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RESEARCH MEMORANDUM

for the

Bureau of Ordnance, Navy Department

EFFECT OF TURBINE AXIAL NOZZLE-WHEEL CLEARANCE ON PERFORMANCE OF MARK 25 TORPEDO POWER PLANT

By Jack W. Hoyt and Harry Kottas

Flight Propulsion Research Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Investigations were made of the turbine from a Mark 25 torpedo to determine the performance of the unit with three different turbine nozzles at various axial nozzle-wheel clearances. Turbine efficiency with a reamed nondivergent nozzle that uses the axial clearance space for gas expansion was little affected by increasing the axial running clearance from 0.030 to 0.150 inch. Turbine efficiency with cast nozzles that expanded the gas inside the nozzle passage was found to be sensitive to increased axial nozzle-wheel clearance. A cast nozzle giving a turbine brake efficiency of 0.525 at an axial running clearance of 0.035 inch gave a brake efficiency of 0.475 when the clearance was increased to 0.095 inch for the same inlet-gas conditions and blade-jet speed ratio. If the basis for computing the isentropic power available to the turbine is the temperature inside the nozzle rather then the temperature in the inlet-gas pipe, an increase in turbine efficiency of about 0.01 is indicated.

INTRODUCTION

At the request of the Bureau of Ordnance, Navy Department, an investigation of the performance of a gas turbine from an aerial torpedo under steady-state conditions using different turbine nozzles is being conducted at the NACA Cleveland laboratory. Power-plant efficiencies with five different turbine-nozzle designs are reported in reference 1. The performance of a single-stage modification of the turbine and an analysis of the relative output of the first and second stages of the turbine is given in reference 2.

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The axial clearance between the nozzle and the wheel of an impulse turbine is usually made as small as possible in order to obtain the best performance from the turbine. The small axial nozzle-wheel clearances that may be maintained during a dynamometer-stand investigation of a turbine, however, are not always desirable in a power plant subjected to the distortions and vibrations accompanying rigorous service conditions. Aerial torpedos, in particular, are given a severe shock load on entering the water and ample clearances are needed in order to avoid rubbing between the nozzle and the wheel.

As the axial nozzle-wheel clearance is changed, the turbine efficiency may be affected. The proper clearance is thus a compromise between the safe clearance required by the application and the improvement in efficiency gained by making the clearance as small as possible.

An investigation with three different turbine nozzles was conducted to indicate the effect of axial nozzle-wheel clearance upon efficiency. In order to provide data for selecting the proper axial nozzle-wheel clearance, the turbine efficiency was determined at various known values of running clearance.

APPARATUS

The standard Mark 25 torpedo power plant is a two-stage counter-rotating impulse gas turbine of the partial-admission type with integral speed-reduction and power-equalizing gearing. The turbine, setup, and instrumentation are described in reference 1. No changes were made in the turbine except the substitution of carbon-ring oil seals for the standard labyrinth oil seals at the turbine bearings, which improved mechanical performance by reducing oil leakage without changing the thermodynamic performance of the unit.

Three different turbine-nozzle designs designated E, H(references 1 and 2), and I were selected for this investigation on the basis of ease of manufacture and good performance. All three nozzles are of the 90° nozzle-arc gas-admission type. For each nozzle, the axial nozzle-wheel clearance was varied by changing shims under the nozzle flange. Because of the high pressure ratios, the gas flow entering the turbine is supersonic relative to the turbine blades.

Nozzle E is a nondivergent reamed nozzle with rounded inlets to the nine cylindrical ports. Expansion of gas to supersonic velocity takes place in the clearance between the nozzle and the forward turbine blades. Nozzle H, produced by the precision lost-wax casting technique, has nine rectangular ports with sharp-edged inlets to the throats. Nozzles E and H are completely described in reference 1. Nozzle I is similar in design to nozzle H and cast 925 by the same technique but has slightly smaller ports to give a lower gas mass flow. The outlet face of nozzle I is shown in figure 1. The nine nozzle ports are rectangular and have sharp-edged inlets to the throats. This type of nozzle uses the entrance-jet contraction due to the sharp-edged port inlets to give the effect of a convergent-divergent nozzle.

Nozzle I was instrumented with an unshielded thermocouple placed just ahead of the inlets to the nozzle ports. The thermocouple was so arranged so as not to disturb the flow entering the nozzle ports. Two temperatures were taken on the nozzle walls opposite the unshielded gas-temperature thermocouple to allow a radiation-loss correction to be calculated for the unshielded thermocouple. Because of the low gas velocity in the region of the thermocouple, impact-recovery correction was neglected.

Radial nozzle settings, as well as the proper allowances for thermal changes in axial clearances, were made to conform with the recommendations of reference 1. Nozzle E was set at a radius of 5.283 inches from the turbine-shaft center line to the midpoint of the nozzle ports. Preliminary investigations revealed that the best radial setting for nozzle I was 5.258 inches from the turbine-shaft center line to the average midpoint of the nozzle ports. This value was also the best setting for nozzle H (reference 1).

PROCEDURE

At each axial nozzle-wheel clearance setting, the effect of pressure ratio and blade-jet speed ratio upon turbine efficiency was investigated. These investigations covered a range of axial running clearances from 0.030 to 0.150 inch, pressure ratios from 8 to 20, and turbine speeds from 6000 to 18,000 rpm with a constant inlet-gas temperature of 1000° F and a pressure of 95 pounds per square inch gage. Because of air-flow limitations, the maximum pressure ratio obtained with nozzle H was 19.

The effect of heat losses from the nozzle upon the power-plant performance was determined by instrumenting one turbine nozzle to give the inlet-gas temperature just upstream of the nozzle throats.

RESULTS AND DISCUSSION

The operating data for nozzles E, H, and I at various clearances
921 are given in tables I, II, and III, respectively.

The brake, wheel, and blade efficiencies were computed according to the method developed in reference 1. Brake efficiency is the ratio of the brake power calculated from the torque and speed at the dynamometer shaft to the isentropic power available; wheel efficiency is the ratio of the brake power plus the mechanical losses in the gears and the bearings to the isentropic power; and blade efficiency is the ratio of the brake power plus the mechanical losses and the disk- and blade-windage losses to the isentropic power.

Axial nozzle-wheel running clearance over a range of 0.030 to 0.150 inch had little effect upon the performance of the turbine with nozzle E (fig. 2); the curves of brake efficiency as a function of axial clearance for constant blade-jet speed ratios are very flat. Some improvement in brake efficiency was shown by increasing the axial running clearance to 0.050 inch, especially at lower blade-jet speed ratios, which indicates that adequate clearance is necessary with nondivergent nozzles such as E. As the clearance is increased, however, the effect of friction upon the jet from the nozzle becomes increasingly important, but only a slight loss in efficiency was occasioned by the use of large axial clearances.

The sharp-edged inlet nozzles (nozzle H) were more sensitive to axial-clearance variations than was the nondivergent nozzle, as shown in figure 3. At a blade-jet speed ratio of 0.20 and a pressure ratio of 15, the brake efficiency decreased from 0.525 at a 0.035-inch axial running clearance to 0.475 at a 0.095-inch axial clearance. Under the same conditions, the brake efficiency with nozzle I (fig. 4) changed from 0.505 at a 0.035-inch running clearance to 0.480 at a 0.095-inch clearance. Small axial clearances are therefore necessary to obtain the best turbine performance with the cast nozzles in which gas expansion takes place inside the nozzle passage.

The investigations with nozzles H and I substantiate the experience with convergent-divergent nozzles at the Massachusetts Institute of Technology (reference 3) where the turbine efficiency was also found to improve as the axial nozzle-wheel clearance was decreased. Comparison between values of axial clearances used in the present investigation and those in reference 3 is obscured because cooling water was sprayed on the outside of the M.I.T. unit, changing the thermal-expansion characteristics and hence the axial running clearance of that unit. The investigations of reference 1 were more representative of actual torpedo conditions in that no cooling was used. Also, changes in axial nozzle-wheel running clearances were measured with dial indicators as the turbine-inlet gas temperature was changed; thus an indication of the effect of thermal expansion on the axial clearance was given. As recommended in reference 1, the cold axial clearances were set in this investigation at 0.015 inch more than the desired running clearance to allow for the decrease in clearance due to thermal expansions at the inlet-gas temperature of 1000° F.

Mark 25 torpedos launched on the proofing range at the Naval Torpedo Station had liberal axial nozzle-wheel clearances. The cold axial nozzle-wheel clearances of 0.142 inch (reference 4) and 0.100 inch (reference 5) for turbines with convergent-divergent nozzles would be a contributing factor to reduced turbine performance.

A comparison of turbine efficiencies with nozzle I, calculated with the isentropic power based upon the temperature in the insulated inlet-gas pipe and isentropic power based upon the temperature inside the nozzle, is shown in figure 5. These data were obtained at inlet-gas conditions of 95 pounds per square inch gage and 1000° F at an axial nozzle-wheel running clearance of 0.035 inch. Data for nozzle I based upon the temperature inside the nozzle are given in table IV. The unshielded thermocouple mounted inside the nozzle was corrected for radiation by the method of reference 6, using the nozzle-wall temperatures taken opposite the thermocouple. The difference between the temperature in the inlet-gas pipe and the temperature inside the nozzle is mainly due to heat losses from the nozzle, the inlet-gas pipe being heavily insulated. Comparison shows that the efficiency computed from the temperature inside the nozzle is about 0.01 higher than that computed from the inlet-gas-pipe temperature (fig. 5). The use of the temperature inside the nozzle does not charge the turbine with a part of the heat losses from the nozzle, which are coincident with the normal operation of the turbine; yet it does more correctly indicate the performance of the nozzle-blade combination. The peak brake efficiency with nozzle I was obtained at an axial nozzle-wheel running clearance of 0.035 inch, a pressure ratio of 8, and a blade-jet speed ratio of 0.20 (fig. 5(a)). At these conditions, the brake efficiencies were 0.509 based on the temperature in the inlet-gas pipe and 0.517 based on the temperature inside the nozzle. At the peak brake efficiencies, the wheel efficiencies based on the temperature in the inlet-gas pipe and on the temperature inside the nozzle were approximately 0.540 and 0.550, respectively and the blade efficiencies based on the temperature in the inlet-gas pipe and on the temperature inside the nozzle were 0.572 and 0.582, respectively.

SUMMARY OF RESULTS

A Mark 25 torpedo power plant was investigated with three different turbine nozzles to determine the effect of axial nozzle-wheel clearance upon turbine performance. The following results were obtained at inlet-gas conditions of 95 pounds per square inch gage and 1000° F:

1. Axial nozzle-wheel running clearance over a range from 0.030 to 0.150 inch had little effect upon turbine efficiency when a nondivergent reamed nozzle was used.

2. Cast nozzles in which gas expansion takes place inside the nozzle passage were sensitive to the effects of axial nozzle-wheel running clearance. A cast nozzle giving a turbine brake efficiency of 0.525 at a pressure ratio of 15, blade-jet speed ratio of 0.20, and an axial nozzle-wheel running clearance of 0.035 inch, gave a brake efficiency of 0.475 when the axial nozzle-wheel running clearance was increased to 0.095 inch.

3. If the basis for computing isentropic power is the temperature inside the nozzle rather than the temperature in the inlet-gas pipe, an increase in turbine efficiency of about 0.01 is indicated.

Flight Propulsion Research Laboratory,
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TABLE I - SUMMARY OF EFFICIENCY DATA FOR MARK 25 POWER PLANT WITH NOZZLE E

AT VARIOUS AXIAL NOZZLE-WHEEL CLEARANCES

[Inlet-gas pressure, 95 lb/sq in. gage; inlet-gas temperature, 1000° F]

Pressure ratio	Axial nozzle-wheel running clearance (in.)	Air mass flow (lb/hr)	Fuel-air ratio	Horsepower available from isentropic expansion	Turbine speed (rpm)	Brake horsepower	Blade-jet speed ratio	Gas density in turbine case (lb/cu ft)	Brake efficiency	Wheel efficiency	Blade efficiency
8	0.030	974.3	0.0136	62.33	6,049	21.03	0.0981	0.0335	0.3374	0.3387	0.3534
		973.5		62.28	8,102	25.04	.1314	.0339	.4021	.4200	.4310
		973.5		62.28	10,105	27.31	.1638	.0339	.4385	.4624	.4825
		973.5		62.28	12,128	28.30	.1966	.0345	.4544	.4854	.5201
		973.5		62.28	14,161	27.91	.2296	.0348	.4481	.4930	.5429
		973.5		62.28	16,184	26.40	.2624	.0348	.4239	.4750	.5612
		973.5		62.28	18,207	23.70	.2952	.0346	.3805	.4456	.5946
15	0.030	973.5	0.0136	75.17	6,069	24.44	0.0896	0.0185	0.3251	0.3262	0.3263
		974.3		75.23	8,082	29.32	.1193	.0190	.3897	.4045	.4110
		974.3		75.23	10,115	33.03	.1493	.0193	.4391	.4589	.4695
		974.3		75.23	12,138	34.92	.1792	.0196	.4642	.4900	.5066
		974.3		75.23	14,141	35.46	.2087	.0203	.4714	.5043	.5298
		974.3		75.23	16,174	35.02	.2387	.0202	.4655	.5078	.5498
		974.3		75.23	18,187	33.32	.2684	.0206	.4429	.4967	.5700
20	0.030	976.2	0.0136	80.58	6,089	25.56	0.0869	0.0152	0.3172	0.3182	0.3183
		977.1		80.65	8,112	31.04	.1158	.0153	.3849	.3988	.4038
		977.1		80.65	10,125	34.87	.1445	.0158	.4324	.4508	.4590
		977.1		80.65	12,158	37.50	.1736	.0158	.4650	.4890	.5015
		977.1		80.65	14,161	38.31	.2022	.0161	.4750	.5058	.5241
		977.1		80.65	16,184	38.03	.2311	.0161	.4715	.5110	.5421
		977.1		80.65	18,197	36.76	.2598	.0166	.4558	.5060	.5611
8	0.050	974.6	0.0136	62.34	6,089	21.75	0.0987	0.0344	0.3489	0.3617	0.3651
		974.6		62.34	8,092	25.63	.1311	.0343	.4111	.4289	.4400
		975.5		62.40	10,115	27.47	.1640	.0340	.4402	.4641	.4841
		975.5		62.40	12,128	28.26	.1966	.0344	.4529	.4838	.5184
		975.5		62.40	14,171	27.74	.2297	.0345	.4446	.4845	.5388
		975.5		62.40	16,204	26.33	.2626	.0347	.4220	.4731	.5595
		975.5		62.40	18,248	23.93	.2958	.0343	.3835	.4486	.5954
15	0.050	976.3	0.0136	75.38	6,069	24.62	0.0896	0.0188	0.3266	0.3371	0.3384
		976.3		75.38	8,072	29.71	.1192	.0195	.3941	.4087	.4152
		976.3		75.38	10,115	33.33	.1493	.0193	.4422	.4619	.4723
		976.3		75.38	12,158	35.34	.1795	.0194	.4688	.4947	.5111
		976.3		75.38	14,181	35.98	.2093	.0198	.4773	.5103	.5350
		976.3		75.38	16,224	35.13	.2395	.0201	.4660	.5084	.5495
		975.5		75.31	18,207	33.54	.2688	.0203	.4454	.4991	.5704
20	0.050	975.5	0.0137	80.54	6,099	25.29	0.0871	0.0156	0.3140	0.3241	0.3246
		975.5		80.54	8,102	30.89	.1157	.0156	.3835	.3973	.4024
		975.5		80.54	10,135	34.80	.1448	.0155	.4321	.4506	.4587
		975.5		80.54	12,158	37.42	.1736	.0154	.4646	.4988	.5007
		975.5		80.54	14,171	38.29	.2024	.0154	.4754	.5063	.5237
		975.5		80.54	16,164	37.93	.2308	.0159	.4709	.5104	.5410
		975.5		80.54	18,207	36.72	.2600	.0162	.4559	.5062	.5596
8	0.070	973.6	0.0136	62.28	6,099	21.63	0.0988	0.0339	0.3473	0.3601	0.3635
		973.6		62.28	8,102	25.26	.1313	.0341	.4056	.4236	.4345
		973.6		62.28	10,125	27.53	.1641	.0339	.4420	.4660	.4862
		973.6		62.28	12,168	28.35	.1972	.0339	.4552	.4864	.5202
		973.6		62.28	14,181	27.90	.2298	.0343	.4480	.4880	.5419
		973.6		62.28	16,194	26.36	.2625	.0343	.4232	.4743	.5589
		973.6		62.28	18,207	23.94	.2951	.0341	.3844	.4494	.5960
15	0.070	971.9	0.0137	75.06	6,120	24.26	0.0903	0.0189	0.3232	0.3340	0.3349
		971.0		74.99	8,082	29.35	.1193	.0188	.3914	.4063	.4123
		971.9		75.06	10,125	32.90	.1495	.0198	.4383	.4582	.4688
		971.9		75.06	12,158	34.82	.1795	.0198	.4639	.4897	.5065
		971.9		75.06	14,171	35.17	.2092	.0200	.4686	.5017	.5269
		971.9		75.06	16,184	34.40	.2389	.0204	.4583	.5005	.5429
		971.9		75.06	18,207	32.88	.2688	.0206	.4380	.4920	.5653
20	0.070	972.8	0.0137	80.32	6,110	24.97	0.0872	0.0156	0.3109	0.3210	0.3216
		971.9		80.24	8,102	30.30	.1157	.0155	.3776	.3916	.3966
		971.9		80.24	10,135	34.13	.1447	.0157	.4253	.4439	.4521
		971.9		80.24	12,168	36.69	.1738	.0156	.4573	.4814	.4939
		971.9		80.24	14,141	37.37	.2019	.0156	.4657	.4966	.5146
		971.9		80.24	16,204	37.01	.2314	.0160	.4612	.5010	.4320
		971.9		80.24	18,217	35.96	.2601	.0164	.4482	.4936	.5532
8	0.090	971.9	0.0137	62.19	6,099	21.75	0.0988	0.0333	0.3497	0.3626	0.3658
		971.9		62.19	8,122	25.51	.1316	.0334	.4102	.4282	.4391
		971.9		62.19	10,115	27.53	.1640	.0334	.4427	.4666	.4864
		971.9		62.19	12,108	28.25	.1962	.0336	.4543	.4851	.5191
		971.9		62.19	14,131	27.61	.2290	.0338	.4440	.4835	.5372
		971.9		62.19	16,154	25.92	.2618	.0340	.4168	.4676	.5523
		971.9		62.19	18,156	23.39	.2943	.0339	.3761	.4409	.5872
15	0.090	971.9	0.0137	75.06	6,120	24.44	0.0903	0.0189	0.3256	0.3363	0.3375
		971.9		75.06	8,132	29.24	.1200	.0193	.3896	.4045	.4106
		971.9		75.06	10,115	32.87	.1493	.0198	.4379	.4578	.4684
		971.9		75.06	12,128	34.69	.1790	.0195	.4622	.4879	.5045
		971.9		75.06	14,141	34.95	.2039	.0200	.4656	.4985	.5240
		971.9		75.06	16,164	34.09	.2386	.0205	.4542	.4964	.5390
		971.9		75.06	18,156	32.49	.2680	.0206	.4329	.4865	.5601
20	0.090	971.9	0.0137	80.24	6,109	25.05	0.0872	0.0158	0.3122	0.3222	0.3230
		971.9		80.24	8,103	30.40	.1166	.0160	.3789	.3928	.3978
		971.9		80.24	10,135	34.37	.1447	.0164	.4233	.4469	.4555
		971.9		80.24	12,158	36.58	.1736	.0159	.4559	.4802	.4928
		971.9		80.24	14,171	37.41	.2024	.0157	.4662	.4973	.5152
		971.9		80.24	16,144	36.87	.2305	.0158	.4595	.4989	.5300
		971.9		80.24	18,207	35.64	.2600	.0161	.4442	.4946	.5431

TABLE I - SUMMARY OF EFFICIENCY DATA FOR MARK 25 POWER PLANT WITH NOZZLE E

AT VARIOUS AXIAL NOZZLE-WHEEL CLEARANCES - Concluded

[Inlet-gas pressure, 95 lb/sq in. gage; inlet-gas temperature, 1000° F]

Pressure ratio	Axial nozzle-wheel running clearance (in.)	Air mass flow (lb/hr)	Fuel-air ratio	Horsepower available from isentropic expansion	Turbine speed (rpm)	Brake horsepower	Blade-jet speed ratio	Gas density in turbine case (lb/cu ft)	Brake efficiency	Wheel efficiency	Blade efficiency
8	0.110	971.9	0.0137	62.19	6,069	21.52	0.0984	0.0333	0.3460	0.3589	0.3621
		971.9		62.19	8,122	25.16	.1316	.0335	.4046	.4226	.4335
		971.9		62.19	10,135	27.22	.1643	.0336	.4377	.4616	.4814
		971.9		62.19	12,158	27.81	.1970	.0339	.4472	.4784	.5126
		971.9		62.19	14,161	26.88	.2295	.0342	.4322	.4721	.5261
		971.9		62.19	16,144	25.43	.2617	.0341	.4089	.4599	.5445
		971.9		62.19	18,156	23.04	.2943	.0342	.3705	.4356	.5826
15	0.110	971.9	0.0137	75.06	6,089	24.34	0.0899	0.0189	0.3243	0.3351	0.3361
		971.9		75.06	8,092	29.17	.1195	.0200	.3886	.4034	.4099
		971.9		75.06	10,115	32.57	.1493	.0195	.4339	.4538	.4644
		971.9		75.06	12,178	34.51	.1798	.0195	.4598	.4857	.5023
		971.9		75.06	14,141	35.18	.2088	.0199	.4687	.5016	.5272
		971.9		75.06	16,174	34.22	.2388	.0199	.4559	.4981	.5397
		971.9		75.06	18,156	32.37	.2680	.0202	.4313	.4852	.5568
20	0.110	974.6	0.0136	80.45	6,109	25.07	0.0872	0.0156	0.3116	0.3217	0.3222
		975.5		80.52	8,092	30.21	.1156	.0154	.3752	.3890	.3942
		975.5		80.52	10,145	34.17	.1449	.0156	.4244	.4429	.4511
		975.5		80.52	12,108	36.31	.1729	.0158	.4509	.4748	.4876
		975.5		80.52	14,171	36.94	.2024	.0157	.4588	.4897	.5076
		976.3		80.59	16,184	36.32	.2311	.0158	.4507	.4901	.5208
		976.3		80.59	18,227	35.96	.2603	.0161	.4338	.4842	.5372
8	0.130	972.8	0.0137	62.24	6,069	21.36	0.0984	0.0332	0.3432	0.3559	0.3593
		972.8		62.24	8,132	25.11	.1318	.0336	.4034	.4214	.4324
		972.8		62.24	10,125	27.03	.1641	.0335	.4343	.4581	.4780
		972.8		62.24	12,158	27.69	.1970	.0337	.4449	.4761	.5096
		972.8		62.24	14,222	26.76	.2305	.0339	.4299	.4703	.5233
		972.8		62.24	16,184	25.17	.2623	.0339	.4044	.4555	.5394
		972.8		62.24	18,227	22.71	.2954	.0337	.3649	.4303	.5747
15	0.130	973.2	0.0137	75.15	6,069	23.90	0.0896	0.0191	0.3180	0.3285	0.3299
		972.3		75.08	8,072	28.91	.1192	.0203	.3851	.3998	.4064
		972.3		75.08	10,115	32.30	.1493	.0200	.4302	.4499	.4607
		972.3		75.08	12,118	34.14	.1789	.0200	.4547	.4804	.4975
		972.3		75.08	14,161	34.72	.2091	.0201	.4624	.4955	.5209
		972.3		75.08	16,144	33.99	.2383	.0202	.4527	.4948	.5366
		972.3		75.08	18,207	31.98	.2688	.0204	.4259	.4800	.5523
20	0.130	973.3	0.0136	80.36	6,120	24.83	0.0874	0.0163	0.3090	0.3189	0.3198
		974.2		80.43	8,153	30.06	.1164	.0157	.3737	.3878	.3926
		974.2		80.43	10,115	33.77	.1445	.0160	.4199	.4383	.4468
		974.2		80.43	12,178	36.04	.1739	.0156	.4481	.4723	.4845
		974.2		80.43	14,151	36.65	.2021	.0158	.4557	.4865	.5047
		974.2		80.43	16,204	35.83	.2314	.0158	.4455	.4850	.5157
		974.2		80.43	18,177	34.32	.2596	.0162	.4267	.4769	.5309
8	0.150	972.8	0.0137	62.25	6,069	21.56	0.0984	0.0326	0.3463	0.3592	0.3624
		971.9		62.19	8,102	25.07	.1313	.0327	.4031	.4211	.4319
		971.9		62.19	10,135	26.82	.1643	.0331	.4313	.4552	.4752
		971.9		62.19	12,118	27.31	.1964	.0333	.4391	.4702	.5038
		972.8		62.25	14,151	26.39	.2294	.0339	.4239	.4638	.5174
		972.8		62.25	16,164	24.77	.2620	.0338	.3979	.4488	.5325
		972.8		62.25	18,217	21.91	.2953	.0335	.3520	.4172	.5608
15	0.150	971.9	0.0137	75.06	6,130	24.08	0.0905	0.0193	0.3208	0.3315	0.3327
		971.9		75.06	8,122	28.77	.1199	.0196	.3833	.3983	.4045
		971.9		75.06	10,125	32.23	.1495	.0189	.4294	.4491	.4594
		971.9		75.06	12,158	34.10	.1795	.0197	.4543	.4801	.4968
		971.9		75.06	14,161	33.97	.2090	.0200	.4526	.4856	.5108
		971.9		75.06	16,154	32.84	.2385	.0202	.4375	.4797	.5213
		971.9		75.06	18,227	31.17	.2691	.0201	.4153	.4694	.5404
20	0.150	971.9	0.0137	80.24	6,069	24.62	0.0867	0.0163	0.3068	0.3168	0.3175
		971.9		80.24	8,082	29.75	.1154	.0165	.3708	.3847	.3898
		971.9		80.24	10,115	33.67	.1444	.0160	.4196	.4382	.4467
		971.9		80.24	12,138	35.80	.1733	.0158	.4462	.4703	.4829
		971.9		80.24	14,171	36.39	.2024	.0160	.4534	.4844	.5026
		971.9		80.24	16,174	35.60	.2310	.0163	.4437	.4833	.5147
		971.9		80.24	18,156	34.11	.2593	.0166	.4251	.4753	.5305

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TABLE II - SUMMARY OF EFFICIENCY DATA FOR MARK 25 POWER PLANT WITH NOZZLE H

AT VARIOUS AXIAL NOZZLE-WHEEL CLEARANCES

[Inlet-gas pressure, 95 lb/sq in. gage; inlet-gas temperature, 1000° F]

Pressure ratio	Axial nozzle-wheel running clearance (in.)	Air mass flow (lb/hr)	Fuel-air ratio	Horsepower available from isentropic expansion	Turbine speed (rpm)	Brake horsepower	Blade-jet speed ratio	Gas density in turbine case (lb/cu ft)	Brake efficiency	Wheel efficiency	Blade efficiency
8	0.035	1141	0.0141	73.04	6,069	27.76	0.0984	0.0333	0.3801	0.3909	0.3938
		1141		73.04	8,122	33.38	.1317	.0336	.4570	.4723	.4817
		1141		73.04	10,135	36.67	.1643	.0339	.5021	.5225	.5396
		1141		73.04	12,148	38.07	.1970	.0347	.5212	.5478	.5774
		1140		72.98	14,161	37.66	.2296	.0349	.5160	.5500	.5971
		1140		72.98	16,164	35.90	.2621	.0346	.4919	.5352	.6088
		1140		72.98	18,197	32.74	.2950	.0350	.4486	.5042	.6328
15	0.035	1140	0.0141	88.10	6,099	30.61	0.0900	0.0189	0.3474	0.3565	0.3575
		1140		88.10	8,112	37.37	.1197	.0189	.4242	.4368	.4421
		1140		88.10	10,115	42.23	.1493	.0194	.4793	.4961	.5051
		1140		88.10	12,148	45.08	.1793	.0196	.5117	.5337	.5479
		1140		88.10	14,161	46.25	.2090	.0201	.5250	.5531	.5748
		1139		88.03	16,184	45.49	.2389	.0209	.5168	.5528	.5890
		1139		88.03	18,217	43.16	.2689	.0210	.4903	.5364	.5987
19	0.035	1139	0.0141	93.05	6,120	31.50	0.0879	0.0160	0.3385	0.3472	0.3478
		1139		93.05	8,122	38.44	.1166	.0161	.4131	.4251	.4296
		1139		93.05	10,115	43.63	.1452	.0163	.4689	.4848	.4923
		1139		93.05	12,148	46.88	.1744	.0163	.5038	.5247	.5358
		1139		93.05	14,151	48.50	.2032	.0170	.5212	.5479	.5648
		1139		93.05	16,164	48.26	.2321	.0174	.5186	.5526	.5818
		1139		93.05	18,207	46.62	.2614	.0178	.5010	.5447	.5960
8	0.055	1141	0.0140	73.00	6,059	27.71	0.0982	0.0334	0.3796	0.3904	0.3933
		1141		73.00	8,112	33.23	.1315	.0334	.4552	.4705	.4799
		1141		73.00	10,095	36.26	.1636	.0333	.4967	.5170	.5338
		1140		72.93	12,118	37.58	.1964	.0339	.5153	.5418	.5706
		1141		73.00	14,141	37.05	.2292	.0342	.5075	.5414	.5874
		1141		73.00	16,194	35.49	.2625	.0340	.4862	.5299	.6017
		1140		72.93	18,197	31.96	.2949	.0342	.4382	.4938	.6194
15	0.055	1141	0.0140	88.11	6,089	30.50	0.0899	0.0190	0.3462	0.3552	0.3561
		1141		88.11	8,102	36.85	.1196	.0189	.4182	.4308	.4362
		1141		88.11	10,105	40.86	.1492	.0191	.4637	.4806	.4895
		1141		88.11	12,108	43.21	.1787	.0197	.4904	.5122	.5266
		1141		88.11	14,141	44.13	.2088	.0206	.5009	.5289	.5511
		1141		88.11	16,184	42.93	.2389	.0207	.4872	.5233	.5598
		1141		88.11	18,207	41.10	.2688	.0209	.4665	.5125	.5758
19	0.055	1145	0.0140	93.51	6,089	30.84	0.0874	0.0164	0.3298	0.3384	0.3390
		1145		93.51	8,102	37.19	.1164	.0165	.3977	.4096	.4141
		1145		93.51	10,125	41.94	.1454	.0162	.4485	.4645	.4718
		1145		93.51	12,158	44.59	.1746	.0164	.4768	.4976	.5088
		1145		93.51	14,161	45.69	.2034	.0171	.4886	.5151	.5321
		1145		93.51	16,194	45.09	.2326	.0175	.4822	.5163	.5453
		1145		93.51	18,227	43.61	.2618	.0179	.4664	.5099	.5607
8	0.075	1144	0.0140	73.21	6,079	27.73	0.0986	0.0331	0.3788	0.3799	0.3924
		1144		73.21	8,132	32.94	.1318	.0340	.4499	.4654	.4745
		1144		73.21	10,095	36.09	.1637	.0337	.4930	.5132	.5303
		1144		73.21	12,138	37.44	.1968	.0338	.5114	.5379	.5667
		1144		73.21	14,141	36.53	.2293	.0340	.4990	.5327	.5785
		1144		73.21	16,204	34.44	.2627	.0340	.4704	.5141	.5856
		1144		73.21	18,197	30.40	.2950	.0342	.4152	.4704	.5958
15	0.075	1142	0.0140	88.24	6,099	29.91	0.0900	0.0190	0.3390	0.3399	0.3490
		1142		88.24	8,112	35.93	.1197	.0192	.4072	.4199	.4251
		1142		88.24	10,095	39.82	.1490	.0190	.4513	.4680	.4769
		1142		88.24	12,158	41.87	.1795	.0194	.4745	.4966	.5105
		1142		88.24	14,191	42.32	.2095	.0200	.4796	.5078	.5291
		1142		88.24	16,184	41.28	.2389	.0204	.4678	.5041	.5347
		1142		88.24	18,177	38.99	.2683	.0206	.4419	.4876	.5499
19	0.075	1142	0.0140	93.28	6,089	29.96	0.0874	0.0160	0.3212	0.3220	0.3304
		1142		93.28	8,102	36.18	.1163	.0161	.3879	.3892	.4043
		1142		93.28	10,115	40.53	.1452	.0161	.4345	.4504	.4579
		1142		93.28	12,138	43.24	.1743	.0158	.4636	.4843	.4952
		1142		93.28	14,161	44.38	.2033	.0168	.4758	.5024	.5190
		1142		93.28	16,184	43.57	.2324	.0171	.4671	.5012	.5297
		1142		93.28	18,177	41.99	.2610	.0174	.4502	.4935	.5433
8	0.095	1142	0.0140	73.10	6,079	27.69	0.0986	0.0327	0.3788	0.3799	0.3925
		1142		73.10	8,122	32.84	.1317	.0334	.4492	.4646	.4739
		1142		73.10	10,115	35.83	.1640	.0331	.4902	.5105	.5271
		1142		73.10	12,148	36.83	.1970	.0333	.5038	.5304	.5588
		1142		73.10	14,141	35.98	.2293	.0337	.4922	.5261	.5715
		1142		73.10	16,194	33.89	.2626	.0340	.4636	.5071	.5789
		1142		73.10	18,187	30.21	.2949	.0339	.4133	.4687	.5932
15	0.095	1142	0.0140	88.24	6,049	29.66	0.0893	0.0186	0.3361	0.3370	0.3462
		1142	.0140	88.24	8,112	35.82	.1197	.0188	.4059	.4186	.4237
		1142	.0140	88.24	10,115	39.43	.1493	.0186	.4468	.4637	.4723
		1142	.0140	88.24	12,138	41.20	.1792	.0192	.4669	.4889	.5026
		1131	.0141	87.40	14,141	41.47	.2087	.0199	.4745	.5029	.5239
		1142	.0140	88.24	16,184	40.27	.2389	.0202	.4564	.4924	.5279
		1142	.0140	88.24	18,197	37.84	.2686	.0205	.4288	.4747	.5369
19	0.095	1142	0.0140	93.28	6,089	29.76	0.0874	0.0165	0.3190	0.3199	0.3285
		1142		93.28	8,092	35.76	.1162	.0161	.3834	.3954	.3999
		1142		93.28	10,125	39.81	.1454	.0160	.4268	.4428	.4500
		1142		93.28	12,148	42.20	.1744	.0160	.4524	.4732	.4842
		1142		93.28	14,161	43.03	.2033	.0160	.4613	.4879	.5039
		1142		93.28	16,184	42.19	.2324	.0169	.4523	.4864	.5145
		1142		93.28	18,187	40.16	.2611	.0173	.4305	.4739	.5233

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TABLE III - SUMMARY OF EFFICIENCY DATA FOR MARK 25 POWER PLANT WITH NOZZLE I AT VARIOUS AXIAL NOZZLE-WHEEL CLEARANCES

[Inlet-gas pressure, 95 lb/sq in. gage; inlet-gas temperature, 1000° F]

Pressure ratio	Axial nozzle-wheel running clearance (in.)	Air mass flow (lb/hr)	Fuel-air ratio	Horsepower available from isentropic expansion	Turbine speed (rpm)	Brake horsepower	Blade-jet speed ratio	Gas density in turbine case (lb/cu ft)	Brake efficiency	Wheel efficiency	Blade efficiency
8	0.035	992.3	0.0139	63.51	6,109	23.64	0.0990	0.0345	0.3722	0.3850	0.3880
		992.3		63.51	8,102	28.04	.1313	.0348	.4415	.4590	.4700
		992.3		63.51	10,085	30.97	.1635	.0349	.4876	.5109	.5314
		992.3		63.51	12,189	32.29	.1976	.0352	.5084	.5391	.5736
		992.3		63.51	14,171	31.62	.2297	.0353	.4979	.5371	.5916
		992.3		63.51	16,184	29.60	.2623	.0351	.4661	.5161	.6015
		992.3		63.51	18,197	26.81	.2949	.0351	.4221	.4861	.6341
15	0.035	991.4	0.0139	76.59	6,109	26.84	0.0902	0.0190	0.3504	0.3610	0.3621
		991.4		76.59	8,132	32.51	.1200	.0191	.4245	.4390	.4452
		991.4		76.59	10,155	36.31	.1499	.0196	.4741	.4937	.5040
		991.4		76.59	12,178	38.41	.1798	.0199	.5015	.5270	.5433
		991.4		76.59	14,131	38.56	.2086	.0207	.5035	.5357	.5616
		991.4		76.59	16,164	37.71	.2386	.0211	.4924	.5339	.5767
		991.4		76.59	18,197	35.56	.2686	.0213	.4643	.5173	.5913
20	0.035	991.4	0.0139	81.88	6,069	27.20	0.0867	0.0165	0.3322	0.3420	0.3429
		990.5		81.81	8,072	33.28	.1153	.0163	.4068	.4202	.4254
		990.5		81.81	10,105	37.53	.1443	.0161	.4587	.4770	.4855
		990.5		81.81	12,148	40.19	.1735	.0163	.4913	.5150	.5277
		990.5		81.81	14,161	41.16	.2022	.0167	.5031	.5334	.5523
		990.5		81.81	16,154	40.67	.2307	.0171	.4971	.5360	.5686
		991.4		81.88	18,217	39.44	.2601	.0174	.4817	.5313	.5878
8	0.055	988.8	0.0139	63.28	6,109	23.29	0.0990	0.0348	0.3680	0.3807	0.3840
		988.8		63.28	8,112	27.56	.1315	.0349	.4355	.4532	.4641
		988.8		63.28	10,115	30.43	.1640	.0348	.4809	.5043	.5245
		989.7		63.34	12,148	31.59	.1969	.0352	.4987	.5294	.5638
		989.7		63.34	14,171	31.24	.2297	.0352	.4932	.5324	.5867
		989.7		63.34	16,184	28.85	.2623	.0351	.4555	.5057	.5911
		989.7		63.34	18,177	26.30	.2946	.0351	.4152	.4790	.6272
15	0.055	989.7	0.0139	76.45	6,039	26.41	0.0892	0.0186	0.3455	0.3558	0.3571
		989.7		76.45	8,062	31.91	.1190	.0187	.4174	.4318	.4381
		989.7		76.45	10,115	35.63	.1493	.0189	.4661	.4854	.4955
		989.7		76.45	12,168	38.01	.1796	.0201	.4972	.5226	.5392
		989.7		76.45	14,161	38.22	.2091	.0205	.4999	.5324	.5578
		989.7		76.45	16,174	37.42	.2388	.0208	.4895	.5311	.5731
		989.7		76.45	18,207	34.56	.2688	.0212	.4560	.5091	.5929
20	0.055	990.5	0.0139	81.81	6,109	27.34	0.0872	0.0156	0.3342	0.3440	0.3447
		990.5		81.81	8,072	33.17	.1153	.0152	.4055	.4189	.4239
		991.4		81.88	10,105	37.46	.1443	.0161	.4575	.4756	.4841
		991.4		81.88	12,158	40.15	.1736	.0161	.4904	.5140	.5267
		991.4		81.88	14,161	40.88	.2022	.0163	.4993	.5296	.5450
		991.4		81.88	16,164	40.27	.2308	.0167	.4918	.5307	.5625
		991.4		81.88	18,197	38.68	.2599	.0168	.4724	.5219	.5765
8	0.075	989.1	0.0139	63.30	6,089	23.30	0.0987	0.0338	0.3681	0.3807	0.3839
		989.1		63.30	8,122	27.65	.1316	.0341	.4368	.4545	.4652
		988.2		63.24	10,135	30.36	.1643	.0341	.4801	.5036	.5234
		988.2		63.24	12,168	31.27	.1972	.0346	.4945	.5251	.5593
		988.2		63.24	14,141	30.71	.2292	.0346	.4856	.5247	.5787
		988.2		63.24	16,204	28.46	.2626	.0349	.4500	.5005	.5852
		988.2		63.24	18,207	25.80	.2951	.0346	.4080	.4722	.6186
15	0.075	989.1	0.0139	76.41	6,049	26.31	0.0893	0.0189	0.3443	0.3547	0.3560
		988.2		76.34	8,112	31.84	.1197	.0189	.4171	.4316	.4376
		988.2		76.34	10,115	35.30	.1493	.0200	.4624	.4819	.4925
		989.1		76.41	12,098	37.51	.1786	.0202	.4909	.5160	.5330
		989.1		76.41	14,161	37.47	.2091	.0208	.4904	.5229	.5498
		989.1		76.41	16,144	37.76	.2383	.0210	.4811	.5224	.5652
		989.1		76.41	18,156	34.64	.2690	.0213	.4533	.5061	.5808
20	0.075	990.9	0.0139	81.84	6,120	27.08	0.0874	0.0157	[illegible]	0.3408	0.3413
		990.9		81.84	8,102	32.65	.1157	.0153	.3984	.4125	.4174
		990.9		81.84	10,115	36.70	.1445	.0154	.4484	.4666	.4746
		990.9		81.84	12,158	39.07	.1736	.0156	.4774	.5011	.5132
		990.9		81.84	14,201	39.73	.2028	.0167	.4855	.5159	.5345
		990.9		81.84	16,184	38.98	.2311	.0169	.4763	.5152	.5470
		990.9		81.84	18,197	37.49	.2599	.0173	.4580	.5075	.5639
8	0.095	987.1	0.0139	63.17	6,049	22.68	0.0990	0.0333	0.3590	0.3715	0.3749
		987.9		63.22	8,092	27.09	.1311	.0339	.4285	.4462	.4570
		987.9		63.22	10,095	29.37	.1636	.0339	.4646	.4880	.5078
		987.9		63.22	12,17[illegible]	30.34	.1974	.0344	.4799	.5105	.5444
		988.8		63.22	14,181	29.26	.2298	.0345	.4624	.5016	.5552
		987.9		63.22	16,184	27.31	.2623	.0343	.4320	.4823	.5653
		987.9		63.22	18,156	24.41	.2943	.0342	.3861	.4499	.5946
15	0.095	987.9	0.0139	76.32	6,069	25.90	0.0896	0.0190	0.3394	0.3493	0.3510
		[illegible]		76.39	8,112	31.17	.1197	.0190	.4090	.4226	.4287
		988.8		76.39	10,115	34.63	.1493	.0201	.4533	.4727	.4934
		[illegible]		76.39	12,138	36.32	.1792	.0204	.4755	.5009	.5177
		[illegible]		76.39	14,171	36.47	.2092	.0209	.4774	.5090	.5359
		[illegible]		76.39	16,184	35.57	.2389	.0212	.4656	.5073	.5501
		988.9		76.39	18,207	33.42	.2698	.0215	.4375	.4906	.5658
20	0.095	990.5	0.0139	81.81	6,120	26.64	0.0874	0.0155	0.3256	0.3355	0.3361
		990.5		81.81	8,122	32.20	.1160	.0153	.3936	.4073	.4122
		990.5		81.81	10,115	35.80	.1445	.0153	.4376	.4557	.4638
		[illegible]		81.74	12,138	38.08	.1733	.0162	.4659	[illegible]	.5023
		989.7		81.74	14,171	39.15	.2024	.0165	.4667	[illegible]	[illegible]
		990.5		81.81	16,164	37.61	.2305	.0170	.4597	.4933	.5309
		990.5		81.81	18,177	35.82	.2596	.0172	.4378	.4972	.5433

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TABLE IV - SUMMARY OF EFFICIENCY DATA FOR MARK 25 POWER PLANT WITH NOZZLE I USING TEMPERATURE INSIDE NOZZLE AS BASIS FOR COMPUTING ISENTROPIC POWER AVAILABLE

[Inlet-gas pressure, 95 lb/sq in. gage; inlet-gas temperature, 1000° F; axial nozzle-wheel running clearance, 0.035 in.]

Pressure ratio	Turbine speed (rpm)	Corrected temperature inside nozzle (°F)	Horsepower available from isentropic expansion[a]	Brake efficiency[a]	Wheel efficiency[a]	Blade efficiency[a]
8	6,109	975	62.37	0.3790	0.3920	0.3951
	8,102	977	62.47	.4489	.4666	.4778
	10,085	979	62.54	.4952	.5189	.5397
	12,189	979	62.54	.5163	.5475	.5825
	14,171	979	62.54	.5056	.5454	.6007
	16,184	979	62.54	.4733	.5241	.6108
	18,197	980	62.60	.4283	.4931	.6433
15	6,109	980	75.51	0.3554	0.3662	0.3672
	8,132	980	75.51	.4305	.4452	.4516
	10,155	980	75.51	.4809	.5007	.5112
	12,178	979	75.46	.5090	.5349	.5514
	14,131	978	75.38	.5115	.5443	.5706
	14,164	976	75.29	.5009	.5431	.5867
	18.197	979	75.46	.4712	.5250	.6002
20	6,069	982	80.81	0.3366	0.3465	0.3475
	8,072	981	80.66	.4126	.4262	.4314
	10,105	980	80.62	.4655	.4840	.4927
	12,148	979	80.56	.4989	.5230	.5359
	14,161	979	80.56	.5109	.5417	.5608
	16,154	979	80.56	.5048	.5443	.5775
	18,217	979	80.64	.4891	.5394	.5969

[a]Based on temperature inside nozzle.

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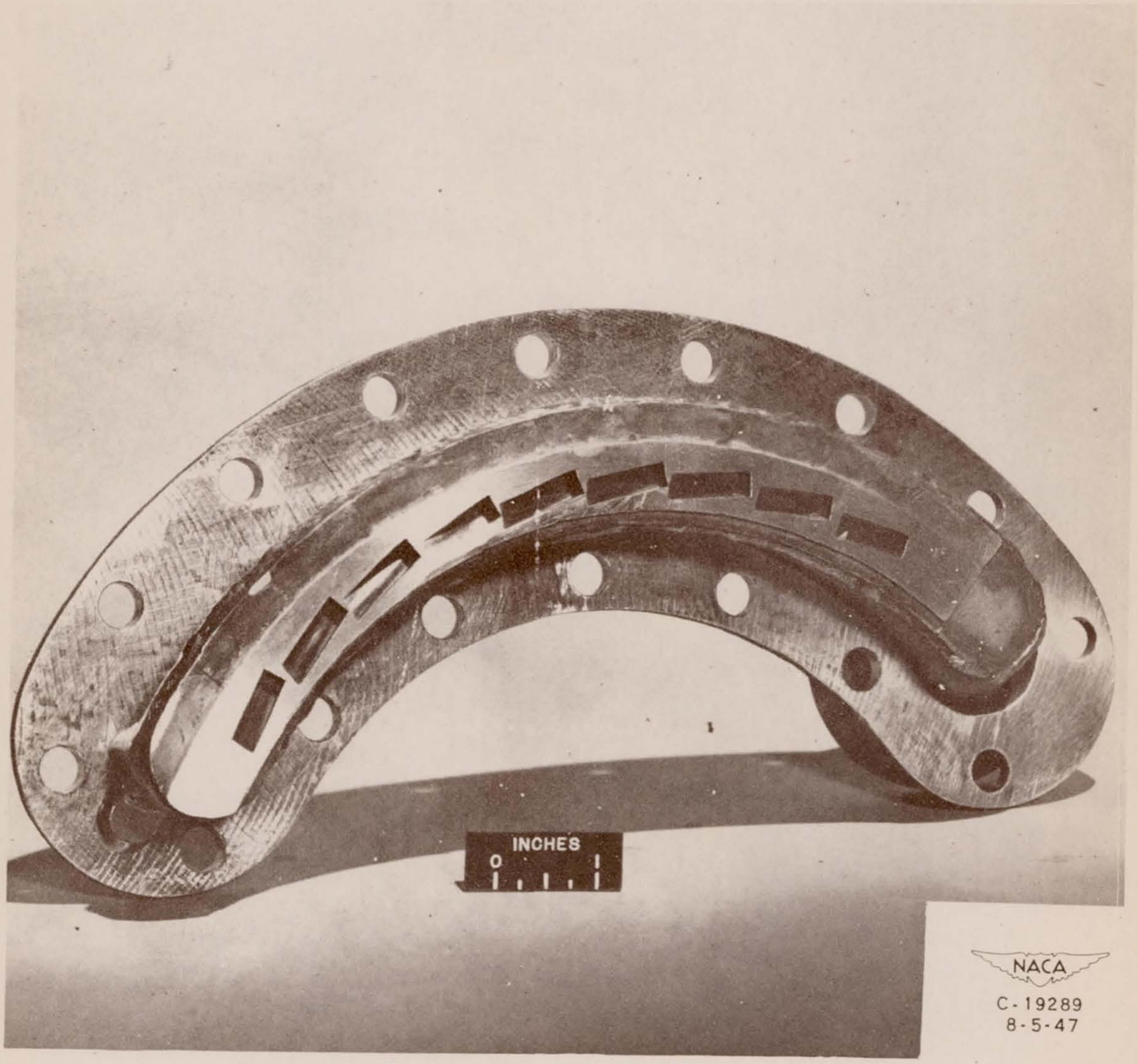


Figure 1. - Outlet face of cast nozzle I designed for turbine of Mark 25 power plant.

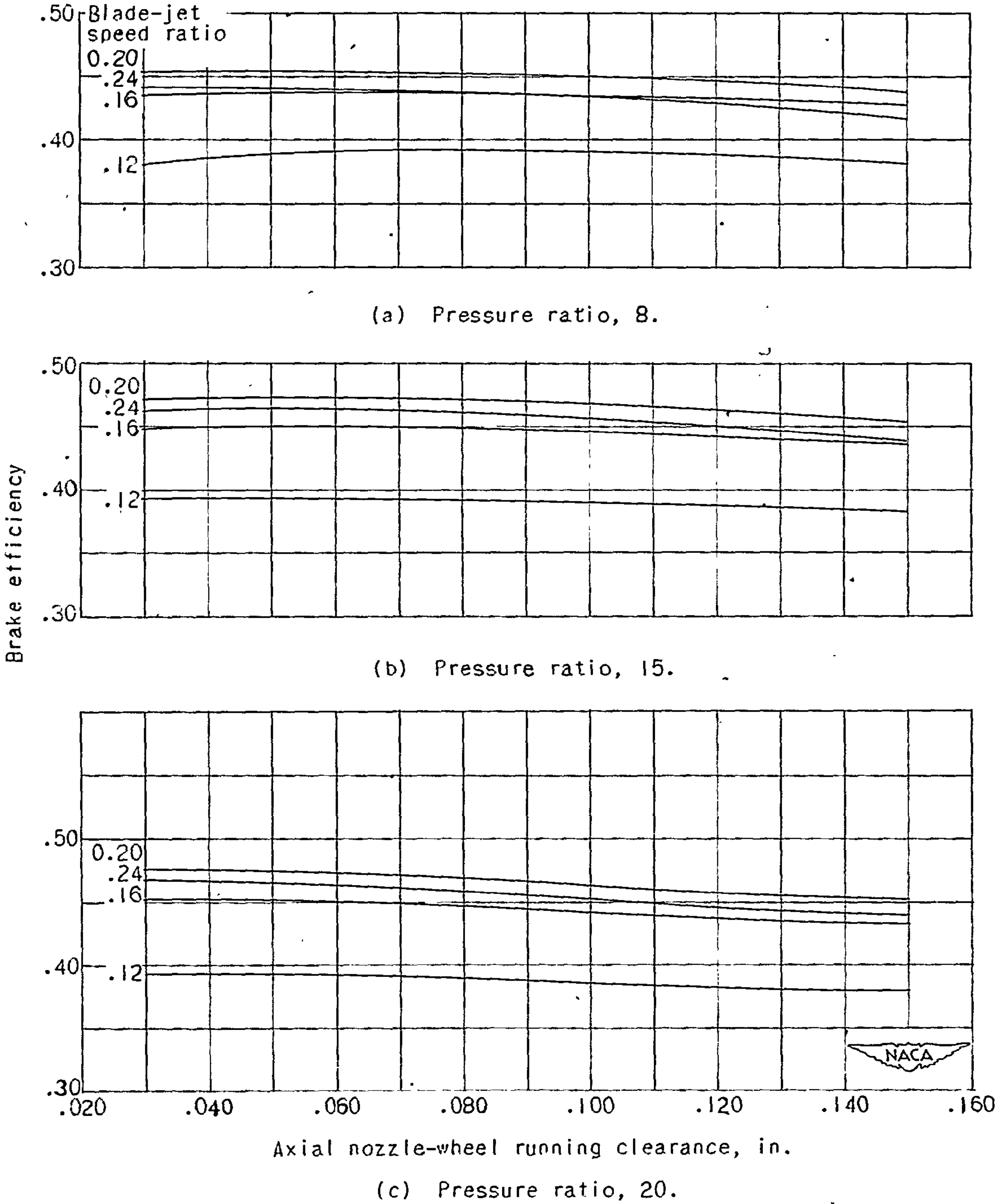
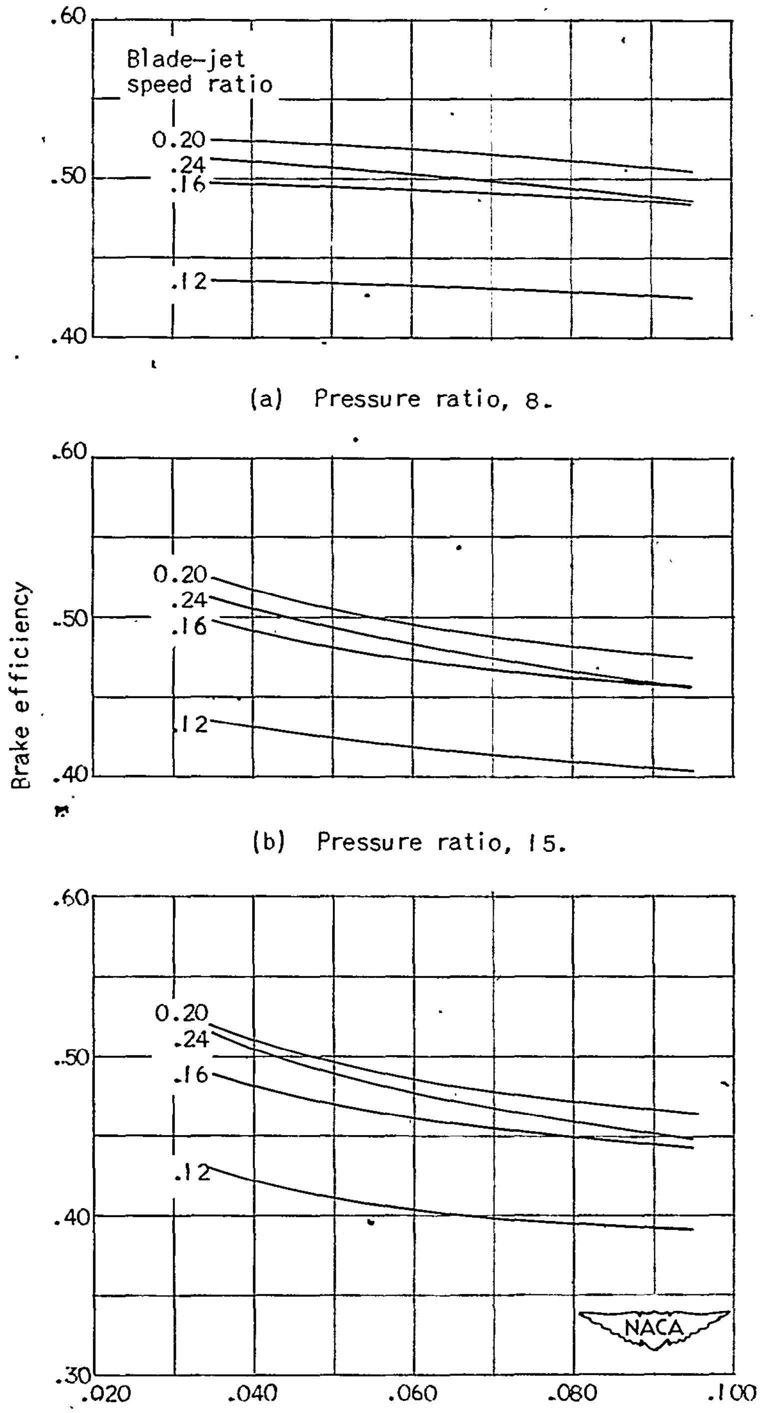


Figure 2. - Effect of axial nozzle-wheel running clearance on brake efficiency in Mark 25 power plant at various blade-jet speed ratios with nozzle E. Inlet-gas pressure, 95 pounds per square inch gage; inlet-gas temperature, 1000° F.



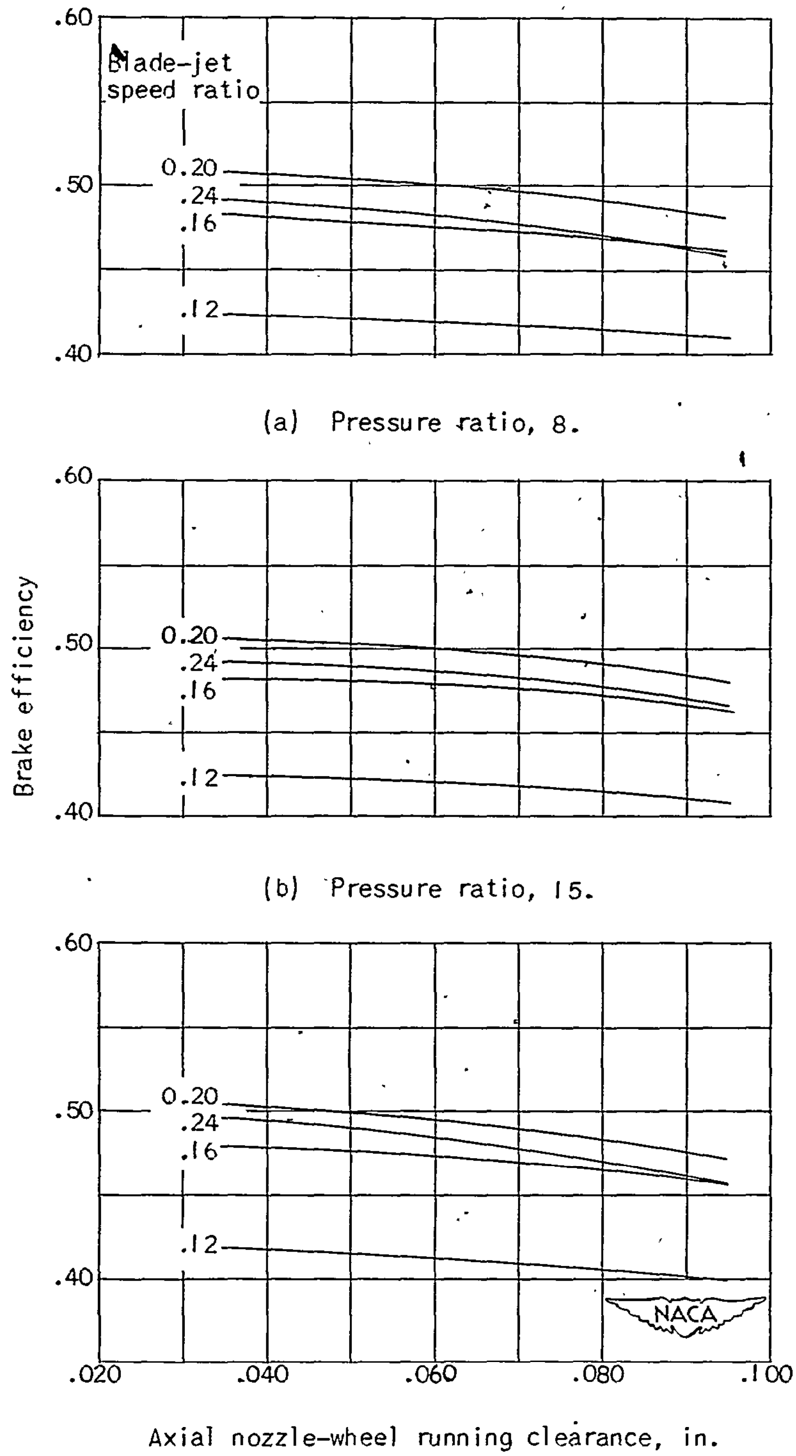
(a) Pressure ratio, 8.

(b) Pressure ratio, 15.

Axial nozzle-wheel running clearance, in.

(c) Pressure ratio, 19.

Figure 3. - Effect of axial nozzle-wheel running clearance in Mark 25 power plant on brake efficiency at various blade-jet speed ratios with nozzle H. Inlet-gas pressure, 95 pounds per square inch gage; inlet-gas temperature, 1000° F.



(c) Pressure ratio, 20.

Figure 4. – Effect of axial nozzle-wheel running clearance in Mark 25 power plant on brake efficiency at various blade-jet speed ratios with nozzle I. Inlet-gas pressure, 95 pounds per square inch gage; inlet-gas temperature, 1000° F.

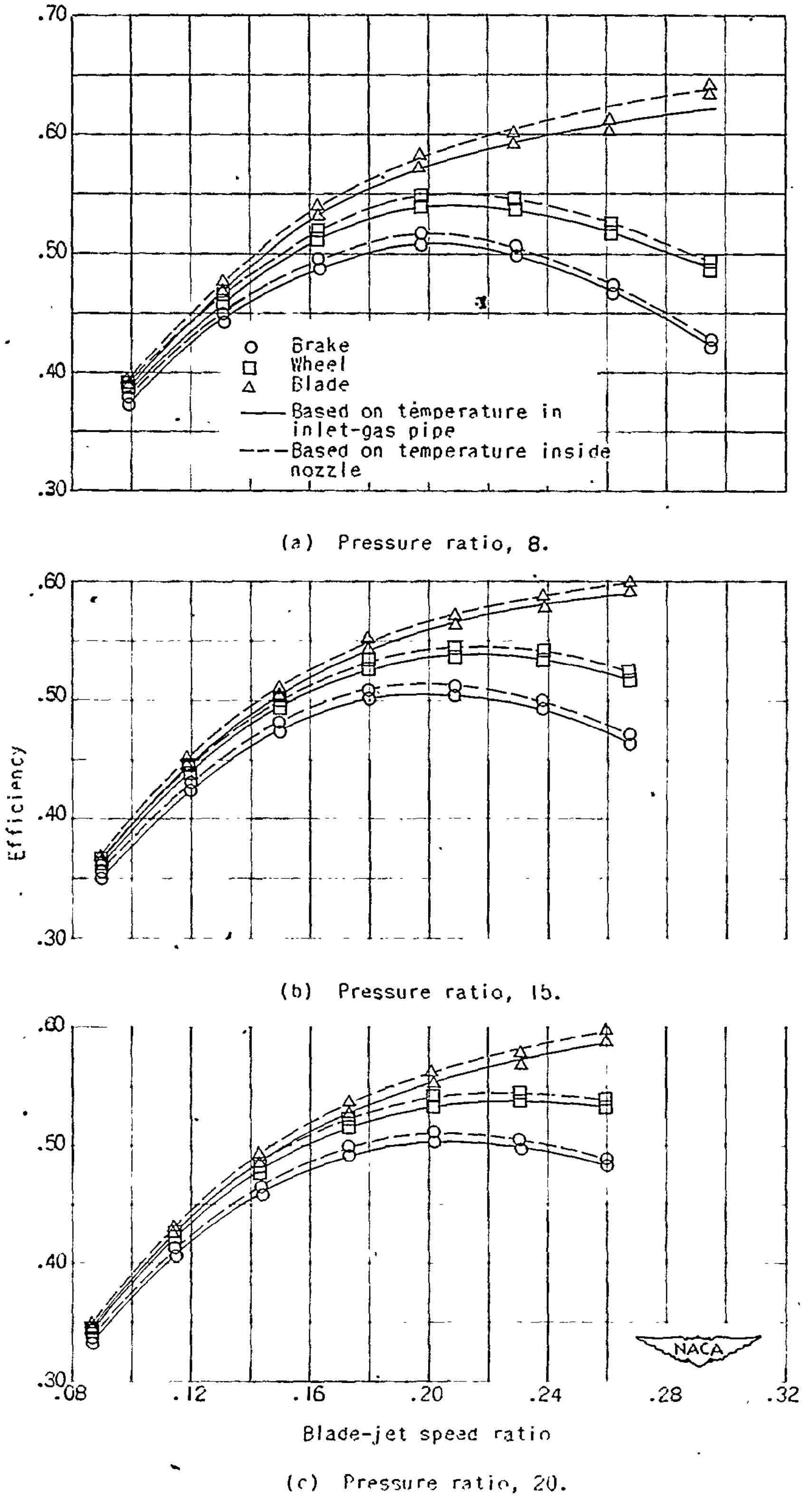


Figure 5. - Variation of efficiency with blade-jet speed ratio in Mark 25 power plant with nozzle 1. Inlet-gas pressure, 95 pounds per square inch gage; inlet-gas temperature, 1000° F; axial nozzle-wheel running clearance, 0.035 inch.