NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 756

THE INDUCTION OF WATER TO THE INLET AIR AS A MEANS OF INTERNAL COOLING IN AIRCRAFT-ENGINE CYLINDERS

By ADDISON M. ROTHROCK, ALOIS KRSEK, Jr., and ANTHONY W. JONES

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft (or mi)
Time	t	second	s	second (or hour)	sec (or hr)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb
Power	P	horsepower (metric)		horsepower	hp
Speed	V	kilometers per hour	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

2. GENERAL SYMBOLS

W Weight$=mg$

g Standard acceleration of gravity$=9.80665$ m/s^2 or 32.1740 ft/sec^2

m Mass$=\frac{W}{g}$

I Moment of inertia$=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C and 760 mm; or 0.002378 lb-ft^{-4} sec^2

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\frac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\frac{L}{qS}$

D Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D0}=\frac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{Di}=\frac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{Dp}=\frac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

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THE INDUCTION OF WATER TO THE INLET AIR AS A MEANS OF INTERNAL COOLING IN AIRCRAFT-ENGINE CYLINDERS

By Addison M. Rothrock, Alois Krsek, Jr., and Anthony W. Jones

SUMMARY

Investigations were conducted on a full-scale air-cooled aircraft-engine cylinder of 202-cubic-inch displacement to determine the effects of internal cooling by water induction on the maximum permissible power and output of an internal-combustion engine. For a range of fuel-air and water-fuel ratios, the engine inlet pressure was increased until knock was detected aurally, the power was then decreased 7 percent holding the ratios constant. The data indicated that water was a very effective internal coolant, permitting large increases in engine power as limited by either knock or by cylinder temperatures.

INTRODUCTION

The induction of water into the inlet air of an internal-combustion engine has been investigated by various persons as a means of improving engine cooling. Prescott in a paper given in Chicago in 1933, presented data for extremely high permissible power outputs obtained by the use of inducted water to suppress knock. (See reference 1.) Kuhring (reference 2) determined the effect of induction of water and of water-alcohol mixtures on the temperatures of a full-scale aircraft engine. Heron and Beatty (reference 3) have shown that water-alcohol mixtures decrease the temperature of a liquid-cooled single-cylinder test engine. Hives and Smith (reference 4) present brief evidence of the increase of permissible brake mean effective pressure as limited by knock when water is inducted with the incoming air. The effectiveness of water and water-alcohol mixtures as internal coolants in a multicylinder engine has also been investigated at Wright Field. The results of these various investigations show that water is an effective internal coolant.

The use of water as an internal coolant is of particular interest if a suitable aftercooler of the exhaust gases can be designed that will permit the recovery of water formed during the combustion process. Investigations at Langley Memorial Aeronautical Laboratory show that the weight of water formed at a fuel-air ratio of 0.067 is 1.25 (based on exhaust-gas analysis) times the weight of the fuel burned, as compared with an estimated weight of water 1.34 (based on hydrogen-carbon ratio) times the weight of the fuel burned. Consequently, the amount of water in the exhaust is sufficient for appreciable internal cooling of the engine.

If a satisfactory water-recovery apparatus can be designed, several advantages will result:

1. The permissible output from the fuel could be materially increased or the octane number of the fuel required could be materially decreased.
2. The water-recovery apparatus may be mounted in an aircraft wing and used as a wing de-icer.
3. The exhaust flame or glow would be eliminated.
4. Intercoolers or aftercoolers in the supercharging system might be eliminated.

The disadvantages of the system are:

1. Increased weight.
2. Bulkiness of water-recovery apparatus.
3. Increased drag.
4. Difficulties in preventing freezing of water.
5. Difficulties if used in conjunction with turbosupercharger.
6. Difficulties if installed in conjunction with exhaust-jet propulsion.

Information on weights of an aftercooler is given in reference 5, in which Kohr presents data on a water-recovery apparatus built for a small airship. The following information is taken from Kohr's data:

Duration of tests, hours	90
Average airspeed, miles per hour	48
Average air temperature, °F	59
Total weight of fuel used, pounds	15, 075
Total weight of water collected, pounds	13, 943
Water collected, percent of fuel	92. 5
Engine horsepower (estimated)	280
Weight condenser less suspension, pounds	400

The horsepower listed is based on the assumption that the brake specific fuel consumption of the engine was 0.6 pound per horsepower-hour. The weight of the aftercooler is then 1.42 pounds per horsepower. Improved design should appreciably decrease this weight. Also the average airspeed of 48 miles per hour is much slower than that of current military aircraft.

Water as an internal coolant is of interest as a means of suppressing knock in short bursts of high power output, that is, during take-off or during combat maneuvers. In these cases it probably would be necessary to use a water-alcohol mixture to prevent freezing. Such a procedure would permit high powers during take-off with a fuel of low octane number.

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The use of water injection as an internal coolant may have immediate application in types of aircraft in which, where weight limitations are not severe, the water necessary for continuous operation can be carried in addition to the fuel or can be recovered from the exhaust gases.

In view of the possibilities offered by the use of internal coolants, a series of investigations on a full-scale air-cooled aircraft-engine cylinder were undertaken using water as the coolant. The investigations were made at Langley Memorial Aeronautical Laboratory during the period from December 1941 to March 1942.

APPARATUS AND PROCEDURE

The determination of the effect of water injection on the increase in permissible indicated mean effective temperature as limited by engine knock over a range of fuel-air ratios from 0.05 to 0.12 are reported herein. The equipment consisted of a full-scale air-cooled aircraft-engine cylinder of 202-cubic-inch displacement mounted on a CUE crankcase. The following conditions were held constant:

Engine speed, rpm	2000
Spark advance, degrees	20
Compression ratio	7.0
Inlet-air temperature, ° F	250

The results have been separated into two groups. Group A includes investigations made with AFD–28 fuel and a constant cooling-air pressure drop of 8.5 inches of water across the engine. Group B includes investigations made with the fuel of 80-octane number and a constant cooling-air pressure drop of 14 inches of water.

In both series of investigations, the term "maximum permissible" as applied to power, indicated mean effective pressure, or inlet pressure refers to the maximum permissible value as limited by fuel knock or detonation and was taken as 93 percent of the value of the audible knock or detonation. Subsequent investigations with knock detectors of various types showed that such procedure agreed very closely with incipient knock as determined by the detectors. The procedure for establishing the maximum permissible values is given in reference 6.

The data recorded include the maximum permissible indicated mean effective pressure, the indicated specific fuel consumption, the maximum permissible inlet pressure, and the temperature of the cylinder and the head at different positions.

The program was started with a CFR fuel designated AFD–28 having a knock rating equal to isooctane plus 1.06 ml TEL by the CFR Aviation (1–C) Method. Owing to the increase of permissible power allowed by water injection, the capacity of the test equipment was reached before large water-fuel ratios (by weight) were tried.

Investigations over a large range of water-fuel ratios were made with another fuel of lower octane rating and lower initial power output than those of the CFR fuel AFD–28. This fuel, a commercial automobile gasoline, was rated 80-octane number by the CFR Aviation Method in accordance with specification AN–VV–F–746.

The water for the investigations made under Group A was injected through a suitable nozzle into the inlet pipe about 15 inches upstream of the inlet port of the engine and 9 inches upstream of the fuel-injection valve. The coolant was continuously injected downstream whereas the fuel spray was directed upstream and was injected only during the inlet stroke. The maximum permissible inlet-air pressure was limited to 60 inches of mercury absolute by the capacity of the coils for heating the inlet air for the Group A investigations. The large water quantities used in the Group B investigations caused erroneous readings in inlet-air temperature because surging of the air mass inside the inlet pipe carried water into contact with the inlet-air thermometer. The water injection nozzle was moved 5 inches farther downsteam to remedy the condition before any data were taken.

Determinations of the value and the position of the cylinder peak pressures for a fuel-air ratio near 0.07, the fuels 80-octane and S–1 plus 6 ml TEL per gallon, and various water-fuel ratios were made with a Farnsboro indicator.

RESULTS

GROUP A

Maximum permissible engine performance.—Figure 1 presents the relation between the fuel-air ratio and the maximum permissible performance for different water-fuel ratios. The data in figure 1 show a marked increase in permissible indicated mean effective pressure with water injection.

The percentage increase in the maximum permissible indicated mean effective pressure with water injection at each of the three water-fuel ratios investigated is as follows:

Fuel-air ratio \ Water-fuel ratio	0.2	0.4	0.6
0.067	22	45	71
.075	33	52	--
.090	13	--	--

If the percentages of increase in indicated mean effective pressure are assumed to be independent of the octane number of the fuel, it is estimated that for a water-fuel ratio of 0.6, an engine requiring a fuel of 100-octane number could operate satisfactorily on a fuel of 80-octane number. The octane numbers estimated for water-fuel ratios of 0.4 and 0.2 are 88 and 94, respectively. The data indicate that the permissible decrease in octane number for moderate quantities of water injected is considerable. No appreciable difference in the indicated specific fuel consumption was noticed over the range of water quantities used.

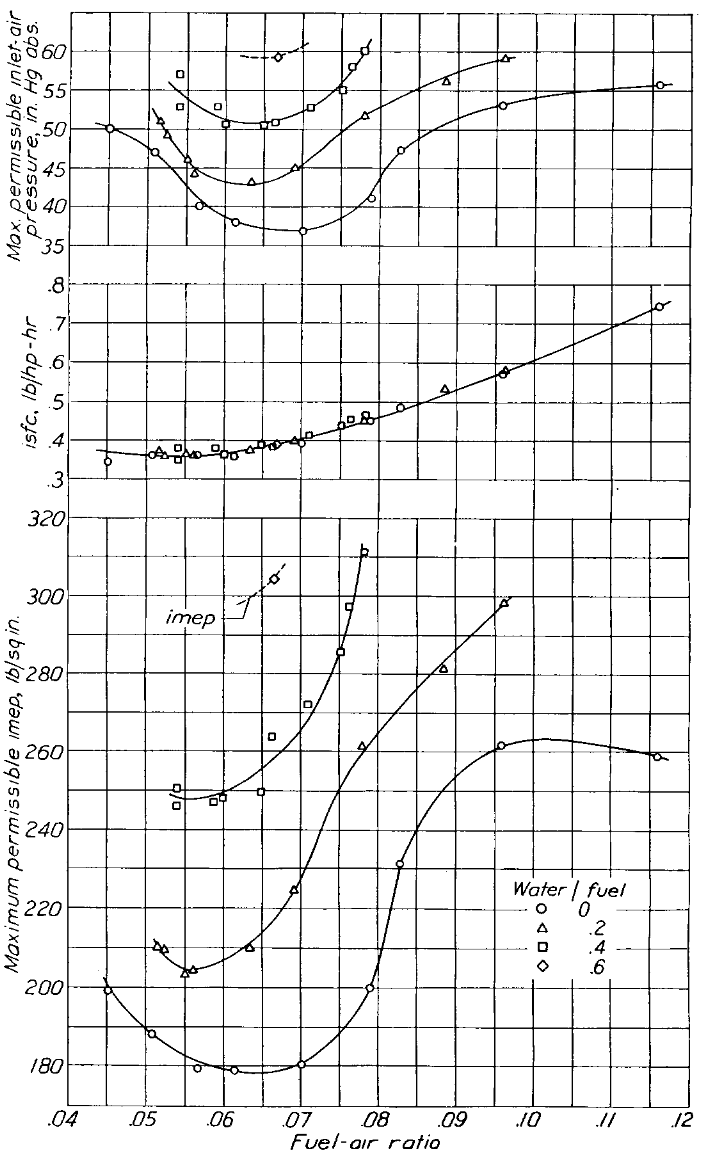


FIGURE 1.—Relation between fuel-air ratio and maximum permissible engine performance for different water-fuel ratios. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 8.5 inches water; fuel, AFD-28; knock rating, isooctane plus 1.06 (CFR Aviation Method).

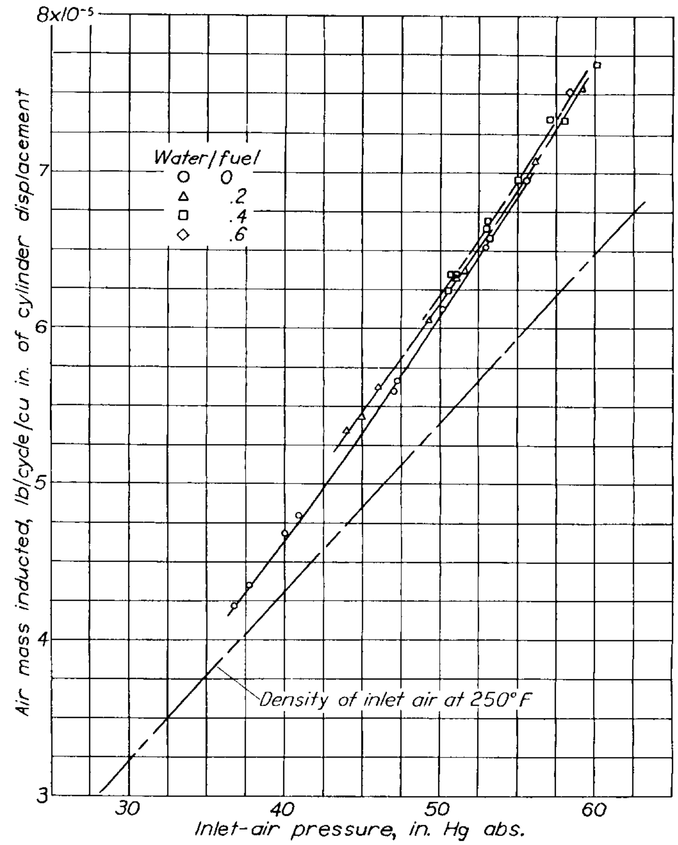


FIGURE 2.—Relation between inlet-air pressure and air mass inducted into cylinder for different water-fuel ratios. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 8.5 inches water; fuel, AFD-28.

Figure 2 shows the relation between the inlet pressure and the air mass inducted, in which the air mass inducted is expressed as pounds per cycle per cubic inch of cylinder displacement. The data show that the air mass inducted increased slightly as the water-fuel ratio was increased. The fact that the amount of air mass inducted increased so slightly with the quantity of water injected seems to indicate that vaporization was taking place within the cylinder rather than within the inlet pipe.

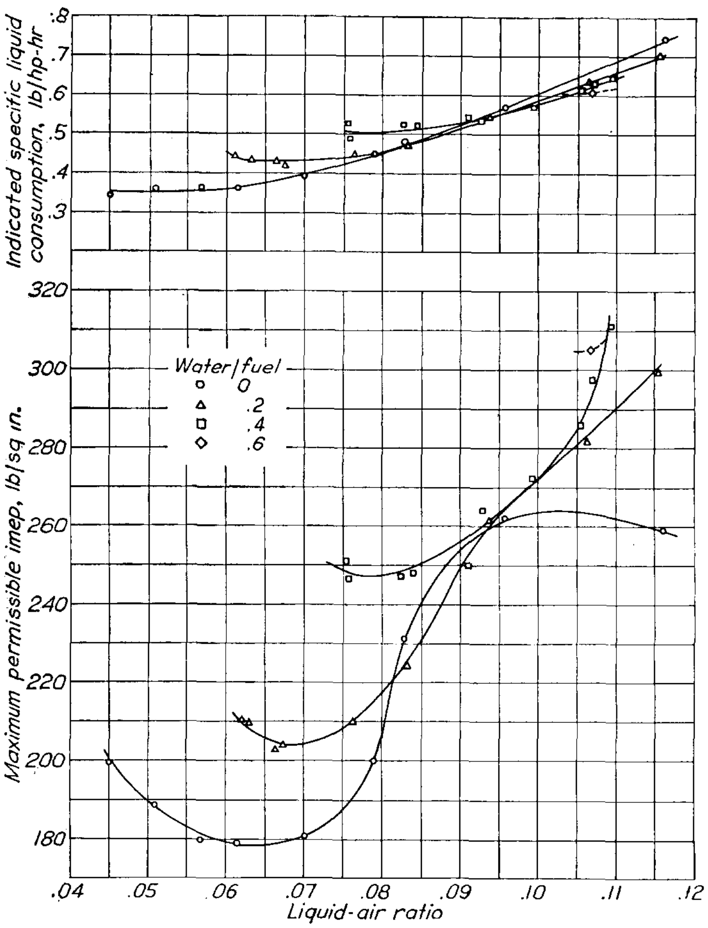


FIGURE 3.—Relation between liquid-air ratio and maximum permissible engine performance for different water-fuel ratios. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 8.5 inches water; fuel, AFD-28.

In figure 3 the performance data are presented on the basis of liquid-air ratio rather than fuel-air ratio, the liquid being the sum of the weights of the fuel and the water. The data show that in the region of liquid-air ratios of 0.093 and higher the indicated specific liquid consumption decreases and the maximum permissible indicated mean effective pressure increases as the water-fuel ratio is increased. By reference to figure 1 in conjunction with figure 3, it is evident that at fuel-air ratios of 0.07 or less, an increase in the water-fuel ratio increases the permissible indicated mean effective pressure; but it also increases the indicated specific liquid consumption. It is therefore apparent that for operations requiring high power (that is, take-off) it is more economical from the standpoint of liquid consumption to use water injection than to increase the fuel flow.

Figure 4 shows the maximum permissible indicated mean effective pressure as a function of the indicated specific liquid consumption. Data at fuel-air ratios less than 0.06 are not included. The data indicate that an increase in the maximum permissible indicated mean effective pressure through the use of water injection can be had at a constant indicated specific liquid consumption in either the lean (fuel-air ratio below 0.07) or the rich (fuel-air ratio above 0.07) region. For an indicated specific liquid consumption between about 0.48 and 0.54, there was not much choice between the use of a rich mixture in fuel only or a lean fuel-air mixture with water added. Additional data at higher water-fuel ratios may change this conclusion.

Engine temperatures.—The temperature data are presented in figure 5. The temperature of the rear spark-plug bushing (fig. 5 (a)) at a fuel-air ratio of 0.067 showed a change of only 18° F as the permissible indicated mean effective pressure was increased from 180 to 305 (fig. 1) through the induction of water at a water-fuel ratio of 0.6. Also, the temperatures at a maximum permissible mean effective pressure of 260 were about the same whether this permissible indicated mean effective pressure was obtained by increasing the fuel-air ratio to 0.095 or by maintaining the fuel-air ratio at 0.067 and using a water-fuel ratio of 0.4. In the rich region, that is, at fuel-air ratios in excess of 0.085, the cylinder barrel under the head (fig. 5 (b)) showed lower temperature, even though the power was higher, with water injection than with straight fuel.

The exhaust-valve-guide temperature (fig. 5 (c)) showed a considerable increase as the maximum inlet pressure was increased with the water injection. This increase is probably caused by the increased mass flow of the gases passing around the exhaust valve and possibly also through increased gas leakage past the guide, resulting from the higher exhaust pressures that occurred as the water-fuel ratio was increased.

The temperature of the head between valves (fig. 5 (d)) showed a noticeable decrease for the higher values of water-fuel ratio, even though the engine power was increased. In

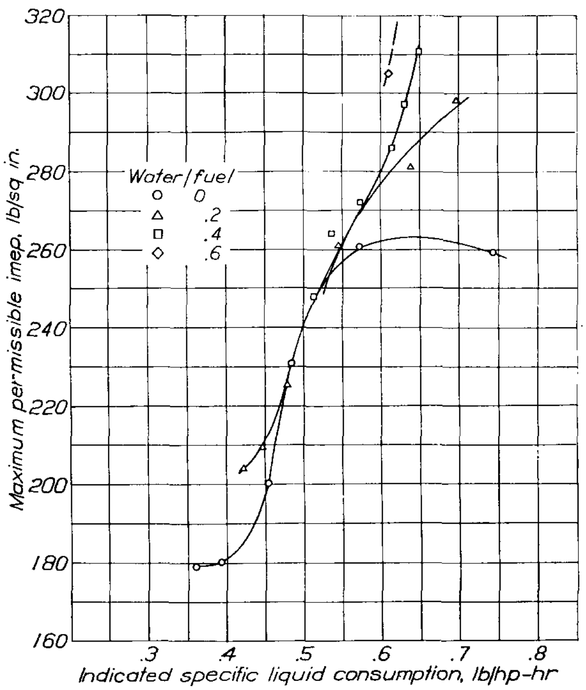
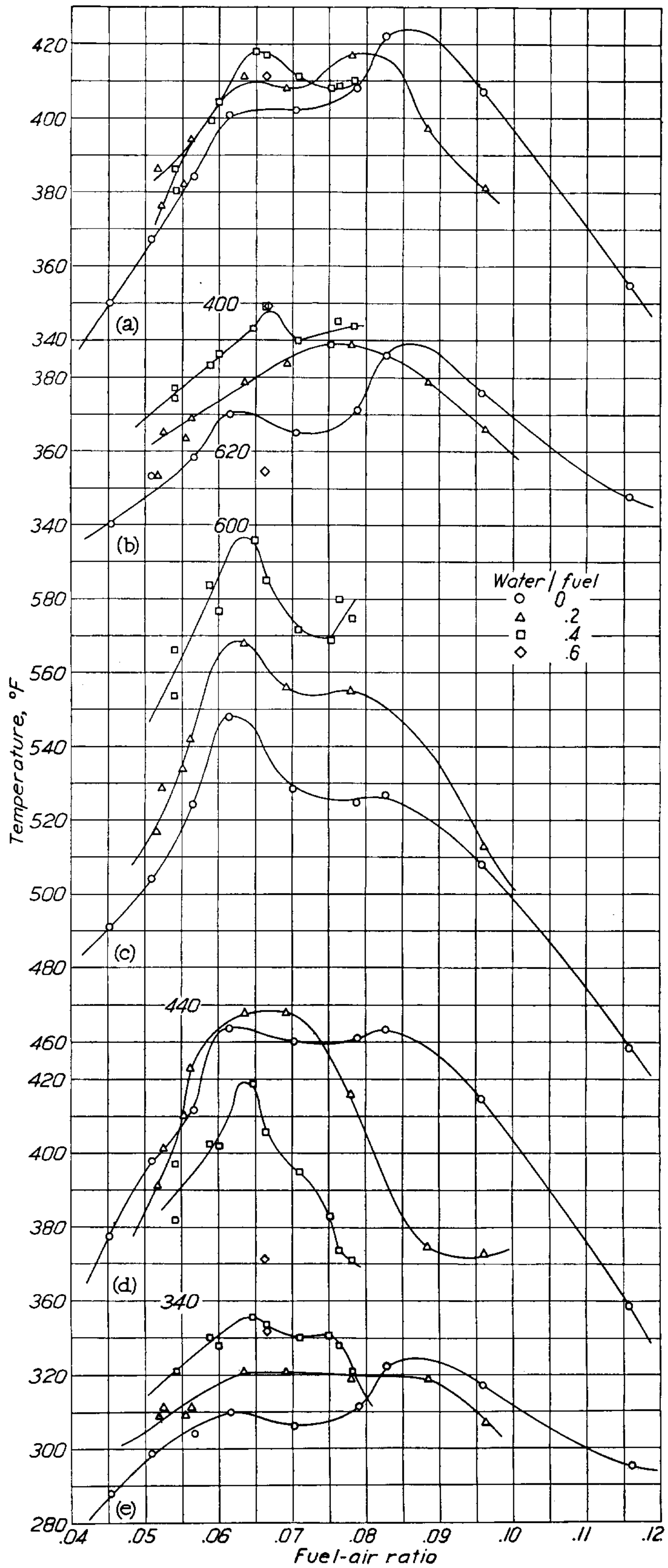


FIGURE 4.—Relation between indicated specific liquid consumption and maximum permissible indicated mean effective pressure for different water-fuel ratios. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 8.5 inches water; fuel, AFD-28.



(a) Rear spark-plug bushing.
(b) Cylinder barrel under head, rear.
(c) Exhaust-valve guide.
(d) Head between valves.
(e) Above cylinder flange, rear.

FIGURE 5.—Relation between fuel-air ratio and engine temperatures at maximum permissible inlet pressure for different water-fuel ratios. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 8.5 inches water; fuel, AFD-28.

this case the incoming charge probably caused this decrease in temperature. The temperature above the cylinder flange (fig. 5 (e)) showed some increase as the water-fuel ratio was increased. In all these investigations it is emphasized that, as the water-fuel ratio was increased, the power was also increased.

Constant inlet-air pressure investigations.—For the data in figure 6, the inlet-air pressure was constant at 35 inches of mercury absolute and the engine was operated over a range of fuel-air ratios at different water-fuel ratios. Over the range of water-fuel ratios investigated, the induction of the water caused little change in the indicated mean effective pressure from 0.060 to 0.090 fuel-air ratio, but a decrease in

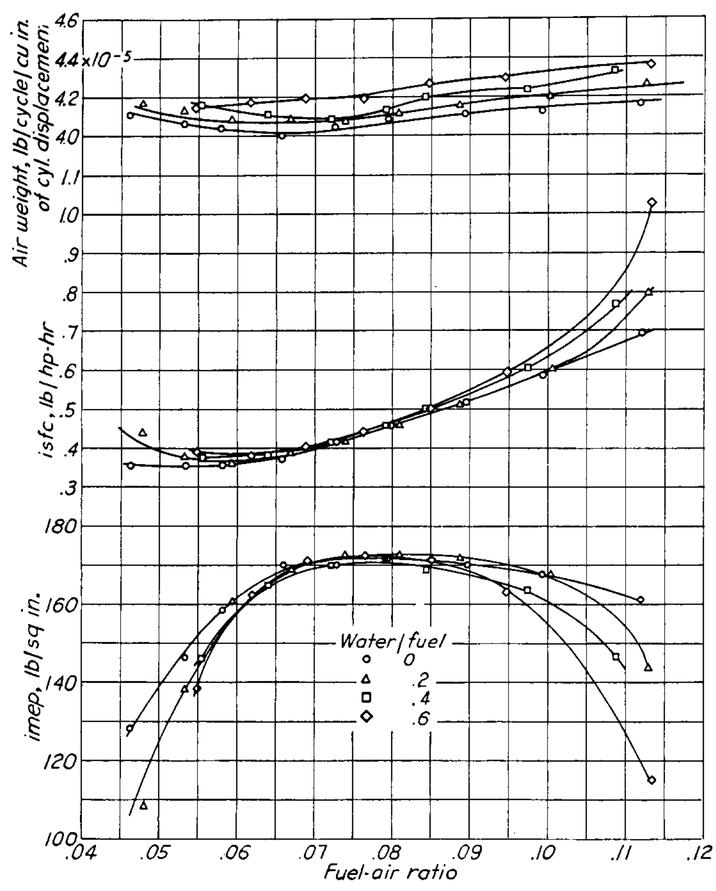
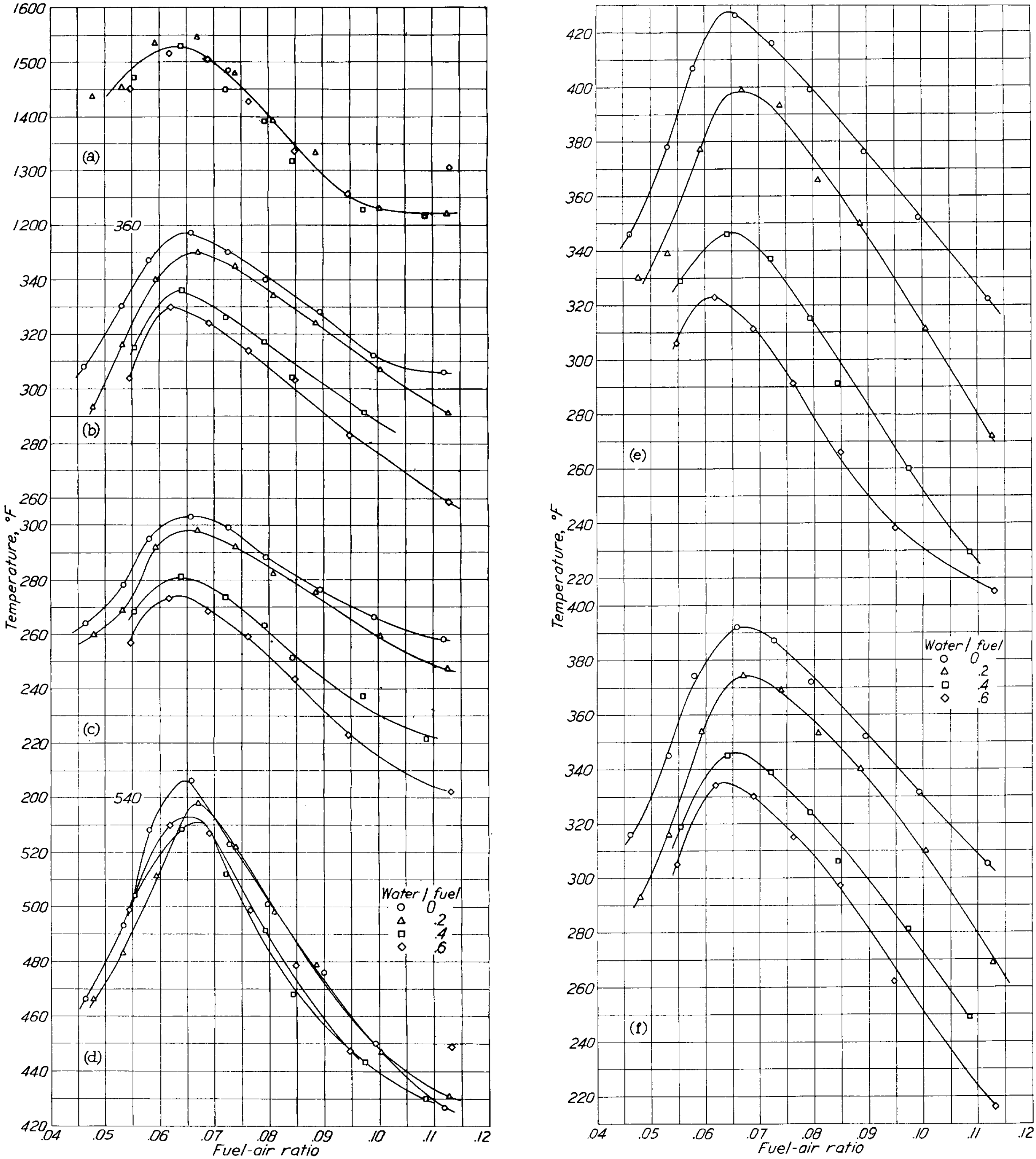


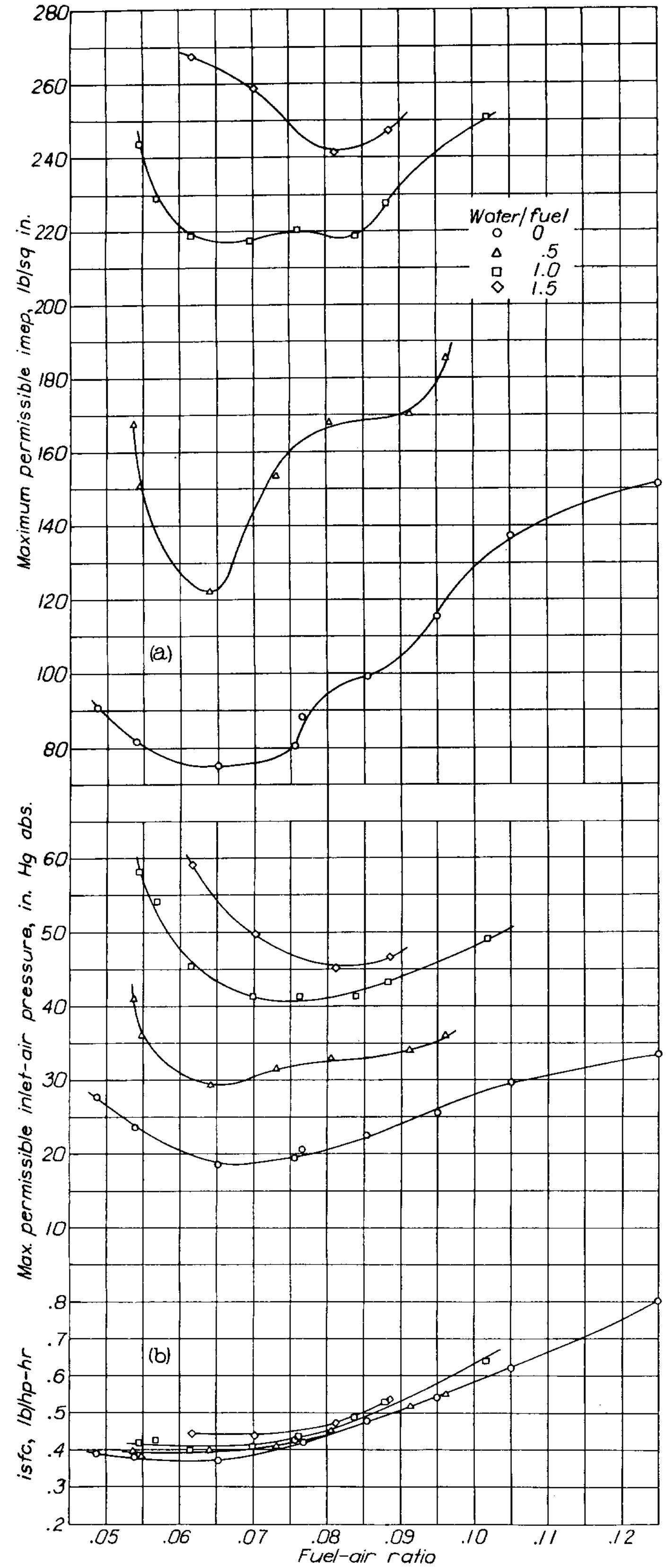
FIGURE 6.—Effect of water injection on engine performance at constant manifold inlet pressure. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 8.5 inches water; fuel, AFD-28; manifold inlet-air pressure, 35.0 inches of mercury absolute.

power was observed with the addition of water at richer fuel-air mixtures. There was some increase in the air mass inducted as the water-fuel ratio was increased. This increase, although small, is reflected in the curve of indicated mean effective pressure within the fuel-air-ratio range of 0.065 to 0.085. The curves of indicated specific fuel consumption in this range show that, within the accuracy of the data, the water caused no change in fuel consumption; an increase in fuel consumption occurred, however, at fuel-air ratios richer than 0.085. From the standpoint of economy it is doubtful whether the small increase in indicated mean effective pressure shown by the curves is sufficiently significant to warrant water injection when a fuel is used at conditions below its maximum permissible performance.



(a) Exhaust gas.
(b) Cylinder barrel under head, rear.
(c) Above cylinder flange, rear.
(d) Exhaust-valve guide.
(e) Head between valves.
(f) Rear spark-plug bushing.

FIGURE 7.—Effect of water injection on engine temperature at constant manifold inlet pressure. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 8.5 inches water; fuel, AFD-28; manifold inlet pressure, 35.0 inches of mercury absolute.



(a) Maximum permissible indicated mean effective pressure.
(b) Indicated specific fuel consumption and maximum permissible inlet-air pressure.

FIGURE 8.—Relation between fuel-air ratio and maximum permissible engine performance for different water-fuel ratios. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 14.0 inches water; fuel, 80-octane number.

From the standpoint of engine cooling, however, water injection can be used to an advantage. All temperatures, except the exhaust, decreased when the water was inducted (figs. 7 (b) to 7 (f)). The exhaust temperatures showed no change with increased water-fuel ratio (fig. 7 (a)).

The exhaust temperatures as recorded in these constant-pressure tests were probably affected by radiation with the result that true gas temperatures were not indicated.

GROUP B

Maximum permissible engine performance.—Figure 8 shows the relation between fuel-air ratio and maximum permissible performance for different water-fuel ratios. The data in figure 8 (a) show the maximum increase in permissible indicated mean effective pressure that was obtained from the fuel of 80-octane number with the use of water injection. At a water-fuel ratio of 1.5 and fuel-air ratios of 0.06 to 0.08, the operation of the engine was rough. Figure 8 (b) shows an increase in indicated specific fuel consumption as the water-fuel ratio was increased at constant fuel-air ratio. For a given power output, the specific fuel consumption is seen to be less with water mixtures.

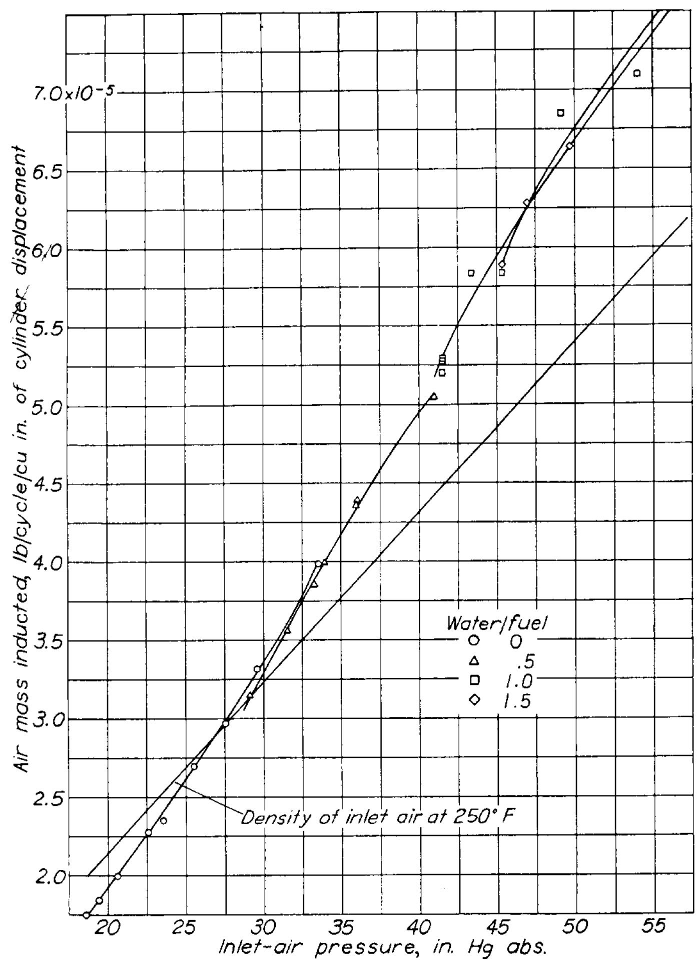


FIGURE 9.—Relation between inlet-air pressure and air mass inducted into cylinder for different water-fuel ratios. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 14.0 inches water; fuel, 80-octane number.

The percentages of increase in maximum permissible indicated mean effective pressure resulting from the water induction are as follows for the fuel of 80-octane number:

Fuel-air ratio \ Water-fuel ratio	0.5	1.0	1.5
0.067	72	189	251
.075	100	175	212
.090	62	121	138

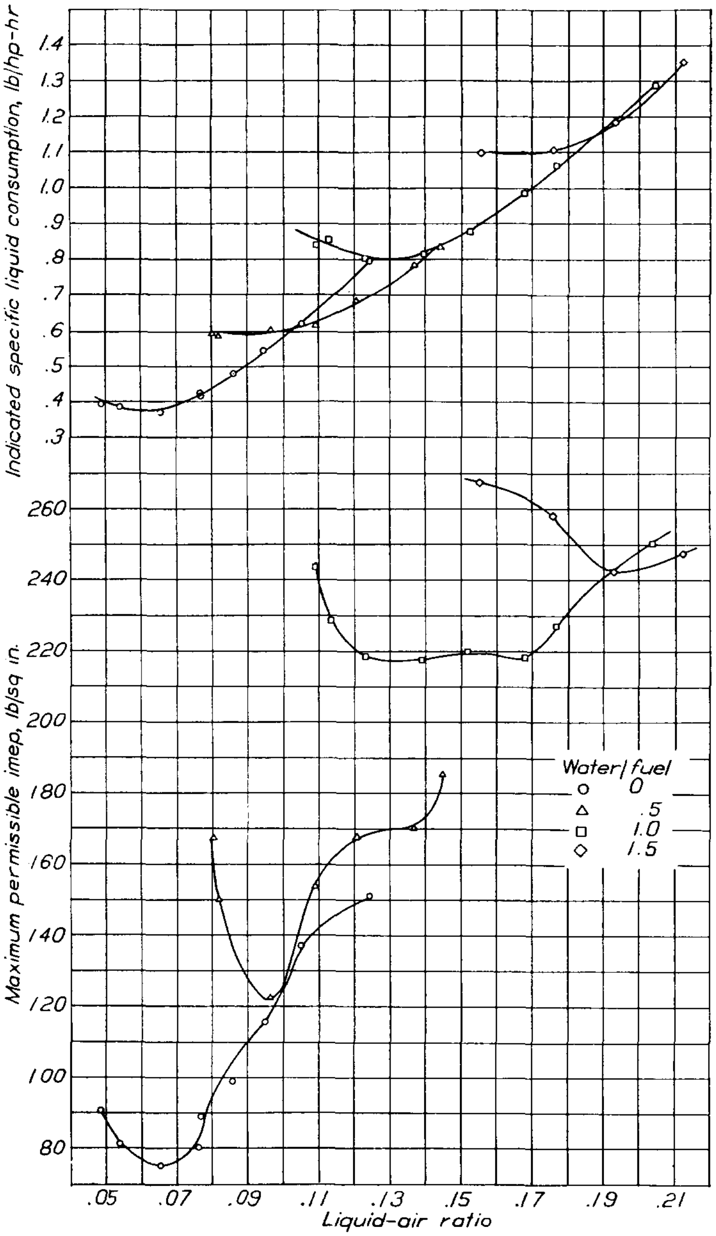


FIGURE 10.—Relation between liquid-air ratio and maximum permissible engine performance for different water-fuel ratios. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 14.0 inches water; fuel, 80-octane number.

Figure 9 shows the relation between the inlet-air pressure and the air mass inducted. The data show little difference in the charge-air flow at a given inlet pressure. This condition seems to indicate that the greater part of the vaporization was taking place within the cylinder at all water-fuel ratios.

Performance data on a total-liquid-air basis is given in figure 10. These data extend over a large liquid-air range

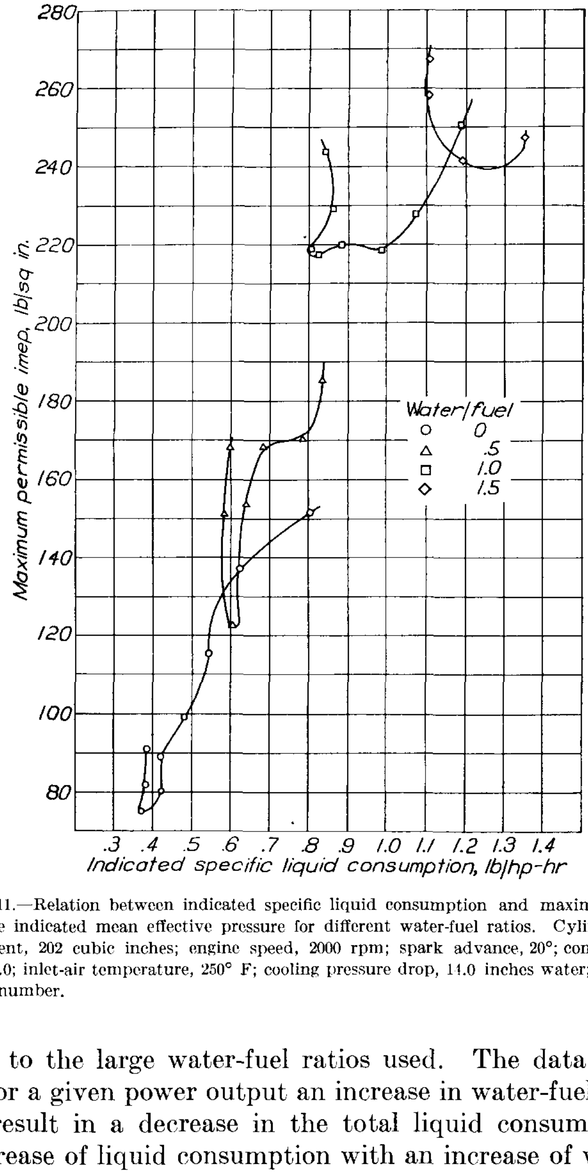
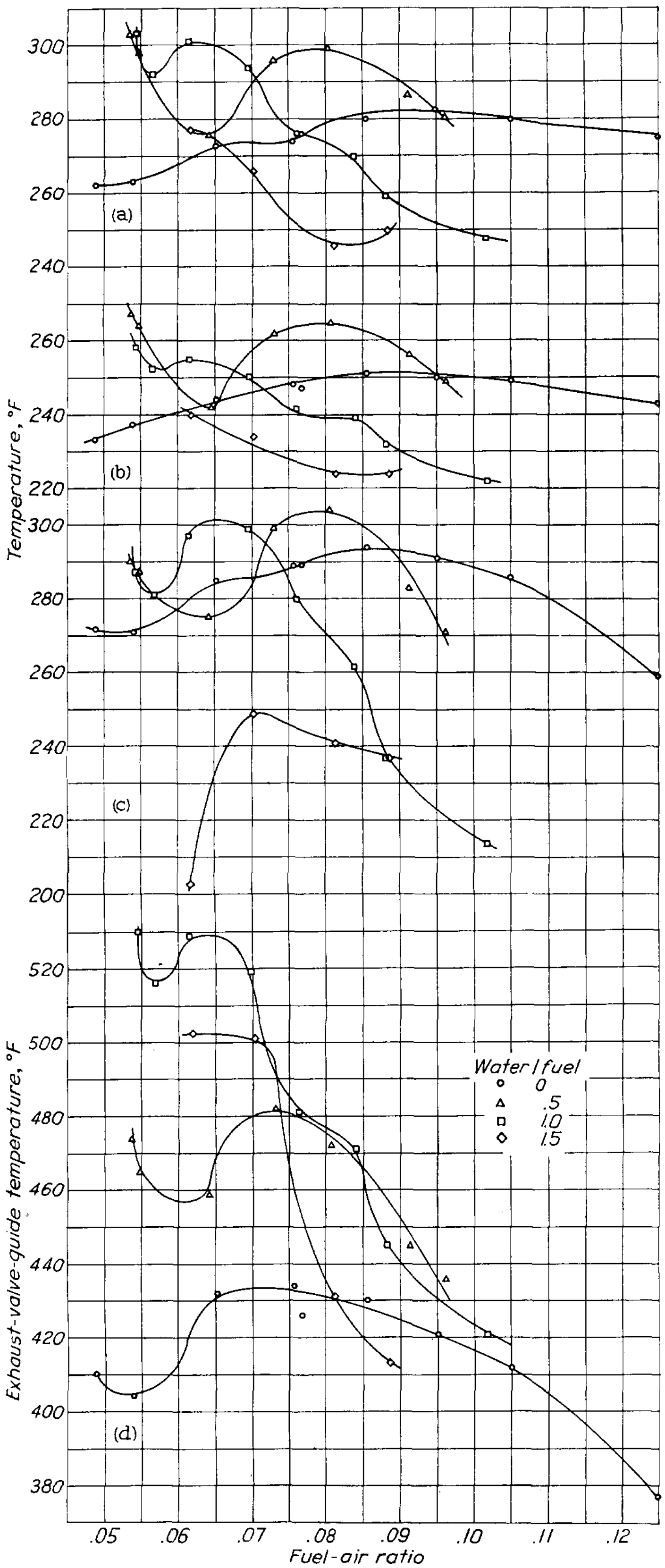


FIGURE 11.—Relation between indicated specific liquid consumption and maximum permissible indicated mean effective pressure for different water-fuel ratios. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 14.0 inches water; fuel, 80-octane number.

owing to the large water-fuel ratios used. The data show that for a given power output an increase in water-fuel ratio may result in a decrease in the total liquid consumption. A decrease of liquid consumption with an increase of water-fuel ratio affords an appreciable saving of fuel with no increase in total liquid weight. It should be stressed, however, that these curves are hardly comparable because powers can be obtained with internal coolants that are otherwise not permitted.

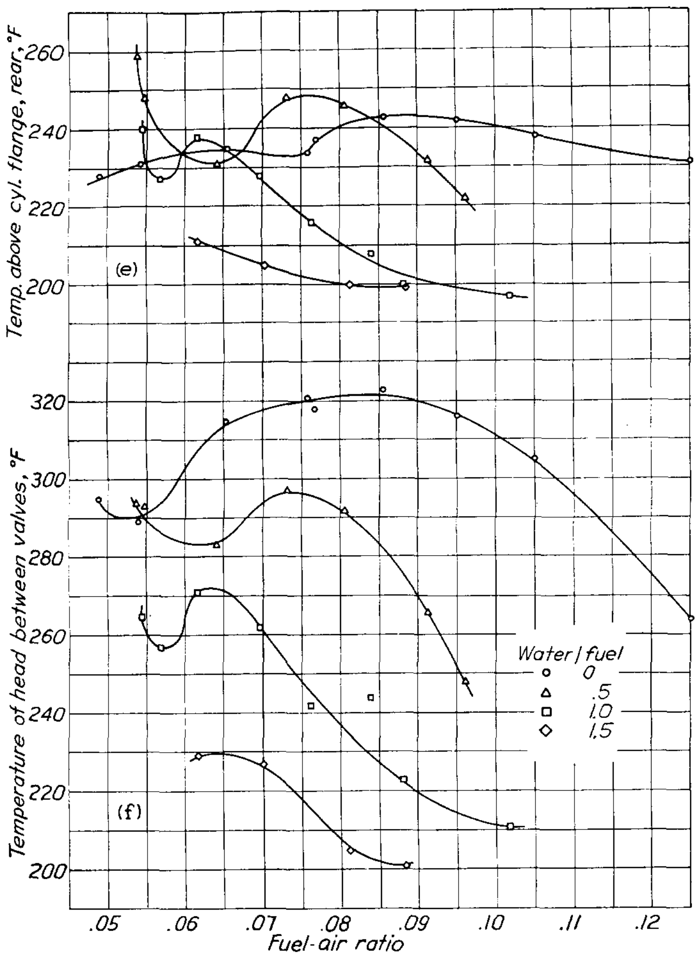


(a) Cylinder barrel under head, rear.
(b) Cylinder barrel middle, rear.
(c) Rear spark-plug bushing.
(d) Exhaust-valve guide.

FIGURE 12.—Relation between fuel-air ratio and engine temperatures at maximum permissible inlet pressure for different water-fuel ratios. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 14.0 inches water; fuel, 80-octane number.

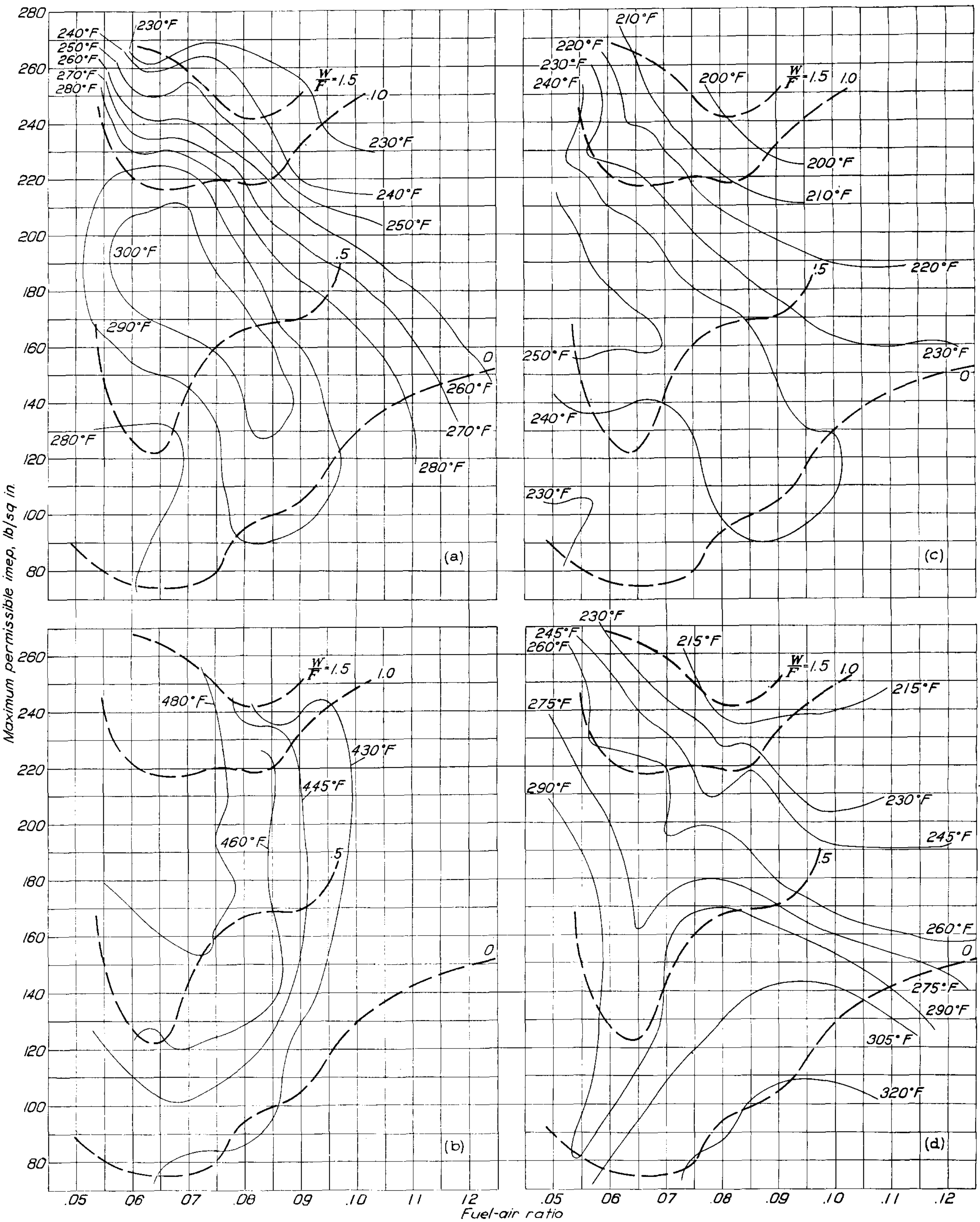
Figure 11, which shows the maximum permissible indicated mean effective pressure as a function of indicated specific liquid consumption, illustrates the economy of water injection more directly than figure 10. Data for all fuel-air ratios are included in this plot, the leanest fuel-air ratio mixture for any particular curve being at the left end. The narrow range of indicated specific liquid consumption for each water-fuel ratio is not indicative of very limited operating conditions, as may be seen by comparison with figure 10.

Figure 12 presents the experimental data for the engine temperatures at various points of the head and cylinder as a function of fuel-air ratio. These data are cross-plotted on



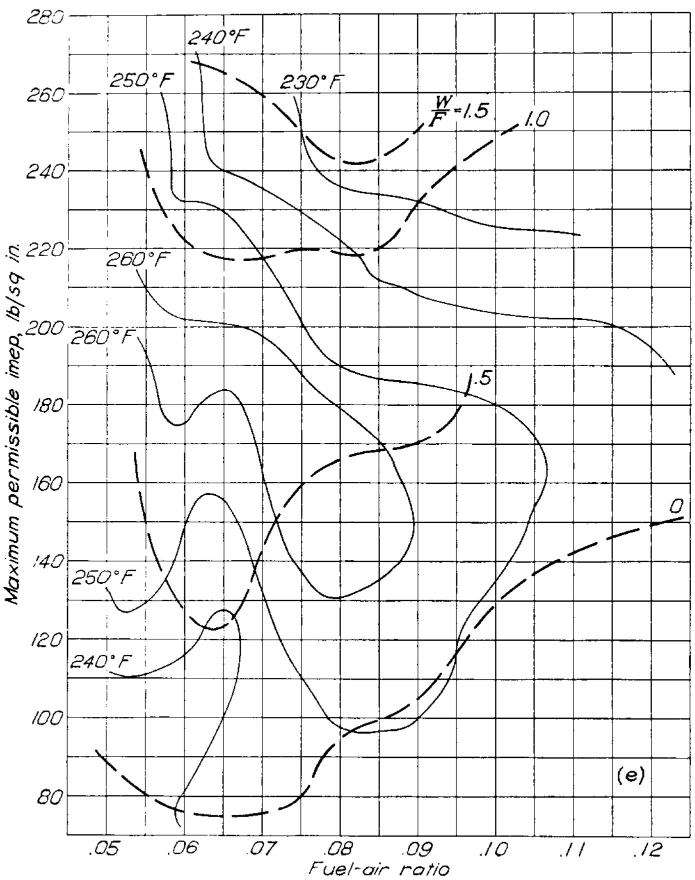
(e) Above cylinder flange, rear.
(f) Head between valves.

FIGURE 12.—Concluded.—Relation between fuel-air ratio and engine temperatures at maximum permissible inlet pressure for different water-fuel ratios. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 14.0 inches water; fuel, 80-octane number.



(a) Rear spark-plug bushing.
(b) Exhaust-valve guide.
(c) Above cylinder flange, rear.
(d) Center of head between valves.

FIGURE 13.—Relation between fuel-air ratio, maximum permissible indicated mean effective pressure, engine temperatures, and water-fuel ratios of 0, 0.5, 1.0, and 1.5. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 14.0 inches water; fuel, 80-octane number.



(e) Cylinder barrel, middle rear.

FIGURE 13.—Concluded.—Relation between fuel-air ratio, maximum permissible indicated mean effective pressure, engine temperatures, and water-fuel ratios of 0, 0.5, 1.0, and 1.5 Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling pressure drop, 14.0 inches water; fuel, 80-octane number.

figure 13 to show the interrelation between the maximum permissible indicated mean effective pressure, fuel-air ratio, water-fuel ratio, and engine temperatures. These curves resemble a contour map in which the contour lines represent constant temperatures. Temperature lines between experimental points were interpolated.

In consideration of the temperatures of cylinder barrel under head, spark-plug bushing, and above cylinder flange, all on the rear of the engine, all temperatures at fuel-air ratios richer than 0.095 were lower with water injection than without water injection regardless ot the amount of water injected or the power output. At a water-fuel ratio greater than 0.5 the preceding result held true for the temperature of the middle-cylinder barrel on the rear of the engine. At fuel-air ratios leaner than 0.095, the temperatures with a water-fuel ratio of 0.5 were usually higher than without water.

Water injection had a noticeable effect in lowering the temperature of the head between the valves. All the temperatures were lower and the differences increased as more water was injected.

The exhaust-valve-guide temperature (figs. 12 (d) and 13 (b)), as in Group A showed a considerable increase with water injection in the lean region (fuel-air ratios of 0.055 to 0.07) as the maximum permissible inlet pressure was increased. At fuel-air ratios richer than 0.07, the temperature increased rapidly until a water-fuel ratio of 0.5 was reached, then remained almost constant until a water-fuel ratio of 1.0 was obtained. Higher water-fuel ratios than 1.0 caused a very rapid decrease in the exhaust-valve-guide temperature.

The exhaust-valve-guide temperature at all water-fuel ratios in both groups of investigations came to a peak at a fuel-air ratio of about 0.065 and decreased rapidly as the fuel-air mixture was enriched. A higher exhaust-valve-guide temperature, shown in table I, was obtained in a later investigation with a straight fuel, S-1 plus 6 ml TEL per gallon, at a fuel-air ratio of 0.072 than with water injection at the same mixture. Table I shows that all engine temperatures with the leaded S-1 fuel, however, were higher than the temperatures when water injection was used. With water injection rather large temperature variations occurred at some points.

Exhaust-gas temperatures measured in all investigations of Groups A and B ranged from 1200° to 1530° F. At a water-fuel ratio of 1.5 and fuel-air ratios between 0.06 and 0.07, the thermocouple in the exhaust stream would burn away before the temperature could be ascertained.

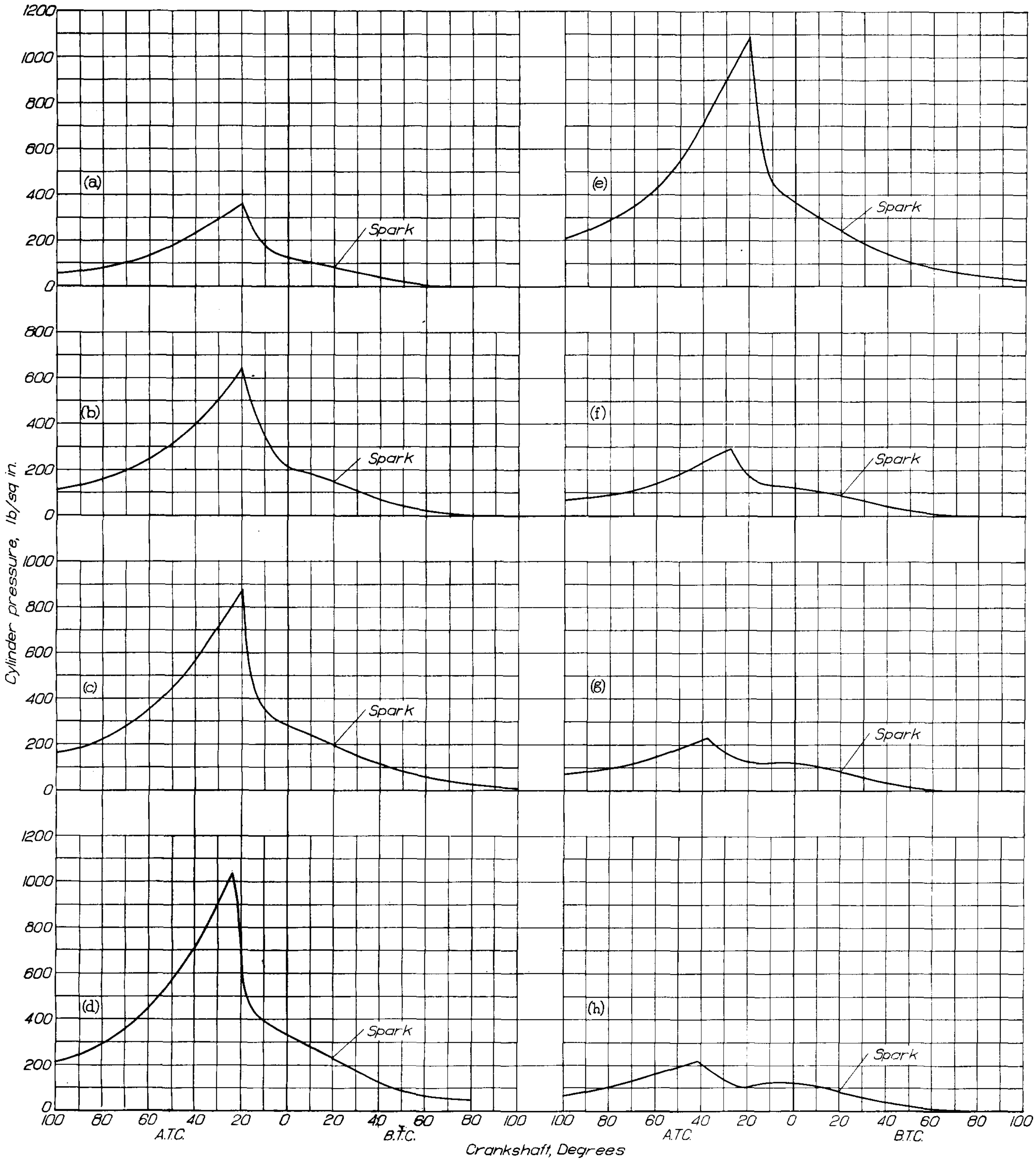
Indicator diagrams.—Indicator diagrams for a time-pressure card were taken with a Farnsboro indicator, using a constant fuel-air ratio of approximately 0.07 and water-fuel ratios of 0, 0.5, 1.0, and 1.5 at maximum permissible performance conditions. The pressure and the temperature results of these investigations are tabulated in table I and

TABLE I.—ENGINE DATA FOR INDICATOR DIAGRAMS

[Cylinder displacement, 202 cu in.; engine speed, 2000 rpm; spark advance, 20°; compression ratio, 7.0; inlet-air temperature, 250° F; cooling-air pressure drop, 14.0 in. of water]

Figure	Fuel	Fuel-air ratio	Water-fuel ratio	Liquid-air ratio	Inlet pressure (in. Hg abs.)	Indicated mean effective pressure (lb/sq in.)	Indicated specific fuel consumption (lb/hp-hr)	Indicated specific liquid consumption (lb/hp-hr)	Maximum cylinder pressure (lb/sq in.)	Position of pressure peak (deg A. T. C.)	Temperature (°F): Cylinder barrel under head, rear	Rear spark-plug bushing	Above cylinder flange, rear	Middle barrel, rear	Head between valves	Exhaust-valve guide
14 (a)	80-octane number	0.072	0	0.072	[a] 19.9	[a] 83	0.413	0.413	360	20	282	298	242	252	332	431
14 (b)	80-octane number	0.072	.5	.109	[a] 31.5	[a] 154	.415	.623	640	20	310	323	263	275	318	487
14 (c)	80-octane number	.070	1.0	.141	[a] 41.5	[a] 219	.407	.814	870	20	308	319	246	270	272	511
	80-octane number	.070	1.5	.177	[a] 49.7	[a] 263	.426	1.07	1030	23	186	275	217	252	240	492
14 (e)	S-1 plus 6 ml TEL	.072	0	0	52.4	263	.421	.421	1080	20	401	419	339	336	439	577
14 (f)	80-octane number	.071	.5	.106	19.9	79	.426	.636	290	28	266	270	232	235	281	433
14 (g)	80-octane number	.071	1.0	.141	19.9	67	.501	1.00	230	38	261	252	224	235	266	443
14 (h)	80-octane number	.071	1.5	.177	19.9	43	.783	1.96	215	42	238	225	198	220	239	451

[a] Maximum permissible.



(a) Water-fuel ratio, 0; inlet-air pressure, 19.9 inches mercury absolute; fuel, 80-octane; fuel-air ratio, 0.072.
(b) Water-fuel ratio, 0.5; inlet-air pressure, 31.5 inches mercury absolute; fuel, 80-octane; fuel-air ratio, 0.072.
(c) Water-fuel ratio, 1.0; inlet-air pressure, 41.5 inches mercury absolute; fuel, 80-octane; fuel-air ratio, 0.070.
(d) Water-fuel ratio, 1.5; inlet-air pressure, 49.7 inches mercury absolute; fuel, 80-octane; fuel-air ratio, 0.070.
(e) Water-fuel ratio, 0; inlet-air pressure, 52.4 inches mercury absolute; fuel, S-1+6 ml TEL/gal; fuel-air ratio, 0.072.
(f) Water-fuel ratio, 0.5; inlet-air pressure, 19.9 inches mercury absolute; fuel, 80-octane; fuel-air ratio, 0.071.
(g) Water-fuel ratio, 1.0; inlet-air pressure, 19.9 inches mercury absolute; fuel, 80-octane; fuel-air ratio, 0.071.
(h) Water-fuel ratio, 1.5; inlet-air pressure, 19.9 inches mercury absolute; fuel, 80-octane; fuel-air ratio, 0.071.

FIGURE 14.—Indicator diagrams. Cylinder displacement, 202 cubic inches; engine speed, 2000 rpm; spark advance, 20° B. T. C.; compression ratio, 7.0; inlet-air temperature, 250° F; cooling-air pressure drop, 14.0 inches water.

faired curves drawn from the indicator diagrams are presented in figures 14 (a) to 14 (d). The data show that the maximum cylinder pressure was lower for a given indicated mean effective pressure with water injection than with fuel alone. At a water-fuel ratio of 1.5, a maximum cylinder pressure of 1030 pounds per square inch at 23° A. T. C. was recorded by the Farnsboro indicator. The corresponding maximum permissible indicated mean effective pressure was 263.4 pounds per square inch. A similar power output without water injection was obtained with S–1 plus 6 ml TEL per gallon. The resulting peak pressure, as may be seen in table I and figure 14 (e) was 1080 pounds per square inch and occurred 20° A. T. C. The action of water injection in this case showed a slight tendency to retard the combustion. The maximum permissible inlet pressure for the S–1 plus 6 ml TEL per gallon under these conditions was not determined.

Additional indicator cards were taken at a constant inlet-air pressure corresponding to the maximum permissible inlet-air pressure for the fuel of 80-octane number without water. The relative indicator diagrams and the data for water-fuel ratios of 0.5, 1.0, and 1.5 are shown in figures 14 (f), 14 (g), 14 (h), and table I. In these cases the effect of the water in retarding combustion was very noticeable. A water-fuel ratio of 1.5 caused the peak cylinder pressure to occur 42° A. T. C. or 22° later in the cycle than with fuel alone.

Dilution of crankcase oil.—Considerable dilution of crankcase oil with water occurred during operation at high water-fuel ratios. After these runs, the volume of oil in the supply tank had increased and after it cooled a heavy gray sludge had formed at the bottom. A sample of the sludge, when put through a centrifuge, was found to contain 30-percent water by weight. In these investigations the oil-in temperature was maintained at 150° F and the oil-out temperature was usually between 190° and 200° F. The temperatures are probably lower than those used with most multicylinder engines and an increase in the oil temperature would be one way to eliminate some of the dilution. When the engine was operated with the diluted oil and without water injection, much of the water came out of the oil.

With high water-fuel ratios the cooling of the engine was carried to an extreme in the rich fuel-air range. Average head, barrel, and flange temperatures recorded were 240°, 200°, and 180° F, respectively. The maintenance of these temperatures above the boiling point of water at atmospheric pressure should further decrease dilution.

CONCLUSIONS

Investigation of water induction in a single-cylinder engine over a range of fuel-air ratios from 0.05 to 0.12 indicated the following conclusions:

1. Water injection allowed a fuel to be operated above its normal maximum permissible performance limits.
2. Water injection allowed a fuel to be operated at a higher indicated mean effective pressure, with a lower indicated specific fuel consumption, or with both, than was permitted without an internal coolant.
3. Water injection had a marked cooling effect on the engine head and cylinder. The exhaust-valve guide was the only point on the head at which the temperature showed a tendency to increase with indicated mean effective pressure. The temperature was less, however, than that obtained with a straight fuel permitting equivalent power.
4. Water injection showed no advantage in fuel economy when the fuel was operated well below its maximum permissible performance limits.
5. Water injection might be a disadvantage if the engine cooling effects are carried to an extreme and cause crankcase-oil dilution. Operation at normal engine and crankcase-oil temperatures should minimize crankcase-oil dilution.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., *August 15, 1942.*

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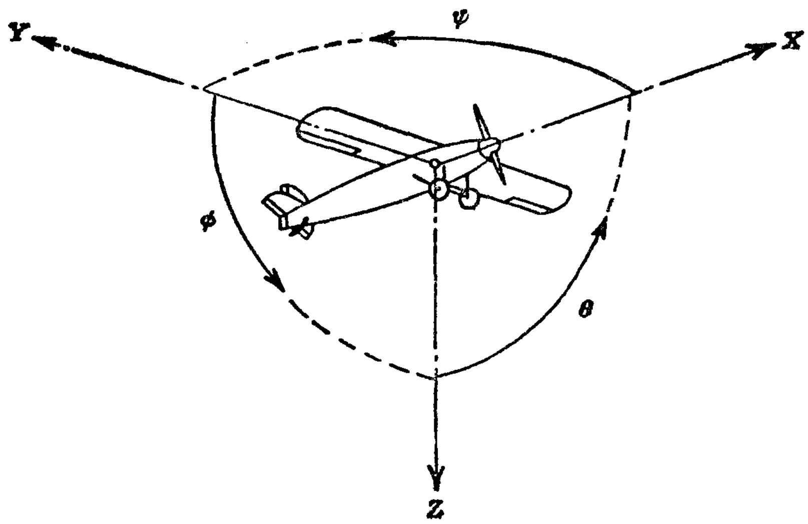

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	φ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D Diameter

p Geometric pitch

p/D Pitch ratio

V' Inflow velocity

V_s Slipstream velocity

T Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$

Q Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$

P Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$

C_s Speed-power coefficient $=\sqrt[5]{\frac{\rho V^5}{P n^2}}$

η Efficiency

n Revolutions per second, rps

Φ Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp=76.04 kg-m/s=550 ft-lb/sec

1 metric horsepower=0.9863 hp

1 mph=0.4470 mps

1 mps=2.2369 mph

1 lb=0.4536 kg

1 kg=2.2046 lb

1 mi=1,609.35 m=5,280 ft

1 m=3.2808 ft

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ABSTRACT

Tests were conducted on single-cylinder engine over a range of fuel/air ratio from 0.05 to 0.12 to determine effects of water injection on maximum permissible power and output of the engine. To obtain range of water/fuel and fuel/.... ratio, engine inlet pressure was increased until fuel knocked. Tests revealed weight of water formed at fuel/air ratio of 0.067, was 1.25 times weight of fuel burned. The results are compared with calculation.

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