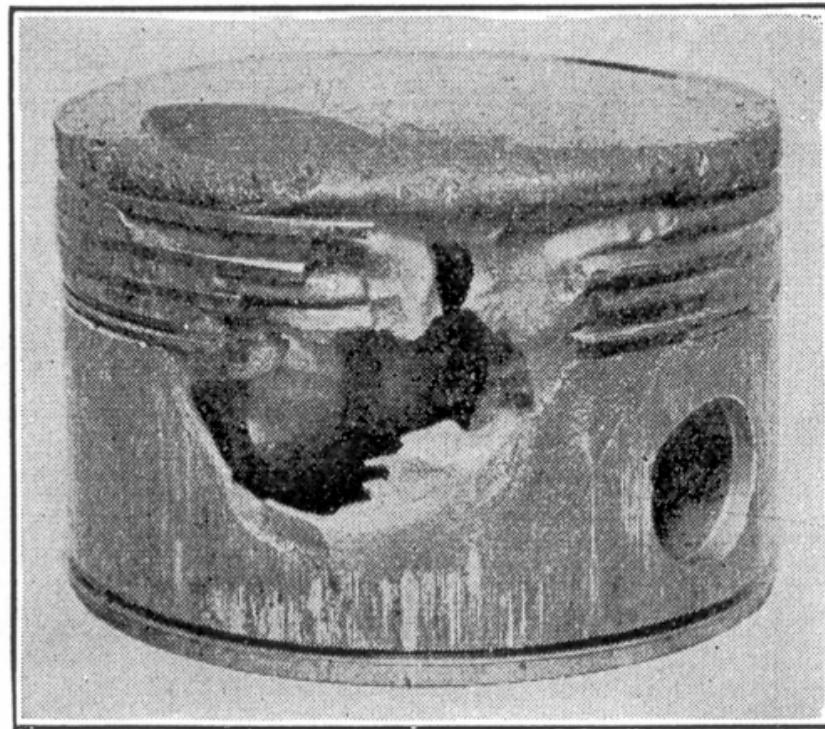


AIRCRAFT PISTON ENGINE WATER INJECTION SYSTEMS

BY PETER LAW



Pete Law at Reno



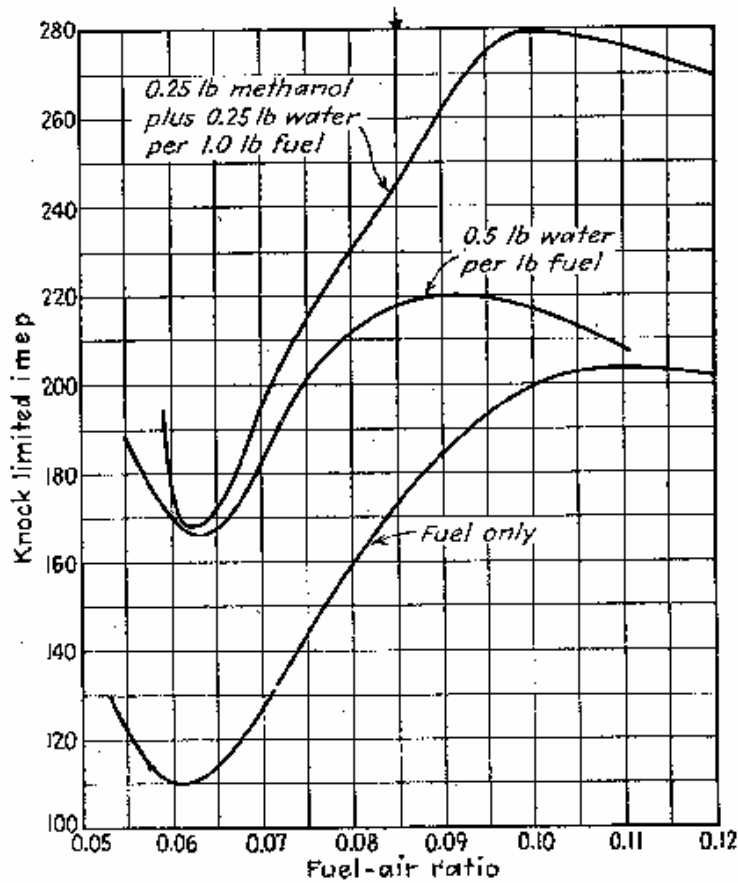
Piston Engine Water Injection – Why it is Used and How it Works

- BACKGROUND

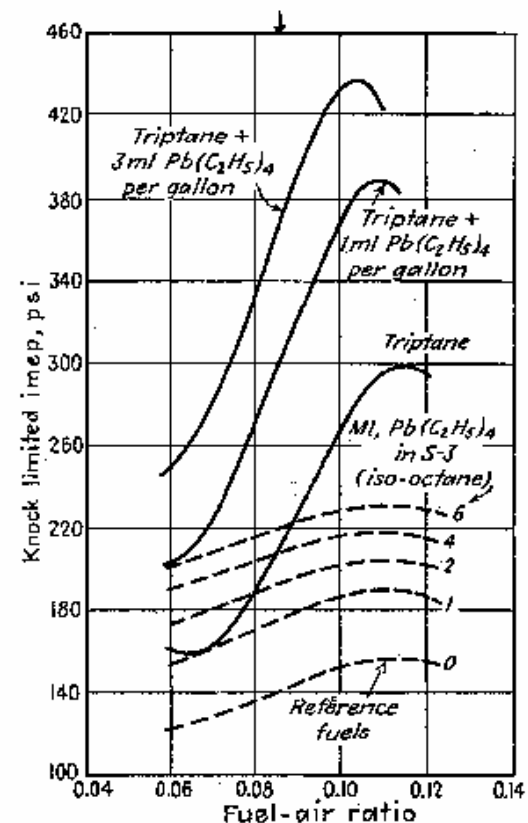
- AT HIGH POWER, COMBUSTION CHAMBERS APPROACH 4,500 °F
- AT THESE CONDITIONS FUEL CAN BURN WITH EXPLOSIVE VIOLENCE AT THE WRONG TIME IN THE CYCLE, MELTING PISTONS
- THIS IS KNOWN AS “DETONATION”, WHICH CANNOT BE TOLLERATED
 - INSIPIENT DETONATION IN ENGINES IS AN AUDIBLE “KNOCK”
- SEVERAL METHODS ARE USED TO INHIBIT DETONATION
 - ANTIKNOCK ADDITIVES OF FUEL SUCH AS AROMATICS (TOLUENE), TETRAETHYL LEAD (2,2,3-Trimethylbutane), TRIPTANE, **MMT**/CI2 (**M**ethylcyclopentadienal **M**anganese **T**ricarbolyI; 24.4% Mn by weight), AND OTHERS THAT STABALIZE AND CONTROL REACTION RATE
 - WATER-ALCOHOL INJECTION IS A VERY POWERFUL AND SIMPLE WAY TO:
 - LOWER CHARGE AND COMBUSTION TEMPERATURES
 - SLOW FLAME FRONT SPEED AND LOWER RATE OF PRESSURE INCREASE
 - EXTEND TIME OF BURNING AND REACTION RATE
 - ALLOW ENGINES TO GO TO HIGHER POWER BEFORE ONSET OF DETONATION
- WATER-ALCOHOL MIXTURE (ADI) IS INJECTED ALONG WITH FUEL INTO SUPERCHARGER INLET
 - THOROUGHLY MIXES IN COMPRESSOR
 - HOPEFULLY ENTERS EACH CYLINDER AS UNIFORM MIXTURE

EFFECT OF FUEL ADDITIVES AND WATER INJECTION ON KNOCK LIMITED IMEP (IMEP IS "INDICATED MEAN EFFECTIVE PRESSURE", MEASURE OF ABSOLUTE POWER)

EFFECT OF WATER-ALCOHOL INJECTION
ON DETONATION - LIMITED IMEP IN A
SUPERCHARGED CFR ENGINE

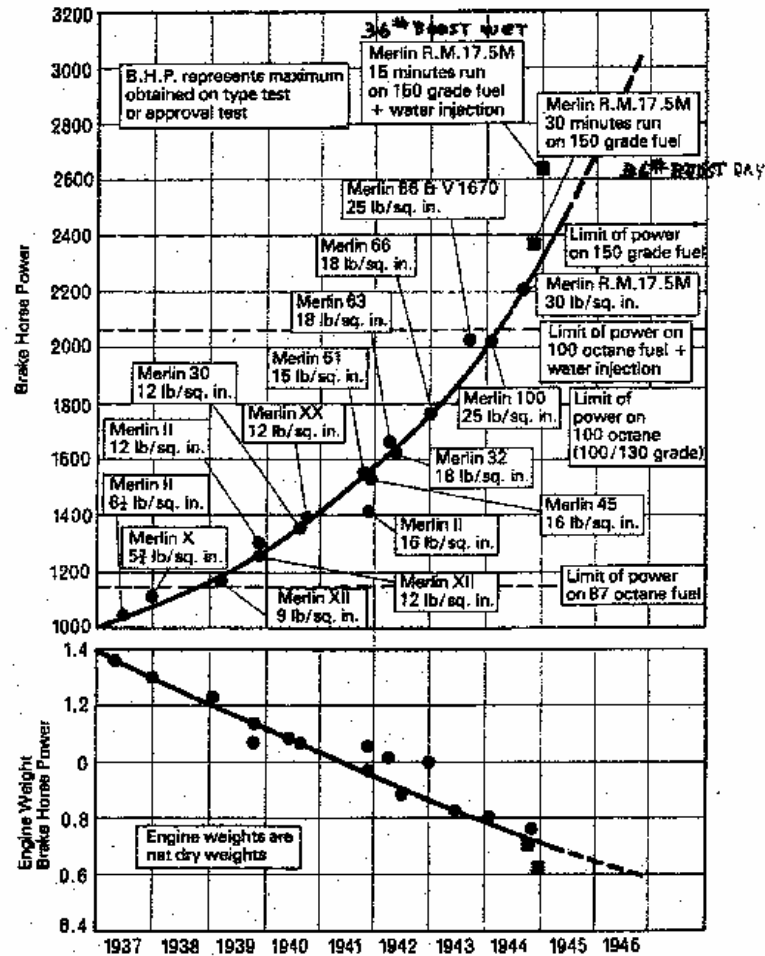


KNOCK - LIMITED IMEP DATA
FOR TETRAETHYL LEAD IN ISO-OCTANE
AND TRIPTANE



NOTICE COMPARISON AT 0.085 F/A RATIO:
TRIPTANE IS SPECTACULAR (But Not Available)

HISTORICAL EFFECTS OF FUELS AND WATER INJECTION ON MERLIN POWER INCREASE



WATER-ALCOHOL "ADI" MIXTURES USED FOR CHARGE COOLING

- ADI (ANTI-DETONATION INJECTION) FLUID IS A MIXTURE OF METHANOL AND WATER; TWO MIXTURE RATIOS ARE USED:

- MOST USED IS 50% METHANOL-50% WATER BY VOLUME

- ALSO USED IS 60% METHANOL-40% WATER BY VOLUME

- COMPARISON CHART FOR VARIOUS FLUIDS (BY VOLUME)

FLUID	ALTITUDE	H ₂ O %	METH. %	BOILING TEMP. °F	SPECIFIC GRAVITY @ 68°F	DENSITY #/FT ³	DENSITY #/GAL	HEAT OF VAPORIZATION BTU/#
WATER	SL	100	0	212	1.00	62.4	8.33	970
	5,000'	100	0	203	↓	↓	↓	976
	10,000'	100	0	194	↓	↓	↓	982
50% METH. 50% H ₂ O	SL	50	50	167	0.93	58.0	7.75	755
	5,000'	50	50	158	↓	↓	↓	760
	10,000'	50	50	150	↓	↓	↓	765
60% METH. 40% H ₂ O	SL	40	60	163	0.91	56.8	7.58	710
	5,000'	40	60	155	↓	↓	↓	715
	10,000'	40	60	147	↓	↓	↓	720
METHANOL	SL	0	100	149	0.782	48.8	6.51	473
	5,000'	0	100	141	↓	↓	↓	477
	10,000'	0	100	132	↓	↓	↓	481

HAS BEEN USED, BUT NOT GOOD RESULTS

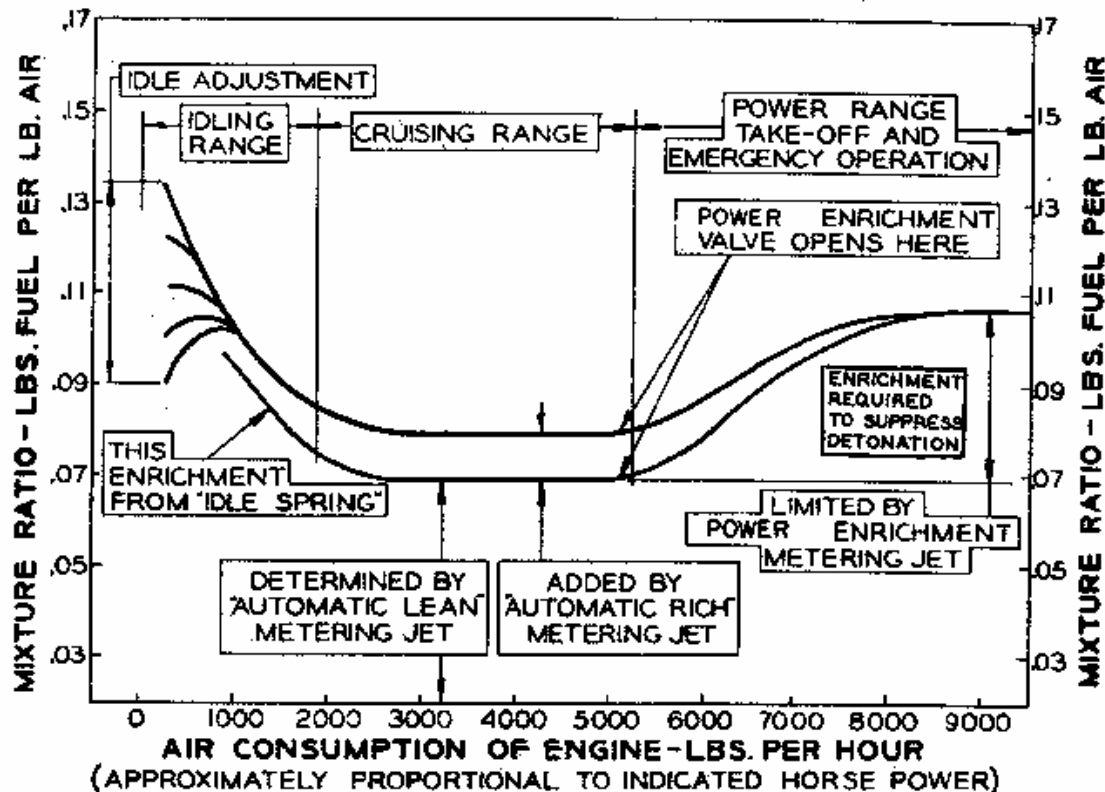
MOST COMMON MIXTURE

USED ON ONE AIRCRAFT

NOT ENOUGH COOLING EFFECT

GENERAL WATER INJECTION SYSTEM ISSUES

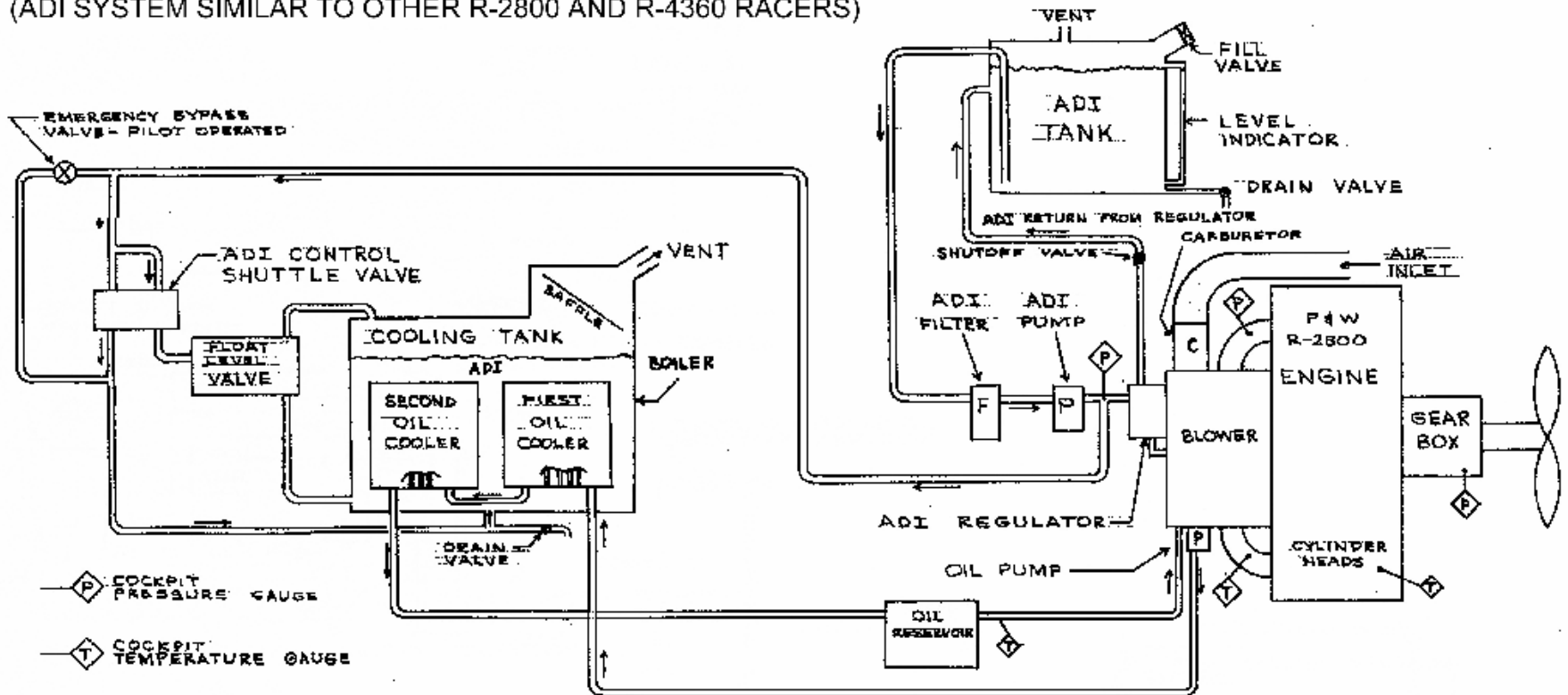
- AT WHAT POWER SETTINGS IS WATER INJECTION USED ON ENGINES?
 - AS POWER INCREASES, A FUEL ENRICHMENT CIRCUIT OPENS IN THE CARBURETOR (AT 50% OF NORMAL POWER) TO SUPPRESS DETONATION. (THIS IS CALLED "POWER ENRICHMENT.")
 - AT ABOUT 75% POWER, THE WATER INJECTION SYSTEM IS ACTIVATED. FOR MOST ENGINES, THIS IS AT 40.-45. " HgA. MANIFOLD PRESSURE.



ADI (AND OIL COOLING SYSTEM) FOR CONQUEST

RACING F8F BEARCAT - CONQUEST

(ADI SYSTEM SIMILAR TO OTHER R-2800 AND R-4360 RACERS)

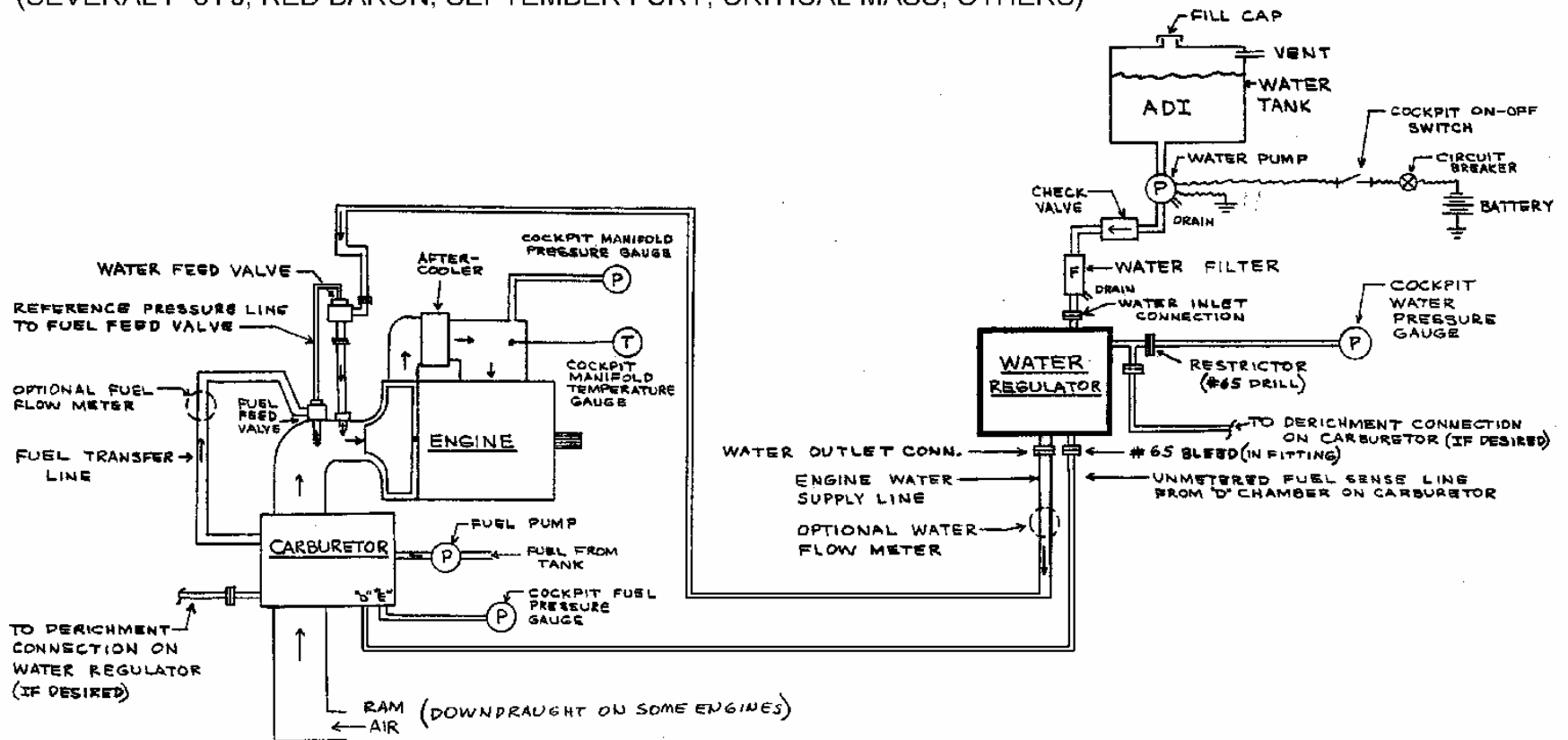


TYPICAL WATER BOILER SYSTEM FOR RADIAL ENGINE APPLICATIONS

WATER REGULATOR SYSTEM SCHEMATIC

SYSTEM FOR MERLINS, GRIFFONS, AND SOME R-3350's

(SEVERAL P-51's, RED BARON, SEPTEMBER FURY, CRITICAL MASS, OTHERS)



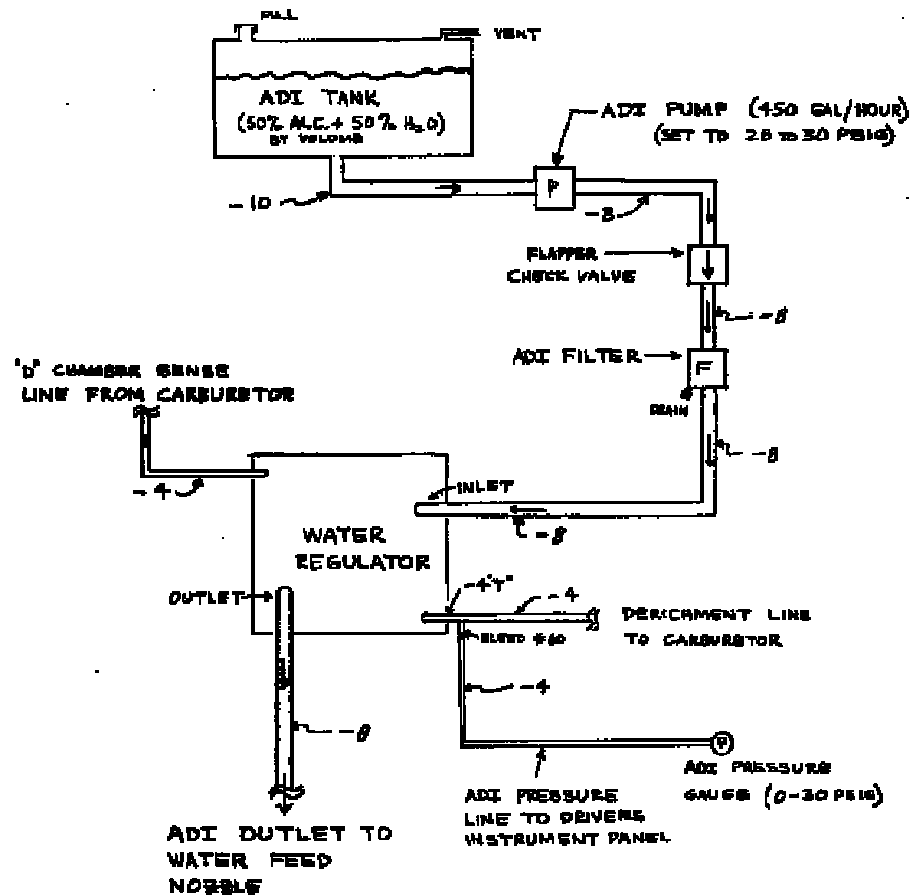
GENERAL WATER INJECTION SYSTEM ISSUES

(Con't)

- WHAT HAPPENS WHEN THE SYSTEM IS ACTIVATED?
 - “ADI” FLUID PUMP IN ADI TANK COMES ON, PUMPS TO REGULATOR
 - “ADI” FLUID PRESSURE IN REGULATOR SENDS PRESSURE SIGNAL TO VALVE IN CARBURETOR THAT REDUCES FUEL FLOW (DERICHMENT), APPROACHES “BEST POWER” F/A RATIO (0.08:1)
 - “ADI” FLUID METERED THROUGH WATER REGULATOR INTO SUPER-CHARGER, REMOVES SOME OF THE HEAT OF COMPRESSION
 - DETONATION TENDENCY IS SUPPRESSED
 - P&W ENGINES MIX ADI WITH FUEL, INJECT THROUGH SINGLE NOZZLE
 - OTHER ENGINES USE SEPARATE FUEL AND ADI NOZZLES
 - AMOUNT OF “ADI” IS CONTROLLED BY PRESSURE FROM CARBURETOR “D” CHAMBER ACTING ON REGULATOR METERING VALVE
 - “D” CHAMBER PRESSURE INCREASES WITH HIGHER POWER SETTINGS, INCREASING FUEL FLOW AND THEREBY ADI FLOW

WATER INJECTION REGULATOR SYSTEM SCHEMATIC

(MORE DETAILED SCHEMATIC SHOWING CONNECTIONS)
(USED ON MOST AIRCRAFT OTHER THAN P&W ENGINES)



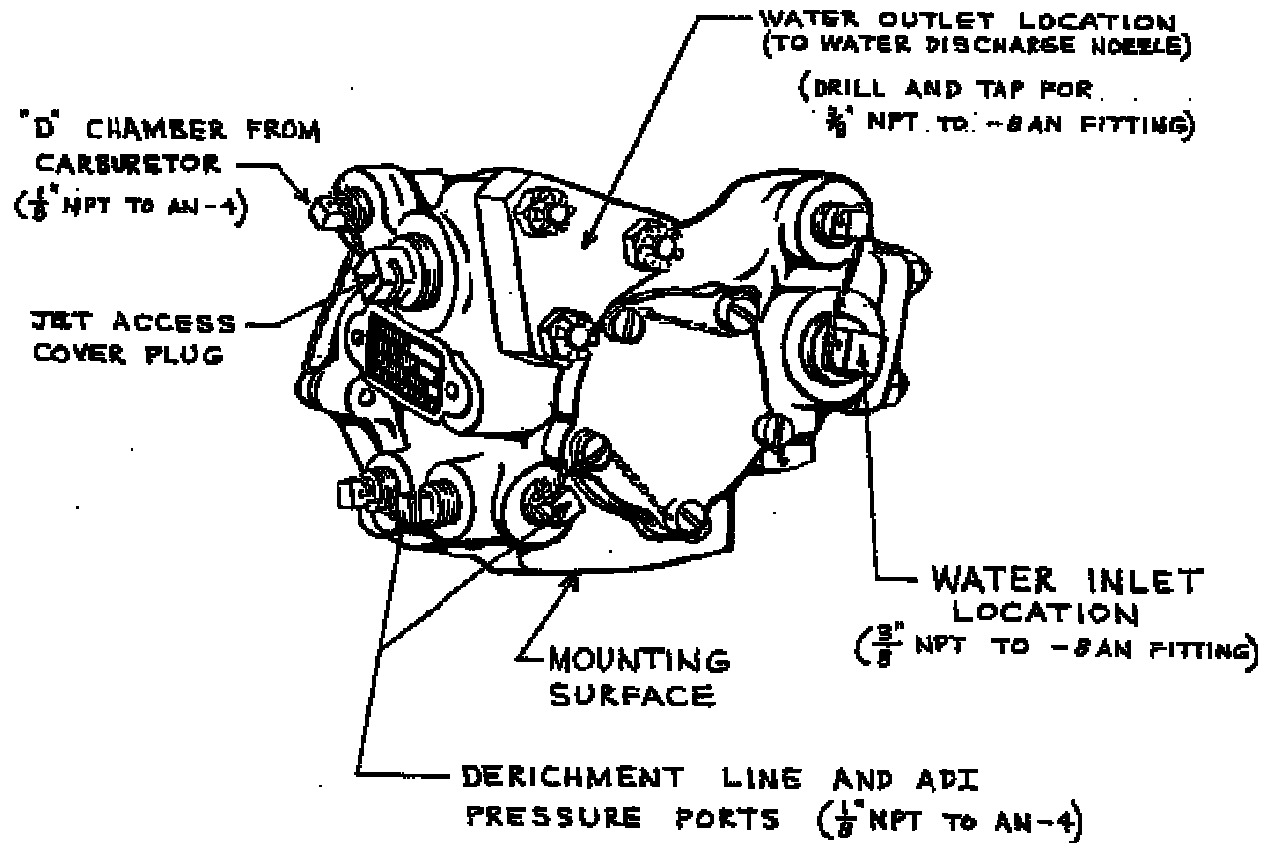
GENERAL WATER INJECTION SYSTEM ISSUES

(Con't)

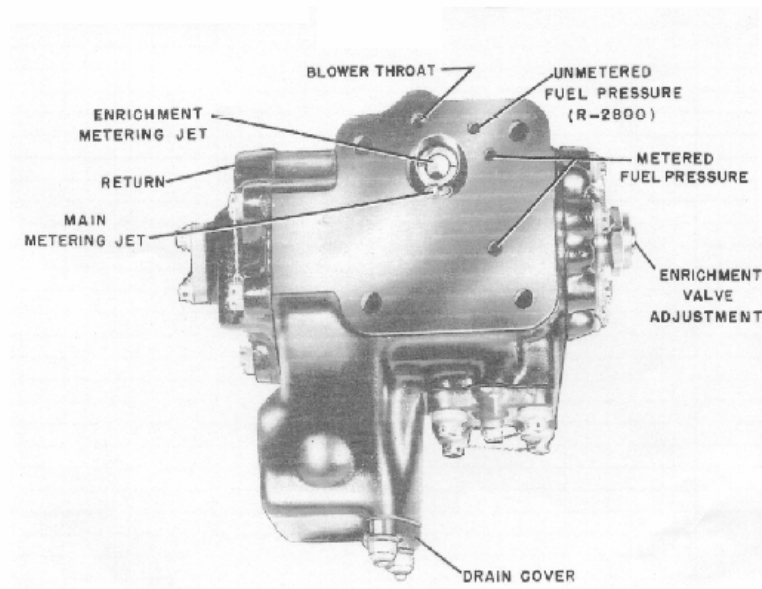
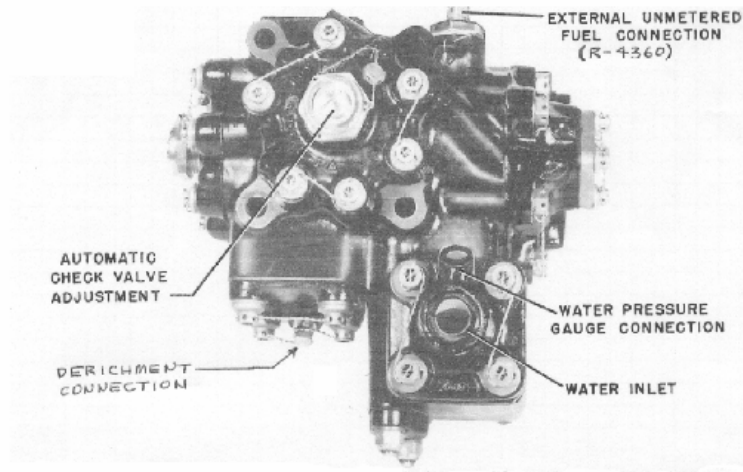
- WHAT HAPPENS WHEN THE SYSTEM IS ACTIVATED (Con't)?
 - JET IN REGULATOR (2 IN R-2800 UNIT) METER ADI FLOW SIMILAR TO WAY CARBURETOR JETS METER FUEL TO ENGINE.
 - ADI PRESSURE GAUGE IN COCKPIT, NEED 22 – 28 psig FOR PROPER ATOMIZATION AND OPERATION
 - COCKPIT INDUCTION TEMPERATURE GAUGE (CHARGE TEMPERATURE) SHOULD BE 80 – 90°C (176 – 194°F) TO INSURE NO DETONATION. REGULATOR JETS ARE EASILY SIZED TO PROVIDE PROPER RANGE
 - SIGNIFICANT POWER INCREASES CAN BE OBTAINED WITH WATER INJECTION WHEN HIGH PERFORMANCE FUEL IS USED.
 - 115/145 FUEL SHOULD BE ADEQUATE FOR RACING AT TAKEOFF OR “WAR EMERGENCY POWER”, BUT HIGHER “RACE” POWER REQUIRES SPECIAL ADDITIVES TO GIVE PERFORMANCE NUMBER OF 170

WATER REGULATOR CONNECTIONS

ISOMETRIC REPRESENTATION SHOWING STANDARD CONNECTIONS
(USE ON MOST AIRCRAFT OTHER THAN P&W ENGINES)

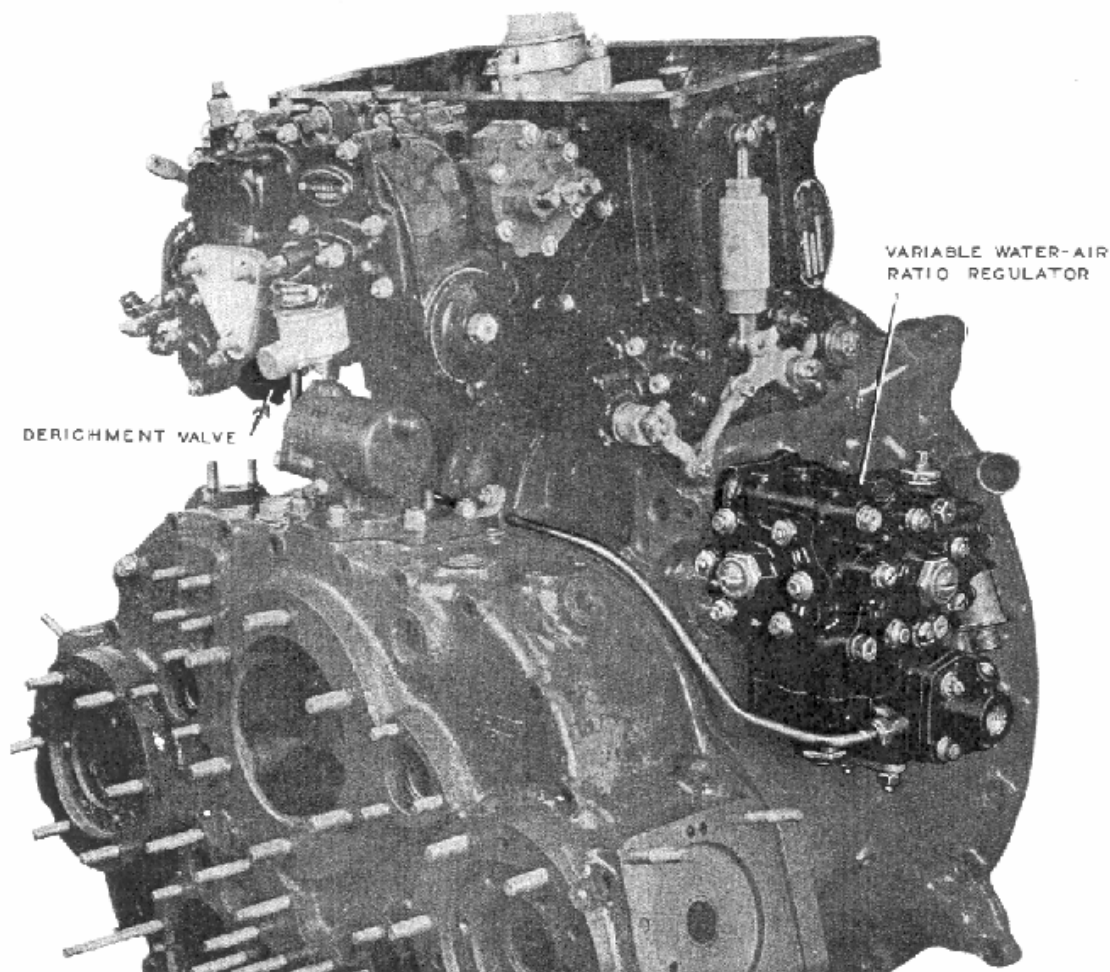


WATER INJECTION REGULATOR FOR P&W R-2800 AND R-4360 ENGINES (LATE MODEL ENGINES)



WATER REGULATOR MOUNTED ON SIDE OF R-2800 ENGINE

PRATT & WHITNEY AIRCRAFT



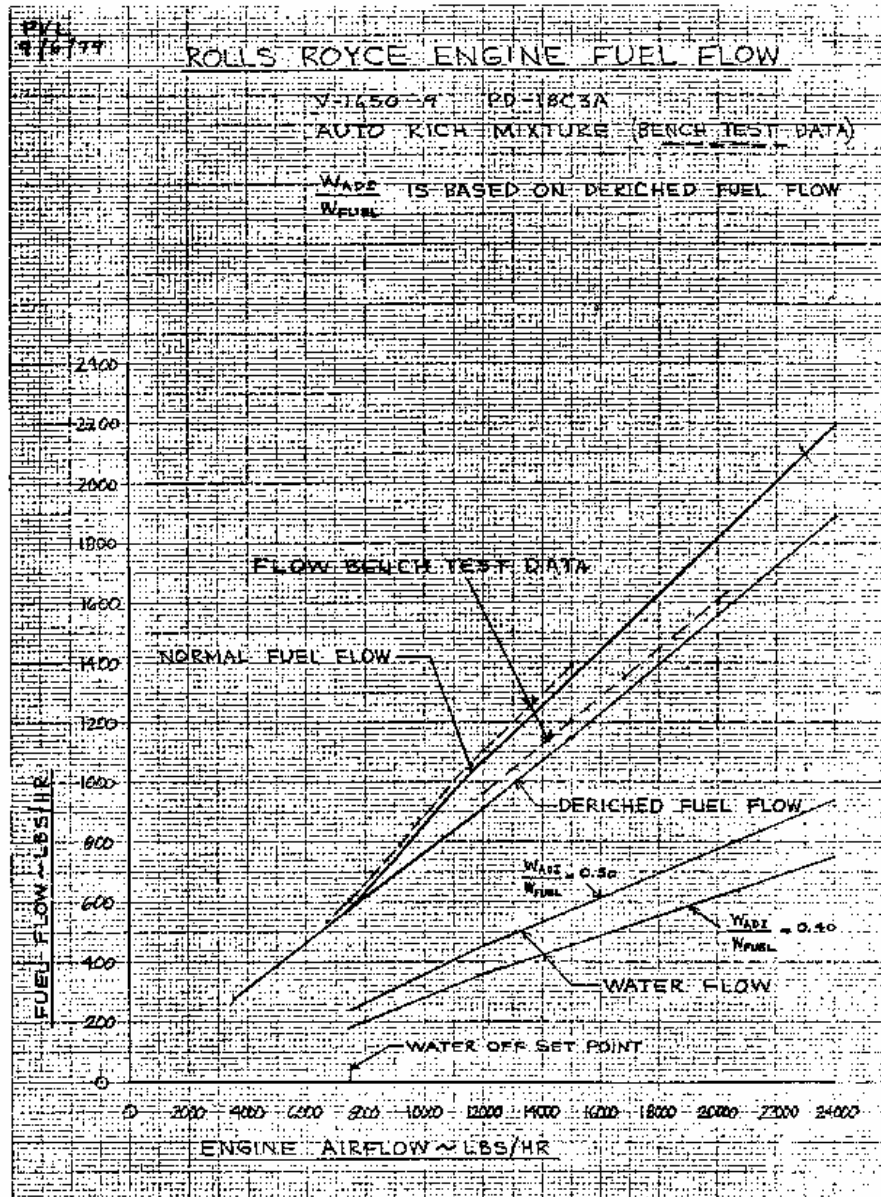
MOCK-UP OF THE DOUBLE WASP CA SERIES ENGINE WATER INJECTION SYSTEM

FUEL AND ADI FLOWRATES FOR VARIOUS LARGE ENGINES

NOTE: FUEL USED IS 115/145 OR V.P. RACING FUEL: S.G. = 0.690, $\gamma = 5.75$ */GAL, LHV = 18,900 BTU/#

ENGINE TYPE	DISP.	BRAKE POWER	AIRFLOW	FUEL FLOW	PERFORMANCE	FUEL/IN/AIR	FUEL FLOW	FUEL FLOW	ADI/IN/AIR	ADI FLOW	ADI FLOW	ADI FLOW
CARBURETOR	10 ³	HP	#/RR	#/HR	%	RATIO	Gal/HR	GAL/MIN	RATIO	#/HR	#A/MIN	#/HR
REFERENCE AIRCRAFT				DERIVED		DERIVED	DERIVED	DERIVED				
V-1650-9 PD-18C3A (STILETTO)	1650	2800	20,400	1630	15	0.080	283	4.72	0.50	815	1.80	
GRIFFON-57/7+	2239	3200	23,400	2020	15	0.086	351	5.85	0.50	1010	2.20	
PR-585 (RED BARON)												
R-2800-79W	2800	3200	23,400	1930	27	0.083	336	5.60	0.40	772	1.70	
PR-585 (CONQUEST I)												
R-3350-93	3350	3700	27,000	2300	20	0.085	400	6.67	0.40	920	2.00	
RR-5852 (SEPTEMBER FURY)												
R-4360-63A	4360	3800	28,000	2340	21	0.084	403	6.72	0.40	936	2.00	
PR-1004 (DREADNOUGHT)												

MERLIN V-1650 FUEL FLOW DATA



MERLIN V-1650 CARBURETOR FLOW BENCH TEST DATA

DAGO RED

PUL-82-8

FRANK TAYLOR (GREY ENGINE) INJECTION CARBURETOR FLOW BENCH TEST S/N 694425-A PUL-82-8 7/21/82

Engine Model: V-1650 Fuel Inlet Pressure: 17 psi Parts List No.: 390543-1
 Engine Mfg.: Packard Nozzle Pressure: 5 ± 1/4 psi Carb. Model: PD-18C3A
 Engine Mfg. Setting: Limits Based on .732-.736 Specific Gravity at 70-80°F. Date Issued: 7-18-45

NAPHTHA

Test Point No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Metering Suction Inches of Water	1.0	30.0	.4	.4	1.2	2.2	2.2	4.4	4.4	8.0	8.0	10.2	10.2	15.3	15.3	20.5	20.5	25.8	25.8	40.0	
Corresponding Air Flow Lb./Hr.			1500	1500	2600	3500	3500	5000	6000	6700	6700	7500	7500	9200	9200	10700	10700	12000	12000	15000	
Mixture Control Lever Position	AR	AR	ICO	AL	AL	AL	AR	AR	AL	AL	AR	AR	AL	AL	AR	AR	AL	AL	AR	AR	
Burette Volume			50	1000	1500	1500	1500	2000	2000	2500	2500	3000	3000	3000	3000	5000	5000	5000	5000	5000	
Time Min.			48.5	30.9	37.5	31.1	28.9	28.9	30.7	29.4	27.1	28.7	31.3	22.7	21.7	29.5	29.7	26.1	25.9		
Limits Max.			0.0	32.0	39.0	32.3	30.1	30.1	32.0	30.6	28.2	29.9	32.5	23.7	22.6	30.7	30.9	27.3	27.1		
In Seconds Obs.																					
Flowmeter Min.			0.0	182	224	270	281	387	364	476	516	584	536	738	772	948	942	1069	1077		
Limits Max.			8.0	189	233	281	303	403	379	495	537	608	558	768	803	986	980	1112	1129		
In Lbs./Hr. Obs.				193	232	276	293	402	378	500	536	610	578	766	790	975	970	1100	1100	1390	
Metering Head Min.	1.1	30.0		1.3					5.5	9.9										24.9	
Head Max.	1.5	40.0		1.9					6.3	10.8											26.9
Inches of Fuel Obs.	1.8	36.5	✓	1.5					5.8	10.0											24.9

Test Point No.	21	22	23	24	25	26
Metering Suction Inches of Water		25.6	40.0	50.0	60.0	70.0
Corresponding Air Flow Lbs./Hr.		12000	15000	16800	18500	20000
Mixture Control Lever Position		AR	AR	AR	AR	AR
Burette Volume		5000	8000			
Time Min.		30.2	24.1			
Limits Max.		31.4	25.1			
In Seconds Obs.						
Flowmeter Min.		927	1158			
Limits Max.		964	1204			
In DEREGIMENT RANGE						
Inches of Fuel Obs.		9.65	12.10	13.50	14.80	16.00

Multi-Point Automatic Mixture Control Calibration Limits:

Flow Method:

Date Issued:

Density:

Low (Rich) Limit:

High (Lean) Limit:

- NOTES: 1. Idle spring must be full lean when adjusting poppet valve.
 2. Increase fuel inlet pressure to 22 psi for Test Point No. 3 only (Idle Cut-Off Check).
 3. AMC Setting: 30.8" H₂O @ 7,500'. OK ✓
 IDLE @ 55 #/HR @ 0.010"

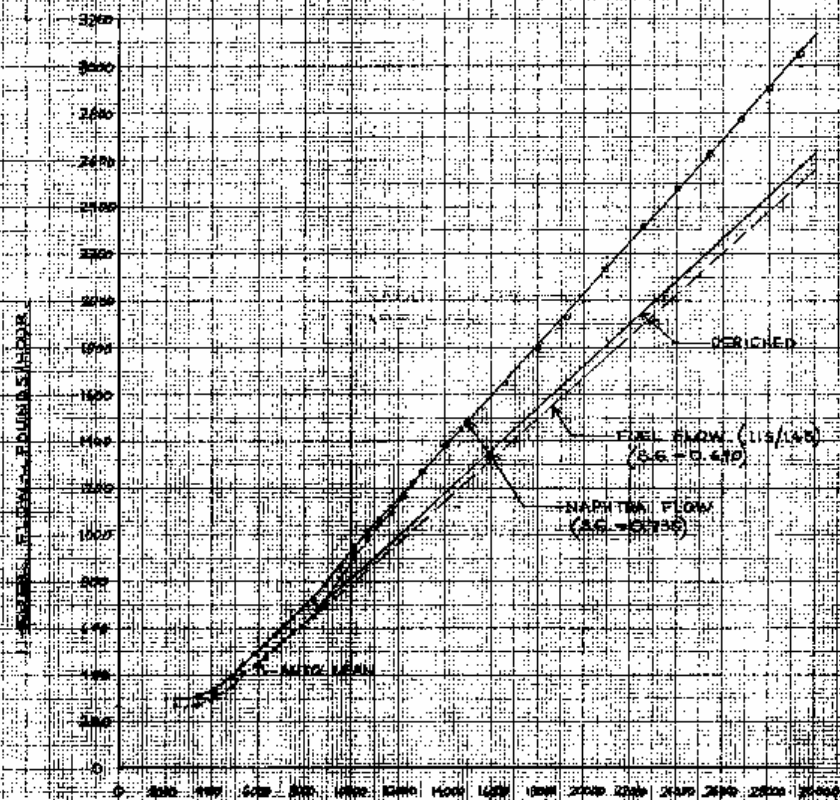
GRIFTON FUEL FLOW DATA

PVL
4/20/75

RED BARON - GRIFFON

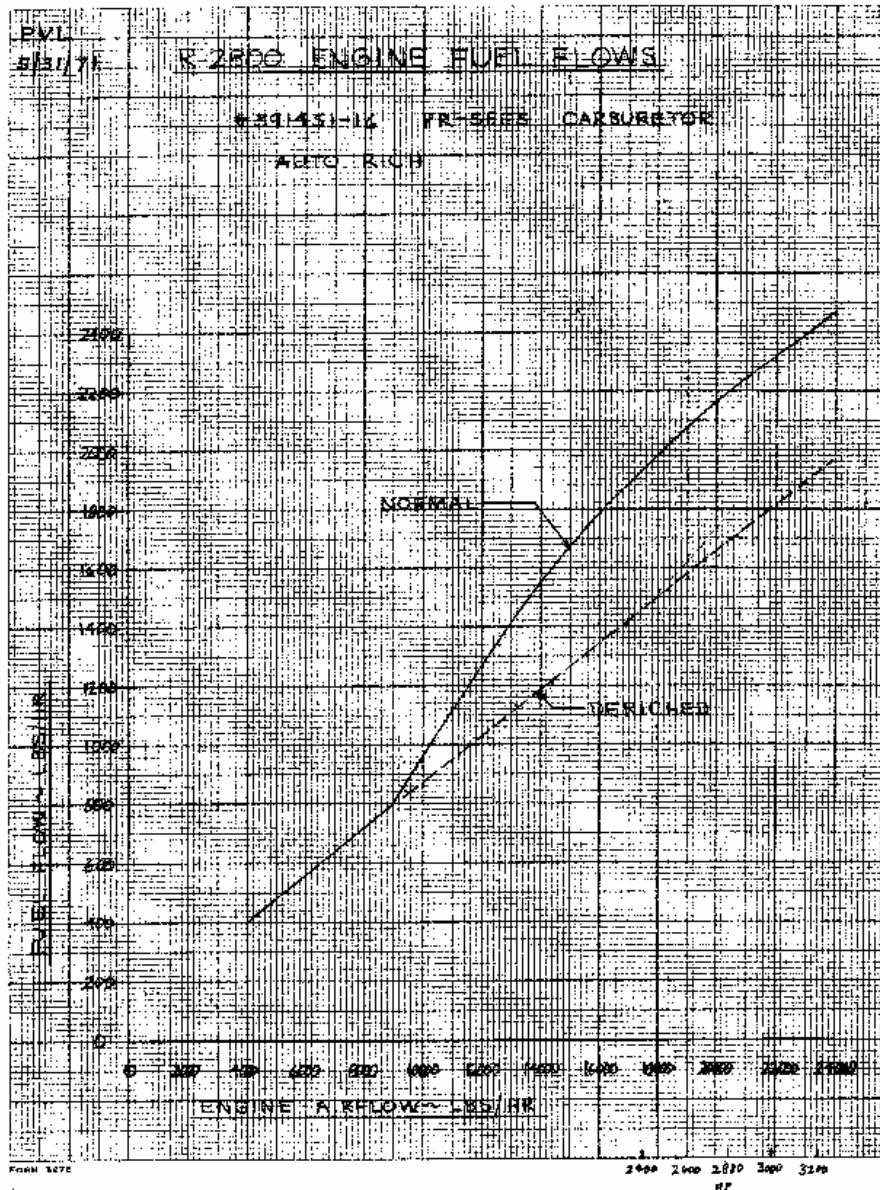
FUEL FLOW VS. AIRFLOW

GRIFTON ENGINE - PR-58MS CARBURATOR - AUTO RICH



PIRELLA ENGINEERING

P&W R-2800 FUEL FLOW DATA



R-2800 CARBURETOR FLOW BENCH TEST DATA

F 8 F BEARCAT CONQUEST I

DARRYL GREENMAYER

INJECTION CARBURETOR FLOW BENCH TEST

FLOWED AS RECEIVED 5/20/75

Engine Model: R-2800-99
 Engine Mfg.: Pratt and Whitney
 Engine Mfg. Setting: PR-58E5-22

Fuel Inlet Pressure: 22.0 psi
 Nozzle Pressure: 10.0 ± 1/4 psi
 Limits Based on .732 - .736 Specific Gravity at 70-80°F.

Parts List No.: 391451-18
 Carb. Model: PR-58E5
 Date Issued: 7-19-57

S/N
688733

NAPHTHA

(Test Spec. No. 241)

Test Point No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Metering Suction Inches of Water	5.0	50.0	0.0	0.6	2.85	2.85	6.4	6.4	10.65	10.65	12.3	18.25	21.3	27.5	27.5	52.1		52.1	"Hg 4.93 6.0
Corresponding Air Flow Lb./Hr.					4000	4000	6000	6000	7800	7800	8400	9700	11000	12500	12500	17000		17000	19000 21000
Mixture Control Lever Position	AR	AR	AR	ICO	AR	AL	AL	AR	AR	AL	AR	AR	AR	AR	AL	AR		AR	AR
Burette Time Limits In Seconds				50	2000	2000	3000	3000	3000	3000	5000	5000	5000	7000	7000	7000		7000	7000
Flowmeter Limits In Lbs./Hr.				0.0	398.9	308.0	430.0	555.9	711.5	543	783	918	1132	1352	1244	1922		1403	1585
Metering Head Inches of Fuel	7.25	3.48	2.8					9.1	14.5					35.6					DERICHMENT RANGE
	7.75	3.70	3.4					9.8	15.7					38.4					
	7.7	6.45	3.6					9.6	15.0					22.3	28.5	36.2		67.0	61.5

Test Point No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Metering Suction Inches of Water																		
Corresponding Air Flow Lbs./Hr.																		
Mixture Control Lever Position																		
Burette Time Limits In Seconds																		
Flowmeter Limits In Lbs./Hr.																		
Metering Head Inches of Fuel																		

Multi-Point Automatic Mixture Control Calibration Limits:

Flow Method: B-1 2320 2600 3000

Date Issued: 10-2-56

Density: 0.7243 0.7511 0.7408 0.7286

Low (Rich) Limit: 18.55 27.55 34.75 38.75

High (Lean) Limit: 21.05 27.95 35.15 39.15

Note No. 1: Increase fuel inlet pressure to 28.0 psi at Test Point No. 4 only (Idle Cut-off Check)

IDLE FLOW IS 55#/HR (GOOD)

POWER ENRICHMENT JET IS 1530 cc

Flowed by AL D. & P.V. Jno

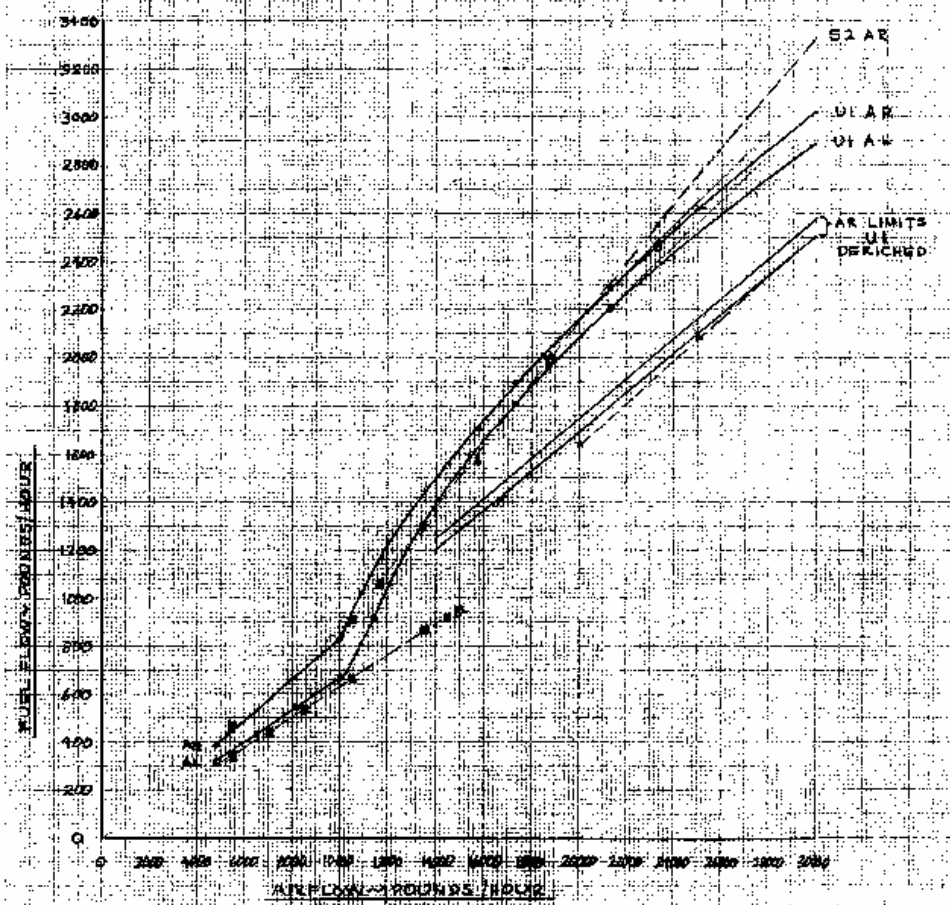
WRIGHT R-3350 FUEL FLOW DATA

USED FOR MICHAEL BROWN'S SEPTEMBER FURY
(PR-58S2 CARBURETOR FOR DIRECT INJECTED R-3350-93)

PVL
1/15/94

CARBURETOR FUEL FLOWS

PR58S1	P/L 340280-17	R3350-24W
PR58S2	P/L 341357-6	TRITGIBSEAL WET
PR58S2	P/L 341742-2	TRITGIBSEAL WET -93
PR58S2	P/L 341744-1	TRITGIBSEAL -93 -93 OK



PVL
2/7/95

WRIGHT R-3350 FUEL/HORSEPOWER DATA

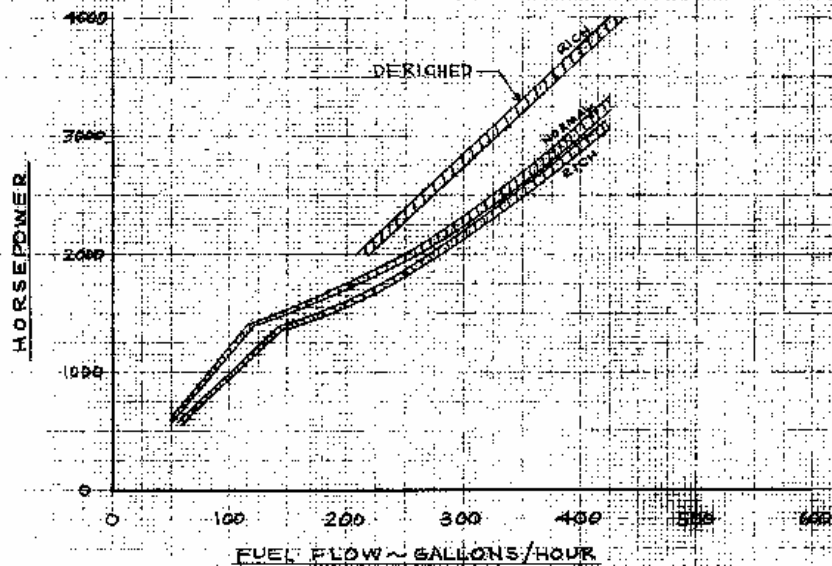
BENDIX PRESSURE CARBURETOR, 77° STANDARD 17

ESTIMATED VALUES

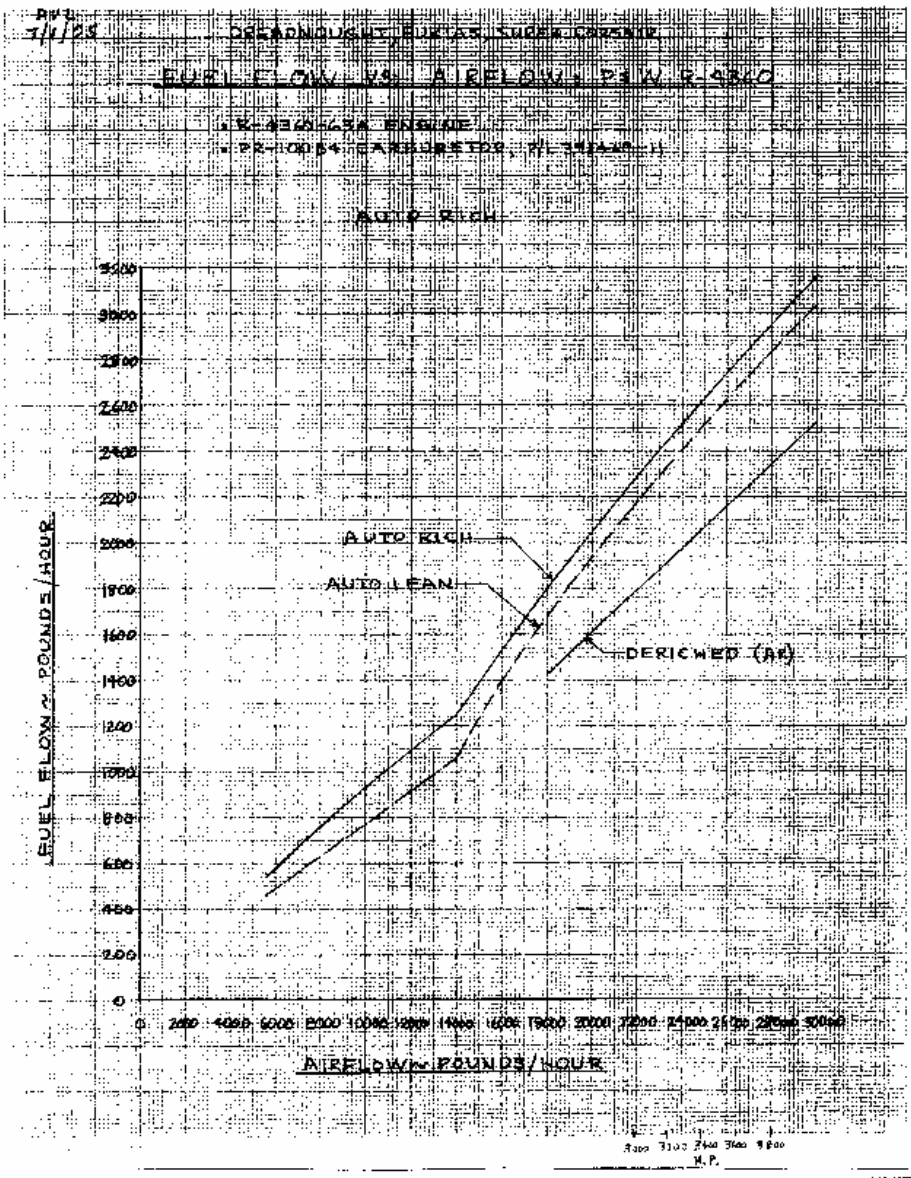
HORSEPOWER = CONSTANT RPM x TORQUE PRESSURE

$$HP = RPM \times T_{max} \times P_{14.7} / 14.7 \quad (0.875 \text{ NOSE RATIO})$$

$$HP = RPM \times T_{max} \times P_{14.7} / 2.01 \quad (0.355 \text{ NOSE RATIO})$$



P&W R-4360-63A FUEL FLOW DATA



CALAC FORM 7920B-1

P&W R-4360-63A CARBURETOR FLOW BENCH TEST DATA

DREADNOUGHT

DREADNOUGHT

SAUNDERS
AIRCRAFT S/N 795198

FLOWED AS RESET

INJECTION CARBURETOR FLOW BENCH TEST

PVL 03-B

P/L Law

4/4/03

MODEL: PR-100B4
Injection Carburetor

Engine Model: R-4360-03
Engine Mfg.: Ford
Engine Mfg. Setting: PR-100B4-12

Fuel Inlet Pressure: 25 P.S.I.
Nozzle Pressure: 10 * 1/4 P.S.I.
Limits Based on .732-.738 Specific Gravity at 70-80°F.

Parts List No.: 391469-11
Carb. Model: PR-100B4
Date Issued: 7-2-58
(Test Spec. No. 215)

NAPHTHA 0.731 @ 78°F

Test Point No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Metering Suction Inches of Water	5.0	50.0	0.0	0.8	3.85	3.85	6.8	9.9	13.2	13.2	17.15	23.0	29.9	41.2	41.2	52.1	"Hg 6.23	"Hg 6.23	"Hg 6.23
Corresponding Air Flow Lb./Hr.					5600	5800	7400	9000	10500	10500	12000	14030	16000	19000	19000	21500	27000	27000	27000
Mixture Control Lever Position	R	R	R	ICQ	R	N	N	N	N	R	N	N	N	N	R	N	N	R	N
Burette Volume				50	3000	3000	3000	3000	5000	5000	5000	5000	7000	8000	9000	9000	9000	9000	9000
Time Min.				48.5	32.3	39.4	30.3	25.2	39.4	29.3	32.0	27.5	28.7	27.8	25.3	24.0	18.6	17.5	23.1
Limits Max.				NF	33.0	41.0	31.5	28.2	32.0	30.4	33.4	28.6	30.9	28.9	X	26.0	19.4	X	24.0
In Seconds Obs.																			
Flowmeter Min.				NF	520	427	558	867	770	957	873	1018	1322	1812	X	2085	2704	X	2182
Limits Max.				6.0	641	444	578	894	801	996	912	1059	1375	1888	2076	2180	2814	3000	2272
In Lbs./Hr. Obs.				✓	555	460	586	698	795	975	910	1055	1360	1810	1915	2100	2750	2850	2210
Metering Head Min.	6.5	83.8	3.2		4.9				17.5					52.2	R				DERICH
Head Max.	6.9	87.8	3.9		5.8				19.0					66.4	2200				RANGE
Inches of Fuel Obs.	7.3	64.8	4.7		5.8				18.5					52.2					

Test Point No.																			
Metering Suction Inches of Water																			
Corresponding Air Flow Lbs./Hr.																			
Mixture Control Lever Position																			
Burette Volume																			
Time Min.																			
Limits Max.																			
In Seconds Obs.																			
Flowmeter Min.																			
Limits Max.																			
In Lbs./Hr. Obs.																			
Metering Head Min.																			
Head Max.																			
Inches of Fuel Obs.																			

Multi-Point Automatic Mixture Control Calibration Limits: DR
N
R
2280

Flow Method: A-2 AMC P/N 391553 1735
R
1775

Date Issued: 7-1-58 (Test Spec. No. 1484)

Density: .0743 .0811 .0408 .0288
Low (Rich) Limit: 29.65 32.8 36.65 37.0
High (Lean) Limit: 32.15 33.2 36.05 37.4

Notes: 1. Increase fuel inlet pressure to 31.0 P.S.I. at Test Point No. 4 only. (Idle Cut-Off Check).

IDLE = 103 #/HR @ 0.010" (AS RECEIVED & AS SENT)
PRIMER FLOW = 420 #/HR @ 25 PSIG

FLOW TEST LIMITS

P/L 391469-11

PVL

8/15/83

P & W R-360 FUEL/HORSEPOWER DATA

BENDIX RE-100B4 CARBURETOR PL 31147-11

ESTIMATED VALUES

