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EFFECT OF TIP CLEARANCE ON PERFORMANCE OF SMALL AXIAL HYDRAULIC TURBINE

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16. Abstract

The first two stages of a six-stage liquid oxygen turbine were tested in water. One- and two-stage performance was determined for one shrouded and two unshrouded blade-end configurations over ranges of clearance and blade-jet speed ratio. First-stage, two-stage, and second-stage efficiencies are included and also the effect of clearance on mass flow for two-stage operation.

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EFFECT OF TIP CLEARANCE ON PERFORMANCE OF SMALL AXIAL HYDRAULIC TURBINE

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SUMMARY

The effect of tip clearance configuration on the performance of the low pressure oxygen turbopump turbine of the Space Shuttle main engine was determined over ranges of clearance up to 8 percent of passage height. The turbine, designed to operate in liquid oxygen, was tested in water with three kinds of tip clearance configurations. These were shrouded blade ends, unshrouded stator and rotor blades of full passage height with clearances recessed in the rotor hub, and outer wall (engine configuration) and unshrouded blade ends projecting into the recessed clearance space. The first and second stages of the six-stage turbine were used in the test program.

Shrouded blading produced the highest efficiency near design clearance and design operation, but differences among the three configurations were small. Efficiency of the second, or repeating, stage was about 10 points lower than that of the first, 0.71 compared to 0.81, because the second stator had end clearance and high reaction. For each percent increase in clearance the first-stage efficiency decreased by 1.2 percent and the second-stage efficiency decreased 4.1 percent.

Flow increased approximately 1.6 percent for each 1 percent clearance for all one- and two-stage configurations tested.

INTRODUCTION

Early studies associated with the Space Shuttle main engine (SSME) included preliminary turbopump component designs. The low pressure oxygen turbopump (LPOT) turbine design included six axial stages with liquid oxygen as the working fluid. The rotor

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*Rocketdyne, Canoga Park, California.

blades and all stator blades except those in the first stage were unshrouded. The stationary wall over the rotor blade tips and the rotating hub under the stator blades were smooth, with running clearance in the active flow path. This led to some concern over possible excessive clearance losses. The single-stage gas turbine tip clearance study reported in reference 1 showed that two other kinds of tip clearance geometry resulted in lower losses and also lower sensitivity to changes in the tip clearance gap. Both included blades of full flow-passage height, one shrouded and the other unshrouded with running clearance recessed in the outer wall. Another investigation, reported in reference 2, reported generally that satisfactory performance was obtained in a multistage axial-flow hydraulic turbine with shrouded blade ends.

A turbine performance study that would include shrouded blade ends and also unshrouded blades with running clearance recessed in the outer wall was requested by NASA. Three configurations were defined by the contractor, Rocketdyne Division of Rockwell International Corporation, for this study - one shrouded and two unshrouded. One of the unshrouded configurations was designated the engine configuration. This had unshrouded blades of full passage height and a design running clearance of 2.5 percent of blade height. The initially proposed configuration with running clearance in the flow path was not included. Each of the three types selected was built with enough parts to permit one- and two-stage testing with nominal clearances of 3.0, 5.5, and 8.0 percent of flow passage height; a total of 18 combinations.

The 18 configurations were run in a water test facility at the contractor's plant. Each was tested over a range of blade-jet-speed ratios to determine effects of clearance type and magnitude on efficiency and flow. The work was performed under contract NAS 3-18545.

This report includes descriptions of the turbine, test equipment, and procedures and test results. Efficiency is shown as a function of blade-jet-speed ratio for each configuration and as a function of clearance at design blade-jet-speed ratio. The effect of clearance on flow at design blade-jet-speed ratio is also shown.

TURBINE DESCRIPTION

The SSME low pressure oxygen turbopump shown in figure 1 is driven by a 15.2-centimeter mean diameter, six-stage axial hydraulic turbine producing 1329 kilowatts at 5500 rpm using a liquid oxygen flow of 73.6 kilograms per second with a 3000 newton per square centimeter pressure drop at 106 K. Turbine design data are summarized in table I. A velocity vector diagram for the first two stages is shown in figure 2. The velocity diagrams represent free stream flow with no blade-end clearance effects. Mass-averaged fluid velocity vectors would be somewhat smaller. Stage geometry is identical for five of the six stages with constant blade profiles from hub to tip to reduce fabrication cost. The first-stage nozzle has an axial inlet velocity, enclosed vanes (no tip leakage), and fewer vanes to provide thicker sections for casting. It also had a larger flow area to accommodate the thrust seal leakage that occurs downstream of the first nozzle. The first-stage rotor is identical to that of the other five stages. The average stage design reaction R is 18 percent. Design tip clearance for the unshrouded nozzles and rotors in the engine configuration was 2.5 percent of the blade height. The first rotor passage height is slightly greater than that of the first stator, 0.904 centimeter compared to 0.864 centimeter (see fig. 3(a)). All subsequent flow passages are 0.904 centimeter in height. The rotor blade-shroud running clearance is recessed in the shroud and the stator blade-hub clearance is recessed in the rotor hub. Major blade dimensions are given in table II. All stages after the first are identical. A description of the complete turbopump system for the SSME is presented in reference 3.

The three tip clearance configurations studied in this investigation are shown in figure 3. The engine configuration described previously is shown in figure 3(a)). Figure 3(b) shows full shrouds for both stator and rotor blade rows with two seal rings on each. The final configuration (fig. 3(c)) is unshrouded but with all blades but those of the first stator projecting 0.038 centimeter beyond the active flow passage. This is slightly more than 4 percent of the passage height. Blade profiles are shown in figure 4.

Each of the tip-clearance geometries shown in figure 3 was run with clearances that were nominally 3.0, 5.5, and 8.0 percent of the flow passage height. The changes were effected by changing the stationary shroud rings over the rotor and the rotating hub rings under the stator blades. All blade hardware tested is shown in figure 5.

APPARATUS, INSTRUMENTATION, AND PROCEDURE

Turbine Test Rig

The hydraulic turbine test facility shown schematically in figure 6 is a full size model of the first two stages of the SSME LPOT hydraulic turbine. Water was the test turbine working fluid. Turbine design characteristics in water at design blade-jet-speed ratio are shown in table III along with the corresponding liquid oxygen numbers for first-stage and two-stage operation. Corresponding velocity vector diagrams are shown in figure 2 as noted in turbine description. Evaluation of the turbopump turbine inlet manifold, discharge collector, and thrust seal were not included. The tester could be operated with the first stage alone and with two stages. It was designed to accept the design unshrouded blading (fig. 3(a)) as well as configurations of shrouded and overlapped blade end configurations (figs. 3(b) and (c)). The test rig was designed to test blade end clearances of 3.0, 5.5, and 8.0 percent of the blade height for each blade end configuration. The clearance was varied by changing clearance ring diameters.

Mechanical features of the tester include O-ring seals to prevent internal leakage in the turbine and a carbon face seal and labyrinth shaft seal to prevent water leakage into the bearing cavity. Two ball bearings carry the turbine thrust load using an enclosed neoprene pad to equalize the load between the bearings. Changing the turbine blading configuration required only the removal of the bolts outside the blading and the exhaust duct elbow.

The turbine was tested in the Rocketdyne Engineering Development Laboratory Rotary Test and Medium Flow Facilities in Canoga Park, California. The test facility provides filtered water from the Medium Flow Facility to the turbine at approximately 0.05 cubic meter per second and at a 400 newton per square centimeter absolute turbine inlet pressure through a pump-fed, closed-loop system from a 40 cubic meter pool. The General Electric model 42G 124, type TLF-2554M, dc dynamometer, which is rated at 223 kilowatts and 6000 rpm, absorbs turbine output power in the Rotary Test Facility. A schematic of the water flow system is shown in figure 6(a). The test section installed in the test facility is shown in figure 6(b).

INSTRUMENTATION

Torque was measured by a Tate-Emery Dynamometer Weighing System, type HFR, S/N 55/1223. Water flow rate was measured using a calibrated Cox, 10.16-centimeter (4-in.) turbine-type flowmeter. Temperature was measured at the tester inlet with a Rosemount model 153 total temperature probe. Locations of turbine pressure measurements are shown in figure 7. Each measurement was made using four-tap piezometer rings plumbed to 28-centimeter diameter, 270° sweep dial Heise gages. Turbine outlet total pressure was measured using four 3-millimeter shroud diameter Kiel probes positioned at the mean diameter in the predicted flow direction for each test velocity ratio. Readings of test parameters at steady-state conditions were hand tabulated.

TEST PROCEDURE

Each configuration was tested at five nominal stage velocity ratios (blade-jet-speed ratio): 0, 0.15, 0.30, 0.45, and 0.60. Test points were run by setting the facility water flow near the facility maximum and adjusting turbine speed for the measured turbine pressure drop to give the desired test point stage velocity ratio. The directions of the turbine outlet total pressure Kiel probes were adjusted to the predicted rotor outlet angle for the test point stage velocity ratio. Test measurements were simultaneously hand recorded after all measurements had stabilized.

A total of 18 configurations were tested and are tabulated with the measured tip clearance in table IV.

Test Data Analysis

The turbine blading power for performance calculations was the sum of the turbine measured power and the facility calibration power. Facility calibration power represents disk friction and mechanical losses. Facility calibration power was determined experimentally prior to turbine testing. The tester with a bladeless rotor was motored by the dynamometer at 1000 rpm steps to 6000 rpm with the tester full of water. The motoring torque was measured and the resulting facility power for the test speed was added to the turbine test power to determine the turbine blading power.

The turbine inlet total pressure p'_{in} was determined from the measured static pressure immediately upstream of the nozzle (four tap piezometer ring) and the velocity head pressure calculated from the measured flow rate and the cross section area at the static pressure measurement. The water volume flow Q was measured upstream of the turbine with a turbine flowmeter. Tester inlet total temperature T'_{in} was measured at the tester inlet. Turbine nozzle inlet total pressure p'_{in} was calculated using the following equations:

$$p'_{in} = p_{in} + \frac{\rho_{in} V_{in}^2}{20\,000}$$

$$V_{in} = \frac{Q}{A_{in}}$$

where ρ_{in} is the water density at measured inlet temperature and A_{in} the nozzle inlet annulus area (0.004124 m^2 for the tester).

Turbine outlet total pressure p'_{out} was measured downstream of the last rotor with four Kiel total pressure probes positioned in the predicted outlet flow direction for the test condition and connected in a piezometer ring. Turbine available power was determined from measured volume flow rate and total pressure drop:

$$P_a = 10\, Q\, \Delta p'$$

Turbine test power was determined from the measured dynamometer torque γ and speed N:

$$P_D = \frac{2\pi\gamma N}{60\ 000}$$

Turbine blading power was the sum of the measured dynamometer power and facility calibration power at the test speed:

$$P_B = P_D + P_F$$

Turbine total-to-total state efficiency is the blading output power divided by the available power:

$$\eta = \frac{P_B}{P_a}$$

Efficiency was analyzed as a function of test-stage velocity ratio (U_m/C_o stage). The average stage isentropic velocity is determined from the turbine total pressure drop, number of stages, and inlet density:

$$C_{o,stg} = 100\sqrt{\frac{2\ \Delta p'}{\rho_{in}\ n}} \qquad (m/sec)$$

Turbine test-stage flow parameter $\left(W/A_N\sqrt{\rho_{in}\ \Delta p'_{stg}}\right)$ was calculated on a stage basis from measured volume flow rate, total pressure drop, number of stages, and inlet density:

$$\frac{w}{A_N\sqrt{\rho_{in}\ \Delta p'_{stg}}} = \frac{Q\rho_{in}}{A_N\sqrt{\dfrac{\rho_{in}(p'_{in} - p'_{out})}{n}}}$$

Second-stage efficiency was determined by inference from one- and two-stage performance. Efficiency was calculated for all two-stage test points by the contractor using an estimated pressure drop distribution. Subsequently, several of these efficiency values were checked with an alternate method using measured interstage static pressures and a total pressure calculated with continuity and the assumption that the relative velocity vector angle was constant at the design angle. All but one of the eight efficiencies checked agreed within one point. The eighth point differed by two points in efficiency. The efficiencies calculated by the contractor using the first method were therefore considered valid and are used in this report.

The assumed relation between liquid oxygen performance and water performance is discussed in appendix B. The conversion of water test results to the liquid oxygen equivalents is described.

RESULTS AND DISCUSSION

The first two stages of a six-stage liquid oxygen turbine were tested in water to determine the effects of tip clearance on efficiency and flow. The 18 configurations evaluated are listed in table IV. Measurements included flow, speed, and torque.

Efficiency

Figure 8 shows efficiency of the first stage plotted as a function of blade-jet-speed ratio. Each of the three kinds of tip clearance is included with nominal clearances of 3.0, 5.5, and 8.0 percent passage height for each. Stage efficiency decreased with increasing clearance in all three cases. Highest efficiency at the design blade-jet-speed ratio of 0.471 was obtained with the shrouded blade ends (fig. 8(b)). The 3.0-percent clearance curve indicates a stage efficiency of 0.814 at that point. This is appreciably higher than the design value of 0.704. Corresponding efficiencies for the unshrouded engine configuration (fig. 8(a)) and the unshrouded overlap configuration (fig. 8(c)) were 0.798 and 0.790, respectively. In all cases efficiency continues to rise with increasing blade-jet-speed ratio because the design value of blade-jet-speed ratio was somewhat lower than the optimum.

Efficiencies for the nine two-stage configurations are shown in figure 9, again plotted as functions of average stage blade-jet-speed ratio. In all cases efficiencies are lower than the corresponding first-stage efficiencies because the second stator has hub running clearance and much higher reaction than the rotors, thus incurring higher losses. The shrouded configuration with the smallest running clearance again showed the highest efficiency at the design blade-jet-speed ratio. It was 0.762 compared to 0.753 and 0.747 for the engine and overlap configurations, respectively.

Figure 10 shows second-stage efficiency as inferred from first- and two-stage performance. At the design blade-jet-speed ratio of 0.465 and minimum clearance the efficiencies were 0.710, 0.710, and 0.669 for the unshrouded, shrouded, and overlap configurations, respectively. The efficiencies are significantly lower than those of the first stage because of the aforementioned losses associated with the running clearance and high reaction in the second stator. The differences resulting from the use of the three kinds of clearance, however, are quite small. The first- and second-stage efficiencies indicate that the six-stage turbine will have an overall total efficiency of 0.717 at design blade-jet-speed ratio and 3-percent clearance. This estimate was made with the assumption that the repeating stages, two through six, would have identical performance. This estimated efficiency is appreciably higher than the design average stage efficiency of 0.682.

Efficiencies at design blade-jet-speed ratios were taken from figures 8 to 10 and crossplotted against clearance in figure 11. The curves indicate that little difference results from using the three kinds of clearance, and again the significantly lower efficiency in the second stage. Figure 12 shows the incremental change in efficiency with clearance referenced to the efficiency determined at a clearance ratio of 3 percent. Sensitivity of efficiency to clearance did not vary appreciably from configuration to configuration. In the first stage the average change was approximately 1.2 percent in efficiency lost for 1 percent increase in clearance. The two-stage average change was much larger, about 2.7 percent in efficiency lost for 1 percent in clearance. This, of course, results from the very high sensitivity to clearance change in the second stage where two running clearances (stator and rotor) are involved. Figure 12(c) shows that the second-stage efficiency dropped 4.1 percent for each percent increase in clearance.

The small differences in efficiency with configuration may be attributed to the fact that each had approximately the same working blade height. In the single-stage gas turbine investigation of reference 1 one of the configurations had a flow passage of constant height through the rotor. Running tip clearance was obtained through removal of blade material, making the blade height smaller than the flow passage height and reducing the working blade height. Increasing running clearance reduced efficiency by significantly increasing the amount of fluid bypassing the rotor blades as well as unloading the blades in the tip region. That reference indicates a lesser effect of clearance when working blade height is maintained. One significant difference between the results of the reference and subject investigations did exist. The reference work indicated an efficiency loss of 0.3 percent for each percent increase in clearance for the shrouded configuration and 0.9 percent for the unshrouded blading of full passage height. The hydraulic turbine first-stage results showed approximately -1:1 for both. Fluid pumping power in the clearance space of a shrouded hydraulic turbine is apparently greater than in a shrouded gas turbine.

Mass Flow

The variation in two-stage flow parameter with configuration and clearance at design blade-jet-speed ratio is shown in figure 13. The values shown were calculated by the contractor using a net flow area derived from the measured rectangular passage flow area, the throat fillet blockage, and the calculated boundary layer blockage. Trends for the three configurations are about the same, but the unshrouded overlap blading passed 2 to 3 percent more mass flow. This occurred because the overlapped blading had a slightly higher effective flow area in the flow passages of the last three blade rows. The pressure drops through those blade rows were therefore somewhat smaller than in the other configurations, producing a lower pressure and higher flow rate and velocity at the throat of the first stator.

The curves in figure 14 show that the ratio of flow increase to clearance increase was almost constant at 1.6:1 for all three two-stage configurations over the entire range of clearance ratios.

SUMMARY OF RESULTS

Three tip clearance configurations were investigated experimentally in a small axial hydraulic turbine to determine the effect of clearance on efficiency and flow.

The major results of the investigation may be stated briefly as follows:

1. The shrouded blades provided the highest efficiency at design clearance and design operation but the maximum efficiency variation among the three configurations was only 0.024 in the first stage and 0.011 in the second.

2. Efficiency of the first stage was 0.814, which is substantially higher than the design value of 0.704.

3. The first- and second-stage efficiencies indicate that the six-stage turbine will have an overall blading total efficiency of 0.717 at design blade-jet-speed ratio and 3-percent clearance.

4. Efficiency of the second stage was, for each configuration, about 10 points lower than that of the first, 0.71 compared to 0.81, at design clearance and blade-jet-speed ratio.

5. The reductions in efficiency with each percent increase in tip clearance were approximately 1.2 percent in the first stage and 4.1 percent in the second or repeating stage.

6. The ratio of flow increase to clearance increase was approximately 1.6:1 for all two-stage configurations over the entire range of clearance investigated.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 14, 1975,
505-04.

APPENDIX A

SYMBOLS

A	flow area, m^2 (ft^2)
CL	blade radial tip clearance, cm (in.)
C_o	jet speed based on total pressures, $C_o = 100\sqrt{2\ \Delta p'/\rho}$, m/sec (ft/sec)
L	blade height, cm (in.)
N	turbine speed, rev/min
n	number of stages
P	turbine power, kW (hp)
p	pressure, N/cm^2 ($lb/in.^2$)
Q	volume flow rate, m^3/sec (gal/sec)
R	stage reaction defined as ratio of kinetic energy increase in rotor to stage specific work
U	blade speed, m/sec (ft/sec)
V	velocity, m/sec (ft/sec)
w	mass flow rate, kg/sec (lb/sec)
γ	torque, N-m (ft-lb)
η_{stg}	stage total-to-total efficiency for turbine stages specified
ρ	turbine working fluid density, kg/m^3 (lb/ft^3)

Subscripts:

a	available or ideal
B	blading
D	dynamometer
F	facility mechanical and fluid friction losses
h	hub
in	inlet
m	mean
N	nozzle throat
out	outlet

stg	stage
t	tip
1	first stator inlet
2	first stator outlet
3	first rotor outlet
4	second stator outlet
5	second rotor outlet

Superscript:

'	total condition

APPENDIX B

CONVERSION OF LPOT TEST RESULTS FROM WATER TO LIQUID OXYGEN WORKING FLUID

The water test data were reduced to the turbine parameters of blading efficiency and stage flow parameter. The water test map parameters were converted to liquid oxygen (LOX) operation for comparison with the predicted performance.

The water test blading efficiency was converted to LOX performance using the Reynolds number correction curve in reference 4. The Reynolds number for the two-stage test turbine in water at the design stage velocity ratio test condition is 5.52×10^{6}. The LOX design Reynolds number is 4.15×10^{7}. The water test efficiency at the design velocity ratio was converted to LOX performance by multiplying by 1.0180 which was determined from the reference.

The representative nozzle flow area in the turbine stage flow parameter is for the particular turbine and operating condition. This area is determined from the ambient measured rectangular nozzle throat area, which is reduced by the thermal change from ambient to operating temperature minus the throat fillet area and the calculated design boundary layer at the throat. The tester nozzle throat flow area was determined as described previously using the measured tester area and design water operation. The resulting water test flow parameter applies directly for operation in LOX with the representative LOX nozzle flow area.

REFERENCES

1. Kofskey, Milton G.: Experimental Investigation of Three Tip-Clearance Configurations Over a Range of Tip Clearance Using a Single-Stage Turbine of High Hub-to-Tip Radius Ratio. NASA TM X-472, 1961.
2. King, J. A.; and Farrell, E. C.: The Transient Performance of a Hydraulic-Turbine-Driven Inducer: Computer Predictions and Test Verification. (R-7747, Rocketdyne, North American Rockwell Corp; NAS3-10280.), NASA CR-72518, 1969.
3. Rothe, K.: Turbopump Configuration Selection for the Space Shuttle Main Engine. ASME Paper 74-FE-23, May 1974.
4. Binsley, R. L.; and Balje, O. E.: Axial Turbine Performance Evaluations. II. ASME Paper 68-GT-14, Mar. 1968.

TABLE I. - SIX-STAGE TURBINE DESIGN

NUMBERS USING LIQUID OXYGEN

Flow rate, kg/sec (lb/sec)	73.6 (162.3)
Speed, rpm	5500
Mean diameter, cm (in.)	15.166 (5.971)
Inlet temperature, K (^{o}R)	106 (191.0)
Inlet total pressure, N/cm^2 (psia)	3325 (4822)
Inlet density, kg/m^3 (lb/ft^3)	1133 (70.76)
Total pressure drop, N/cm^2 (psi)	3000 (4349)
Power, kW (hp)	1329 (1782)
Stage total efficiency	0.682
Stage blade-jet-speed ratio, U_m/C_o	0.467

TABLE II. - TURBINE BLADE CHARACTERISTICS

[Average mean diameter constant for all blade rows at 15.20 cm (5.984 in.); all dimensions at water test temperature.]

	First stator	First rotor	Second stator	Second rotor
Number of blades	43	67	61	67
Passage height, cm (in.)	0.864 (0.340)	0.904 (0.356)	0.904 (0.356)	0.904 (0.356)
Axial chord, cm (in.)	1.153 (0.454)	0.889 (0.350)	0.889 (0.350)	0.889 (0.350)
Aspect ratio	0.75	1.02	1.02	1.02
Solidity based on axial chord	1.04	1.25	1.14	1.25
Leading edge radius, cm (in.)	0.056 (0.022)	0.023 (0.009)	0.041 (0.016)	0.023 (0.009)
Trailing edge radius, cm (in.)	0.023 (0.009)	0.013 (0.005)	0.013 (0.005)	0.013 (0.005)

TABLE III. - DESIGN OPERATING CONDITIONS

	First stage		Two stages	
	Engine	Test	Engine	Test
Fluid	Liquid oxygen	Water	Liquid oxygen	Water
Flow rate, kg/sec (lb/sec)	73.6 (162.3)	45.4 (100)	73.6 (162.3)	45.4 (100)
Speed, rpm	5500	[a]3600	5500	[a]3370
Mean diameter, cm (in.)	15.166 (5.971)	15.199 (5.984)	15.166 (5.971)	15.199 (5.984)
Inlet temperature, K (^{o}R)	106 (191)	294 (530)	106 (191)	294 (530)
Inlet total pressure, N/cm^2 (psia)	3325 (4822)	[a]241 (350)	3325 (4822)	[a]372 (540)
Inlet density, kg/m^3 (lb/ft^3)	1133 (70.76)	1000 (62.4)	1133 (70.76)	1000 (62.4)
Total pressure drop, N/cm^2 (psi)	488 (708)	[a]186 (270)	983.8 (1426.9)	[a]324 (470)
Power, kW (hp)	223.2 (299.3)	62.6 (83.9)	438.6 (588.2)	125.0 (167.6)
Stage total efficiency	0.704	0.691	0.686	0.674
Stage blade-jet-speed ratio, U/C_o	0.471	0.471	0.469	0.469

[a]Nominal in test series.

TABLE IV. - CONFIGURATIONS TESTED

Configu- ration	Turbine staging	Tip con- figuration	Average clearance, CL/L, percent	Measured radial clearance		
				First rotor	Second nozzle	Second rotor
1	First stage	Shrouded	8.1	0.0729	------	------
2	Two stages		8.1	.0754	0.0711	0.0724
3	First stage		5.9	.0533	------	------
4	Two stages		5.7	.0516	.0482	.0538
5	First stage		3.2	.0292	------	------
6	Two stages		3.1	.0264	.0272	.0300
7	First stage	Overlapped	9.3	.0838	------	------
8	Two stages		7.9	.0734	.0673	.0724
9	First stage		5.6	.0508	------	------
10	Two stages		5.3	.0495	.0445	.0500
11	First stage		3.1	.0279	------	------
12	Two stages		2.8	.0272	.0216	.0272
13	Two stages	Unshrouded	2.9	.0262	.0244	.0279
14	First stage		2.9	.0262	------	------
15	First stage		5.6	.0505	------	------
16	Two stages		5.5	.0505	.0465	.0521
17	First stage		8.3	.0752	------	------
18	Two stages		8.1	.0752	.0711	.0739

TABLE V. - MEASURED BLADE ELEMENT THROAT AREAS

AT WATER TEST TEMPERATURES

Tip configuration	Throat area, cm^2			
	First nozzle	First rotor	Second nozzle	Second rotor
Unshrouded	9.619	14.064	9.181	14.155
Shrouded	9.619	14.058	9.181	14.187
Overhung	9.619	14.677	9.594	14.684

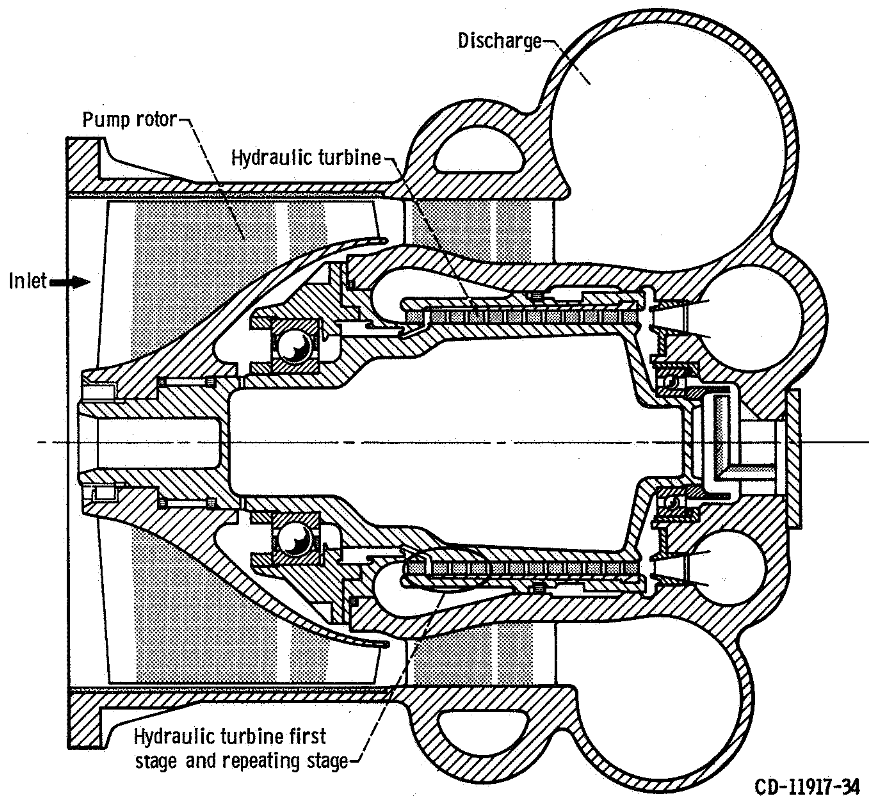
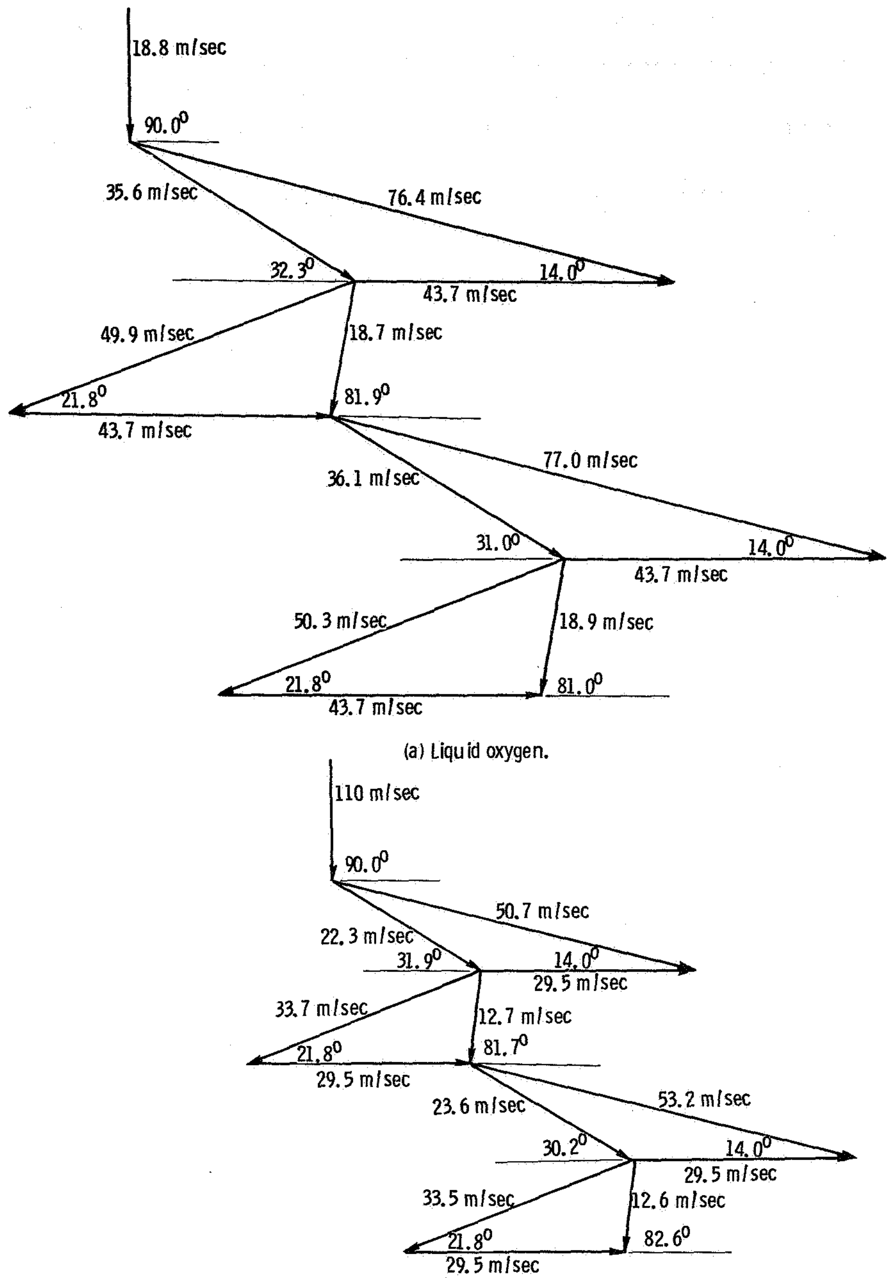


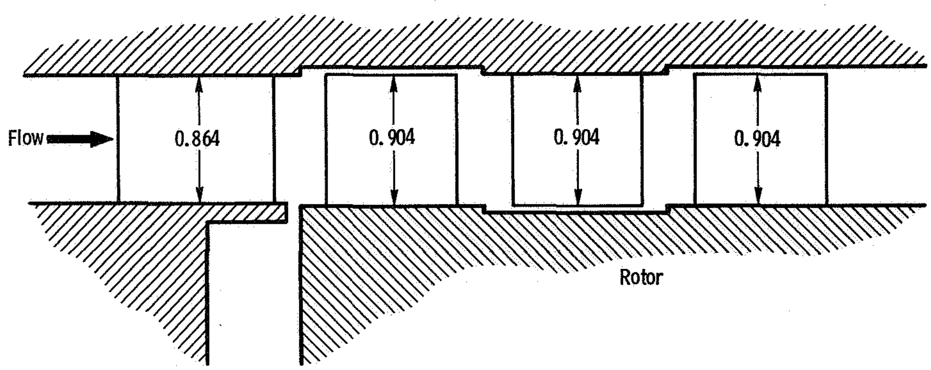
Figure 1. - SSME low-pressure oxidizer turbopump.



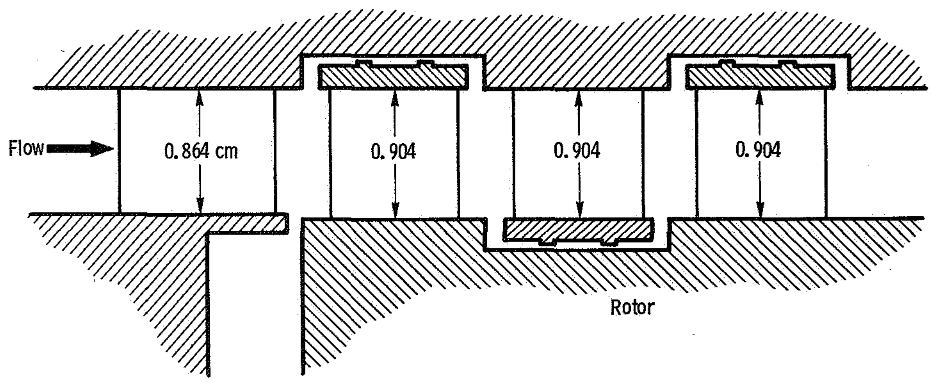
(a) Liquid oxygen.

(b) Water.

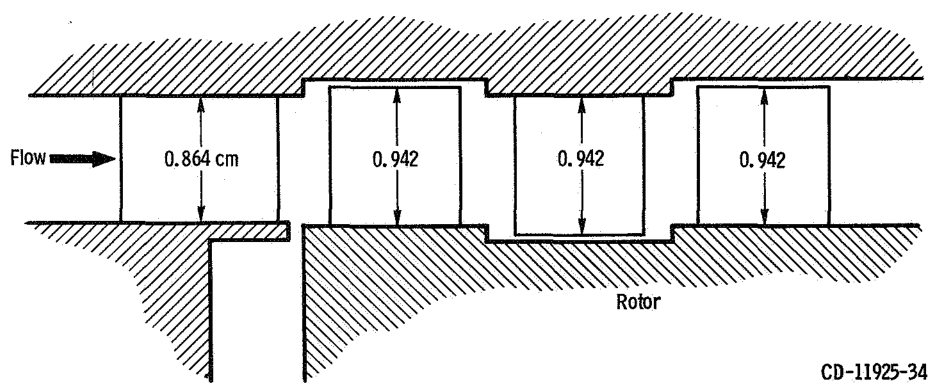
Figure 2. - Two-stage mean section velocity diagrams. Blade end clearance losses not included in vectors.



(a) Unshrouded blade ends - engine configuration.



(b) Shrouded blade ends.



(c) Unshrouded blade ends with 0.38 centimeter overlap.

Figure 3. - Turbine sections.

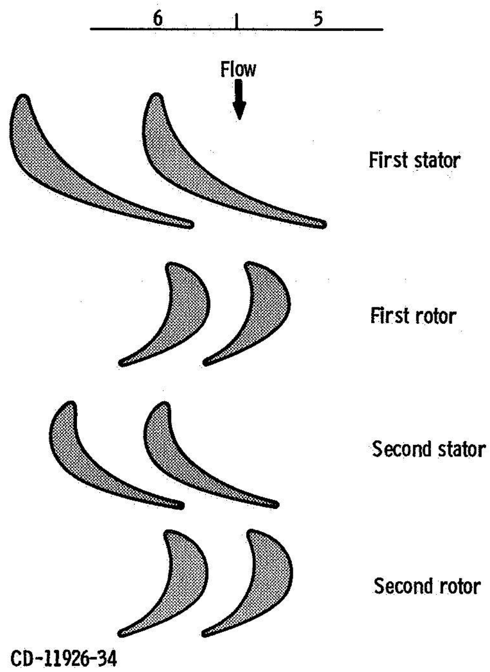


Figure 4. - Blade profiles.

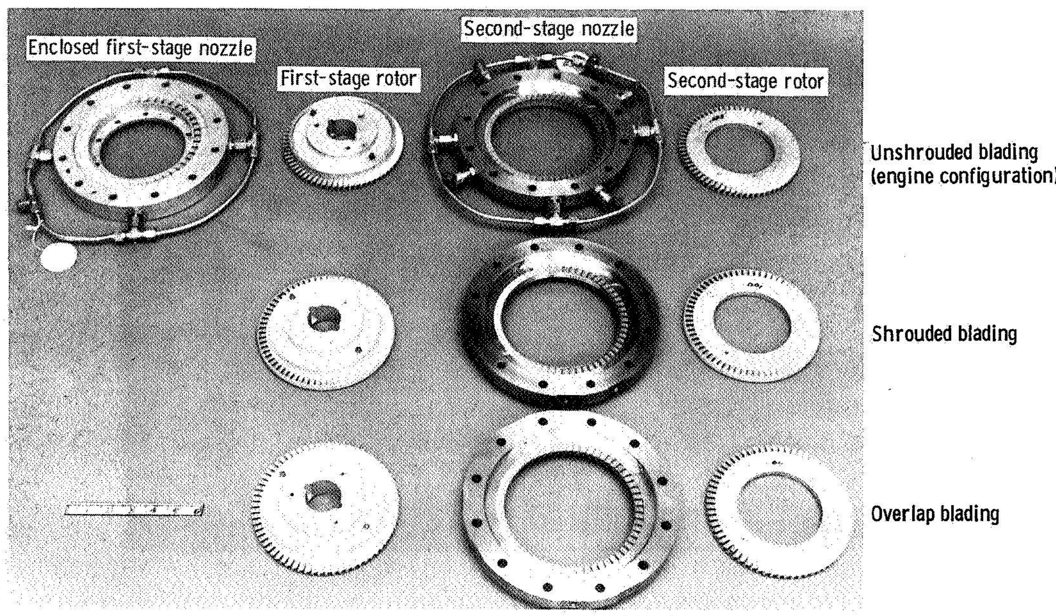
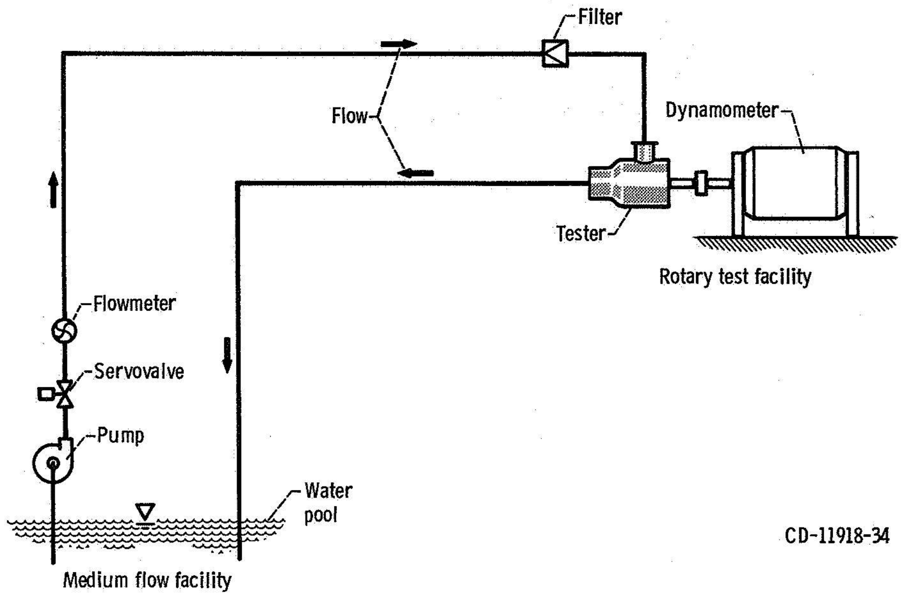
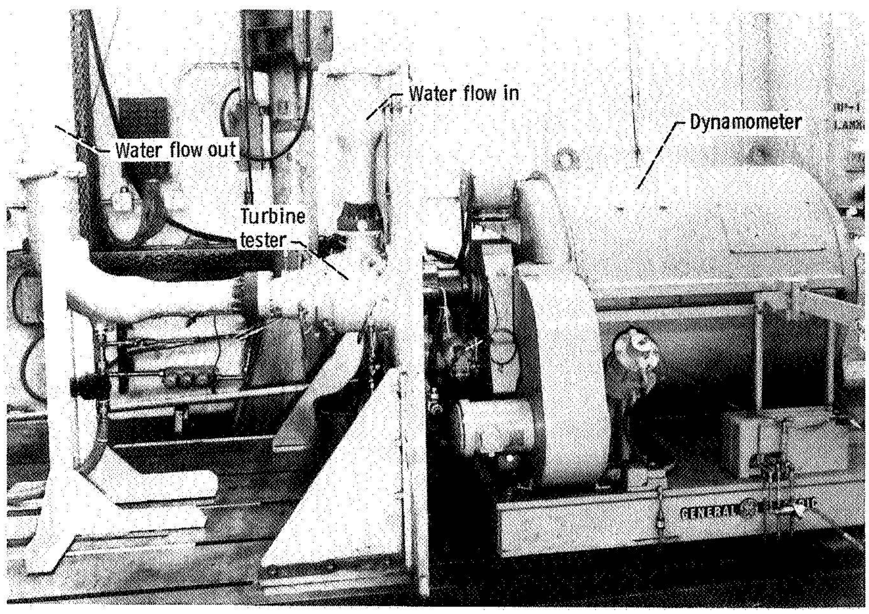


Figure 5. - Test blading.



(a) Flow schematic.



(b) Turbine tester.

Figure 6. - Hydraulic turbine test facility.

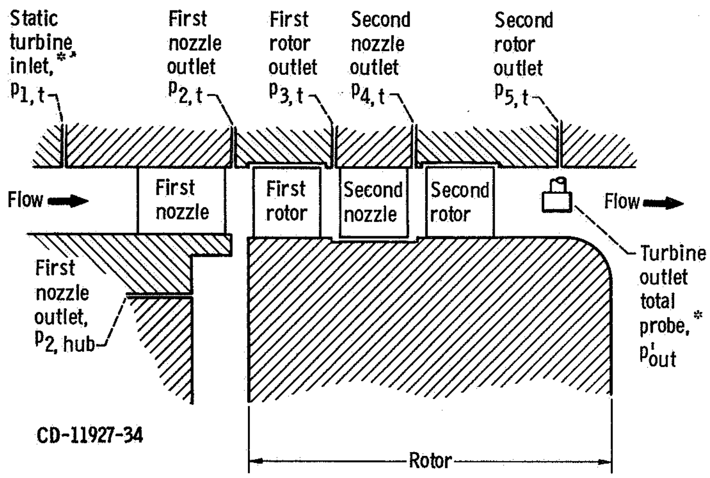
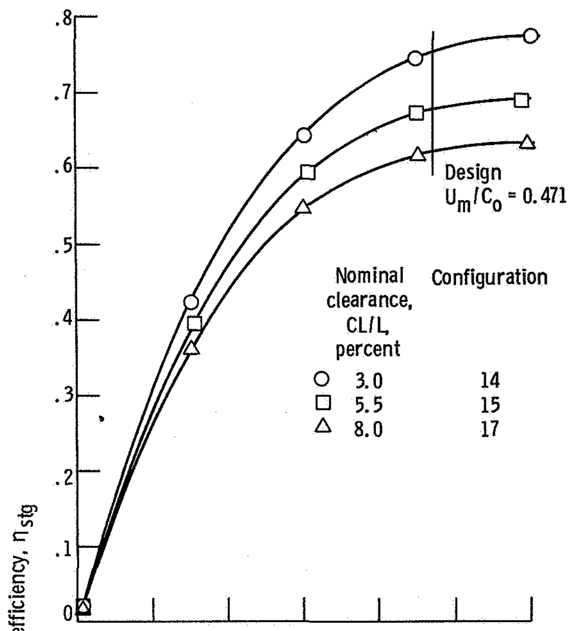
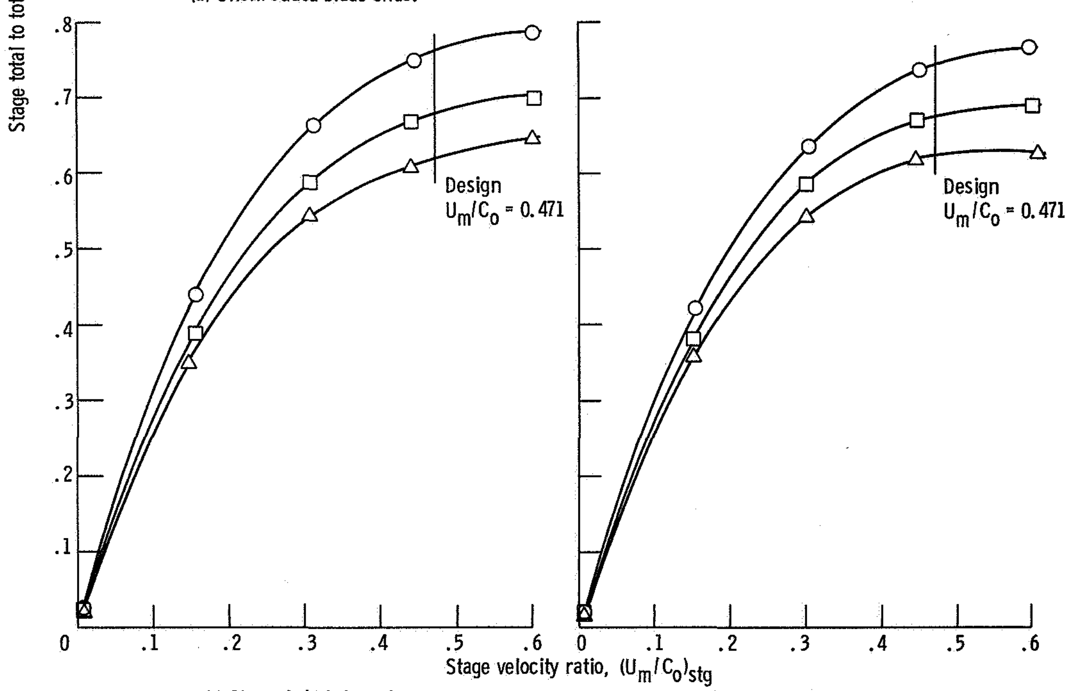


Figure 7. - Location of turbine pressure measurements. Each pressure measured with four tap piezometer ring. (Asterisk denotes primary performance instrumentation.)



(a) Unshrouded blade ends.



(b) Shrouded blade ends. (c) Overlapped blade ends.

Figure 8. - Effect of clearance on first-stage efficiency.

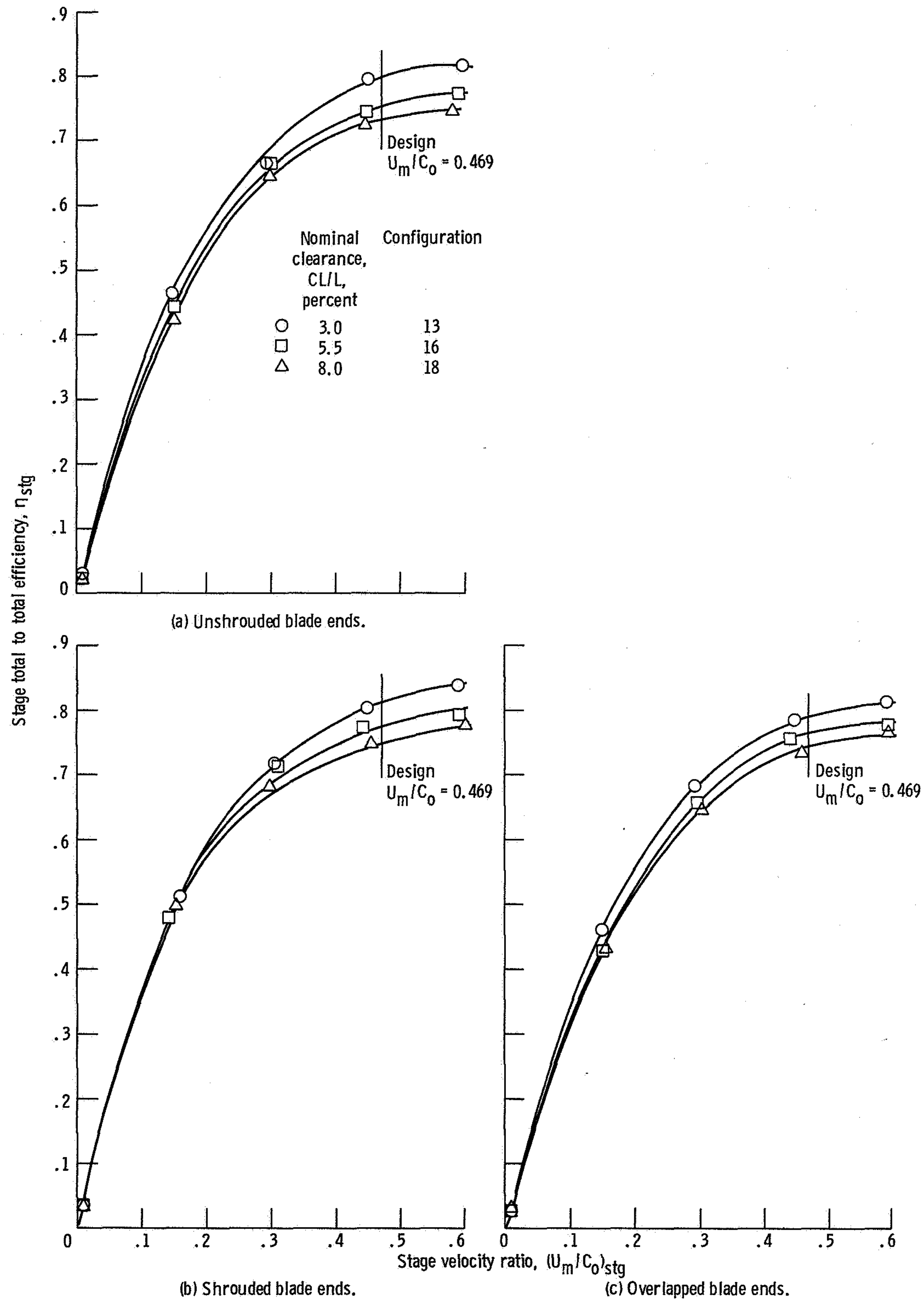


Figure 9. - Effect of clearance on two-stage efficiency.

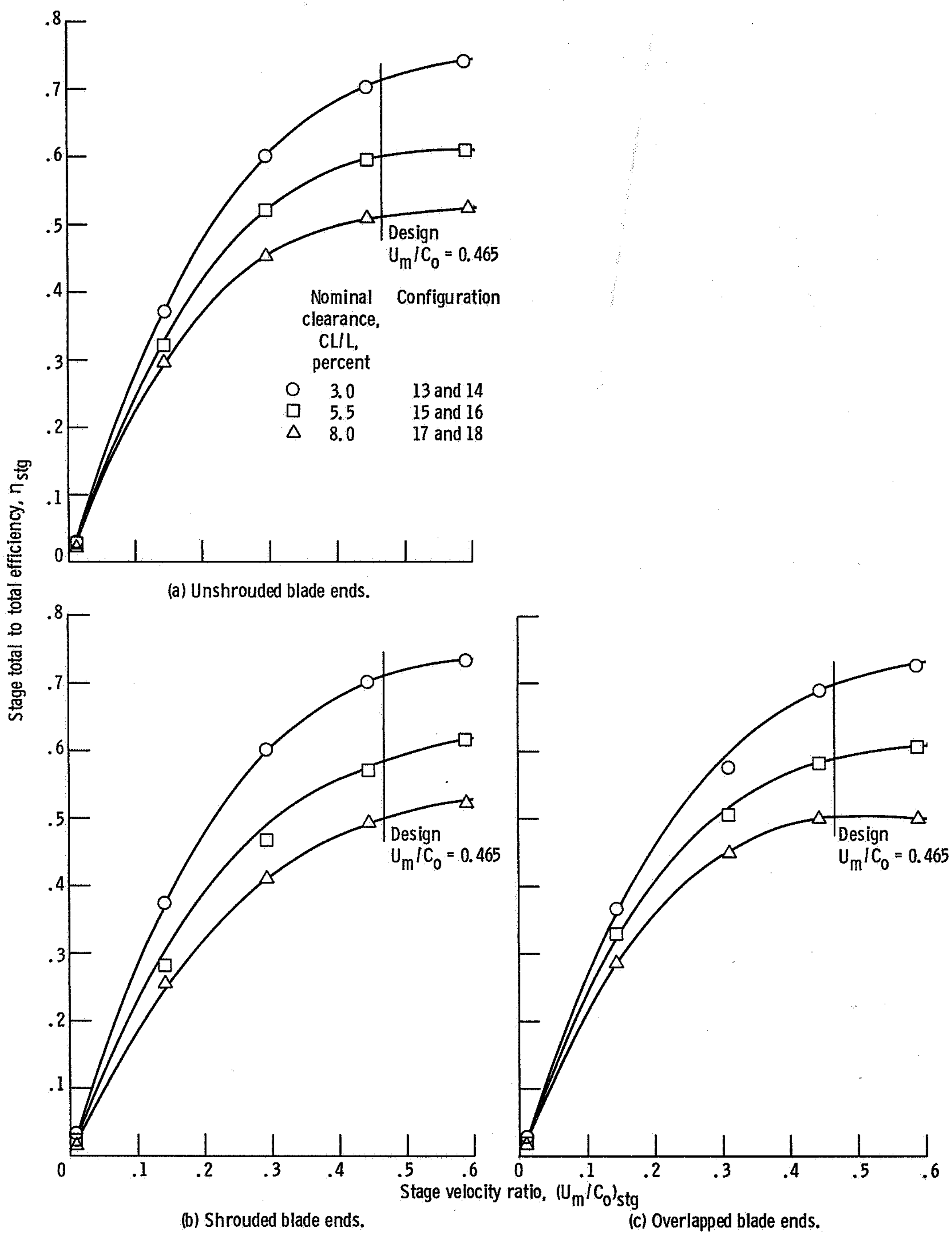


Figure 10. - Effect of clearance on second-stage performance.

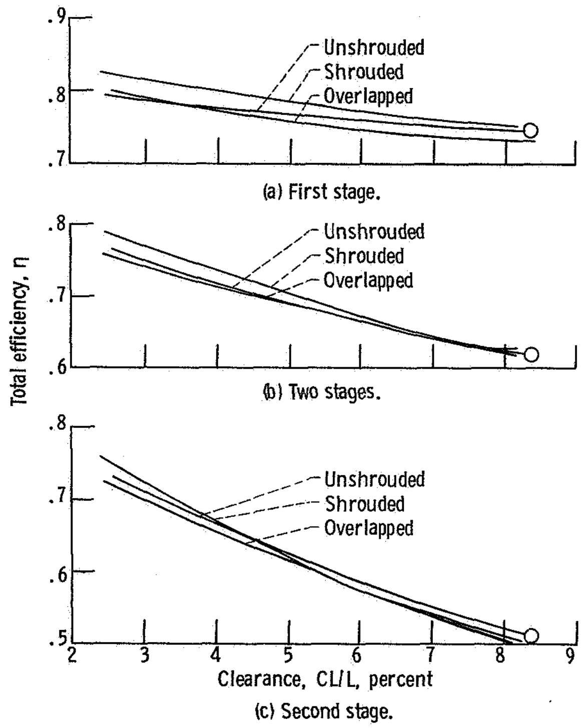


Figure 11. - Effect of clearance on efficiency at design blade-jet speed ratio.

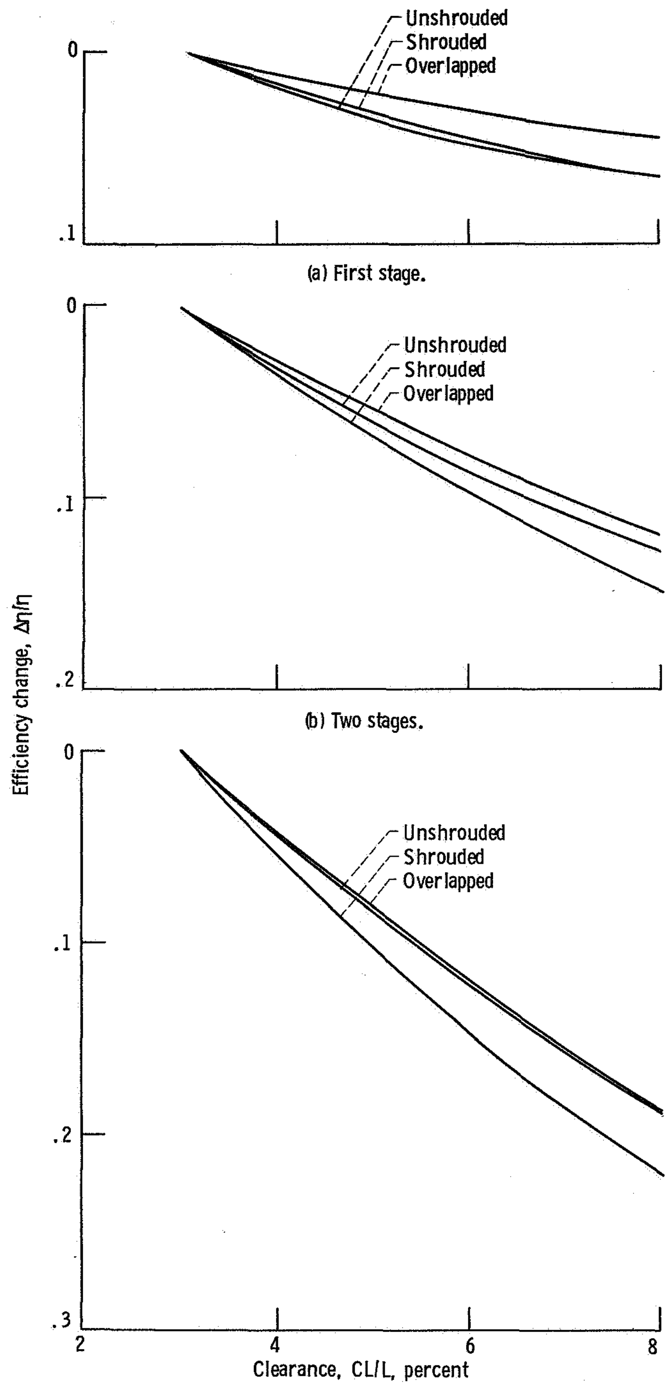


Figure 12. - Incremental effect of clearance on efficiency at design blade-jet-speed ratio.

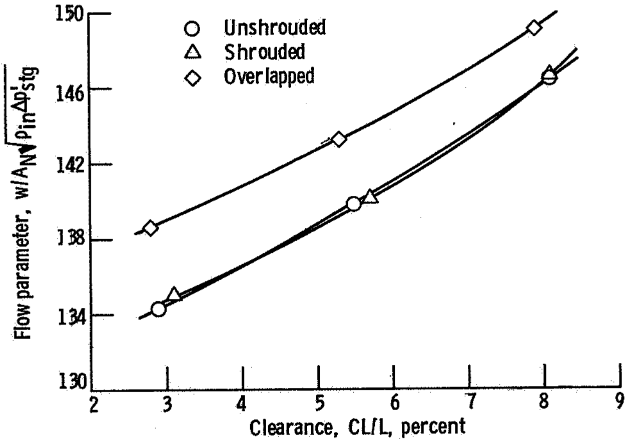


Figure 13. - Effect of clearance on two-stage flow parameter at design blade-jet-speed ratio.

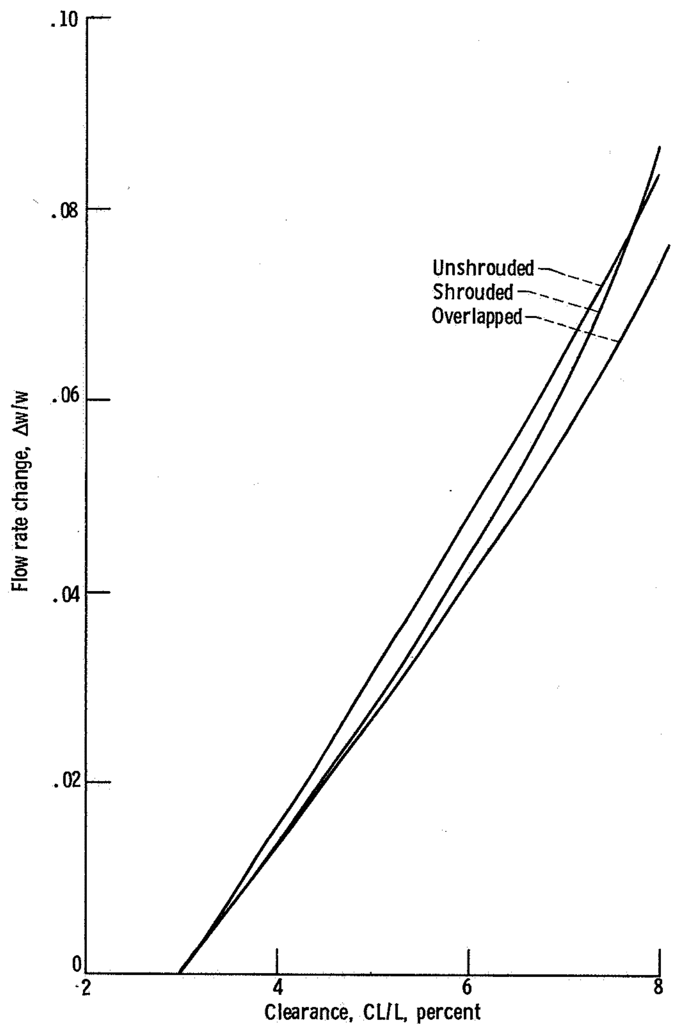


Figure 14. - Incremental change in two-stage flow with clearance at design blade-jet-speed ratio.

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