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STUDY OF ESTIMATION METHODS FOR HYDROGEN CONTENT AND
HEAT OF COMBUSTION OF AVIATION TURBINE FUELS

Leonard C. Angello

Air Force Aero Propulsion Laboratory
Wright-Patterson Air Force Base, Ohio

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**STUDY OF ESTIMATION METHODS FOR HYDROGEN
CONTENT AND HEAT OF COMBUSTION OF
AVIATION TURBINE FUELS**

*FUELS AND LUBRICATION DIVISION (SF)
FUELS BRANCH (SFF)*

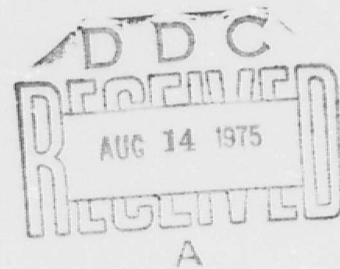
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This technical report has been reviewed and is approved for publication.

Leonard C. Angello
LEONARD C. ANGELLO
Project Engineer

FOR THE COMMANDER

Arthur V. Churchill
ARTHUR V. CHURCHILL
Chief, Fuels Branch
Fuels and Lubrication Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A study was performed to determine the suitability of several newly developed equations for calculation of hydrogen content and net heat of combustion of JP-4 and Jet A fuels. Results of the evaluation indicate that two of the five hydrogen content equations and three of the four net heat of combustion equations are unconditionally acceptable for both JP-4 and Jet A fuels. The estimated standard deviations of the acceptable hydrogen content		

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and net heat of combustion equations are between ± 0.17 and ± 0.18 percent hydrogen and between ± 47 and ± 59 BTU per pound.

Additional results based on comparisons between calculated and conventional fuel specification methods indicate that the precision of the calculated methods are superior and that incorporation of calculated methods into future fuel specification will result in substantial cost savings.

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FOREWORD

This report was prepared by the Fuels Branch (SFF), Fuels and Lubrication Division of the Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, under Work Unit 30480546 "Development Fuel Test Methods". Mr. L. C. Angeilo was the project engineer.

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SECTION I
INTRODUCTION

The value of using the hydrogen content of jet fuel as a measure of the fuel's combustion performance and an evaluation of the use of correlation equations to accurately calculate a fuel's hydrogen content based on other measured fuel properties (aniline point and gravity) have been documented by Martel and Angello (Reference 1). Subsequently, new correlation equations for calculating the hydrogen content and the heat of combustion of jet fuels have become available. It is the purpose of this report to evaluate these new equations and to determine their suitability for use in jet fuel specifications.

SECTION II

NEW CORRELATION EQUATIONS

1. HYDROGEN CONTENT

In Reference 1 the potential value of using a fuel's hydrogen content for predicting its combustion characteristics was discussed. Also, an equation for calculating the hydrogen content of a jet fuel was found to be reasonably accurate (see Equation 3 in Table 1). Equation 3 requires only the measured values of gravity and aniline point. (Note that in Table 1 Equation 3 has been modified to accept the gravity in °API rather than specific gravity and to accept the aniline point in °F rather than in °C. °API is a density measurement devised by the American Petroleum Institute.)

Bert and Painter (Reference 2) have recently developed four new equations for calculating the hydrogen content of fuels. Equations 1A and 2 were developed for various aviation gasolines and jet fuels (termed commercial fuels). Equations 1 and 2A were developed for both commercial jet fuels and for various pure hydrocarbons, special solvents, and high temperature fuels (HTF) produced for Air Force tests. Equations 1, 1A, 2 and 2A require the measured values of gravity, volume fraction of aromatics, and distillation data of the fuel. See Table 1 for these equations.

2. NET HEAT OF COMBUSTION

Currently American Society for Testing and Materials (ASTM) test method D-1405 lists five different equations for calculating the net heat of combustion for various aviation fuels. These equations (A1, A2, A3, A4, and A5 listed in Table 2) require the measured values of the fuel's gravity and aniline point, and are widely used in existing jet fuel specifications.

TABLE 1
EQUATIONS FOR CALCULATING THE HYDROGEN CONTENT OF FUELS

Type Fuel	Equation Number	Equation	Stand. Error of Estimate	Source
All Fuels	1	$H = 10.56 + 0.0632(G) - 4.109(A) + 0.00721(A)(V) + 0.0000568(G)(V) - 0.0496(G)(A)$	0.199	Ref. 2
Commercial Fuels	1A	$H = 10.50 + 0.063(G) - 1.788(A) + 0.00343(A)(V) + 0.0000623(G)(V) - 0.0734(G)(A)$	0.159	Ref. 2
Commercial Fuels	2	$H = 10.54 + 0.0617(G) + 0.0000645(G)(V) - 0.0847(G)(A)$	0.160	Ref. 2
All Fuels	2A	$H = 10.33 + 0.0619(G) + 0.000080(G)(V) - 0.1025(G)(A)$	0.241	Ref. 2
Jet Fuels	3	$H = 8.124 + 0.0586(G) + 0.02165(A_n)$	0.23	Ref. 3
A_n = aniline point (°F) H = weight percent hydrogen G = gravity, °API A = volume fraction aromatics (i.e., 100% aromatics = 1.0) V = average of 10%, 50%, and 90% distillation data in °F (D86)				

TABLE 2
EQUATIONS FOR CALCULATING THE NET HEAT OF COMBUSTION OF FUELS

Type Fuel	Equation Number	Equation	Standard Error of Estimate*	Source
AvGas 100-130 115-145	A1	$Q = 18,037 + 0.0883(A_n)(G)$	23	D1405
JP-3	A2	$Q = 17,940 + 0.1056(A_n)(G)$	28	D1405
JP-4	A3	$Q = 17,977 + 0.1056(A_n)(G)$	19	D1405
JP-5	A4	$Q = 17,914 + 0.1056(A_n)(G)$	30	D1405
Jet A Jet A-1	A5	$Q = 17,919 + 0.10923(A_n)(G)$	-	D1405
Kerosene Distillates	B	$Q = 17,942 + 0.10455(A_n)(G)$	22.8	Ref. 4
All Fuels Except Pure Hydrocarbons	C	$Q = 15.48(G) - 3.41(A) + 0.0194(G)(V) - 0.216(A)(G)$ $+ 0.000306(A)(G)(V) + 17,687$	22.6	Ref. 4
All Fuels	D	$Q = 16.24(G) - 3.007(A) + 0.01714(G)(V) - 0.2983(A)(G)$ $+ 0.00053(A)(G)(V) + 17,685$	38.1	Ref. 4
<p>Q = net heat of combustion, Btu/lb A_n = aniline point (°F) G = gravity (°API) A = volume percent aromatics V = average of 10%, 50%, and 90% distillation data in °F (D86) *Standard Error of Estimate as stated in Reference 4.</p>				

Bert and Painter (Reference 4) have recently developed three new equations for calculating the net heat of combustion. Equation B (see Table 2) is very similar to the ASTM D-1405 equations and is suitable for kerosene distillates. Equation C is suitable for all fuels except pure hydrocarbons and Equation D is suitable for all fuels including pure hydrocarbons. Equations C and D require the measured values of gravity, volume percent of aromatics, and distillation data.

SECTION III

SOURCE OF DATA FOR EVALUATION STUDY

Hydrogen content and heating value data on 19 JP-4 and 16 Jet A fuels were obtained from samples compiled for the Air Force JP-4 and the Coordinating Research Council Jet A Fuel Surveys. These surveys were conducted in 1971 and 1972 and the measured properties are recorded in References 5 and 6.

It should be noted that during the course of this study, the hydrogen contents recorded for fuel samples JP-4-9 and JP-4-17 were remeasured in 1973 and found to be incorrect. The corrected hydrogen contents for these samples are found in Appendix A along with the other measured parameters used in the study of the new hydrogen content equations.

Heating value data (Appendix B) on three additional Jet A fuels was also incorporated in the study of the heating value equations. Sample A-1 is a conventional Jet A fuel, sample A-2 is the same base fuel after desulfurization and sample A-4 is the base fuel after desulfurization and hydrogenation.

Appendix B lists the measured parameters for the fuels used in the study of the new heating value equations.

SECTION IV
ACCURACY COMPARISON

1. HYDROGEN CONTENT EQUATIONS

Appendix A lists the measured fuel properties and the differences between the measured and calculated hydrogen contents for the 35 fuels used in the study. Table 3 is another representation of the error distribution by fuel grouping.

In Table 4 and for the rest of this report, "Groups I and II" refer respectively to the JP-4 fuels and the Jet A fuels taken separately. "Group III" refers to all the fuels in Group I and II taken collectively.

The purpose of Group I and II is to generate data that can help determine future specification changes. Group III is used to provide an indication of the overall versatility of the new calculated hydrogen content equations.

Tables 4, 5, and 6 show comparative statistical analysis by fuel group of the differences between measured and calculated values of hydrogen content shown in Appendix A. The equation statistics compared in each table are the average difference ($\bar{\Delta}$), the standard deviation of the average difference ($S_{\bar{\Delta}}$), the equation standard deviation (S) and the equation variance (S^2). Sample calculation of these statistics are shown in Appendix C.

By using the average difference and standard deviation, we can compute the τ statistic as shown in Appendix D and use it to test for equation bias. Table 7 compares by fuel group the critical τ value with the computed τ values of the five hydrogen equations. Note that the critical τ values shown in Table 7 are for two-tailed significance tests at the 95 percent confidence interval with $N-1$ degrees of freedom.

TABLE 3

FREQUENCY DISTRIBUTION OF DIFFERENCES BETWEEN MEASURED
AND CALCULATED HYDROGEN CONTENT

Difference Range Percent Hydrogen	Group I JP-4 Fuels					Group II Jet A Fuels					Group III All Fuels	
	Equation No.					Equation No.					Equation No.	
	1	1A	2	2A	3	1	1A	2	2A	3	1	2
0 to 0.059	5	5	5	4	6	4	3	3	1	3	9	8
.06 to .10	5	5	5	3	2	3	4	3	3	7	8	8
.11 to .15	2	2	2	5	1	3	3	4	3	1	5	6
.16 to .20	2	2	2	2	1	4	3	4	5	3	6	6
.20 to .25	3	3	2	2	2	1	2	1	2		4	3
.26 to .30			1	1	2				1	1	0	1
.31 to .35	1	1	1	2	1					1	1	1
.36 to .40	1	1			3						1	
.41 to .45			1		1	1	1	1			1	2
.46 to .50									1			

TABLE 4

ANALYSIS OF DIFFERENCES IN MEASURED AND
CALCULATED HYDROGEN CONTENT FOR DATA
GROUP I (JP-4 FUELS)

STATISTIC	EQUATION NUMBER				
	1	1A	2	2A	3
Average Difference, $\bar{\Delta}$	0.011	0.002	-0.023	0.039	0.167
Standard Deviation of Average Difference, $S_{\bar{\Delta}}$	0.171	0.173	0.174	0.174	0.168
Equation Standard Deviation, S	0.177	0.178	0.181	0.184	0.247
Equation Variance S^2	0.031	0.032	0.033	0.034	0.061

TABLE 5

ANALYSIS OF DIFFERENCES IN MEASURED AND
CALCULATED HYDROGEN CONTENT FOR DATA
GROUP II (JET A FUELS)

STATISTIC	EQUATION NUMBER				
	1	1A	2	2A	3
Average Difference, $\bar{\Delta}$	0.070	0.083	0.079	0.136	0.026
Standard Deviation of Average Difference, $S_{\bar{\Delta}}$	0.153	0.153	0.153	0.154	0.156
Equation Standard Deviation, S	0.175	0.181	0.180	0.216	0.163
Equation Variance, S^2	0.031	0.033	0.032	0.047	0.027

TABLE 6

ANALYSIS OF DIFFERENCES IN MEASURED AND
CALCULATED HYDROGEN CONTENT FOR DATA
GROUP III (ALL FUELS)

STATISTIC	EQUATION NUMBER				
	1	1A	2	2A	3
Average Difference, $\bar{\Delta}$	0.038	0.038	0.024	0.083	0.103
Standard Deviation of Average Difference, $S_{\bar{\Delta}}$	0.164	0.167	0.171	0.170	0.175
Equation Standard Deviation, S	0.171	0.174	0.175	0.193	0.207
Equation Variance, S^2	0.029	0.030	0.031	0.037	0.043

TABLE 7
COMPARISON OF τ STATISTICS FOR THE CALCULATED
HYDROGEN CONTENT EQUATIONS

Fuel Group	Equation Number					Critical τ 0.025, n-1
	1	1A	2	2A	3	
I (JP-4 Fuels) n = 19	0.28	0.05	-0.13	0.98	4.33*	2.10
II (Jet A Fuels) n = 16	1.83	2.17*	2.07	3.53*	.667	2.13
III (All Fuels) n = 35	1.37	1.35	0.83	2.89*	3.48*	2.04

* Exceeds Critical τ

Examination of Table 7 reveals that several equation-fuel group combinations indicate significant bias. Consequently, for Group I fuels, only Equations 1, 1A, 2 and 2A are unbiased estimators of hydrogen content. Similarly, for Group II fuels, only Equation 1, 2, and 3 are unbiased and for Group III fuels only Equations 1, 1A and 2 are unbiased. Note that although Table 7 indicates that Equation 1A is unbiased for data Group III, it is believed that this result should be considered suspect by way of the following intuitive argument.

From Table 7 it can be seen that Equation 1A exhibits a significant bias for the Group II fuels but none for the Group I fuels. Since, as stated earlier, Group III is the combination of the fuels from Groups I and II, and since Group I is composed of three more fuels than Group II, it is not unreasonable to suspect a hidden bias in the results of Table 7 for this particular equation-fuel group combination due to averaging.

In conclusion, Table 8 is a summary of the five calculated hydrogen equations, their standard deviations and the fuel group for which they are valid. The results of Table 8 are summarized below:

(1) For JP-4 fuels, the applicable equations are Equations 1, 1A, 2, and 2A of which Equation 1 has the lowest standard deviation.

TABLE 8
SUMMARY OF THE STANDARD DEVIATIONS OF THE
CALCULATED HYDROGEN CONTENT EQUATIONS BY
FUEL GROUP

Fuel Group	Equation Number				
	1	1A	2	2A	3
I (JP-4 Fuels)	.177	.178	.181	.184	.247*
II (Jet A Fuels)	.175	.181*	.180	.216*	.163
III (All Fuels)	.171	.174*	.175	.193*	.207*

*Denotes equation biased for the fuel group indicated.

(2) For Jet A fuels, the applicable equations are Equations 1, 2 and 3 with Equation 3 having lowest standard deviation.

(3) For the combination of the JP-4 and Jet A fuels, the applicable equations are either Equation 1 or 2 with Equation 1 having the lower standard deviation.

2. NET HEAT OF COMBUSTION EQUATIONS

Appendix B lists the measured fuel properties and the differences between the measured and calculated net heats of combustion for the 39 fuels used in the study. Note that the measured net heats of combustion in Appendix B have been corrected for sulfur content so that they can be directly compared to the calculated values obtained from Equations A3, A5, B, C, and D of Table 2. Table 9 gives the error distribution of Table 10 by fuel group, and Tables 10, 11, and 12 give comparative statistical analyses of the error differences of Appendix B. Note that the statistics shown for the equation - fuel group combination, A3/A5 - Group III, were calculated by pooling the errors of Equation A3 for JP-4 fuels with the errors of Equation A5 for Jet A fuels.

Table 13 states the results of an analysis of bias similar to the one used for the evaluation of the hydrogen content equations in Section IV, Subsection 1 of this report. The results of this table indicate that the only equation - fuel group combinations showing significant bias at the 95 percent confidence interval are Equation A3 for Group I fuels and the A3/A5 equation combination for Group III fuels.

Table 14 is a summary of the calculated heat of combustion equations evaluated, their standard deviations, and the fuel group for which they are valid. The results of Table 14 are summarized below.

(1) For JP-4 fuels, the applicable equations are Equations B, C, and D with Equation B having the lowest standard deviation.

(2) For Jet A fuels, the applicable equations are Equations A5, B, C, and D with Equation C having the lowest standard deviation.

(3) For the combination of JP-4 and Jet A fuels, the applicable equations are Equation B, C, and D of which Equation B has the lowest standard deviation.

TABLE 9

FREQUENCY DISTRIBUTION OF DIFFERENCES BETWEEN MEASURED
AND CALCULATED NET HEAT OF COMBUSTION

Difference Range Btu/lb	Group I JP-4 Fuels				Group II Jet A Fuels				Group III All Fuels		
	Equation				Equation				Equation		
	A3	B	C	D	A5	B	C	D	B	C	D
0 to 5		1	1	1	1	1	3	2	2	4	3
6 to 10		3			1	2	2	2	5	2	2
11 to 15		2						1	2		1
16 to 20	2	2	3	2	1	1	1	1	3	4	3
21 to 25	2	3	4	4		1			4	4	4
26 to 30	3		1	1	4					1	1
31 to 35	2	1		1		1	5	3	2	5	4
36 to 40			2	2	1	4	2	4	4	4	6
41 to 45	2	1				1			2		
46 to 50			1	1	2					1	1
51 to 55	1				3	1	1		1	1	
56 to 60		1	2	1		2		1	3	2	2
61 to 65		2	1	2	1		1	1	2	2	3
66 to 70	3	1	1	2	1	1	1	1	2	2	3
71 to 75	1		1			1		1	1	1	1
76 to 80						1	1		1	1	
81 to 85	1		1	1	2					1	1
86 to 90		1							1		
91 to 95		1							1		
96 to 100							1			1	
>100	2		1	1	2	2	1	2	2	2	3

TABLE 10

ANALYSIS OF DIFFERENCES IN MEASURED AND
CALCULATED NET HEAT OF COMBUSTION FOR DATA
GROUP I (JP-4 FUELS)

STATISTIC	EQUATION NUMBER			
	A3	B	C	D
Average Difference, $\bar{\Delta}$	-40.9	+ 1.6	-17.6	-14.8
Standard Deviation of Average Difference, $S_{\bar{\Delta}}$	45.6	45.4	49.6	50.7
Equation Standard Deviation, S	63.8	46.8	54.4	54.5
Equation Variance, S^2	4070	2190	2959	2970

TABLE 11

ANALYSIS OF DIFFERENCES IN MEASURED AND
CALCULATED NET HEAT OF COMBUSTION FOR DATA
GROUP II (JET A FUELS)

STATISTIC	EQUATION NUMBER			
	A5	B	C	D
Average Difference, $\bar{\Delta}$	-22.6	-14.6	- 0.6	- 3.1
Standard Deviation of Average Difference, $S_{\bar{\Delta}}$	55.0	55.7	51.9	53.0
Equation Standard Deviation, S	61.5	59.3	53.4	54.7
Equation Variance, S^2	3782	3516	2852	2992

TABLE 12

ANALYSIS OF DIFFERENCES IN MEASURED AND
CALCULATED NET HEAT OF COMBUSTION FOR DATA
GROUP III (ALL FUELS)

STATISTIC	EQUATION NUMBER			
	A3/A5	B	C	D
Average Difference, $\bar{\Delta}$	-31.7	- 6.5	- 9.1	- 8.9
Standard Deviation of Average Difference, $S_{\bar{\Delta}}$	50.7	50.8	50.8	51.5
Equation Standard Deviation, S	60.9	51.9	52.4	53.0
Equation Variance, S^2	3709	2694	2746	2809

TABLE 13

COMPARISON OF τ STATISTICS FOR THE CALCULATED NET
HEAT OF COMBUSTION EQUATIONS

Fuel Group	Equation Number				Critical $\tau_{0.025, n-1}$
	A3/A5	B	C	D	
I (JP-4 Fuels; n = 19)	-3.91*	+0.15	-1.55	-1.27	2.10
II (Jet A Fuels) n = 19	-1.79	-1.14	-0.05	-0.25	2.10
III (All Fuels) n = 38	-3.85*	-0.79	-1.10	-1.07	2.02
*Exceeds Critical τ					

TABLE 14

SUMMARY OF THE STANDARD DEVIATIONS OF THE
CALCULATED NET HEAT OF COMBUSTION EQUATIONS
BY FUEL GROUP

Fuel Group	Equation Number			
	A3/A5	B	C	D
I (JP-4 Fuels)	63.8*	46.8	54.4	54.5
II (Jet A Fuels)	61.5	59.3	53.4	54.7
III (All Fuels)	60.9*	51.9	52.4	53.0

*Denotes equation biased for the fuel group indicated.

SECTION V
PRECISION COMPARISON

1. HYDROGEN CONTENT

Precision is defined as the repeatability and reproducibility of test methods and does not reflect on the absolute accuracy of test results. Thus a highly precise test method may or may not give accurate answers, but it will give repeatable and reproducible answers.

The precision of the measured smoke point (D1322), the measured luminometer number (D1740), and the measured hydrogen content (D1018) are compared with the estimated precision for the methods for calculating the hydrogen content of fuels (see Appendix E for sample calculation). The relative precision of each method has been calculated by dividing the repeatability (r) and reproducibility (R) by the typical value for a JP-4 fuel as shown in Table 15.

From Table 15 it is apparent that smoke point and luminometer number are much less precise than the measured or calculated values of a fuel's hydrogen content. Thus, a calculation method for determining the fuel's hydrogen content can be used in lieu of smoke point or luminometer number while simultaneously improving the precision.

Although the accuracy of calculated hydrogen content values are certainly not as good as measured values, the calculated hydrogen content values are considered to be superior to measured values of smoke point and luminometer numbers due to their improved precision.

2. NET HEAT OF COMBUSTION

Table 16 compares the relative precision of measuring or calculating the net heat of combustion for the methods of interest. From the table it is again apparent that measured values are much less precise than calculated values and that calculated methods for determining a fuel's heat of combustion can be used in place of the measured methods while simultaneously improving precision.

TABLE 15
PRECISION LIMITS FOR COMBUSTION TEST METHODS

Method	Typical JP-4 Value	Repeatability r	Relative Precision r/Typical Value	Reproducibility R	Relative Precision R/Typical Value
D-1018 Hydrogen Content	14.0%	0.11%	0.8%	0.18%	1.3%
D-1322 Smoke Point	25. mm	1 mm	4.0%	3 mm	12.0%
D-1740 Luminometer Nr.	55 LN	5 LN	9.1%	7 LN	12.7%
Calculated Hydrogen Content					
Equations 1 and 1A	14.0%	0.03%	0.2%	0.08%	0.6%
Equations 2 and 2A	14.0%	0.03%	0.2%	0.09%	0.6%

TABLE 16
PRECISION LIMITS FOR NET HEAT OF COMBUSTION TEST METHODS

Method	Typical JP-4 Value	Repeatability r	Relative Precision r/Typical Value	Reproducibility R	Relative Precision R/Typical Value
D-240 - Bomb Calorimeter	18,700 $\frac{\text{Btu}}{\text{lb}}$	55 $\frac{\text{Btu}}{\text{lb}}$	0.29%	175 $\frac{\text{Btu}}{\text{lb}}$	0.94%
D-2382 - Bomb Calorimeter	18,700 $\frac{\text{Btu}}{\text{lb}}$	22 $\frac{\text{Btu}}{\text{lb}}$	0.12%	56 $\frac{\text{Btu}}{\text{lb}}$	0.30%
Calculated Net Heat of Combustion					
Equations A3, A5 and B	18,700 $\frac{\text{Btu}}{\text{lb}}$	3 $\frac{\text{Btu}}{\text{lb}}$	0.02%	9 $\frac{\text{Btu}}{\text{lb}}$	0.05%
Equations C and D	18,700 $\frac{\text{Btu}}{\text{lb}}$	8 $\frac{\text{Btu}}{\text{lb}}$	0.04%	23 $\frac{\text{Btu}}{\text{lb}}$	0.12%

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In stating the above result, it is again recognized that measured values of net heat of combustion are more accurate than calculated values. However, for most purposes, calculated values are sufficiently accurate to justify their use.

SECTION VI
COST SAVING COMPARISON

Table 17 summarizes the estimated manhours and cost of typical jet fuel specification tests based on values obtained from the Air Force Quality Control Laboratory, Wright-Patterson AFB, Ohio and the Humble Oil and Refining Company. Using this table, the following potential cost savings can be calculated:

Calculated Hydrogen Content - Currently, Smoke Point or Luminometer Number are used to specify a fuel's combustion performance despite conclusive evidence that hydrogen content is the best measure of combustion performance (Reference 1). The use of Equations 1 or 2 to calculate hydrogen content in lieu of running either Smoke Point or Luminometer Number results in a saving per test of \$2.38 (\$2.80 less \$.42) for Smoke Point and \$13.58 (\$14.00 less \$.42) for Luminometer Number.

Calculated Heating Value - The ASTM D1405 method is currently widely used for calculating heating value; however, this method requires that the aniline point be measured. By using Equations C or D, the aniline point would not be required resulting in a saving of \$3.50 per test.

The Air Force Fuel Quality Control Laboratories, under the Command of the Air Force Logistics Command, San Antonio Air Logistics Center, Aerospace Fuels Directorate, conduct about 2400 smoke point tests and 3000 aniline-gravity tests on jet fuels per year. In addition, another 5000 smoke point and aniline gravity tests are performed for the Air Force by fuel suppliers each year. By substituting the calculated hydrogen content for the smoke point and the calculated heat of combustion for the aniline-gravity heat of combustion measurement, approximately \$32,000 annual savings are possible.

TABLE 17

ESTIMATED MAN-HOURS AND COST OF FUEL TESTS

Test Method	Estimated Man-hours	Estimated Costs*
D-287 Gravity	0.17	\$ 2.38
D-86 Distillation	0.50	\$ 7.00
D-1319 Per Cent Aromatics & Olefins	0.50	\$ 7.00
D-611 Aniline Point	0.25	\$ 3.50
D-1322 Smoke Point	0.20	\$ 2.80
D-1740 Luminometer Number	1.0	\$14.00
Calculated Hydrogen Content	0.03	\$.42
Calculated Heating Value	0.03	\$.42
*Based on an assumed cost of \$14.00 per hour including overhead		

SECTION VII

CONCLUSIONS

1. CALCULATED HYDROGEN CONTENT

a. It appears from the data that Equations 1 and 2 will provide unbiased estimates of hydrogen content for either JP-4 or Jet A type fuels with estimated standard deviations of between 0.17 and 0.18 weight percent hydrogen.

b. The relative precision of calculated hydrogen content by use of Equation 1 or 2 is an order of magnitude better than that of measured Smoke Point or measured Luminometer Number.

c. Substantial savings can be realized by replacing Smoke Point and Luminometer Number specifications for JP-4 and Jet A fuels with a calculated hydrogen content method using Equation 1 or 2.

2. CALCULATED NET HEAT OF COMBUSTION

a. The data studied indicate that Equations B, C, and D will provide unbiased estimates of net heat of combustion for JP-4 and Jet A fuels. The estimated standard deviations of Equations C and D with parameters of gravity, aromatic content, and average distillation temperature are between 52 and 55 Btu per pound. The estimated standard deviation of Equation B with parameters of aniline point and gravity is between 47 and 59 Btu per pound.

b. The relative precision of calculated net heat of combustion by use of Equation C or D is equal to that of using an aniline-gravity equation and better than that of measuring net heat of combustion.

c. Substantial savings can be realized by replacing the aniline-gravity equations now used for JP-4 and Jet A fuel specifications with either Equation C or D.

SECTION VIII
RECOMMENDATIONS

1. It is recommended that all Air Force aircraft turbine fuel specifications be revised to specify a minimum hydrogen content as the fuel combustion parameter in lieu of smoke point, luminometer number, or smoke volatility index.
2. It is recommended that for JP-4, JP-5, and JP-8 fuels the hydrogen content calculation method be allowed as an alternative to the measured hydrogen content (ASTM D-1018). Equation 1 of Table 1 of this report is recommended.
3. It is recommended that the calculated heat of combustion method, ASTM D-1405 (i.e., the aniline-gravity method), be replaced with Equation C of Table 2 of this report in all applicable Air Force aircraft turbine fuel specifications.

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5. Ford, J. C., Bradley, R. P. and Angello, L. C., JP-4 Thermal Stability Survey, AF Aero Propulsion Laboratory, Technical Report AFAPL-TR-73-27, June 1973.
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APPENDIX A

HYDROGEN CONTENT EVALUATION DATA

Fuel Reference	MEASURED PROPERTIES					MEASURED MINUS CALCULATED, % WEIGHT					Fuel Type	
	Gravity °API	Average Distillation Temperature, of	Aniline Point of	Aromatic Content % Volume	Smoke Point mm	Measured Hydrogen % Weight	Equation Number			(3)		
							(1)	(2)	(2A)			
JP-4-1	53.9	293.3	133.0	10.8	27	14.33	-0.03	-0.04	-0.06	-0.01	+0.17	JP-4
JP-4-2	52.7	317.3	136.5	10.8	27	14.43	+0.07	+0.06	+0.04	+0.08	+0.26	JP-4
JP-4-3	55.9	298.3	134.0	9.3	28	14.69	+0.09	+0.08	+0.07	+0.10	+0.39	JP-4
JP-4-4	50.6	340.7	145.0	8.9	27	14.59	+0.22	+0.21	+0.20	+0.21	+0.36	JP-4
JP-4-5	56.8	301.7	143.0	8.3	27	14.96	+0.23	+0.22	+0.21	+0.23	+0.41	JP-4
JP-4-6	54.4	268.0	108.5	24.8	18	13.76	+0.14	+0.13	+0.07	+0.28	+0.10	JP-4
JP-4-7	51.9	329.7	141.5	9.7	27	14.55	+0.16	+0.15	+0.13	+0.15	+0.32	JP-4
JP-4-8	56.9	265.3	130.0	12.6	27	14.31	-0.07	-0.08	-0.11	-0.02	+0.04	JP-4
JP-4-9	51.3	322.7	130.0	17.8	25	14.00	+0.03	+0.03	0.00	+0.11	+0.06	JP-4
JP-4-10	47.2	333.7	126.0	14.6	21	13.62	-0.23	-0.24	-0.26	-0.19	+0.00	JP-4
JP-4-11	47.2	317.7	123.0	12.8	21	13.82	-0.04	-0.06	-0.09	-0.01	+0.27	JP-4
JP-4-12	55.4	270.0	125.0	12.2	21	13.94	-0.37	-0.38	-0.41	-0.32	-0.14	JP-4
JP-4-13	52.6	332.0	143.0	11.8	27	14.70	+0.33	+0.33	+0.31	+0.35	+0.40	JP-4
JP-4-14	54.1	301.0	137.5	8.7	25	14.32	-0.18	-0.19	-0.21	-0.18	+0.05	JP-4
JP-4-15	53.1	289.0	128.0	11.3	25	14.25	-0.01	-0.02	-0.05	+0.02	+0.24	JP-4
JP-4-16	51.6	331.0	139.0	11.6	24	14.14	-0.15	-0.16	-0.18	-0.14	-0.02	JP-4
JP-4-17	51.0	298.0	118.0	21.9	20	13.69	+0.03	+0.02	-0.03	+0.13	+0.02	JP-4
JP-4-18	54.4	305.3	138.0	9.9	27	14.54	+0.06	+0.05	+0.03	+0.06	+0.24	JP-4
JP-4-19	56.1	330.3	154.5	6.9	23	14.78	-0.07	-0.08	-0.09	-0.11	+0.02	JP-4
870-3	42.0	415.0	147.5	13.4	19	13.98	+0.20	+0.21	+0.20	+0.23	+0.20	Jet A
970-1	43.3	407.3	142.0	15.6	19	13.81	+0.03	+0.04	+0.03	+0.08	+0.07	Jet A
970-2	42.3	415.0	141.0	18.5	18	13.81	+0.17	+0.19	+0.19	+0.26	+0.15	Jet A
970-3	39.6	418.3	136.5	18.0	18	13.47	+0.02	+0.03	+0.02	+0.09	+0.07	Jet A
970-4	45.4	399.7	146.0	16.0	19	14.04	+0.14	+0.15	+0.14	+0.19	+0.09	Jet A
1070-1	41.5	431.7	146.0	19.2	18	13.69	+0.08	+0.10	+0.11	+0.17	-0.03	Jet A
1170-2	45.0	396.7	147.5	17.3	18	13.95	+0.13	+0.15	+0.14	+0.20	+0.00	Jet A
171-1	48.1	382.3	141.5	20.2	23	13.93	+0.04	+0.06	+0.06	+0.15	-0.08	Jet A
171-2	46.6	385.7	143.0	15.5	21	14.03	+0.07	+0.08	+0.07	+0.12	+0.08	Jet A
171-3	47.9	381.3	146.5	14.6	22	14.27	+0.19	+0.20	+0.19	+0.23	+0.17	Jet A
171-5	46.2	391.7	144.0	17.5	20	13.65	-0.23	-0.22	-0.22	-0.16	-0.30	Jet A
271-1	47.0	391.3	145.5	17.2	20	14.36	+0.41	+0.42	+0.42	+0.48	+0.33	Jet A
271-3	50.0	380.0	143.0	17.5	20	14.05	-0.08	-0.06	-0.06	0.00	-0.10	Jet A
371-1	47.0	393.0	147.0	16.6	20	13.99	+0.01	+0.02	+0.02	+0.07	-0.07	Jet A
371-2	47.6	379.7	142.5	18.3	19	14.03	+0.12	+0.13	+0.13	+0.20	+0.03	Jet A
471-1	48.2	381.0	148.0	13.8	20	13.96	-0.18	-0.17	-0.18	-0.14	-0.19	Jet A

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APPENDIX B

NET HEAT OF COMBUSTION EVALUATION DATA

Fuel Reference	MEASURED PROPERTIES										MEASURED MINUS CALCULATED, BTU/LB				Fuel Type
	Gravity °API	Average Distillation Temperature, °F	Aniline Point °F	Aromatic Content % Volume	Total Sulfur % Weight	Sulfur Correction Btu/lb	Sulfur Free Heating Value Measured Btu/lb	(A3/A5)	(B)	(C)	(D)				
JP-4-1	53.9	293.3	133.0	10.8	0.061	9.	18,777.	+ 43.	+ 86.	+ 60.	+ 62.	JP-4			
JP-4-2	52.7	317.3	136.5	10.8	0.030	4.	18,652.	- 85.	- 42.	- 71.	- 69.	JP-4			
JP-4-3	55.9	298.3	134.0	9.3	0.017	2.	18,695.	- 73.	- 31.	- 85.	- 83.	JP-4			
JP-4-4	50.6	340.7	145.0	8.9	0.076	11.	18,727.	- 25.	+ 18.	+ 3.	+ 5.	JP-4			
JP-4-5	56.8	301.7	143.0	8.3	0.042	6.	18,697.	-138.	- 94.	-115.	-114.	JP-4			
JP-4-6	54.4	268.0	108.5	24.8	0.009	1.	18,573.	- 28.	+ 14.	+ 26.	+ 40.	JP-4			
JP-4-7	51.9	329.7	141.5	9.7	0.022	3.	18,770.	+ 17.	+ 60.	+ 39.	+ 40.	JP-4			
JP-4-8	56.9	265.3	130.0	12.6	0.009	1.	18,779.	+ 21.	+ 63.	+ 58.	+ 62.	JP-4			
JP-4-9	51.3	322.7	130.0	17.8	0.063	9.	18,572.	-109.	- 67.	- 63.	- 60.	JP-4			
JP-4-10	47.2	333.7	126.0	14.6	0.066	9.	18,571.	- 34.	+ 7.	- 24.	- 23.	JP-4			
JP-4-11	47.2	317.7	123.0	12.8	0.137	19.	18,525.	- 66.	- 24.	- 69.	- 67.	JP-4			
JP-4-12	55.4	270.0	125.0	12.2	0.040	6.	18,667.	- 41.	+ 1.	- 36.	- 32.	JP-4			
JP-4-13	52.6	332.0	143.0	11.8	0.088	13.	18,705.	- 66.	- 23.	- 23.	- 22.	JP-4			
JP-4-14	54.1	301.0	137.5	8.7	0.102	15.	18,732.	- 30.	+ 13.	- 20.	- 19.	JP-4			
JP-4-15	53.1	289.0	128.0	11.3	0.008	1.	18,711.	+ 16.	+ 58.	+ 19.	+ 22.	JP-4			
JP-4-16	51.6	331.0	139.0	11.6	0.008	1.	18,684.	- 51.	- 8.	- 25.	- 23.	JP-4			
JP-4-17	51.0	298.0	118.0	21.9	0.032	5.	18,579.	- 33.	+ 8.	+ 22.	+ 28.	JP-4			
JP-4-18	54.4	305.3	138.0	9.9	0.020	3.	18,703.	- 67.	- 24.	- 48.	- 47.	JP-4			
JP-4-19	56.1	330.3	154.5	6.9	0.042	6.	18,864.	- 28.	+ 16.	+ 17.	+ 19.	JP-4			
870-3	42.0	415.0	147.5	13.4	0.144	20.	18,480.	-116.	-110.	-100.	-102.	Jet A			
970-1	49.3	407.3	142.0	15.6	0.072	10.	18,621.	+ 30.	+ 36.	+ 36.	+ 33.	Jet A			
970-2	47.3	415.0	141.0	18.5	0.165	23.	18,488.	- 83.	- 78.	- 62.	- 68.	Jet A			
970-3	39.6	418.3	136.5	18.0	0.092	13.	18,501.	- 8.	- 6.	+ 4.	- 2.	Jet A			
970-6	45.4	399.7	146.0	16.0	0.003	0.	18,614.	- 29.	- 21.	- 6.	- 9.	Jet A			
1070-1	41.5	431.7	146.0	19.2	0.022	3.	18,541.	- 40.	- 35.	- 4.	0	12.	Jet A		
1170-2	45.0	396.7	147.5	17.3	0.048	7.	18,562.	- 82.	- 74.	- 35.	- 39.	Jet A			
171-1	48.1	382.3	141.5	20.2	0.004	1.	18,691.	+ 29.	+ 38.	+ 68.	+ 64.	Jet A			
171-2	46.6	385.7	143.0	15.5	0.056	8.	18,600.	- 47.	- 39.	- 33.	- 35.	Jet A			
171-3	47.9	381.3	146.5	14.6	0.067	10.	18,632.	- 53.	- 43.	- 31.	- 32.	Jet A			
171-5	46.2	391.7	144.0	17.5	0.007	1.	18,693.	+ 47.	+ 55.	+ 77.	+ 74.	Jet A			
271-1	47.0	391.3	145.5	17.2	0.025	4.	18,602.	- 64.	- 56.	- 32.	- 36.	Jet A			
271-3	50.0	380.0	143.0	17.5	0.075	11.	18,649.	- 51.	- 40.	- 33.	- 36.	Jet A			
371-1	47.0	393.0	147.0	16.6	0.109	18.	18,605.	- 68.	- 59.	- 36.	- 39.	Jet A			
371-2	47.6	379.7	142.5	18.3	0.044	6.	18,644.	- 16.	- 7.	+ 19.	+ 16.	Jet A			
471-1	48.2	381.0	148.0	13.8	0.020	3.	18,669.	- 29.	- 19.	- 7.	- 8.	Jet A			
A-1	44.4	416.0	152.	10.9	0.036	5.	18,651.	- 5.	+ 3.	- 2.	- 1.	Jet A			
A-2	44.7	415.0	154.	11.0	0.001	0.	18,772.	+101.	+110.	+114.	+115.	Jet A			
A-4	46.4	410.0	165.5	1.6	0.001	0.	18,813.	+ 55.	+ 68.	+ 51.	+ 59.	Jet A			

APPENDIX C

SAMPLE CALCULATIONS OF STATISTICS
 FOUND IN TABLES 4, 5, 6, 10, 11, AND 12
 (VALUE FROM APPENDIX A, EQUATION 1, JP-4 FUELS)

(A) AVERAGE DIFFERENCE, $\bar{\Delta}$

$$\bar{\Delta} = \frac{\Sigma \Delta}{N}$$

$$= \frac{[(-0.03) + (0.07) + (0.09) + \dots + (-0.18)]}{19}$$

$$= \frac{0.72}{19}$$

$$= 0.038$$

(B) STANDARD DEVIATION OF AVERAGE DIFFERENCE, $S_{\bar{\Delta}}$

$$S_{\bar{\Delta}} = \sqrt{\frac{\Sigma (\Delta - \bar{\Delta})^2}{N - 1}}$$

$$= \sqrt{\frac{[(-0.03 - 0.038)^2 + (0.07 - 0.038)^2 + \dots + (-0.18 - 0.038)^2]}{18}}$$

$$= \sqrt{\frac{[0.485]}{18}}$$

$$= \pm 0.164$$

(C) ESTIMATE OF EQUATION STANDARD DEVIATION, S

$$S = \sqrt{\frac{\sum \Delta^2}{N - 2}}$$

$$= \sqrt{\frac{[(-0.03)^2 + (0.07)^2 + (0.09)^2 + \dots + (-0.18)^2]}{17}}$$

$$= \sqrt{\frac{0.5309}{17}}$$

$$= \sqrt{0.0312}$$

$$= \pm 0.177$$

APPENDIX D

SAMPLE CALCULATION OF THE τ STATISTIC

The determination of a bias estimator by application of the τ test is based on the assumption that the difference, Δ , between the estimated value and the true value of the estimate is a normally distributed random variable with zero population mean. This assumption leads to the following hypotheses:

H_0 : $\mu = 0$, and the estimator is unbiased

H_1 : $\mu \neq 0$, and the estimator is biased

The rejection or acceptance of these hypotheses will depend on the decision rule chosen. For Equation 1 and the Group 1 data, the following decision rule is adopted based on a two tailed test for a 0.05 level of significance and $n-1$ degrees of freedom:

(1) Reject H_0 if the τ score of the sample mean is outside the range + 2.10 to -2.10.

(2) Accept H_0 otherwise.

Given this decision rule the τ score for the sample mean can be calculated as shown below:

$$\tau = \frac{\bar{\Delta} - \mu}{s_{\Delta}} \sqrt{n}$$

where $\bar{\Delta}$ = sample mean = 0.011% H_2

s_{Δ} = sample standard deviation = 0.171% H_2

μ = population mean = 0

n = sample size = 19

$$\tau = \frac{0.011-0}{0.171} \sqrt{19} = 0.28$$

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Since the sample mean τ score, 0.28, lies inside the range 2.10 to -2.10, the null hypothesis is accepted indicating that Equation 1 is an unbiased estimator for JP-4 fuels.

APPENDIX E

SAMPLE CALCULATION OF THE ESTIMATED
PRECISION LIMITS ON CALCULATED FUEL PROPERTIES

(A) REPEATABILITY OF CALCULATED HYDROGEN CONTENT

$$H = 10.56 + 0.0632(G) - 4.109(A) + 0.00721(A)(V) + 0.0000568(G)(V) - 0.0496(G)(A)$$

D 287	Gravity	$r = \pm 0.2$	$r^2 = 0.04$
D 1319	Aromatic	$r = \pm 0.5 \times 10^{-2}$	$r^2 = 0.25 \times 10^{-4}$
D 86	Volatility	$r = \pm 5$	$r^2 = 25$

Evaluation made at $G = 44$; $A = 0.12$; $V = 400$

$$\begin{aligned} \text{Contribution from G Errors} &= (0.04)[6.32 \times 10^{-2} + 56.8 \times 10^{-6}(4 \times 10^2) - 4.96 \times 10^{-2} (12 \times 10^{-2})]^2 \\ &= (0.04)[632 \times 10^{-4} + 227 \times 10^{-4} - 59.5 \times 10^{-4}]^2 \\ &= (0.04)[799.5 \times 10^{-4}]^2 \\ &= (0.04)(63.92 \times 10^{-4}) \\ &= 2.557 \times 10^{-4} \end{aligned}$$

$$\begin{aligned} \text{Contribution from A Errors} &= 0.25 \times 10^{-4}[-4.109 + 4 \times 10^2(0.721 \times 10^{-2}) - (44)(0.0496)]^2 \\ &= 0.25 \times 10^{-4}[-4.109 + 2.884 - 2.182]^2 \\ &= 0.25 \times 10^{-4}[11.608]^2 \\ &= 2.902 \times 10^{-4} \end{aligned}$$

$$\begin{aligned}
 \text{Contribution from V Errors} &= (25) [12 \times 10^{-2}(0.721 \times 10^{-2}) + 44(0.568 \times 10^{-4})]^2 \\
 &= 25[8.652 \times 10^{-4} + 24.992 \times 10^{-4}]^2 \\
 &= 25[0.3364 \times 10^{-2}]^2 \\
 &= 25(0.1132 \times 10^{-4}) \\
 &= 2.829 \times 10^{-4} \\
 r_H^2 &= (2.557 + 2.902 + 2.829) \times 10^{-4} \\
 &= 8.288 \times 10^{-4} \\
 r_H &= \pm 2.88 \times 10^{-2} \\
 &= \pm 0.03
 \end{aligned}$$

2

(B) REPRODUCIBILITY CALCULATED HYDROGEN CONTENT

$$H = 10.56 + 0.0632(G) - 4.109(A) + 0.00721(A)(V) + 0.0000568(G)(V) - 0.0496(G)(A)$$

D 287	Gravity R = ±0.5	R ² = 0.25
D 1319	Aromatic R = ±1.7 × 10 ⁻²	R ² = 2.89 × 10 ⁻⁴
D 86	Volatility R = ±13	R ² = 169

Evaluation made at G = 44; A = 0.12; V = 400

$$\begin{aligned}
 \text{Contribution from G Errors} &= (0.25)[6.32 \times 10^{-2} + 0.568 \times 10^{-4} (4 \times 10^{+2}) - 4.96 \times 10^{-2}(0.12)]^2 \\
 &= (0.25)[6.32 \times 10^{-2} + 2.27 \times 10^{-2} - 0.595 \times 10^{-2}]^2 \\
 &= (0.25)[7.995 \times 10^{-2}]^2 \\
 &= (0.25) (63.920 \times 10^{-4}) \\
 &= 15.980 \times 10^{-4}
 \end{aligned}$$

$$\begin{aligned}
 \text{Contribution from A Errors} &= 2.89 \times 10^{-4} [-4.109 + 4 \times 10^2 (0.721 \times 10^{-2} - (44)(0.0496))]^2 \\
 &= 2.89 \times 10^{-4} [4.109 + 2.884 - 2.182]^2 \\
 &= 2.89 \times 10^{-4} [11.608] \\
 &= 33.547 \times 10^{-4}
 \end{aligned}$$

$$\begin{aligned}
 \text{Contribution from V Errors} &= 169 [12 \times 10^{-2} (0.721 \times 10^{-2}) + 44 (0.568 \times 10^{-4})]^2 \\
 &= 169 [0.0865 \times 10^{-2} + 24.995 \times 10^{-2}]^2 \\
 &= 169 [0.3364 \times 10^{-2}]^2 \\
 &= 169 [0.1132 \times 10^{-4}] \\
 &= 19.131 \times 10^{-4}
 \end{aligned}$$

$$\text{Total } R_H^2 = (15.980 + 33.547 + 19.131) \times 10^{-4}$$

$$= 68.658 \times 10^{-4}$$

$$R_H = \pm 8.296 \times 10^{-2}$$

$$= \pm 0.08$$