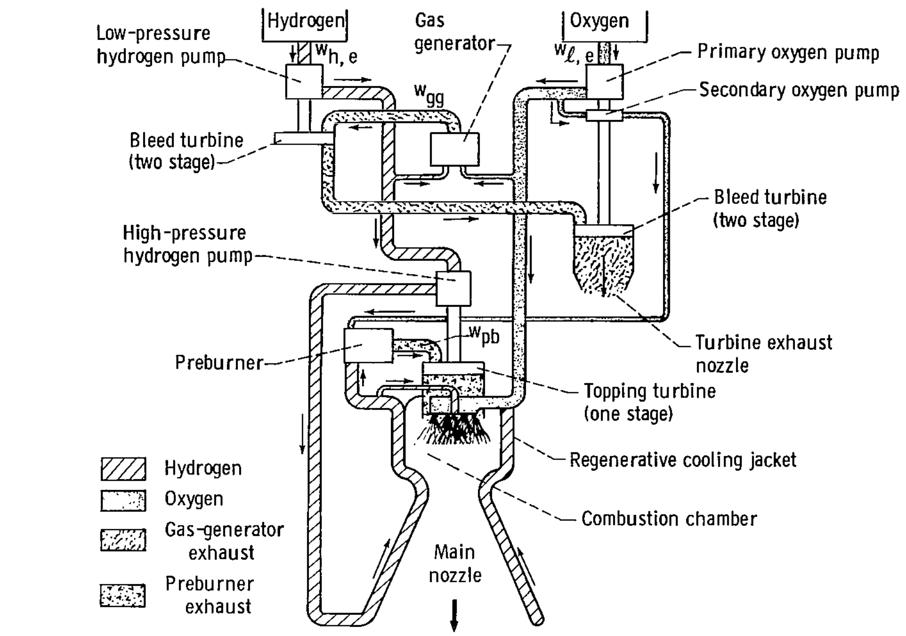
feed-system-pressure losses. After leaving the fuel pump, the hydrogen receives heat as it passes through the nozzle cooling jacket, after which it is injected, with the oxygen, into the combustion chamber. At the pump exits, small amounts of the two propellants are bled off and enter a gas generator, where the hydrogen is burned fuel rich to obtain the proper turbine inlet temperature. The combustion gases are expanded in the two turbines, in series, and then exhausted overboard through a nozzle. Because of the lower energy and pressure, and consequently lower specific impulse of the bleed flow, the engine specific impulse is less than the specific impulse obtained in the main expansion nozzle. For this reason the bleed rate must be minimized resulting in high-specific-work turbines.

Hot-Topping System

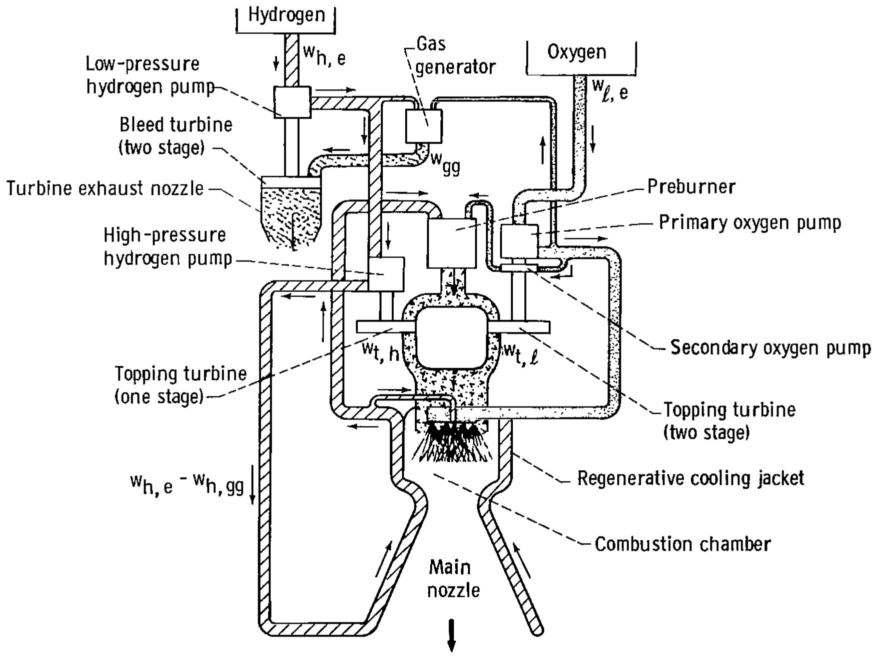
Figure 1(b) is a schematic diagram of the hot-topping system. The essential differences between this engine and the bleed engine are the large amounts of gas passing through the turbines and the disposition of this gas after leaving the turbines. Except for the absence of the bleed fluid, the hydrogen flow path is identical to that of the bleed system until the hydrogen leaves the nozzle cooling jacket. At this point, the major portion of the fuel enters a preburner where it is burned with oxygen. The combustion products are then expanded in the two turbines and injected into the combustion chamber along with the remaining oxygen and hydrogen that was bypassed. Bypassing a part of the hydrogen around the preburner and turbines provides a means of turbopump control. The secondary oxygen pump (fig. 1(b)) further pressurizes the oxygen going to the preburner, which comprises about 11 percent of the total oxygen. This is necessary because of the higher pressure of the hydrogen at this point. It is apparent that all the propellant leaving the tanks is expanded in the thrust-chamber nozzle resulting in an engine specific impulse equal to the specific impulse of the expanding gases in the nozzle. It may also be noted that, for a given chamber pressure, the pressure in the feed system is higher for this engine than for the bleed engine because of the expansion across the turbines.

Pressure-Staged System

The pressure-staged system is a combination of the two basic systems already described. Two slightly different schematic drawings of this engine are illustrated in figure 2. In this feed system, the hydrogen is pressurized in two distinct stages rather than in one stage. The low-pressure fuel pump is driven by a bleed turbine, and the high-pressure fuel pump is driven by a topping turbine. The oxygen pump may be driven by a second bleed turbine, as shown in figure 2(a), or a second topping turbine, as shown



(a) Oxygen pump driven by bleed turbine.



(b) Oxygen pump driven by topping turbine.

Figure 2. - Schematic drawings of pressure-staged feed systems.

TABLE I. - ENGINE CONDITIONS

	Feed system		
	Gas generator	Hot topping	Pressure staged
Thrust chamber oxidant-fuel ratio	7.0	7.0	7.0
Feed system pressure loss:			
Oxygen	$0.4 P_c$	$0.4 P_c$	$0.4 P_c$
Hydrogen:	$.6 P_c$	$.6 P_c$	$.6 P_c$
Upstream of topping turbine	----	$.4 P_c$	$.4 P_c$
Downstream of topping turbine	----	$.2 P_c$	$.2 P_c$
Pumps:			
Overall efficiency	0.75	0.75	0.75
Density used for isentropic headrise, lb/cu ft:			
Oxygen	71.2	71.2	71.2
Hydrogen	(a)	(a)	(a)
Turbines:			
Inlet temperature, ^{o}R	1400, 1800	1400, 1800	1400, 1800
Bleed, hydrogen:			
Static efficiency	(b)	----	0.60, 0.58
Pressure ratio	5	----	5
Mean blade speed, ft/sec	1200	----	1200
Number of stages	1 to 6	----	2
Topping:			
Hydrogen:			
Total efficiency range	----	0.65 to 0.86	0.65 to 0.86
Mean blade speed, ft/sec	----	1200	1200
Number of stages	----	1	1
Oxygen:			
Total efficiency range	----	0.63 to 0.86	0.62 to 0.86
Mean blade speed, ft/sec	----	800	800
Number of stages	----	2	2

[a]Average value based on inlet and exit pressures.
[b]See table III, p. 9.

in figure 2(b). The secondary oxygen pump serves the same purpose as the secondary pump described for the hot-topping system.

By pressurizing the hydrogen in a bleed turbopump only partly, at a given chamber pressure, the bleed rate of this engine is less than that of the bleed engine; however, the maximum system pressure is higher, although not as high as that of the hot-topping engine.

METHOD OF ANALYSIS

In order to conduct the analysis it was necessary to assume a number of engine conditions that are given in table I and discussed in the following paragraphs. The equations used for each of the three feed systems as well as the details of the calculating procedure are presented in appendix A.

Engine Conditions

The basic engine conditions discussed include feed-system pressure losses, pump work, and turbopump efficiencies.

Feed-system pressure losses. - The decrease in propellant pressure between the pump exit and the combustion chamber was assumed to be a percentage of the chamber pressure: 40 percent for oxygen and 60 percent for hydrogen were used in the analysis. These values were based on the pressure losses of two hydrogen-oxygen engines currently being developed, with chamber pressures up to 1000 pounds per square inch absolute, and the estimated pressure losses of an advanced hydrogen-oxygen engine with a chamber pressure of 3000 pounds per square inch absolute. These pressure losses include the pressure drops in the propellant lines, valves, and injectors, and, in the case of the hydrogen, also the pressure loss in the nozzle regenerative cooling jacket.

In addition to the magnitude of the hydrogen pressure loss, the manner of distributing this loss in the feed system, for those engines with a topping turbine, also influenced the pumping requirements. For the hot-topping and pressure-staged feed systems analyzed, the major portion of the feed-system plumbing occurs upstream of the topping turbine. Therefore, it was assumed that two-thirds of the pressure losses occur upstream of the topping turbine and the remaining part downstream.

Another system pressure condition specified was the pressure in the preburner and gas-generator components. The pressures of the hydrogen and oxygen entering the gas generator in the bleed and pressure-staged systems varied over the range of chamber pressure and, in the case of the pressure-staged system, for different values of hydrogen work split. Therefore, this component was assumed to operate at the lower of the two propellant pressures with the higher propellant pressure throttled to match. In the case of the preburner, the operating pressure was established by the hydrogen pressure, and the oxygen was further pressurized by a secondary pump. The additional turbine power needed for this purpose was not included in the analysis, since, for the largest oxygen pressure increase, it amounted to only a 2.5-percent increase in turbine specific work.

Pump work. - The propellant headrise, for both the oxygen and hydrogen, was calculated from the equation

$$\Delta h_p = \frac{144}{J} \frac{\Delta P}{\eta \rho}$$

(All symbols are defined in appendix B.) The oxygen was treated as an incompressible fluid with a density of 71.2 pounds per cubic foot. An average value of hydrogen density $\bar{\rho}$, corresponding to the average of the pump inlet and exit pressures of a constant-entropy process, was used to obtain the isentropic fuel headrise. Hydrogen properties were obtained from reference 2 with the assumption that the hydrogen leaving the propellant tank was a boiling fluid at a pressure of 15 pounds per square inch absolute. Utilizing the incompressible fluid headrise equation to calculate the hydrogen headrise gave a value within 1.0 percent of that obtained from an enthalpy-entropy chart at pressures for which data were available.

Turbopump efficiencies. - An efficiency of 0.75 was used for all propellant pumps of each feed system. This value was not varied in the analysis; however, due to the widely varying values of turbine specific work of the different feed systems and the dependence of turbine efficiency on this parameter, the turbine efficiency was calculated from the velocity diagrams. The number of turbine stages, the overall speed-work parameter λ, and the blade-jet speed ratio ν were used in these calculations.

With the particular series flow arrangement of the hydrogen- and oxygen-pump-drive-bleed turbines used in the analysis, the bleed rate was independent of the oxygen turbine efficiency. With the given bleed rate, as determined by the hydrogen turbine, the oxygen-bleed-turbine pressure ratio was adjusted until the required work output was obtained. Two-stage oxygen-bleed turbines were considered for this purpose.

The efficiency values for all the hydrogen bleed turbines of the bleed and pressure-staged feed systems were determined by utilizing the blade-jet speed ratio. The value of this parameter was calculated from the gas-generator gas properties given in table II, an arbitrarily selected mean blade speed of 1200 feet per second, and a total-to-static pressure ratio of 5. The resulting values of hydrogen-bleed-turbine efficiencies are given in table III for the two inlet temperatures and a varying number of turbine stages.

The gas properties of the combustion products of hydrogen and oxygen (table II) were

TABLE II. - GAS PROPERTIES OF COMBUSTION OF HYDROGEN AND OXYGEN

Gas generator		Preburner	
Propellant conditions at burner inlet			
Liquid hydrogen at 36.7° R, liquid oxygen at 162.2° R		Liquid hydrogen at 150° R, liquid oxygen at 162.2° R	
Combustion temperature, °R			
1400	1800	1400	1800
Oxidant-fuel ratio			
0.75	0.98	0.66	0.90
Specific heat, Btu/(lb)(°R)			
2.06	1.89	2.365	2.23
Ratio of specific heats			
1.376	1.358	1.365	1.344

TABLE III. - HYDROGEN-BLEED-TURBINE EFFICIENCIES

Number of stages									
1		2		3		4		6	
Inlet temperature, °R									
1400	1800	1400	1800	1400	1800	1400	1800	1400	1800
Static efficiency									
0.43	0.41	0.60	0.58	0.69	0.67	0.74	0.72	0.80	0.78

calculated by the method presented in reference 3. The higher temperature of the hydrogen entering the preburner resulted from an assumed amount of heat addition by this propellant in the nozzle regenerative cooling jacket.

Bleed-system calculations were made for the range of fuel turbine stages shown in table III to illustrate the effect of stage number. Pressure-staged feed-system calculations were only made for a two-stage hydrogen-pump-drive-bleed turbine.

Total efficiencies rather than static efficiencies were used for all of the topping turbines of the hot-topping and pressure-staged systems because the specific-work output of these turbines is small compared with the kinetic energy leaving the turbine. The loss in total pressure of the gases at the exits of the turbines is accounted for in the feed-system pressure loss. The turbine efficiency was determined from the calculated value of the overall speed-work parameter and the curves presented in reference 4. Mean blade speeds of 1200 and 800 feet per second were set for the hydrogen and oxygen turbines, respectively. The lower speed of the oxygen turbine was used, among other reasons, because of the lower rotative speed of the oxygen pump. With single-stage fuel turbines and two-stage oxidizer turbines, the ranges of total-to-total efficiencies were 0.65 to 0.86 and 0.62 to 0.86, respectively.

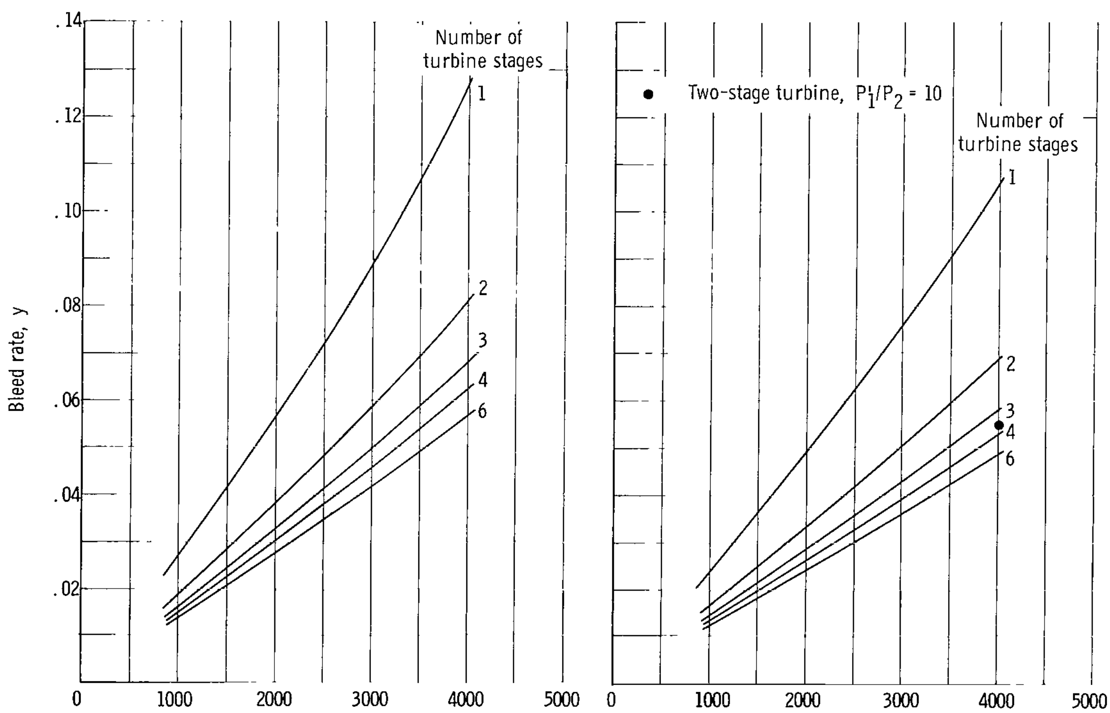
RESULTS AND DISCUSSION

The results of the analysis are presented in terms of bleed rate, engine specific impulse, and maximum feed-system pressure as affected by the engine chamber pressure, turbine inlet temperature, and turbine-exhaust thrust-recovery factor for each of the feed systems. In addition, the relative increase in the vehicle hydrogen tankage required for the bleed and pressure-staged engines to equal the engine thrust and ignition time of an engine without bleed is also presented. It is recognized that the basic engine assumptions made in order to conduct the analysis influenced the absolute values of the curves; however, the results do provide a number of general conclusions as well as a comparison of the different feed systems.

Bleed System

In figures 3 to 5 the engine characteristics of the bleed system are presented showing the effects of combustion chamber pressure, turbine inlet temperature, number of turbine stages, and turbine-exhaust thrust-recovery factor.

Bleed rate. - The bleed rate (fig. 3) is seen to be almost linearly dependent on chamber pressure, reaching a maximum value of 12.6 percent for a single-stage turbine at 1400° R and a chamber pressure of 4000 pounds per square inch absolute. Utilizing multistage turbines reduces the bleed rate substantially where the biggest individual re-



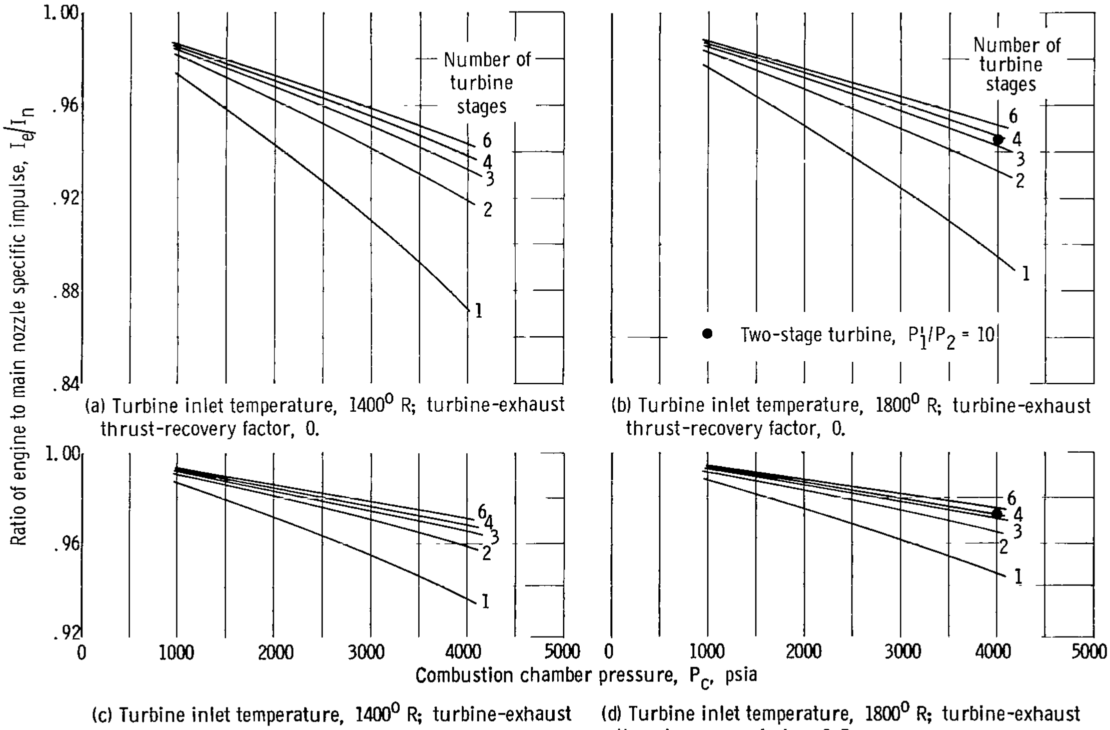
(a) Turbine inlet temperature, 1400° R.

(b) Turbine inlet temperature, 1800° R.

Figure 3. - Bleed rate of bleed system.

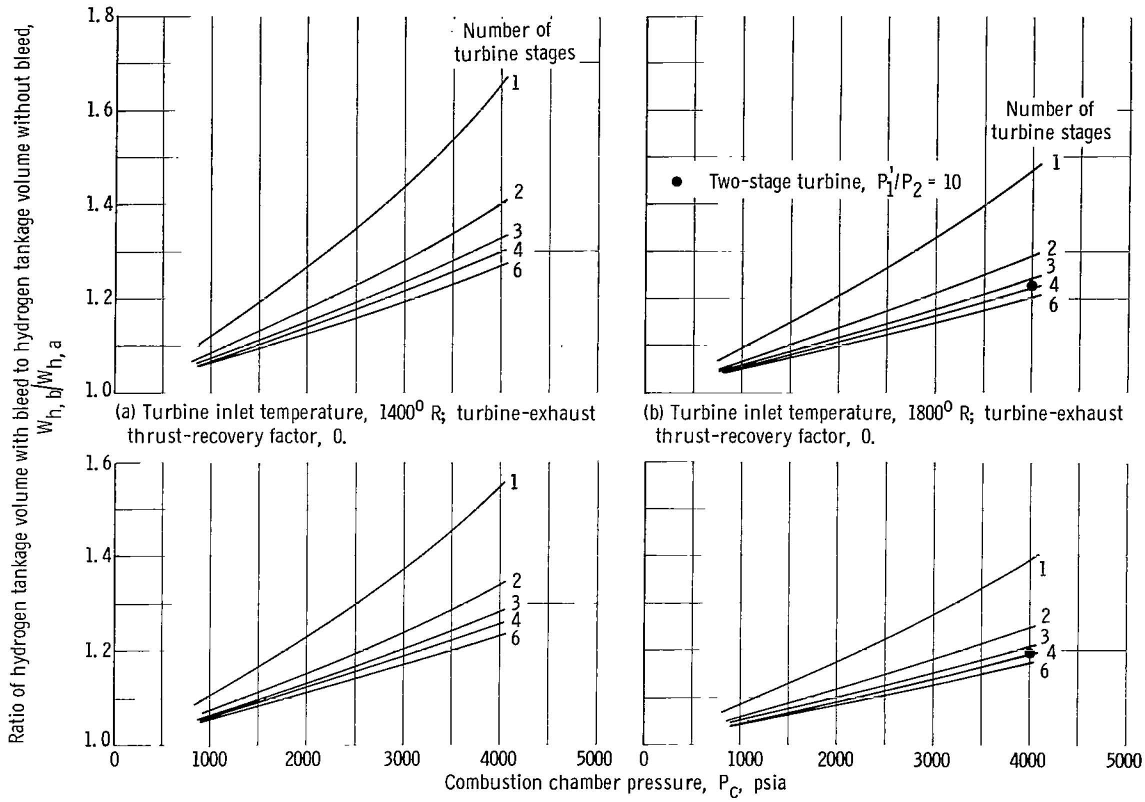
duction is realized by adding a second stage. As more turbine stages are added, however, the mechanical complexity of the turbopump increases. Raising the turbine inlet temperature provides a further reduction in the bleed rate, but this approach may be limited by the turbine stresses and available high-temperature metals. The combined effect of increasing the inlet temperature to 1800° R and adding a second turbine stage results in a bleed rate of approximately 1.7 percent for each increase in chamber pressure of 1000 pounds per square inch. An additional means of reducing the bleed rate is accomplished by taking advantage of the high turbine inlet pressure and utilizing a greater expansion ratio than the value of 5 used in the analysis. This effect was investigated for a two-stage turbine at 1800° R with a pressure ratio of 10 at a chamber pressure of 4000 pounds per square inch absolute. The bleed rate is seen to decrease from 6.8 to 5.4 percent, denoted by the single data point in figure 3.

Specific impulse and hydrogen tankage volume. - Figure 4 indicates the loss in specific impulse from that obtained in the main expansion nozzle. For the case of zero thrust recovery of the bleed rate (figs. 4(a) and (b)), the specific-impulse loss is equal to the amount of bleed. This loss is reduced by the ratio of turbine-exhaust-nozzle impulse to main-nozzle impulse and is shown in figures 4(c) and (d) for $\epsilon = 0.5$ where the impulse loss is halved.



(c) Turbine inlet temperature, 1400° R; turbine-exhaust thrust-recovery factor, 0.5.
(d) Turbine inlet temperature, 1800° R; turbine-exhaust thrust-recovery factor, 0.5.

Figure 4. - Effect of combustion chamber pressure and number of turbine stages on engine specific impulse for bleed system.



(c) Turbine inlet temperature, 1400° R; turbine-exhaust thrust-recovery factor, 0.5.

(d) Turbine inlet temperature, 1800° R; turbine-exhaust thrust-recovery factor, 0.5.

Figure 5. - Effect of combustion chamber pressure and number of turbine stages on hydrogen tankage volume for bleed system.

For the requirements of a specified amount of engine thrust and burning time, the propellant flow rates and propellant tankage volumes are determined by the engine specific impulse. The ratio of the hydrogen tankage required for a bleed system to that of an engine with a zero bleed rate is shown in figure 5 for two values of the turbine-exhaust thrust-recovery factor. It is readily seen that, even for low percentages of bleed rate, a significant additional amount of hydrogen must be provided. For a bleed system with a two-stage fuel turbine at 1800° R, and a turbine-exhaust thrust-recovery factor of 0.5, the hydrogen tankage volume increases about 6 percentage points for each increase in chamber pressure of 1000 pounds per square inch. The large increase of hydrogen volume is due to the low oxidant-fuel ratio in the gas generator. An increase in the oxygen tankage volume is also required but it is very small in comparison with the hydrogen and is therefore not shown. The maximum increase in oxygen volume calculated was 7 percent, which occurred at the same time that the hydrogen volume increased by 66 percent. The single data points shown in figures 4 and 5 represent the two-stage turbine with a pressure ratio of 10.

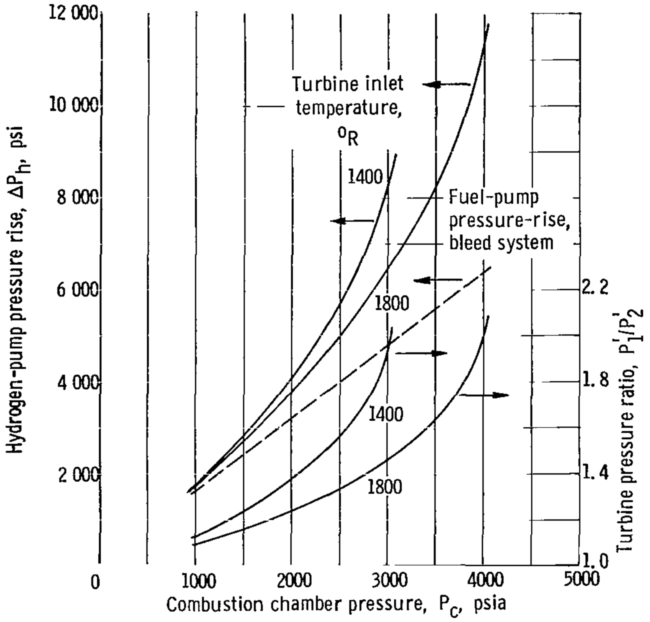


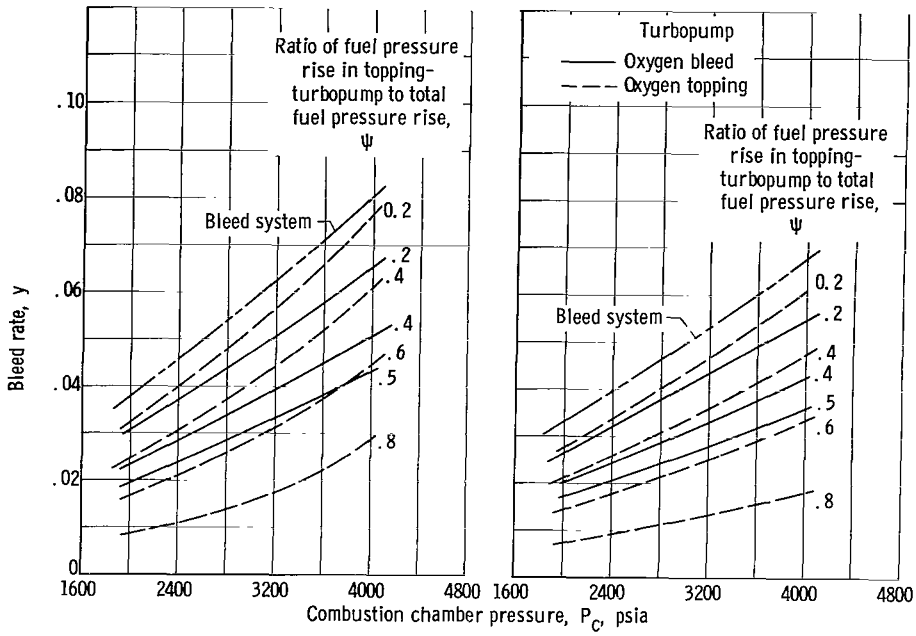
Figure 6. - Required fuel-pump pressure rise and turbine pressure ratio of hot-topping system.

Hot-Topping System

Figure 6 shows the chief characteristics of the hot-topping feed system. As stated earlier, this propellant feed system has no bleed rate, and therefore, no loss in specific impulse resulting in the minimum vehicle propellant tankage for a given engine thrust and ignition time. At a given chamber pressure, however, the system pressures are higher than those for the bleed system. At a chamber pressure of 1000 pounds per square inch absolute, the difference in the maximum system pressure of the two systems is very small, but as the chamber pressure increases above this value, the difference increases rapidly. For example, the maximum propellant pressures of a hot-topping system with a turbine inlet temperature of 1800° R were 1700 pounds per square inch at a chamber pressure of 1000 pounds per square inch absolute and 11 300 pounds per square inch at a chamber pressure of 4000 pounds per square inch absolute, whereas the corresponding values for the bleed system were 1600 and 6400 pounds per square inch. The increased pressures of the hot-topping system add to the problem of designing the high-pressure components for this engine.

Also shown in figure 6 is the importance of the turbine inlet temperature at chamber pressures of 3000 pounds per square inch absolute and above. For the particular hot-topping system analyzed, chamber pressures are limited to about 3000 and 4000 pounds per square inch absolute for turbine inlet temperatures of 1400° and 1800° R, respectively. These limits are imposed because of an inadequate amount of energy from the preburner gases that results in the turbine being unable to drive the pumps at any pressure ratio.

A number of possibilities exist that would reduce the demands of the hot-topping system on the turbopumps. The turbine pressure ratio and, hence, the maximum system pressure, would be reduced (1) by having feed-system pressure losses lower than the estimate used in the analysis, (2) by reducing the amount of hydrogen bypassing the preburner (in the analysis 20 percent of the hydrogen bypassed the preburner), and (3) by increasing the turbine inlet temperature. Also, at high chamber pressures, the turbine efficiency could be increased by adding another stage to the turbine.



(a) Turbine inlet temperature, 1400° R. (b) Turbine inlet temperature, 1800° R.

Figure 7. - Bleed rate of pressure-staged system.

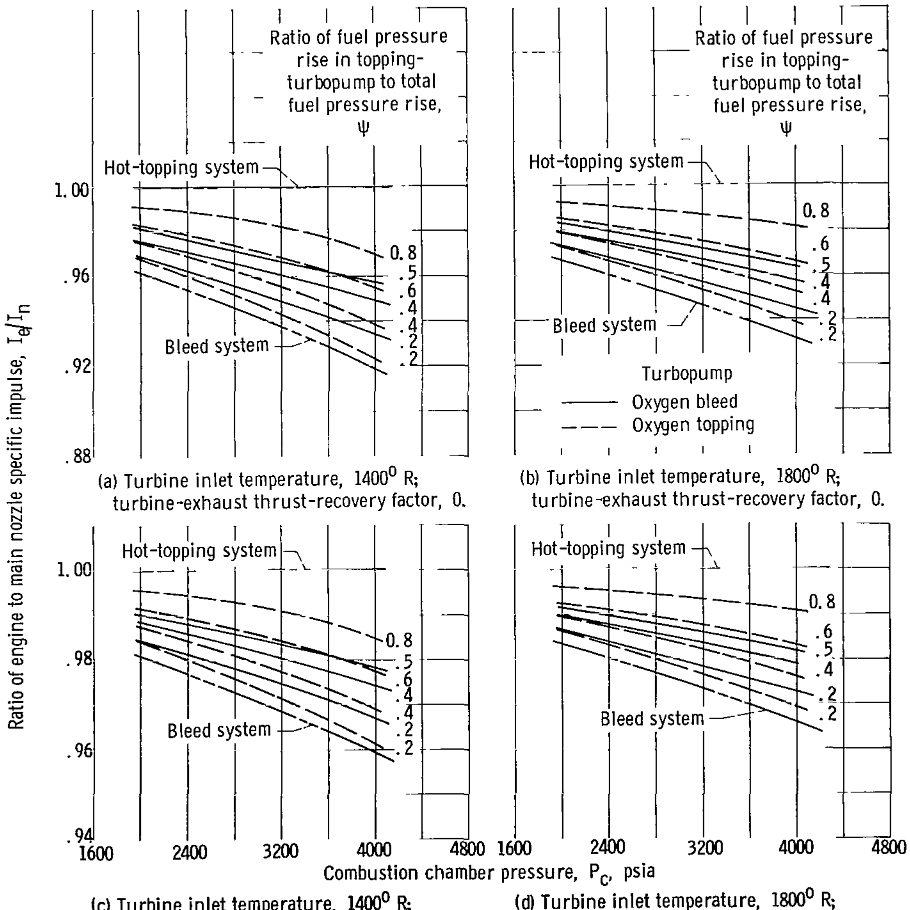
Pressure-Staged System

Figures 7 to 10 illustrate the engine characteristics of the pressure-staged system. The calculations for this system were made for a range of chamber pressures from 2000 to 4000 pounds per square inch absolute. Below a chamber pressure of 2000 pounds per square inch absolute, the engine characteristics of this system were similar to the bleed and hot-topping systems.

Bleed rate. - Figure 7 shows the bleed rate of the two pressure-staged systems and, for comparison, a bleed system with a two-stage fuel turbine. The solid curves represent the feed system with an oxygen-bleed turbopump (fig. 2(a), p. 5), and the dashed curves the feed system with an oxygen-topping turbopump (fig. 2(b)). The ratio of the hydrogen pressure rise in the topping turbopump to the total hydrogen pressure rise is represented by ψ.

The bleed rates of either pressure-staged system are lower than those of the bleed system over the entire range of chamber pressure. This difference increases with higher values of ψ, that is, with an increase in that part of the total hydrogen pressure rise that is added in the topping turbopump. At either turbine inlet temperature, comparison of the two curves for the bleed-rate of the pressure-staged system for the same values of ψ shows that the feed system with the oxygen-bleed turbopump requires a lower bleed rate than the feed system with the oxygen-topping turbopump. This lower bleed rate results because the entire preburner gas flow is expanded in the single topping turbine of the system shown in figure 2(a), whereas it is divided between the two topping turbines of the system shown in figure 2(b). Because of the higher weight flow of the single topping turbine, the turbine pressure ratio is lower, and, hence, the required overall hydrogen headrise is less for this feed system. Therefore, at the same value of ψ, the pressure-staged system with one topping turbine requires a lower bleed rate than the pressure-staged system with two topping turbines.

As the bleed rate of the pressure-staged system with the oxygen-bleed turbopump decreases, by increasing the values of ψ, the pressure ratio of the oxygen-pump-drive turbine increases. This pressure ratio may only be allowed to increase to a certain point, after which the oxygen turbopump dictates the bleed rate. This limit was arbitrarily established at an oxygen bleed turbine pressure ratio of 10, which occurs at a value of ψ of about 0.5. Curves of ψ higher than 0.5 for the pressure-staged system with an oxygen-bleed turbopump are not shown in the figures.



(c) Turbine inlet temperature, 1400° R; turbine-exhaust thrust-recovery factor, 0.5.

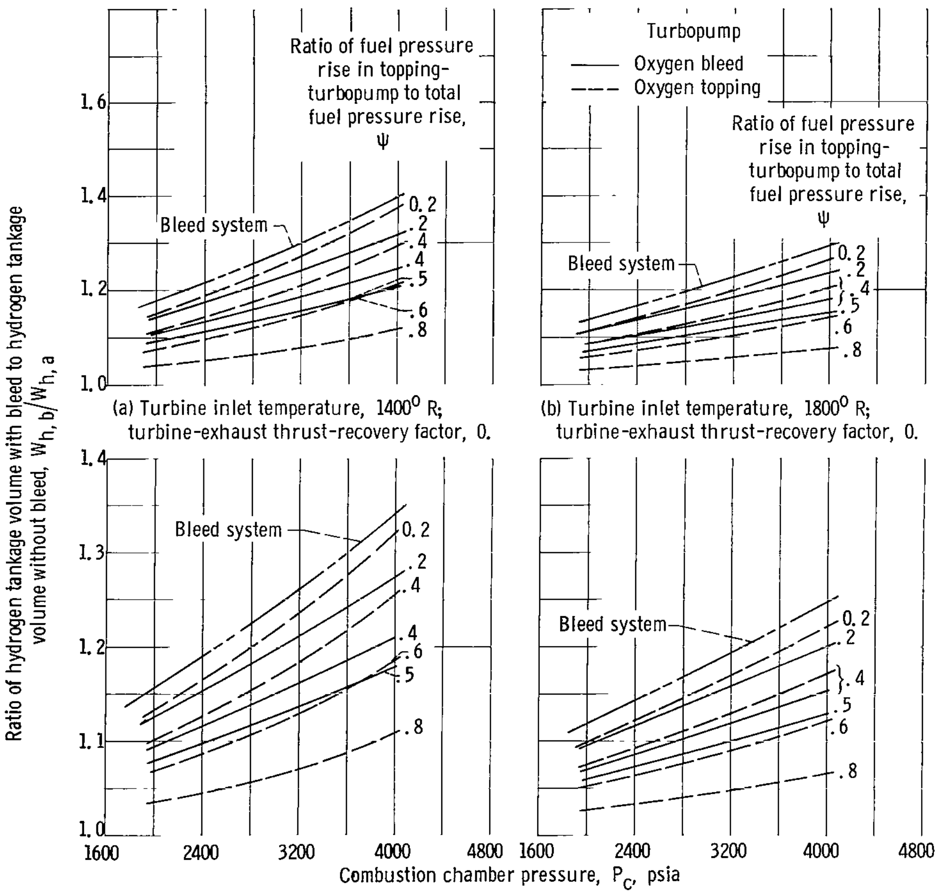
(d) Turbine inlet temperature, 1800° R; turbine-exhaust thrust-recovery factor, 0.5.

Figure 8. - Effect of chamber pressure and topping-bleed turbopump work split on engine specific impulse for pressure-staged system.

Specific impulse and hydrogen tankage volume. - The loss of specific impulse of the pressure-staged system is shown in figure 8. Comparison of these curves with the bleed-system curves indicates that sizable reductions of this loss are possible by utilizing a pressure-staged system with a high value of ψ.

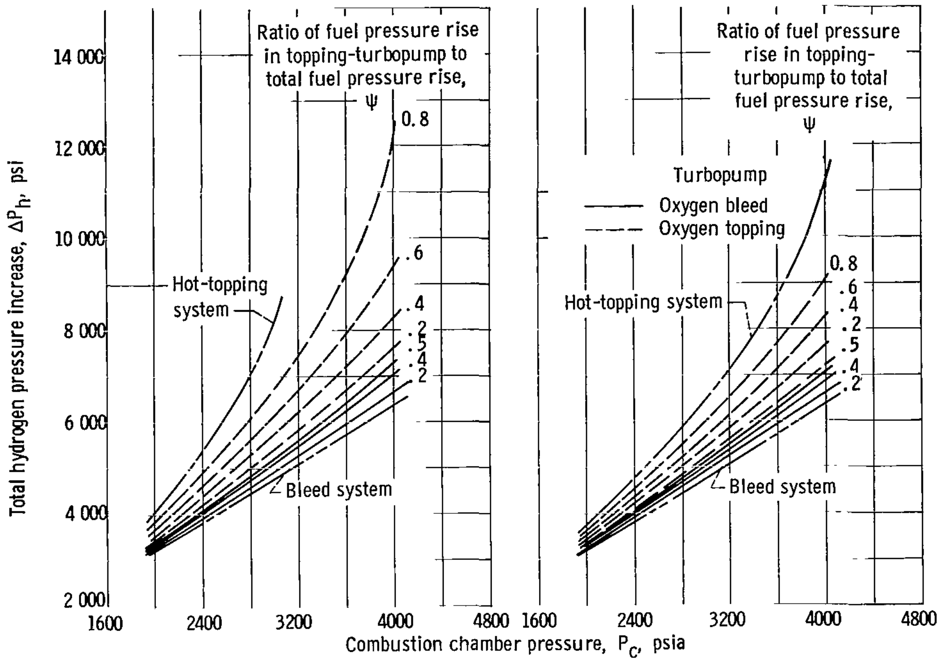
The hydrogen tankage increase, shown in figure 9, is again compared with the fuel tankage of an engine having an equal amount of engine thrust and burning time, but without any bleed. A substantial reduction in the amount of additional hydrogen is realized at all chamber pressures for high values of ψ.

Hydrogen pressure rise. - The total hydrogen pressure rise is shown in figure 10 together with the bleed and hot-topping systems. At high values of ψ, the fuel pressure rise is nearly as high as that of the hot-topping system, although the pressure increase would be divided between the two pumps. At low values of ψ, the system pressures are less severe, but the gains in specific impulse over the bleed system are not as large. Also, if either high or low values of ψ are designed for, the feed system is complicated



(c) Turbine inlet temperature, 1400° R; turbine-exhaust thrust-recovery factor, 0.5.
(d) Turbine inlet temperature, 1800° R; turbine-exhaust thrust-recovery factor, 0.5.

Figure 9. - Effect of chamber pressure and topping-bleed turbopump work split on hydrogen tankage volume for pressure-staged system.



(a) Turbine inlet temperature, 1400° R. (b) Turbine inlet temperature, 1800° R.

Figure 10. - Effect of chamber pressure and topping-bleed turbopump work split on total hydrogen pressure increase for pressure-staged system.

TABLE IV. - COMPARISON OF FEED SYSTEMS

Feed system	Bleed rate, percent	Specific-impulse loss, percent	Hydrogen-tankage volume increase, percent	Bleed-topping-turbopump work split, ψ	Hydrogen pressure rise per pump, psi	Total hydrogen pressure rise, psi	Oxygen pressure rise, psi
Chamber pressure, 2000 psia							
Bleed	3.3	1.65	12	0	3 200	3 200	2800
Hot topping	0	0	0	1.0	3 800	3 800	2800
Pressure staged:							
Oxygen-bleed turbopump	1.7	.85	6	.5	1675, 1675	3 350	2800
Oxygen-topping turbopump	1.4	.7	5.2	.6	1415, 2125	3 540	2800
Chamber pressure, 4000 psia							
Bleed	6.8	3.4	25	0	6 400	6 400	5600
Hot topping	0	0	0	1.0	11 300	11 300	5600
Pressure staged:							
Oxygen-bleed turbopump	3.6	1.8	13	.5	3525, 3525	7 050	5600
Oxygen-topping turbopump	3.4	1.7	12.2	.6	3310, 4960	8 270	5600

by a third turbopump that is doing only a small part of the work. Therefore, an intermediate value of ψ appears to be a logical compromise for designing an engine that employs a pressure-staged feed system.

Example

To illustrate the order of magnitude of the engine parameters investigated for each of the three feed systems, two examples are cited in table IV. The independent variables common to all the feed systems are (1) turbine-exhaust thrust-recovery factor, $\epsilon = 0.5$, (2) turbine inlet temperature, 1800° R, and (3) two-stage fuel-bleed turbines. At a chamber pressure of 2000 pounds per square inch absolute, there are only moderate differences in bleed rate, increased hydrogen tankage volume, and maximum system pressures of the different feed systems. At a chamber pressure of 4000 pounds per square inch, however, these differences become more pronounced. At this chamber pressure, the hot-topping system again has a zero bleed rate, but the maximum system pressure is significantly higher than that for the other feed systems. The maximum system pressure is reduced for the pressure-staged system, but it requires a bleed rate of about 3.5 percent and an increase in the relative hydrogen tankage volume of about 12.5 percent. A further reduction in maximum system pressure, to only 57 percent of the hot-topping-system value, is realized for the bleed system, but the bleed rate and relative hydrogen tankage volume have increased to 6.8 and 25 percent, respectively.

SUMMARY OF RESULTS

An analysis was made of bleed, hot-topping, and pressure-staged turbopump feed systems suitable for high-pressure hydrogen-oxygen rocket engine applications. The independent variables considered were (1) chamber pressures from 1000 to 4000 pounds per square inch absolute, (2) turbine inlet temperatures of 1400° and 1800° R, and (3) turbine-exhaust thrust-recovery factors of 0 and 0.5. The results of the analysis are summarized as follows:

1. The bleed rate of the bleed feed system increased approximately linearly with chamber pressure reaching a maximum value of 12.6 percent at a chamber pressure of 4000 pounds per square inch absolute for a single-stage fuel turbine with an inlet temperature of 1400° R. Increasing the number of turbine stages to two and the inlet temperature to 1800° R, reduced the bleed rate to approximately 1.7 percent for each increase in chamber pressure of 1000 pounds per square inch. Even small values of bleed rate and the consequent specific-impulse loss, however, require significant increases in the

relative amount of vehicle propellant tankage, when compared with an engine having zero bleed. For the two-stage turbine at 1800° R, the hydrogen tankage increased about 6 percentage points for each increase in chamber pressure of 1000 pounds per square inch.

2. The hot-topping system has no loss of specific impulse and, therefore, results in the minimum amount of vehicle propellants for a specified engine thrust and burning time. At a given chamber pressure, however, the maximum system pressure of this engine system is higher than that for the bleed system. With a turbine inlet temperature of 1800° R the maximum system pressures of the hot-topping system were 1700 and 11 300 pounds per square inch absolute at chamber pressures of 1000 and 4000 pounds per square inch absolute, respectively. By comparison, the corresponding values for the bleed system were 1600 and 6400 pounds per square inch absolute.

3. For a given hot-topping system of known system pressure losses, hydrogen flow rates, and chamber pressure, there is a minimum value of turbine inlet temperature below which the system is not feasible. For the particular hot-topping system analyzed, the chamber pressure was limited to about 3000 and 4000 pounds per square inch absolute for turbine inlet temperatures of 1400° and 1800° R, respectively.

4. The pressure-staged system represents a compromise between the lower engine pressures of the bleed system and the higher specific impulse of the hot-topping system. By dividing the total hydrogen-pump power requirement equally between the bleed and topping turbopumps, the bleed rate, specific-impulse loss, and increased amount of vehicle propellants are reduced to about one-half of the corresponding bleed-system values. The maximum system pressure, however, is higher, varying from 3350 to 7050 pounds per square inch at chamber pressures of 2000 and 4000 pounds per square inch absolute, respectively, compared with 3200 to 6400 pounds per square inch for the bleed system.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 30, 1965.

APPENDIX A

FEED-SYSTEM EQUATIONS AND CALCULATING PROCEDURES

Bleed System

The bleed rate of the bleed-engine system (fig. 1(a), p. 3), was calculated from the power balance between the hydrogen pump and its drive turbine:

$$w_{gg}\eta_{t,h}c_{p,1}T_1'\left[1-\left(\frac{P_2}{P_1'}\right)^{(\gamma-1)/\gamma}\right]=\frac{144\ \Delta P_h w_{h,e}}{J\bar{\rho}_h\eta_{p,h}} \tag{A1}$$

Dividing equation (A1) by $w_{h,e}+w_{\ell,e}$, replacing ΔP_h by $1.6\ P_c$, and expressing the bleed rate as $w_{gg}/(w_{h,e}+w_{\ell,e})$ yield

$$y=\frac{w_{gg}}{w_{h,e}+w_{\ell,e}}=\frac{144\times 1.6\ P_c}{J\bar{\rho}_h\eta_{p,h}\eta_{t,h}c_{p,1}T_1'\left[1-\left(\frac{P_2}{P_1'}\right)^{(\gamma-1)/\gamma}\right]\left[1+\left(\frac{o}{f}\right)_{e,b}\right]} \tag{A2}$$

Since the oxidant-fuel ratio in the combustion chamber is fixed at a constant value of 7.0, the engine oxidant-fuel ratio $(o/f)_{e,b}$ is a function of the bleed rate y and the gas-generator oxidant-fuel ratio. An expression for $(o/f)_{e,b}$ can be obtained by equating the total hydrogen flow leaving the tank to the fuel going to the combustion chamber plus the fuel going to the gas generator:

$$w_{h,e}=w_{h,c}+w_{h,gg}$$

or

$$w_{h,e}=\frac{w_c}{1+\left(\frac{o}{f}\right)_c}+\frac{w_{gg}}{1+\left(\frac{o}{f}\right)_{gg}}$$

Then

$$\frac{w_{h,e}}{w_{h,e} + w_{\ell,e}} = \frac{1 - y}{1 + \left(\frac{o}{f}\right)_c} + \frac{y}{1 + \left(\frac{o}{f}\right)_{gg}} \tag{A3}$$

Similarly, for oxygen,

$$\frac{w_{\ell,e}}{w_{h,e} + w_{\ell,e}} = \frac{(1 - y)\left(\frac{o}{f}\right)_c}{1 + \left(\frac{o}{f}\right)_c} + \frac{y\left(\frac{o}{f}\right)_{gg}}{1 + \left(\frac{o}{f}\right)_{gg}} \tag{A4}$$

Dividing equation (A4) by equation (A3) results in the expression for the engine oxidant-fuel mixture ratio:

$$\left(\frac{o}{f}\right)_{e,b} = \frac{(1 - y)\left[1 + \left(\frac{o}{f}\right)_{gg}\right]\left(\frac{o}{f}\right)_c + y\left[1 + \left(\frac{o}{f}\right)_c\right]\left(\frac{o}{f}\right)_{gg}}{(1 - y)\left[1 + \left(\frac{o}{f}\right)_{gg}\right] + y\left[1 + \left(\frac{o}{f}\right)_c\right]} \tag{A5}$$

Equations (A2) and (A5) were then solved simultaneously.

Because a portion of the propellants is expended to drive the turbines, the engine specific impulse is reduced, and thus, for a specified amount of engine thrust and burning time, the propellant flow must be increased. The magnitude of these effects is illustrated by the following equations. The engine specific impulse is expressed as

$$I_e = I_n(1 - y + \epsilon y)$$

or

$$\frac{I_e}{I_n} = 1 - y + \epsilon y \tag{A6}$$

where ϵ, the turbine-exhaust recovery factor, is equal to I_m/I_n. Equation (A6) indicates the degradation of the engine specific impulse below the specific impulse of a zero bleed engine.

The effect of the bleed rate on the propellant flow rate, for a given amount of engine thrust, may be examined by first defining $w_{e,a}$ as the total propellant flow (i.e., sum of the hydrogen and oxygen flow rates leaving the tanks) of an engine with zero bleed and $w_{e,b}$ similarly for an engine with bleed. Then the total propellant flow of the bleed system is

$$w_{e,b} = \frac{w_{e,a}}{1 - y + \epsilon y}$$

Also

$$w_{e,b} = w_{h,b}\left[1 + \left(\frac{o}{f}\right)_{e,b}\right]$$

$$w_{e,a} = w_{h,a}\left[1 + \left(\frac{o}{f}\right)_{e,a}\right]$$

and

$$\frac{w_{h,b}}{w_{h,a}} = \frac{1 + \left(\frac{o}{f}\right)_{e,a}}{1 + \left(\frac{o}{f}\right)_{e,b}}\left(\frac{1}{1 - y + \epsilon y}\right) \tag{A7}$$

Similarly for the increase in oxygen flow rate

$$\frac{w_{\ell,b}}{w_{\ell,a}} = \left[\frac{1 + \left(\frac{o}{f}\right)_{e,a}}{1 + \left(\frac{o}{f}\right)_{e,b}}\right]\frac{\left(\frac{o}{f}\right)_{e,b}}{\left(\frac{o}{f}\right)_{e,a}}\left(\frac{1}{1 - y + \epsilon y}\right) \tag{A8}$$

Equations (A7) and (A8) not only show the increase in propellant flow due to the bleed rate but also indicate the individual increases in tankage volume of the hydrogen and oxygen.

Hot-Topping System

As stated in the description of the hot-topping system, the hot gases from the combustion of hydrogen and oxygen in the preburner provide the energy to drive the turbopumps. For this analysis, 80 percent of the total amount of hydrogen available at the exit of the nozzle cooling jacket entered the preburner with an amount of oxygen necessary to achieve the required turbine inlet temperature. At the preburner exit, the hydrogen-rich gas is divided into two parts and expanded equally across the two topping turbines. The ratio of fuel-turbine to oxidizer-turbine weight flow is determined by the fuel and oxidizer pump requirements. The total preburner flow is

$$w_{pb} = w_{t,h} + w_{t,\ell}$$

or

$$\frac{w_{t,h}}{w_{pb}} + \frac{w_{t,\ell}}{w_{pb}} = 1 \tag{A9}$$

As discussed previously, the oxygen pressure rise is 1.4 P_c, with the additional pressurization of the oxygen going to the preburner neglected. The hydrogen pressure rise includes the topping turbine expansion in addition to the system losses:

$$\Delta P_h = \left[1.2\left(\frac{P_1'}{P_2'}\right) + 0.4\right]P_c \tag{A10}$$

Then the power balance between the fuel pump and its drive turbine is

$$w_{t,h}\eta_{t,h}'c_{p,1}T_1'\left[1 - \left(\frac{P_2'}{P_1'}\right)^{(\gamma-1)/\gamma}\right] = \frac{144\,\Delta P_h w_{h,e}}{J\bar{\rho}_h\eta_{p,h}}$$

Replacing $w_{t,h}$ by 0.8 $w_{h,e}\left[1 + (o/f)_{pb}\right](w_{t,h})/(w_{pb})$, dividing by $w_{h,e}$, and utilizing equations (A9) and (A10) yield

$$0.8\left(1 - \frac{w_{t,\ell}}{w_{pb}}\right)\left[1 + \left(\frac{o}{f}\right)_{pb}\right]\eta_{t,h}'c_{p,1}T_1'\left[1 - \left(\frac{P_2'}{P_1'}\right)^{(\gamma-1)/\gamma}\right] = \frac{144\left[1.2\left(\frac{P_1'}{P_2'}\right) + 0.4\right]P_c}{J\bar{\rho}_h\eta_{p,h}} \tag{A11}$$

Similarly for the oxygen turbopump

$$0.8\,\frac{w_{t,\ell}}{w_{pb}}\left[1+\left(\frac{o}{f}\right)_{pb}\right]\eta'_{t,\ell}c_{p,1}T'_1\left[1-\left(\frac{P'_2}{P'_1}\right)^{(\gamma-1)/\gamma}\right]=\frac{144\times 1.4\,P_c}{J\rho_\ell\eta_{p,\ell}}\left(\frac{o}{f}\right)_{e,a} \tag{A12}$$

Equations (A11) and (A12), involving the unknowns P'_1/P'_2, the turbine pressure ratio and $w_{t,\ell}/w_{pb}$, the fraction of the preburner flow passing through the oxygen turbine, were solved iteratively. The procedure followed was to assume values of $\eta_{t,h}$, $\eta_{t,\ell}$, and $\bar{\rho}_h$, to solve equations (A11) and (A12) for P'_1/P'_2 and $w_{t,\ell}/w_{pb}$, and to calculate new values of $\eta_{t,h}$, $\eta_{t,\ell}$, and $\bar{\rho}_h$. The calculated values of $\eta_{t,h}$, $\eta_{t,\ell}$, and $\bar{\rho}_h$ then replaced the initial values, and the procedure was repeated until all dependent variables converged.

Pressure-Staged System

The oxygen pressure rise of the pressure-staged system is again $1.4\,P_c$, and the total hydrogen pressure rise is expressed by equation (A10). The manner in which this pressure rise is divided between the two fuel pumps is arbitrary and is denoted by ψ, the ratio of the hydrogen pressure rise in the topping turbopump to the total hydrogen pressure rise.

Feed system with single topping turbine. - Using the same approach as that for the bleed system gives the bleed rate of the pressure-staged system of figure 2(a) as

$$y=\frac{144(1-\psi)\left[1.2\left(\dfrac{P'_1}{P'_2}\right)_v+0.4\right]P_c}{J\left\{\bar{\rho}_h\eta_{p,h}\eta_{t,h}c_{p,1}T'_1\left[1-\left(\dfrac{P_2}{P'_1}\right)^{(\gamma-1)/\gamma}\right]\right\}_u\left[1+\left(\dfrac{o}{f}\right)_{e,b}\right]} \tag{A13}$$

and the equation relating the high-pressure hydrogen-pump requirement to the topping turbine work is

$$0.8\left[1+\left(\frac{o}{f}\right)_{pb}\right]\left\{\eta'_{t,h}c_{p,1}T'_1\left[1-\left(\frac{P'_2}{P'_1}\right)^{(\gamma-1)/\gamma}\right]\right\}_v=\frac{144\psi\left[1.2\left(\dfrac{P'_1}{P'_2}\right)_v+0.4\right]P_c}{J\bar{\rho}_{h,v}\eta_{p,h,v}} \tag{A14}$$

The turbine inlet temperatures of both hydrogen turbopumps were set equal to the same value but the turbine gas properties, pressure ratios, and efficiencies plus the average values of hydrogen density differed. For this reason, in equation (A13) the subscript u is used to indicate the bleed or low-pressure turbopump, and in equation (A14) the subscript v is used to indicate the topping or high-pressure turbopump. Equations (A5) to (A8) are valid for both of the pressure-staged feed systems. To solve for the unknowns $(P_1'/P_2')_v$, y, and $(o/f)_{e,b}$, an iterative method similar to that used for the hot-topping system was followed. In this case initial values of $\eta'_{t,h,v}$, $\bar{\rho}_{h,v}$, and $\bar{\rho}_{h,u}$ were assumed, and equations (A5), (A13), and (A14) were solved for the unknowns $(P_1'/P_2')_v$, y, and $(o/f)_{e,b}$.

Feed system with two topping turbines. - The expression for the bleed rate of this feed system is the same as equation (A13), and the high-pressure fuel-pump equation is nearly identical to equation (A11) except for the inclusion of ψ. Again, utilizing 80 percent of the available hydrogen and dividing the preburner gas flow into two equally expanded flows gives the equation relating the high-pressure fuel-pump requirement to the topping turbine work:

$$0.8\left(1 - \frac{w_{t,\ell}}{w_{pb}}\right)\left[1+\left(\frac{o}{f}\right)_{pb}\right]\left\{\eta'_{t,h}c_{p,1}T'_1\left[1 - \left(\frac{P'_2}{P'_1}\right)^{(\gamma-1)/\gamma}\right]\right\}_v = \frac{144\psi\left[1.2\left(\frac{P'_1}{P'_2}\right)_v + 0.4\ P_c\right]}{J\bar{\rho}_{h,v}\eta_{p,h,v}} \tag{A15}$$

Equating the oxygen pump power requirement to the oxygen turbine work output and neglecting the additional pressurization of the oxygen going to the preburner result in the equation

$$0.8\frac{w_{t,\ell}}{w_{pb}}\left[1+\left(\frac{o}{f}\right)_{pb}\right](w_{h,e} - w_{h,gg})\eta'_{t,\ell}c_{p,1}T'_1\left[1 - \left(\frac{P'_2}{P'_1}\right)_v^{(\gamma-1)/\gamma}\right] = \frac{144\times 1.4\ P_c w_{\ell,e}}{J\rho_\ell\eta_{p,\ell}} \tag{A16}$$

To solve equation (A16), an expression for $w_{\ell,e}/(w_{h,e} - w_{h,gg})$ must be derived:

$$\frac{w_{\ell,e}}{w_{h,e} - w_{h,gg}} = \frac{w_{\ell,e}}{w_{h,e} - \dfrac{w_{gg}}{w_{h,e} + w_{\ell,e}}\left[\dfrac{w_{h,e} + w_{\ell,e}}{1 + \left(\frac{o}{f}\right)_{gg}}\right]} = \frac{\left(\frac{o}{f}\right)_{e,b}\left[1 + \left(\frac{o}{f}\right)_{gg}\right]}{1 + \left(\frac{o}{f}\right)_{gg} - y\left[1 + \left(\frac{o}{f}\right)_{e,b}\right]}$$

Substituting this expression into equation (A16) gives

$$0.8\,\frac{w_{t,\ell}}{w_{pb}}\left[1 + \left(\frac{o}{f}\right)_{pb}\right]\eta'_{t,\ell}c_{p,1}T'_1\left[1 - \left(\frac{P'_2}{P'_1}\right)_v^{(\gamma-1)/\gamma}\right] = \frac{144 \times 1.4\,P_c\left(\frac{o}{f}\right)_{e,b}\left[1 + \left(\frac{o}{f}\right)_{gg}\right]}{J\rho_\ell\eta_{p,\ell}\left\{1 + \left(\frac{o}{f}\right)_{gg} - y\left[1 + \left(\frac{o}{f}\right)_{e,b}\right]\right\}} \tag{A17}$$

Setting the turbine inlet temperatures of all three turbines equal to the same value, equations (A5), (A13), (A15), and (A17) containing the unknowns y, $(o/f)_{e,b}$, $(P'_1/P'_2)_v$, and $w_{t,\ell}/w_{pb}$ were solved simultaneously. This was done by an iterative procedure similar to that followed for the pressure-staged system of figure 2(a).

APPENDIX B

SYMBOLS

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

g gravitational constant, 32.17 ft/sec^2

Δh specific work, Btu/lb

J mechanical equivalent of heat, 778.2 ft-lb/Btu

I specific impulse, sec

o/f oxidant-fuel mixture ratio

P absolute pressure, psia

ΔP propellant pressure increase, psi

T absolute temperature, $^{\circ}$R

U blade speed, ft/sec

w weight flow, lb/sec

y bleed rate, equal to ratio of gas-generator-component flow to total propellant flow

γ ratio of specific heats

ϵ turbine-exhaust thrust-recovery factor, I_m/I_n

η efficiency

λ overall speed-work parameter, $U^2/gJ\,\Delta h$

ν blade-jet speed ratio, $U/\sqrt{2gJ\,\Delta h_{id}}$

ρ propellant density, lb/cu ft

ψ ratio of fuel pressure rise in topping-turbopump to total fuel pressure rise

Subscripts:

a cycle with zero bleed flow

b cycle with bleed flow

c combustion chamber

e engine

gg gas generator

h hydrogen propellant

id ideal or isentropic

ℓ oxygen propellant

m turbine exhaust nozzle

n main expansion nozzle

p pump

pb preburner

t turbine

u bleed turbopump

v topping turbopump

1 turbine inlet

2 turbine exit

Superscripts:

(') total state

($\bar{\ }$) average

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