NASA TECHNICAL NOTE

NASA TN D-2712

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NASA TN D-2712

ANALYSIS OF TURBOPUMP FEED SYSTEMS FOR HYDROGEN-NUCLEAR ROCKETS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1965

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SUMMARY

An analysis was made of turbopump feed systems for hydrogen-nuclear rockets. The study was concerned with investigating the feasibility of low temperature topping turbine systems, bleed rates for bleed turbine systems, and the possible advantage of a combination bleed and topping system. The range of chamber pressure investigated was from 300 to 1000 pounds per square inch absolute, and the range of system loss assumed was from 350 to 750 pounds per square inch. Conservative estimates of the pump and turbine component efficiencies were used, and conservative mechanical design limitations were observed. It is felt, therefore, that the results are commensurate with current mechanical design technology and component performance expectations.

The results of the topping turbine driven feed systems showed that for turbine inlet temperatures of 1200° R or above the topping turbine pressure ratio would be small and would not represent a major consideration affecting the system feasibility. The feasibility of topping systems was shown to be critically dependent on turbine inlet temperature in the range 300° to 500° R. A low temperature or waste heat topping system having a turbine inlet temperature of 300° R was shown to be feasible at a 400 psia chamber pressure, marginal at 600 psia, and not feasible for chamber pressures above 600 psia. The bleed rates that were required for the range of operating conditions used herein varied from 0.037 to 0.101 for a single-shaft bleed turbine system and from 0.027 to 0.076 for a two-shaft bleed turbine system. The decrease in bleed rate cited is the reflection of improved turbine performance of the two-shaft bleed system, which effects a six-stage turbine within the mechanical limitation of three stages per unit.

A combined bleed and topping system was examined for system conditions of 800-psia chamber pressure and 450-psi system loss. The example case, at which the topping turbine developed 0.75 of the total pump power, resulted in a bleed rate of 0.029. The corresponding bleed rates were 0.0725 for a single-shaft pure bleed system and 0.054 for a two-shaft bleed system. Thus, the combination bleed and topping system offers an advantage in bleed rate over a pure bleed system for assumed engine conditions for which a pure topping system would not function.

INTRODUCTION

The hydrogen-nuclear rocket is currently receiving considerable interest as a candidate propulsion system for future contemplated space ventures. In recent years, for example, a considerable effort has been put into NERVA (nuclear engine for rocket vehicle application). Also, a study of an analytical hydrogen-nuclear engine that utilizes a tungsten water-moderated reactor is currently being conducted at the NASA Lewis Research Center.

In the hydrogen-nuclear rocket the propulsion fluid is pure hydrogen that is heated by nuclear energy in a reactor. A turbopump feed system is required to pump the hydrogen from its tank storage pressure to the high pressure required in the nozzle chamber, from which it is expanded in the nozzle jet. The types of turbopump feed systems commonly considered are the bleed system and the topping system. The bleed system utilizes a small fraction of the propellant flow to drive the turbopump with an associated loss in overall specific impulse. In a topping system, all (or most) of the propellant is passed through the topping turbine and then through the reactor and thrust chamber. Thus, all the propellant is capable of developing full thrust in the thrust chamber. There is a system disadvantage to the topping turbopump, however, in that pump discharge pressure must be increased to compensate for the pressure ratio across the topping turbine.

Some analyses have been made of hydrogen-nuclear turbopump feed systems (e.g., refs. 1 and 2). Reference 1 presents turbopump weight and payload weight characteristics for a variety of bleed turbopump configurations for an assumed mission. The analysis of reference 2 also determines turbopump weight and payload weight characteristics for three assumed missions considering a bleed turbopump system and hot and cold topping systems.

This report presents the results of a thermodynamic or system study of turbopump feed systems for hydrogen-nuclear rocket application. The types of systems considered were a topping system, a bleed system, and a combination bleed and topping system. The range of rocket chamber pressure considered was 300 to 1000 pounds per square inch absolute, and the range of system pressure loss used was 350 to 750 pounds per square inch. System pressure loss is defined herein to consist of all of the pressure drops in the system from the hydrogen storage tank to the nozzle chamber excluding the pressure changes across the pump or turbine. The values of turbine inlet temperature assumed ranged from 300° to 1200° R. The results of this study are used to demonstrate

(1) Range of conditions where topping systems are feasible

(2) Bleed rate expenditure required for bleed systems

(3) Relative advantages and compromises that are made possible by using a combination bleed and topping system

These results are not dependent on rocket size or propellant rate.

SYMBOLS

c_p specific heat at constant pressure, Btu/lb

Δh_s isentropic enthalpy change, Btu/lb

p static pressure, psia

SL system loss, psi

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

y bleed rate, ratio of propellant flow through bleed turbine to total propellant flow, dimensionless

γ ratio of specific heats, dimensionless

η efficiency, dimensionless

Subscripts:

bt bleed turbine

p pump

tt topping turbine

1 station at tank outlet or first pump inlet, see fig. 1

2 station at pump discharge

3 station at topping turbine inlet

4 station at topping turbine outlet, reactor core inlet

5 station at rocket chamber

TYPES OF TURBOPUMP FEED SYSTEMS CONSIDERED

Figure 1 presents a diagramatic sketch of the three systems considered herein. The topping system shown is considered a waste-heat type, wherein the energy used to heat the hydrogen before it enters the topping turbine is obtained entirely from cooling the nozzle skirt and the reactor jacket. For topping systems, other than the waste-heat type, provision must be made to further heat the hydrogen before it enters the topping turbine, such as an auxiliary heat exchanger or a segmented reactor. The bleed system has passages in the reactor core to heat the bleed gas to the desired turbine inlet temperature. The combination bleed and topping feed system employs features and components of both the bleed and topping systems. The concept of the combined system considered herein is that of the bleed turbine being used to augment a waste-heat topping system in the range of assumed engine operating conditions where the topping system alone would not be feasible.

METHOD OF ANALYSIS

This analysis is a thermodynamic study of turbopump feed systems. The results

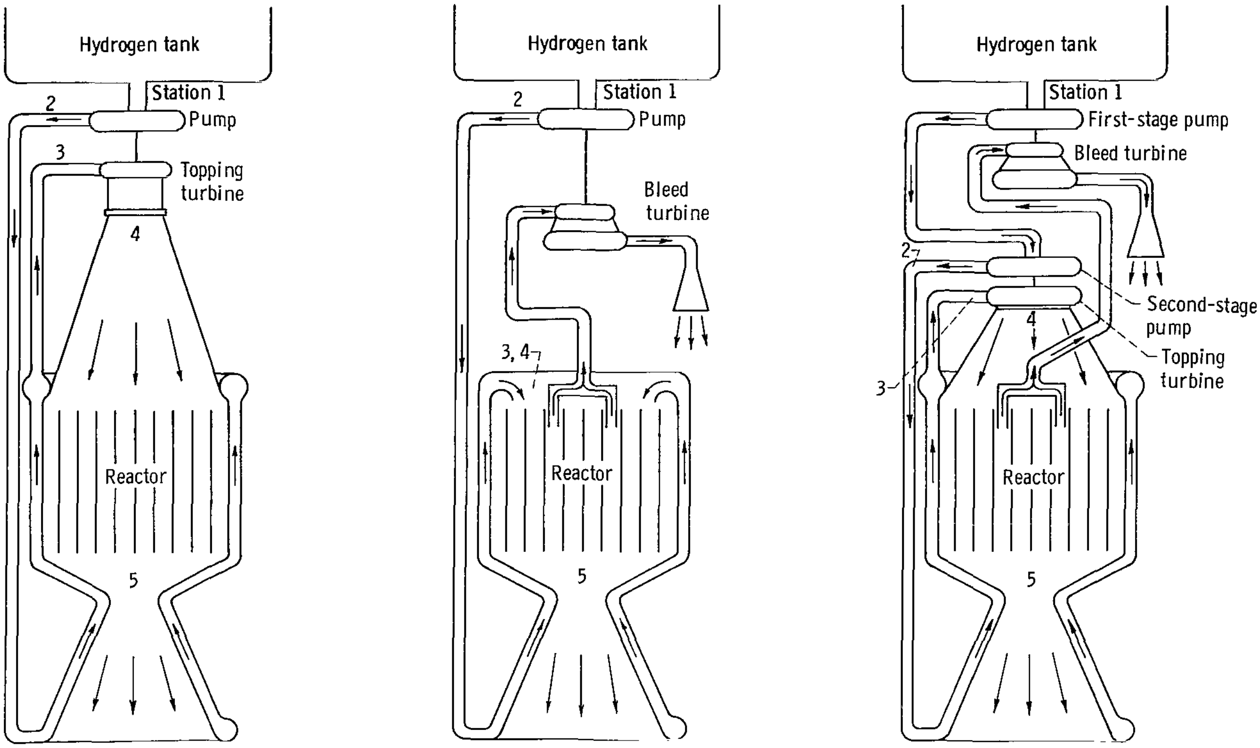


Figure 1. - Conceptual sketch of hydrogen-nuclear rocket propellant feed systems.

therefore depend only on turbopump component efficiencies and engine operating parameters. The component efficiencies selected are somewhat lower than those based on a best engineering estimate thereby providing some margin of conservatism in the procedure. In addition to component efficiencies, the other pertinent variables that affect the propellant feed system are system pressure loss and rocket chamber pressure. These factors are discussed in the following paragraphs.

System Loss

In a study of this type it is convenient to define and use the parameter, system loss, as a key system variable. As defined herein, system loss includes all pressure loss between the storage tank and the rocket chamber excluding the pressure changes across the pump and turbine. For a bleed system this parameter could be expressed in symbols as

$$SL = p_2 - p_5 \tag{1}$$

and for a topping or combined system as

$$SL = (p_2 - p_3) + (p_4 - p_5) \tag{2}$$

since the line loss between the storage tank and the pump is considered negligible. The system loss value together with the chamber pressure fix the requirements of the turbopump feed system. The range of system loss values used herein was 350 to 750 psi. It is felt that this range is representative of the system loss that might be encountered in an actual engine of this type.

Another factor that has a small additional effect on topping systems or combined bleed and topping systems is the breakdown of system loss. The major contributors to the system loss (fig. 1) are

(1) Nozzle skirt cooling passages

(2) Reactor outer jacket cooling passages

(3) Heating passages through the reactor core

In a system having a topping turbine, this component would be situated in the flow path downstream of the reactor jacket heat exchanger and upstream of the reactor core (see fig. 1). It was assumed herein that five-ninths of the system loss occurred before the topping turbine and four-ninths of the loss occurred downstream. This distribution of pressure loss, expressed in equation form, is

$$\left.\begin{aligned} p_2 - p_3 &= \frac{5}{9}\left[(p_2 - p_3) + (p_4 - p_5)\right] = \frac{5}{9}\,SL \qquad \text{(psi)} \\ p_4 - p_5 &= \frac{4}{9}\left[(p_2 - p_3) + (p_4 - p_5)\right] = \frac{4}{9}\,SL \qquad \text{(psi)} \end{aligned}\right\} \tag{3}$$

This loss distribution was based on an engineering estimate of the losses in the various components of this type of engine.

Chamber Pressure

The range of chamber pressure assumed in this study was 300 to 1000 psia. This selection was made to bracket the pressure values currently being considered for this type of engine.

Pump Work

The required pump work was based on an isentropic enthalpy rise from saturated liquid at 30 psia to the required pump discharge pressure. The enthalpy rise was taken from an enthalpy-entropy chart for parahydrogen given in reference 3. The isentropic enthalpy rise is a unique function of pump discharge pressure, varies nearly linearly with discharge pressure, and can be expressed to within 1 percent accuracy by the following equation:

$$\Delta h_{s,p} = 42.822\ p_2 \times 10^{-3} - 1.0203\ p_2^2 \times 10^{-6} - 1.28 \qquad \text{(Btu/lb)} \tag{4}$$

The tank storage pressure has a minor effect on pump work. At a discharge pressure of 3500 psia for example, the ideal pump work changes by about 2.5 percent for a storage pressure of 1 or 3 atmospheres as compared to 2 atmospheres used herein.

The isentropic pump work, as mentioned before, is a unique function of pump discharge pressure (see eq. (4)). The pump discharge pressure is in turn dependent on chamber pressure, system pressure loss, and topping turbine pressure ratio as follows:

$$p_2 = \frac{p_3}{p_4}\left(p_5 + \frac{4}{9}\,SL\right) + \frac{5}{9}\,SL \qquad \text{(psia)} \tag{5}$$

For the case of a bleed system the topping turbine pressure ratio is 1.0 and the pump discharge pressure is

$$p_2 = p_5 + SL \qquad \text{(psia)}$$

The isentropic pump work curves are shown as the solid lines in figure 2 over the range of conditions investigated.

Turbine Work

The turbine work calculations will be discussed separately for the bleed and topping systems. One common condition that was arbitrarily imposed was that any turbine should be able to develop its required power from 0.80 of the flow available to it. This allows for a 0.20 flow bypass, which can be used for control or emergency purposes.

Topping turbine work. - The isentropic work output of the turbine depends on the turbine inlet temperature and the pressure ratio. The work outputs were evaluated over a range of pressure ratio for turbine inlet temperatures from 300° to 1200° R. In the temperature range below 500° R, the thermodynamic tables of reference 3 were used to

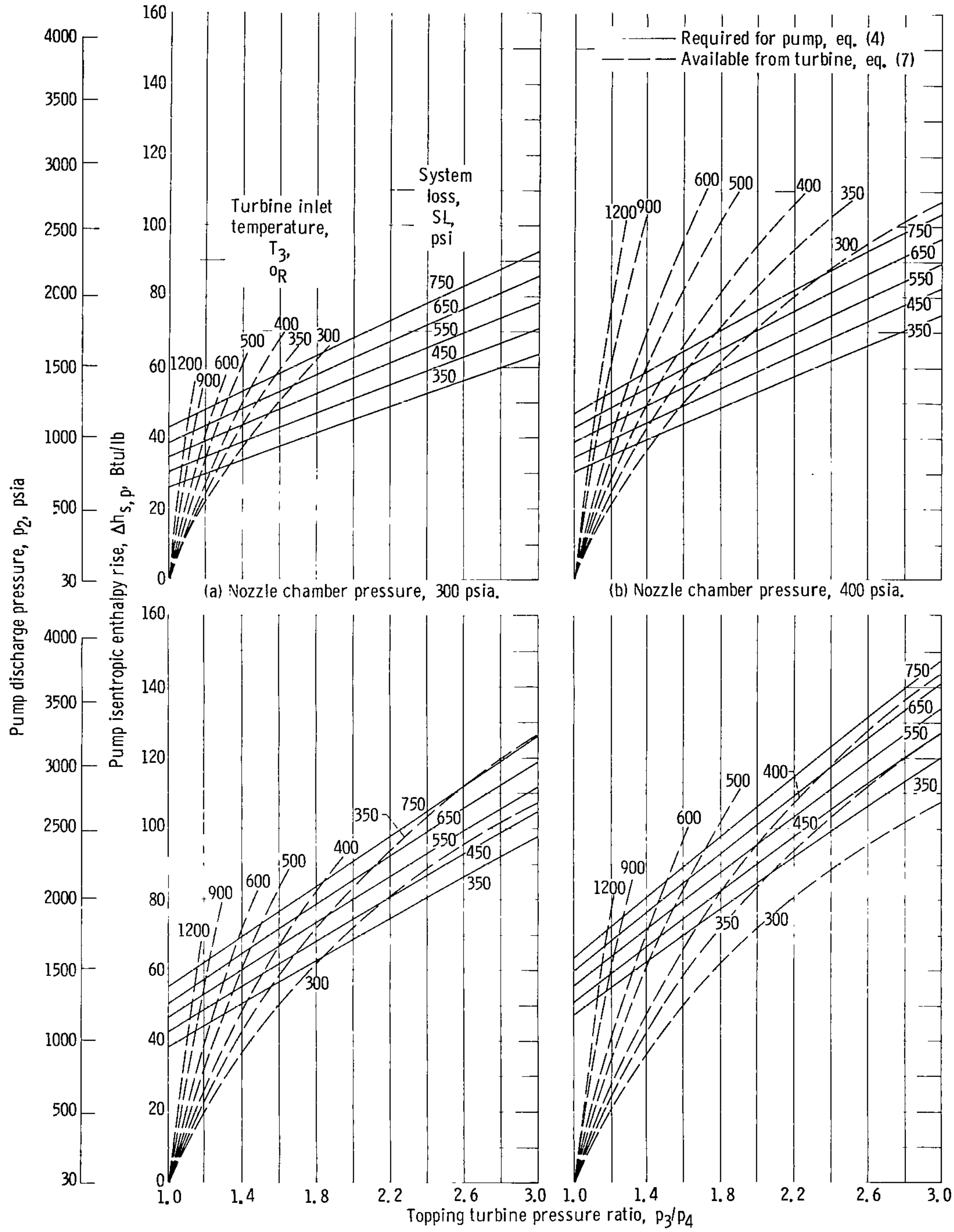
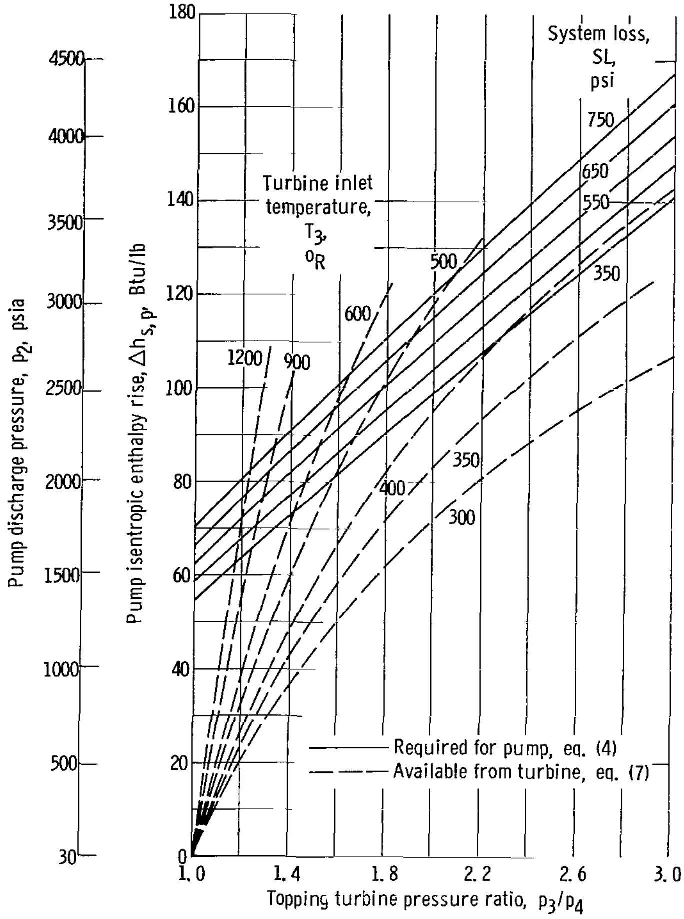


Figure 2. - Topping system matching curves. Comparison of required and available work on basis of pump isentropic enthalpy rise. Topping turbine efficiency, 0.70; pump efficiency, 0.65; propellant flow bypass ratio, 0.20.



(e) Nozzle chamber pressure, 1000 psia.

Figure 2. - Concluded. Topping system matching curves. Comparison of required and available work on basis of pump isentropic enthalpy rise. Topping turbine efficiency, 0.70; pump efficiency, 0.65; propellant flow bypass ratio, 0.20.

obtain the isentropic enthalpy change of the gas, which was assumed to be parahydrogen. For temperatures of 500° R and above, specific heat c_p and specific heat ratio γ values were taken from reference 4 to compute the isentropic enthalpy drop across the turbine as follows:

$$\Delta h_{s,tt} = c_p T_3 \left[1 - \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}}\right] \quad \text{(Btu/lb)} \tag{6}$$

In order for the pump and topping turbine to be matched, their actual specific enthalpy change must be equated. When allowing for the 0.20 flow bypass, the equal work condition in terms of ideal work is

TABLE I. - TURBINE ISENTROPIC ENTHALPY CHANGE

FOR VARIOUS TURBINE INLET TEMPERATURES

AND PRESSURE RATIOS

Pressure ratio	Inlet temperature, °R						
	300	350	400	500	600	900	1200
	Turbine isentropic enthalpy change, Btu/lb						
1.1	29.8	33.8	38.5	50.3	57.3	84.4	111.0
1.2	56.8	65.5	75.1	91.6	108.3	159.5	209.9
1.3	80.1	93.6	107.5	130.6	154.3	226.5	298.7
1.4	101.2	118.5	135.2	165.4	197.2	287.9	379.2
1.5	121.2	140.6	161.1	199.0	234.5	343.6	452.5
1.75	163.2	189.4	217.2	270.0	316.4	464.1	611.4
2.0	198.1	229.7	262.4	330.0	387.7	564.3	743.6
2.25	227.5	264.8	302.2	381.0	447.3	649.6	856.1
2.5	253.0	295.8	337.4	426.2	499.5	723.5	953.6
2.75	275.5	323.5	367.2	466.3	545.5	788.4	1039.3
3.0	295.3	348.3	394.3	502.1	587.9	846.2	1115.6

$$\frac{\Delta h_{s,p}}{\eta_p} = \Delta h_{s,tt}\eta_{tt}\ 0.80 \qquad (\text{Btu/lb})$$

or

$$\Delta h_{s,p} = \Delta h_{s,tt}\eta_{tt}\eta_p\ 0.80 \qquad (\text{Btu/lb}) \tag{7}$$

The right side of equation (7) was plotted in figure 2 over the range of conditions investigated. This quantity can be considered work available from the turbine expressed in terms of isentropic pump work.

The efficiency values used for the topping study were 0.65 and 0.70 for the pump and turbine, respectively. The values are somewhat lower than could be reasonably expected. Efficiency values of 0.70 to 0.75, for example, have been demonstrated for high-pressure-rise hydrogen pumps designed for this type of application. Thus, the results are felt to be conservative.

The use of pump isentropic work as a comparison base in figure 2 yields a certain utilitarian advantage. The required work (eq. (4)) is the actual pump isentropic enthalpy change and is obviously independent of the assumptions regarding component efficiencies or flow bypass fraction. The turbine available work (eq. (7)) depends on the component efficiencies and the flow bypass fraction, as well as the turbine isentropic enthalpy change. The turbine isentropic enthalpy changes are therefore listed in table I for the range of turbine inlet temperatures and turbine pressure ratios. Turbine available work curves could then be generated for different component efficiencies or flow bypass fractions using these tabulated enthalpy changes and applying the desired efficiency and flow bypass constants in the manner of equation (7).

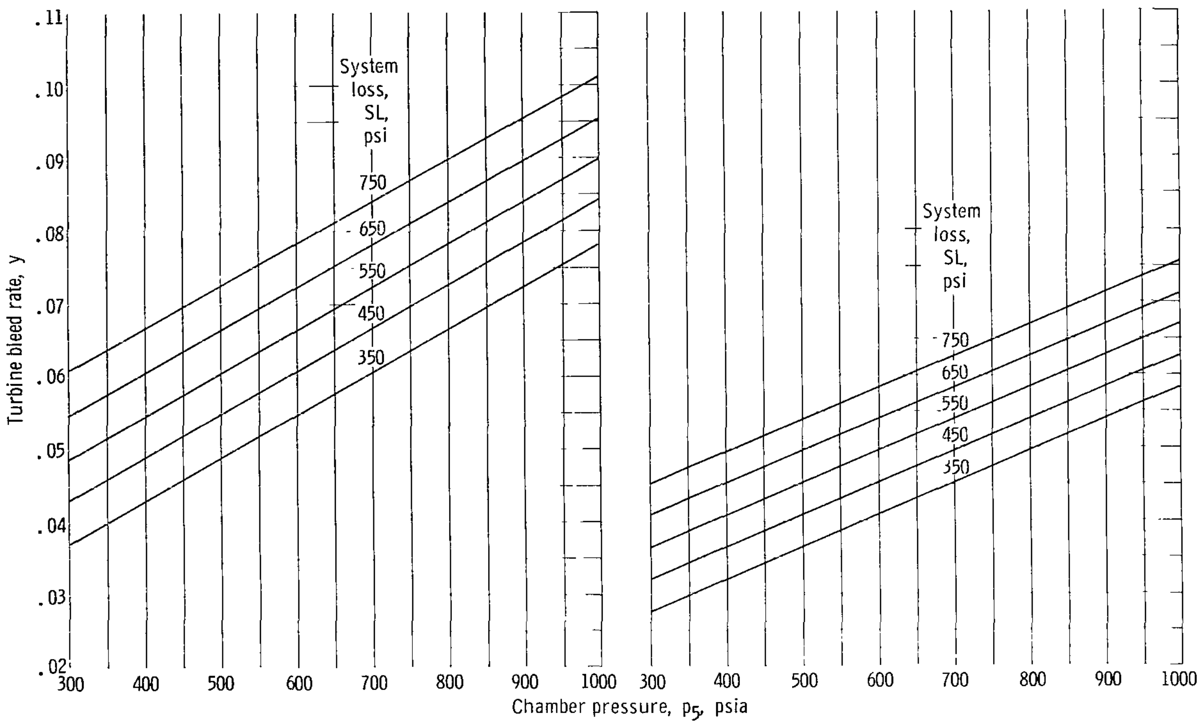
Bleed turbine. - The work output of the bleed turbine and the resulting bleed flow rates were calculated (using the thermodynamic properties given in ref. 5) as follows. It was assumed that bleed hydrogen was available at 1660° R and at an inlet pressure equal to rocket chamber pressure. It was also assumed that the isentropic enthalpy drop across the turbine was equal to 0.50 of the total energy content of the gas, which corresponds to a turbine pressure ratio of 10.9. This pressure ratio represents a reasonable compromise between obtaining a high specific work output (which increases with pressure ratio) and tolerating a large or exorbitant turbine outlet area (which would also increase with pressure ratio). A mean blade speed of 1250 feet per second was assumed, and a limit of three stages was imposed from mechanical considerations when assuming the turbine component cantilevered from one end of the turbopump shaft. A bleed turbine efficiency could then be estimated by using reference 6 and knowing ideal enthalpy drop, blade speed, and number of stages. The efficiency used herein was 0.47, which was downgraded from the value of 0.51 estimated from reference 6. The bleed rate can then be calculated from the bleed turbine enthalpy drop in the following way:

$$y = 1.25 \frac{\Delta h_{s,p}}{\Delta h_{s,bt} \eta_{bt} \eta_p} \tag{8}$$

The pump efficiency was again assumed to be 0.65. The pump isentropic enthalpy rise can be obtained from figure 2 by using the abscissa value of topping turbine pressure ratio of 1. The 1.25 factor was used to allow for the 0.20 flow bypass for control purposes. The bleed flow rates are shown in figure 3(a) as a function of chamber pressure and system loss.

Bleed turbine - two-shaft system. - Because of the high energy content of the hydrogen bleed gas, it would be desirable from the standpoints of turbine efficiency and bleed rate to utilize 10 or more stages in the bleed turbine. As mentioned in the preceding section, the turbine was limited to three stages from mechanical considerations with a resulting efficiency of 0.47. One logical way of improving this system would be to divide the total pump work into two equal-work pump units on separate shafts with each unit being driven by a three-stage turbine. By directing the bleed flow through the two turbines in series, a six-stage bleed turbine is effected.

The bleed rates were therefore determined for the two-shaft bleed system maintaining the same blade speed, inlet temperature, and pressure ratio (10.9 across both sections) that were used for the single-shaft system. The efficiency for the two-shaft bleed



(a) Single-shaft bleed system. Bleed turbine efficiency, 0.47.
(b) Two-shaft bleed system. Bleed turbine efficiency, 0.63.

Figure 3. - Effect of chamber pressure and system loss on bleed rate. Pump efficiency, 0.65; bleed turbine inlet temperature, 1660° R; bleed turbine pressure ratio, 10.9; bleed flow bypass for bleed turbine, 0.20.

system was increased to 0.63 (ref. 6 indicates 0.66). The bleed rates for the two-shaft bleed system are shown in figure 3(b) for the range of chamber pressure and system loss that were investigated.

Combined bleed and topping system. - The concept of a combined bleed and topping system considered herein is that in which a single-shaft bleed system is used to augment a waste-heat topping system for engine conditions where a topping system alone would not be feasible. The combined system is also a two-shaft system. The total required isentropic pump work and the isentropic pump work available from the topping turbopump were obtained from figure 2 for any selected topping turbine pressure ratio. The deficiency in pump work or the difference in these two quantities is then the $\Delta h_{s,p}$ value used in equation (8) to determine the bleed rate for the bleed turbopump.

RESULTS AND DISCUSSION

The results of this analytical study will be discussed in three parts: First, the topping system feasibility study; second, the propellant required for the bleed system; and finally, the possibilities of the combined bleed and topping system. The component efficiencies used herein are felt to be conservative, and the range of operating conditions are believed to include the values currently of interest.

Topping System Study

The topping system pump and turbine matching curves are presented in figure 2. The dashed lines are the turbine available work curves, which vary only with turbine pressure ratio and turbine inlet temperature. Because the turbine work curves are not affected by nozzle chamber pressure or system loss they are repeated for the different parts of figure 2. The pump work curves, which are the solid lines in figure 2, vary with each chamber pressure as well as with system loss. The intersection of the pump and turbine work curves represents the pressure ratio at which the pump and turbine work are equal. A range of turbine inlet temperatures from 300° to 1200° R was used to show the effect of this parameter. For an inlet temperature of 1200° R or above, the topping turbine will develop the required work at quite low pressure ratios. In figure 2(e) it can be seen that a turbine pressure ratio of 1.23 is required for the most severe pressures investigated. Also noted in figure 2(e) is the high sensitivity of topping systems to turbine inlet temperature in the low temperature range. At a turbine inlet temperature of approximately 380° R the topping turbine would not develop the required power for any of the system loss values used. At 500° R turbine inlet temperature, however, the topping turbine will develop the required power even for the highest value of pressure loss.

Although a range of turbine inlet temperature up to 1200° R was investigated in figure 2 to show the effect of this parameter, it is desired to have topping systems that operate on waste heat, that is, the heat picked up in the nozzle skirt and reactor jacket. This would avoid the complications of a segmented reactor or a hot bleed heat exchanger although the turbine inlet temperature would probably not exceed 300° R. By referring to figure 2 it can be seen that at this turbine inlet temperature a topping system appears feasible at chamber pressures of 400 psia, marginal at 600 psia, and not feasible at chamber pressures higher than 600 psia.

From the results shown in figure 2, the following three conclusions can be drawn regarding the feasibility of topping systems:

(1) For turbine inlet temperatures of 1200° R or higher, the topping turbine pressure ratio is small and is not a major consideration affecting system feasibility.

(2) For turbine inlet temperatures from 300° to 500° R, the feasibility of the system is very sensitive to turbine inlet temperature.

(3) A waste heat topping system limited to a turbine inlet temperature of 300° R would not work for chamber pressures much greater than 600 psia.

Also included in figure 2 is an auxiliary ordinate from which the pump discharge pressure can be read. The pump discharge pressure for a bleed turbopump can be obtained for the same system loss and chamber pressure by reading this ordinate where the system loss curve for the topping turbopump intersects the line corresponding to a topping turbine pressure ratio of 1. These two values of pump discharge pressure can then be compared to indicate the increase in pump discharge germane to the topping turbopump system. It is beyond the scope of this report to try to assess this effect; however, it is necessary to recognize it as an inherent disadvantage of topping turbopump systems.

Bleed System Study

The required bleed rates for the single-shaft and two-shaft bleed turbine systems are shown in figures 3(a) and (b), respectively. In figure 3(a) the bleed rates vary from 0.037 to 0.101 over the range of chamber pressure and system loss considered. For the system values of 600-psia chamber pressure and 400-psi system loss, which are felt to be typical of a contemporary engine of this type, a bleed rate of 0.057 would be required. The corresponding range of bleed rates (fig. 3(b)) for the two-shaft system would be from 0.027 to 0.076. The bleed rate for the assumed engine having typical system values would be 0.043. As mentioned in the METHOD OF ANALYSIS section, the two-shaft system is a means of affecting a six-stage turbine within the mechanical limitation of three stages per unit. The reduction in required bleed rate for the two-shaft system is then the reflection of the increased turbine efficiency attainable.

In bleed systems operating with hot hydrogen, it would be desirable to employ 10 (or more) turbine stages to efficiently utilize the energy content of the hydrogen. It was assumed herein that mechanical consideration limited the turbine to three stages cantilevered from the turbopump shaft. The results of figures 3(a) and (b) show that with such a limitation imposed, the bleed rate can be reduced by employing a two-shaft system. For the case cited, using typical system values, this reduction amounted to 0.014.

Combination Bleed and Topping Systems

When considering topping systems or combination bleed and topping systems it is desirable to have the topping turbine operate with waste heat, that is, without the complications of a segmented reactor or an auxiliary heat exchanger. This requirement would result in a topping turbine inlet temperature of about 300° R. If the rocket chamber

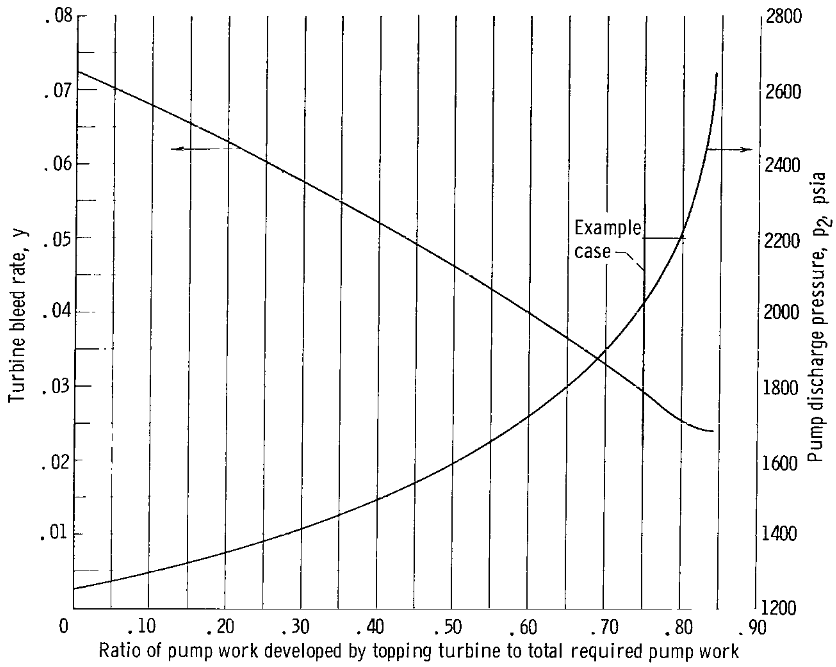


Figure 4. - Effect of bleed system and topping system work split on bleed rate and pump discharge pressure for combined bleed and topping turbopump feed system. Chamber pressure, 800 psia; system loss, 450 psi; pump efficiencies, 0.65; topping turbine efficiency, 0.70; bleed turbine efficiency, 0.47; propellant flow bypass for topping turbine, 0.20; bleed flow bypass for bleed turbine, 0.20; bleed turbine inlet temperature, 1660° R; bleed turbine pressure ratio, 10.9.

pressure were 800 psia and the system loss were 450 psi, such a topping system would not function (fig. 2(d)). The bleed rate requirement for these operating parameters would be 0.0725 for a single-shaft configuration and 0.054 for a two-shaft arrangement if a bleed system were employed. It is therefore of interest to consider the possibilities of a combined bleed and topping system for these specific conditions.

By referring to the 300° R turbine inlet temperature curve of figure 2(d), it can be seen that as the topping turbine pressure ratio is varied the increment of work that must be supplied by the bleed system varies. The bleed turbine bleed rate was then determined as that required to develop this incremental work using the same performance assumptions that were discussed previously for bleed turbine systems. The results of using a combined bleed and topping feed system are shown in figure 4. The point of 0-percent topping turbine work has a 0.0725 bleed rate, which is the same as in figure 3(a) where the 450-psi system loss line crosses the 800-psia chamber pressure abscissa value. As the topping turbine pressure ratio is increased, the ratio of topping turbine work to total work increases and bleed rate decreases. At a topping turbine pressure ratio of 2.4 the fraction of work developed in the topping turbine is 0.842 and the bleed rate is 0.02375. The point is used as the right termination of the curve in figure 4. If the topping turbine pressure ratio is increased above 2.4, the percent of total work de-

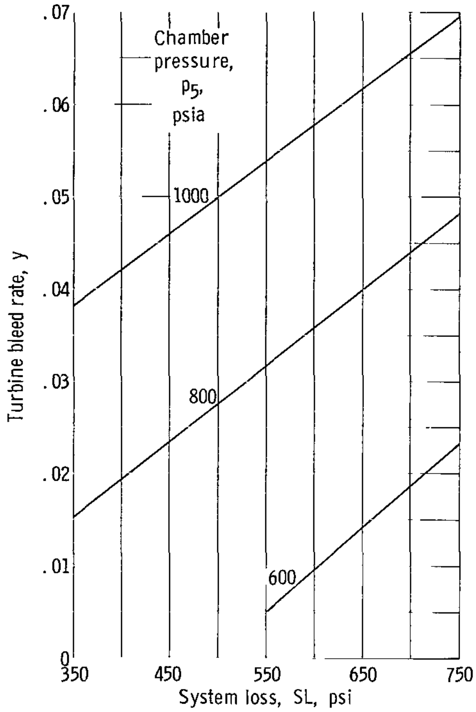


Figure 5. - Bleed rates required for combined bleed and topping turbopump systems for pressure ratio of minimum bleed rate. Topping turbine efficiency, 0.70; bleed turbine efficiency, 0.47; pump efficiencies, 0.65; propellant flow bypass for topping turbine, 0.20; bleed flow bypass for bleed turbine, 0.20; bleed turbine inlet temperature, 1660° R; bleed turbine pressure ratio, 10.9.

veloped by the topping turbine continues to increase; however, the bleed rate starts to increase again from this minimum point. This effect can also be noted in figure 2(d) from the curve of required pump work and the curve of available work from the turbine. Also shown in figure 4 is the curve of pump discharge pressure as a function of bleed rate.

The example case chosen for discussion is that when the topping turbine develops 0.75 of the total work. This combined system would require a bleed rate of 0.029. The attendant increase in pump discharge pressure would be from 1250 psia for pure bleed system to 2020 psia for the combined system. For the combined system, however, this pressure would be developed by two pumps with a bleed system pump discharge pressure of 510 psia, leaving a rise of 1510 psi for the topping system pump. Thus, for the example case the combined bleed and topping system does not cause a prohibitive increase in the severity of the pump problem.

In figure 5, the bleed rates are shown for combined bleed and topping systems over the range of system loss and chamber pressure considered. Only one point is shown for each chamber pressure - system loss combination; that being the point of minimum bleed rate. The bleed rates for the combined bleed and topping system were lower than those obtained with the single-shaft or two-shaft bleed systems. This reduction in bleed rate ranged from 0.031 to 0.062 compared to a single-shaft bleed system and from 0.006 to 0.045 compared to a two-shaft bleed system. Thus it can be concluded that a combined bleed and topping system can attain some of the advantage of a pure topping system for imposed engine conditions for which a pure topping system would not function. For the example case the combined system effected a reduction in bleed rate from 0.0725 to 0.029 as compared to a single-shaft bleed system and from 0.054 to 0.029 as compared to a two-shaft bleed system.

SUMMARY OF RESULTS

An analysis of turbopump feed systems has been made to determine the feasibility of low temperature topping systems, bleed system bleed rates, and possibilities of combined systems for hydrogen-nuclear rockets. The range of chamber pressures investigated was from 300 to 1000 psia, and the range of system loss assumed was from 350 to 750 psi. Conservative values of component efficiency were used as well as mechanical limitations, chamber pressure, and system loss values that were felt to be commensurate with current design technology. The results of the analysis are as follows:

1. For topping systems using a turbine inlet temperature of 1200° R or higher, the topping turbine pressure ratio is small and is not a major consideration effecting the feasibility of the system. At temperatures from 300° to 500° R, topping system feasibility is very sensitive to small changes in turbine inlet temperature.

2. For the system loss values used herein a waste-heat topping system operating with a turbine inlet temperature of 300° R would be feasible at 400-psia chamber pressure, marginal at 600 psia, and not feasible for chamber pressures exceeding 600 psia.

3. The bleed rates that were determined varied from 0.037 to 0.101 for the single-shaft bleed system over the range of chamber pressure and system loss values considered. The corresponding variation for the two-shaft bleed system was from 0.027 to 0.076. The bleed rates determined using the values of chamber pressure and system loss (600 psia and 400 psi, respectively) that are felt to be typical of a contemporary engine of this type were 0.057 for the single-shaft system and 0.043 for the two-shaft configuration.

4. A combined bleed and topping feed system was examined for a chamber pressure of 800 psia and a system loss of 450 psi. For the example point, where the topping turbine developed 75 percent of the total pump work, the combined system required a bleed rate of 0.029. The corresponding bleed rates for pure bleed systems at these same operating conditions were 0.0725 for a single-shaft configuration and 0.054 for a two-shaft arrangement.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 2, 1964.

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