REPORT No. 822

CALCULATIONS OF ECONOMY OF 18-CYLINDER RADIAL AIRCRAFT ENGINE WITH EXHAUST-GAS TURBINE GEARED TO THE CRANKSHAFT

By Richard W. Hannum and Richard H. Zimmerman

SUMMARY

Calculations based on dynamometer test-stand data obtained on an 18-cylinder radial engine were made to determine the improvement in fuel consumption that can be obtained at various altitudes by gearing an exhaust-gas turbine to the engine crankshaft in order to increase the engine-shaft work.

The calculations indicated that, for turbine and auxiliary supercharger efficiencies of 85 percent, minimum net brake specific fuel consumptions of 0.357 pound per brake horsepower-hour at an altitude of 10,000 feet and of 0.323 pound per brake horsepower-hour at 30,000 feet can be obtained by gearing the exhaust-gas turbine to the engine crankshaft and operating the engine at a speed of 2000 rpm, an inlet-manifold pressure of 40 inches of mercury absolute, and a fuel-air ratio of 0.063.

The reduction in net brake specific fuel consumption that can be obtained if the exhaust-gas turbine supplies all the auxiliary supercharger power and if its residual power is transmitted through gears to the engine crankshaft, as compared with auxiliary turbosupercharging, is approximately 14 percent at an altitude of 10,000 feet and 21 percent at 30,000 feet.

The net brake specific fuel consumption with a geared turbine is a minimum for engine exhaust pressures approximately 25 percent above inlet-manifold pressure and varies only slightly from the minimum for a range of exhaust pressures from 5 to 45 percent above inlet-manifold pressure.

INTRODUCTION

The use of an exhaust-gas turbine to drive a supercharger at high altitudes is an effective method of maintaining sea-level engine power at altitude. Analysis has shown, however, that the waste energy of exhaust gases is recovered more effectively by maintaining an engine exhaust pressure higher than the minimum required for turbosupercharging and thus increasing the work output of the exhaust-gas turbine. The extra turbine power beyond that required for supercharging can be supplied to the engine crankshaft through suitable gearing (compound operation).

The purpose of the analysis reported is to determine the improvement in net brake specific fuel consumption that can be obtained if an engine is equipped with a geared turbine and supercharger as compared with the engine using a standard turbosupercharger. The calculated values of specific fuel consumption presented for an engine-turbine combination were based on NACA test data obtained on an 18-cylinder radial engine. Operating conditions for which the brake specific fuel consumption of the combination is a minimum are given. The required turbine-nozzle area is also calculated to indicate the size of turbine suitable for geared operation.

Because the engine, the turbine, and the supercharger have different characteristics, elements designed to give maximum efficiency at some operating conditions are incorrectly matched at other conditions. Provision must therefore be made to obtain satisfactory performance over the entire operating range. The problem of obtaining a wide operating range is briefly discussed.

The investigation reported was conducted at the NACA Cleveland Laboratory in the fall of 1944.

METHODS

This analysis is based on dynamometer test-stand data obtained with an 18-cylinder radial engine operated at various speeds, inlet-manifold pressures, and exhaust pressures. The data were obtained with the carburetor-inlet pressure adjusted by a butterfly valve in the charge-air intake pipe ahead of the engine to provide the desired inlet-manifold pressure with wide-open engine throttle in all runs. Pertinent specifications of the engine are as follows:

Displacement, cubic inches	2804
Compression ratio	6.65
Valve timing:	
Inlet opens, degrees B. T. C.	20
Inlet closes, degrees A. B. C.	76
Exhaust opens, degrees B. B. C.	76
Exhaust closes, degrees A. T. C.	20
Valve overlap, degrees	40
Engine-stage supercharger impeller diameter, inches	11
Engine-stage supercharger gear ratio	7.6:1
Spark advance, degrees B. T. C.	25

The test data and the values of air flow and brake horsepower, corrected to a carburetor-air temperature of 90° F, are shown in table I. Although the carburetor-air temperatures obtained in flight depend upon the amount of auxiliary supercharging and intercooling used, the arbitrary use of a temperature of 90° F for all calculations was considered justified in this analysis because specific fuel consumption is almost independent of carburetor temperature. The engine performance at an engine speed of 2000 rpm and a fuel-air ratio of 0.063 for various engine exhaust pressures, obtained

TABLE I.—SUMMARY OF PERTINENT TEST DATA ON 18-CYLINDER RADIAL AIRCRAFT ENGINE

Run	Engine speed (rpm)	Fuel-air ratio	Carburetor-air pressure (in. Hg abs.)	Carburetor-air temperature (°F)	Inlet-manifold pressure (in. Hg abs.)	Inlet-manifold mixture temperature (°F)	Engine exhaust pressure (in. Hg abs.)	Engine power (bhp)	Exhaust-gas temperature (° F)	Cylinder-head temperature (° F)	Cooling-air pressure drop (in. water)	Cooling-air temperature (° F)	Fuel flow (lb/hr)	Charge-air flow (lb/hr)	Corrected charge-air flow (lb/hr)[1]	Corrected engine power (bhp)
319	1612	0.0853	31.22	92	39.98	120	8.00	1106	1356	331	12.9	110	610	7150	7109	1099.5
320	1602	.0859	31.20	92	40.00	128	19.00	1050	1427	336	13.1	111	552	6426	6430	1047.7
321	1604	.0848	31.00	92	39.95	127	27.75	994	1445	332	13.2	114	528	6228	6239	996.6
322	1600	.0847	31.00	93	39.95	129	37.65	926	1437	337	13.1	114	505	5965	5958	929.9
323	1600	.0859	31.00	95	39.99	132	47.90	844	1407	341	13.1	115	486	5689	5688	845.8
324	1601	.0851	30.89	96	40.05	137	59.30	752	1375	341	13.2	115	453	5321	5340	754.5
247	1800	.0847	29.33	91	40.00	131	8.30	1207	1439	348	13.1	114	654	7722	7739	1207.6
248	1792	.0842	29.15	91	40.00	132	16.20	1174	1456	351	12.8	114	621	7373	7413	1180.2
249	1801	.0853	29.10	91	39.98	135	24.60	1126	1480	359	12.8	114	606	7106	7158	1133.4
250	1795	.0853	29.18	92	40.02	137	32.10	1080	1498	352	13.0	114	592	6937	6964	1084.6
251	1795	.0848	29.08	93	39.92	140	39.20	1020	1496	354	12.9	114	570	6724	6775	1028.4
252	1794	.0847	29.10	94	40.00	145	49.15	934	1473	365	12.7	115	543	6412	6456	940.1
229	2006	.0853	27.50	91	40.25	137	7.96	1372	1493	349	13.9	94	737	8636	8566	1360.2
230	1999	.0849	27.30	90	40.00	138	16.25	1328	1545	351	13.8	95	707	8330	8334	1324.0
231	1994	.0855	27.30	90	40.05	138	24.40	1283	1525	352	13.8	95	698	8108	8152	1284.8
232	1995	.0850	27.25	90	40.05	141	32.20	1233	1533	354	13.9	94	682	8028	8025	1237.5
233	2008	.0854	27.05	90	40.10	144	39.92	1175	1524	356	14.2	94	665	7790	7806	1176.6
234	1994	.0854	27.05	90	39.95	147	49.30	1087	1509	359	14.2	94	638	7474	7505	1091.9
313	2202	.0861	26.90	102	39.95	163	8.92	1413	1516	359	18.2	116	787	9137	9239	1428.7
314	2196	.0854	25.88	103	40.00	164	19.15	1375	1541	359	18.4	115	761	8906	9015	1391.8
315	2195	.0858	25.83	104	40.05	166	28.35	1320	1551	362	18.3	115	745	8687	8793	1336.7
316	2207	.0853	25.61	107	40.05	170	37.55	1262	1545	364	18.4	115	718	8417	8535	1267.9
317	2202	.0850	25.55	107	40.00	174	48.30	1155	1534	369	18.6	117	686	8063	8162	1168.5
318	2197	.0853	25.50	108	40.00	178	59.75	1023	1509	378	18.6	117	646	7874	7707	1040.7
325	2405	.0857	24.29	100	39.90	175	7.82	1477	1567	354	22.2	109	844	9850	9943	1491.3
326	2403	.0853	24.20	102	40.10	176	18.65	1447	1573	354	22.8	109	826	9658	9757	1458.9
327	2395	.0856	24.09	103	40.00	178	28.72	1382	1577	354	23.1	109	802	9367	9197	1401.7
328	2398	.0854	23.95	104	40.00	180	38.65	1309	1506	357	22.2	109	777	9101	9224	1328.6
329	2398	.0852	23.85	105	40.09	184	48.09	1220	1556	361	23.2	109	748	8784	8891	1234.2
330	2405	.0853	23.62	107	40.15	188	58.42	1085	1541	366	23.2	109	704	8251	8329	1097.4
122	1992	.0856	20.70	104	30.03	157	8.30	936	1390	331	9.8	115	518	6018	6143	949.1
123	2000	.0857	20.62	104	30.05	158	14.98	912	1475	331	9.8	115	512	5972	6057	922.8
124	2001	.0861	20.55	105	30.03	160	22.40	871	1510	333	9.8	115	500	5807	5877	880.1
125	1996	.0859	20.53	106	30.03	162	28.70	820	1433	333	9.9	115	485	5645	5723	834.1
126	1994	.0861	20.48	106	30.00	165	35.03	767	1425	334	9.9	115	467	5422	5530	781.0
127	1999	.0852	20.33	108	29.95	170	42.53	708	1430	338	9.8	115	445	5230	5306	714.1
11	1997	.0844	23.35	93	34.00	152	8.70	1093	1427	356	8.8	117	587	6952	6964	1096.2
12	1993	.0846	23.33	93	34.00	154	16.30	1057	1438	360	8.9	117	571	6754	6841	1063.7
13	1997	.0843	23.20	94	33.90	156	22.60	1022	1453	358	8.9	117	561	6663	6707	1032.4
14	1994	.0841	23.25	94	34.00	159	28.85	983	1482	359	8.8	117	546	6494	6541	987.8
15	1992	.0840	23.10	96	34.00	164	40.20	885	1470	365	8.9	118	517	6156	6215	893.4
303	1997	.0849	30.98	88	44.95	131	9.30	1579	1518	351	27.8	99	840	9880	9879	1574.2
304	1992	.0852	30.89	85	44.92	131	18.88	1521	1539	354	27.3	99	818	9601	9613	1528.2
305	1995	.0853	30.91	88	45.00	133	30.75	1457	1538	350	27.6	99	796	9274	9263	1458.5
306	1999	.0859	30.78	86	45.03	135	40.00	1384	1526	349	27.1	99	775	9022	8836	1374.2
307	2004	.0852	30.68	87	45.00	140	52.20	1278	1508	351	27.9	100	736	8516	8606	1284.1
308	2004	.0848	30.35	89	44.97	146	63.95	1145	1510	359	27.5	100	681	8036	8017	1142.6
353	2001	.0694	27.60	91	40.00	148	8.12	1351	1640	354	24.7	104	585	8478	8462	1351.2
354	2000	.0691	27.46	92	39.98	150	18.48	1299	1680	356	24.6	105	557	8201	8278	1310.7
355	1998	.0692	27.35	93	40.00	152	28.60	1246	1659	360	24.5	104	555	8006	8010	1248.0
356	2001	.0691	27.80	93	40.01	155	38.60	1166	1655	366	24.7	104	529	7654	7669	1167.8
430	2005	.0630	26.19	90	38.00	151	7.80	1233	1662	351	23.0	108	504	7999	7979	1230.4
431	1994	.0631	26.12	90	37.95	153	19.92	1168	1700	348	24.2	109	486	7708	7741	1175.1
432	2009	.0631	25.92	91	38.08	156	30.09	1123	1702	348	24.7	110	475	7538	7495	1114.0
433	1996	.0626	25.90	92	37.95	159	39.08	1024	1686	358	24.2	110	446	7124	7210	1030.9
434	2011	.0630	25.79	94	38.00	164	48.50	967	1661	374	24.6	111	438	6944	6951	963.4

[1] Corrected to carburetor-air temperature of 90° F and for variations of engine speed and manifold pressure from nominal.

at an inlet-manifold pressure of 38 inches of mercury absolute, was extrapolated to an inlet-manifold pressure of 40 inches of mercury absolute. These data are listed in table II.

TABLE II.—ESTIMATED PERFORMANCE OF 18-CYLINDER RADIAL AIRCRAFT ENGINE

[Engine speed, 2000 rpm; inlet-manifold pressure, 40 in. Hg absolute; fuel-air ratio, 0.063; carburetor-air temperature, 90° F; carburetor-air pressure, 27.35 in. Hg absolute]

Engine exhaust pressure (in. Hg absolute)	Engine power (bhp)	Exhaust temperature (° F)	Charge-air flow (lb/hr)
10	1302	1694	8438
20	1260	1724	8247
30	1201	1724	8000
40	1127	1705	7710
50	1043	1677	7396
60	962	1646	7084

For the computation of net brake horsepower of the combination, the auxiliary supercharger and the turbine were assumed to be on the same shaft and the difference between their powers to be transmitted through gears to the engine crankshaft. The exhaust-gas temperatures used in computing turbine power are included in tables I and II. The temperatures in table I were measured approximately 1¼ feet downstream of the junction of the two halves of the exhaust manifold. The calculated turbine work is that resulting from expansion of the entire engine exhaust-gas flow from engine exhaust static pressure to the altitude atmospheric pressure. The calculated auxiliary supercharger power is that required to compress the engine combustion-air flow from the altitude atmospheric static pressure to the engine carburetor pressure. All supercharger computations presented relate to the auxiliary supercharger because the power of the engine-stage supercharger is contained in the measured engine power listed in the tables of data. Supercharger and turbine efficiencies of 85 percent were used in most of the computations. In addition, some computations were made with efficiencies of 70 percent in order to show the effect of supercharger and turbine efficiencies on performance of the combination. A gear efficiency of 95 percent was used for the calculations. The net power, when the turbine power is greater than the supercharger power, therefore is:

$$\text{engine power}+0.95\,(\text{turbine power}-\text{auxiliary supercharger power})$$

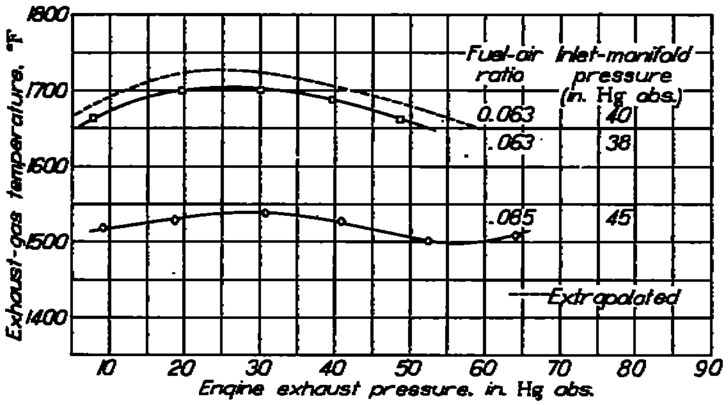

FIGURE 1.—Variation of exhaust-gas temperature with engine exhaust pressure at two fuel-air ratios and three inlet-manifold pressures. 18-cylinder radial aircraft engine; engine speed, 2000 rpm.

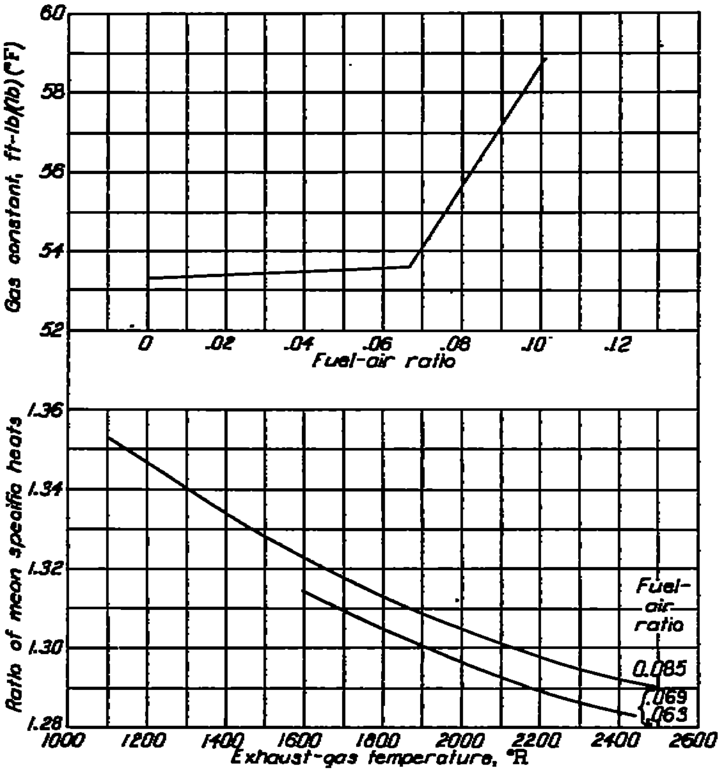

FIGURE 2.—Variation of gas constant with fuel-air ratio and variation of ratio of mean specific heats with exhaust-gas temperature. Hydrogen-carbon ratio, 0.175. (Data from reference 1.)

The fuel flow was divided by the net power to give a net brake specific fuel consumption for the combination.

At each condition computed, the supercharger and the turbine were assumed to be matched to the engine for operation with engine throttle full open and turbine waste gate closed.

DISCUSSION OF CURVES

The variation of exhaust-gas temperature with engine exhaust pressure at two fuel-air ratios and three inlet-manifold pressures at an engine speed of 2000 rpm is presented in figure 1.

Variation of the gas constant for exhaust gas with fuel-air ratio and the variation of the ratio of mean specific heats with exhaust-gas temperature for three fuel-air ratios were taken from reference 1 and plotted in figure 2. These values were

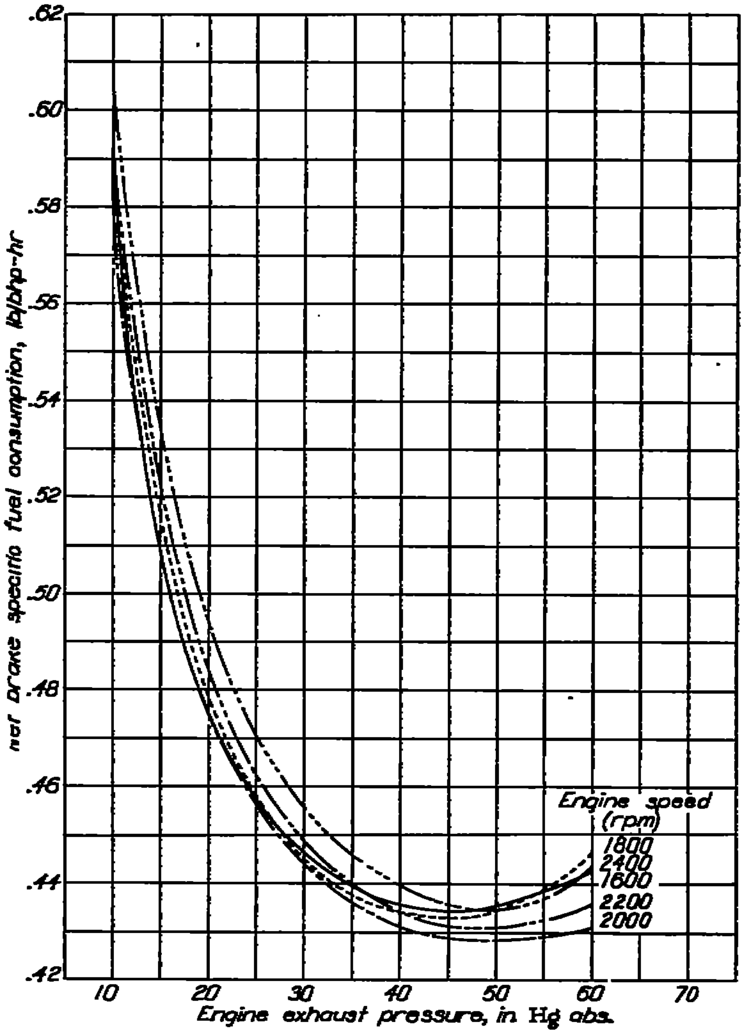

FIGURE 3.—Variation of net brake specific fuel consumption with engine exhaust pressure at various engine speeds. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.085; inlet-manifold pressure, 40 inches of mercury absolute; altitude, 30,000 feet; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 85 percent; gear efficiency, 95 percent.

used in the equations of reference 1 to compute the turbine power. The values of the ratio of mean specific heats are accurate for expansion from the exhaust-gas temperatures through a pressure ratio of 3, and a negligible error is introduced in the range of pressure ratios considered.

The net brake specific fuel consumption of the engine-turbine-supercharger combination at various engine speeds for a fuel-air ratio of 0.085, an inlet-manifold pressure of 40 inches of mercury absolute, and an altitude of 30,000 feet is given in figure 3. This figure indicates that minimum specific fuel consumption can be obtained at a speed of approximately 2000 rpm. Because it is reasonable to expect that this speed will also give minimum specific fuel consumption for fuel-air ratios less than 0.085, all subsequent curves are plotted for a speed of 2000 rpm.

The variation in net brake specific fuel consumption of the combination with engine exhaust pressure at an engine speed of 2000 rpm, an altitude of 30,000 feet, and at various inlet-manifold pressures and fuel-air ratios is shown in figure 4. For a fuel-air ratio of 0.085, the minimum net brake specific fuel consumption decreases as inlet-manifold pressure is increased; a large drop in net brake specific fuel consumption also occurs when the fuel-air ratio is decreased from 0.085 to 0.063. The effect of reducing fuel-air ratio is much greater than that of increasing inlet-manifold pressure. It may be concluded that the most efficient operation occurs at a fuel-air ratio of approximately 0.063 and at the highest inlet-manifold pressure permissible from considerations of engine knock and cooling. At a fuel-air ratio of 0.063 and an engine speed of 2000 rpm, using AN-F-28, Amendment 2, fuel, incipient knock occurred during tests at an inlet-manifold pressure of 39 inches of mercury absolute and an engine exhaust pressure of 28 inches of mercury absolute. The knock became progressively worse as exhaust pressure was increased. The runs at this fuel-air ratio were therefore limited to an inlet-manifold pressure of 38 inches of mercury absolute. Figure 5 presents curves of net brake horsepower of the combination that correspond to the specific-fuel-consumption curves of figure 4.

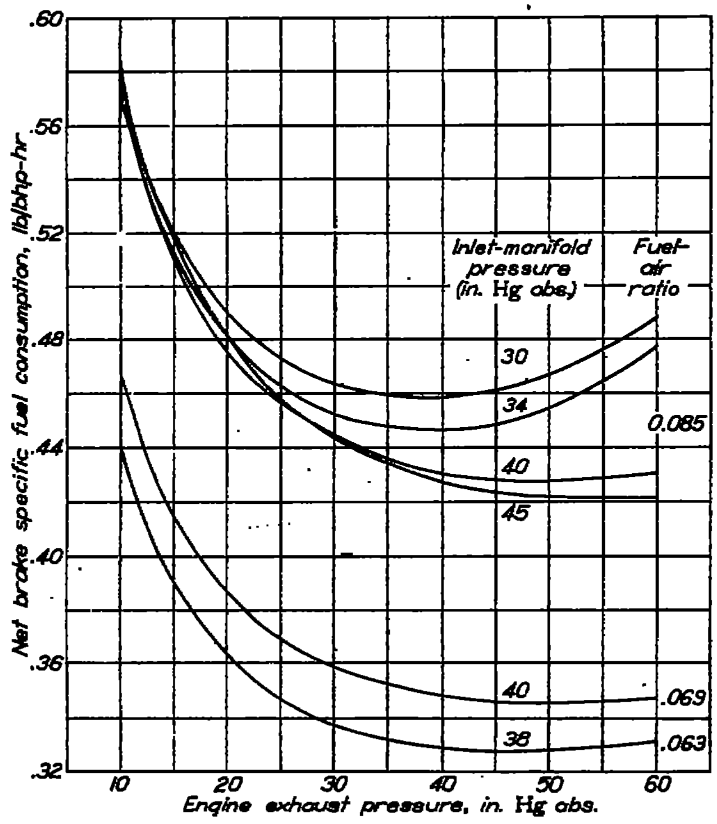

FIGURE 4.—Variation of net brake specific fuel consumption with engine exhaust pressure at various inlet-manifold pressures and fuel-air ratios. 18-cylinder radial aircraft engine with geared turbine and supercharger; engine speed, 2000 rpm; altitude, 30,000 feet; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 85 percent; gear efficiency, 95 percent.

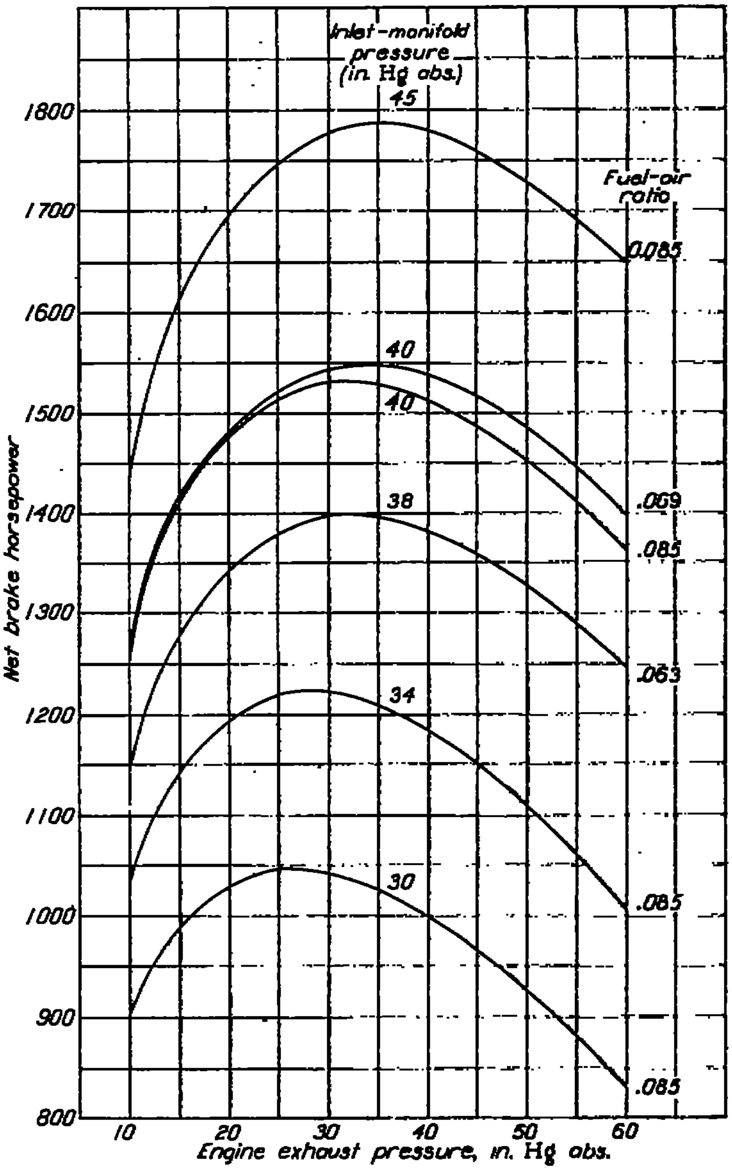

FIGURE 5.—Variation of net brake horsepower with engine exhaust pressure at various inlet-manifold pressures and fuel-air ratios. 18-cylinder radial aircraft engine with geared turbine and supercharger; engine speed, 2000 rpm; altitude, 30,000 feet; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 85 percent; gear efficiency, 95 percent.

Net brake horsepower and net brake specific fuel consumption are shown in figure 6 for an engine speed of 2000 rpm, an inlet-manifold pressure of 38 inches of mercury absolute, and a fuel-air ratio of 0.063 at various altitudes and engine exhaust pressures. Similar curves were calculated assuming a fuel having a higher knock rating than AN-F-28 in the lean range for an inlet-manifold pressure of 40 inches of mercury absolute, based on the extrapolated performance given in table II (fig. 7). In figure 7, maximum net power at an altitude of 30,000 feet occurs at an engine exhaust pressure of approximately 33 inches of mercury absolute. Minimum net brake specific fuel consumption at an altitude of 30,000 feet occurs at an engine exhaust pressure of approximately 50 inches of mercury absolute. There is a trend toward lower optimum engine exhaust pressure at higher altitudes, but the curves are flat and little change in net brake specific fuel consumption occurs between engine exhaust pressures of 42 and 60 inches of mercury absolute. In general, net brake specific fuel consumption is a minimum for engine exhaust pressures approximately 25 percent above inlet-manifold pressure and varies only slightly from the minimum for a range of exhaust pressures from 5 to 45 percent above inlet-manifold pressure. The minimum net brake specific fuel consumptions at 10,000 and 30,000 feet are 0.357 and 0.323 pound per brake horsepower-hour, respectively. If the system is designed to operate at the exhaust pressure for maximum net power, a sacrifice in specific fuel consumption of approximately 3 percent would result.

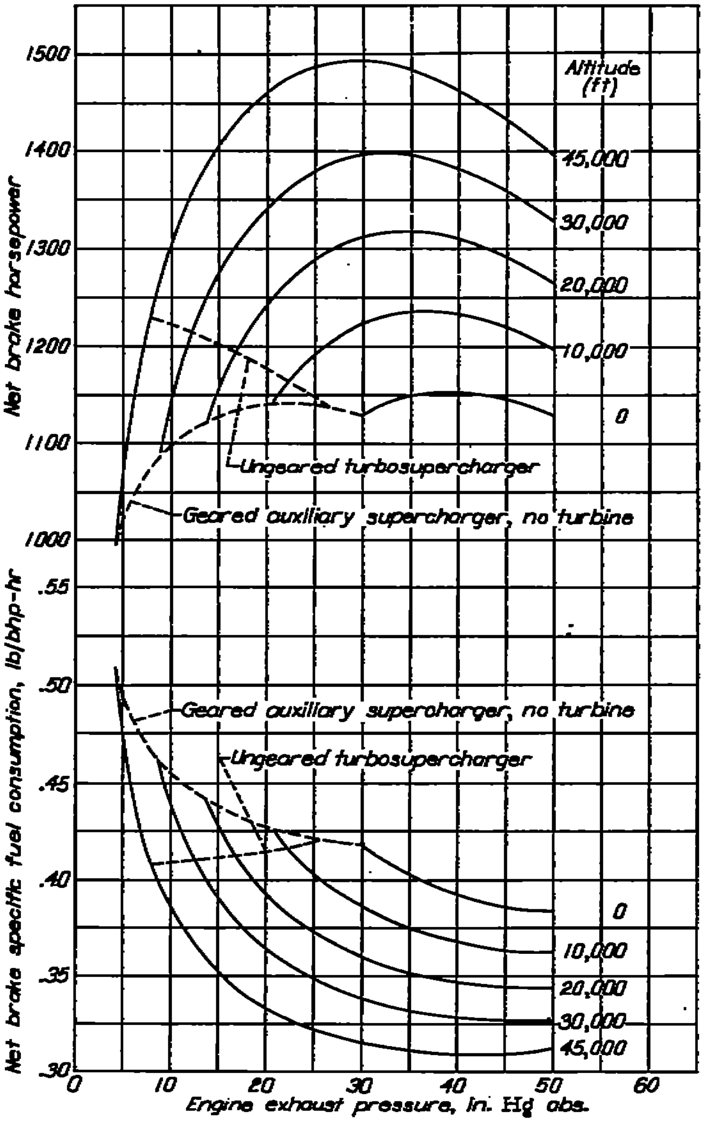

FIGURE 6.—Variation of net brake horsepower and brake specific fuel consumption with engine exhaust pressure at various altitudes. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; engine speed, 2000 rpm; inlet-manifold pressure, 38 inches of mercury absolute; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 85 percent; gear efficiency, 95 percent.

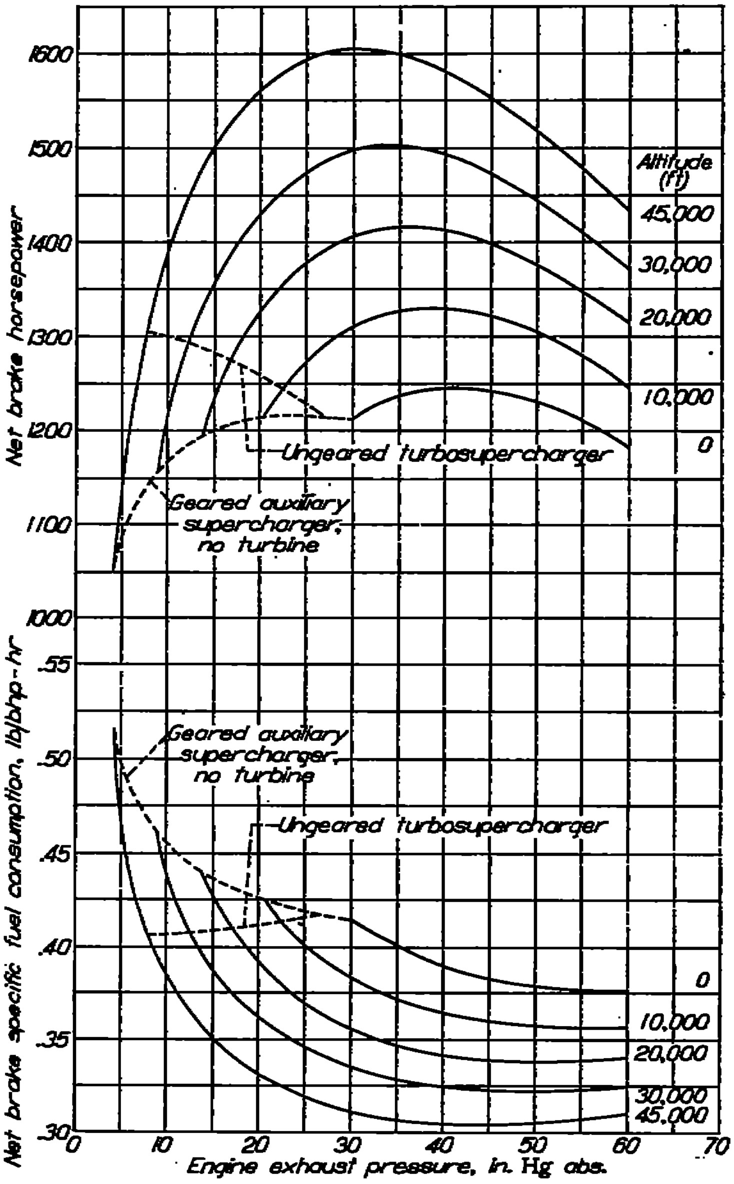

FIGURE 7.—Variation of net brake horsepower and brake specific fuel consumption with engine exhaust pressure at various altitudes. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; engine speed, 2000 rpm; inlet-manifold pressure, 40 inches of mercury absolute; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 85 percent; gear efficiency, 95 percent.

Table III shows the power produced by the engine and the turbine and the power required for the auxiliary supercharger.

For comparison with the optimum geared-turbine arrangement, cross curves are shown in figures 6 and 7 that represent the following cases:

(*a*) Engine with geared auxiliary supercharger and no turbine

(*b*) Engine with ungeared auxiliary turbosupercharger

Current turbosupercharger operation with closed waste gate is approximated by case (*b*). Figure 7 indicates a reduction in net brake specific fuel consumption of 21 percent at an altitude of 30,000 feet and 14 percent at 10,000 feet with the optimum geared-turbine arrangement, as compared with case (*b*).

Calculations were also made for case (*a*) with individual exhaust stacks for auxiliary jet propulsion, assuming the optimum stacks for no engine-power loss, a speed of 350 miles per hour, and a propeller efficiency of 85 percent. The stacks provide an effective increase in engine shaft power of 152 horsepower at 10,000 feet and 203 horsepower at 30,000 feet. The net brake specific fuel consumption is reduced to 0.375 pound per brake horsepower-hour at 10,000 feet and 0.401 pound per brake horsepower-hour at 30,000 feet. The net brake specific fuel consumption obtained for case (*a*) with individual exhaust stacks for auxiliary jet propulsion was lower than that obtained for the engine with ungeared auxiliary turbosupercharger (case (*b*)) at 10,000 feet, equal at 30,000 feet, but higher than that obtained with compound operation at both altitudes.

TABLE III.—ENGINE, TURBINE, AND AUXILIARY SUPERCHARGER POWERS

[Engine speed, 2000 rpm; inlet-manifold pressure, 40 in. Hg abs.; fuel-air ratio, 0.063]

Engine exhaust pressure (in. Hg abs.)	Engine power (bhp)	Turbine power, 85 percent efficiency (bhp)	Auxiliary supercharger power, 85 percent efficiency (bhp)	Excess turbine power, 95 percent gear efficiency (bhp)	Net power (bhp)	Turbine power, 70 percent efficiency (bhp)	Auxiliary supercharger power, 70 percent efficiency (bhp)	Excess turbine power, 85 percent gear efficiency (bhp)	Net power (bhp)
Altitude, 10,000 feet									
20.58	1257	0	37	−39	1218	0	45	−53	1204
30.00	1201	154	36	112	1313	127	44	71	1272
40.00	1127	252	35	206	1333	207	42	140	1267
50.00	1043	311	33	263	1306	256	41	183	1226
60.00	952	344	32	297	1249	283	39	207	1159
Altitude, 20,000 feet									
13.75	1289	0	90	−95	1194	0	109	−128	1161
20.00	1260	158	89	66	1326	130	108	19	1279
30.00	1201	306	86	208	1409	252	105	125	1326
40.00	1127	388	83	289	1416	319	101	185	1312
50.00	1043	433	79	336	1379	356	97	220	1263
60.00	952	453	76	359	1311	373	92	239	1191
Altitude, 30,000 feet									
8.88	1306	0	146	−154	1152	0	177	−209	1097
10.00	1302	52	146	−99	1203	43	177	−158	1144
20.00	1260	327	143	175	1435	269	174	81	1341
30.00	1201	455	138	301	1502	375	168	176	1377
40.00	1127	521	133	368	1495	429	162	227	1354
50.00	1043	553	128	404	1447	455	155	255	1298
60.00	952	563	122	418	1370	463	149	268	1220
Altitude, 45,000 feet									
4.36	1319	0	255	−269	1050	0	310	−365	954
10.00	1302	336	253	79	1381	277	307	−35	1267
20.00	1260	568	247	304	1564	467	300	142	1402
30.00	1201	668	240	407	1608	550	291	220	1421
40.00	1127	711	231	456	1583	586	281	259	1386
50.00	1043	724	221	478	1521	596	269	278	1321
60.00	952	715	211	479	1431	589	256	283	1235

The effect on net brake specific fuel consumption of decreasing the supercharger and turbine efficiencies from 85 to 70 percent and the gear efficiency from 95 to 85 percent is presented in figure 8. These calculations were made for an engine speed of 2000 rpm, an inlet-manifold pressure of 40 inches of mercury absolute, a fuel-air ratio of 0.063, and an altitude of 30,000 feet. The reduction in the efficiencies of turbine, supercharger, and gears causes an 11-percent increase in the minimum net brake specific fuel consumption. This percentage change in fuel consumption may be assigned to the several changes in component efficiencies as follows:

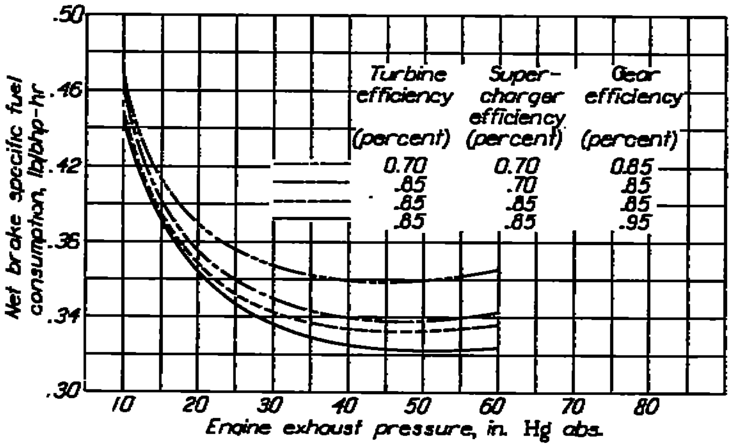

FIGURE 8.—Variation of net brake specific fuel consumption with engine exhaust pressure for various turbine and supercharger efficiencies. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; engine speed, 2000 rpm; altitude, 30,000 feet; inlet-manifold pressure, 40 inches of mercury absolute; carburetor-air temperature, 90° F.

Component	Reduction in component efficiency (percent)		Increase in net brake specific fuel consumption (percent)
	From—	To—	
Turbine	85	70	6.3
Supercharger	85	70	1.6
Gear	95	85	3.1
Total			11.0

The reduction in fuel consumption possible if the turbine were provided with an exhaust nozzle for jet propulsion is shown in figure 9. It was assumed that the tail pipe and the nozzle conserve the turbine-exit velocity with negligible loss. Jet propulsion provides an additional reduction in net brake specific fuel consumption at 350 miles per hour of 3.2 percent at 10,000 feet and 3.7 percent at 30,000 feet. Calculations indicated that, for the cases of figure 9, there is little gain in decreasing the jet-nozzle area and increasing the engine exhaust pressure.

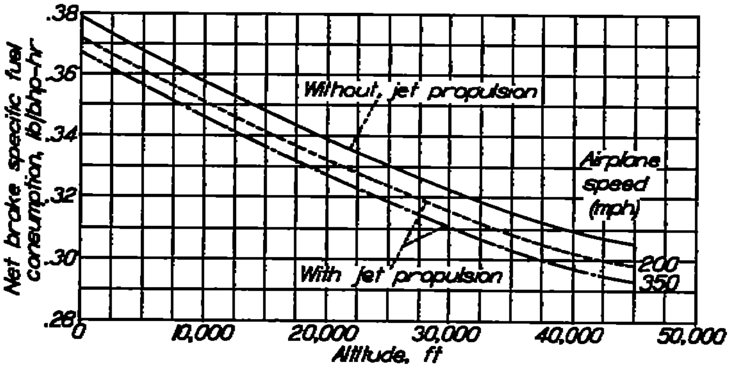

FIGURE 9.—Comparison of net brake specific fuel consumption for engine with geared turbine with and without jet propulsion at various airplane speeds and altitudes. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; engine speed, 2000 rpm; inlet-manifold pressure, 40 inches of mercury absolute; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 85 percent; gear efficiency, 95 percent.

The cooling-air pressure drop required to maintain a temperature of 400° F at the rear spark-plug boss on the average cylinder and approximately 450° F on the hottest cylinder (assuming NACA standard atmosphere) at various exhaust pressures and altitudes is given in figure 10. A cross curve is included to show the pressure drop available at an indicated airspeed of 200 miles per hour, assuming that 80 percent of the dynamic pressure can be made available for cooling.

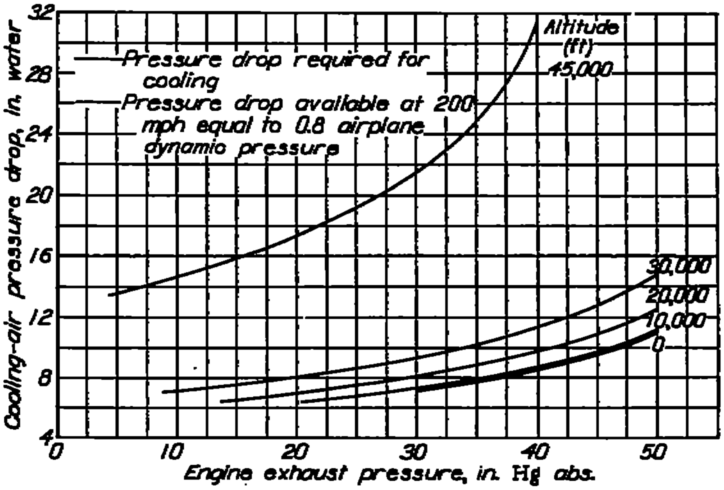

FIGURE 10.—Variation of cooling-air pressure drop with engine exhaust pressure at various altitudes. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; engine speed, 2000 rpm; inlet-manifold pressure, 40 inches of mercury absolute; carburetor-air temperature, 90° F; allowable average rear-spark-plug-boss temperature, 400° F; allowable maximum rear-spark-plug-boss temperature, 450° F; NACA standard atmosphere.

The curves of figure 10 indicate that operation with a high exhaust pressure increases the pressure drop required for cooling. It is possible to reduce the cooling-air pressure drop required, to lessen tendency toward knock, and to increase net power with only a small increase in specific fuel consumption by operating at an exhaust pressure below that required for minimum net brake specific fuel consumption. For example, figure 7 shows that minimum specific fuel consumption at an altitude of 30,000 feet is obtained at an exhaust pressure of 50 inches of mercury. The following table is a comparison of the specific fuel consumption, required cooling-air pressure drop, and engine power for this exhaust pressure and for an exhaust pressure of 42 inches of mercury absolute, taken from figures 7 and 10, respectively:

Engine exhaust pressure (in. Hg abs.)	Net brake specific fuel consumption (lb/bhp-hr)	Net power (hp)	Required cooling-air pressure drop (in. water)
50	0.323	1445	14.8
42	.325	1500	11.9

The effective turbine-nozzle areas required at various engine speeds and exhaust pressures for an inlet-manifold pressure of 40 inches of mercury absolute are shown in figure 11. The areas are almost independent of altitude if supercritical flow exists through the turbine nozzles. At an engine speed of 2000 rpm and an engine exhaust pressure of 50 inches of mercury absolute, figure 11 indicates a required effective turbine-nozzle area of 8 square inches. For an exhaust pressure of 42 inches of mercury absolute, the required area is 10 square inches.

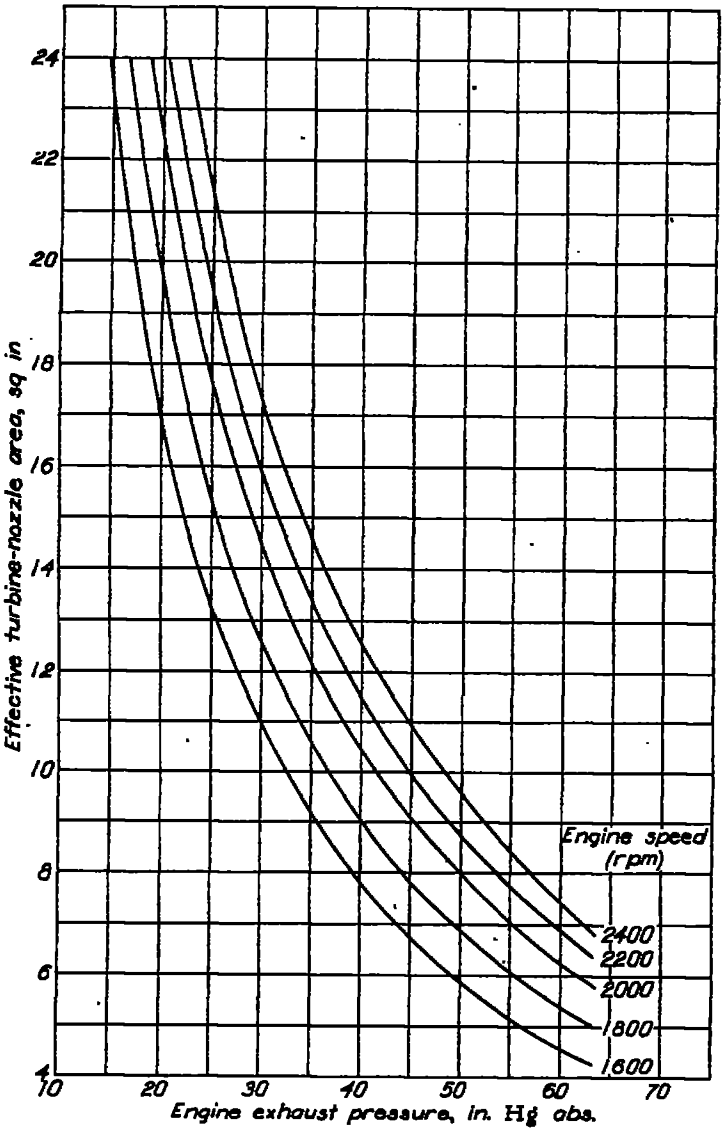

FIGURE 11.—Variation of turbine-nozzle area with engine exhaust pressure at various engine speeds. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; inlet-manifold pressure, 40 inches of mercury absolute; carburetor-air temperature, 90° F.

It is noted in figure 4 that minimum specific fuel consumption is obtained at nearly a constant ratio of engine exhaust pressure to inlet-manifold pressure. A given turbine-nozzle area would provide a nearly constant ratio of engine exhaust pressure to inlet-manifold pressure for a given engine speed. Hence, a turbine-nozzle area chosen to give minimum specific fuel consumption at one inlet-manifold pressure would give minimum specific fuel consumption at other inlet-manifold pressures at the same engine speed. Figure 11 indicates that the required turbine-nozzle area to hold a constant ratio of engine exhaust pressure to inlet-manifold pressure increases nearly proportionately with engine speed.

DISCUSSION OF OPERATION

The characteristics of conventional aircraft engines, superchargers, and exhaust-gas turbines are such that a given set of elements can be made to match for compound operation over only a limited range of engine and flight conditions. A full discussion of the operating problems of a compound engine that will give maximum efficiency over the entire operating range is beyond the scope of this report; nevertheless, a compromise that can be used to obtain the benefits of compound-engine operation over a range of cruising conditions will be discussed.

It is assumed that on each engine two turbosuperchargers are connected by parallel ducts with a modification that permits all the exhaust gas to be passed through only one of the turbosuperchargers and a clutch and gear train to connect that turbosupercharger to the engine crankshaft. At high engine speeds, both turbosuperchargers are free and operate in parallel. At low engine speeds, both are free but only one is required to supercharge the engine. At medium engine speeds, only one turbosupercharger is used and it is geared to the engine crankshaft and operates with a high nozzle-box pressure to provide extra power for the propeller.

For example, a system designed for geared operation with maximum economy at the following conditions is considered:

Engine speed, rpm	2000
Inlet-manifold pressure, inches mercury absolute	40
Altitude, feet	30,000

At these conditions, a turbine with a closed waste gate and an effective nozzle area of 10 square inches will produce an engine exhaust pressure of 42 inches of mercury absolute and, according to figure 7, will give a net brake specific fuel consumption very close to the minimum. For expansion from 42 inches of mercury absolute to atmospheric pressure at an altitude of 30,000 feet, the theoretical turbine-nozzle discharge velocity is 3115 feet per second. For a turbine-wheel pitch-line velocity of 1200 feet per second, the corresponding blade-to-jet speed ratio is 0.385, which gives an efficiency close to the peak value for a single-stage impulse turbine. The turbine should be equipped with a gear train to provide the correct pitch-line velocity at an engine speed of 2000 rpm.

With the same engine speed and inlet-manifold pressure at lower altitudes, engine exhaust pressure remains at 42 inches of mercury absolute down to the altitude at which the pressure ratio across the turbine nozzles is subcritical and then increases to approximately 44 inches of mercury absolute at sea level. The turbine-nozzle discharge velocity is reduced to 1660 feet per second and at constant engine speed the corresponding blade-to-jet speed ratio is 0.723, giving a low turbine efficiency. Also the inlet-manifold pressure provided by the engine-stage supercharger and the geared turbosupercharger increases with a reduction in altitude, and throttling of the superchargers is necessary. At some low altitude, the loss of turbine efficiency, the waste of supercharger power, and excessive heating of the charge would make it advantageous to declutch the turbosupercharger.

Efficient cruise operation at altitudes lower than 30,000 feet can be obtained by slightly reducing the engine speed without changing the ratio with which the turbosupercharger is geared. Little throttling of the supercharger would then be necessary, the turbine efficiency would be near its peak, and over a wide range of altitudes the engine exhaust pressure could be maintained at a high enough value to realize a substantial decrease in net brake specific fuel consumption.

At high altitudes and at engine speeds considerably lower than 2000 rpm, the geared turbosupercharger (designed for the conditions listed) operates at too low a speed and is unable to maintain the required carburetor-air pressure. At very high engine speeds (relative to 2000 rpm) at all altitudes, the turbosupercharger tip speeds exceed the safe value. For both these cases the turbosupercharger should be declutched and operated as a free turbosupercharger.

The range of satisfactory compound operation could be greatly increased by the use of a variable gear ratio between the engine and the turbosupercharger, variable turbine-nozzle area, and variable diffuser vanes to prevent supercharger surge, but these features require considerable development.

Although current equipment cannot be combined to give satisfactory compound operation over the entire range of engine speeds, the foregoing discussion indicates that reductions as great as 21 percent in the minimum brake specific fuel consumption at which the engine can cruise can be attained over a narrow range of engine speeds by the addition of a clutch between the engine and one turbosupercharger; the turbosupercharger can be connected to the engine at these speeds and disengaged at other speeds.

SUMMARY OF RESULTS

Calculations, based on test data for an 18-cylinder radial aircraft engine having a 2804-cubic-inch displacement and 40° valve overlap, gave the following results concerning operation of the engine with a geared exhaust-gas turbine and supercharger:

1. Specific fuel consumption decreased with a decrease in fuel-air ratio to a fuel-air ratio in the neighborhood of 0.063.
2. Specific fuel consumption decreased with increase in inlet-manifold pressure for a constant fuel-air ratio.
3. Minimum specific fuel consumption was obtained at the maximum inlet-manifold pressure for knock-free operation at a fuel-air ratio of about 0.063. Any appreciable increase in fuel-air ratio to avoid knock had a greater adverse effect on economy than the favorable effect of the corresponding permissible increase in inlet-manifold pressure.
4. Minimum specific fuel consumption of this combination occurred at an engine speed of 2000 rpm for the engine under consideration.
5. The net brake specific fuel consumption of the combination was a minimum for engine exhaust pressure approximately 25 percent above inlet-manifold pressure and varied only slightly from the minimum for a range of exhaust pressures from 5 to 45 percent above inlet-manifold pressure.
6. The minimum net brake specific fuel consumption of the combination at an engine speed of 2000 rpm, a fuel-air ratio of 0.063, an inlet-manifold pressure of 40 inches of mercury absolute, and with turbine and supercharger efficiencies of 85 percent was 0.323 pound per brake horsepower-hour at 30,000 feet and 0.357 pound per brake horsepower-hour at 10,000 feet.
7. A reduction in turbine and supercharger efficiencies from 85 to 70 percent and a reduction in gear efficiency from 95 to 85 percent resulted in an 11-percent increase in the minimum brake specific fuel consumption at 30,000 feet and at the same engine conditions.
8. The effective turbine-nozzle area required at an engine speed of 2000 rpm to maintain the optimum ratio of engine exhaust pressure to inlet-manifold pressure for minimum specific fuel consumption of this engine combination was approximately 8 square inches at all altitudes. The required nozzle area increased with engine speed.
9. The provision of an exhaust nozzle to conserve the turbine-exhaust velocity for jet propulsion would allow an additional reduction in fuel consumption at an airplane speed of 350 miles per hour of 3.2 percent at 10,000 feet and 3.7 percent at 30,000 feet.
10. The reduction in net brake specific fuel consumption possible with this system, as compared with the usual ungeared-turbosupercharger arrangement, was approximately 14 percent at 10,000 feet and 21 percent at 30,000 feet.
11. The engine cylinder temperature increased with increase in engine exhaust pressure. Cooling considerations may therefore necessitate the choice of an engine exhaust pressure somewhat lower than optimum, with a small sacrifice in economy.

AIRCRAFT ENGINE RESEARCH LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
CLEVELAND, OHIO, *January 1, 1945*.

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