THE OCTANE REQUIREMENT

OF

SPARK IGNITION ENGINES

by

G.E. BLEIMSCHEIN

Submitted to the University of Cape Town in partial fulfilment

for the degree of Master of Science in Engineering

The University of Cape Town has been given the right to reproduce this thesis in whole or in part. Copyright is held by the author.

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

University of Cape Town

I, Georg Eduard Bleimschein, submit this thesis in partial fulfilment of the requirements for the degree of Master of Science in Engineering. I claim that this is my original work and that it has not been submitted in this or in a similar form for a degree at any other University.

Signed by candidate

G.E. Bleimschein BSc.(Eng.) Mechanical

29th day of April 1991.

ABSTRACT

The thesis covers the fundamentals of refining and fuel technology, engine technology as regards parameters which influence knock and the results of engine tests.

Definitions of octane number and the interpretation of the system developed to establish these numbers using the CFR engine are given. The literature survey covers the fundamental refining processes which are used to upgrade gasoline components in order to raise their octane quality or to achieve a more suitable distillation range. Some of the reactions which take place are described and operating conditions for the reactions to occur are given. The chemistry of fuels which affects their octane quality is given and discussed. Generally, aromatics have very good octane values but straight chain paraffins are poor in this regard.

The parameters which affect fuel performance in spark ignition engines may be summarized as follows:

Research Octane Number
Motor Octane Number
Distillation
Flammability limits
Density
Latent heat of vapourisation
Calorific value
Vapour pressure
Viscosity
Auto-ignition temperature
Stoichiometric air/fuel ratio
Flash point

These properties are analyzed and values are provided for the commonly used gasoline components.

Engine technology is described especially with regard to the parameters which affect knock, such as fuel/air ratio, compression ratio, combustion chamber shape and spark plug location. The chemical reactions which precede knock together with the most widely accepted knock theory are presented.

Tests were conducted using a Heenan and Froude eddy current engine dynamometer and sophisticated computerized data acquisition systems were used to obtain the results. Four current engines popular in the local market were selected as they were known to be knock sensitive. These were:

Toyota 1,6l	16 valve carburettor
Volkswagen 1,8l	8 valve carburettor
Nissan 1,8l	8 valve twin carburettor
Ford 3,0l	12 valve carburettor

Cylinder pressures were measured using an in cylinder pressure transducer while knock was determined with an accelerometer mounted on the cylinder head of the engine. The engines were operated on primary reference fuels (blends of iso-octane and n-heptane) and on some unleaded Sasol fuels. The ignition timing curves for maximum brake torque were established using commercial Aviation Gasoline 100/130 and all the tests were run at wide open throttle.

The brake mean effective pressure curve for each engine was determined and the influence of advancing and retarding the ignition timing by 10^{o} was found for each data point. While the ignition timing advance curves for the Toyota and Volkswagen engines were fairly well optimized, the timing curves for the Nissan and Ford engines could be improved.

Fuel consumption measurements were made and it was established that the Nissan engine had a substantially higher fuel consumption than the other engines due to some unknown malfunction. The primary reference fuel octane requirements of all the engines displayed a linear fall with an increase of engine speed. However, the octane requirement using the Sasol fuels displayed no clear trend except that a higher octane requirement was found for these fuels compared to the primary reference fuels, particularly at higher engine speeds. This phenomenon was attributed to the sensitivity of the Sasol fuels.

The knock characteristics of each engine were examined by the analysis of cylinder pressure diagrams and cylinder pressure spectra. It was found that up to the fourth circumferential mode and the first radial mode could be found for each engine under knocking conditions. An analysis of the cylinder pressure diagrams showed that knock only occurred after the pressure rise rate had reached its peak and that the onset of knock could occur before or after the pressure peak was reached.

The period of combustion was established for the Volkswagen engine and it was found that there was a linear relationship between the period of combustion and the logarithm of the engine speed. Peak cylinder pressures for the Volkswagen engine were also established and it was found that the scatter of results increased with engine speed.

ACKNOWLEDGEMENTS

The author wishes to thank the following for their invaluable support and assistance:

Professor T. Priede for having provided inspiration and given such valuable comments and guidance.

Professor R.K. Dutkiewicz and the staff of the Energy Research Institute for having conducted the test programme.

Mr P.W. Schaberg of the Energy Research Institute for having provided the results of the engine tests.

Mrs I.E. von Bentheim for having done the final typing of the thesis.

The National Energy Council for having sponsored the tests.

The BP and Sasol Laboratories for having blended the fuels.

My wife, Susan, and children Theresa and Carl, for their patience while my time was devoted to this thesis.

TABLE OF CONTENTS

Page

Abstract ..... (i)
Acknowledgements ..... (iv)
Table of Contents ..... (v)
List of Figures ..... (ix)
List of Tables ..... (xi)
Nomenclature ..... (xii)
Glossary ..... (xiii)

CHAPTER ONE

INTRODUCTION AND SCOPE 1
1. Hydrocarbon fuel properties 2
2. Fuel combustion in engines 3

CHAPTER TWO

HYDROCARBON FUEL PROPERTIES 7
2.1 Distillation 7
2.2 Solvent extraction 8
2.3 Thermal cracking and reforming 8
2.4 Catalytic cracking and reforming 9
2.5 Hydrocracking 11
2.6 Polymerisation 11
2.7 Alkylation 12
2.8 Isomeration 13
2.9 Physical properties 13
2.9.1 Octane numbers 14
2.9.2 Distillation 17
2.9.3 Flammability limits 18
2.9.4 Density 18
2.9.5 Latent heat of vapourisation 18
2.9.6 Calorific value 19
2.9.7 Vapour pressure 19
2.9.8 Viscosity 19
2.9.9 Auto-ignition temperature 20
2.9.10 Stoichometric air/fuel ratio 20
2.9.11 Flash point 21

CHAPTER THREE

ENGINE TECHNOLOGY 22
3.1 Early development 22
3.2 Limits of combustion 24
3.3 Knock in Otto engines 25
3.3.1 Physical mechanism of knock 26
3.3.2 Chemical reactions prior to knock 27
3.3.3 Flame velocity or rate of burning 29
3.3.4 Fuel-air ratio 30
3.3.5 Compression ratio 30
3.3.6 Combustion chamber shape 31

CHAPTER FOUR

INSTRUMENTATION AND TEST PROCEDURE 34
4.1 Engine test cell 34
4.2 Engine instrumentation 34
4.2.1 Piezo-electric pressure transducer 35
4.2.2 Crankshaft angle marker 35
4.2.3 Accelerometer 35
4.2.4 Spark pulse 35
4.2.5 Additional measurements 36
4.3 Data acquisition system 36
4.4 Test procedure 37

CHAPTER FIVE

RESULTS 39
5.1 Maximum brake torque and spark timing 40
5.2 Brake specific fuel comsuption 46
5.3 Octane requirement 47
5.4 Effect of fuel sensitivity on octane requirement 50
5.5 Knock characteristics 55
5.5.1 Knock characteristics of the Toyota engine 57
5.5.2 Knock characteristics of the Volkswagen engine 60
5.5.3 Knock characteristics of the Nissan engine 64
5.5.4 Knock characteristics of the Ford engine 70
5.6 Period of combustion 74
5.7 Peak cylinder pressures 76

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS 77
6.1 Primary reference fuels 77
6.2 Cylinder pressure diagrams 77
6.3 Occurrence of knock 77
6.4 Maximum brake torque and spark timing 78
6.5 Brake specific fuel consumption 78
6.6 Octane requirements - primary reference fuel 78
6.7 Octane requirement - Sasol fuel 79
6.8 Combustion period 79
6.9 Cylinder pressure spectrum 80
6.10 Peak cylinder pressure 80

CHAPTER SEVEN

REFERENCES 81

APPENDIX A - LIST OF APPENDICES

Appendix 1.1 Standard test method for knock characteristics of motor fuels by the research method 87
Appendix 1.2 Standard test method for knock characteristics of motor and aviations fuels by the motor method 101
Appendix 1.3 Structural features of some simple fuel components 122

Appendix 2.1 Flowsheet for simple refinery 123
Appendix 2.2 Two-stage crude oil distillation unit 124
Appendix 2.3 Fluid catalytic cracker 125
Appendix 2.4 Catalytic polymerisation 126
Appendix 2.5 Alkylation 127
Appendix 2.6 Physical properties of hydrocarbons - paraffins and aromatics 128
Appendix 2.7 Effect of oxygenates on distillation 130
Appendix 2.8 Summer 1989 U.S. gasoline component properties 131
Appendix 2.9 Blending octane of main gasoline components 132

Appendix 4.1	Photographs - Nissan engine and dynamometer	133
Appendix 4.2	Position of the pressure transducer in the Ford cylinder head	134
Appendix 4.3	Schematic diagram of engine instrumentation	135
Appendix 4.4	Aviation gasoline 100/130: Typical analysis	136
Appendix 4.5	Sasol unleaded petrol/alcohol blend characteristics	137
Appendix 5.1	Knock damage to the Ford piston	138
Appendix 5.2	Scuffing damage to the Ford piston	139
Appendix 5.3	Catastrophic failure of a Nissan piston due to knock	140
Appendix 5.4	Toyota octane requirement using primary reference fuel	141
Appendix 5.5	Volkswagen octane requirement using primary reference fuels	142
Appendix 5.6	Nissan octane requirement using primary reference fuels	143
Appendix 5.7	Ford octane requirement using primary reference fuels	144
Appendix 5.8	Volkswagen combustion chamber	145
Appendix 5.9	Cylinder pressure diagrams at 1500 and 2000 r/min	146
Appendix 5.10	Cylinder pressure diagrams at 2500 and 3000 r/min	147
Appendix 5.11	Cylinder pressure diagrams at 3500 and 4000 r/min	148
Appendix 5.12	Cylinder pressure diagrams at 4500 and 5000 r/min	149

LIST OF FIGURES

		Page
Figure 1.1	ASTM-CFR Knock testing engine	1
Figure 1.2	Molecular structure and critical compression ratio for various paraffin hydrocarbons	4
Figure 1.3	Molecular structure and critical compression ratio for various aromatic hydrocarbons	5
Figure 3.1	The ideal pressure-volume diagram for an Otto engine	23
Figure 3.2	Combustion chamber shapes with P indicating possible spark plug locations	32
Figure 5.1	Typical knocking combustion chamber pressure diagram	39
Figure 5.2	Toyota: Engine brake torque and spark timing	41
Figure 5.3	Volkswagen: Engine brake torque and spark timing	42
Figure 5.4	Nissan: Engine brake torque and spark timing	43
Figure 5.5	Ford: Engine brake torque and spark timing	44
Figure 5.6	bmep and spark timing	45
Figure 5.7	Brake specific fuel consumption	46
Figure 5.8.1	Normal combustion	47
Figure 5.8.2	Trace knock	48
Figure 5.8.3	Knock	48
Figure 5.8	Octane requirement of the engines at MBT using primary reference fuels	49
Figure 5.10	Octane requirement of the Toyota engine using Sasol fuels	51
Figure 5.11	Octane requirement of the Volkswagen engine at MBT timing using Sasol fuels	52
Figure 5.12	Octane requirement of the Nissan engine at MBT using Sasol fuels	53
Figure 5.13	Octane requirement of the Ford engine at MBT using Sasol fuels	54
Figure 5.14	Circumferential modes	56
Figure 5.15	Toyota cylinder pressure diagram at 1500 r/min	57
Figure 5.16	Toyota cylinder pressure diagram at 3000 r/min	57
Figure 5.17	Toyota cylinder pressure diagram at 4000 r/min	58
Figure 5.18	Toyota cylinder pressure spectrum at 1500 r/min	59
Figure 5.19	Toyota cylinder pressure spectrum at 3000 r/min	59
Figure 5.20	Volkswagen cylinder pressure spectrum at 1500 r/min	61
Figure 5.21	Volkswagen cylinder pressure spectrum at 3000 r/min	62
Figure 5.22	Volkswagen cylinder pressure spectrum at 5000 r/min	62
Figure 5.23	Comparison of the Volkswagen cylinder pressure spectra over the speed range	64
Figure 5.24	Nissan cylinder pressure diagram at 1500 r/min showing trace knock	65

Figure 5.25	Nissan cylinder pressure diagram at 1500 r/min showing knock	65
Figure 5.26	Nissan cylinder pressure diagram at 1500 r/min showing knock	66
Figure 5.27	Nissan cylinder pressure diagrams at 1500 r/min of four sequential combustion cycles	67
Figure 5.28	Nissan cylinder pressure spectrum for cycle 2	68
Figure 5.29	Nissan cylinder pressure spectrum for cycle 3	68
Figure 5.30	Nissan cylinder pressure diagram and spectrum at 3500 r/min	69
Figure 5.31	Ford cylinder pressure diagram at 1500 r/min	70
Figure 5.32	Ford cylinder pressure diagram at 2500 r/min	70
Figure 5.33	Ford cylinder pressure diagram at 4000 r/min	71
Figure 5.34	Ford cylinder pressure diagram at 1500 r/min	72
Figure 5.35	Ford cylinder pressure spectrum at 2500 r/min	72
Figure 5.36	Volkswagen measured period of combustion	74
Figure 5.37	Volkswagen peak cylinder pressures	76

LIST OF TABLES

		Page
Table 4.1	Engine details	38
Table 5.1	Differences between Sasol and PR Fuel octane requirements	55
Table 5.2	Analysis of the pressure peaks in Figure 5.15	60
Table 5.3	Analysis of the pressure peaks in Figure 5.20	62
Table 5.4	Nissan knock analysis	67
Table 5.5	Analysis of the pressure peaks in Figure 30	69
Table 5.6	Ford cylinder pressure spectrum at 1500 r/min	73
Table 5.7	Ford cylinder pressure spectrum at 2500 r/min	73

NOMENCLATURE

Upper case:

K	Degrees Kelvin
MJ/kg	Mega Joules per kilogram
Nm	Newton metre
Pa	Pascal
V	Volt

Lower case:

cm^3	Cubic centimetre
cSt	Centistoke
dB	Decibel
g	Gravitational acceleration
g/kWh	Grams per kilowatt hour
hp	Horsepower
kg/l	Kilograms per litre
kHz	Kiloherz
kJ/l	Kilojoule per litre
kPa	Kilopascal
kW	Kilowatt
mm	Millimetre
mmHg	Millimetres of Mercury
msec	Millisecond
m/s	Metres per second
pC/bar	Picocoulomb per bar
pC/g	Picocoulomb per gravitational acceleration
r/min	Revolutions per minute
vol%	Percentage volume

Greek:

µPa	Micro Pascals

Other:

o	Degrees crankangle
°C	Degrees Celsius
%	Percentage
kW	Kilowatt

GLOSSARY

Upper case:

ASTM	American Society for Testing and Materials
BTDC	Before Top Dead Centre
CA	Crank angle
CFR	Co-operative Fuel Research Committee
Cx	Carbon chain length
F	Frequency
IP	Institute of Petroleum
MBT	Maximum Brake Torque
MON	Motor Octane Number
OR	Octane Requirement
PRF	Primary Reference Fuel
RON	Research Octane Number
RON 100°C	Research Octane Number of the distillate to 100°C
T	Period of Combustion
TDC	Top Dead Centre
WOT	Wide Open Throttle

Lower case:

bmep	Brake Mean Effective Pressure
bsfc	Brake Specific Fuel Consumption
cyl	Cylinder
f	Frequency
iso	Isomer
log	Logarithm
n	Normal

CHAPTER ONE

INTRODUCTION AND SCOPE

The resistance to knock of a spark ignition engine fuel is related in terms of octane number. By definition iso-octane has a number of 100 whereas normal heptane has a number of 0. The octane number of a fuel is the percentage of iso-octane in a blend of the two hydrocarbons which gives the same knock intensity under identical operating conditions in the CFR (Co-operative Fuel Research Committee) engine.

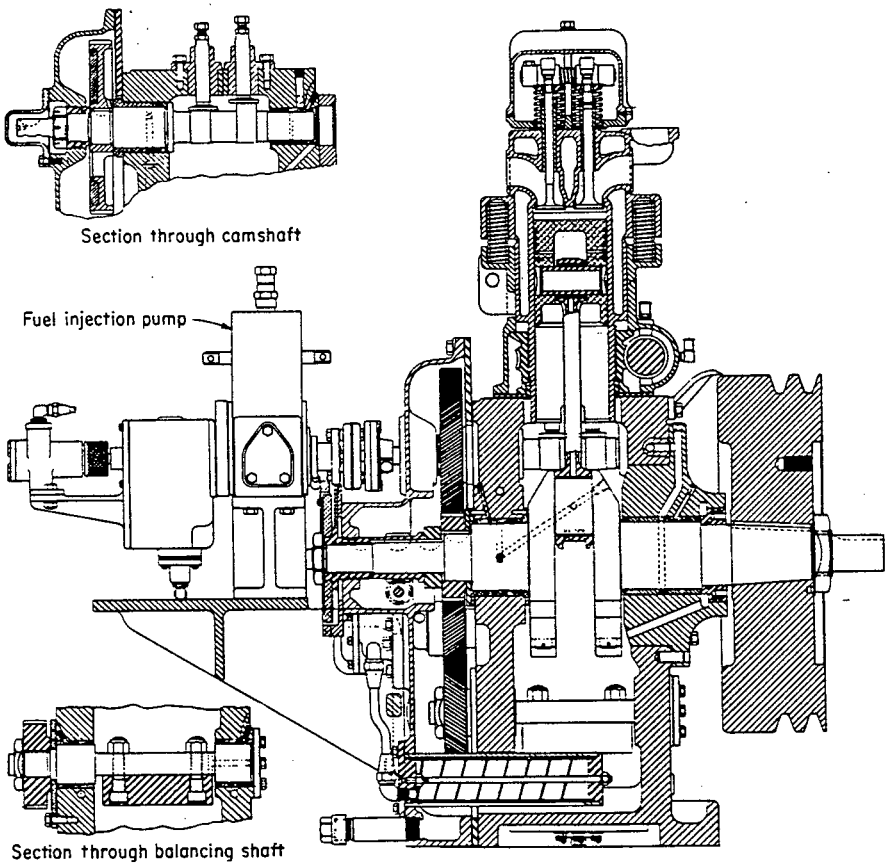


Figure 1.1: ASTM-CFR Knock testing engine

There are two different methods by which octane numbers are determined. The less severe measurement is the RON (Research Octane Number) whereas the more severe measurement is the MON (Motor Octane Number). The measurement of MON is done at a higher engine speed and more advanced ignition timing than the RON measurement. The test methods for the determination of octane numbers are stipulated by the American Society for Testing and Materials (ASTM) in methods ASTM-D-2699 for RON and ASTM-D-2670 for MON[37]. These methods appear as Appendics 1.1 and 1.2.

1. HYDROCARBON FUEL PROPERTIES

Hydrocarbon fuels can generally be classified into four categories, and their typical shapes are shown in Appendix 1.3.

Paraffins:
These components generally have a low sensitivity and the octane numbers vary considerably with the extent of branching found in the molecules. The normal molecules have a low knock resistance whereas the isomers have good knock resistance. In particular, methyl groups on the second from the end or centre carbon atoms in the chain reduce the knocking tendency substantially[3].

Olefins:
These components generally have a very high sensitivity but good octane numbers. The molecule chain length does not influence these properties to any great extent with the exception of acetylene, ethylene and propylene which have a lower knock resistance than the corresponding saturated hydrocarbons.

Naphthenes:
Generally these components have good knock resistance and a moderate sensitivity. An increasing number of double bonds in the ring enhances the knock resistance of the molecule.

Aromatics:
Aromatics have very good knock resistance but with high sensitivities. The highest knock resistance is to be found in xylene.

2. FUEL COMBUSTION IN ENGINES

The octane requirement of an engine is defined as the minimum octane number of the fuel which is just adequate to avoid knock. It has been established that the RON, MON and the RON of the fuel which distills below 100°C are all important in defining the engine's octane requirement.

The octane requirement of engines varies dramatically and is primarily influenced by design considerations. The following factors are the most important in determining the engine octane requirement:

1) Compression ratio
2) Combustion chamber shape
3) Spark plug location
4) Induction swirl
5) Ignition timing
6) Fuel/air ratio
7) Inlet air temperature

Under fixed operating conditions it is possible to define the critical compression ratio for particular fuel components. The critical compression ratio determined in a variable compression ratio engine was measured by Lowell[40] and the results are given in Figures 1.2 and 1.3.

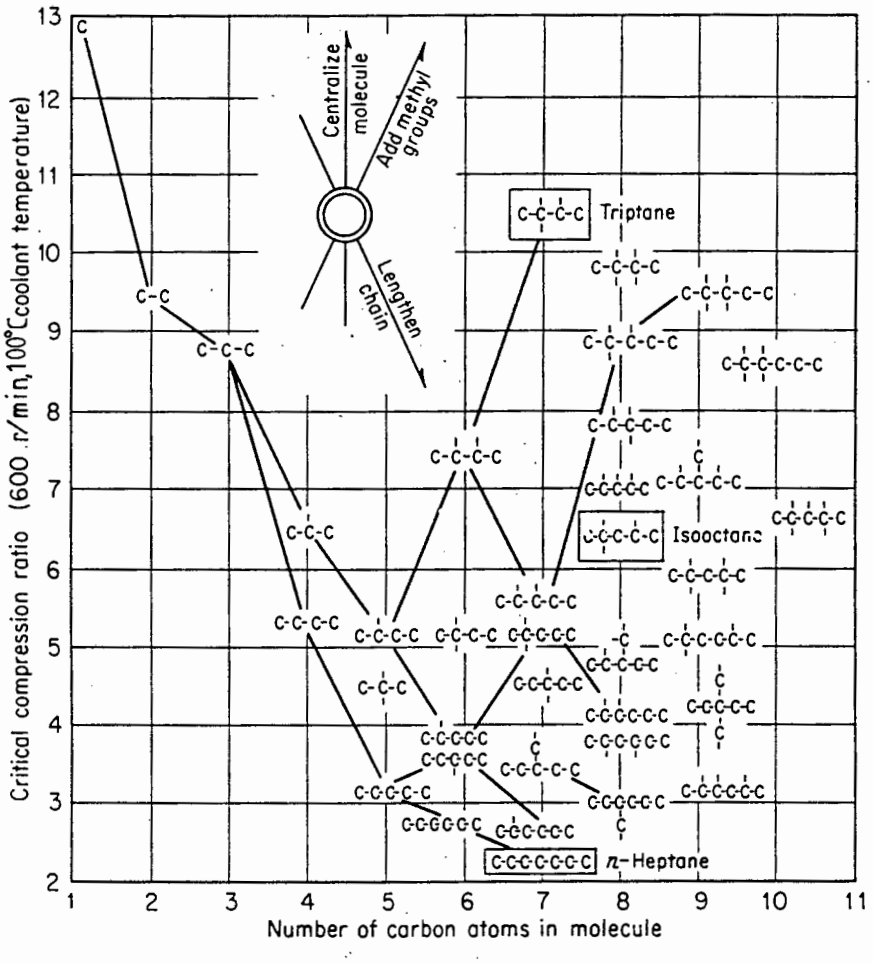


Figure 1.2: Molecular structure and critical compression ratio for various paraffin hydrocarbons

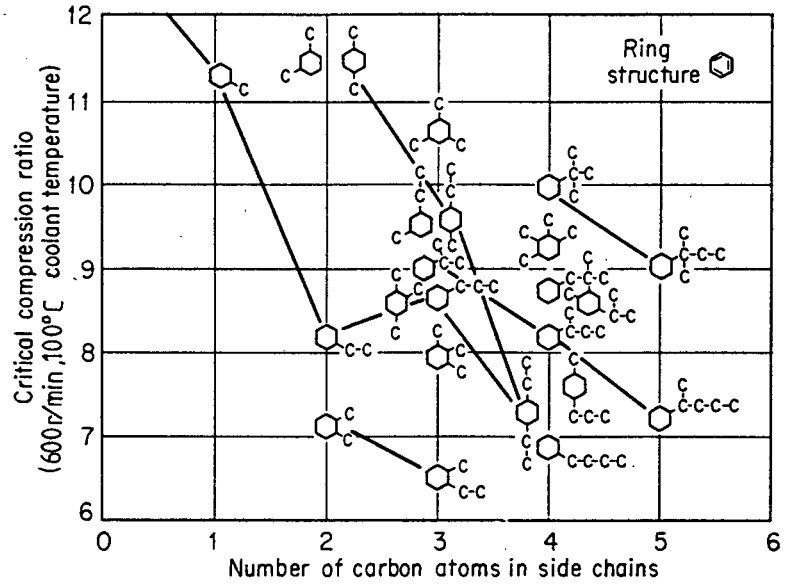


Figure 1.3: Molecular structure and critical compression ratio for various aromatic hydrocarbons

Generally the following assumptions can be made for the critical compression ratio:

1) It reduces with an increase in relative molecular mass
2) It increases with cyclisation and isomerisation
3) It is very high with aromatics

A particular engine can have critical octane requirements at different load/speed areas of its operating range. Some engines are very sensitive to low speed accelerating knock whereas others are critical at high constant speed or under cold operating conditions.

Engine knock is closely related to the spontaneous ignition temperature of the fuels. Generally the auto-ignition temperatures decrease strongly with increasing chain length from butane to octane, while branched molecules such as iso-octane have a much higher auto-ignition temperature. The auto-ignition temperatures given in Table 2.6 are virtually independent of air/fuel ratio between 0.8 and 1.4. This finding is contradictory to the production engine knock limits where it was established that the knock limit is strongly dependent on the air/fuel ratio.

CHAPTER TWO

HYDROCARBON FUEL PROPERTIES

The hydrocarbons used in gasolines are generally derived from crude oil. The Sasol oil from coal process synthesises various components for use in gasoline and other fuels from gasified coal. In both of these processes various different components need to be isolated in order to yield marketable products. The processes involved are essentially distillation, solvent extraction, thermal cracking and reforming, catalytic cracking and reforming, polymerisation, alkylation and isomerisation. A schematic refinery layout is given in Appendix 2.1.

2.1 DISTILLATION

Distillation is the fundamental process for separating cuts of hydrocarbons with different distillation points or ranges. This process is normally conducted in a bubble plate column and the basic principles are as follows:

2.1.1 Separation depends upon differences in boiling point.

2.2.2 The smaller the difference in boiling point, the more difficult the separation, requiring more trays and more reflux.

2.2.3 Distillation pressure may be varied to change the actual boiling temperature so that a cut may be evaporated or condensed at a more convenient temperature.

Primary distillation generally occurs at high pressure to separate gases, atmospheric pressure to separate straight run gasoline, naphtha, kerosine and atmospheric gas oil and under vacuum to produce heavy gas oil and waxy distillate. The remaining residue is very viscous and is used for bitumen and fuel oil production. A schematic two stage crude oil distilation unit is shown in Appendix 2.2.

2.2 SOLVENT EXTRACTION

Solvent extraction processes depend on the high solubility of a component in the carrier material relative to a lower solubility for the components which need to be separated. The processes are used to separate aromatics from paraffins and were first developed to extract aromatics from kerosine in order to improve the smoke point. The extracted aromatic compounds have good properties as gasoline and can be used as blending components.

2.3 THERMAL CRACKING AND REFORMING

This process was developed to augment the quantity of gasoline obtained from a quantity of crude oil, but the improved engine performance of these products made them valuable. The thermal cracking process consists of heating surplus quantities of heavy oils to 400-500°C under pressure and then to release the product into a fractionating column at a lower pressure. Large molecules will crack into small highly reactive components which tend to recombine during the process to yield a wide range of reformed hydrocarbons.

If this process is too severe the gas yield becomes large and this is not desirable. In order to optimise yield and efficiency, the process is conducted in small steps and products are recycled. Viscosity breaking is a modification of the cracking process used to crack heavy waxes and yields small quantities of gasoline components.

Thermal reforming is used to change the properties of products already in the gasoline distillation range. It is applied principally to heavy benzines and naphthas obtained by straight run distillation and to the waste residues from subsidiary distillation processes.

The essential features of this process consist of a heater, a fractioning column and a stabilising column. The low grade feedstock is pumped through the heater to raise its temperature to 500-550°C and under a pressure of 5-6 MPa depending on the extent of reforming needed. The reaction products are discharged from the heater through a control valve where the pressure is reduced allowing the

charge to vapourise. The temperature of the product is reduced as it is quenched by cold oil before entering the fractionating column. This stops the reaction and prevents excessive coke formation. The bottoms of the fractionating column are blended to fuel oil and the tops are further processed in the condenser. The incompressible products are used for refinery gas. The condensed product still contains propane and butane and this is drawn off in the stabilising column. The olefinic material is then used in other conversion processes such as alkylation and polymerisation and the residue is kept for further treatment before being blended to gasoline.

2.4 CATALYTIC CRACKING AND REFORMING

Catalytic cracking is a refinement of thermal cracking as the presence of a suitable catalyst improves the process efficiency. When used in the cracking process, carbon is deposited on the catalyst which gradually loses its efficiency until it needs to be regenerated by the burning off of the carbon. The catalytic cracking process can take place on a fixed or moving bed catalyst or a fluid catalyst, the latter being the most modern.

In the fluid catalytic cracking process the reaction is effected by using a catalyst so finely powdered as to be carried by the oil vapours and which behaves, in effect, as a fluid. A schematic layout of a catalytic cracker is given in Appendix 2.3. Hot catalyst at a temperature of about 550^{o}C passing down the standpipe meets the preheated fresh oil vapourised by preheating in a furnace. The mixture of oil vapour and catalyst is forced up the reactor feed line and the hot mixture enters the reactor which being of much larger cross sectional area , reduces the vapour velocity sufficiently to allow the catalyst to settle into a bed whose depth can be raised in order to regulate the reaction time. This bed of catalyst is maintained in a turbulent state by the oil vapours which in passing upwards make contact with the catalyst and a uniform temperature of about 500^{o}C is established throughout the bed. As the reaction progresses, the catalyst becomes coated with coke and descends to the lower part of the reactor where the remaining oil vapours are stripped from the catalyst. The spent catalyst is then dropped out of the reactor through a valve and is then blown up the regenerator riser by compressed air.

In the regenerator the oxygen burns the coke off the catalyst thereby releasing heat. During this process cooling is needed as the catalyst may not be exposed to a temperature greater than 550°C and thus usable steam is generated. The regenerated catalyst is then fed down the standpipe to pass through the process again. The combustion gases in the regenerator pass through a cyclone and electrostatic precipitator to remove the catalyst and to return it to the regenerator. In the reactor the vapours pass through a cyclone to separate the catalyst and return it to the unit. The cracked vapours pass to the fractionator from where the catalyst fines are washed out or settle under gravity. The vapours are separated into gas, unstabilised spirit, light gas oil and heavy gas oil.

Thermal cracking and reforming all result in the production of olefinic gasolines, which are somewhat unstable and tend to form gums when in contact with air. Catalytic reforming refers to the processes whereby naphtha and other light straight run distillates are reformed in the presence of hydrogen which serves to convert olefins into saturated paraffins. Five types of reforming are generally used;

2.4.1 Aromatisation or the dehydrogenation of naphthenes to aromatics.

2.4.2 Dehydrocyclisation or the simultaneous conversion of normal paraffins to naphthenes and dehydrogenation to aromatics.

2.4.3 Hydrocracking is the reduction of chain length with the simultaneous saturation of the reformed molecules.

2.4.4 Desulphurisation is the reduction of sulphur bodies to hydrocarbons with the conversion of the sulphur to hydrogen sulphide which can easily be eliminated.

2.4.5 Isomerisation or the rearrangement of the molecule to give a branched structure.

Each of these five reactions has desirable end products, either aromatics or iso-paraffins, and reaction 4 is particularly welcome as the product is usually desulphurised to such an extent that it is virtually sulphur free and requires no further treatment before use in gasoline. During the reaction the upper limit of the boiling range of the feedstock is not changed to any marked extent and no heavy discards are made. Gas is produced which contains an excess of hydrogen and hydrogen sulphide which can be used in further refinery processes. Some coke does form on the catalyst and thus it is necessary to regenerate the catalyst from time to time.

2.5 HYDROCRACKING

All hydrocracking processes are characterized by the treatment of heavy fractions to yield lighter fractions in a catalytic operation under relatively high hydrogen pressure. This process can be applied to the production of C3/C4 gases from naphtha to luboil manufacture from deasphalted oils.

Hydrocrackers can use either fixed bed or fluidised bed catalyst systems with product flowing down or up respectively. As the processing severity increases the olefins are first saturated, then desulphurisation takes place, then denitrogenation and de-oxygenation. At this stage only limited cracking takes place but an increase in severity will lead to hydrocracking and the saturation of aromatics and subsequent molecular cracking.

Modern hydrocrackers are of the two-stage or series-flow design in which the saturation processes take place in the first stage and the cracking reactions take place in the second stage. The hydrogenation function takes place in the presence of a sulphided metal such as cobalt, molybdenum or nickel whereas the cracking reaction takes place in an acidic support such as alumina.

Both two-stage and series-flow hydrocracking are flexible processes and may be employed to yield only naphtha or lighter products or, in a different mode, only gas oil and lighter products.

2.6 POLYMERISATION

The cracked gases obtained from thermal cracking and reforming were often only used for refinery fuel. However modern refineries are in a position to polymerise short chain olefinic molecules such as C3 and C4 into longer chain molecules such as C6, C7 and C8 which fall into the gasoline distillation range. The process takes place under pressure and a temperature of 200-300^{o}C and yields an olefinic end product.

The catalytic polymerisation process is shown diagrammatically in Appendix 2.4. The feedstock in which the active components are propylenes and butylenes, is

heated and passed through a series of reactors containing the catalyst. The polymerised product leaving the reactor passes to a stabiliser in which unreacted gas is separated as an overhead product for refinery fuel, and stabilised polymer gasoline is withdrawn from the base to storage for blending to gasoline. The catalyst is regenerated by means of hot flue gases and the reactors are manifolded so that any one can be isolated for regeneration and afterwards switched back into operation. The process can be used to polymerise butanes in the absence of other olefins which yields a stream rich in iso-octane having a RON of 90-95.

2.7 ALKYLATION

These modern processes have been developed to combine paraffins and olefins to form a longer chain paraffin and a schematic plant layout is shown in Appendix 2.4. The process is primarily used to combine iso-butene and normal-butene with iso-butane to form iso-octane. In addition to providing a saturated product in a single stage the alkylation process increases the output as it uses one part of saturated iso-butane for each butene which is normally in short supply. The process uses strong sulphuric acid as the catalyst. The iso-butane required for the process is obtained from the fractionation of the C4 cuts produced during crude distillation and also by the isomerisation of the n-butane from the same source. The olefinic hydrocarbons are obtained from the cracking operations by the fractionation of the C3, C4 and C5 hydrocarbons from cracked gasoline.

The plant is operated as follows: fresh feedstock consisting of iso-butane and C3, C4 and C5 olefins is introduced into an emulsion of hydrocarbons and 98 percent sulphuric acid which is kept circulating continuously through a reaction vessel and a heat exchanger, the whole system kept just above atmospheric pressure. The reaction occurs at about 5^{o}C and a chiller is needed to remove the heat generated during the reaction. Liquid product is continuously drawn off the unit to a fractionating system consisting of an iso-butane tower, a stabiliser and a rerun tower.

Unreacted iso-butane is recovered as an overhead in the first tower, depropanised in a second tower and recycled back to the feedstock. The

bottoms from the first tower are pumped to the stabilising column in which n-butane is recovered as an overhead. The product from the base of the stabiliser passes to a rerun tower in which the alkylate is drawn off overhead and the bottoms are used for thermal reforming operations.

2.8 ISOMERISATION

In this process n-butane is contacted with aluminium chloride in the presence of hydrochloric acid gas. Recently other processes have been developed to isomerise normal-pentane to yield iso-pentane and these processes are often associated with catalytic reforming. The normal-pentane is passed over a platinum catalyst in the presence of hydrogen. The hydrogen is not made or consumed in the reaction and the iso-pentane is separated by distillation from the unchanged normal-pentane which is recycled.

2.9 PHYSICAL PROPERTIES

The following physical fuel properties are important in determining their suitability as engine fuels:

2.9.1 Research Octane Number
2.9.2 Motor Octane Number
2.9.3 Distillation
2.9.4 Flammability limits
2.9.5 Density
2.9.6 Latent heat of vapourisation
2.9.7 Calorific value
2.9.8 Vapour pressure
2.9.9 Viscosity
2.9.10 Autoignition temperature
2.9.11 Stoichiometric air/fuel ratio
2.9.12 Flash point

For blended gasolines these parameters are as follows according to Palmer[1] and Menrad[27]:

Property	Units	Value/Range
RON	-	80-100
MON	-	75-90
Distillation	°C	25-215
Flammability limits: low	vol%	1.4
high		7.6
Density at 20°C	kg/l	0.72-0.78
Latent heat of vapourisation	kJ/l	23.1
Calorific value	MJ/l	33
Vapour pressure at 37,8°C (RVP)	kPa	70
Viscosity at 20°C	cSt	0.37-0.44
Auto-ignition temperature		°C 370
Stoichiometric air/fuel ratio	-	14.6
Flash point	°C	-43

2.9.1 Octane numbers

There is ample evidence, from a wide selection of cars which have been employed to assess the anti-knock ratings of gasolines, that light knock induced while accelerating with a wide open throttle from a low engine speed will not cause damage or abnormal wear rates. In many cases the cars have been subjected to extensive periods of operation under these conditions without suffering any damage[29].

During a test to determine the difference between acceleration times between 1500 and 2500 r/min, it was found that slight knocking did not have a tangible effect on performance.

High speed knock is however detrimental to engines and Appendices 5.1 and 5.3 indicate typical damage sustained by pistons. In these examples, knock was initiated on the piston edge and this resulted in the erosion of material. During sustained operation the piston overheated and this eventually resulted in melting of the piston crown in the vicinity of the spark plug location. High speed knock has also been found to lead to piston seizure without noticeable damage to the piston. This may be due to uniform overheating of the piston leading to excessive

expansion and lubricant film break down. Aluminium cylinder heads have also been eroded due to high speed knock and damage manifests itself as a series of holes around the perimeter of the combustion chamber where the post-ignition is initiated.

The Research Octane Number (RON) is determined in the single cylinder Co-operative Fuel Research (CFR) engine[37] by matching the knock intensity of Primary Reference Fuels (PRF) to the knock produced by the commercial or test fuel. PRF's having octane numbers below 100 are blends of iso-octane and n-heptane and those above 100 octane number are blends of iso-octane and tetraethyl lead.

The Motor Octane Number (MON) is also determined in the CFR engine but under more severe conditions than the Research method. The sensitivity of the fuel is defined as the difference between the RON and MON and is positive if the RON is greater than the MON, which is normally the case. However, the laboratory ratings obtained in the CFR engine do not necessarily give a reliable guide to gasoline anti-knock quality when the fuel is used in modern engines.

Motor gasolines need to meet some contradictory requirements which are not reflected in a single laboratory test method. These are:

- The fuel should have good anti-knock quality when the cars are accelerated from low engine speeds.

- The second demand is that gasoline should offer adequate anti-knock protection when an engine is running at or near wide open throttle, under constant speed conditions, particularly in the high speed range. Again there are no laboratory methods to determine the ability of a fuel to resist knock in vehicle engines running at constant speeds.

The fuel parameters which affect knock under these low speed accelerating conditions are predominantly the octane number quality of the most volatile fractions of the gasoline. This is because in conventional engines fitted with carburettors the front end of the most volatile portions of the fuel tend to reach the combustion chamber while the heavier fractions tend to lag behind in the inlet manifold. If the front end of the gasoline has a high octane number then a good

road anti-knock performance will be achieved. Conversely, a low octane front end will result in poor road anti-knock in those engines which encourage the fuel to segregate into light and heavy fractions. These facts have been known for some time and various laboratory methods have been devised to measure fuel anti-knock quality related to the anti-knock performance obtained when car engines are accelerated from low engine speeds.

Catalytic reformate gasoline is poor in front end octane quality and is often produced in refineries which need to boost gasoline production. This product however has very good anti-knock properties under wide open throttle constant speed conditions.

The refiner adopts several methods to improve the low speed road anti-knock performance of catalytic reformate fuels:

- incorporation of tetamethyl lead which has a low boiling point.

- addition of high octane value volatile components produced during cracking.

- removal of the low octane front end of the catalytic reformate and replacing it with a low boiling point high octane material.

Laboratory Motor Method octane number determinations are done at higher engine speeds, higher air/fuel mixture temperatures and greater spark advances than are the Research method ratings. The Motor method is thus more severe than the Research method and it has been found that gasolines of constant RON which have a high MON will generally have a good anti-knock performance in multi cylinder engines under severe high speed conditions. However the relationship between gasoline anti-knock quality in vehicle engines at high constant speed conditions and Motor octane or sensitivity is not precise.

Fuels of constant Research octane number but of different olefin content indicate a lower high constant speed anti-knock rating for those with a high olefin content. Olefin content is often a better indicator of a fuels performance under high speed engine conditions than MON or fuel sensitivity[1],[15].

When catalytically cracked gasoline is used as a blending component it will usually raise the total olefin content and sensitivity levels of the finished product, dependent upon the other components used. A compromise normally has to be made to meet the required production quantities and the front end octane number. The octane numbers of some gasoline components is given in Appendix 2.6.

2.9.2 Distillation

The distillation temperature of gasoline components is an important determinant for other fuel physical characteristics such as density, vapour pressure, viscosity, autoignition temperature, flash point and stoichiometric fuel/air ratio. The refining process, as described earlier in this Chapter, depends almost entirely on the separation of crude oil into its constituents by means of distillation temperature. A typical distillation curve of a motor gasoline is given in Appendix 2.7 and shows the influence which methanol and ethanol have. Generally the distillation curve needs to encompass components of low boiling point such as butane and also components with a boiling point of about 200°C.

Depression of the distillation curve as caused by the alcohols is not desirable as it leads to a large increase in the vapour pressure of the fuel which may lead to poor hot weather driveability and hot start difficulties. Generally, aromatics and naphthenes have higher boiling points than paraffins for the same carbon chain length. Fuels with mono boiling points such as propane, butane, methanol or ethanol can be used successfully in engines but do have certain drawbacks. Propane or butane tend to reduce peak engine power as they are evaporated before being introduced to the engine inlet air stream thus no benefit of the latent heat of vapourisation of the fuel to increase the induction air density is gained. Methanol and ethanol do not provide good cold weather driveability as they have very high latent heats of vapourisation and their high boiling points make them inadequately volatile for good operation in a cold engine. However, once the engine has warmed up and adequate quantities of heat from the cooling water or exhaust are available to vapourise the fuel the vehicle driveability becomes acceptable. The boiling points of some gasoline components and refinery streams are given in Appendices 2.6 and 2.9 respectively.

2.9.3 Flammability limits

Hydrocarbon fuels tend to have similar flammability limits[5]. Alcohols and ethers tend to have wider ranges and hydrogen has a very wide range, being particularly flammable at very low concentrations as can be seen in Appendix 2.6. The flammability of fuel/air mixtures is also dependent on the pressure and temperature of the mixture.

2.9.4 Density

The relative density of hydrocarbon gasoline components varies between 0.54 and 0.8 at 20°C. The density of the fuel is the major determinant in establishing the calorific value of the product and this in turn influences the fuel/air ratio and engine fuel consumption. Generally the density of the fuels increases with the increase in number of carbon atoms and with increasing carbon/hydrogen ratio. As a result of this factor, aromatics have high relative densities. Knock is dependent on fuel/air ratio thus density becomes an important factor in establishing knock free operation in fuel systems where the mixture is prepared on a volumetric basis. The relative densities of gasoline blending components is given in Appendix 2.6.

2.9.5 Latent heat of vapourisation

The latent heat of vapourisation of fuels is important in establishing the extent to which the fuel/air mixture is cooled during vapourisation of the fuel. In order to ensure that the fuel is vapourised before combustion, use is made of inlet manifold heating. This can be achieved by using a cooling water heated inlet manifold, an exhaust generated "hot spot" or an electrical resistance heater. In some systems the heat is obtained by routing hot air from near the exhaust manifold to the inlet system.

The control of inlet air heating is crucial to driveability during the warm up phase of operation. Once the engine has warmed up, it is desirable to reduce the heat supplied to the inlet air so that the engine's power is not adversely affected. The latent heats of some commonly used gasoline components is given in Appendix 2.6.

2.9.6 Calorific value

The calorific value of the fuel should be as high as possible so that a small volume and mass of fuel is needed to achieve a specific amount of work. For vehicular applications it is important to store the fuel at or near to atmospheric temperature and pressure and in a fuel tank which is as small and light as possible.

The calorific value of fuels is largely determined by the carbon/hydrogen ratio[10]. The calorific value of carbon is 30 MJ/kg whereas the calorific value of hydrogen is 120 MJ/kg. The calorific values of some gasoline components are given in Appendix 2.6.

2.9.7 Vapour pressure

The vapour pressure of gasoline components is important in determining the driveability of a vehicle during the warm up phase of operation. The vapour pressure of fuels is strongly dependent on pressure and temperature. This parameter is normally determined according to the Reid Vapour Pressure test which is described in method ASTM D 2551[37]. A high gasoline vapour pressure can lead to vapour lock problems in vehicles if temperatures are high and atmospheric pressures are low, i.e. conditions encountered at high altitudes. The vapour pressure of various gasoline components is given in Appendix 2.6.

2.9.8 Viscosity

Viscosity is not as important in gasoline as in middle distillates. However, with the proposed use of high pressure fuel injection systems in direct injection spark ignition engines, this parameter will become increasingly important as the high pressure pumps require a minimum fuel viscosity to provide adequate lubrication. Gasoline viscosity is relevant in the air/fuel mixing tubes in carburettors but other fuel physical properties are more influential.

The viscosity of gasoline is temperature dependent and lies between 0.37 and 0.44 cSt at 20°C. Viscosity can be determined by a number of methods but the reverse flow viscometer is the most relevant for gasoline under normal operating conditions. This test is described in method ASTM D 445.

2.9.9 Auto-ignition temperature

Spontaneous ignition is a process whereby a combustible mixture undergoes chemical reaction leading to the rapid evolution of heat in the absence of any concentrated source of ignition such as a spark[8]. The delay time from when autoignition conditions are satisfied and the combustion process actually commences is analysed in this document. Generally, there is a correlation between mixture pressure and temperature and autoignition occurrence.

The autoignition temperature of gasoline components is an important physical parameter which affects the anti-knock properties. Extensive studies of autoignition have shown that there are substantial differences between the processes which occur for different hydrocarbons[30].

Paraffin autoignition chemistry is dominated by hydrogen abstraction from the fuel, followed by the intramolecular alkylperoxy isomerisation mechanism. Olefin autoignition chemistry differs markedly being controlled by radical addition to the double bond. Hydroxyl radical addition is followed by oxygen addition to the adjacent radical site, followed by scission forming two carbonyls. Hydroperoxyl radical addition yields an epoxy directly. The differences in octane qualities between olefins and paraffins imply significant differences in their respective autoignition chemistries. The autoignition temperatures of various gasoline components is given in Appendix 2.6.

2.9.10 Stoichometric air/fuel ratio

The stoichiometric air/fuel ratio is dependent on the composition of the fuel. It is closely associated with the hydrogen, carbon and oxygen content of the fuel. As engines do not operate under stoichiometric conditions for the major part of the load cycle, the lower and upper inflammability limits become important. However, operation close to these limits is not normal as the engine would function erratically, particularly near the lower inflammability limit. The stoichiometric air/fuel ratios of some gasoline components is given in Appendix 2.6.

2.9.11 Flash point

The flash point of gasoline components is dependent on the carbon chain length. The flash point of gasoline is of the order of -40°C and it is safe to store this fuel in a closed container as there is a vapour above the liquid fuel which is too rich to ignite with even a high intensity spark. However, if stored in an open container, due care needs to be exercised as the vapour is easily ignited. Flash point is an important consideration for middle distillates such as kerosene or diesel.

Numerous methods to determine flash point have been established. The most important ones are the Abel and Pensky Martens Closed Cup methods described by IP 170[38] and ASTM D 93[37] respectively.

CHAPTER THREE

ENGINE TECHNOLOGY

3.1 EARLY DEVELOPMENT

All early piston engines were provided with a combustible charge which was ignited at about atmospheric pressure[41]. A number of scientists described engines in which the combustible mixture was compressed before ignition during the nineteenth century. It was shown that the compression of the charge before ignition improved efficiency and economy. In 1862 a Frenchman, Beau de Rochas, set out the fundamental principles underlying the economical operation of the piston engine. He listed the following conditions under which maximum economy would be obtained, namely:

- Smallest possible surface-volume ratio for the cylinder.
- Most rapid expansion process possible.
- Maximum possible expansion.
- Maximum possible pressure at the start of the expansion process.

The first two conditions are designed to reduce the heat loss to a minimum, thus retaining the inherently available energy in the combustion products. The third condition anticipates expanding the gases to the fullest possible extent to obtain the most work. The fourth condition allows for a high pressure throughout the cycle and also for a higher expansion ratio as possible, both resulting in more work.

Beau de Rochas also described the four stages of the four stroke engine which is described with the following pressure-volume diagram.

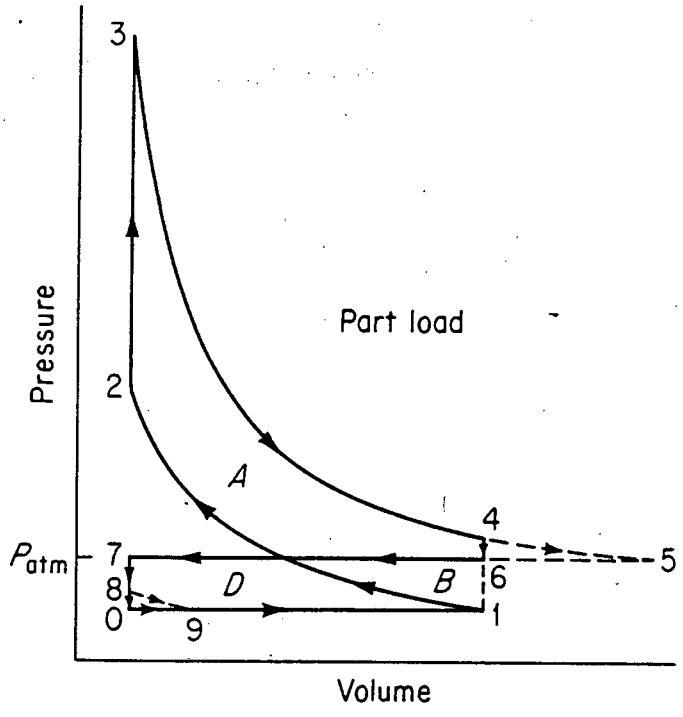


Figure 3.1: The ideal pressure-volume diagram for an Otto engine

0 to 1) Induction
1 to 2) Compression
2 to 4) Ignition and expansion
4 to 7) Exhaust

These phases are the basis of operation of the four stroke engine.

The Otto engine was developed in Germany in 1876 and operated on the principles set down by Beau de Rochas. Most modern engines operate in the same manner as Otto's gas engine and consequently the term Otto cycle is used for the series of events that make up the cycle in current four-stroke-cycle engines. Early engines were very heavy and bulky and had a small power output and rotational speed when compared to the modern engines.

The combustion process is as follows:

The homogeneously mixed air/fuel mixture is compressed in the cylinder to a pressure of 8 to 15 bar, reaching a temperature of 400 to 600°C, which is

however not enough to cause spontaneous ignition. Ignition is produced by a high voltage spark generated by the ignition system.

The characteristics and quality of the combustion process in the spark ignition engine are highly dependent on how the flame front advances from the source of ignition in terms of time and space.

The flame front is propagated by means of heat entrainment, radiation and conduction and in particular by turbulence and directed gas flow. A maximum combustion pressure of 30 to 40 bar and as high as 70 bar in racing engines is reached during combustion. The maximum combustion temperature is 2000 to 2500°C.

Average flame velocity throughout combustion is about 10 to 25 m/s and reaches a maximum with a 10% air deficiency and at high engine speed dropping in the case of a richer or leaner mixture and at lower engine speed as a result of reduced turbulence.

Flame speed is only 1 to 4.5 m/s in a static homogeneous stoichiometric fuel/air mixture[31]. Combustion is most effective when the flame travel is short, the mixture is ignited at the hottest point of the combustion chamber and the flame front advances towards the cooler parts of the chamber without a closed flame front being formed. This is achieved by the appropriate arrangement of the spark plug and valves as well as suitable design and cooling of the combustion chamber.

The fuel/air mixture needs to burn as quickly as possible to permit high engine speeds, but this process should also occur smoothly and progressively to prevent knock.

3.2 LIMITS OF COMBUSTION

Already during the earliest stages of development of the four stroke spark ignition engine it became evident that knock was a limiting factor in engine performance[2],[7]. Only during the past few years have exhaust emissions become a further limiting factor to engine performance[4]. The onset of knock in

Otto engines can lead to overheating, loss of output and serious damage[28] to the engine components, especially pistons, scuffing and total seizure as can be seen in Appendices 5.1, 5.2 and 5.3.

3.3 KNOCK IN OTTO ENGINES

The theory of knock in Otto engines was presented by Ricardo in 1923[41]. During the following years a mass of information on this subject was compiled which enabled the effect on knock of engine design and changing engine variables and fuel composition and additives to be predicted with reasonable accuracy. Despite 60 years of research into knock the fundamental principles of this phenomenon still present certain problems. However, the accepted basis of the theory is as follows:

In a normal combustion cycle the flame travels uniformly compressing and heating the unburnt flammable mixture before it. The unburnt charge is heated by radiation and compression from the advancing flame front. If the temperature and pressure are below certain critical values then the flame will travel across the combustion chamber in a regular and controlled manner until combustion of the end gas is completed. However, if the critical temperature and pressure conditions are exceeded the end gas ignites spontaneously resulting in knock[14],[21]. The high rate of combustion and consequent momentary upset of the pressure equilibrium generates a shock wave which impinges on the cylinder wall giving the high pitched knocking sound[17],[18]. The study of knock is complicated by the phenomenon that the normal flame velocity and pressure development prior to self ignition of the end gas give no indication whether or not knock will occur.

The occurrence of knock depends on the pressure-temperature-time relationship of the mixture in the end gas. Consequently any condition which raises the temperature or pressure such as increasing compression ratio, cylinder filling efficiency, air intake temperature, flame path length or lowering the engine speed will encourage knock.

Two primary approaches are used when studying knock:

- A study of the physical phenomena of the knocking process by means of pressure measurement and high speed flame photography[22],[25],[31]. The combustion chamber acoustical characteristics are important in analyzing knock as high amplitude high pressure oscillations are induced when the end gas ignites spontaneously[18].

- A study of the preflame chemical reactions occurring in the end gas prior to knock determines the limiting critical chemical factors controlling the onset of knock.

3.3.1 Physical mechanism of knock

In order to reduce the large number of factors which influence the onset of knock, it is necessary to eliminate some of the factors which control knock. The two primary considerations are to reduce the combustion chamber to a simple hemispherical design and to reduce turbulence to a minimum. Knock is thus studied in a stagnant homogeneous fuel/air mixture which undergoes rapid compression. A transparent quartz glass cylinder head allows photographs to be taken so that the flame propagation can be studied.

Tadakuri Hayushi[31] has done pioneering work using a rapid compression and expansion machine in which clear photographic evidence of the onset of knock is given.

The onset of knock is characterized by a rapid and abrupt pressure rise in the combustion chamber. This is clearly evident from pressure traces taken during combustion. When colour photographs of knocking combustion are examined, it can be seen that the normal combustion has a blue colour whereas the colour changes to white throughout the combustion chamber when knocking occurs. After knock the colour changes through brown to black. A further characteristic of knocking combustion is that soot is produced in the combustion chamber directly after knock has occurred. The velocity of the wave which is generated by the knock has been calculated to be 1700 m/s. The speed of sound in the burnt portion of the combustion chamber is 1100 m/s at a temperature of 3000 K whereas the speed of sound in the unburnt portion of the combustion chamber is

600 m/s at a temperature of 900 K. Knock thus generates a shock wave which is propagated through the unburnt portion of the fuel/air mixture at a speed 2.8 times that of sound.

3.3.2 Chemical reactions prior to knock

Numerous research findings have shown that preflame chemical reactions take place in the unburnt mixture which becomes pre-sensitized leading to auto-ignition which is followed by knock. These phenomena have been studied in depth by Chun and Heywood[7] and Leppard[22].

Comprehensive studies of preflame reactions were made by Downes, Walsh and Wheeler[32] using in cylinder sampling techniques and it was found that the chemical substances in the end gas were the same under knocking and normal combustion conditions. It was found that aldehydes and organic peroxides played the critical role in determining whether knock would occur depending on certain critical concentrations being met.

Auto-ignition of hydrogen and oxygen have been studied in steady flow processes through a tube and it was found that at 10 to 15°C before the auto-ignition temperature of 556°C, only a small quantity of hydrogen peroxide (H_2O_2) was formed and that water formation increased with an increase of temperature. Engine tests indicated that the incipient knock compression ratios were somewhat lower than those of iso-octane but the variation with air/fuel ratio was similar according to Anzilotti[33].

The overall combustion of heptane and oxygen is as follows:

$$C_7H_{16} + 11O_2 \text{----} > 7CO_2 + 8H_2O$$

However, the reaction does not proceed in one step but passes through an intermediate peroxide phase as follows:

$$C_7H_{16} + O_2 \text{----} > C_7H_{15}OOH$$

The peroxides then decompose as follows at the end gas temperature:

$$ROOH \text{ ----> } (R\text{-}\underset{\underset{O}{\|}}{C}\text{-}H) + (R\text{-}\underset{\underset{O}{\|}}{C}\text{-}R) + (R\text{-}CH{=}CH\text{-}R)$$

Peroxides Aldehydes Ketones Olefins

These products are relatively inert.

The bivalent radical CO in the aldehydes and ketones is chemically distinct from carbon monoxide. It occurs in aldehydes and ketones as well as some other substances and compounds containing it are termed carbonyls[5].

Peroxides can also decompose into highly excited radicals as follows:

$$ROOH \text{ ----> } RO^{*} + OH^{*}$$

These radicals can react readily with hydrocarbon molecules and promote rapid oxidation of a hydrocarbon[43].

In the decomposition of the organic peroxides a considerable amount of formaldehyde (HCHO) is formed. A few of these molecules are formed with an excess of energy and radiate, thus indicating the presence of a cool flame. Spectrometric investigations of n-heptane preflame reactions indicate that the integrated cool-flame radiation intensity was an approximate index of the increase in carbonyl concentration in the cool-flame region with heptane when motoring conditions were not severe enough to cause the blue flame to appear.[34]

The preflame reactions which occur between the blue-flame and auto-ignition are believed to be chain branching which accelerate the reaction rate and cause the explosion of the end mixture. Anzilotti and Tomsic[35] studied the combustion of hydrogen and carbon monoxide in engines and concluded that the relatively simple hydrogen-oxygen reaction may play a major part in the reactions leading to hydrocarbon knock. According to Lewis and von Elbe[42] the following reactions lead to the steady state nonexplosive situation at combinations of temperature and pressure less severe than those which lead to knock. The highly energized radical HO_2^{*} plays an important role in these reactions.

$$H + O_2 + M \text{ ----> } HO_2^* + M$$

$$HO_2^* + H_2 \text{ ----> } H_2O_2 + M$$

An increase in temperature or pressure to the auto-ignition limit promotes the following chain branching explosive reactions which result in auto-ignition:

$$H + O_2 \text{ ----> } HO^* + O$$

$$O + H_2 \text{ ----> } HO^* + H$$

$$HO^* + H_2 \text{ ----> } H_2O + H$$

The last reaction is highly exothermic. The experiments conducted by Anzilotti and Tomsic[35] with mixtures of air and carbon monoxide and various water-vapour contents indicated that the knock tendency of these mixtures was related to the presence of the H, HO_2^* and HO^* radicals.

3.3.3 Flame velocity or rate of burning

The time needed for the flame to travel from the spark plug through the combustion chamber depends on the fuel, mixture ratio, temperature and pressure conditions, turbulence and combustion chamber design[41]. A high rate of burning allows less time for the end mixture to lose energy by heat transfer to the combustion chamber walls which tends to produce knock. A fast combustion speed allows less time for the end mixture to attain the condition required for spontaneous ignition of the end gases which tends to prevent knock.

High combustion speeds require small optimum spark advances which lead to the end gas combustion occurring at or near the piston top dead centre position when compared to lower rates of burning. This tends to increase the onset of knock. If the flame speed is high enough to permit it to pass through the mixture

in less time than the ignition lag required for the end mixture to auto-ignite under the continuously increasing temperature and pressure to which it is subjected, the end gas will burn normally and combustion knock will not occur[7],[8].

3.3.4 Fuel-air ratio

The majority of fuels tend to auto-ignite at fuel air ratios which are about 10% richer than stoichiometric when tested in a CFR engine at 900 r/min, 100°C water temperature and with an ignition advance of 28 to 30°[26],[35].

A non-homogeneous mixture of fuel and air in the cylinder and maldistribution between cylinders results in one cylinder of a multi-cylinder engine having a greater tendency to knock. Usually the retardation of ignition timing or the increase of mixture strength will lead to a reduction of knock tendency in the most sensitive cylinders. As the various fractions of the gasoline have different anti-knock properties, the mixture distribution becomes an important factor in determining the engine octane requirement[6],[16]. The lighter gasoline fractions tend to have good research and motor octane ratings and are most likely to vapourise readily and will also be distributed equally between the cylinders of the engine[9],[22]. The heavier fractions will tend to condense on the walls of the inlet manifold and will thus not be equally distributed between the engine cylinders. This is complicated by the use of tetraethyl lead which, with a boiling point of 110°C, tends to condense in the inlet manifold. In order to control these phenomena a front end octane number is specified at 100°C to ensure that the fuel will give adequate knock protection while the engine is warming up[15].

3.3.5 Compression ratio

The increase of compression ratio decreases the clearance end gas fraction and consequently decreases the mixture temperature and also the end mixture temperature history. This effect on mixture temperature reduces the tendency to knock, but the influence of increasing compression ratio offsets the reduction of mixture temperature due to the smaller amount of end gas, thus the net effect of increasing compression ratio is to increase the onset of knock. Dilution of the inlet air with about 20% of cold exhaust gas tends to reduce the onset of knock appreciably and is also beneficial in the reduction of NO_x exhaust emissions.

The allowable compression ratio with incipient knock increases rapidly with an increase in octane number of the fuel, particularly with the fuels of higher octane number. This characteristic is the same for constant inlet manifold pressure and constant brake mean effective pressure. For a constant antiknock quality of fuel the allowable compression ratio can be increased by reducing the inlet manifold pressure. Thus, for a given fuel, the power output can be increased by supercharging to the knock limit at a low compression ratio. Likewise, the engine could be operated at a high compression ratio provided that the inlet manifold pressure was controlled. The supercharging work and the throttling losses lead to a reduction of efficiency.

3.3.6 Combustion chamber shape

Combustion chamber shape depends on the valve arrangement, despite the large number of variations which are possible with piston and cylinder head shape. Some of the shapes used are illustrated in Figure 3.2.

T-head (practically obsolete)
L-head
  Inlet valve beside exhaust valve
  The same as *a* with high-turbulence head
F-head. Inlet valve over exhaust valve or in cylinder head
Valve-in-head
  Vertical valves with cylindrical combustion chamber
  Valves at an angle with domed combustion chamber
  Vertical valves and turbulent combustion chamber
  Valves in line but not vertical; turbulent combustion chamber

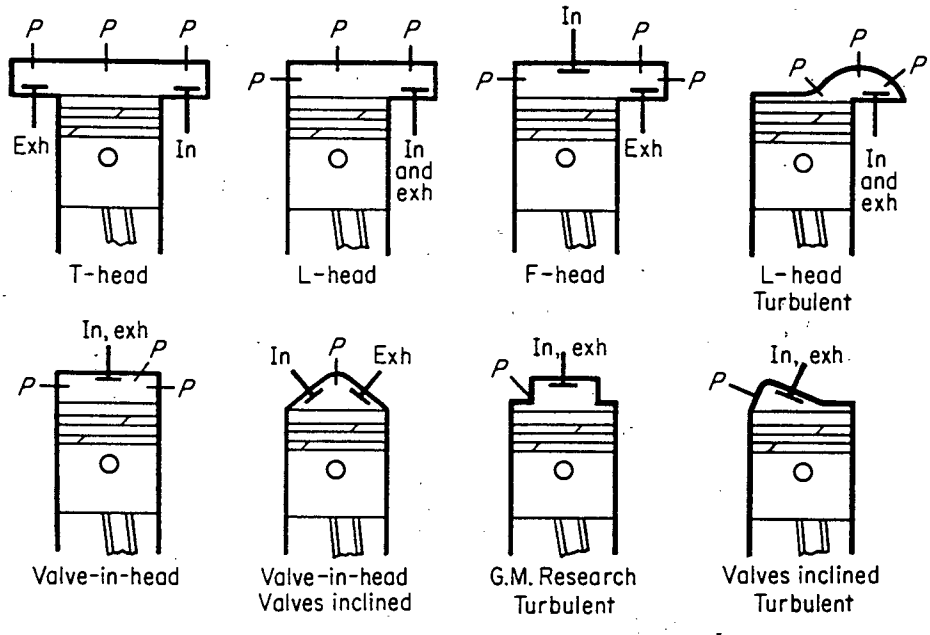


Figure 3.2: Combustion chamber shapes with P indicating possible spark plug locations.

The T,L,F an L head turbulent combustion chambers are now obsolete except for some small industrial engines where the low cost of a L head has certain advantages. Most modern automotive engines have their valves in the cylinder head and the four engines studied in this report have this layout.

Generally, combustion is best in a compact chamber as the fuel octane requirement will be low as the flame travel path length is short. Design of the piston and cylinder head to form a bowl surrounded by a raised area where there is only a small gap between the cylinder head and piston at TDC provides a compact combustion chamber as well as squish which promotes high turbulence,

thus ensuring high speed combustion. A very high compression ratio without the threat of knock can be sustained in such a combustion chamber if there are no hot spots present. The combustion chambers of the engines used in the test comply with these design considerations.

Spark plug location is also important in the layout of a combustion chamber. The spark plug should be located as centrally as possible to reduce the flame path length to a minimum. It should also be located at the hottest point on the cylinder head, which normally implies a position near the exhaust valve. Two spark plugs on opposite sides of the combustion chamber provide a very short flame path and such a design is used in large bore spark ignition engines.

CHAPTER FOUR

INSTRUMENTATION AND TEST PROCEDURE

The engines were fitted on to cradles which are attached to the Heenan & Froude Mark 1 eddy current dynamometer. This type of dynamometer is suitable for constant speed operation and also for rapid cycling. The dynamometer test cell temperature can be controlled at a temperature above ambient. Data was recorded on floppy disks using an IBM XT personal computer. This allowed the computerized processing of data thus eliminating manual error.

4.1 ENGINE TEST CELL

A photograph of the engine dynamometer coupled to the Nissan engine is to be found in Appendix 4.1. The positions of the pressure transducer, accelerometer and crankshaft angle markers can be seen.

The engine test cell is equipped with a Heenan & Froude Mark 1 eddy current dynamometer. The specifications for the unit are as follows:

Speed range: 0 - 10 000r/min
Torque range: 0 - 200Nm
Power range: 0-150hp

4.2 ENGINE INSTRUMENTATION

A diagram of the instrumentation and examples of traces is given in Appendix 4.3. Each engine was fitted with the following instrumentation:

4.2.1 Piezo-electric pressure transducer

The VW and Toyota engines were fitted with Kistler 6121 pressure transducers with a sensitivity of approximately 14 pC/bar.

The Nissan and Ford engines were fitted with AVL 8QP pressure transducers with a sensitivity of approximately 12 pC/bar.

The signal from the pressure transducer was fed to the computerscope via a PCB-F462 A charge amplifier with an output of 10 bar/volt.

The position of the pressure transducer in the Ford cylinder head is shown in Appendix 4.2.

4.2.2 Crankshaft angle marker

The crankshaft angle marker used is an AVL type 360C unit which gives output pulses for each 10^{o} of crankshaft angular displacement as well as top dead centre.

4.2.3 Accelerometer

A Bruell and Kjaer type 4369 accelerometer with a sensitivity of 22,2 pC/g was used.

The signal was fed to the computerscope via a PCB-F462 A charge amplifier with an output selected between 50g/volt and 20g/volt. The accelerometer was mounted horizontally on the engines' cylinder head.

4.2.4 Spark pulse

An inductive pickup was fitted to the number 1 cylinder spark plug lead in order to determine the spark and this allowed the measurements of spark timing in conjunction with the crankshaft angle marker.

4.2.5 Additional measurements

The following measurements were also made:

Engine torque
Engine speed
Outlet cooling water temperature
Water pressure
Sump oil temperature
Oil pressure
Inlet manifold pressure
Exhaust manifold back pressure
Fuel consumption by means of measuring bulbs
Inlet air temperature

4.3 DATA ACQUISITION SYSTEM

The data was acquired through an IBM XT personal computer fitted with a RC Electronics computerscope.

This equipment has 16 input channels and has a 12 bit analogue-digital converter. The input voltage range is -10V to + 10V and is based on the IBM XT computer.

During the tests four channels were operational and a sampling rate of 66,7 kHz was used. 16384 Data points were recorded on each channel for each record.

The channels were allocated as follows:

Channel # 1 : Cylinder pressure
Channel # 2 : TDC and spark pulses
Channel # 3 : 10^{o} crank angle pulses
Channel # 4 : Accelerometer trace

The data was stored on floppy disks for later processing, inspection and interpretation.

4.4 TEST PROCEDURE

All the engines were installed on the dynamometer with their standard air filtration systems an as close as possible to normal under bonnet fitment. The engine inlet air temperature was kept constant at 45°C by pre-heating the air with an electrical system and the exhaust back pressure did not exceed 20mm Hg. All the tests were done at full load and wide open throttle conditions. The engines were operated in the speed range of 1500 r/min to 5000 r/min in increments of 500 r/min.

At the start of the tests, each engine was operated on Aviation Gasoline 100/130 (a typical analysis is given in Appendix 4.4), in order to establish the maximum brake torque (MBT) at each data point with the minimum spark advance needed to achieve the peak torque value. The brake torque with 10° spark advance and retard at wide open throttle.

The engines were then run on the primary reference fuels blended from iso-octane and n-heptane to Research Octane Numbers from 86 to 100 RON in increments of 2 RON. The tests were done starting at 5000 r/min and working downwards to 1500 r/min in 500 r/min intervals. In each instance the timing was adjusted to the maximum brake torque timing determined on Aviation Gasoline 100/130. The test was started using the fuel of 100 RON and then using lower RON primary reference fuels until heavy knock set in. This allowed a trace of the fuel octane requirement needed to cause heavy knock at each data point to be established.

The engines were also operated on 3 unleaded alcohol-petrol blends with a design sensitivity of 10. The alcohol portion consisted of 60% ethanol, 30% propanol, 7% pentanol and 3% higher alcohols. The fuel properties are given in Appendix 4.5.

The relevant details of the four engines are given in the table below:

	Toyota	Volkswagen	Nissan	Ford
Engine Type	in-line 4 cyl. (16 valve)	in-line 4 cyl. (8 valve)	in-line 4 cyl. (8 valve)	Vee 6 cyl. (12 valve)
Capacity (cm^3)	1587	1781	1770	2993
Bore (mm)	81	81	83	93.67
Stroke (mm)	86.4	78	72.42	
Compression ratio	9.5:1	10:1	9.5:1	9.5:1
Compression pressure (bar, cranking)	13.1	13.0	12.0	12.0
Peak power (kW)	70	70	68	110
Spark timing (^{O}BTDC at idle)	10 deg	6 deg	10 deg	12 deg
Spark plugs	Champion N9YC	Champion N9YC	NGK BPR7ES	NGK BPR7ES
Combustion Chamber shape	Spherical	Bath Tub	Wedge shape	Bowl-in-piston

Table 4.1: Engine details

CHAPTER FIVE

RESULTS

Figure 5.1 depicts the normal representation of the results obtained during the tests. The crankangle is indicated in intervals of 10° from the top dead centre position of the cylinder fitted with the pressure transducer and accelerometer. The combustion chamber pressure is indicated in bar on the vertical axis of the combustion pressure diagram and the cylinder head vibration together with the time scale plotted in milliseconds are indicated on the horizontal axis.

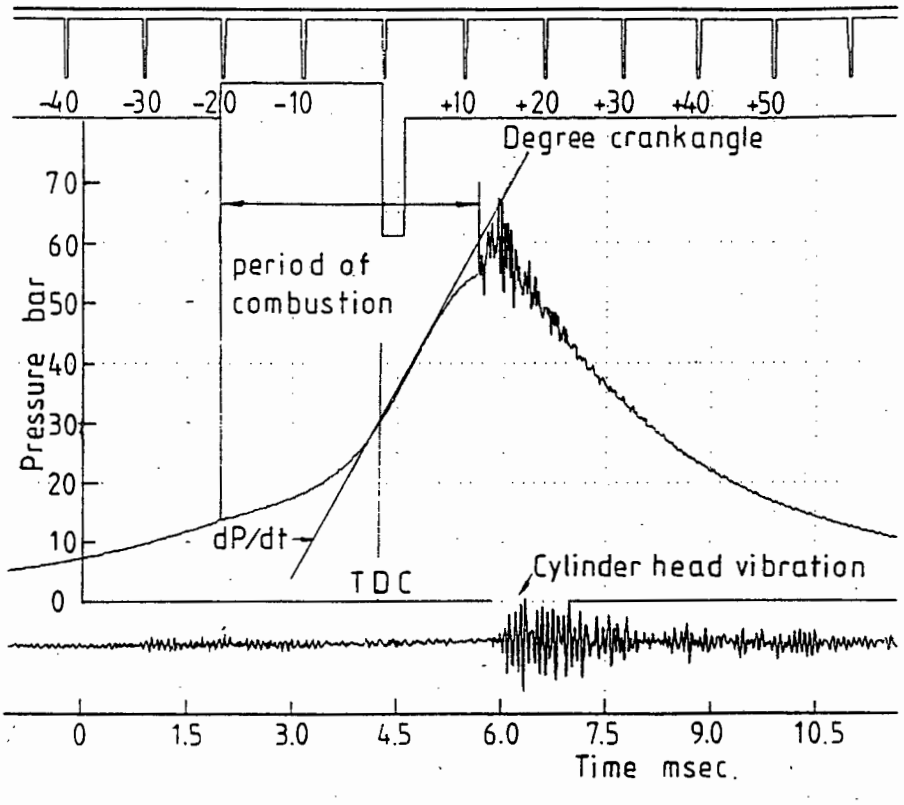


Figure 5.1: Typical knocking combustion chamber pressure diagram

Considerable difficulties were experienced with the Ford and Nissan engines. The torque of the Ford engine fell off in the mid speed range between 2500 to 3500 r/min. A compression test revealed that the compression pressures in cylinders 2 and 3 were much lower than the other cylinders. The engine was dismantled and it was found that the piston ring clearances were much larger than specification and also one piston had suffered knock and scuffing damage. Appendices 5.1 and 5.2 show the extent of the damage to the piston. The engine was rebuilt to specification and new components were fitted so that the test could be resumed.

The Nissan engine displayed a considerable loss of torque above 4000 r/min when compared to the suppliers data. It was found that the cyclonic air filter caused a restriction in the inlet system which lead to the torque loss. Removal of the cyclonic filter restored the engine torque to the manufacturers specification and removal of the air filter housing end cap produced a higher torque. It is evident that the air filter system on this engine causes a loss in torque and engine efficiency. The catastrophic failure of a Nissan piston during an earlier test is shown in Appendix 5.3.

5.1 MAXIMUM BRAKE TORQUE AND SPARK TIMING

Commercial aviation gasoline 100/130 with a RON of 103 was used to establish the maximum brake torque (MBT) at wide open throttle (WOT) for each data point through the speed range 1500 to 5000 r/min in intervals of 500 r/min.

The MBT curves plotted against the brake mean effective pressure (bmep) in bar and the engine brake torque in Nm for the engines is shown in Figures 5.2, 5.3, 5.4 and 5.5 for the Toyota, Volkswagen, Nissan and Ford engines respectively. The influence on the MBT of advancing and retarding the ignition timing by 10^{o} is also shown in the diagrams. Generally, the fall off in torque is greater when the ignition timing is retarded and this is particularly evident in the Volkswagen engine. The actual torque drop when the ignition timing is advanced and retarded is larger in the Volkswagen and Nissan engines than in the Toyota and Ford engines. The Volkswagen engine displayed a marked torque drop at 2500 r/min which may be ascribed to resonances in the inlet and/or exhaust manifolds which

disrupted the otherwise good flow. The other engines did not display this phenomenon and generally produced smooth torque curves.

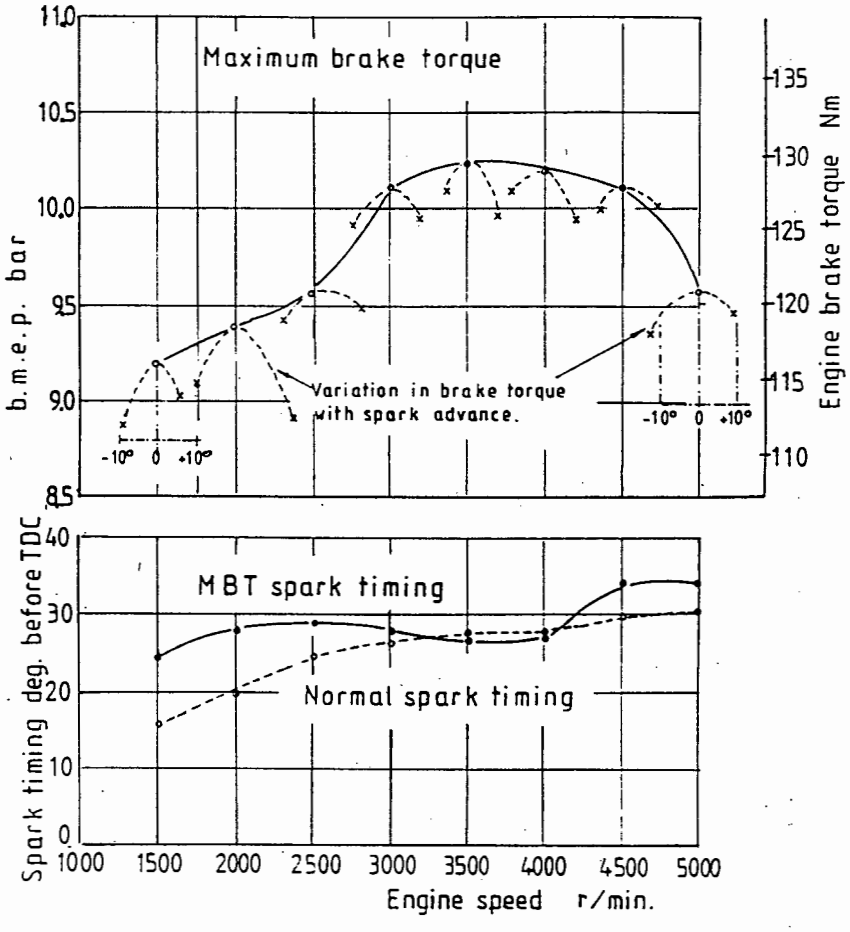


Figure 5.2: Toyota: Engine brake torque and spark timing

The MBT spark timing is compared with the normal spark timing for all the engines. Figure 5.2 indicates that the MBT timing is more advanced than the normal spark timing for the speed range tested except between 3000 and 4000 r/min.

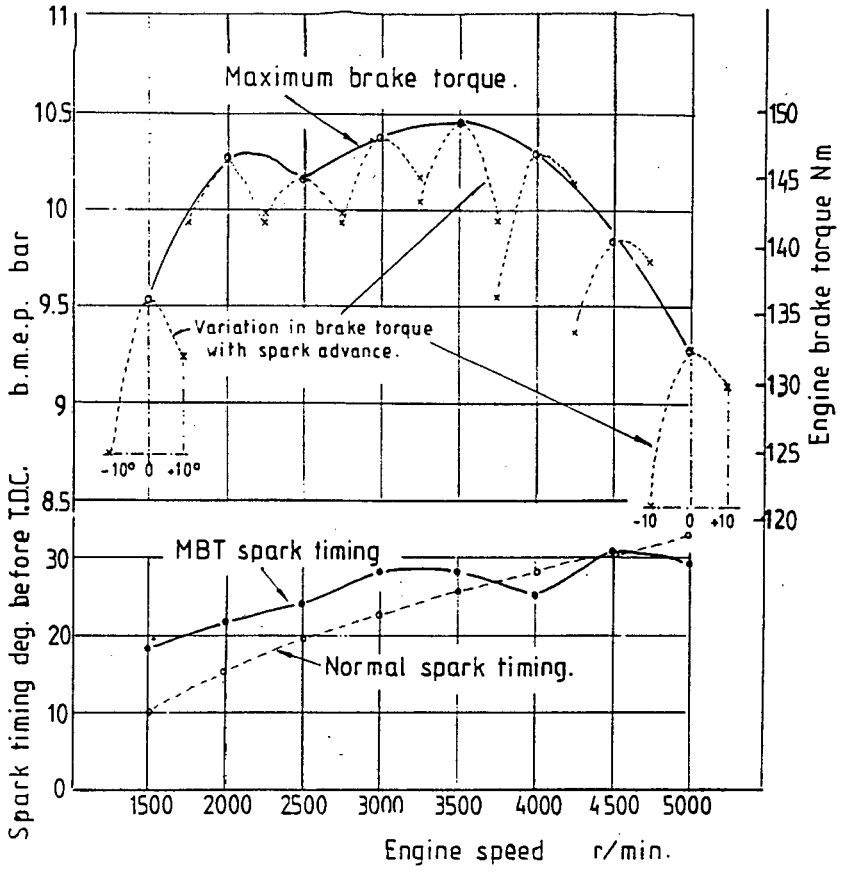


Figure 5.3: Volkswagen: Engine brake torque and spark timing

However, the difference is small especially when compared to the differences at low and high speed. The Volkswagen engine (Figure 5.3) displayed similar characteristics but in this instance the MBT spark timing was less than the normal spark timing at 4000 and 5000 r/min. The differences are again small especially when compared to the differences at low speeds.

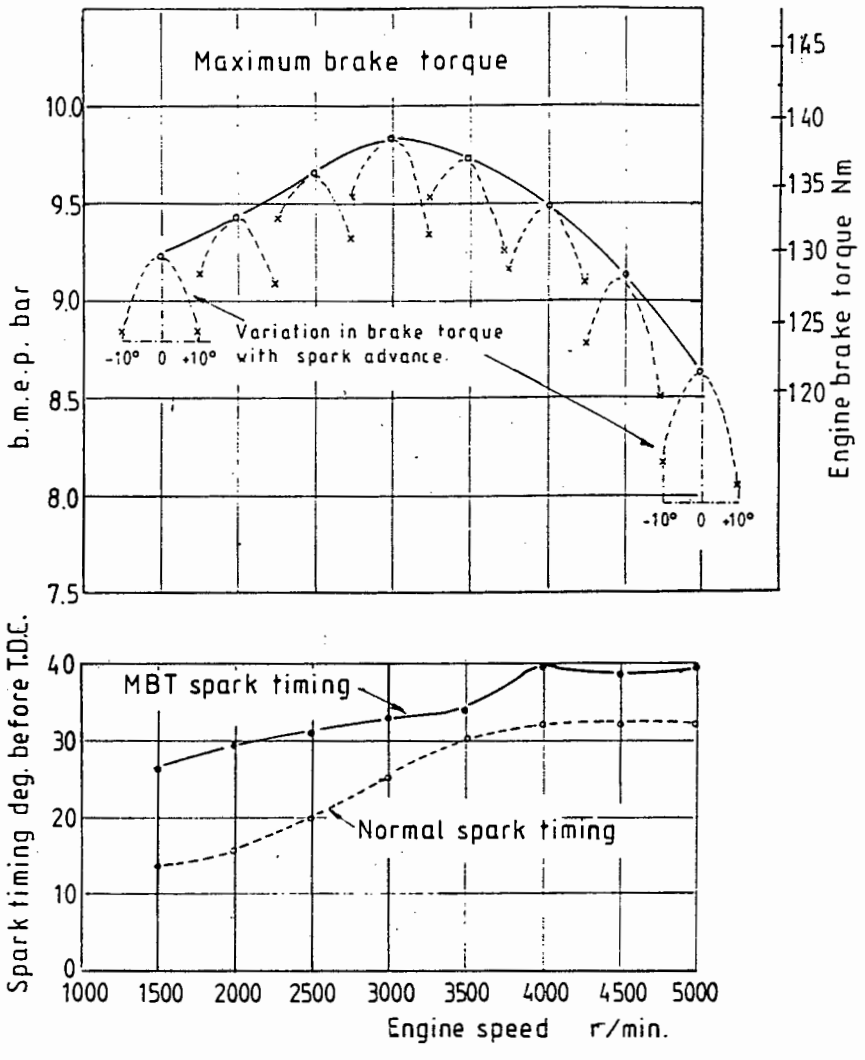


Figure 5.4: Nissan: Engine brake torque and spark timing

In the Nissan engine (Figure 5.4) the MBT spark timing is advanced from the normal spark timing over the whole speed range and in particular at low speeds. The curves follow one another closely and there are no crossover points. The engine is thus not optimized for efficiency and maximum torque.

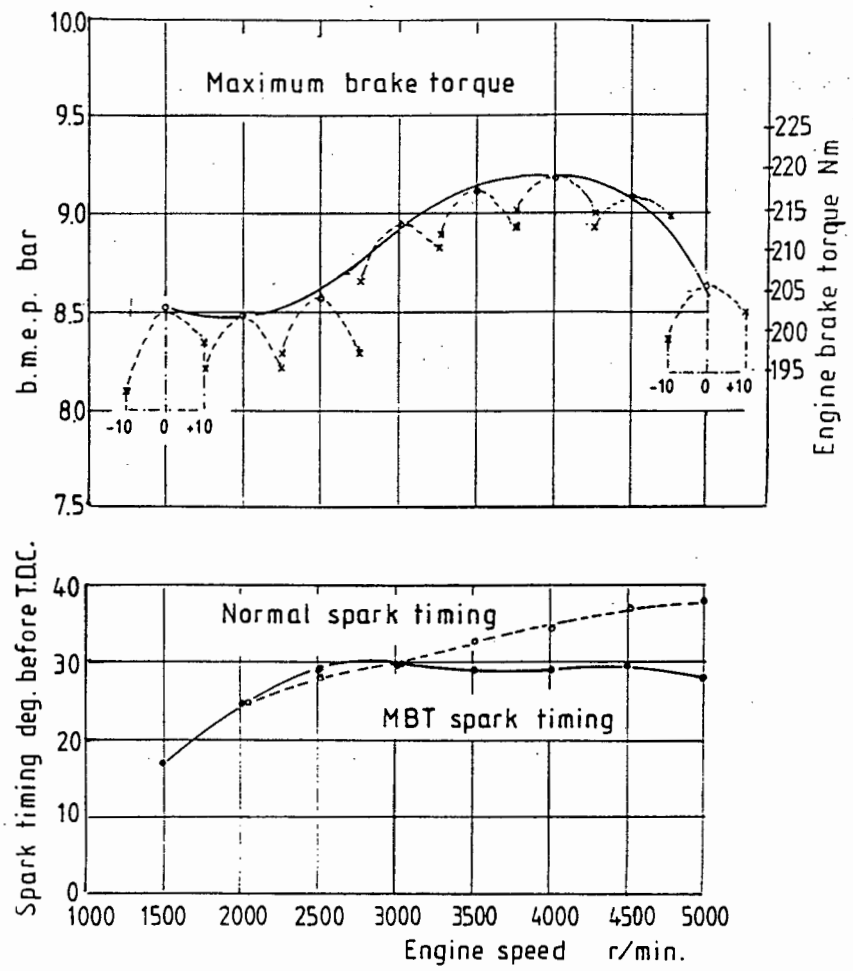


Figure 5.5. Ford: Engine brake torque and spark timing

Figure 5.5 for the Ford engine indicates that the normal spark timing is advanced relative to the MBT spark timing above 3000 r/min. This indicates that the engine is not optimized for torque and efficiency and is probably more knock sensitive than necessary.

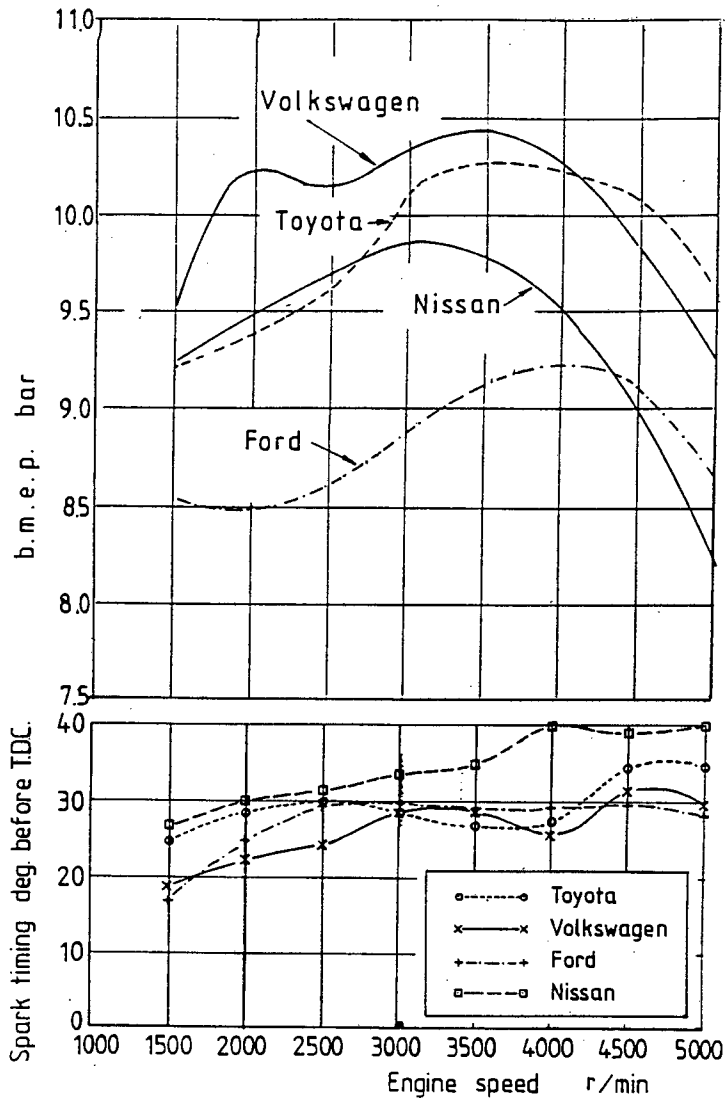


Figure 5.6: bmep and spark timing

Figure 5.6 depicts the brake mean effective pressure (bmep) and the spark timing at MBT for all four engines. The highest bmep, 10,4 bar, was recorded for the Volkswagen engine and the Toyota engine achieved 10,25 bar. The Nissan and Ford engines achieved only 9,75 and 9,2 bar respectively. The Toyota engine has a very rapid bmep rise from 1500 to 3000 r/min and then an almost constant bmep up to 4500 r/min which is characteristic of four valve per cylinder engines. The Volkswagen engine displays a unique drop in bmep at 2500 r/min which may be attributed to resonances in the inlet and/or exhaust manifolds.

Both the Nissan and Volkswagen engines have a sharp fall off in bmep from the peak values with increasing engine speed. The Toyota and Volkswagen engines have their peak bmep at 3500 r/min whereas the Nissan and Ford peaks occur at 3000 and 4000 r/min respectively. The Ford and Nissan engines display a smooth bmep increase from 1500 r/min which promotes steady acceleration in a vehicle.

The Volkswagen and Toyota engines are high performance power plants due to their high brake mean effective pressure. The Toyota and Volkswagen engines have peak cylinder pressures of 65 to 70 bar while the Nissan and Ford engines have peak pressures of between 40 and 60 bar.

5.2 BRAKE SPECIFIC FUEL CONSUMPTION

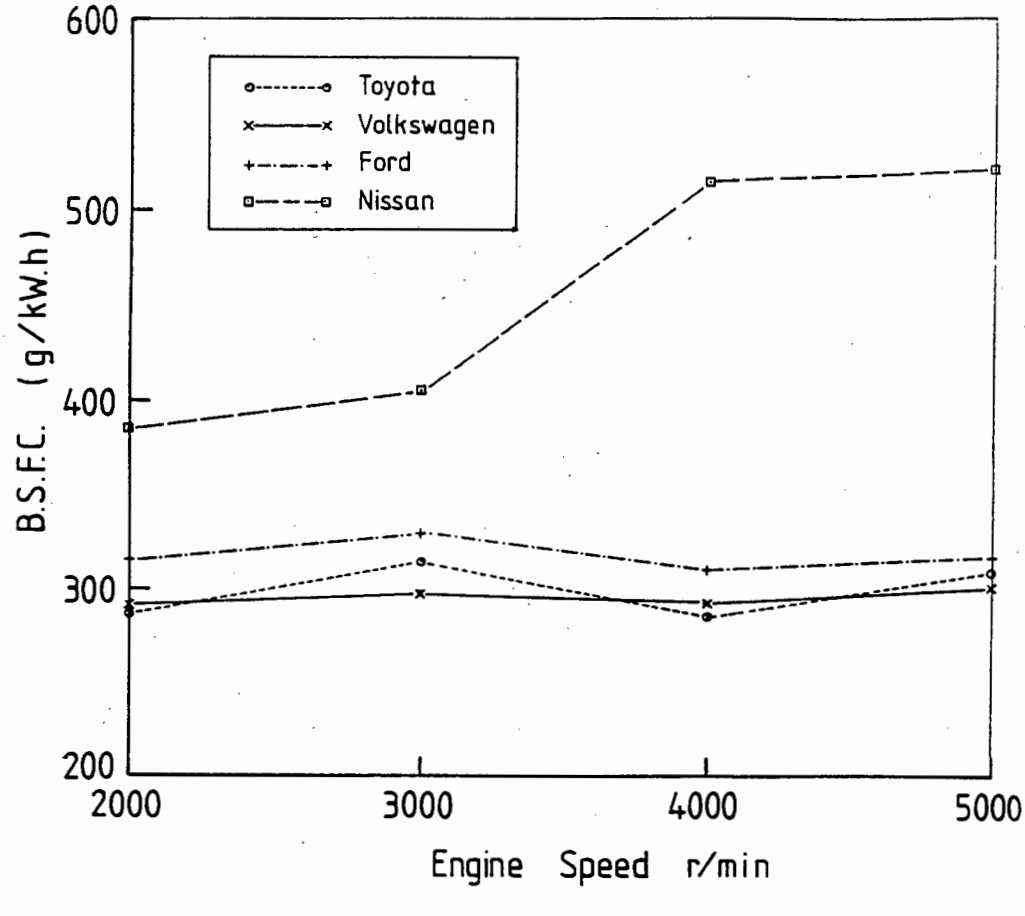


Figure 5.7: Brake specific fuel consumption

The brake specific fuel consumptions of the engines are shown in Figure 5.7. The lowest consumption is achieved by the Volkswagen engine at under 300 g/kW.h. This is largely due to the high compression ratio of the engine. The Toyota engine attains its lowest fuel consumption at 4000 r/min while it is slightly worse than the Volkswagen engine at other speeds. The Ford engine fuel consumption is higher than that of the Volkswagen and Toyota engines throughout the speed range but particularly at low speeds. The fuel consumption of the Nissan engine is very high and well outside manufacturers specifications thus there is something fundamentally wrong with the engine. The tests on this engine will be repeated and the results will be reported separately.

5.3 OCTANE REQUIREMENTS

Figure 5.8 depicts the three different levels of combustion knock as shown on the cylinder pressure diagrams recorded at MBT and 1500 r/min. These can be used to clearly define the knock in an engine for the primary reference fuels and production gasolines. The different levels of combustion knock are defined as follows:

Figure 5.8.1) Normal combustion.
Figure 5.8.2) Trace knock.
Figure 5.8.3) Knock.

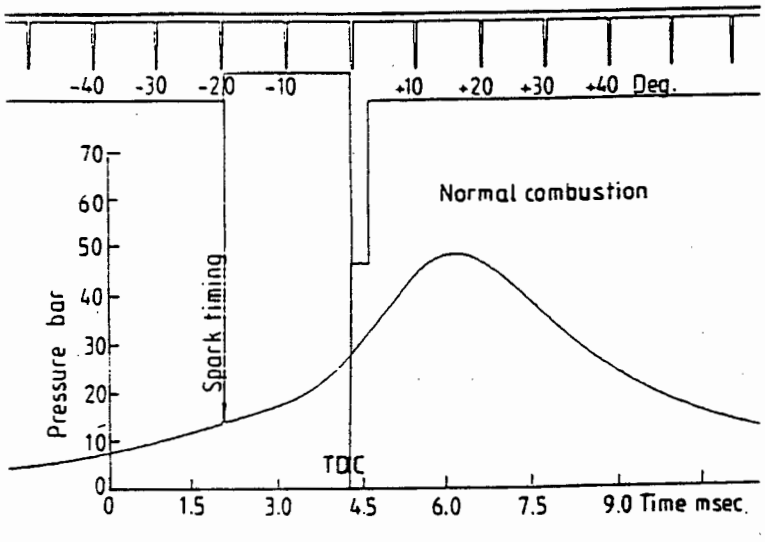


Figure 5.8.1: Normal combustion

Figure 5.8.1 depicts normal or knock free combustion which occurs with no pressure oscillations on the pressure diagram.

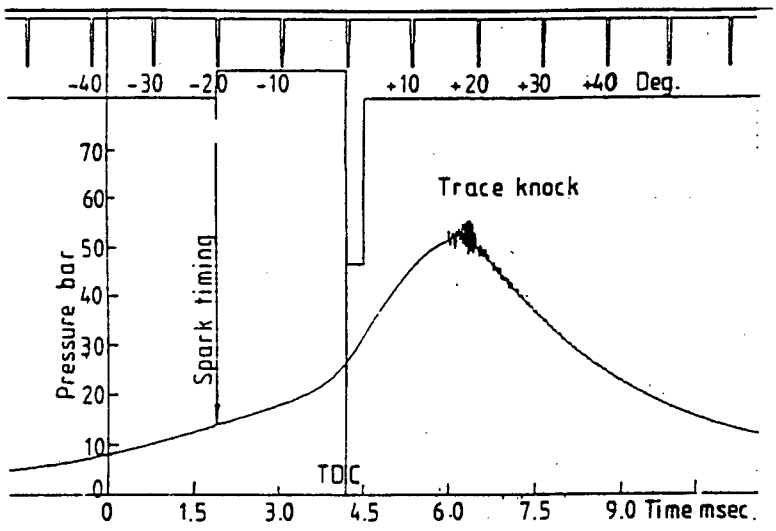


Figure 5.8.2: Trace knock

Figure 5.8.2 shows trace knock on the pressure diagram. A rapid pressure rise has occurred and lead to oscillations in the combustion chamber. The peak to trough pressure variation does however not exceed 5 bar.

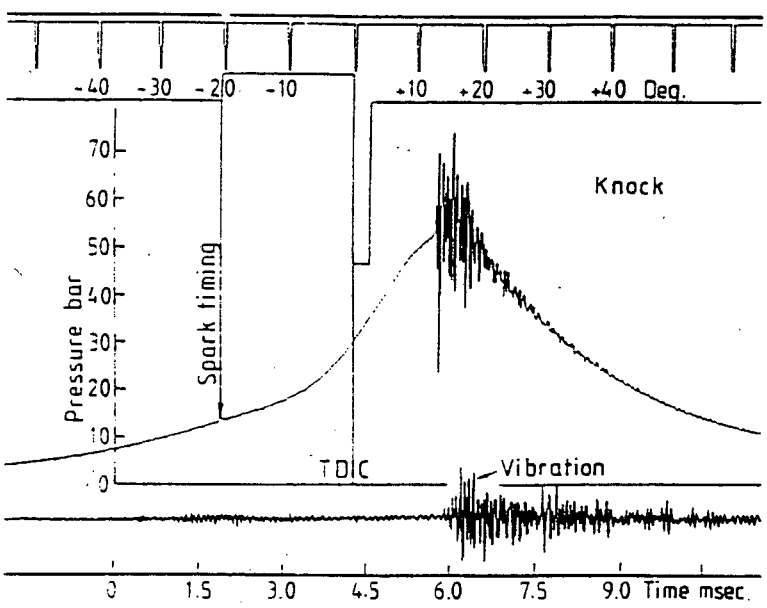


Figure 5.8.3: Knock

Figure 5.8.3 shows knock on the engine pressure diagram. A peak to trough pressure variation of more than 5 bar occurs after the large pressure rise when knock first occurred. The vibration trace also indicates the occurance of knock. In this instance knock occurs before the peak cylinder pressure under normal combustion is reached which is normal for low speeds. At speeds above 3000 r/min, knock normally occurs after the peak combustion pressure is reached. (See Figure 5.14).

The octane requirement of the engines using primary reference fuels is shown in Appendices 5.4, 5.5, 5.6 and 5.7. All the results are combined in Figure 5.8.

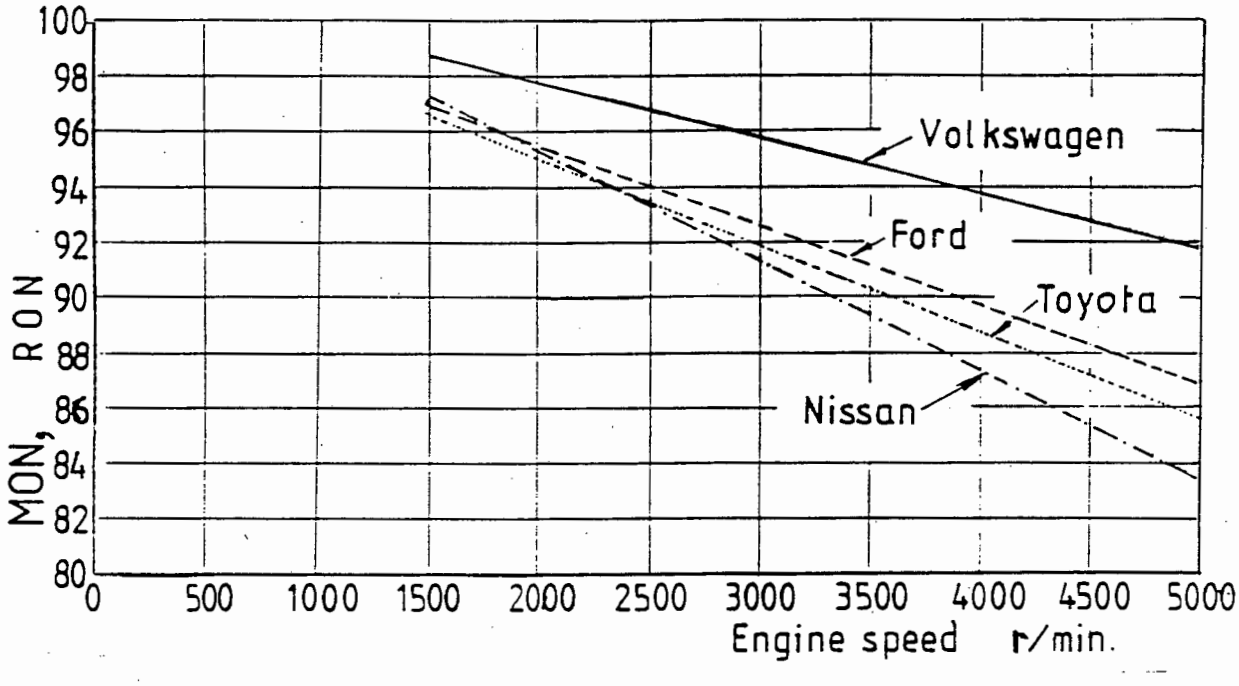


Figure 5.8: Octane requirement of the engines at MBT using primary reference fuels

In all cases the primary reference fuel octane requirement decreases linearly with an increase of engine speed. However, the slopes of the lines are different and indicate the influence which engine design has on octane requirement.

The octane requirement of all the engines is similar at low speed but there are substantial differences at higher speeds. At 1500 r/min, three engines have an octane requirement of 96.5 to 97.5 and one engine has a requirement of 98.5. At 5000 r/min the octane requirements vary between 83.0 and 91.5. The octane requirement reduces by 7 numbers for the Volkswagen engine and by 14 in the Nissan engine.

The octane requirement line can be defined by the equation:

$$OR = KN + C$$

where: K = Slope of the line
N = Engine speed in r/min
C = Constant

Substitution of the results obtained yields the following equations which define the primary reference fuel octane requirement of the engines:

Toyota engine	$OR = -0.0032\,N + 102$
Volkswagen engine	$OR = -0.0020\,N + 102$
Nissan engine	$OR = -0.0041\,N + 103.5$
Ford engine	$OR = -0.0029\,N + 101.2$

5.4 EFFECT OF FUEL SENSITIVITY ON OCTANE REQUIREMENT

The sensitivity (RON - MON) of the primary reference fuels is zero by definition. However, commercial fuels seldom have zero sensitivity, thus three Sasol fuel with design sensitivities of 10 were tested. The test fuels are defined in Table 4.2.

Figures 5.10 to 5.13 indicate the octane requirement of the engines using Sasol fuel. The following abbreviations are used to identify combustion stability in these Figures:

O - No knock
Tr - Trace knock
K - Knock

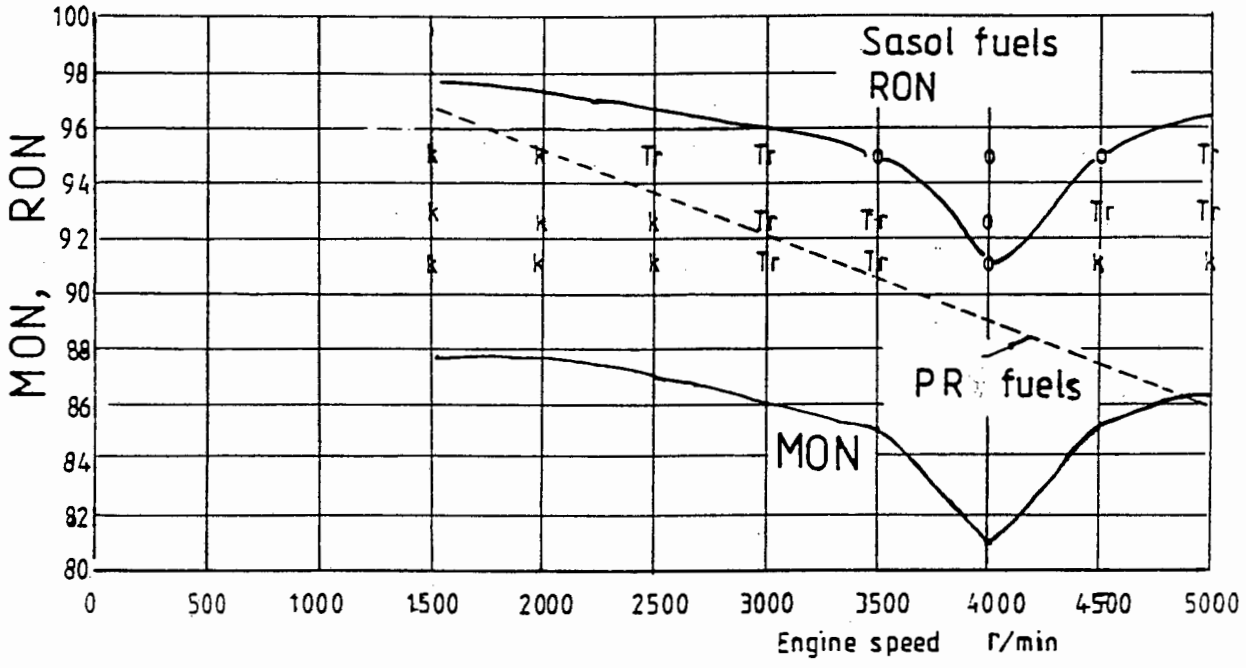


Figure 5.10: Octane requirement of the Toyota engine using Sasol fuels

Figure 5.10 illustrates the octane requirement of the Toyota engine at MBT timing using the unleaded Sasol fuels. The octane requirement-engine speed relationship is no longer linear and a considerably higher RON is need to avoid knock. However, as the MON of these test fuels is about 10 numbers lower than the RON, the engine octane requirement in terms of the primary reference fuels lies between the Sasol fuel RON and MON requirements.

It is evident that the low speed knock characteristics of the engine on the Sasol fuels are approximated by the PRF RON and the high speed knock is defined more accurately by the MON. This engine displayed a sharp drop in octane requirement at 4500 r/min, but thereafter the octane requirement increased substantially. Thus at 5000 r/min the Sasol fuel needs a RON 10 numbers higher, or the some MON, than the PRF to achieve the same knock protection. This illustrates the close correlation between high speed knock and MON.

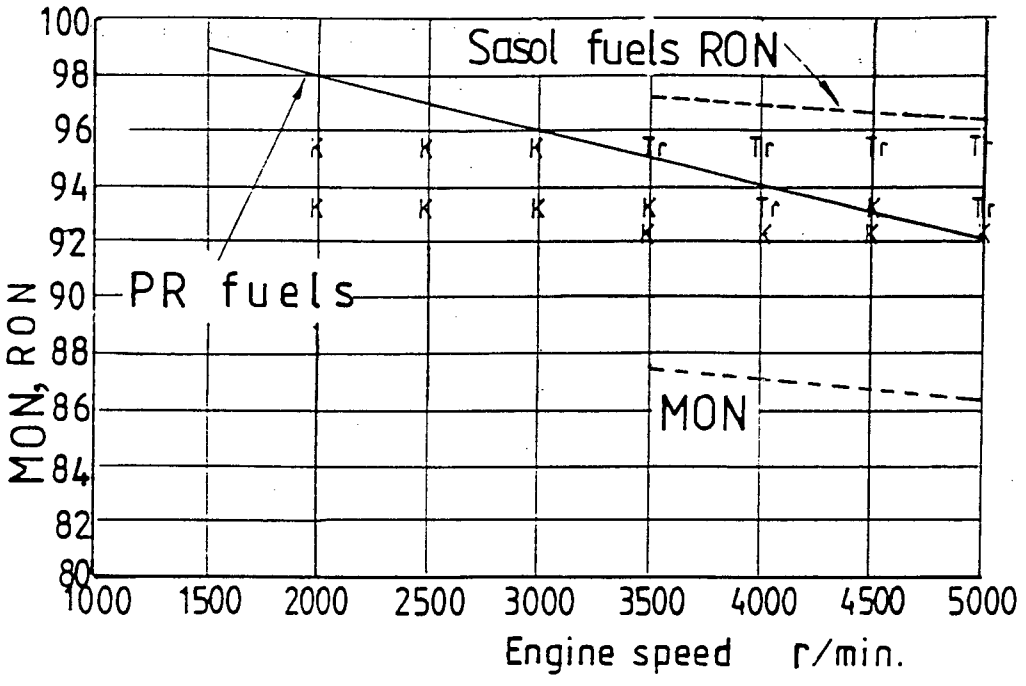


Figure 5.11: Octane requirement of the Volkswagen engine at MBT timing using Sasol fuels

The octane requirement of the Volkswagen engine is given in Figure 5.11. The octane requirement could not be plotted throughout the speed range but it is evident that the RON requirement is higher for the Sasol fuels than for the primary reference fuels. However, the MON requirement is less than indicated by the PRF octane requirements. This engine is thus unlikely to be prone to high speed knock.

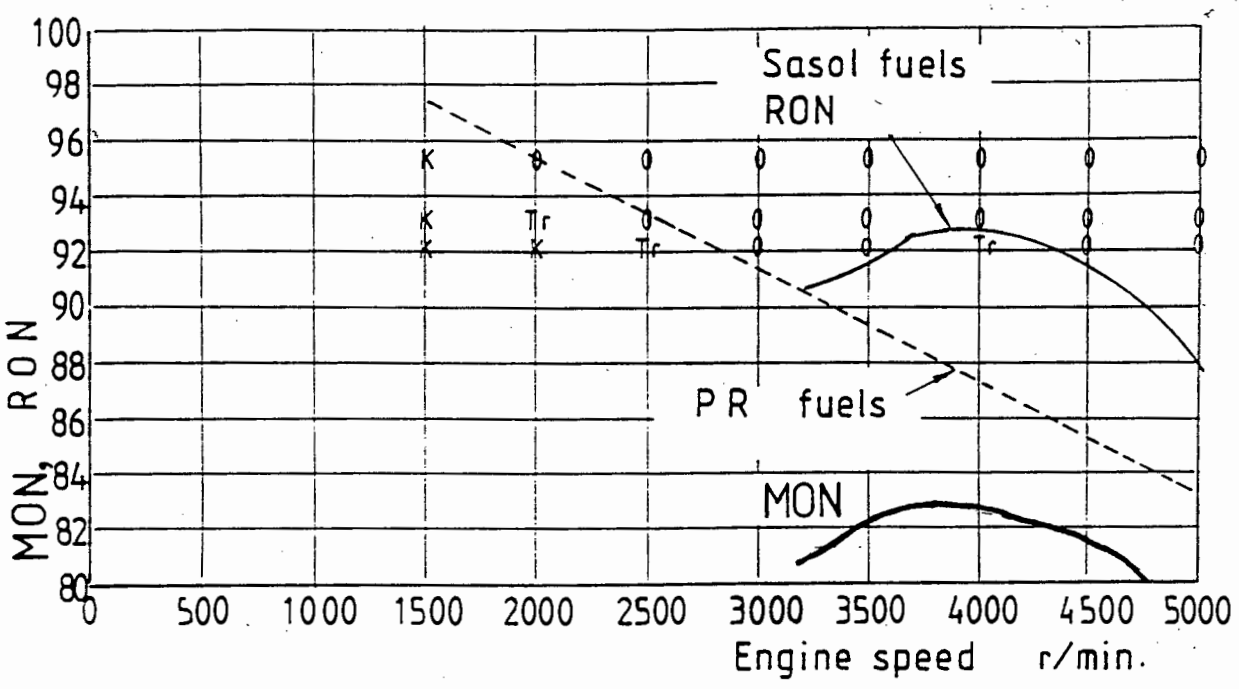


Figure 5.12: Octane requirement of the Nissan engine at MBT using Sasol fuels

Figure 5.12 shows the octane requirement of the Nissan engine. This engine has the lowest PRF octane requirements thus it was not possible to achieve knock using the Sasol fuels except at 4000 r/min where trace knock occurred with the Sasol 92.2 RON and 81.4 MON fuel. Again the knock at high speed is best approximated by the MON of the fuel. In the low speed range the engine octane requirement is best defined by the RON of the fuel tested.

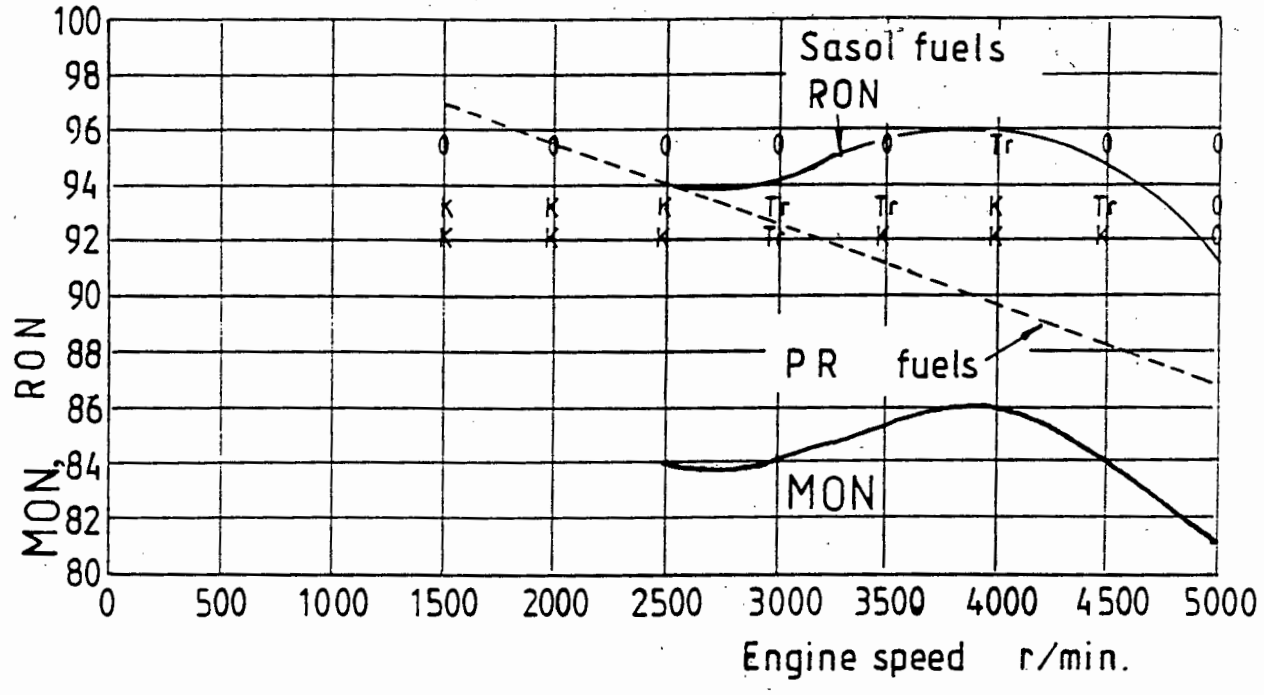


Figure 5.13: Octane requirement of the Ford engine at MBT using Sasol fuels

Figure 5.13 shows the octane requirement of the Ford engine. Again the knock characteristics with the Sasol fuels are best approximated by the RON in the low speed range and by the MON in the high speed range. At 4000 r/min the engine octane requirement is 95.5 RON and 84.5 MON on the Sasol fuels and 89.5 for the primary reference fuels.

In all the engines tested, the octane requirement is higher with the Sasol fuels than with the primary reference fuels, thus the knock tendency can be expressed as the difference:

= Octane requirement with the test fuel-octane requirement with the primary reference fuel

$$\text{Delta K} = OR_{\text{test fuel}} - OR_{\text{PR Fuel}}$$

The following table gives the values measured for the Sasol 95.5 RON fuel:

Engine speed r/min	Toyota	Delta K Volkswagen	Nissan	Ford
1500	0	-	-	-
2000	2	-	-	-
2500	3	-	-	2
3000	4	-	-	2
3500	5	2	3	4
4000	2	3	5	6
4500	7	4	6	7
5000	10	4	4	4

Table 5.1: Differences between Sasol and PR Fuel octane requirements

In conclusion, the fuel RON defines octane requirement in the low speed portion of the engine speed range and the MON is the more accurate determinant in the high speed portion of the engine speed range. Accordingly it is important to define both the RON and MON of commercial gasolines to ensure satisfactory operation throughout the speed range of production engines.

In some countries the gasoline octane quality is controlled by the anti-knock index which is equal to the average of the RON and MON.

$$\text{Anti-knock index} = (\text{RON} + \text{MON})/2$$

This measure does not ensure satisfactory knock protection at high speeds as a fuel of high sensitivity, greater than 10, would not necessarily have an adequately high MON. Additionally, the octane number of the fuel which distills up to a temperature of 100°C is important in controlling low speed knock while the engine is warming up after a cold start.

5.5 KNOCK CHARACTERISTICS

An analysis of the results facilitates correlation of the various parameters such as the peak cylinder pressure, rate of pressure rise, duration of combustion and cylinder pressure spectra with the knock intensity and natural frequency of the cylinder pressure oscillations. The vibration oscillograms recorded in the vicinity of one cylinder also record knock in adjacent cylinders.

The characteristics of knock can also be described in the frequency domain by cylinder pressure spectra. The cylinder pressure is considered to be a sound pressure in the combustion chamber and its spectrum through the frequency range is expressed as a sound pressure level in dB re 20 μPa. Electronic frequency analyzers can normally only average spectra over a number of engine combustion cycles, thus there is a large error in such results as there are cycle to cycle variations in spark ignition engines.

In order to overcome this problem, a Fourier Transform of the digitized waveform data is computed. The complex nature of the pressure signal requires great care to be taken in determining the time-window to be analyzed. As commercial programmes cannot perform this task satisfactorily, a new programme was developed by Paul Schaberg as a part of his presently unpublished MSc thesis. The programme incorporates a fast Fourier Transform algorithm and allows the flexibility necessary for analyzing cylinder pressure diagrams accurately.

The fundamental circumferential modes for a flat disc shaped chamber are shown in Figure 5.14.

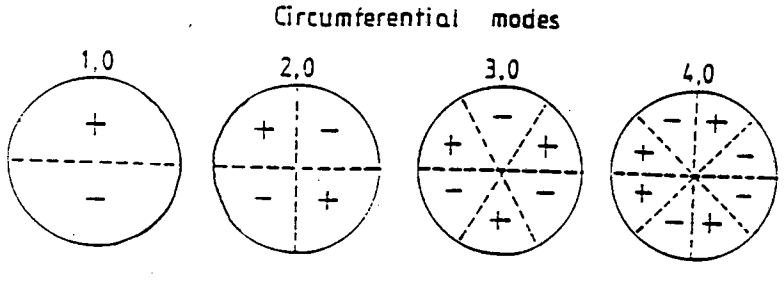


Figure 5.14: Circumferential modes

5.5.1: Knock characteristics of the Toyota engine

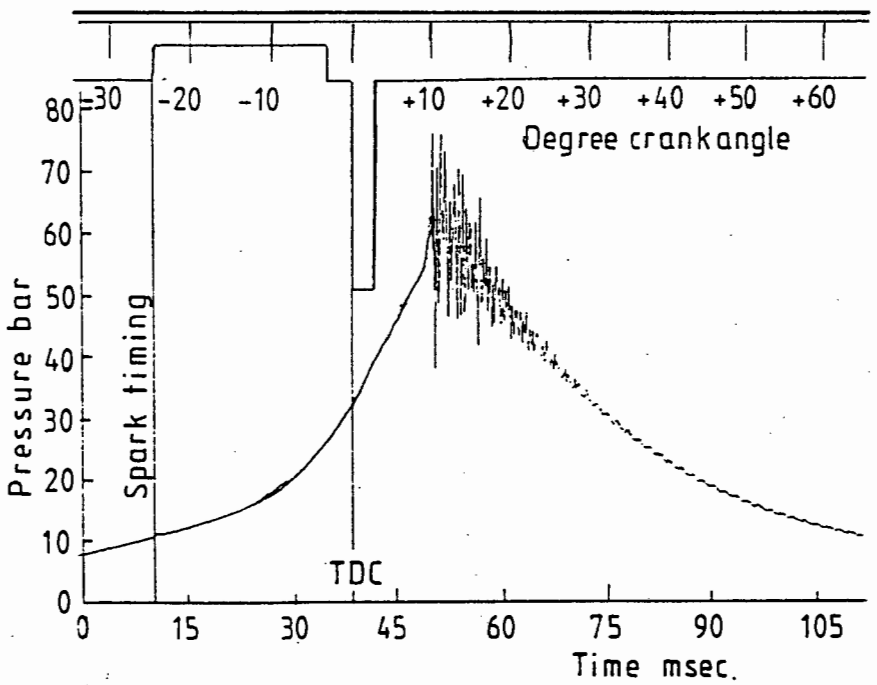


Figure 5.15: Toyota cylinder pressure diagram at 1500 r/min

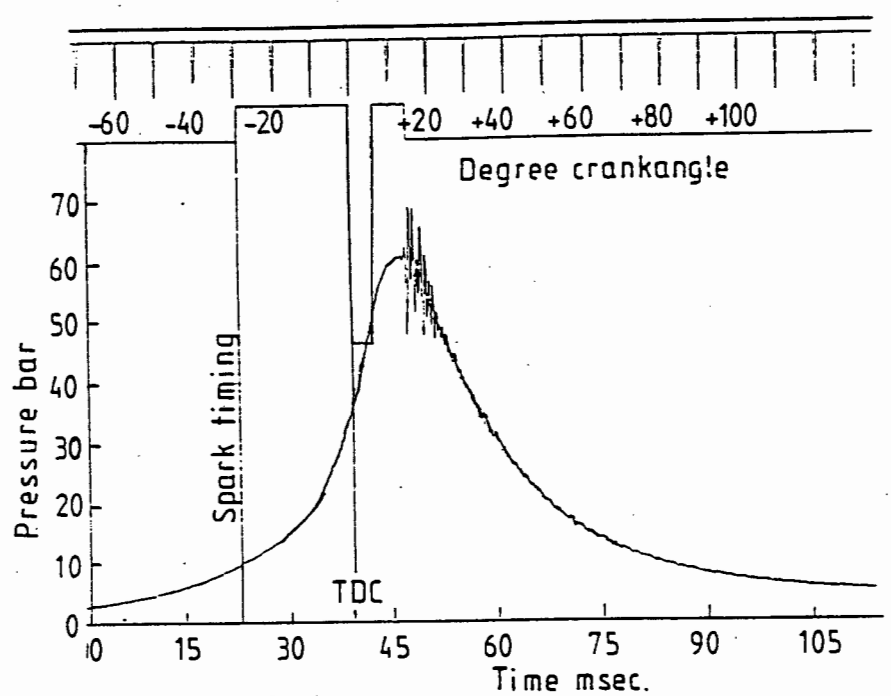


Figure 5.16: Toyota cylinder pressure diagram at 3000 r/min

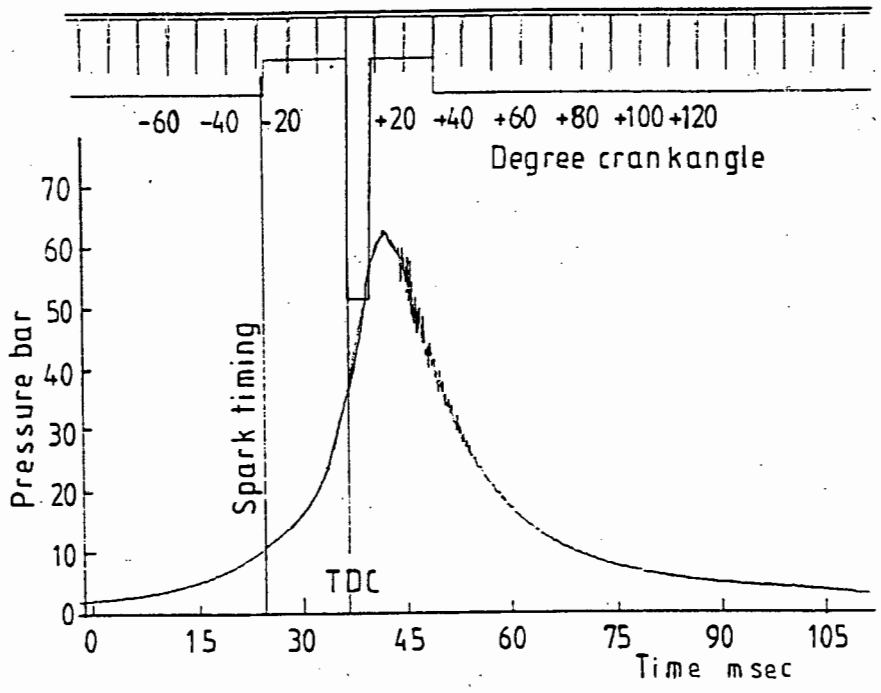


Figure 5.17: Toyota cylinder pressure diagram at 4000 r/min

Three cylinder pressure diagrams recorded at 1500, 3000 and 4000 r/min and showing the occurance of knock are depicted in Figures 5.15, 5.16 and 5.17 respectively. At 1500 r/min a large amplitude high frequency pressure oscillation occurs before the peak cylinder pressure is reached under knocking conditions. At 3000 r/min the onset of knock is delayed till after the peak cylinder pressure is reached and is of smaller amplitude than at 1500 r/min. At 4000 r/min, the amplitude is small and the oscillations only occur some time after the peak pressure is reached.

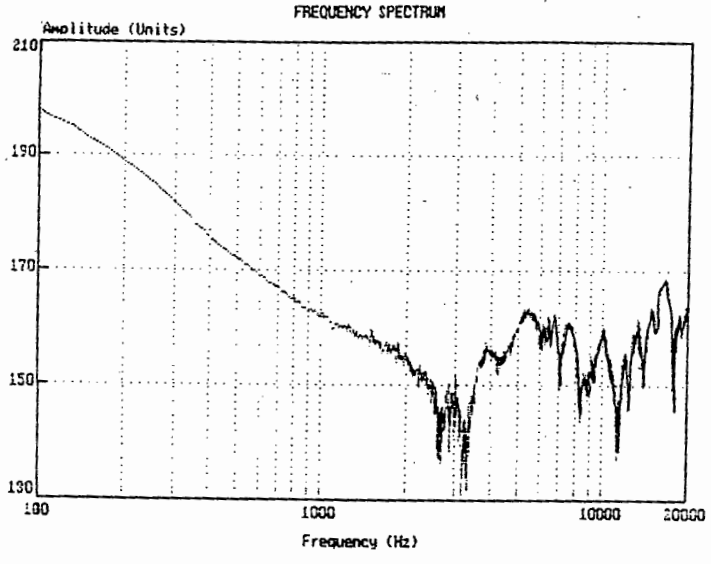


Figure 5.18: Toyota cylinder pressure spectrum at 1500 r/min

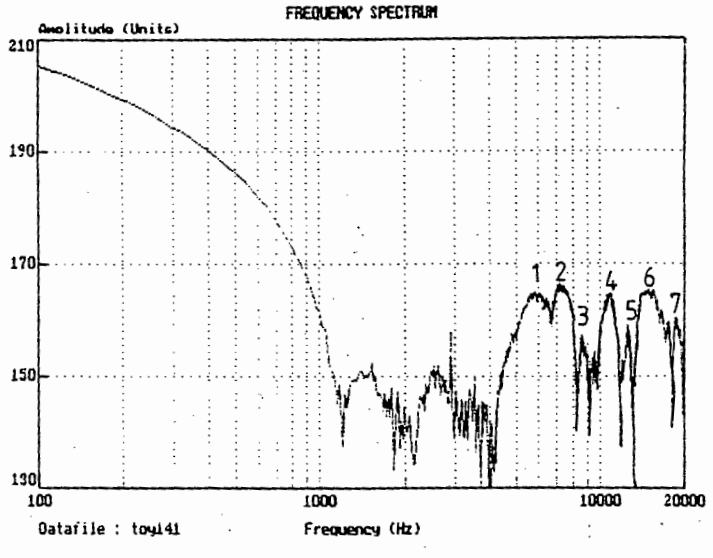


Figure 5.19: Toyota cylinder pressure spectrum at 3000 r/min

Figure 5.18 and 5.19 depict the cylinder pressure frequency spectra at 1500 and 3000 r/min respectively. The spectra show the same characteristics in the high frequency range from 3000 to 20 000 Hz. The individual peaks at 3000 r/min are presented in the table below:

Frequency peak	Frequency F_n (Hz)	Ratio $F_n/F_{1,0}$	Mode	Theoretical ratio $F_n/F_{1,0}$
1	5 811	split		1,0 mode
2	7 158	f_{ave}=6485 Hz		1,0
3	8 580	?	?	-
4	10 875	1,677	2,0	1,659
5	12 521	1,931	0,1	2,081
6	14 766	2,277	3,0	2,282
7	18 657	2,877	4,0	2,888

Table 5.2: Analysis of the pressure peaks in Figure 5.15

In this instance the 1,0 mode is degenerate in the sense that the nodal line shifts from its diametral position which causes the mode to be split into multiple components, each with their own distinct frequency and nodal line. Two frequency peaks are detected with frequencies of 5811 and 7158 Hz. In the degenerate mode these are the highest and lowest frequencies which could exist, and their average provides good correlation with the theoretically determined ratios. Thus the three higher circumferential modes and the first radial mode can be identified. The frequency peak at 8580 Hz cannot be identified.

5.5.2 Knock characteristics of the Volkswagen engine

Appendix 5.8 shows a drawing of the Volkswagen combustion chamber in which the position of the pressure transducer is indicated. The combustion chamber has two squish zones, one adjacent to and the other opposite the spark plug with clearance heights of 2.4 and 1.0 mm respectively. The combustion chamber height is 14.0 mm.

Cylinder pressure diagrams for each data point from 1500 to 5000 r/min in steps of 500 r/min are shown in Appendices 5.9 through 5.12. The diagrams clearly indicate that the knock occurs before the cylinder pressure has reached its peak value at low speeds but that it only occurs after the pressure peak above 3000 r/min. At 1500 r/min knock occurs at a combustion chamber pressure of 7

bar below and before the peak and at 5000 r/min it occurs at 5 bar below and after the combustion chamber pressure peak.

Knock only occurs after 10° beyond the top dead centre position of the piston throughout the speed range. This may be due to the flame front being quenched in the narrow squish zone adjacent to the pressure transducer when the piston is at TDC. Spontaneous ignition of the end gas can thus only occur when the squish zone height is increased from 1.0 mm to a height greater than 2.0 mm. For the engine stroke of 78.0 mm the piston will have had a displacement of 1.185 mm in the 10° interval from TDC.

The cylinder pressure spectra for the engine at 1500, 3000 and 5000 r/min are given in Figures 5.20, 5.21 and 5.22 respectively.

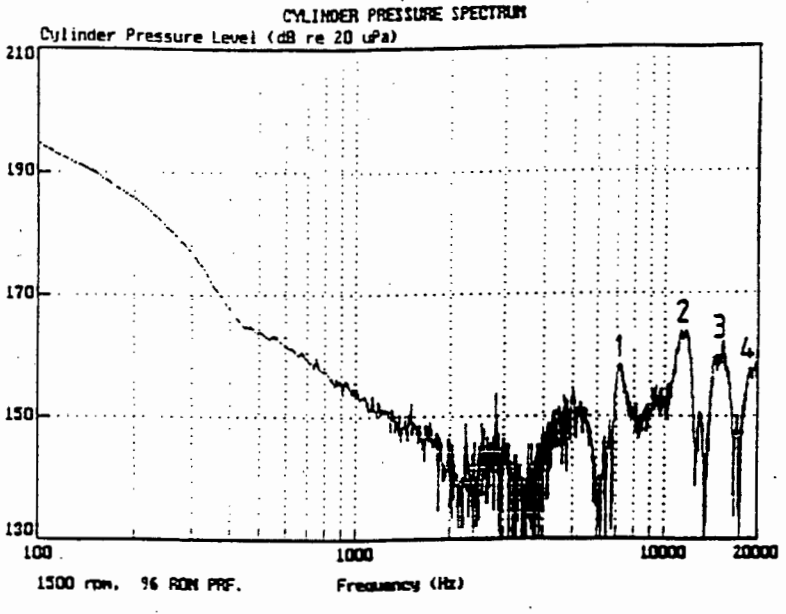


Figure 5.20: Volkswagen cylinder pressure spectrum at 1500 r/min

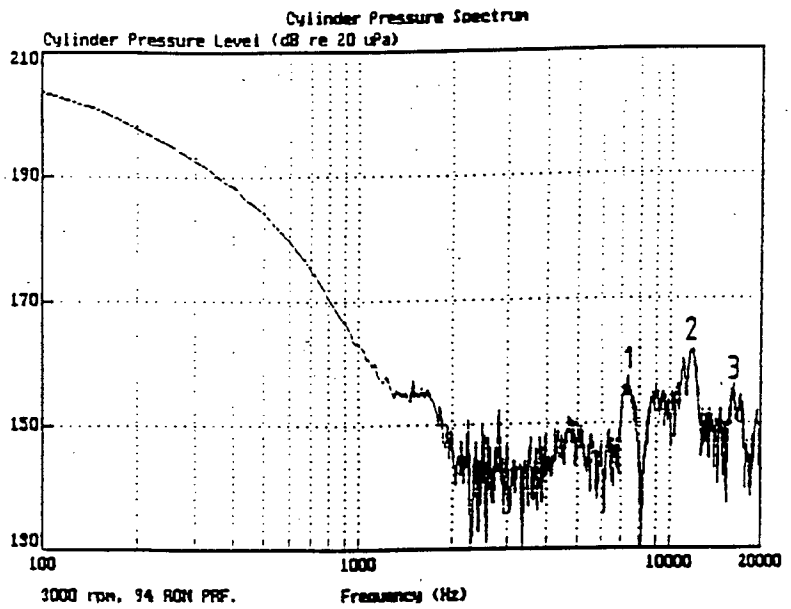


Figure 5.21: Volkswagen cylinder pressure spectrum at 3000 r/min

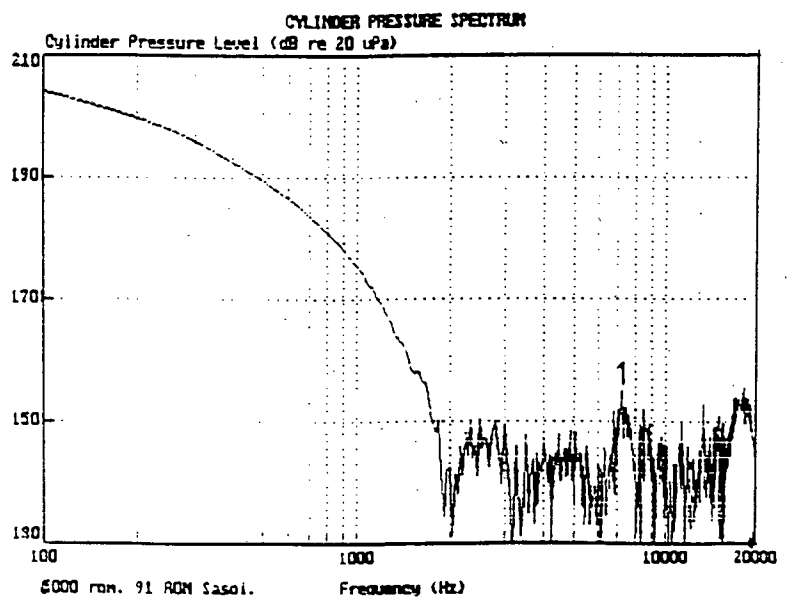


Figure 5.22: Volkswagen cylinder pressure spectrum at 5000 r/min

The cylinder pressure spectrum shown in Figure 5.20 indicates that the highest cylinder pressure levels are recorded in the low frequency range and are due to the main pressure rise from combustion and the associated harmonics. Above 400 Hz the cylinder harmonics decay at a constant rate of about 32 dB/decade.

Figure 5.20 shows four distinct peaks identified as 1,2,3 and 4 which are due to various modes of excitation of the combustion chamber cavity during the very rapid pressure rise occuring due to knock.

Table 5.2 gives the measured frequencies, the ratio between the measured and fundamental frequencies, the type modes and the theoretical ratios with the fundamental of these modes as defined in the theory for a cylindrical disc shaped cavity.

Frequency peak	Frequency F_n (Hz)	Ratio $F_n/F_{1,0}$	Mode	Theoretical ratio $F_n/F_{1,0}$
1	7 088	1,000	1,0	1,000
2	11 285	1,592	2,0	1,659
3	15 488	2,185	3,0	2,282
4	19 668	2,775	4,0	2,888

Table 5.3: Analysis of the pressure peaks in Figure 5.20

It is evident that there is a good correlation between the experimental and theoretical ratios despite the complex combustion chamber shape. The highest level recorded is that of the 2,0 mode at a frequency of 11285 Hz. The broad peak at about 5000 Hz cannot be accounted for and may be due to the complex combustion chamber shape.

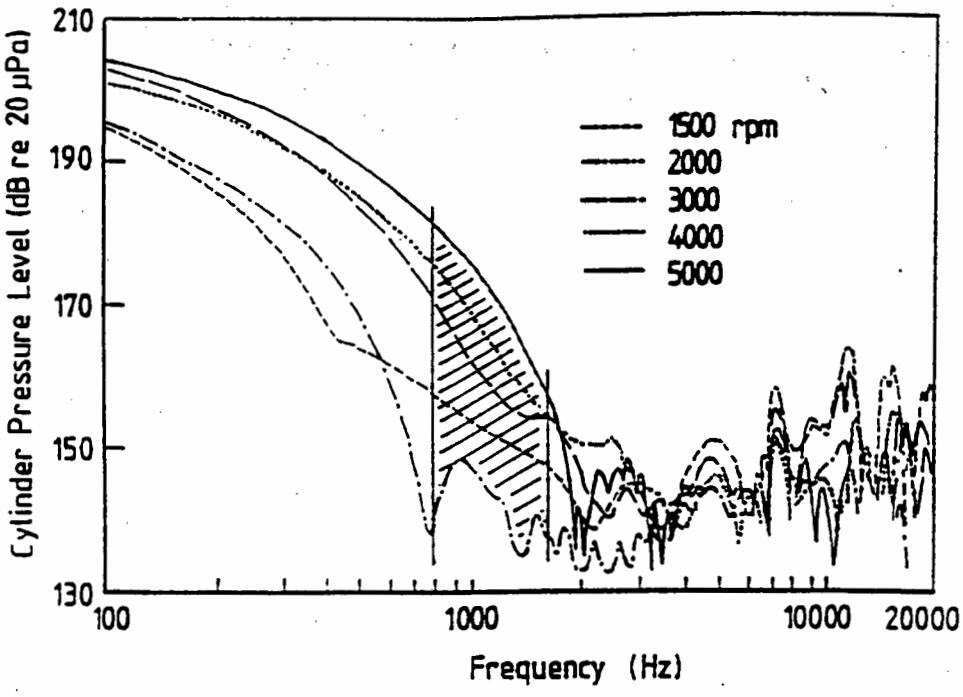


Figure 5.23: Comparison of the Volkswagen cylinder pressure spectra over the speed range

A direct comparison of the spectra over the speed range is shown in Figure 5.23. The cylinder pressure level increases dramatically with engine speed in the 800 to 1000 Hz range. As this is the lower part of the frequency range of maximum engine structural vibration, the engine vibration due to combustion will increase accordingly. By comparison, the level of the cylinder pressure oscillations due to knock is independent of speed and depends on the severity of knock only, and this accounts for the difficulty in detecting an increase in the engine structure vibration when high speed knock occurs.

5.5.3 Knock characteristics of the Nissan engine

Figures 5.24, 5.25 and 5.26 show the cylinder pressure diagrams for three successive combustion cycles at 1500 r/min.

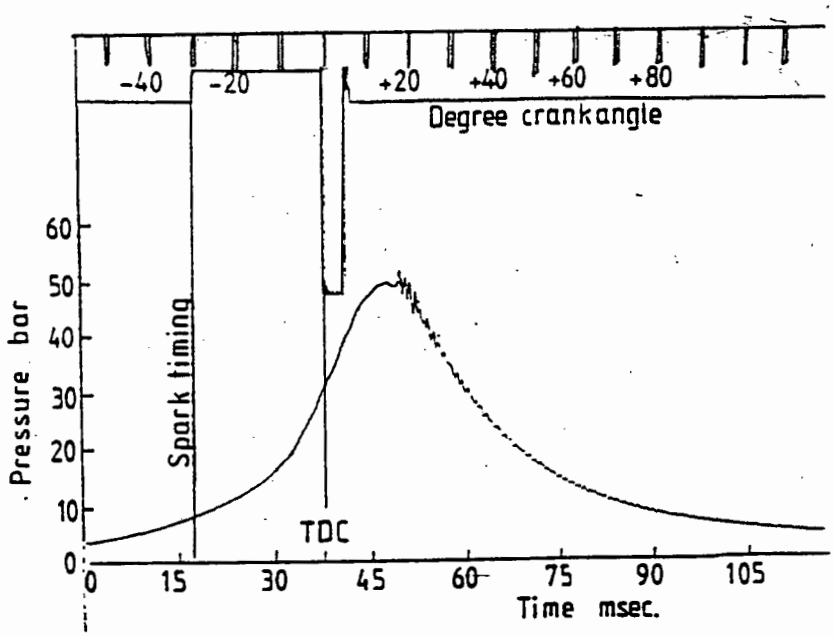


Figure 5.24: Nissan cylinder pressure diagram at 1500 r/min showing trace knock

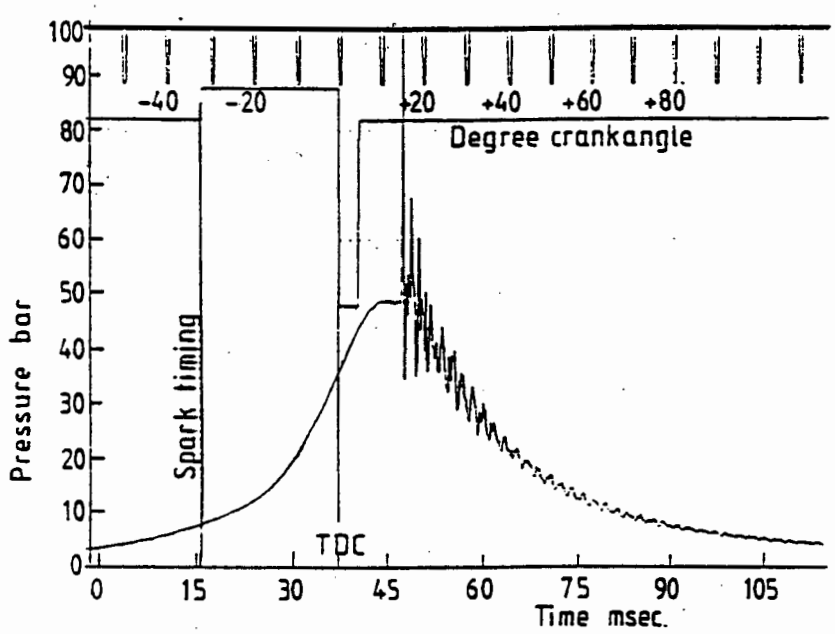


Figure 5.25: Nissan cylinder pressure diagram at 1500 r/min showing knock

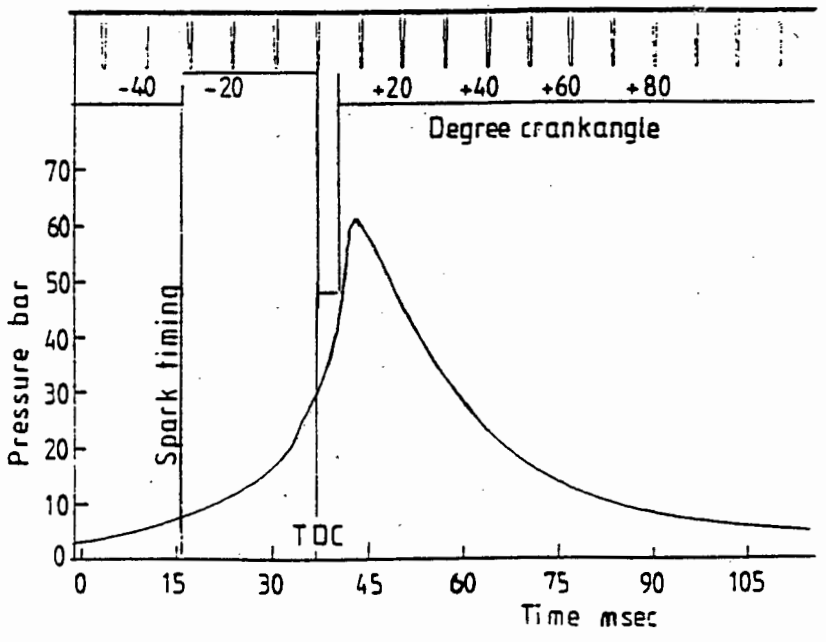


Figure 5.26: Nissan cylinder pressure diagram at 1500 r/min showing no knock

The first cycle illustrated in Figure 5.24 shows trace knock while the subsequent cycle shown in Figure 5.25 shows intense knock. The next cycle illustrated by Figure 5.26 shows knock free combustion but with a very fast pressure rise rate leading to a high peak pressure. This phenomenon may be due to the fine carbon particles produced during intense knock, and which remain behind in the cylinder in the end gas, which may be responsible for propagating the flame front during the next combustion cycle.

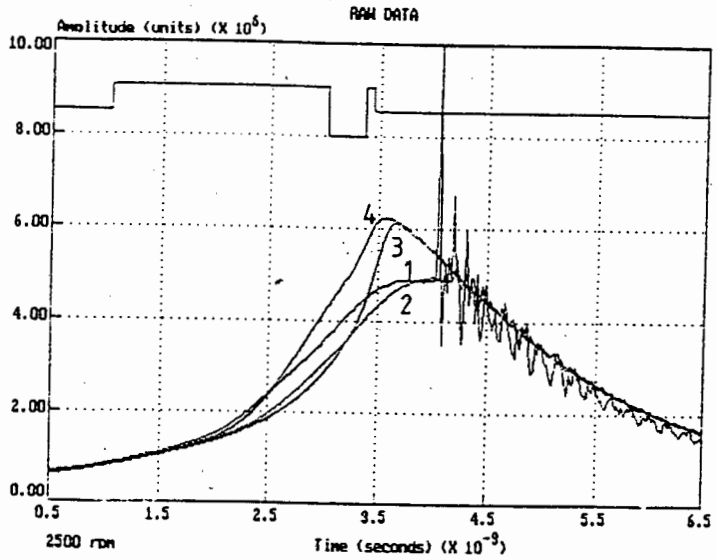


Figure 5.27: Nissan cylinder pressure diagrams at 1500 r/min of four sequential combustion cycles

Figure 5.27 shows four sequential pressure diagrams plotted by aligning the TDC points. As can be seen, the peak pressures prior to knock of cycles 1 and 2 are the same. In cycle 3 the pressure rise rate is the highest in the latter part of combustion whereas in cycle 4 the pressure rise rate is low and uniform. In both of these cases the peak pressures are higher.

Table 5.4 gives the relevant details of six sequential cycles:

Cycle	Peak pressure (bar)	Pressure rise rate (bar/msec)	Peak knock pressure (bar)
1	49	28	2
2	48	26	50
3	61	80	0
4	62	44	0
5	44	18	0
6	45	25	1

Table 5.4: Nissan knock analysis

From the above data it can be seen that the pressure rise rates of the knock free cycles 3 and 4 are of comparable magnitude to those of normally aspirated diesel engines. This phenomenon of fast combustion was also noted in the Ford engine.

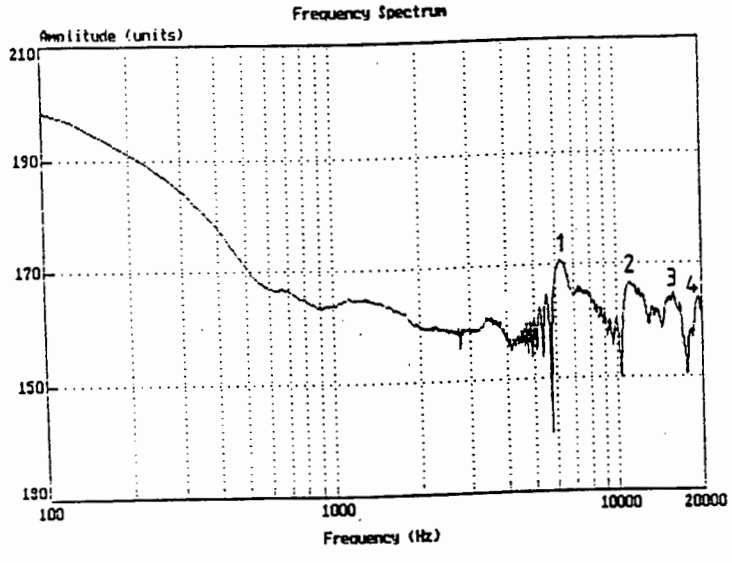


Figure 5.28: Nissan cylinder pressure spectrum for cycle 2

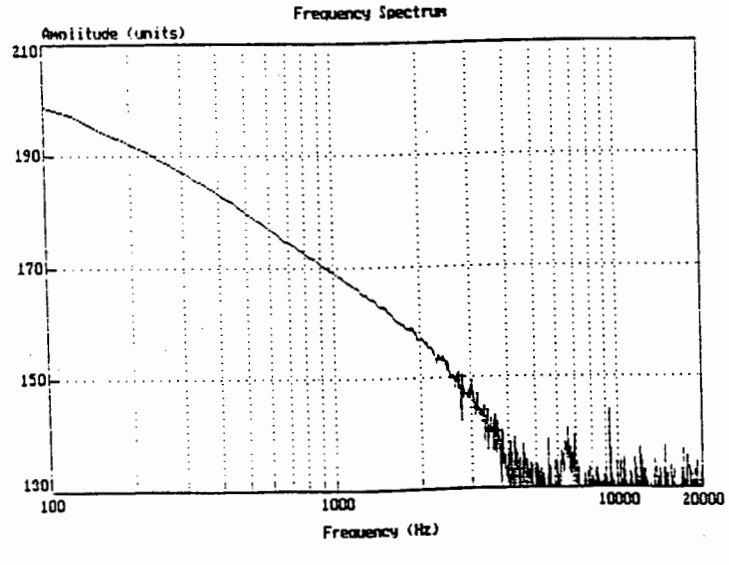


Figure 5.29: Nissan cylinder pressure spectrum for cycle 3

Figure 5.28 indicates marked peaks due to pressure oscillations due to intense knock during cycle 3. These peaks are 20 dB higher than the flat spectrum for cycle 3 shown in Figure 5.29. It is also apparent that the knock promotes high frequency oscillations in the combustion chamber.

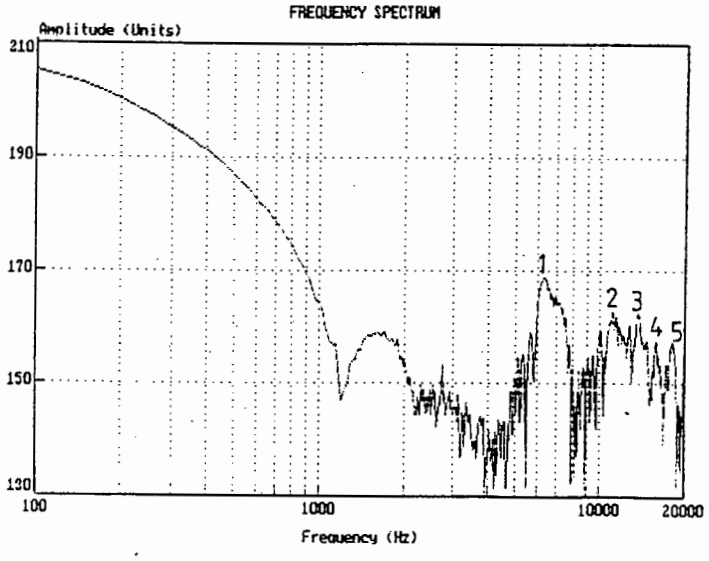


Figure 5.30: Nissan cylinder pressure diagram and spectrum at 3500 r/min

The cylinder pressure diagram and its associated spectrum at 3500 r/min are shown in Figure 5.30. The circumferential mode at 6350 Hz as well as the other major modes are identified. The mode of the peak at 15 850 Hz cannot be identified.

Frequency peak	Frequency F_n (Hz)	Ratio $F_n/F_{1,0}$	Mode	Theoretical ratio $F_n/F_{1,0}$
1	6 305	1,000	1,0	1,000
2	11 121	1,764	2,0	1,659
3	13 719	2,176	3,0	2,282
4	15 850	2,514	4,0	-
5	18 127	2,875	5,0	2,888

Table 5.5: Analysis of the pressure peaks in Figure 30

5.5.4 Knock characteristics of the Ford engine

Figures 5.30, 5.31 and 5.32 show the pressure diagrams for the Ford engine at 1500, 2500 and 4000 r/min respectively.

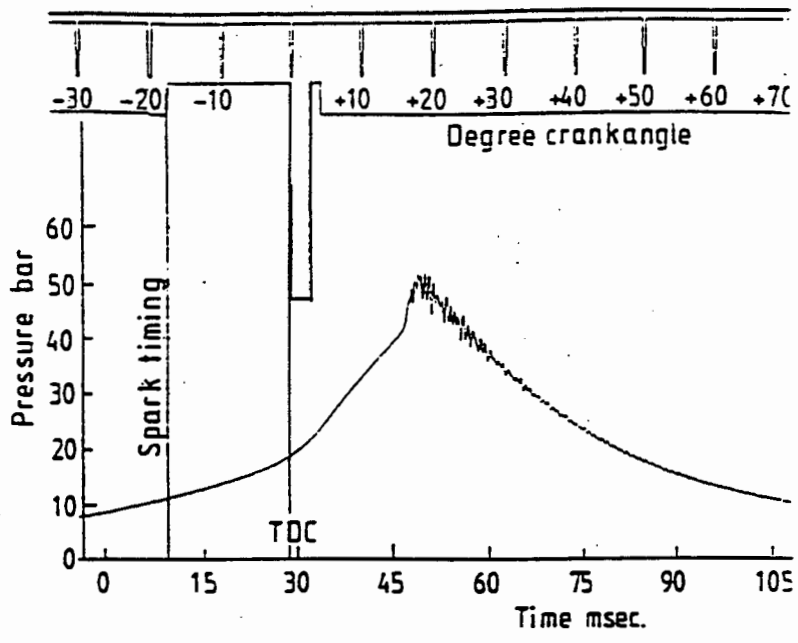


Figure 5.31: Ford cylinder pressure diagram at 1500 r/min

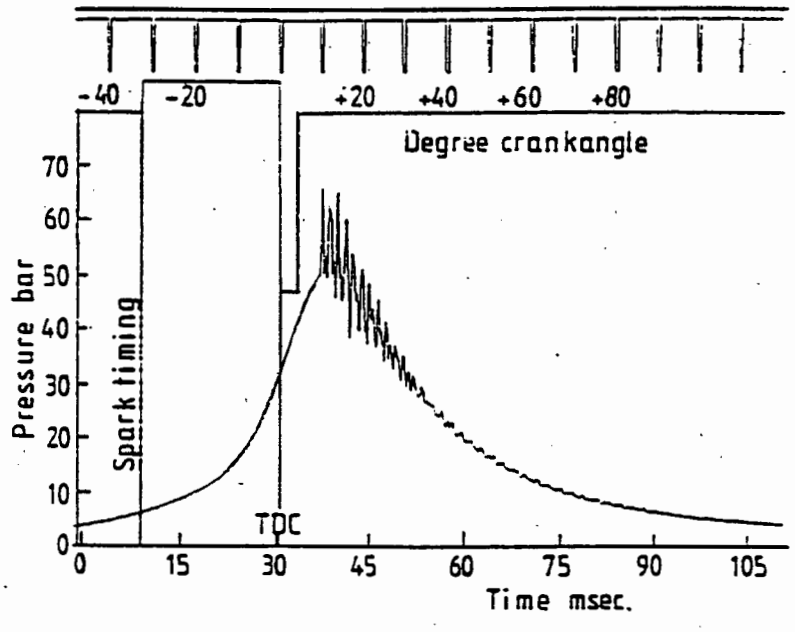


Figure 5.32: Ford cylinder pressure diagram at 2500 r/min

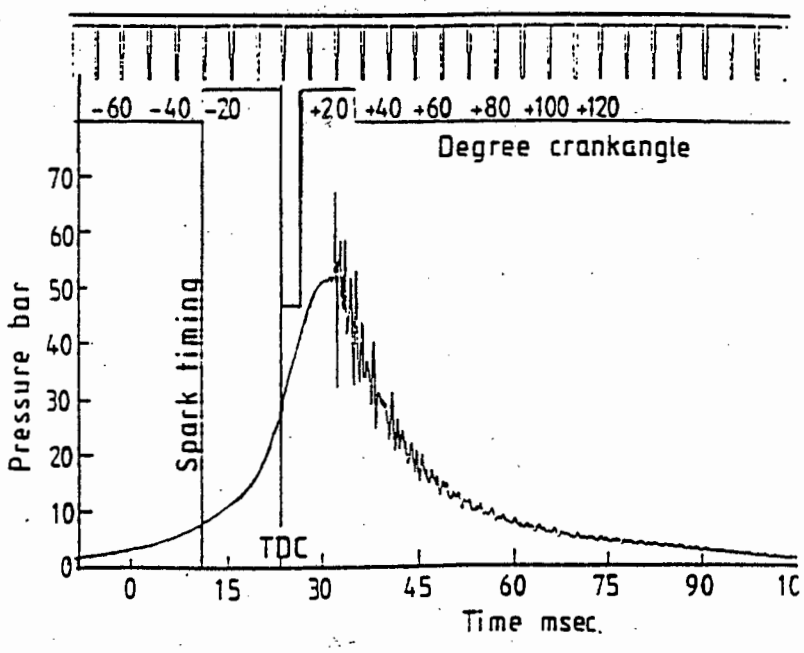


Figure 5.33: Ford cylinder pressure diagram at 4000 r/min

The above diagrams display a fundamental change in the knock characteristics with changes in engine speed. At 1500 r/min the pressure rise rate is about 60 bar/msec which is commonly achieved in diesel engines. By comparison the Volkswagen engine achieved an almost instantaneous pressure rise at the same engine speed under knocking conditions as is evident from Appendix 5.9.

As the engine speed increases, the pressure rise rate also increases in the Ford engine. At 2500 r/min the pressure rise rate is 330 bar/msec and at 4000 r/min it is 1000 bar/msec.

Similar pressure developments have been reported by Konig and Sheppard[39] by observing combustion in an optically accessible engine. It is postulated that there may be numerous points at which auto-ignition takes place thus leading to an acceleration of the flame front rather than the virtual instantaneous combustion of the end gas, thus resulting in a lower rate of pressure rise. The phenomenon may be engine speed dependent as higher temperatures and turbulence are needed to generate the multiple auto-ignition centres in the combustion chamber.

The multiple auto-ignition in the combustion chamber could be the transition to the more common instantaneous combustion of the end gas when knock occurs, especially at high engine speeds. The peak pressures prior to knock in the Ford engine are substantially lower than in the Volkswagen engine as they are of the order of 40 to 50 bar while they are between 55 and 70 bar in the Volkswagen engine which operates at much higher brake mean effective pressure.

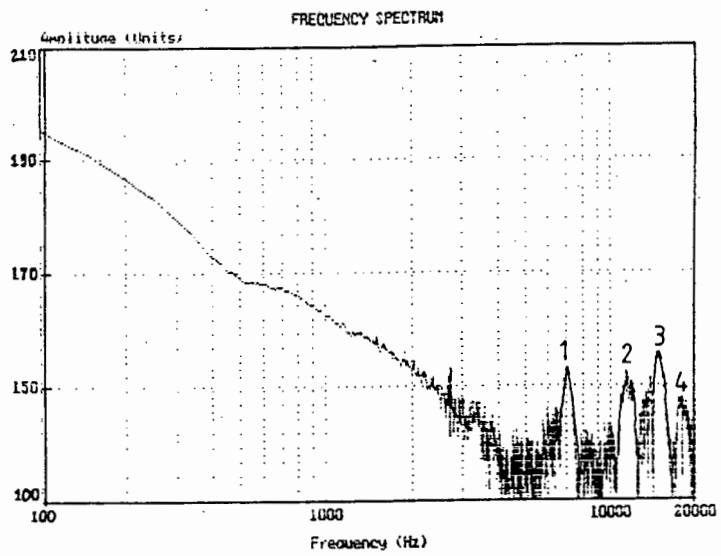


Figure 5.34: Ford cylinder pressure spectrum at 1500 r/min

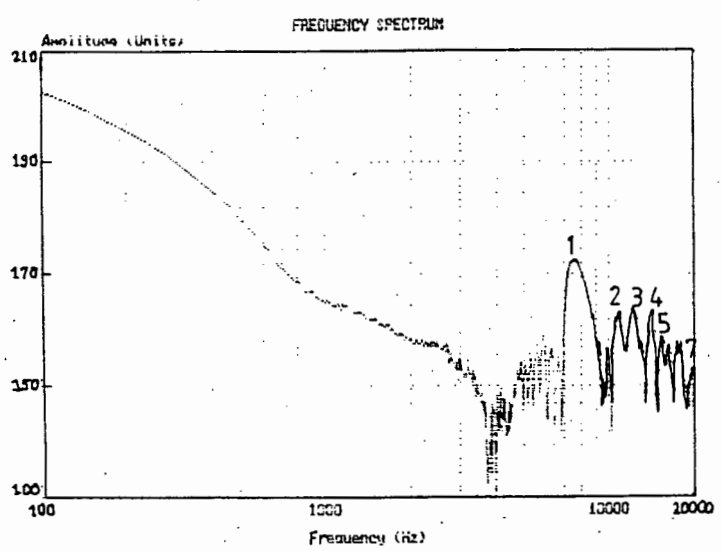


Figure 5.35: Ford cylinder pressure spectrum at 2500 r/min

The cylinder pressure spectra at 1500 and 2500 r/min are shown in Figures 5.34 and 5.35 respectively. In Figure 5.34, four peaks and three distinct circumferential modes can be distinguished and these are analyzed in Table 5.6.

Frequency peak	Frequency F_n (Hz)	Ratio $F_n/F_{1,0}$	Mode	Theoretical ratio $F_n/F_{1,0}$
1	7 080	1,000	1,0	1,000
2	11 423	1,613	2,0	1,659
3	14 762	2,085	3,0	2,081
4	17 900	2,520	?	?

Table 5.6; Ford cylinder pressure spectrum at 1500 r/min

The cylinder pressure spectrum at 2500 r/min shows a large number of peaks which are analyzed in the following table:

Frequency peak	Frequency F_n (Hz)	Ratio $F_n/F_{1,0}$	Mode	Theoretical ratio $F_n/F_{1,0}$
1	7 636	1,000	1,0	1,000
2	10 879	1,425	?	?
3	12 113	1,586	2,0	1,659
4	15 628	1,882	?	?
5	15 628	2,296	?	2,081
6	17 532	2,296	3,0	2,282
7	21 364	2,798	4,0	2,888

Table 5.7 Ford cylinder pressure spectrum at 2500 r/min

There is good correlation between the measured and calculated frequencies, based on a flat cylinder, but some frequencies cannot be accounted for. The combustion chamber is flat on the cylinder head side, but the deep depression in

the piston may be responsible for the frequencies which cannot be identified. There is a decrease in the fundamental frequency of the pressure oscillations from 1500 to 2500 r/min by about 20 dB. The frequency of the fundamental at 2500 r/min is also higher than that at 1500 r/min and this may be due to the higher temperature in the combustion chamber.

5.6. PERIOD OF COMBUSTION

The onset of knock defines the end of combustion as any remaining fuel burns instantaneously at the first sign of knock. The time interval between the ignition spark and knock is thus the period of combustion. There is a difference between the period of combustion for different engines and this is particularly valid for fast burn engine designs.

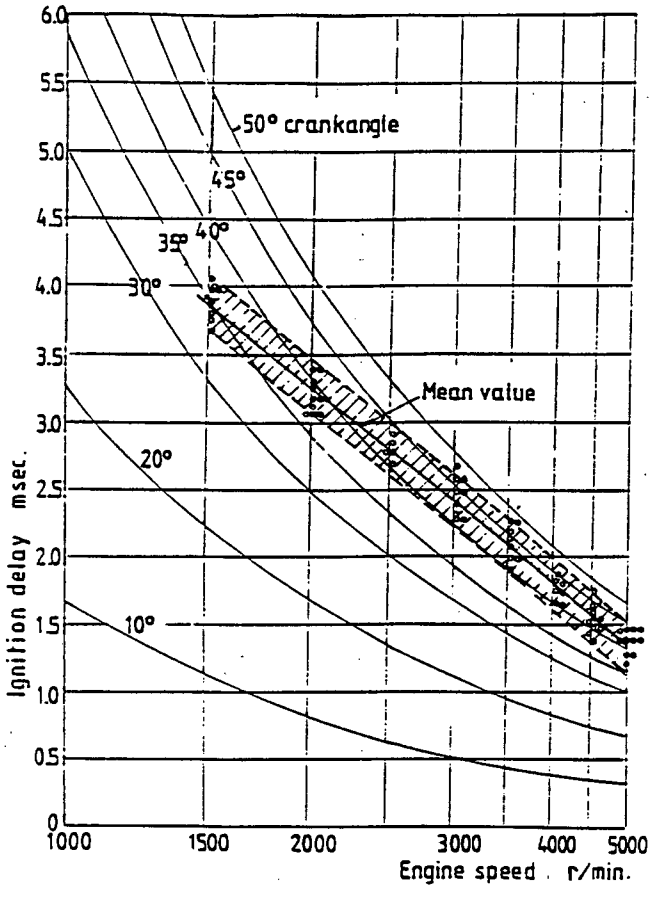


Figure 5.36: Volkswagen measured period of combustion

An example of the period of combustion for the Volkswagen engine at MBT spark timing is shown in Figure 5.36. A linear relationship between period of combustion and the logarithm of engine speed is achieved despite some scatter.

The period of combustion can thus be expressed by the following equation:

$$\text{Period of combustion} = T = m \log_{10} N + C$$

where m = the slope of the line
N = the engine speed
C = constant

m and C thus represent the engine characteristics.

For Figure 5.36, the equation becomes:

$$\text{Period of combustion} = -4{,}82 \log_{10} N + 19{,}17$$

Since there is a linear relationship of the period of the combustion on the log-speed basis, the reduction of the period can be expressed as 1,45 msec per doubling of the engine speed.

The period of combustion can also be expressed in terms of degree crankangle as shown in Figure 5.36. It is evident that the period of combustion is 35° at 1500 r/min but that this increases to 42° at 3000 r/min.

5.7 Peak cylinder pressures

The peak cylinder pressures define the cycle to cycle variations in combustion experienced in engines.

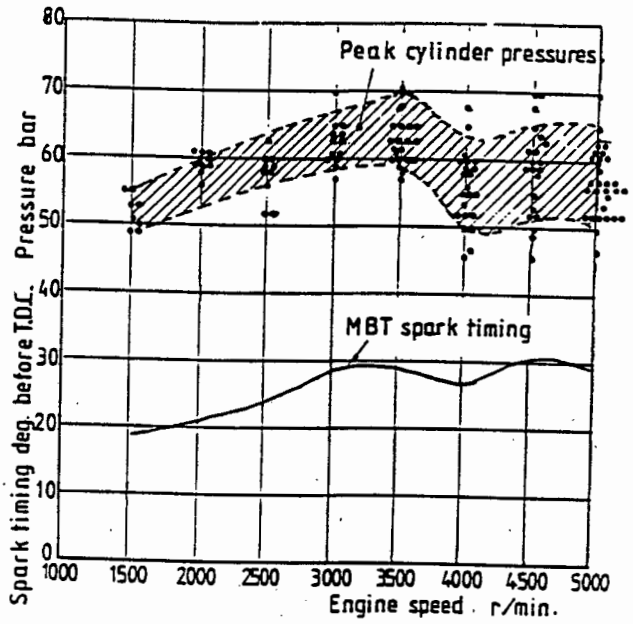


Figure 5.37: Volkswagen peak cylinder pressures

The peak cylinder pressures recorded for the Volkswagen engine at different engine speeds as well as the MBT spark timing is shown in Figure 5.37. It is evident that the variation is about 5 bar at 1500 r/min but that it increases up to 20 bar at 4000 r/min. The band of measured peak cylinder pressures is similar to the MBT spark timing curve, thus the ignition timing of an engine is a major parameter controlling peak cylinder pressures.

The peak cylinder pressure of 70 bar occurs at 3500 r/min which is the same speed at which the engine produces the peak torque according to Figure 5.3.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 PRIMARY REFERENCE FUELS

The primary reference fuels iso-octane and n-heptane, have distillation temperatures of 99,2 and 88,4°C respectively. The octane number of these fuels is thus 100 for the distillate up to 100°C, known better as the RON 100°C. While cold start and operation of the engines after cold start did not form a part of this work, it is evident that the RON 100°C of the primary reference fuels was very high compared to commercial gasolines.

6.2 CYLINDER PRESSURE DIAGRAMS

The cylinder pressure diagrams used throughout this thesis were selected as being typical for the data point being analyzed. The large cycle-to-cycle variations in the cylinder pressure diagrams, especially under knocking conditions, were thus averaged by the selection of a typical diagram.

6.3 OCCURRENCE OF KNOCK

All the data suggests that knock only occurs when the pressure rise rate is already past its peak value. This is valid for knock initiation before or after the combustion pressure has reached its peak. It may thus be postulated that the pressure rise rate does not affect the start of knock directly and also that a high pressure rise rate does not necessarily lead to knock. Knock is initiated by a number of other factors which include the peak combustion pressure, combustion temperature and combustion time[8],[11].

6.4 MAXIMUM BRAKE TORQUE AND SPARK TIMING

A comparison of the actual engine spark timing and that needed to give the maximum brake torque shows that the Ford engine is not optimized to yield the maximum efficiency and engine torque as the ignition timing is over advanced in the high speed part of the operating range. The Nissan ignition has a large retard from the timing for maximum brake torque, but this is probably required in order to provide knock protection with commercial fuels which do not have the same octane quality as Aviation Gasoline 100/130.

The spark timing for the Volkswagen and Toyota engines are near optimum when the limitations of distribution advance curves through the engine speed range are considered.

6.5 BRAKE SPECIFIC FUEL CONSUMPTION

The brake specific fuel consumption was found to be virtually independent of engine speed with the exception of the Nissan engine which was not operating satisfactorily. The b s f c normally reaches 400 g/KW.h at engine speeds below 2000 r/min and above 5000 r/min, but these areas were not covered by this thesis and should be considered if the full engine speed range b s f c is required.

6.6 OCTANE REQUIREMENTS - PRIMARY REFERENCE FUEL

The tests using the primary reference fuels show a linear decline in the octane requirement of the engines with increasing engine speed. The octane requirement may thus be expressed by the equation:

$$OR = KN + C$$

where K = slope of the line
N = engine speed in r/min
C = constant

The following relationships were established for the engines:

Toyota engine	OR = -0,0032N + 102
Volkswagen engine	OR = -0,0020N + 102
Nissan Engine	OR = -0,0041N + 103.5
Ford engine	OR = -0,0029N + 101.2

6.7 OCTANE REQUIREMENT - SASOL FUEL

When operated on the Sasol fuels, no linear relationship for octane requirement could be established through the engine speed range. However, it is evident that the octane requirement of the engines at low speeds is much the same as for the primary reference fuels. However, at mid-range and high engine speeds, there is an increasing disparity between the engines research octane number requirement and that indicated by the primary reference fuels. However, the motor octane number becomes more relevant in engines operating at high speed.

It is thus important to define the Research and Motor octane numbers of the fuel in order to achieve satisfactory knock protection throughout the engine speed range.

6.8 COMBUSTION PERIOD

The combustion period of the Volkswagen engine decreases with the log of the engine speed according to the following relationship:

Combustion period = $m \log_{10} N + C$

where m = slope of the line
N = engine speed in r/min
C = constant

The following actual relationship was determined for the Volkswagen engine:

Period of combustion = $-4{,}82 \log_{10} N + 19{,}17$

The relationship for the other engines has not been established as a part of this work.

6.9 CYLINDER PRESSURE SPECTRUM

The fundamental frequency of the knock induced cylinder pressure oscillations is between 5000 and 7500 Hz which corresponds with the 1,0 circumferential mode.

The higher order modes could be established for all the engines but there were anomalous results in some cases. The first radial mode and up to the fourth circumferential modes could be established for the engines. It was found that high intensity knock had a sound pressure level of 175 dB whereas trace knock had a level of 160 dB.

6.10 PEAK CYLINDER PRESSURE

The peak cylinder pressure of the Volkswagen engine shows large cycle-to-cycle variations through the speed range. Variation in peak cylinder pressure changes through the engine speed range from about 5 bar at 1500 r/min to 20 bar at 5000 r/min. The variation is particularly large when the engine is operated under knocking conditions.

CHAPTER SEVEN

REFERENCES

1. Palmer, F.H.
   The vehicle performance of gasolines containing oxygenated supplements. EFOA Conference, Rome, Italy, October 1987

2. Sutton, D.L., Williams, D.
   Knock protection - future fuels and engines. SAE 841289

3. Croudace, M.C., Jessup, P.J.
   Studies of octane properties of mixtures of isomeric hexane. SAE 881604

4. Swain, M.R., Swain, M.N., Blanco, J.A., Adt., R.R.
   The effect of alternative gasolines on knock and intake valve sticking. SAE 872040

5. Freeman, J.H., Williams, J.E.
   Alcohols and ethers. API publication 4261, 2nd Edition. July 1988

6. Haas, A., Mcelhiney, G., Ginzel, W., Buchsbaum, A.
   Gasoline quality. Science and Technology, Erdoel und kohle, bd 43, Januar 1990

7. Chun, K.M., Heywood, J.B.
   Characterization of knock in a spark ignition engine. SAE 890156

8. Cowell, L.H., Lefevbre, A.H.
   Influence of pressure on auto-ignition characteristics of gaseous hydrocarbon-air mixtures. SAE 860068

9. Dorn, P., Mourao, A.M., Herbstman, S.
   The properties and performance of modern automotive fuels. SAE 861178

10. Bosch automotive handbook, 2nd edition, Robert Bosch, Stuttgart

11. Daneshyar, H., Fuller, D.E.
Definition and measurement of turbulence parameters in reciprocating I.C. engines. SAE 861529

12. Hall, M.J., Bracco, F.V.
Cycle resolved velocity and turbulence measurements near the cylinder wall of a firing S.I. engine. SAE 861530

13. Witze, P.O., Mendes-Lopes, J.M.C.
Direct measurement of the turbulent burning velocity in a homogeneous charge engine. SAE 861531

14. Spicher, U., Kollmeier, H.-P.
Detection of flame propagation during knocking combustion by optical fiber diagnostics. SAE 861532

15. Sefer, N.R., Erwin, J.
Synthetic gasolines and diesel fuels from processing of shale oils and coal liquids. SAE 861542

16. Rajan, S., Kappos, C.
Combustion, emissions and fuel distribution characteristics of synthetic gasoline in multicylinder engines. SAE 861545

17. Schaberg, P.W., Priede, T., Dutkiewicz, R.K.
Effects of a rapid pressure rise on engine vibration and noise. SAE 900013

18. Priede, T., Dutkiewicz, R.K.
The effect of normal combustion and knock on gasoline engine noise. SAE 891126

19. Ziegler, G.F.W., Zettlitz, A., Meinhart, P., Herweg, R., Maly, R., Pfister, W.
Cycle resolved two-dimensional flame visualisation in a spark ignition engine. SAE 881634

20. Glover, A.R., Hundleby, G.E., Hadded, O.
An investigation into turbulence in engines using scanning lda. SAE 880379

21. Najt, P.M.
Evaluating threshold knock with a semi-empirical model - initial results. SAE 872149

22. Leppard, W.R.
The auto-ignition chemistry of n-Butane: an experimental study. SAE 872150

23. Callison, J.C.
Octane number requirements of vehicles at high altitude. SAE 872160

24. Yamauchi, T., Sasayama, T.
The effect of methanol-gasoline mixing ratio on performance of internal combustion engines. SAE 900584

25. Nutton, D., Pinnock, R.A.
Closed loop ignition and fueling control using optical combustion sensors. SAE 900486

26. Schug, K.P., Guttman, H.J., Preuss, A.W., Schadlich, K
Effects of ferrocene as a gasoline additive on exhaust emissions and fuel consumption of catalyst equipped cars. SAE 900154

27. Menrad, H., Decker, G., Wegener, R.
The potential of methanol and lpg as new fuels for transportation resources and conservation, 10(1983) Volkswagenwerk AG, Germany

28. Menrad, H., Geffers, W., Wegener, R., Weidmann, K.
Motorische auswiarkungen von sauerstoffhaltigen komponenten in ottokraftstoffen. Technischen Arbeitstagung Hohenheim, Mineraloel Technik, April 1988, Volkswagenwerk AG, Germany

29. Addicott, J.L., Marshall, E.L., Perrett, J.B., Grevett, S.P., Tharby, R.D.
Spark knock. The Institution of Mechanical Engineers, Volume 182, Part 2A, Proceedings 1967-68

30. Leppard, W.R.
A comparison of Olefin and Paraffin auto-ignition chamistries: A motored engine study. SAE 892081

31. Tadajuni Hayashi, Masahiro Taki, Shiji Kojima, Teruki Kondo.
Photographic observation of knock with a rapid compression and expansion machine. SAE 841336

32. Downs, D., Walsh, A.D., Wheeler, R.W.
A study of the reactions which lead to knock in spark ignition engines. Procedures of the Royal Society of Engineers, Vol. 243, AS70, 1951

33. Anzilotti, W.F., Rogers, J.D., Scott, G.W., Tomsic, V.T.
Combustion of hydrogen as related to knock. Industrial Chemical Engineering, 43:1314, 1954

34. Piepenberg, R.J., Pahnke, A.J.
Spectrometric investigations of n-Heptane preflame reactions in a motored engine. Industrial Chemical Engineering, 49:2067, 1957

35. Anzilotti, W.F., Tomsic, V.J.
Combustion of hydrogen and co as related to knock. Fifth Symposium on Combustion, pp356-366, Reinhold Publishing Corp, New York 1955

36. Editorial
Fuel reformulations, alternatives cover a broad spectrum. Oil and Gas Journal, 18 June 1990

37. American Society for Testing and Materials
Annual Book of ASTM Standards, Vol 05.01

38. Institute of Petroleum
28th Edition of ip standards Part 1 1969

39. Konig, G., Sheppard, G.C.W.
End gas auto ignition and knock in spark ignition engines. SAE 902135

40. Lowell, W.G.
Engine knock and molecular structure of hydrocarbons. SAE 2:532 1948

41. Priede, T.
Reciprocating internal combustion engines. Energy Research Institute, Report No. 103, 1986

42. Lewis, B., von Elbe, G.
Combustion flames and explosions: the thermal reaction. Academic Press Inc., New York, 1951

43. Lichty, L.C.
Combustion engine process. McGraw-Hill Book Co., New York.

APPENDICES

APPENDIX 1.1

Designation: D 2699 – 88a$^{\epsilon 1}$

An American National Standard

Designation: 237/69

Standard Test Method for Knock Characteristics of Motor Fuels by the Research Method[1]

This standard is issued under the fixed designation D 2699; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

$^{\epsilon 1}$ NOTE—Editorial changes were made in paragraph 9.1.19 October 1988.

CAUTION—A recalibration of toluene fuel blends has been completed. A revision to change the octane values and broaden the rating tolerances contained in Table 5 is in progress.

1. Scope

1.1 This test method covers the determination of the knock characteristics of motor gasolines, intended for use in spark-ignition engines, in terms of ASTM – IP research octane numbers.

1.2 In this test method, inch-pound units are the preferred system of measurement.

1.3 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Specific precautionary statements are given in Annex 8.

2. Referenced Documents

2.1 *ASTM Standards:*

D 439 Specification for Automotive Gasoline[2]

D 4057 Practice for Manual Sampling of Petroleum and Petroleum Products[3]

3. Descriptions of Terms Specific to This Standard

3.1 *check fuels*—calibrated auxiliary fuels which may be used to obtain additional information on engine operating conditions. (They are not substitutes for toluene standardization fuels.)

3.2 *cylinder height*—the relative position of the engine cylinder with respect to the piston which is indicated by a micrometer, dial indicator or digital counter.

3.3 *detonation meter*—the electronic amplifier/signal conditioning equipment that accepts the electrical signal from the detonation pickup and provides an electrical signal for display on a knockmeter or strip chart recorder.

3.4 *detonation pickup*—a magnetrostrictive-type transducer that mounts in the engine cylinder and is exposed to combustion chamber pressure to provide a voltage signal to the detonation meter proportional to the rate-of-change of cylinder pressure.

3.5. *digital counter reading*—a numerical indication of cylinder height, indexed to a basic setting at a prescribed compression pressure when the engine is motored.

3.6 *guide tables*—the specific relationship between cylinder height (compression ratio) and octane number at standard knock intensity for specific primary reference fuel blends tested at standard barometric pressure.

3.7 *knock intensity*—a measure of the level of combustion-related knock produced when fuel is evaluated in the knock testing unit.

3.8 *knockmeter*—the 0 to 100-division indicating meter that displays the knock intensity provided by the detonation meter.

3.9 *maximum knock intensity fuel/air ratio*—that proportion of fuel to air which produces the highest knock intensity for each fuel in the knock test unit, provided this occurs within specified carburetor sight glass fuel level limits.

3.10 *micrometer reading*—a numerical indication of cylinder height, indexed to a basic setting at a prescribed compression pressure when the engine is motored.

3.11 *octane number*—the measure of the resistance of a fuel to knock, which is assigned to a test fuel based upon operation in the knock testing unit at the same standard knock intensity as that of a specific primary reference fuel blend.

3.12 *primary reference fuels*—ASTM *iso*octane, ASTM *n*-heptane, volumetrically proportioned mixtures of ASTM *iso*octane and ASTM *n*-heptane, or blends of ASTM dilute tetraethyllead in ASTM *iso*octane which define the octane number scale.

3.12.1 *primary reference fuel blends above 100 octane*—the millilitres per U.S. gallon of ASTM dilute tetraethyllead in ASTM *iso*octane that characterizes octane numbers above 100 in accordance with an empirically determined relationship.

---

[1] This test method is under the jurisdiction of ASTM Committee D-2 on Petroleum Products and Lubricants.

Current edition approved March 25 and April 29, 1988. Published February 1989. Originally published as D 2699 – 68. Last previous edition D 2699 – 86.

[2] *Annual Book of ASTM Standards*, Vol 05.01.

[3] *Annual Book of ASTM Standards*, Vol 05.03.

TABLE 1 Conversion of Millilitres of Tetraethyllead per U.S. Gallon in *Iso*octane to Octane Numbers Above 100

NOTE—Deleted 1986. See Table 29.

3.12.2 *primary reference fuel blends below 100 octane*—the volume percent of ASTM *iso*octane in a blend with ASTM *n*-heptane that identifies the octane number of the blend, ASTM *iso*octane being assigned as 100 and ASTM *n*-heptane as zero octane number.

3.13 *spread*—the sensitivity of the detonation meter expressed in knockmeter divisions per octane number.

3.14 *standard knock intensity*—that level of knock produced when a primary reference fuel blend of specific octane number is used in the knock testing unit at maximum knock intensity fuel/air ratio, with the cylinder height (compression ratio) set to the prescribed guide table value, and the detonation meter adjusted to produce a knockmeter reading of 50.

3.15 *toluene standardization fuels*—those volumetrically proportioned blends of two or more of the following: reference fuel grade toluene, ASTM *n*-heptane, dilute tetraethyllead, and ASTM *iso*octane that have empirically determined octane numbers and prescribed rating tolerances. These blends are sensitive to engine operating conditions and

TABLE 2 Guide Table for Standard Knock Intensity at 29.92 in. Hg (101.3 kPa) Barometric Pressure—Micrometer Readings for Research Octane Numbers Apply for All Altitudes

See Table 4 for Corrections for Other Barometric Pressures

Research Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Research Octane Number
	Micrometer Setting, in.										
40	0.759	0.759	0.759	0.759	0.758	0.758	0.758	0.758	0.757	0.757	40
41	0.757	0.756	0.756	0.756	0.756	0.755	0.755	0.755	0.755	0.754	41
42	0.754	0.754	0.753	0.753	0.753	0.753	0.752	0.752	0.752	0.751	42
43	0.751	0.751	0.750	0.750	0.750	0.749	0.749	0.749	0.748	0.748	43
44	0.748	0.747	0.747	0.747	0.747	0.748	0.746	0.746	0.745	0.745	44
45	0.745	0.744	0.744	0.744	0.743	0.743	0.743	0.742	0.742	0.742	45
46	0.741	0.741	0.741	0.740	0.740	0.740	0.739	0.739	0.739	0.738	46
47	0.738	0.738	0.737	0.737	0.737	0.738	0.738	0.736	0.735	0.735	47
48	0.735	0.734	0.734	0.733	0.733	0.733	0.732	0.732	0.732	0.731	48
49	0.731	0.731	0.730	0.730	0.729	0.729	0.729	0.728	0.728	0.728	49
50	0.727	0.727	0.727	0.726	0.728	0.725	0.725	0.725	0.724	0.724	50
51	0.724	0.723	0.723	0.723	0.722	0.722	0.721	0.721	0.721	0.720	51
52	0.720	0.720	0.719	0.719	0.718	0.718	0.718	0.717	0.717	0.717	52
53	0.716	0.718	0.715	0.715	0.715	0.714	0.714	0.713	0.713	0.713	53
54	0.712	0.712	0.711	0.711	0.711	0.710	0.710	0.710	0.709	0.709	54
55	0.708	0.708	0.707	0.707	0.707	0.706	0.706	0.705	0.705	0.705	55
56	0.704	0.704	0.703	0.703	0.703	0.702	0.702	0.702	0.701	0.701	56
57	0.700	0.700	0.699	0.699	0.699	0.698	0.698	0.697	0.697	0.697	57
58	0.696	0.696	0.695	0.695	0.695	0.694	0.694	0.693	0.693	0.692	58
59	0.692	0.692	0.691	0.691	0.690	0.690	0.689	0.689	0.689	0.688	59
60	0.688	0.687	0.687	0.687	0.686	0.686	0.685	0.685	0.684	0.684	60
61	0.683	0.683	0.682	0.682	0.681	0.681	0.681	0.680	0.680	0.679	61
62	0.679	0.678	0.678	0.677	0.677	0.677	0.676	0.676	0.675	0.675	62
63	0.674	0.674	0.673	0.673	0.673	0.672	0.672	0.671	0.671	0.671	63
64	0.670	0.670	0.669	0.669	0.668	0.668	0.667	0.667	0.666	0.666	64
65	0.666	0.665	0.665	0.664	0.664	0.663	0.663	0.662	0.662	0.661	65
66	0.661	0.660	0.660	0.659	0.659	0.658	0.658	0.657	0.657	0.656	66
67	0.658	0.655	0.655	0.654	0.654	0.653	0.653	0.652	0.652	0.651	67
68	0.651	0.650	0.650	0.649	0.649	0.648	0.648	0.647	0.647	0.647	68
69	0.648	0.645	0.645	0.645	0.644	0.643	0.643	0.643	0.642	0.642	69
70	0.641	0.641	0.640	0.640	0.639	0.639	0.638	0.638	0.637	0.637	70
71	0.638	0.638	0.635	0.635	0.634	0.634	0.633	0.633	0.632	0.632	71
72	0.631	0.631	0.630	0.630	0.629	0.629	0.628	0.627	0.627	0.626	72
73	0.628	0.625	0.625	0.624	0.623	0.623	0.622	0.622	0.621	0.621	73
74	0.620	0.619	0.619	0.618	0.618	0.617	0.616	0.616	0.615	0.615	74
75	0.614	0.613	0.613	0.612	0.611	0.611	0.610	0.610	0.609	0.609	75
76	0.608	0.607	0.606	0.606	0.605	0.605	0.604	0.603	0.602	0.602	76
77	0.601	0.600	0.600	0.599	0.598	0.598	0.597	0.596	0.596	0.595	77
78	0.594	0.594	0.593	0.592	0.592	0.591	0.590	0.590	0.589	0.588	78
79	0.587	0.587	0.586	0.585	0.584	0.584	0.583	0.582	0.581	0.581	79
80	0.580	0.579	0.578	0.578	0.577	0.576	0.576	0.575	0.574	0.574	80
81	0.573	0.572	0.571	0.571	0.570	0.570	0.569	0.568	0.567	0.567	81
82	0.566	0.565	0.564	0.564	0.563	0.562	0.562	0.561	0.560	0.559	82
83	0.558	0.558	0.557	0.556	0.555	0.555	0.554	0.553	0.552	0.552	83
84	0.551	0.550	0.549	0.549	0.548	0.547	0.546	0.546	0.545	0.544	84

TABLE 2 *Continued*

Research Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Research Octane Number
	Micrometer Setting, In.										
85	0.543	0.542	0.541	0.540	0.539	0.539	0.538	0.537	0.536	0.535	85
86	0.534	0.534	0.533	0.532	0.531	0.530	0.529	0.528	0.527	0.527	86
87	0.526	0.525	0.524	0.523	0.522	0.521	0.520	0.519	0.518	0.517	87
88	0.517	0.516	0.515	0.514	0.513	0.512	0.511	0.510	0.509	0.508	88
89	0.507	0.508	0.505	0.504	0.503	0.502	0.501	0.500	0.499	0.498	89
90	0.497	0.498	0.495	0.494	0.493	0.492	0.491	0.490	0.489	0.488	90
91	0.487	0.488	0.485	0.484	0.483	0.482	0.481	0.480	0.479	0.478	91
92	0.478	0.475	0.474	0.473	0.472	0.471	0.470	0.469	0.468	0.467	92
93	0.466	0.464	0.463	0.462	0.460	0.459	0.458	0.457	0.456	0.455	93
94	0.454	0.452	0.451	0.450	0.448	0.447	0.446	0.414	0.443	0.442	94
95	0.441	0.440	0.438	0.437	0.436	0.434	0.433	0.431	0.430	0.429	95
96	0.427	0.426	0.424	0.423	0.422	0.420	0.418	0.417	0.416	0.414	96
97	0.413	0.411	0.410	0.408	0.406	0.405	0.403	0.402	0.400	0.399	97
98	0.397	0.395	0.393	0.392	0.390	0.388	0.386	0.384	0.382	0.380	98
99	0.379	0.377	0.375	0.374	0.372	0.369	0.367	0.365	0.363	0.362	99
100	0.360	0.357	0.356	0.354	0.351	0.348	0.348	0.345	0.342	0.339	100
101	0.338	0.336	0.333	0.331	0.328	0.326	0.325	0.322	0.320	0.317	101
102	0.315	0.313	0.312	0.310	0.307	0.305	0.303	0.301	0.299	0.297	102
103	0.295	0.293	0.291	0.289	0.287	0.285	0.283	0.281	0.279	0.277	103
104	0.275	0.273	0.272	0.271	0.269	0.267	0.266	0.264	0.262	0.261	104
105	0.259	0.258	0.257	0.255	0.253	0.251	0.250	0.249	0.247	0.246	105
106	0.245	0.243	0.242	0.241	0.239	0.238	0.237	0.236	0.234	0.233	106
107	0.232	0.231	0.230	0.229	0.228	0.227	0.225	0.224	0.223	0.222	107
108	0.221	0.220	0.219	0.218	0.217	0.216	0.215	0.214	0.213	0.212	108
109	0.210	0.209	0.208	0.207	0.206	0.205	0.204	0.203	0.202	0.202	109
110	0.200	0.199	0.198	0.198	0.197	0.196	0.195	0.194	0.193	0.192	110
111	0.191	0.190	0.189	0.188	0.187	0.186	0.185	0.184	0.184	0.183	111
112	0.182	0.181	0.180	0.179	0.178	0.177	0.178	0.175	0.174	0.173	112
113	0.172	0.171	0.171	0.170	0.169	0.169	0.167	0.166	0.165	0.164	113
114	0.163	0.163	0.162	0.161	0.160	0.159	0.158	0.157	0.156	0.155	114
115	0.155	0.154	0.153	0.152	0.151	0.150	0.148	0.147	0.148	0.145	115
116	0.144	0.143	0.142	0.141	0.140	0.138	0.137	0.138	0.135	0.134	116
117	0.133	0.132	0.131	0.130	0.129	0.128	0.128	0.125	0.124	0.123	117
118	0.122	0.121	0.120	0.119	0.118	0.117	0.115	0.114	0.113	0.112	118
119	0.111	0.110	0.109	0.108	0.107	0.106	0.104	0.103	0.102	0.101	119
120	0.100	0.099	0.098	0.097	...	...	...	...	...	...	120

Tolerance is ± 0.010 in. at all levels.
Equivalent digital counter reading = (1.012-micrometer reading) 1410.

dictate whether a knock testing unit is in acceptable condition as a prerequisite to fuel testing at any specific octane level.

4. Summary of Test Method

4.1 *The ASTM – IP Research Octane Number* of a fuel is determined by comparing its knocking tendency with those for blends of ASTM reference fuels of known octane number under standard operating conditions. This is done by varying the compression ratio for the sample to obtain standard knock intensity as measured by an electronic detonation meter. At this point, one of the two following procedures may be used:

4.1.1 *Bracketing Procedure*—The knockmeter reading for the sample is bracketed at constant compression ratio between knockmeter readings for two reference blends and the rating of the sample is calculated by interpolation.

4.1.2 *Compression Ratio Procedure*—The rating of the sample is read from Table 2 or 3 for the cylinder height required for standard knock intensity for the sample. By this procedure, reference fuels are used only to establish standard known intensity, which is done frequently.

NOTE 1—This test method combines the bracketing Test Method D 2699 and the former compression ratio Method D 2722.

5. Significance and Use

5.1 The research method octane number correlates with full-scale spark-ignited engine antiknock performance at low speed. In conjunction with the motor method, it provides a means of defining the antiknock quality of a motor gasoline for use in vehicles on the road. These laboratory tests for octane number (O.N.) utilize a single-cylinder engine and require critical adjustment of the fuel/air ratio and compression ratio to produce a standard knock intensity condition. The antiknock quality of a gasoline sample is determined by comparing it with that of primary reference fuel blends whose composition establishes the octane scale.

5.2 Empirical correlations are developed which permit calculation of vehicle antiknock performance based on the following general equation:

Antiknock index = (k_1 × research O.N.) + (k_2 × motor O.N.) + k_3

5.3 The values of k_1, k_2, and k_3 vary from vehicle to vehicle, depending on operating conditions as well as engine and transmission characteristics. The coefficients are based on road-octane number determinations for representative fuels used in the laboratory tests.

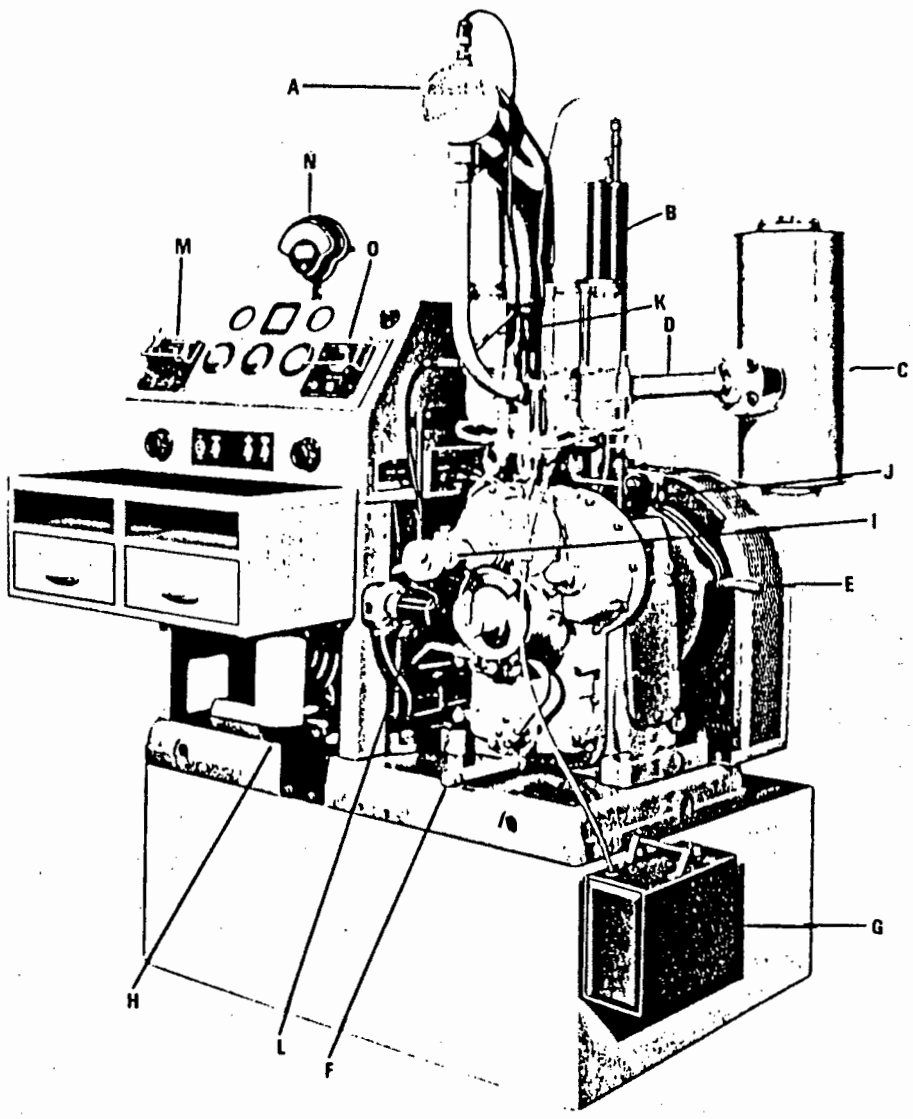
5.4 It is common to simplify the above equation to represent the average antiknock performance of the total vehicle population. The current version of the equation used in Specification D 439 is:

Antiknock index = 0.5 research O.N. + 0.5 motor O.N. + 0

Or as more commonly written:

$$\text{Antiknock index} = \frac{(R + M)}{2}$$

The antiknock quality of gasoline is also important in the operation of stationary and other nonautomotive engine applications.



A—Intake Surge Pipe
B—Coolant Condenser
C—Exhaust Surge Tank
D—Exhaust Manifold
E—Crank for Adjusting Compression Ratio
F—Oil Drain Cap
G—Waste Fuel Can, Closed for Safety
H—Oil Filter
I—Ignition Breaker
J—Cylinder Clamp
K—Intake Air Thermometer
L—Ignition coil
M—Detonation Meter, Model 501-T
N—Knockmeter
O—Temperature Controller

FIG. 3 Research Unit

5.5 This test method is used by engine manufacturers, petroleum refiners, and marketers, and in commerce as a primary specification measurement to ensure proper matching of fuel antiknock quality and engine requirement.

6. Apparatus

6.1 The knock testing unit[4] illustrated in Fig. 3 consists of a single-cylinder engine of continuously variable compression ratio, with suitable loading and accessory equipment and instruments, mounted on a stationary base. The engine and equipment specified in Annex A1 on Apparatus shall be used without modification and installed as directed in Annex A5 on Installation and Assembly. It is important to provide a proper foundation for the unit as described in A5.2.3 of Annex A5. It is necessary to keep the apparatus in good mechanical condition, as described in Annex A4 on Maintenance.

[4] Available from the Waukesha Engine Div., Fuel Research Dept., Dresser Industries, Waukesha, WI 53186.

7. Reference Materials

7.1 *ASTM Knock Test Reference Materials*, conforming to the specifications and requirements of Sections A2.6 and A2.7 of Annex A2 on Reference Materials and Blending

TABLE 3 Guide Table for Standard Knock Intensity at 29.92 in. Hg (101.3 kPa) Barometric Pressure—Digital Counter Readings for Research Octane Numbers Apply for All Altitudes

See Table 4 for Corrections for Other Barometric Pressures

Research Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Research Octane Number
	Digital Counter Setting										
40	357	357	357	357	358	359	359	359	360	360	40
41	361	361	361	362	362	363	363	363	364	364	41
42	364	365	365	366	366	368	367	367	368	368	42
43	368	369	369	370	370	370	371	371	372	372	43
44	373	373	373	374	374	375	375	375	376	376	44
45	377	377	378	378	379	379	380	380	381	382	45
46	382	383	383	384	384	385	385	386	386	387	46
47	387	388	388	389	389	389	390	390	390	390	47
48	391	391	392	392	393	393	394	395	395	396	48
49	396	397	397	398	399	399	400	400	401	402	49
50	402	403	403	404	404	405	405	406	408	406	50
51	407	408	408	409	410	410	411	411	412	412	51
52	412	413	413	414	414	415	415	416	417	417	52
53	418	418	419	419	420	420	421	422	422	423	53
54	423	424	424	425	426	426	427	427	428	428	54
55	429	429	430	430	431	432	432	433	433	434	55
56	435	435	436	436	437	437	438	439	439	440	56
57	440	441	441	442	442	443	443	444	444	445	57
58	446	446	447	446	448	449	449	450	450	451	58
59	451	452	453	453	454	454	455	455	456	457	59
60	457	458	458	459	460	460	461	461	462	462	60
61	463	464	465	465	466	467	467	468	469	470	61
62	470	471	471	472	472	473	474	474	475	475	62
63	476	477	478	478	478	479	479	480	481	481	63
64	482	483	484	484	485	485	486	486	487	488	64
65	488	489	490	491	491	492	492	493	494	495	65
66	495	496	497	498	498	499	500	501	501	502	66
67	502	503	503	504	505	506	507	508	508	509	67
68	509	510	510	511	512	513	513	514	515	515	68
69	516	517	517	518	519	519	520	520	521	522	69
70	523	524	525	525	526	526	527	527	528	529	70
71	530	631	532	532	533	533	534	534	535	536	71
72	537	538	539	539	540	540	541	542	543	544	72
73	545	548	546	547	548	548	549	550	551	552	73
74	553	554	554	555	556	557	558	559	560	560	74
75	561	562	563	564	665	566	567	567	568	569	75
76	570	571	572	573	574	575	576	577	578	579	76
77	580	581	581	582	583	584	585	586	587	588	77
78	589	590	591	592	593	594	595	596	597	598	78
79	599	600	601	602	603	604	605	606	607	608	79
80	609	610	611	612	613	614	615	616	617	618	80
81	619	620	621	622	623	624	625	626	627	628	81
82	629	630	631	632	633	634	635	636	637	639	82
83	640	641	642	643	644	645	616	647	646	649	83
84	650	651	652	653	654	656	657	658	659	660	84

TABLE 3 *Continued*

Research Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Research Octane Number
	Digital Counter Setting										
85	661	663	664	666	667	668	669	670	671	672	85
86	673	674	676	677	678	680	681	682	683	684	86
87	685	687	688	689	691	692	694	695	697	698	87
88	699	700	701	702	704	705	706	708	709	711	88
89	712	713	715	716	718	719	721	722	723	725	89
90	726	728	729	730	732	733	735	736	737	739	90
91	740	742	743	744	746	747	749	750	752	753	91
92	756	757	759	760	761	763	764	766	767	768	92
93	770	772	774	776	778	780	781	783	784	785	93
94	787	789	791	793	795	797	799	801	802	804	94
95	805	807	809	811	812	814	816	818	820	822	95
96	824	826	828	830	832	835	837	839	841	843	96
97	845	847	849	852	854	856	858	860	862	864	97
98	867	870	873	875	877	880	883	885	888	891	98
99	893	895	898	900	903	906	909	912	915	917	99
100	919	924	925	928	932	938	939	940	944	949	100
101	950	953	957	960	964	967	969	973	976	980	101
102	983	986	987	990	994	997	1000	1003	1005	1008	102
103	1011	1014	1017	1019	1022	1025	1028	1031	1034	1036	103
104	1039	1042	1043	1045	1048	1050	1052	1055	1057	1059	104
105	1062	1063	1065	1067	1070	1073	1074	1076	1079	1080	105
106	1081	1084	1088	1087	1090	1091	1093	1094	1097	1098	106
107	1100	1101	1103	1104	1105	1107	1110	1111	1112	1114	107
108	1115	1117	1118	1120	1121	1122	1124	1125	1127	1128	108
109	1131	1132	1134	1135	1138	1138	1139	1141	1142	1142	109
110	1145	1148	1148	1148	1149	1151	1152	1153	1155	1158	110
111	1158	1159	1160	1162	1163	1165	1168	1167	1167	1169	111
112	1170	1172	1173	1175	1178	1177	1179	1180	1162	1183	112
113	1184	1188	1188	1187	1189	1189	1191	1193	1194	1196	113
114	1197	1197	1199	1200	1201	1203	1204	1206	1207	1208	114
115	1208	1210	1211	1213	1214	1215	1218	1220	1221	1222	115
116	1224	1225	1227	1228	1230	1232	1234	1235	1237	1238	116
117	1239	1241	1242	1244	1245	1246	1249	1251	1252	1253	117
118	1255	1256	1258	1259	1260	1262	1265	1268	1268	1269	118
119	1270	1272	1273	1275	1276	1277	1280	1282	1283	1285	119
120	1288	1287	1289	1290	...	...	...	...	...	...	120

Tolerance is ±14 digital counter units at all levels.

$$\text{Equivalent micrometer reading} = 1.012 - \frac{\text{digital counter reading}}{1410}.$$

Accessories, shall be used and are as follows:

7.1.1 *ASTM iso*octane, (2,2,4-trimethylpentane),

7.1.2 ASTM *n*-heptane,

7.1.3 ASTM 80 octane blend of 7.1.1 and 7.1.2, and

7.1.4 ASTM *dilute* tetraethyllead.

7.2 *ASTM Reference Fuel Grade Toluene*, conforming to the specifications in A2.7.1.4 of Annex A2, is blended with ASTM *iso*octane, or ASTM *n*-heptane, or both, to obtain the standardization fuels used to check engine rating characteristics or to temperature-tune engines as prescribed in Section 13. Other fuels prepared from ASTM reference materials as directed in Section 13 of this method and Section A2.2 of Annex A2 may be used to check engine rating characteristics more extensively.

8. Sampling

8.1 Sampling shall be done in accordance with the applicable procedure described in Practice D 4057.

9. Standard Operating Conditions

9.1 The following standard operating conditions (see Annex A3 on Operation for further details) are mandatory:

9.1.1 *Engine Speed*, 600 ± 6 r/min, with a maximum variation of 6 r/min during a test.

9.1.2 *Spark Timing*, constant, 13.0° btdc.

9.1.3 *Spark Plug Gap*, 0.020 ± 0.005 in. (0.51 ± 0.13 mm).

9.1.4 *Breaker-Point Gap*, 0.020 in. (0.51 mm). For a breakerless ignition system, the basic setting for transducer to rotor (vane) gap is 0.003 to 0.005 in. (0.08 to 0.13 mm).

9.1.5 *Rocker Arm Carrier Adjustment:*

9.1.5.1 *Basic Threaded Rocker-Arm Carrier Support Setting*—Each rocker arm carrier support shall be threaded into the cylinder so that the distance between the machined surface of the cylinder and the underside of the fork is 1-7/32 in. (31 mm).

9.1.5.2 *Basic Rocker Arm Carrier Setting*—The rocker arm carrier shall be set horizontal at an uncompensated digital counter reading of 722 (micrometer reading of 0.500).

9.1.5.3 *Basic Rocker Arm Setting*—With the rocker arm carrier set in the basic setting and the valves closed, the rocker arms should be in the horizontal position.

9.1.6 *Valve Clearances*, 0.008 ± 0.001 in. (0.20 ± 0.03 mm) measured with the engine hot and running under standard operating conditions for 100 octane number.

9.1.7 *Crankcase Lubricating Oil*P, SAE 30, having a kinematic viscosity of 9.62 to 12.93 cSt (mm^2/s) at 210°F (99°C) and a viscosity index of not less than 85. OilsP containing viscosity index improvers or multi-graded oilsP shall not be used.

9.1.8 *Oil Pressure*, 25 to 30 psi (0.17 to 0.20 MPa) gage under operating conditions.

9.1.9 *Oil Temperature*, 135 ± 15°F (57 ± 8.5°C) with the temperature-sensing element completely immersed in the crankcase oilP.

TABLE 3a Guide Table for Standard Knock Intensity at 29.92 in. Hg (101.3 kPa) Barometric Pressure—Research Octane Numbers for Digital Counter Readings Apply for All Altitudes

Digital Counter Units	0	1	2	3	4	5	6	7	8	9	Digital Counter Units
					Research Octane Numbers						
450	58.8	59.0	59.1	59.3	59.5	59.6	59.8	60.0	60.1	60.3	450
460	60.4	60.6	60.8	61.0	61.1	61.2	61.4	61.6	61.7	61.8	460
470	62.0	62.2	62.4	62.5	62.6	62.8	63.0	63.1	63.3	63.6	470
480	63.7	63.8	64.0	64.1	64.2	64.4	64.6	64.8	65.0	65.1	480
490	65.2	65.4	65.6	65.7	65.8	66.0	66.1	66.2	66.4	66.5	490
500	66.6	66.8	67.0	67.2	67.3	67.4	67.5	67.6	67.8	68.0	500
510	68.2	68.3	68.4	68.6	68.7	68.8	69.0	69.2	69.3	69.4	510
520	69.8	69.8	69.9	70.0	70.1	70.2	70.4	70.6	70.8	70.9	520
530	71.0	71.1	71.2	71.4	71.6	71.8	71.9	72.0	72.1	72.2	530
540	72.4	72.8	72.7	72.8	72.9	73.0	73.2	73.3	73.4	73.6	540
550	73.7	73.8	73.9	74.0	74.2	74.3	74.4	74.5	74.6	74.7	550
560	74.8	75.0	75.1	75.2	75.3	75.4	75.5	75.6	75.8	75.9	560
570	76.0	76.1	76.2	76.3	76.4	76.5	76.6	76.7	76.8	76.9	570
580	77.0	77.2	77.3	77.4	77.5	77.8	77.7	77.8	77.9	78.0	580
590	78.1	78.2	78.3	78.4	78.5	78.8	78.7	78.8	78.9	79.0	590
600	79.1	79.2	79.3	79.4	79.5	79.6	79.7	79.8	79.9	80.0	600
610	80.1	80.2	80.3	80.4	80.5	80.6	80.7	80.8	80.9	81.0	610
620	81.1	81.2	81.3	81.4	81.5	81.8	81.7	81.8	81.9	82.0	620
630	82.1	82.2	82.3	82.4	82.5	82.8	82.7	82.8	82.8	82.9	630
640	83.0	83.1	83.2	83.3	83.4	83.5	83.8	83.7	83.8	83.9	640
650	84.0	84.1	84.2	84.3	84.4	84.4	84.5	84.6	84.7	84.8	650
660	84.9	85.0	85.0	85.1	85.2	85.2	85.3	85.4	85.5	85.6	660
670	85.7	85.8	85.9	86.0	86.1	86.2	86.2	86.3	86.4	86.4	670
680	86.5	86.6	86.7	86.8	86.9	87.0	87.0	87.1	87.2	87.3	680
690	87.4	87.4	87.5	87.6	87.6	87.7	87.8	87.8	87.9	88.0	690
700	88.1	88.2	88.3	88.4	88.4	88.5	88.6	88.6	88.7	88.8	700
710	88.8	88.9	89.0	89.1	89.2	89.2	89.3	89.4	89.4	89.5	710
720	89.6	89.6	89.7	89.8	89.8	89.9	90.0	90.0	90.1	90.2	720
730	90.3	90.4	90.4	90.5	90.6	90.8	90.7	90.6	90.8	90.9	730
740	91.0	91.0	91.1	91.2	91.3	91.4	91.4	91.5	91.6	91.6	740
750	91.7	91.8	91.8	91.9	91.9	92.0	92.0	92.1	92.2	92.2	750
760	92.3	92.4	92.4	92.5	92.6	92.6	92.7	92.8	92.9	93.0	760
770	93.0	93.0	93.1	93.2	93.2	93.2	93.3	93.4	93.4	93.4	770
780	93.5	93.6	93.6	93.7	93.8	93.9	94.0	94.0	94.0	94.1	780
790	94.2	94.2	94.2	94.3	94.4	94.4	94.4	94.5	94.6	94.6	790
800	94.8	94.7	94.8	94.8	94.9	95.0	95.0	95.1	95.2	95.2	800
810	95.2	95.3	95.4	95.4	95.5	95.6	95.6	95.6	95.7	95.8	810
820	95.8	95.6	95.9	96.0	96.0	96.0	96.1	96.2	96.2	96.2	820
830	96.3	96.4	96.4	96.4	96.5	96.5	96.6	96.6	96.6	96.7	830
840	96.8	96.8	96.9	96.9	97.0	97.0	97.0	97.1	97.2	97.2	840
850	97.2	97.3	97.3	97.4	97.4	97.4	97.5	97.6	97.6	97.6	850
860	97.7	97.8	97.8	97.8	97.9	97.9	98.0	98.0	98.0	98.1	860
870	98.1	98.1	98.2	98.2	98.2	98.3	98.4	98.4	98.4	98.5	870
880	98.5	98.5	98.6	98.6	98.6	98.7	98.7	98.8	98.8	98.8	880
890	98.9	98.9	99.0	99.0	99.0	99.1	99.1	99.2	99.2	99.2	890
900	99.3	99.3	99.4	99.4	99.4	99.5	99.5	99.5	99.6	99.6	900
910	99.6	99.7	99.7	99.7	99.8	99.8	99.8	99.9	100.0	100.0	910
920	100.0	100.0	100.1	100.1	100.1	100.2	100.2	100.3	100.3	100.3	920
930	100.4	100.4	100.4	100.4	100.4	100.5	100.5	100.5	100.6	100.6	930
940	100.7	100.7	100.8	100.8	100.8	100.8	100.8	100.9	100.9	100.9	940

TABLE 3a *Continued*

Digital Counter Units	0	1	2	3	4	5	6	7	8	9	Digital Counter Units
					Research Octane Numbers						
950	101.0	101.0	101.1	101.1	101.1	101.2	101.2	101.2	101.2	101.3	950
960	101.3	101.3	101.4	101.4	101.4	101.4	101.5	101.5	101.6	101.6	960
970	101.6	101.6	101.7	101.7	101.7	101.8	101.8	101.8	101.8	101.9	970
980	101.9	101.9	102.0	102.0	102.0	102.1	102.1	102.2	102.2	102.3	980
990	102.3	102.3	102.4	102.4	102.4	102.4	102.5	102.5	102.5	102.6	990
1000	102.6	102.6	102.7	102.7	102.8	102.8	102.8	102.9	102.9	102.9	1000
1010	103.0	103.0	103.0	103.1	103.1	103.1	103.2	103.2	103.2	103.3	1010
1020	103.3	103.4	103.4	103.4	103.5	103.5	103.5	103.6	103.6	103.6	1020
1030	103.7	103.7	103.7	103.8	103.8	103.8	103.9	103.9	104.0	104.0	1030
1040	104.0	104.1	104.1	104.2	104.2	104.3	104.3	104.4	104.4	104.4	1040
1050	104.5	104.6	104.6	104.6	104.7	104.7	104.8	104.8	104.8	104.9	1050
1060	104.9	105.0	105.0	105.1	105.2	105.2	105.2	105.3	105.3	105.4	1060
1070	105.4	105.4	105.5	105.5	105.6	105.6	105.7	105.7	105.8	105.8	1070
1080	105.9	106.0	106.0	106.1	106.1	106.2	106.2	106.3	106.3	106.4	1080
1090	106.4	106.5	106.6	106.8	106.7	106.7	106.8	106.8	106.9	107.0	1090
1100	107.0	107.1	107.2	107.2	107.3	107.4	107.4	107.5	107.5	107.6	1100
1110	107.6	107.7	107.8	107.8	107.9	108.0	108.0	108.1	108.2	108.2	1110
1120	108.3	108.4	108.5	108.8	108.6	108.7	108.7	108 8	108.9	108.9	1120
1130	109.0	109.0	109.1	109.2	109.2	109.3	109.4	109.4	109.5	109.6	1130
1140	109.6	109.7	109.8	109.9	110.0	110.0	110.1	110.2	110.2	110.4	1140
1150	110.4	110.5	110.6	110.7	110.8	110.8	110.9	111.0	111.0	111.1	1150
1160	111.2	111.2	111.3	111.4	111.4	111.5	111.8	111.7	111.8	111.9	1160
1170	112.0	112.0	112.1	112.2	112.2	112.3	112.4	112.5	112.6	112.6	1170
1180	112.7	112.8	112.8	112.9	113.0	113.0	113.2	113.3	113.4	113.4	1180
1190	113.5	113.6	113.6	113.7	113.8	113.8	113.9	114.0	114.1	114.2	1190
1200	114.3	114.4	114.4	114.5	114.6	114.6	114.7	114 8	114.9	115.0	1200
1210	115.1	115.2	115.2	115.3	115.4	115.5	115.5	115.6	115.6	115.6	1210
1220	115.7	115.8	115.9	116.0	116.0	116.1	116.2	116.2	116.3	116.4	1220
1230	116.4	116.4	116.5	116.6	116.6	116.7	116.8	116.8	116.9	117.0	1230
1240	117.0	117.1	117.2	117.2	117.3	117.4	117.5	117.5	117.6	117.6	1240

$$\text{Equivalent micrometer reading} = 1.012 - \frac{\text{digital counter units}}{1410}.$$

9.1.10 *Coolant Temperature*, 212 ± 3°F (100 ± 1.5°C), constant within ±1°F (±0.5°C) during a test.

9.1.11 *Intake Air Humidity*, 25 to 50 grains of water/lb (0.00356 to 0.00712 kg of water/kg) of dry air (as described in Section A1.14 of Annex A1).

9.1.12 *Inlet-Air Temperature* shall be measured at the hole provided in the inlet-air pipe with ASTM Thermometer 83F and maintained within ±2°F (±1.1°C) of the temperature specified for the prevailing barometric pressure in Table 4. This temperature is used for making the basic micrometer or digital counter setting, obtaining standard knock intensity, and making the initial check on rating characteristics. Other temperatures may be used later in the test as outlined in Section 13, but the initial testing is done at the temperature specified in Table 4.

9.1.13 *Carburetor Venturi*, 9/16-in. (14.3 mm) diameter at the throat.

9.1.14 *Basic Cylinder Height Setting*—After the engine reaches the mandatory temperatures, set the basic cylinder height as described in Section A3.2.

9.1.15 *Fuel-Air Ratio* shall be that for maximum knock intensity for each test and reference fuel■. It is obtained by varying the carburetor bowl height. The final fuel level must be in the range from 0.7 to 1.7 on the sight glass; otherwise a change in jet size is mandatory. Additional information about these adjustments and jet sizes may be found in Sections A3.12 and A4.38 of Annexes A3 and A4.

9.1.16 *Knockmeter Reading Limits*—The operational range for knock intensity readings on the knockmeter shall be from 20 to 80. Knock intensity is a nonlinear characteristic below 20 and the knockmeter has the potential to be nonlinear above 80.

9.1.17 *Basic Detonation Meter Spread*, 10 to 18 knockmeter divisions per octane number at the 90 octane level. Spread has a characteristic variation with octane level but if properly set at 90 octane number need not in most cases be altered for ratings for 80 to 102 octane number.

9.1.18 *Reference Fuels, Bracketing Procedure*—The knockmeter reading of the test fuel■ must be bracketed by two adjacent reference fuel blends■ selected from the reference fuel system of either 3.12.1 or 3.12.2, but never by a combination of 3.12.1 and 3.12.2. The two blends■ must not differ by more than two octane numbers. In the range between 100.0 and 103.5 octane number, only the following reference fuel■ pairs shall be used:

100.0 and 100.7
100.7 and 101.3
101.3 and 102.5
102.5 and 103.5

9.1.19 *Reference Fuels, Compression Ratio Procedure*—The knockmeter reading of the test fuel■ must match that of

a reference fuel■ blend selected from the reference fuel systems of either 3.12.1 or 3.12.2. In the range between 100.0 and 103.5 octane number, only the following reference fuels■ shall be used: 100.7, 101.3, 102.5, and 103.5. Permissible differences between test fuel and reference fuel octane values are specified in 16.1.3.

9.1.20 *Sample Handling*—All samples■ shall be cooled to a temperature between 35°F (2°C) and 50°F (10°C) *before* the container is opened and the sample■ is introduced into the appropriate carburetor bowl.

10. Starting and Stopping Engine

10.1 *Starting the Engine*—While the engine is being motored, turn on the ignition and start the engine by setting the carburetor to draw fuel■ from one float bowl. Turn on cooling water.

TABLE 4 Corrections to Research Method Engine Guide Table and Intake Air Temperature Conditions to Achieve Standard Knock Intensity at Various Barometric Pressures

NOTE—Intake air temperatures are in degrees Fahrenheit; the equivalent temperatures in degrees Celsius are shown in parentheses.

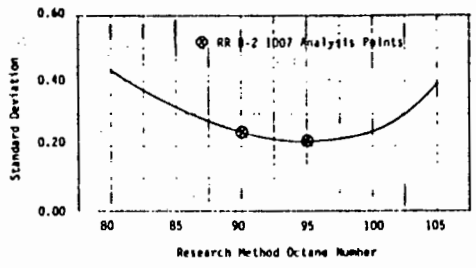
Barometric Pressure, in. Hg (kPa)		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Barometric Pressure, in. Hg (kPa)
	The intake air temperature listed for each prevailing barometric pressure must be used for ratings or as the reference for temperature tuning. To determine the compression ratio measure that provides standard knock intensity at a prevailing barometric pressure: SUBTRACT the listed micrometer correction from the guide table micrometer reading in Table 2. ADD the listed digital counter correction to the guide table digital counter reading in Tables 3 or 3a. To convert an observed engine compression ratio measure at the prevailing barometric pressure to that for 29.92 in. Hg (101.3 kPa): ADD the listed micrometer correction to the observed engine micrometer reading. SUBTRACT the listed digital counter correction from the observed engine digital counter reading.											
21.0 (71.1)	Counter Corrections	250	247	244	241	239	236	233	230	227	225	21.0 (71.1)
	Micrometer Corrections	0.178	0.176	0.174	0.172	0.170	0.168	0.166	0.164	0.162	0.160	
	Intake Air Temperatures	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	
22.0 (74.5)	Counter Corrections	222	219	216	213	211	208	205	202	199	197	22.0 (74.5)
	Micrometer Corrections	0.158	0.156	0.154	0.152	0.150	0.148	0.146	0.144	0.142	0.140	
	Intake Air Temperatures	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	
23.0 (77.9)	Counter Corrections	194	191	188	185	183	180	177	174	171	169	23.0 (77.9)
	Micrometer Corrections	0.138	0.136	0.134	0.132	0.130	0.128	0.126	0.124	0.122	0.120	
	Intake Air Temperatures	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	
24.0 (81.2)	Counter Corrections	166	163	160	157	155	152	149	146	143	141	24.0 (81.2)
	Micrometer Corrections	0.118	0.116	0.114	0.112	0.110	0.108	0.106	0.104	0.102	0.100	
	Intake Air Temperatures	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	
25.0 (84.7)	Counter Corrections	138	135	132	129	127	124	121	118	115	113	25.0 (84.7)
	Micrometer Corrections	0.098	0.096	0.094	0.092	0.090	0.088	0.086	0.084	0.082	0.080	
	Intake Air Temperatures	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	60 (15.6)	61 (16.1)	63 (17.2)	64 (17.8)	66 (18.9)	
26.0 (88.0)	Counter Corrections	110	107	104	101	99	96	93	90	87	85	26.0 (88.0)
	Micrometer Corrections	0.078	0.076	0.074	0.072	0.070	0.068	0.066	0.064	0.062	0.060	
	Intake Air Temperatures	67 (19.4)	69 (20.6)	70 (21.1)	72 (22.2)	73 (22.8)	75 (23.9)	76 (24.4)	78 (25.6)	79 (26.1)	81 (27.2)	
27.0 (91.4)	Counter Corrections	82	79	76	73	71	68	65	62	59	57	27.0 (91.4)
	Micrometer Corrections	0.058	0.056	0.054	0.052	0.050	0.048	0.046	0.044	0.042	0.040	
	Intake Air Temperatures	82 (27.8)	84 (28.9)	85 (29.4)	88 (30)	88 (31.1)	89 (31.7)	91 (32.8)	92 (33.3)	94 (34.4)	95 (35)	
28.0 (94.8)	Counter Corrections	54	51	48	45	43	40	37	34	31	29	28.0 (94.8)
	Micrometer Corrections	0.038	0.036	0.034	0.032	0.030	0.028	0.026	0.024	0.022	0.020	
	Intake Air Temperatures	97 (36.1)	98 (36.7)	100 (37.8)	101 (38.3)	103 (39.4)	104 (40)	106 (41.1)	107 (41.7)	109 (42.8)	110 (43.3)	
29.0 (98.2)	Counter Corrections	26	23	20	17	15	12	9	6	3	1	29.0 (98.2)
	Micrometer Corrections	0.018	0.016	0.014	0.012	0.010	0.008	0.006	0.004	0.002	0.000	
	Intake Air Temperatures	111 (43.9)	113 (45)	114 (45.6)	116 (46.7)	117 (47.2)	119 (48.3)	120 (48.9)	122 (50)	123 (50.6)	125 (51.7)	

Barometric Pressure, in. Hg (kPa)		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Barometric Pressure, in. Hg (kPa)
	The intake air temperature listed for each prevailing barometric pressure must be used for ratings or as the reference for temperature tuning. To determine the compression ratio measure that provides standard knock intensity at a prevailing barometric pressure: ADD listed micrometer correction from the guide table micrometer reading in Table 2. SUBTRACT the listed digital counter correction to the guide table digital counter reading in Tables 3 or 3a. To convert an observed engine compression ratio measure at the prevailing barometric pressure to that for 29.92 in. Hg (101.3 kPa): SUBTRACT the listed micrometer correction to the observed engine micrometer reading. ADD the listed digital counter correction from the observed engine digital counter reading.											
30.0 (101.6)	Counter Corrections	2	5	8	11	13	16	19	22	25	27	30.0 (101.6)
	Micrometer Corrections	0.002	0.004	0.006	0.008	0.010	0.012	0.014	0.016	0.018	0.020	
	Intake Air Temperatures	126 (52.2)	127 (52.8)	129 (53.9)	130 (54.4)	132 (55.6)	133 (56.1)	135 (57.2)	136 (57.8)	138 (58.9)	139 (59.4)	

[A] To set the digital counter indicator so that the bottom counter reading is compensated to 29.92 in. Hg (101.3 kPa), position the indicator drive knob so that the lower counter disengaged and then change the engine compression ratio so that the two digital counter readings differ by the value listed in Table 4 for the prevailing barometric pressure. After setti compensation return indicator drive knob to position 1:

Top counter reading must be greater than the bottom compensated reading for pressures numerically less than 29.92 in. Hg (101.3 kPa).

Top counter reading must be less than the bottom compensated reading for pressures numerically greater than 29.92 in. Hg (101.3 kPa).



NOTE—See *Annual Book of ASTM Standards*, Vol 05.03.

FIG. 3a Reproducibility Standard Deviation of Research Method

TABLE 5 Octane Numbers and Engine Acceptance Rating Tolerances for Toluene Standardization Fuel Blends

Octane No.	Rating Tolerance	Composition, vol %		
		Toluene	*Iso*-octane	*n*-Heptane
65.2	±0.4	50	0	50
75.5	±0.3	58	0	42
85.0[A]	±0.3	66	0	34
89.3[A]	±0.3	70	0	30
93.4[A]	±0.3	74	0	26
96.9[A]	±0.2	74	5	21
99.6[A]	±0.3	74	10	16
103.3	±0.4	74	15	11
108.0	±0.8	74	20	6
113.7	±0.9	74	26	0

[A] Blends recalibrated by the National Exchange Group in 1986. All other blends have O.N. values obtained for the original calibration programs in the late 1950's. These blends are being considered for recalibration also.

10.2 *Stopping the Engine*—Turn off the fuel, drain all fuel bowls, turn off the ignition, turn off water to the exhaust spray and coolant condenser, and motor the engine for 1 min before stopping the synchronous motor. To avoid possible corrosion and warpage of engine intake and exhaust valves and seats between operating periods, close both valves by turning the flywheel to tdc on the compression stroke.

11. Adjusting Knock Measurement Instrumentation

11.1 The following adjustments and operational guide lines (see Annex A7 on Instrumentation for further details) are important to proper use of the knock measurement instrumentation which includes the detonation pickup, detonation meter, and indicating knockmeter:

11.1.1 Knockmeter needle mechanical zero,

11.1.2 Detonation meter zero,

11.1.3 Time constant,

11.1.4 Meter reading (meter output signal level),

11.1.5 Spread (meter gain or sensitivity level), and

11.1.5.1 Basic spread setting shall be 10 to 18 knockmeter divisions per octane number at 90 octane number. Spread varies with octane level and the values obtained between 80 and 102 octane number will normally provide suitable resolution and signal stability for optimum test measurement.

12. Adjustments for Standard Knock Intensity

12.1 With the engine at equilibrium temperature and the carburetor set for maximum knock, adjust the cylinder height for standard knock intensity (9.1.15) at the micrometer or digital counter reading obtained from Table 2, 3, or 3a for the octane number of the reference fuel blend being used and corrected in accordance with Table 4 for the barometric pressure at the time of the test. Unless the intake air temperature is varied in order to obtain the calibrated ratings on the toluene standardization fuel blends as described in 13.2, maintain it at the value specified for the prevailing barometric pressure in Table 4.

TABLE 6 Exact Intake Air Temperature Tuning Octane Number Limits for Toluene Standardization Fuel Blends

Octane No.	Rating Tolerance	Composition, vol %		
		Toluene	*Iso*-octane	*n*-Heptane
65.2	±0.9	50	0	50
75.5	±0.8	58	0	42
85.0	±0.7	66	0	34
89.3	±0.6	70	0	30
93.4	±0.5	74	0	26
96.9	±0.5	74	5	21
99.8	±0.8	74	10	16
103.3	±1.2	74	15	11
108.0	±1.7	74	20	6
113.7	±2.2	74	26	0

NOTE 2—Any correctly adjusted mercury barometer or a properly compensated aneroid barometer may be used to measure barometric pressure. Aneroid barometers should be calibrated at least once a year.

12.2 Under the conditions specified in 12.1, set the METER READING controls to obtain a 50 knockmeter reading. Turn off the ignition. The engine should cease firing instantly. If it does, the testing unit is ready for a check of its rating characteristics with an appropriate basic toluene standardization fuel. If it does not, the engine conditions are unsatisfactory. Examine the engine for objectionable combustion chamber and spark plug deposits. Remedy such conditions and repeat the operations in Section 12.

13. Check on Rating Characteristics

13.1 The octane rating of each sample must be determined on an engine that has been qualified on a toluene standardization fuel whose value is no further from the sample octane number than that for the nearest blend listed in Table 5 (Note 3). In the event the rating for the toluene standardization fuel is not within the tolerance specified in Table 5, correction of knock testing unit operating conditions will be necessary unless the optional permissible correction by intake air temperature tuning is applied. Intake air temperature tuning to the calibration octane number for the toluene standardization fuel blend may be utilized if the rating, at the intake air temperature prescribed for the prevailing barometric pressure, does not exceed the limit in Table 6. If the rating at standard operating conditions, including the intake air temperature prescribed by the prevailing barometric pressure, exceeds the limit in Table 6, the knock testing unit must be examined and corrected.

NOTE 3—The situation may exist where there is reasonable assurance the engine will rate the toluene standardization fuels within the rating tolerances given in Table 5. In such cases, time usually can be saved by rating the test fuel first if its expected rating is completely unknown or cannot be estimated closely enough to select the required basic toluene standardization fuel.

13.1.1 Additional information relating to both toluene standardization fuel testing and the use of check fuels

consisting of leaded blends of ASTM *iso*octane■ and ASTM *n*-heptane■ is included in A3.14.

13.2 *Temperature Tuning*—To adjust (tune) toluene standardization fuel■ ratings by adjustment of intake air temperature, the following must apply:

13.2.1 The initial rating on the toluene standardization fuel■ must be obtained at the intake air temperature shown in Table 4.

13.2.2 The cylinder height used for this rating must be the micrometer or digital counter setting shown in Table 2 or 3, corrected for the prevailing barometric pressure in accordance with Table 4 for the calibrated rating of the toluene standardization fuel■ used.

13.2.3 The rating must be within the octane number limits shown in Table 6.

13.2.4 The cylinder height used in 13.2.2 must be maintained for tests on the toluene standardization fuel■ at other intake air temperatures.

13.3 *Frequency of Checking:*

13.3.1 In laboratories where an overnight engine shutdown occurs, the first check on rating characteristics shall be made at or near the beginning of each operating day and as frequently thereafter as required to conform with 13.1.

13.3.2 For laboratories where operation is essentially continuous or where it is planned to test more than one fuel■ in a given period of operation, the rating check of a given toluene standardization fuel■ is applicable only to test fuels■ rated during the next 7 h.

13.3.3 When there is a change of operators or when an engine shutdown of more than 2 h occurs, it is desirable to make a check on rating characteristics.

13.3.4 If during any engine shutdown, adjustments or changes are made in the equipment, a recheck of rating characteristics must be made at or near the beginning of the next operating period.

14. Obtaining Maximum Knock Fuel-Air Ratio and Standard Knock Intensity

14.1 *Preliminary Adjustment of Cylinder Height*—Pour the quantity of cooled sample■ (9.1.19) required for a test into one of the carburetor tanks. Set the fuel level of this carburetor at the estimated maximum knock position and turn the selector valve to operate on this fuel■. Allow time for equilibrium engine conditions, and then adjust the cylinder height for a knockmeter reading of 45 to 47. The desired average knockmeter reading is 50. Time can usually be saved by making the preliminary cylinder height adjustment for a reading lower than 50, as it may increase when the fuel level is adjusted for maximum knock.

14.2 *Adjustment of Fuel-Air Ratio*—Determine the fuel level for a maximum reading on the knockmeter by the procedure described in the example in 14.2.1.

14.2.1 With a setting, for example, of 1.3 on the etched glass scale, allow the knockmeter needle to reach equilibrium and record the reading. Then obtain and record knockmeter reading for richer fuel-air ratios by raising the fuel level by 0.1 increments to 1.2, 1.1 . . . , until the knockmeter reading has decreased at least five divisions from the maximum. Reset the fuel level at the position for which the maximum knockmeter reading was obtained, for example, 1.2. Follow the same procedure for leaner fuel-air ratios by setting in turn at 1.3, 1.4 . . . , until the knockmeter reading has decreased at least five divisions from the maximum. Set the fuel level at the position for which the maximum knockmeter reading was obtained, or between the two positions for which the reading was the same, for example 1.25. This is the position for maximum knock. Verify it at least once by settings at levels 0.1 on either side, in the example just given at both 1.15 and 1.35. If higher knockmeter readings are obtained at either of these positions, the setting is in error and the entire procedure must be repeated. For each setting of the fuel level, allow the knockmeter needle to reach equilibrium before recording readings.

14.3 *Sample Cooling*—Cooling of the critical carburetor assembly components is mandatory if there is excessive gasoline vaporization as evidenced by bubbling in the sight glass, fluctuating sight glass fuel level, or uneven engine combustion.

14.3.1 *Standard Coolant*—Jacketed carburetor components are described in A1.12.2 of Annex 1. The circulated coolant (water or a water antifreeze solution) must not be cooler than 33°F (0.5°C) in the carburetor coolant exchangers. This coolant may be circulated when rating any gasoline sample.

14.4 *Final Adjustment of Cylinder Height*—After locating the fuel level for maximum knock, adjust the cylinder height, if required, for a knockmeter reading of 50.

14.4.1 *Bracketing Procedure*—Use this cylinder height for the remainder of the test, provided that later observations show that it is within the tolerances specified in 15.9 for the knock rating of the sample■.

14.4.2 *Compression Ratio Procedure*—Allow sufficient time for the engine and knockmeter to reach equilibrium. This time will vary with the fuel■, deposits from the previous fuel■ on which the engine was operated, testing range, and the condition of the equipment. When the engine has reached equilibrium, make a final adjustment of the cylinder height, if necessary, so that the knockmeter reading is 50 ± 1.

15. Bracketing Procedure for Rating the Sample

NOTE 4—For compression ratio procedure, go directly to Section 16.

15.1 Bracket or match the knocking tendency of the test sample■ by the knocking tendency of reference fuels■ from one of the fuel systems defined in 7.1 or 7.2.

15.2 *Reference Fuel Blends*—Use specified combinations of the reference materials listed in 7.1 to prepare the necessary reference fuel blends■ for making the knocking tendency comparison required in 15.1. Thoroughly mix all such reference fuel blends■ before use. Detailed information on the blending procedures is given in Section A2.4 of Annex A2. The specified combinations of the reference materials are as follows (Note 5):

15.2.1 ASTM *n*-heptane■ and ASTM 80 octane blend■,

15.2.2 ASTM 80 octane blend■ and ASTM *iso*octane■ and

15.2.3 ASTM *iso*octane■ and ASTM *dilute* tetraethyllead■.

NOTE 5—ASTM *n*-heptane■ and ASTM *iso*octane■ can be used to make a laboratory 80-octane number blend■ for use in place of the ASTM 80-octane blend■ specified in 15.2.1 and 15.2.2. However, this practice is *not* recommended.

15.3 *First Bracketing Reference Fuel*—Based on the cylinder height determined in 14.4, make a reference fuel blend■ near the estimated octane number of the sample■ and pour it into one of the other carburetor tanks. Set the fuel level on this carburetor at the estimated maximum knock position and turn the selector valve to operate on this fuel■. When the knockmeter needle has reached equilibrium, adjust the fuel level for maximum knock as described in 14.2 and record the knockmeter reading.

15.4 *Second Bracketing Reference Fuel*—Make a second reference fuel blend■ that it is expected will bracket the knockmeter reading of the sample■ and that differs from the first reference fuel■ by no more than two octane numbers (9.1.17). Pour this reference fuel blend■ into the third carburetor tank. Set the fuel level on this carburetor at the estimated maximum knock position and turn the selector valve to operate on this fuel■. When the knockmeter needle has reached equilibrium, adjust the fuel level for maximum knock as described in 14.2 and record the knockmeter reading. If the readings for the two reference fuel blends■ bracket that for the sample■, or if the reading for the sample■ matches that of one of the reference fuel blends■, proceed with the test as described in 15.7.

15.5 *Checking Conformance to Standard Knock Intensity*—If the knockmeter readings for the first and second reference fuel blends■ do not meet the requirements in 15.4, estimate the rating of the sample■ from the knockmeter readings obtained. If the cylinder height is within the specified tolerances given in Tables 2 and 3, for the estimated ratings of the sample■, proceed with the test as described in 15.6. If not, make the required adjustments to the cylinder height and detonation meter and repeat the procedure in 15.3 and 15.4 as required.

15.6 *Third Bracketing Reference Fuel*—If a third reference fuel blend■ is required to bracket or match the knockmeter reading of the sample■, prepare a blend■ that differs from the second reference fuel blend■ by no more than two octane numbers (9.1.17). Drain the carburetor containing the first reference fuel blend■ and pour the third reference fuel■ into the tank of this carburetor. Follow the instructions given in 15.4 to obtain a maximum knockmeter reading on this fuel■.

15.7 *Order of Readings*—At this point, one series of knockmeter readings has been obtained on the sample■ and on the bracketing reference fuels■. With the three carburetor bowls set to give maximum knock, take another knockmeter reading on each fuel■ in the following order (Note 6): (*1*) sample■, (*2*) second bracketing reference fuel■, and (*3*) first bracketing reference fuel■. In taking this series of readings, verify the carburetor settings for maximum knock as described in 14.2. Allow sufficient time after fuel changes for the engine and knockmeter needle to reach equilibrium. The amount of time required for equilibrium readings will vary with the fuel■, deposits from the previous fuel■ on which the engine was operated, testing range, and condition of the equipment.

NOTE 6—This sequence of reference fuel readings is reversed from that followed in the first series. This reversal is helpful in detecting residual deposit effects from the sample■ that delay the obtaining of true knock intensity readings on the reference fuels■.

15.8 *Number of Knockmeter Readings*—For completion of a test, the required minimum number of knockmeter readings is as follows:

15.8.1 Two knockmeter readings on the sample■ and two on each bracketing reference fuel■ constitute a test provided (*1*) the difference in ratings calculated from the first and second series is no greater than 0.3 octane number, and (*2*) the average reading on the test sample■ is within the specified limits of 50 ± 5.

15.8.2 Three knockmeter readings on the sample■ and three on each bracketing reference fuel■ constitute a test provided (*1*) the difference in ratings calculated from the first and second series of readings is no greater than 0.5 octane number, (*2*) the rating calculated from the third series of readings is between the ratings calculated from the first and second series of readings, and (*3*) the average reading on the test sample■ is within the specified limits of 50 ± 5.

15.8.3 If the difference in ratings calculated from the first and second series of knockmeter readings is greater than 0.5 octane number, or if the rating calculated from the third series of readings is not between the ratings calculated from the first and second series of readings, discard all readings and repeat the test procedures described in Sections 14 and 15.

15.9 *Checking Conformance to Standard Knock Intensity*—If the requirements of 15.8 are met, make certain that the cylinder height measured by either the micrometer or digital counter is within ±0.010 of the values shown in Table 2 or within ±14 units of values shown in Table 3, corrected in accordance with Table 4 for the prevailing barometric pressure, for the octane number of the reference fuel blend■ that matches the sample■. If the cylinder height is not within these tolerances, adjust it to the correct height and adjust the METER READING controls again to give a 50 knockmeter reading. After these adjustments have been made repeat the test on the fuel sample■.

15.10 For subsequent testing of fuel samples■, knockmeter reading is used as a guide for obtaining standard knock intensity by adjusting cylinder height to obtain a knockmeter reading of 50 at the maximum knock fuel-air ratio for the fuel sample■. At the completion of each test, check for conformance to standard knock intensity as described in 15.9.

15.10.1 When the engine is being operated at the intake air temperature shown in Table 4, readjust the intake air temperature for agreement with the value shown in this table if the barometric pressure changes more than 0.10 in. Hg (0.34 kPa) during an operating period. If there are similar changes in barometric pressure when an engine has been standardized in accordance with 13.2, repeat the operations described therein.

15.11 *Calculation:*

15.11.1 Average the knockmeter readings obtained in accordance with the detailed instructions given in 15.8, and Section A3.15 of Annex A3 for the sample■ and the two bracketing reference fuels■.

15.11.2 Use the average knockmeter readings of 15.11.1 and calculate the octane number to the second decimal as in the example in A3.16.1.4 of Annex A3.

15.11.3 Round the calculated octane number of 15.11.2 to the nearest tenth. Any octane number ending exactly in 5

in the second decimal shall be rounded to the nearest even tenth number; for example, round 95.55 and 95.65 to 95.6.

16. Compression Ratio Procedure for Rating the Sample

16.1 *Reading the Octane Number:*

16.1.1 *Reading the Cylinder Height Indicator*—Obtain the micrometer or digital counter reading for the final cylinder height used in 14.4 and correct it to a barometric pressure of 29.92 in. Hg (101.3 kPa) in accordance with Table 4.

16.1.2 *Converting to Equivalent Octane Number*—Using Table 2, 3, and 3a read the octane number equivalent to the cylinder height indicator reading obtained in 16.1.1.

16.1.3 The octane rating of the sample■ is not acceptable if it differs by more than the appropriate value given below from the octane number of the reference fuel blend■ last used to establish standard knock intensity.

Sample Rating Range in Octane Number	Maximum Permissible Octane Number Difference Between Reference Fuel and Sample
Below 90	2.0
90 to 100	1.0
100 to 102	0.7
102 to 105	1.3
Above 105	2.0

When the difference between the reference fuel■ and sample■ exceeds the listed value, reestablish the standard knock intensity as described in Section 12, but using a reference fuel blend■ with an octane number differing from the sample■ by not more than the listed limits. If the knockmeter reads 50 for this new reference fuel blend■, the sample■ rating may be accepted. If not, repeat Section 12 with the new reference fuel blend■ and retest the sample■ as described in Section 14.

16.1.4 The standard knock intensity should be reestablished in accordance with Section 12 or 16.1.3 after every fourth sample■ tested in the range below 100 octane number and after every second sample■ tested in the range above 100 octane number. More frequent rechecking of standard knock intensity may be required in testing "sensitive" gasolines■ of high octane numbers or in rating fuels■ covering a wide octane range.

16.2 *Calculation:*

16.2.1 Determine the engine rating (16.1.2) and round this value to the nearest tenth. Any octane number ending exactly in 5 in the second decimal shall be rounded to the nearest even tenth number; for example, round 95.55 and 95.65 to 95.6.

17. Report

17.1 Report the number obtained in 15.11.3 or 16.2.1 as the ASTM – IP research octane number.

18. Precision and Bias

18.1 *Precision*—The precision of this test method as determined by the statistical examination of interlaboratory replicate test results at the two most commonly used octane levels is as follows:

18.1.1 *Repeatability*—At the 90.0 and 95.0 octane levels, the differences between two test results obtained by the same operator with the same apparatus under constant operating conditions on identical test material would, in the long run, in the normal and correct operation of the test method, exceed the values in the following table only 1 case in 20.

18.1.2 *Reproducibility*—At the 90.0 and 95.0 octane levels, the difference between two single and independent results obtained by different operators working in different laboratories on identical test material would, in the long run, in the normal and correct operation of the test method, exceed the values in the following table only 1 case in 20.

Average Research Octane Number Level	Repeatability Limits Octane Number	Reproducibility Limits Octane Number
90	0.2	0.7
95	0.2	0.6

18.2 The above precision limits were calculated from the replicate octane number results obtained by the National Exchange Motor Fuels Group (NEG) participating in cooperative testing programs October 1979 through July 1983. These data were analyzed by procedures detailed in the "Manual on Determining Precision Data for ASTM Methods on Petroleum Products and Lubricants."[5]

18.3 *Reproducibility*—At the 80, 85, 100, 105, and 110 octane levels, the difference between two single and independent results obtained by different operators working in different laboratories on identical test material would, in the long run, in the normal and correct operation of the test method, exceed the values in the following table only 1 case in 20.

Average Research Octane Number Level	Reproducibility Limits Octane Number
80	1.2
85	0.9
...	...
100	0.7
105	1.1
110	2.3

18.4 The above precision limits are given in the interest of maintaining continuity with previous issues of this test method. These values are based on NEG data from 1957 through 1982 for single determinations by each participating laboratory.

18.5 *Standard Deviation*—Extensive data over the years have shown that the reproducibility of fuel ratings among laboratories varies with octane number level. This variation is shown in Fig. 3a, where the Standard Deviation is plotted against Octane Number level. The curve for this figure is based on ASTM National Exchange Group data from 1966 through 1982 with some earlier data for octane levels below 90.

18.6 *Bias*—The bias statement is currently being developed.

[5] Available from ASTM Headquarters. Request Research Report RR: D-2 1007.

The American Society for Testing and Materials takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, 1916 Race St., Philadelphia, PA 19103.

APPENDIX 1.2

Designation: 2700 – 88a

An American National Standard

Designation: 236/83

Standard Test Method for Knock Characteristics of Motor and Aviation Fuels by the Motor Method[1]

This standard is issued under the fixed designation D 2700; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This test method was adopted as a joint ASTM - IP Standard in 1969.

CAUTION—A recalibration of toluene fuel blends has been completed. A revision to change the octane values and broaden the rating tolerances contained in Table 16 is in progress.

1. Scope

1.1 This test method covers the determination of the knock characteristics of motor and aviation gasolines intended for use in spark-ignition engines.

1.2 The knock characteristics of motor gasolines are reported in terms of ASTM-IP motor octane numbers.

1.3 The knock characteristics of aviation gasolines are reported in terms of aviation method octane numbers below 100 and aviation method performance numbers above 100.

1.4 In this test method, inch-pound units are the preferred system of measurement.

1.5 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Specific precautionary statements are given in Annex 8.

2. Referenced Documents

2.1 *ASTM Standards:*

D 439 Specification for Automotive Gasoline[2]

D 4057 Practice for Manual Sampling of Petroleum and Petroleum Products[3]

3. Descriptions of Terms Specific to This Standard

3.1 *check fuels*—calibrated auxiliary fuels which may be used to obtain additional information on engine operating conditions. (They are not substitutes for toluene standardization fuels.)

3.2 *cylinder height*—the relative position of the engine cylinder with respect to the piston which is indicated by a micrometer, dial indicator, or digital counter.

3.3 *detonation meter*—the electronic amplifier/signal conditioning equipment that accepts the electrical signal from the detonation pickup and provides an electrical signal for display on a knockmeter or strip chart recorder.

3.4 *detonation pickup*—a magnetostrictive-type transducer that mounts in the engine cylinder and is exposed to combustion chamber pressure to provide a voltage signal to the detonation meter proportional to the rate-of-change of cylinder pressure.

3.5 *digital counter reading*—a numerical indication of cylinder height, indexed to a basic setting at a prescribed compression pressure when the engine is motored.

3.6 *guide tables*—the specific relationship between cylinder height (compression ratio) and octane number at standard knock intensity for specific primary reference fuel blends tested at standard barometric pressure.

3.7 *knock intensity*—a measure of the level of combustion-related knock produced when fuel is evaluated in the knock testing unit.

3.8 *knockmeter*—the 0 to 100-division indicating meter that displays the knock intensity provided by the detonation meter.

3.9 *maximum knock intensity fuel/air ratio*—that proportion of fuel to air which produces the highest knock intensity for each fuel in the knock test unit, provided this occurs within specified carburetor sight glass fuel level limits.

3.10 *micrometer reading*—a numerical indication of cylinder height, indexed to a basic setting at a prescribed compression when the engine is motored.

3.11 *octane number*—the measure of the resistance of a fuel to knock, which is assigned to a test fuel based upon operation in the knock testing unit at the same standard knock intensity as that of a specific primary reference fuel blend.

3.11.1 *ASTM-IP correlated aviation method rating based on motor octane number*—the empirical relationship between motor octane number and the discontinued aviation method (D 614) (lean-mixture) rating as given in Table 8 and designated as octane number for gasolines below 100 and performance number for gasolines above 100.

---

[1] This test method is under the jurisdiction of ASTM Committee D-2 on Petroleum Products and Lubricants.

Current edition approved March 25 and June 13, 1988. Published February 1989. Originally published as D 2700 – 68. Last previous edition D 2700 – 86.

[2] *Annual Book of ASTM Standards*, Vol 05.01.

[3] *Annual Book of ASTM Standards*, Vol 05.03.

3.12 *primary reference fuels*—ASTM *iso*octane, ASTM *n*-heptane, volumetrically proportioned mixtures of ASTM *iso*octane and ASTM *n*-heptane, or blends of ASTM dilute tetraethyllead in ASTM *iso*octane which define the octane number scale.

3.12.1 *primary reference fuel blends above 100 octane*—the millilitres per U.S. gallon of ASTM dilute tetraethyllead in ASTM *iso*octane that characterizes octane numbers above 100 in accordance with an empirically determined relationship.

3.12.2 *primary reference fuel blends below 100 octane*—the volume percent of ASTM *iso*octane in a blend with ASTM *n*-heptane that identifies the octane number of the blend, ASTM *iso*octane being assigned as 100 and ASTM *n*-heptane as zero octane number.

3.13 *spread*—the sensitivity of the detonation meter expressed in knockmeter divisions per octane number.

3.14 *standard knock intensity*—that level of knock produced when a primary reference fuel blend of specific octane number is used in the knock testing unit at maximum knock intensity fuel/air ratio, with the cylinder height (compression ratio) set to the prescribed guide table value, and the detonation meter adjusted to produce a knockmeter reading of 50.

3.15 *toluene standardization fuels*—those volumetrically proportioned blends of two or more of the following: reference fuel grade toluene, ASTM *n*-heptane, dilute tetraethyllead, and ASTM *iso*octane that have empirically determined octane numbers and prescribed rating tolerances. These blends are sensitive to engine operating conditions and dictate whether a knock testing unit is in acceptable condition as a prerequisite to fuel testing at any specific octane level.

4. Summary of Test Method

4.1 *The ASTM - IP Motor Octane Number* of a fuel is determined by comparing its knocking tendency with those for blends of ASTM reference fuels of known octane number under standard operating conditions. This is done by varying the compression ratio to obtain standard knock intensity, as measured by an electronic detonation meter. At this point, one of the two following procedures may be used:

4.1.1 *Bracketing Procedure*—The knockmeter reading for the sample is bracketed at constant compression ratio between knockmeter readings for two reference blends and the rating of the sample is calculated by interpolation.

4.1.2 *Compression Ratio Procedure*—The rating of the sample is read from the applicable table, 9 through 14, for the cylinder height required for standard knock intensity for the sample. By this procedure, reference fuels are used only to establish standard knock intensity, which is done frequently.

NOTE 1—This test method combines the bracketing Test Method D 2700 and the former compression ratio Method D 2723.

5. Significance and Use

5.1 The motor method octane number correlates with full-scale spark-ignited engine antiknock performance at high speed. In conjunction with the research method, it provides a means of defining the antiknock quality of a motor gasoline for use in vehicles on the road. These laboratory tests for octane number (O.N.) utilize a single-cylinder engine and require critical adjustment of the fuel/air ratio and compression ratio to produce a standard knock intensity condition. The antiknock quality of a gasoline sample is determined by comparing it with that of primary reference fuel blends whose volumetric composition establishes the octane scale.

5.2 Empirical correlations have been developed which permit calculation of vehicle antiknock performance based on the following general equation:

$$\text{Antiknock index} = (k_1 \times \text{research O.N.}) + (k_2 \times \text{motor O.N.}) + k_3$$

5.3 The values of k_1, k_2, and k_3 vary from vehicle to vehicle, depending on operating conditions as well as engine and transmission characteristics. The coefficients are based

TABLE 7 Conversion of Millilitres of Tetraethyllead per U.S. Gallon in Isooctane to Octane Numbers Above 100

NOTE—Deleted 1986. See Table 29.

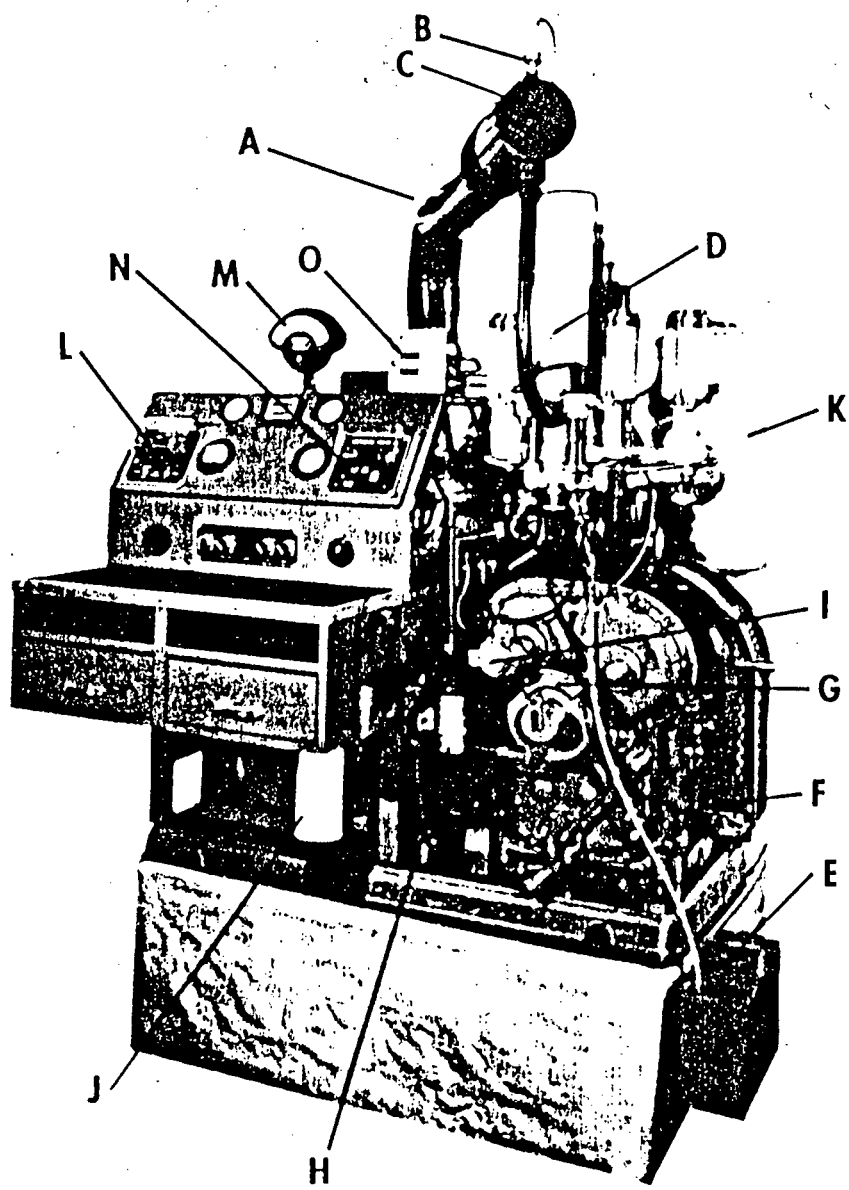
TABLE 8 ASTM Conversion of Motor Octane Numbers to Aviation Ratings[A,B,C]

Motor Octane Number	0.0	0.2	0.4	0.6	0.8
75	73.59	73.81	74.04	74.27	74.49
76	74.72	74.95	75.17	75.40	75.63
77	75.85	76.08	76.30	76.53	76.75
78	76.98	77.20	77.43	77.65	77.88
79	78.10	78.33	78.55	78.77	79.00
80	79.22	79.44	79.67	79.89	80.11
81	80.33	80.55	80.78	81.00	81.22
82	81.44	81.66	81.88	82.10	82.32
83	82.55	82.77	82.99	83.21	83.43
84	83.65	83.86	84.08	84.30	84.52
85	84.74	84.96	85.18	85.40	85.61
86	85.83	86.05	86.27	86.48	86.70
87	86.92	87.13	87.35	87.57	87.78
88	88.00	88.22	88.43	88.65	88.86
89	89.08	89.29	89.51	89.72	89.94
90	90.15	90.37	90.58	90.79	91.01
91	91.22	91.43	91.65	91.86	92.07
92	92.29	92.50	92.71	92.92	93.13
93	93.35	93.56	93.77	93.98	94.19
94	94.40	94.61	94.82	95.04	95.25
95	95.46	95.67	95.88	96.09	96.29
96	96.50	96.71	96.92	97.13	97.34
97	97.55	97.76	97.96	98.17	98.38
98	98.57	98.74	98.91	99.08	99.25
99	99.43	99.60	99.77	99.95	100.54
100	101.07	101.60	102.14	102.67	103.21
101	103.74	104.27	104.81	105.34	105.88
102	106.41	106.94	107.48	108.01	108.55
103	109.08	109.61	110.15	110.68	111.22
104	111.75	112.28	112.82	113.35	113.89
105	114.42	114.95	115.49	116.02	116.56
106	117.09	117.62	118.16	118.69	119.23
107	119.76	120.29	120.83	121.36	121.90
108	122.43	122.96	123.50	124.03	124.57
109	125.10	125.63	126.17	126.70	127.24
110	127.77	128.30	128.84	129.37	129.91

[A] This table converts ASTM-IP motor octane numbers to aviation method ratings equivalent to those of the now-discontinued Method D 614, Test for Knock Characteristics of Aviation Fuels by the Aviation Method.

[B] Correlation information is given in ASTM Research Report 69:D-2, "Aviation Gasoline Antiknock Quality by ASTM Methods D 614 and D 357."

[C] Aviation ratings above the line are in terms of octane number and ratings below the line are in terms of performance number.



A—Air Induction Pipe
B—Intake Air Heater
C—Induction Surge Pipe
D—Intake Air Thermometer
E—Waste Fuel Can, Closed for Safety
F—Oil Level Sight Glass
G—Spark Timing Scale
H—Ignition Coil
I—Ignition Timer
J—Oil Filter
K—Exhaust Surge Tank
L—Detonation Meter Model 501-T
M—Knockmeter
N—Temperature Control
O—Digital Counter

FIG. 4 Motor Unit

on road-octane number determinations for representative fuels used in the laboratory tests.

5.4 It is common to simplify the above equation to represent the average antiknock performance of the total vehicle population. The current version of the equation used in Specification D 439 is:

Antiknock index = 0.5 research O.N. + 0.5 motor O.N. + 0 or as more commonly written:

$$\text{Antiknock index} = \frac{(R + M)}{2}$$

The antiknock quality of gasoline■ is also important in the operation of stationary and other nonautomotive engine applications.

5.5 Motor method octane number is also used to determine the antiknock quality of aviation gasolines■ at lean-mixture (cruising) operating conditions. This motor rating must be converted to a number equivalent to the former

Aviation Method determination by an empirically derived correlation.

5.6 This test method is used by engine manufacturers, petroleum refiners and marketers, and in commerce as a primary specification measurement to ensure proper matching of fuels■ and engines.

6. Apparatus

6.1 The knock testing unit[4] illustrated in Fig. 4 consists of a single-cylinder engine of continuously variable compression ratio, with suitable loading and accessory equipment and instruments, mounted on a stationary base. The engine and equipment specified in Annex 1 on Apparatus shall be used without modification and installed as directed in Annex 5 on Installation and Assembly. It is important to provide a proper foundation for the unit as described in A5.2.3 of Annex 5. It is necessary to keep the apparatus in good mechanical condition, as described in Annex 4 on Maintenance.

[4] Available from the Waukesha Engine Div., Fuel Research Dept., Dresser Industries, Waukesha, WI 53186.

7. Reference Materials

7.1 *ASTM Knock Test Reference Materials*, conforming to the specifications and requirements of Sections A2.6 and A2.7 of Annex 2 on Reference Materials and Blending Accessories, shall be used and are as follows:

7.1.1 ASTM *iso*octane■ (2,2,4-trimethylpentane),

7.1.2 ASTM *n*-heptane■,

7.1.3 ASTM 80 octane blend■ of 7.1.1 and 7.1.2, and

TABLE 9 Guide Table for Standard Knock Intensity at 29.92 in. Hg (101.3 kPa) Barometric Pressure—Micrometer Readings for Motor Octane Numbers Apply for Sea Level to 1600 ft (500 m) Altitude (9/16 Venturi)

See Table 15 for Corrections for Other Barometric Pressures

Motor Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Motor Octane Number
	Micrometer Setting, in.										
40	0.891	0.891	0.890	0.890	0.889	0.889	0.888	0.888	0.887	0.887	40
41	0.887	0.888	0.886	0.888	0.885	0.885	0.884	0.884	0.883	0.883	41
42	0.883	0.882	0.882	0.881	0.881	0.880	0.889	0.880	0.879	0.879	42
43	0.878	0.878	0.877	0.877	0.878	0.878	0.878	0.875	0.875	0.874	43
44	0.874	0.873	0.873	0.872	0.872	0.871	0.871	0.871	0.870	0.870	44
45	0.869	0.869	0.868	0.868	0.867	0.867	0.868	0.868	0.865	0.865	45
46	0.864	0.864	0.864	0.863	0.883	0.862	0.862	0.861	0.861	0.860	46
47	0.860	0.859	0.859	0.858	0.858	0.857	0.857	0.856	0.856	0.855	47
48	0.855	0.854	0.854	0.853	0.853	0.852	0.852	0.851	0.851	0.850	48
49	0.850	0.849	0.849	0.848	0.848	0.847	0.847	0.848	0.846	0.845	49
50	0.845	0.844	0.844	0.843	0.842	0.842	0.841	0.841	0.840	0.840	50
51	0.839	0.839	0.838	0.838	0.837	0.837	0.836	0.838	0.835	0.835	51
52	0.834	0.833	0.833	0.832	0.832	0.831	0.831	0.830	0.830	0.829	52
53	0.828	0.828	0.827	0.827	0.826	0.826	0.825	0.824	0.824	0.823	53
54	0.823	0.822	0.822	0.821	0.820	0.820	0.819	0.819	0.818	0.818	54
55	0.817	0.817	0.816	0.815	0.815	0.814	0.814	0.813	0.812	0.812	55
56	0.811	0.811	0.810	0.810	0.809	0.808	0.808	0.807	0.806	0.806	56
57	0.805	0.805	0.804	0.804	0.803	0.802	0.802	0.801	0.800	0.800	57
58	0.799	0.799	0.798	0.797	0.797	0.798	0.795	0.795	0.794	0.794	58
59	0.793	0.793	0.792	0.791	0.791	0.790	0.789	0.789	0.788	0.788	59
60	0.787	0.786	0.786	0.785	0.784	0.784	0.783	0.783	0.782	0.781	60
61	0.780	0.780	0.779	0.779	0.778	0.777	0.776	0.776	0.775	0.775	61
62	0.774	0.773	0.773	0.772	0.771	0.771	0.770	0.769	0.769	0.768	62
63	0.767	0.767	0.766	0.765	0.765	0.764	0.763	0.763	0.762	0.761	63
64	0.760	0.760	0.759	0.759	0.758	0.757	0.756	0.756	0.755	0.755	64
65	0.754	0.753	0.752	0.752	0.751	0.750	0.750	0.749	0.748	0.748	65
66	0.747	0.746	0.745	0.745	0.744	0.743	0.742	0.742	0.741	0.740	66
67	0.739	0.739	0.738	0.737	0.736	0.736	0.735	0.734	0.733	0.733	67
68	0.732	0.731	0.730	0.730	0.729	0.728	0.727	0.727	0.726	0.725	68
69	0.724	0.723	0.722	0.722	0.721	0.720	0.719	0.718	0.718	0.717	69
70	0.716	0.715	0.714	0.714	0.713	0.712	0.711	0.710	0.709	0.709	70
71	0.708	0.707	0.708	0.705	0.704	0.703	0.702	0.702	0.701	0.700	71
72	0.699	0.698	0.697	0.698	0.696	0.695	0.694	0.693	0.692	0.691	72
73	0.690	0.689	0.688	0.687	0.688	0.685	0.684	0.683	0.683	0.682	73
74	0.681	0.680	0.679	0.878	0.877	0.676	0.675	0.674	0.673	0.672	74
75	0.671	0.670	0.669	0.668	0.687	0.666	0.665	0.664	0.663	0.662	75
76	0.661	0.660	0.659	0.658	0.657	0.656	0.655	0.654	0.653	0.652	76
77	0.651	0.650	0.649	0.648	0.647	0.745	0.644	0.643	0.642	0.640	77
78	0.639	0.638	0.637	0.636	0.634	0.633	0.632	0.631	0.630	0.629	78
79	0.627	0.626	0.625	0.624	0.622	0.621	0.620	0.619	0.617	0.616	79
80	0.615	0.614	0.612	0.611	0.610	0.609	0.608	0.607	0.605	0.604	80
81	0.603	0.602	0.600	0.599	0.598	0.597	0.598	0.594	0.593	0.592	81
82	0.591	0.590	0.588	0.587	0.586	0.584	0.583	0.582	0.581	0.580	82
83	0.578	0.577	0.576	0.575	0.573	0.572	0.571	0.570	0.568	0.567	83
84	0.566	0.564	0.563	0.562	0.560	0.559	0.558	0.556	0.555	0.554	84

TABLE 9 *Continued*

Motor Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Motor Octane Number
	Micrometer Setting, in.										
85	0.552	0.551	0.549	0.548	0.546	0.545	0.544	0.542	0.541	0.540	85
86	0.538	0.537	0.536	0.534	0.533	0.532	0.530	0.529	0.528	0.526	86
87	0.524	0.523	0.521	0.520	0.519	0.517	0.516	0.514	0.513	0.511	87
88	0.510	0.509	0.507	0.508	0.504	0.503	0.501	0.500	0.498	0.497	88
89	0.498	0.494	0.493	0.491	0.490	0.488	0.487	0.485	0.484	0.483	89
90	0.481	0.480	0.478	0.477	0.475	0.474	0.472	0.471	0.470	0.468	90
91	0.467	0.465	0.464	0.462	0.461	0.459	0.458	0.457	0.455	0.454	91
92	0.452	0.451	0.449	0.448	0.448	0.445	0.444	0.442	0.441	0.439	92
93	0.438	0.436	0.435	0.433	0.432	0.431	0.429	0.428	0.426	0.425	93
94	0.423	0.422	0.420	0.419	0.418	0.416	0.415	0.413	0.412	0.410	94
95	0.409	0.408	0.406	0.405	0.403	0.402	0.400	0.399	0.398	0.396	95
96	0.395	0.393	0.392	0.391	0.389	0.388	0.387	0.385	0.384	0.382	96
97	0.381	0.380	0.378	0.377	0.376	0.374	0.373	0.371	0.370	0.369	97
98	0.367	0.366	0.365	0.363	0.362	0.361	0.359	0.358	0.357	0.355	98
99	0.354	0.353	0.352	0.350	0.349	0.348	0.348	0.345	0.344	0.342	99
100	0.340	0.339	0.338	0.337	0.338	0.335	0.334	0.333	0.332	0.331	100
101	0.331	0.330	0.329	0.328	0.327	0.328	0.325	0.324	0.323	0.322	101
102	0.321	0.320	0.319	0.318	0.317	0.317	0.316	0.315	0.314	0.313	102
103	0.312	0.311	0.311	0.310	0.309	0.309	0.308	0.308	0.307	0.307	103
104	0.308	0.305	0.304	0.303	0.302	0.301	0.300	0.299	0.298	0.298	104
105	0.297	0.296	0.295	0.294	0.293	0.292	0.291	0.291	0.290	0.289	105
106	0.288	0.288	0.287	0.288	0.285	0.284	0.284	0.283	0.282	0.282	106
107	0.281	0.280	0.280	0.279	0.278	0.277	0.277	0.278	0.275	0.275	107
108	0.274	0.274	0.273	0.272	0.272	0.271	0.270	0.270	0.269	0.269	108
109	0.268	0.267	0.267	0.266	0.265	0.265	0.264	0.264	0.263	0.263	109
110	0.262	0.262	0.261	0.260	0.260	0.259	0.258	0.258	0.257	0.257	110
111	0.256	0.255	0.255	0.254	0.254	0.253	0.253	0.252	0.251	0.251	111
112	0.250	0.249	0.249	0.248	0.248	0.247	0.246	0.246	0.245	0.245	112
113	0.244	0.243	0.243	0.242	0.242	0.241	0.240	0.240	0.239	0.238	113
114	0.238	0.237	0.237	0.236	0.235	0.235	0.234	0.234	0.233	0.232	114
115	0.232	0.231	0.231	0.230	0.230	0.229	0.228	0.228	0.227	0.227	115
116	0.226	0.225	0.225	0.224	0.224	0.223	0.222	0.222	0.221	0.221	116
117	0.220	0.219	0.219	0.218	0.218	0.217	0.216	0.206	0.215	0.215	117
118	0.214	0.214	0.213	0.121	0.212	0.211	0.211	0.210	0.210	0.209	118
119	0.209	0.208	0.208	0.207	0.206	0.208	0.205	0.204	0.203	0.203	119
120	0.202	0.202	0.201	0.200	...	...	...	...	...	...	120

Tolerance is ±0.020 in. below 85 octane number and ±0.025 in. above 85 octane number.
Equivalent digital counter reading = (1.012-micrometer reading) 1410.

7.1.4 ASTM *dilute* tetraethyllead■.

7.2 *ASTM Reference Fuel Grade Toluene*■, conforming to the specifications in A2.7.1.4 of Annex 2, is blended with ASTM *iso*octane■, or ASTM *n*-heptane■, or both, to obtain standardization fuels■ used to check engine rating characteristics as prescribed in Section 13. Other fuels■ prepared from ASTM reference materials as directed in Section 13 of this method and Section A2.2 of Annex 2 may be used to check engine rating characteristics more extensively.

8. Sampling

8.1 Sampling shall be done in accordance with the applicable procedure described in Practice D 4057.

9. Standard Operating Conditions

9.1 The following standard operating conditions (see Annex 3 on Operation for further details) are mandatory:

9.1.1 *Engine Speed*, 900 ± 9 rpm, with a maximum variation of 9 rpm during a test.

9.1.2 *Spark Timing*, set as described in A4.40 of Annex 4.

9.1.2.1 *Basic Distributor Control Arm Setting*, horizontal when uncompensated digital counter reading is 264 (micrometer reading 0.825).

9.1.2.2 *Basic Spark Setting*, 26° BTDC at an uncompensated digital counter reading of 264 (micrometer reading 0.825).

9.1.2.3 *Spark Change with Compression Ratio*, automatically controlled to give:

Micrometer Reading, in.[A]	Digital Counter Reading	Spark Advance, deg
0.825	264	26
0.773	337	25
0.721	410	24
0.669	484	23
0.617	556	22
0.565	630	21
0.513	704	20
0.461	777	19
0.408	851	18
0.356	925	17
0.304	998	16
0.252	1072	15
0.200	1145	14

[A] Metric equivalents may be found in the back of this manual.

9.1.3 *Spark Plug Gap*, 0.020 ± 0.005 in. (0.51 ± 0.13 mm).

9.1.4 *Breaker-Point Gap*, 0.020 in. (0.51 mm). For a breakerless ignition system, the basic setting for transducer to rotor (vane) gap is 0.003 to 0.005 in. (0.08 to 0.13 mm).

9.1.5 *Rocker Arm Carrier Adjustment:*

9.1.5.1 *Basic Threaded Rocker-Arm Carrier Support Setting*—Each rocker arm carrier support shall be threaded into the cylinder so that the distance between the machined surface of the cylinder and the underside of the fork is 1-7/32 in. (31 mm).

9.1.5.2 *Basic Rocker Arm Carrier Setting*—The rocker arm carrier shall be set horizontal at an uncompensated digital counter reading of 722 (micrometer reading of 0.500).

9.1.5.3 *Basic Rocker Arm Setting*—With the rocker arm carrier set in the basic setting and the valves closed, the

TABLE 10 Guide Table for Standard Knock Intensity at 29.92 in. Hg (101.3 kPa) Barometric Pressure—Digital Counter Readings for Motor Octane Numbers Apply for Sea Level to 1600 ft (500 m) Altitude (9/16 Venturi)
See Table 15 for Corrections for Other Barometric Pressures

Motor Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Motor Octane Number
	Digital Counter Setting										
40	171	171	172	172	173	174	175	175	176	176	40
41	176	177	178	178	179	179	180	180	181	182	41
42	182	183	184	185	185	186	186	187	188	188	42
43	189	189	190	190	191	192	192	193	194	195	43
44	195	198	198	197	197	198	199	199	200	201	44
45	202	202	203	203	204	204	205	206	207	207	45
46	208	209	209	210	211	212	212	213	213	214	46
47	214	215	216	217	218	219	219	220	220	221	47
48	221	222	223	224	225	226	228	227	227	228	48
49	228	229	230	231	232	233	233	234	234	235	49
50	235	236	237	238	239	240	241	242	243	243	50
51	244	244	245	245	246	247	248	249	250	250	51
52	251	252	252	253	254	255	256	257	257	258	52
53	259	259	260	261	262	263	264	265	265	266	53
54	268	267	268	269	270	271	272	273	274	274	54
55	275	275	276	277	278	279	280	281	282	282	55
56	283	283	284	285	286	187	288	289	290	291	56
57	292	292	293	294	295	296	297	298	299	299	57
58	300	301	302	303	304	305	306	306	307	307	58
59	308	309	310	311	312	313	314	315	316	316	59
60	317	318	319	320	321	322	323	324	325	326	60
61	327	328	329	329	330	331	332	333	334	335	61
62	336	337	337	338	339	340	341	342	334	344	62
63	345	346	347	346	349	350	351	352	353	354	63
64	355	356	357	357	358	359	360	361	362	363	64
65	364	365	366	367	368	369	370	371	372	373	65
66	374	375	376	377	378	379	380	381	382	383	66
67	384	385	388	388	389	390	391	392	393	394	67
68	395	396	397	398	399	400	401	402	403	405	68
69	408	407	408	409	410	412	413	414	415	416	69
70	417	419	420	421	422	423	424	428	427	428	70
71	429	430	431	433	434	436	437	438	439	440	71
72	441	443	444	445	448	447	448	450	451	453	72
73	454	455	457	458	460	481	462	463	464	465	73
74	467	468	470	471	472	474	475	477	478	479	74
75	481	482	464	485	488	488	489	491	492	494	75
76	495	496	498	499	501	502	503	505	506	508	76
77	509	510	512	513	515	517	519	520	522	524	77
78	526	527	529	531	533	534	536	537	539	540	78
79	542	544	546	548	550	551	553	554	556	558	79
80	580	662	564	565	587	568	570	571	573	575	80
81	577	578	580	582	584	585	587	589	591	592	81
82	594	598	598	599	601	603	605	608	608	610	82
83	612	613	615	617	619	620	622	623	625	627	83
84	629	631	633	635	637	639	641	643	644	646	84
85	648	650	652	654	656	658	660	662	664	666	85
86	668	670	672	674	675	677	679	681	683	685	86
87	688	690	692	694	895	898	699	702	704	706	87
88	708	709	712	714	716	718	721	722	725	726	88
89	726	730	732	735	736	739	740	743	745	746	89

TABLE 10 *Continued*

Motor Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Motor Octane Number
	Digital Counter Setting										
90	749	750	753	754	757	759	761	763	764	767	90
91	769	771	773	776	777	780	781	783	785	787	91
92	790	791	794	795	798	800	801	804	805	808	92
93	809	812	814	816	818	819	822	824	826	828	93
94	831	832	835	836	838	840	842	845	846	849	94
95	850	852	855	856	859	860	863	864	866	869	95
96	870	873	874	876	879	880	881	884	886	888	96
97	890	891	894	895	897	900	901	904	905	907	97
98	910	911	912	915	917	916	921	922	924	926	98
99	928	929	931	934	935	936	939	941	942	945	99
100	948	949	950	952	953	955	956	957	959	960	100
101	960	962	963	965	966	967	969	970	972	973	101
102	974	976	977	979	980	980	981	983	984	986	102
103	987	988	988	990	991	991	993	993	994	994	103
104	995	997	998	1000	1001	1003	1004	1005	1006	1007	104
105	1008	1010	1011	1012	1014	1015	1016	1017	1018	1019	105
106	1020	1021	1022	1024	1025	1026	1027	1028	1029	1030	106
107	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	107
108	1041	1041	1042	1043	1044	1045	1046	1046	1047	1048	108
109	1049	1050	1051	1052	1053	1053	1054	1055	1056	1057	109
110	1058	1056	1059	1060	1061	1062	1063	1063	1064	1065	110
111	1066	1067	1068	1069	1069	1070	1071	1072	1073	1073	111
113	1074	1075	1076	1077	1078	1079	1080	1080	1081	1082	112
113	1083	1084	1084	1085	1088	1087	1088	1089	1090	1091	113
114	1092	1093	1093	1094	1095	1098	1097	1097	1098	1099	114
115	1100	1101	1101	1103	1103	1104	1105	1105	1107	1107	115
116	1108	1110	1110	1111	1111	1112	1114	1114	1115	1115	116
117	1117	1118	1118	1120	1120	1121	1122	1122	1124	1124	117
118	1125	1125	1127	1128	1128	1129	1129	1131	1131	1132	118
119	1132	1134	1134	1135	1136	1136	1136	1139	1141	1141	119
120	1142	1142	1144	1145	...	...	...	...	...	...	120

Tolerance is ±28 digital counter units below 85 octane number and ±35 units above 85 octane number

$$\text{Equivalent micrometer reading} = 1.012 - \frac{\text{digital counter reading}}{1410}.$$

rocker arms should be in the horizontal position.

9.1.6 *Valve Clearances*, 0.008 ± 0.001 in. (0.20 ± 0.03 mm), measured with the engine hot and running under standard operating conditions for 100 octane number.

9.1.7 *Crankcase Lubricating Oil*, SAE 30, having a kinematic viscosity of 9.62 to 12.93 cSt (mm^2/s) at 210°F (99°C) and a viscosity index of not less than 85. Oils containing viscosity index improvers or multi-graded oils shall not be used.

9.1.8 *Oil Pressure*, 25 to 30 psi (0.17 to 0.20 MPa) gage under operating conditions.

9.1.9 *Oil Temperature*, 135 ± 15°F (57 ± 8.5°C) with the temperature-sensitive element completely immersed in the crankcase oil.

9.1.10 *Coolant Temperature*, 212 ± 3°F (100 ± 1.5°C) constant within ±1°F (±0.5°C) during a test.

9.1.11 *Intake Air Humidity*, 25 to 50 grains of water/lb (0.00356 to 0.00712 kg of water/kg) of dry air (as described in Section A1.14 of Annex 1).

9.1.12 *Intake Air Temperature*, 100 ± 5°F (38 ± 2.8°C) as indicated by a mercury thermometer at the hole provided in the intake air pipe.

9.1.13 *Intake Mixture Temperature*, shall be measured at the hole provided in the intake manifold using ASTM thermometer 86°F and be maintained at 300 ± 2°F (149 ± 1.1°C). If intake mixture temperature tuning is used to establish the exact calibration octane number of a toluene standardization fuel blend, the temperature selected must be between 285°F (141°C) and 315°F (157°C) and this temperature must then be maintained within ±2°F (±1.1°C) for rating purposes.

9.1.14 *Carburetor Venturi*, with throat size dependent on altitude as follows:

Altitude, ft (m)	Diameter of Venturi Throat, in. (mm)
0 to 1600 (500)	9/16 (14.3)
1600 to 3300 (500 to 1000)	19/32 (15.1)
Over 3300 (1000)	3/4 (19.1)

9.1.15 *Basic Cylinder Height Setting*—After the engine reaches the mandatory temperatures, set the basic cylinder height as described in Section A3.2.

9.1.16 *Fuel-Air Ratio*, shall be that for maximum knock intensity for each test and reference fuel. It is obtained by varying the carburetor bowl height. The final fuel level must be in the range from 0.7 to 1.7 on the sight glass; otherwise a change in jet size is mandatory. Additional information about these adjustments and jet sizes may be found in Sections A3.12 and A4.38 of Annexes 3 and 4.

9.1.17 *Knockmeter Reading Limits*—The operational range for knock intensity readings on the knockmeter shall be from 20 to 80. Knock intensity is a nonlinear character-

istic below 20 and the knockmeter has the potential to be nonlinear above 80.

9.1.18 *Basic Detonation Meter Spread*, 10 to 18 knockmeter divisions per octane number at the 90 octane level. Spread has a characteristic variation with octane level but if properly set at 90 octane number need not in most cases be altered for ratings from 80 to 102 octane number.

9.1.19 *Reference Fuels Bracketing Procedure*—The knockmeter reading of the test fuel■ must be bracketed by those of two reference fuel blends■ selected from the reference fuel system of either 3.12.1 or 3.12.2, but never by a combination of 3.12.1 and 3.12.2. The two blends must not differ by more than two octane numbers. In the range between 100.0 and 103.5 octane number, only the following reference fuel■ pairs shall be used:

100.0 and 100.7
100.7 and 101.3
101.3 and 102.5
102.5 and 103.5

9.1.20 *Reference Fuels, Compression Ratio Procedure*—The knockmeter reading of the test fuel■ must match that of a reference fuel■ blend selected from the reference fuel systems of either 3.12.1 or 3.12.2. In the range between 100.0 and 103.5 octane number, only the following reference fuels■ shall be used: 100.7, 101.3, 102.5, and 103.5. Permissible differences between test fuel and reference fuel octane values are specified in 16.1.3.

TABLE 10a Guide Table for Standard Knock Intensity at 29.92 in. Hg (101.3 kPa) Barometric Pressure—Motor Octane Numbers for Digital Counter Readings Apply for Sea Level to 1600 ft (500 m) Altitude (⁹⁄₁₆ Venturi)

Digital Counter Setting	0	1	2	3	4	5	6	7	8	9	Digital Counter Setting
	Motor Octane Number										
170	40.0	40.1	40.3	40.4	40.5	40.7	40.9	41.1	41.3	41.5	170
180	41.7	41.8	42.0	42.1	42.2	42.4	42.6	42.7	42.9	43.1	180
190	43.3	43.4	43.6	43.7	43.8	44.0	44.2	44.4	44.5	44.7	190
200	44.8	44.9	45.1	45.3	45.5	45.6	45.8	45.9	46.0	46.2	200
210	46.3	46.4	46.6	46.8	46.9	47.1	47.2	47.3	47.4	47.6	210
220	47.8	48.0	48.1	48.2	48.3	48.5	48.6	48.8	48.9	49.1	220
230	49.2	49.3	49.4	49.6	49.8	49.9	50.1	50.2	50.3	50.4	230
240	50.5	50.6	50.8	50.9	51.1	51.3	51.4	51.5	51.8	51.8	240
250	5.19	52.0	52.2	52.3	52.4	52.5	52.6	52.8	52.9	53.0	250
260	53.2	53.3	53.4	53.5	53.6	53.8	53.9	54.1	54.2	54.3	260
270	54.4	54.5	54.6	54.7	54.9	55.0	55.2	55.3	55.4	55.5	270
280	55.8	55.7	55.9	58.1	58.2	58.3	56.4	56.5	56.6	56.7	280
290	56.8	56.9	57.1	57.2	57.3	57.4	57.5	57.8	57.7	57.9	290
300	58.0	58.1	58.2	58.3	58.4	58.8	58.7	58.8	58.9	59.0	300
310	59.2	59.3	59.4	59.5	59.8	59.7	59.8	60.0	60.0	60.2	310
320	60.3	60.4	60.5	60.8	60.7	60.8	60.9	61.0	61.1	61.3	320
330	61.4	61.5	61.6	61.7	81.8	61.9	62.0	62.1	62.3	62.4	330
340	62.5	62.8	62.7	62.8	62.9	83.0	63.1	63.2	63.3	63.4	340
350	63.5	83.6	63.7	63.8	63.9	84.0	64.1	63.4	64.4	64.5	350
360	64.6	64.7	64.8	64.9	65.0	65.1	65.2	65.3	65.4	65.5	360
370	65.6	65.7	65.8	65.9	66.0	66.1	66.2	66.3	66.4	66.5	370
380	66.6	66.7	66.8	66.9	67.0	67.1	67.2	67.2	67.3	67.4	380
390	67.5	87.6	67.7	67.8	67.9	68.0	68.1	68.2	68.3	68.4	390
400	68.5	68.8	68.7	68.8	68.8	68.9	69.0	69.1	69.2	69.3	400
410	69.4	69.4	69.5	69.6	69.7	69.8	69.9	70.0	70.0	70.1	410
420	70.2	70.3	70.4	70.5	70.8	70.7	70.7	70.8	70.9	71.0	420
430	71.1	71.2	71.2	71.3	71.4	71.5	71.5	71.8	71.7	71.8	430
440	71.9	72.0	72.0	72.1	72.2	72.3	72.4	72.5	72.6	72.6	440
450	72.7	72.8	72.8	72.9	73.0	73.1	73.2	73.2	73.3	73.4	450
460	73.4	73.5	73.6	73.7	73.8	73.9	73.9	74.0	74.1	74.2	460
470	74.2	74.3	74.4	74.4	74.5	74.6	74.7	74.7	74.8	74.9	470
480	74.9	75.0	75.1	75.2	75.2	75.3	75.4	75.4	75.5	75.6	480
490	75.6	75.7	75.8	75.9	75.9	76.0	76.1	76.1	76.2	76.3	490
500	76.4	76.4	76.5	76.6	76.6	76.7	76.8	76.8	76.9	77.0	500
510	77.1	77.1	77.2	77.3	77.3	77.4	77.4	77.5	77.6	77.6	510
520	77.7	77.7	77.8	77.8	77.9	78.0	78.0	78.1	78.1	78.2	520
530	78.3	78.3	78.4	78.4	78.5	78.8	78.6	78.7	78.7	78.8	530
540	78.9	78.9	79.0	79.0	79.1	79.1	79.2	79.3	79.3	79.4	540
550	79.4	79.5	79.5	79.6	79.7	79.7	79.8	79.8	79.9	80.0	550
560	80.0	80.1	80.1	80.2	80.2	80.3	80.4	80.4	80.5	80.5	560
570	80.6	80.7	80.7	80.8	80.8	80.9	80.9	81.0	81.1	81.1	570
580	81.2	81.2	81.3	81.4	81.4	81.5	81.5	81.6	81.6	81.7	580
590	81.8	81.8	81.9	81.9	82.0	82.0	82.1	82.2	82.2	82.3	590
600	82.3	82.4	82.4	82.5	82.6	82.6	82.7	82.7	82.8	82.8	600
810	82.9	83.0	83.0	83.1	83.1	83.2	83.2	83.3	83.4	83.4	610
620	83.5	83.5	83.6	83.7	83.7	83.8	83.8	83.9	83.9	84.0	620
630	84.0	84.1	84.2	84.2	84.3	84.3	84.4	84.4	84.5	84.5	630
640	84.6	84.6	84.7	84.7	84.8	84.8	84.9	84.9	85.0	85.0	640

TABLE 10a *Continued*

Digital Counter Setting	0	1	2	3	4	5	6	7	8	9	Digital Counter Setting
	Motor Octane Number										
650	85.1	85.1	85.2	85.2	85.3	85.3	85.4	85.4	85.5	85.5	650
660	85.6	85.6	85.7	85.7	85.8	85.8	85.9	86.0	86.0	86.1	660
670	86.1	86.2	86.2	86.3	86.3	86.4	86.4	86.6	86.5	86.6	670
680	86.6	86.7	86.7	86.8	86.8	86.9	86.9	87.0	87.0	87.1	680
690	87.1	87.2	87.2	87.3	87.3	87.4	87.4	87.5	87.5	87.6	690
700	87.6	87.7	87.7	87.8	87.8	87.9	87.9	88.0	88.0	88.1	700
710	88.1	88.2	88.2	88.2	88.3	88.3	88.4	88.4	88.5	88.5	710
720	88.8	88.6	88.7	88.7	88.8	88.8	88.9	88.9	89.0	89.0	720
730	89.1	89.1	89.2	89.2	89.3	89.3	89.4	89.4	89.5	89.5	730
740	89.6	89.6	89.7	89.7	89.8	89.8	89.9	89.9	90.0	90.0	740
750	90.1	90.1	90.2	90.2	90.3	90.3	90.4	90.4	90.5	90.5	750
760	90.6	90.6	90.7	90.7	90.8	90.8	90.9	90.9	91.0	91.0	760
770	91.1	91.1	91.2	91.2	91.2	91.3	91.3	91.4	91.4	91.5	770
780	91.5	91.6	91.6	91.7	91.7	91.8	91.8	91.9	91.9	92.0	780
790	92.0	92.1	92.1	92.2	92.2	92.3	92.3	92.4	92.4	92.5	790
800	92.5	92.6	92.6	92.7	92.7	92.8	92.8	92.9	92.9	93.0	800
810	93.0	93.1	93.1	93.2	93.2	93.3	93.3	93.4	93.4	93.5	810
820	93.5	93.8	93.6	93.7	93.7	93.8	93.8	93.9	93.9	94.0	820
830	94.0	94.0	94.1	94.1	94.2	94.2	94.3	94.3	94.4	94.4	830
840	94.5	94.5	94.8	94.8	94.7	94.7	94.8	94.8	94.9	94.9	840
850	95.0	95.0	95.1	95.1	95.2	95.2	95.3	95.3	95.4	95.4	850
860	95.5	95.5	95.6	95.8	95.7	95.7	95.8	95.8	95.9	95.9	860
870	96.0	96.0	96.1	96.1	96.2	96.2	96.3	96.3	96.4	96.4	870
880	96.5	96.6	96.8	96.7	96.7	96.8	96.8	96.9	96.9	97.0	880
890	97.0	97.1	97.1	97.2	97.2	97.3	97.3	97.4	97.4	97.5	890
900	97.5	97.6	97.6	97.7	97.7	97.8	97.8	97.9	97.9	98.0	900
910	98.0	98.1	98.2	98.2	98.3	98.3	98.4	98.4	98.5	98.5	910
920	98.6	98.6	98.7	98.8	98.8	98.9	98.9	99.0	99.0	99.1	920
930	99.1	99.2	99.2	99.3	99.3	99.4	99.5	99.5	99.6	99.6	930
940	99.7	99.7	99.8	99.8	99.9	99.9	99.9	100.0	100.0	100.1	940
950	100.2	100.2	100.3	100.4	100.4	100.5	100.6	100.7	100.7	100.8	950
960	100.9	101.0	101.1	101.2	101.2	101.3	101.4	101.5	101.6	101.6	960
970	101.7	101.8	101.8	101.9	102.0	102.0	102.1	102.2	102.2	102.3	970
980	102.4	102.6	102.8	102.7	102.8	102.8	102.9	103.0	103.2	103.3	980
990	103.3	103.4	103.8	103.6	103.8	104.0	104.0	104.1	104.2	104.2	990
1000	104.3	104.4	104.4	104.5	104.6	104.7	104.8	104.9	105.0	105.0	1000
1010	105.1	105.2	105.3	105.3	105.4	105.5	105.8	105.7	105.8	105.9	1010
1020	106.0	106.1	106.2	106.2	106.3	106.4	106.5	106.6	106.7	106.8	1020
1030	106.9	107.0	107.1	107.2	107.3	107.4	107.5	107.6	107.7	107.8	1030
1040	107.9	108.0	106.2	106.3	108.4	108.5	108.8	106.8	108.9	109.0	1040
1050	109.2	109.2	109.3	109.4	109.6	109.7	109.8	109.9	110.0	110.2	1050
1060	110.3	110.4	110.5	110.8	110.8	110.9	111.0	111.1	111.2	111.4	1060
1070	111.5	111.6	111.7	111.8	112.0	112.1	112.2	112.3	112.4	112.5	1070
1080	112.7	112.8	112.9	113.0	113.1	113.3	113.4	113.5	113.6	113.7	1080
1090	113.8	113.9	114.0	114.2	114.3	114.4	114.5	114.6	114.8	114.9	1090

9.1.21 *Sample Handling*—All samples■ shall be cooled to a temperature between 35°F (2°C) and 50°F (10°C) *before* the container is opened and the sample■ is introduced into the appropriate carburetor bowl.

10. Starting and Stopping Engine

10.1 *Starting the Engine*—While the engine is being motored, turn on the ignition and start the engine by setting the carburetor to draw fuel■ from the float bowl. Turn on cooling water.

10.2 *Stopping the Engine*—Turn off the fuel■, drain all fuel bowls, turn off the ignition, turn off water to the exhaust spray and coolant condenser, and motor the engine for 1 min before stopping the synchronous motor. To avoid possible corrosion and warpage of engine intake and exhaust valves and seats between operating periods, close both valves by turning the flywheel to tdc on the compression stroke.

11. Adjusting Knock Measurement Instrumentation

11.1 The following adjustments and operational guide lines (see Annex 7 on Instrumentation for further details) are important to proper use of the knock measurement instrumentation which includes the detonation pickup, detonation meter, and indicating knockmeter:

11.1.1 Knockmeter needle mechanical zero,

11.1.2 Detonation meter zero,

11.1.3 Time constant,

11.1.4 Meter reading (meter output signal level),

11.1.5 Spread (meter gain or sensitivity level), and

11.1.5.1 Basic spread setting shall be 10 to 18 knockmeter divisions per octane number at 90 octane number. Spread varies with octane level and the values obtained between 80 and 102 octane number will normally provide suitable resolution and signal stability for optimum test measurement.

12. Adjustments for Standard Knock Intensity

12.1 With the engine at equilibrium temperature and the carburetor set for maximum knock, adjust the cylinder height for standard knock intensity (10.1.16) at the micrometer or digital counter setting obtained from Tables 9 through 14 for the octane number of the reference fuel blend being used and corrected in accordance with Table 15 for the barometric pressure at the time of the test.

NOTE 2—Any correctly adjusted mercury barometer or a properly compensated aneroid barometer may be used to measure barometric pressure. Aneroid barometers should be calibrated at least once a year.

12.2 Under the conditions specified in 12.1, set the METER READING controls to obtain a 50 knockmeter reading and then turn off the ignition. The engine should cease firing instantly. If it does, the testing unit is ready for a check of its rating characteristics with an appropriate basic toluene standardization fuel. If it does not, the engine conditions are unsatisfactory. Examine the engine for objectionable combustion chamber and spark plug deposits.

TABLE 11 Guide Table for Standard Knock Intensity at 29.92 in. Hg (101.3 kPa) Barometric Pressure—Micrometer Readings for Motor Octane Numbers Apply for 1600 to 3300 ft (500 to 1000 m) Altitude (1 9/32 Venturi)
See Table 15 for Corrections for Other Barometric Pressures

Motor Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Motor Octane Number
	Micrometer Setting, in.										
40	0.980	0.980	0.979	0.979	0.978	0.978	0.977	0.977	0.976	0.976	40
41	0.975	0.975	0.974	0.974	0.973	0.973	0.972	0.972	0.971	0.971	41
42	0.970	0.970	0.969	0.969	0.968	0.968	0.967	0.967	0.966	0.966	42
43	0.965	0.965	0.964	0.964	0.963	0.963	0.962	0.962	0.961	0.961	43
44	0.960	0.960	0.959	0.959	0.958	0.958	0.957	0.957	0.956	0.956	44
45	0.955	0.954	0.954	0.953	0.953	0.952	0.952	0.951	0.951	0.950	45
46	0.950	0.949	0.949	0.948	0.948	0.947	0.947	0.946	0.945	0.945	46
47	0.944	0.944	0.943	0.943	0.942	0.942	0.941	0.941	0.940	0.940	47
48	0.939	0.938	0.938	0.937	0.937	0.936	0.936	0.935	0.934	0.934	48
49	0.933	0.933	0.932	0.932	0.931	0.930	0.930	0.929	0.929	0.928	49
50	0.928	0.927	0.926	0.926	0.925	0.925	0.924	0.923	0.923	0.922	50
51	0.922	0.921	0.920	0.920	0.919	0.919	0.918	0.918	0.917	0.916	51
52	0.916	0.915	0.914	0.914	0.913	0.913	0.912	0.911	0.911	0.910	52
53	0.910	0.909	0.908	0.908	0.907	0.906	0.906	0.905	0.905	0.904	53
54	0.903	0.903	0.902	0.901	0.901	0.900	0.899	0.899	0.898	0.898	54
55	0.897	0.898	0.896	0.895	0.894	0.894	0.893	0.892	0.892	0.891	55
56	0.890	0.890	0.889	0.888	0.887	0.887	0.886	0.885	0.885	0.884	56
57	0.883	0.883	0.882	0.881	0.881	0.880	0.879	0.879	0.878	0.877	57
58	0.876	0.876	0.875	0.874	0.874	0.873	0.872	0.871	0.871	0.870	58
59	0.869	0.869	0.868	0.867	0.868	0.866	0.865	0.864	0.863	0.863	59
60	0.862	0.861	0.860	0.860	0.859	0.858	0.857	0.856	0.856	0.855	60
61	0.854	0.953	0.853	0.852	0.851	0.850	0.850	0.849	0.848	0.847	61
62	0.846	0.846	0.845	0.844	0.843	0.842	0.842	0.841	0.840	0.839	62
63	0.838	0.837	0.837	0.836	0.835	0.834	0.833	0.832	0.832	0.831	63
64	0.830	0.829	0.828	0.827	0.827	0.826	0.825	0.824	0.823	0.822	64
65	0.822	0.821	0.820	0.819	0.818	0.817	0.816	0.815	0.814	0.814	65
66	0.813	0.812	0.811	0.810	0.809	0.808	0.807	0.806	0.805	0.805	66
67	0.804	0.803	0.802	0.801	0.800	0.799	0.798	0.797	0.796	0.795	67
68	0.794	0.793	0.792	0.791	0.790	0.790	0.789	0.788	0.787	0.786	68
69	0.785	0.784	0.783	0.782	0.781	0.780	0.779	0.778	0.777	0.776	69
70	0.775	0.774	0.773	0.772	0.771	0.770	0.769	0.768	0.767	0.766	70
71	0.765	0.764	0.763	0.762	0.761	0.760	0.759	0.758	0.756	0.755	71
72	0.754	0.753	0.752	0.751	0.750	0.749	0.748	0.747	0.746	0.745	72
73	0.744	0.743	0.742	0.740	0.739	0.738	0.737	0.736	0.735	0.734	73
74	0.733	0.732	0.730	0.729	0.728	0.727	0.728	0.725	0.724	0.723	74
75	0.721	0.720	0.719	0.718	0.717	0.716	0.714	0.713	0.712	0.711	75
76	0.710	0.709	0.707	0.706	0.705	0.704	0.703	0.702	0.700	0.699	76
77	0.698	0.697	0.696	0.694	0.693	0.692	0.691	0.690	0.688	0.687	77
78	0.686	0.685	0.683	0.682	0.681	0.680	0.679	0.677	0.676	0.675	78
79	0.674	0.672	0.671	0.670	0.669	0.667	0.666	0.665	0.664	0.662	79
80	0.661	0.660	0.658	0.657	0.658	0.655	0.653	0.652	0.651	0.649	80
81	0.648	0.647	0.645	0.644	0.643	0.642	0.640	0.639	0.638	0.636	81
82	0.635	0.634	0.632	0.631	0.630	0.628	0.627	0.828	0.624	0.623	82
83	0.622	0.620	0.619	0.618	0.618	0.615	0.613	0.612	0.611	0.609	83
84	0.608	0.607	0.605	0.604	0.602	0.601	0.600	0.598	0.597	0.596	84

TABLE 11 *Continued*

Motor Octane Number	Micrometer Setting, in.										Motor Octane Number
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	
85	0.594	0.593	0.591	0.590	0.588	0.587	0.588	0.584	0.583	0.582	85
86	0.580	0.579	0.577	0.578	0.575	0.573	0.572	0.570	0.569	0.568	86
87	0.566	0.565	0.563	0.562	0.561	0.559	0.558	0.556	0.555	0.553	87
88	0.552	0.551	0.549	0.548	0.548	0.545	0.543	0.542	0.540	0.539	88
89	0.538	0.536	0.535	0.533	0.532	0.530	0.529	0.527	0.526	0.525	89
90	0.523	0.522	0.520	0.519	0.517	0.516	0.514	0.513	0.512	0.510	90
91	0.509	0.507	0.506	0.504	0.503	0.501	0.500	0.499	0.497	0.496	91
92	0.494	0.493	0.491	0.490	0.488	0.487	0.488	0.484	0.483	0.481	92
93	0.480	0.478	0.477	0.475	0.474	0.473	0.471	0.470	0.468	0.467	94
94	0.465	0.464	0.462	0.461	0.460	0.458	0.457	0.455	0.454	0.452	94
95	0.451	0.450	0.448	0.447	0.445	0.444	0.442	0.441	0.440	0.438	95
96	0.437	0.435	0.434	0.433	0.431	0.430	0.429	0.427	0.426	0.424	96
97	0.423	0.422	0.420	0.419	0.418	0.416	0.415	0.413	0.412	0.411	97
98	0.409	0.408	0.407	0.405	0.404	0.403	0.401	0.400	0.399	0.397	98
99	0.398	0.395	0.394	0.392	0.391	0.390	0.388	0.387	0.386	0.385	99
100	0.383	0.381	0.379	0.378	0.377	0.376	0.375	0.374	0.372	0.371	100
101	0.370	0.369	0.367	0.368	0.364	0.383	0.362	0.360	0.359	0.358	101
102	0.357	0.355	0.355	0.354	0.352	0.351	0.350	0.349	0.347	0.346	102
103	0.345	0.345	0.344	0.343	0.342	0.341	0.340	0.339	0.338	0.337	103
104	0.336	0.335	0.334	0.333	0.332	0.331	0.330	0.330	0.329	0.328	104
105	0.328	0.327	0.328	0.325	0.325	0.324	0.323	0.323	0.322	0.321	105
106	0.321	0.321	0.320	0.319	0.318	0.318	0.317	0.318	0.316	0.315	106
107	0.314	0.313	0.313	0.312	0.312	0.311	0.311	0.310	0.309	0.308	107
108	0.308	0.306	0.307	0.308	0.308	0.308	0.305	0.304	0.303	0.303	108
109	0.302	0.302	0.301	0.301	0.300	0.300	0.299	0.299	0.299	0.298	109
110	0.297	0.297	0.298	0.298	0.298	0.298	0.295	0.294	0.294	0.294	110
111	0.294	0.293	0.293	0.292	0.291	0.291	0.290	0.290	0.289	0.289	111
112	0.288	0.287	0.288	0.288	0.285	0.285	0.284	0.284	0.283	0.283	112
113	0.282	0.282	0.282	0.281	0.280	0.279	0.279	0.278	0.277	0.277	113
114	0.278	0.275	0.274	0.274	0.273	0.273	0.272	0.272	0.271	0.270	114
115	0.270	0.269	0.269	0.268	0.268	0.287	0.266	0.268	0.265	0.265	115
116	0.264	0.263	0.263	0.282	0.281	0.260	0.260	0.259	0.258	0.258	116
117	0.257	0.258	0.258	0.255	0.255	0.254	0.253	0.253	0.252	0.252	117
118	0.251	0.250	0.250	0.249	0.249	0.248	0.248	0.247	0.247	0.246	118
119	0.248	0.245	0.245	0.244	0.244	0.243	0.242	0.242	0.241	0.240	119
120	0.240	0.239	0.239	0.238	...	...	...	...	...	...	120

Tolerance is ± 0.020 in. below 85 octane number and ±0.025 in. above 85 octane number.
Equivalent digital counter reading = (1.012 − micrometer reading) 1410.

Remedy such conditions and repeat the operations in Section 12.

13. Check on Rating Characteristics

13.1 The octane rating of each sample■ must be determined on an engine that has been qualified on a toluene standardization fuel■ whose value is no further from the sample octane number than that for the nearest blend■ listed in Table 16 (Note 3).

NOTE 3—The situation may exist where there is reasonable assurance the engine will rate the toluene■ standardization fuels within the rating tolerances. In such cases, time usually can be saved by rating the test fuel■ first if its expected rating is completely unknown or cannot be estimated closely enough to select the required toluene standardization fuel■.

13.1.1 Additional information relating to both toluene standardization fuel■ testing and the use of leaded blends■ of ASTM *iso*octane■ and ASTM *n*-heptane■ is included in A3.14.

13.1.2 *Intake Mixture Temperature Tuning*—If a toluene standardization fuel blend within the 79.0 to 93.0 octane number range does not rate within the tolerances given in Table 16, it is permissible to adjust the intake mixture temperature within the range of 285°F (141°C) and 315°F (157°C) so that the toluene standardization fuel blend rating is exactly equal to the calibration value. The selected intake mixture temperature can be used for all test fuels whose octane numbers are no more than ±2.0 octane numbers from the toluene standardization fuel blend used.

13.1.2.1 When an intake mixture temperature other than 300°F (149°C) is used, standard knock intensity must be established at that intake mixture temperature using primary reference fuel and the prescribed guide table cylinder height setting for the octane number of the primary reference fuel.

13.2 *Frequency of Checking:*

13.2.1 In laboratories where an overnight engine shutdown occurs, the first check on rating characteristics shall be made at or near the beginning of each operating day and as frequently thereafter as required to conform with 13.1.

13.2.2 For laboratories where operation is essentially continuous or where it is planned to test more than one fuel■ in a given period of operation, the rating check of a given

basic toluene standardization fuel■ is applicable only to test fuels■ rated during the next 7 h.

13.2.3 When there is a change of operators or when an engine shutdown of more than 2 h occurs, it is desirable to make a check on rating characteristics.

13.2.4 If during any engine shutdown, adjustments or changes are made in the equipment, a recheck of rating characteristics must be made at or near the beginning of the next operating period.

14. Obtaining Maximum Knock Fuel-Air Ratio and Standard Knock Intensity

14.1 *Preliminary Adjustment of Cylinder Height*—Pour the quantity of cooled sample■ (9.1.21) required for a test into one of the carburetor tanks. Set the fuel level of this carburetor at the estimated maximum knock position and turn the selector valve to operate on this fuel■. Allow time for equilibrium engine conditions and then adjust the cylinder height for a knockmeter reading of 45 to 47. The desired average knockmeter reading is 50. Time can usually be saved by making the preliminary cylinder height adjustment for a reading lower than 50, as it may increase when the fuel level is adjusted for maximum knock.

14.2 *Adjustment of Fuel-Air Ratio*—Determine the fuel level for a maximum reading on the knockmeter by the procedure described in the example in 14.2.1.

TABLE 12 Guide Table for Standard Knock Intensity at 29.92 in. Hg (101.3 kPa) Barometric Pressure—Digital Counter Readings for Motor Octane Numbers Apply for 1600 to 3300 ft (500 to 1000 m) Altitude (19/32 Venturi)
See Table 15 for Corrections for Other Barometric Pressures

Motor Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Motor Octane Number
	Digital Counter Setting										
40	45	45	46	47	48	48	49	49	50	51	40
41	52	53	54	54	55	55	56	56	57	58	41
42	59	60	61	61	62	62	63	63	64	65	42
43	66	67	68	68	69	69	70	70	71	72	43
44	73	74	75	75	78	76	77	78	79	79	44
45	80	81	82	83	84	85	85	86	86	87	45
46	87	88	89	90	91	92	92	93	94	94	46
47	95	96	97	98	99	99	100	100	101	102	47
48	103	104	105	106	106	107	108	109	110	110	48
49	111	111	112	113	114	115	116	117	117	118	49
50	119	120	121	121	122	123	124	125	126	127	50
51	127	128	129	130	131	132	133	133	134	135	51
52	136	137	138	138	139	140	141	142	143	144	52
53	144	145	146	147	148	149	150	151	151	152	53
54	153	154	155	156	157	158	159	160	161	161	54
55	162	163	164	165	166	167	168	169	170	171	55
56	172	173	174	175	176	177	178	179	179	180	56
57	181	182	183	184	185	186	187	188	189	190	57
58	191	192	193	194	195	198	197	198	199	200	58
59	201	202	203	204	205	208	207	209	210	211	59
60	212	213	214	215	216	217	219	220	220	221	60
61	223	224	225	226	227	228	229	230	231	232	61
62	233	234	235	237	238	239	240	241	243	244	62
63	245	246	247	248	250	251	252	253	254	255	63
64	257	258	259	260	281	262	264	265	266	267	64
65	268	269	271	272	274	275	278	278	279	280	65
66	281	282	283	285	286	288	289	290	291	292	66
67	293	295	296	298	299	300	302	303	305	306	67
68	307	309	310	312	313	314	315	316	317	319	68
69	320	321	323	324	328	327	329	330	331	333	69
70	334	336	337	338	340	341	343	344	345	347	70
71	348	350	351	352	354	355	357	359	361	362	71
72	364	365	367	368	369	371	372	374	375	376	72
73	378	379	381	383	385	386	388	389	391	392	73
74	393	395	397	399	400	402	403	405	406	408	74
75	410	412	413	415	418	418	420	422	423	424	75
76	426	428	430	431	433	434	436	438	440	441	76
77	443	444	448	448	450	451	453	455	457	458	77
78	460	461	463	465	467	468	470	472	474	475	78
79	477	479	481	482	484	486	488	489	491	493	79
80	495	497	499	501	502	504	506	508	510	512	80
81	513	515	517	519	520	522	524	526	528	530	81
82	532	534	536	537	539	541	543	545	547	548	82
83	550	552	554	556	558	560	562	564	566	568	83
84	570	572	574	576	578	580	582	584	585	587	84

TABLE 12 *Continued*

Motor Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Motor Octane Number
	Digital Counter Setting										
85	589	591	593	595	597	599	601	603	605	607	85
86	609	611	613	615	617	619	621	623	625	627	86
87	629	631	633	634	638	638	640	642	644	647	87
88	649	651	653	655	657	659	661	663	665	667	88
89	669	671	673	675	877	679	681	683	685	687	89
90	689	691	693	695	697	699	702	704	706	708	90
91	710	712	714	716	718	720	722	724	726	728	91
92	730	732	734	738	738	740	742	744	746	748	92
93	750	752	754	757	759	761	763	765	767	769	93
94	771	773	775	777	779	781	763	785	787	789	94
95	791	793	795	797	799	801	803	805	807	809	95
96	811	813	815	817	819	821	823	825	827	829	96
97	830	832	834	838	838	840	842	844	846	848	97
98	850	852	854	858	857	859	861	863	865	867	98
99	869	870	872	874	876	877	879	881	883	885	99
100	887	890	892	894	895	897	898	900	902	904	100
101	905	907	909	911	913	915	917	919	921	922	101
102	924	926	927	928	930	932	933	935	937	939	102
103	940	941	942	943	945	946	948	949	950	952	103
104	953	955	956	957	959	960	961	962	963	964	104
105	965	966	967	968	969	970	971	972	973	974	105
106	974	975	976	977	978	979	980	981	982	983	106
107	984	985	986	987	987	988	989	990	991	992	107
108	993	993	994	995	995	996	997	998	999	1000	108
109	1001	1001	1002	1003	1004	1004	1005	1005	1006	1007	109
110	1008	1008	1009	1009	1010	1010	1011	1012	1012	1013	110
111	1013	1014	1014	1015	1016	1017	1018	1018	1019	1020	111
112	1021	1022	1023	1024	1025	1025	1026	1027	1028	1028	112
113	1029	1029	1030	1031	1032	1033	1034	1035	1036	1037	113
114	1038	1039	1041	1041	1042	1042	1043	1044	1045	1046	114
115	1046	1048	1048	1049	1049	1050	1053	1052	1053	1053	115
116	1055	1056	1056	1058	1059	1060	1060	1062	1063	1063	116
117	1085	1066	1066	1067	1067	1069	1070	1070	1072	1072	117
118	1073	1074	1074	1078	1078	1077	1077	1079	1079	1080	118
119	1080	1081	1081	1083	1083	1084	1086	1086	1087	1089	119
120	1089	1090	1090	1091	...	...	...	...	...	...	120

Tolerance is ±28 digital counter units below 85 octane number and ±35 units above 85 octane number.

$$\text{Equivalent micrometer reading} = 1.012 - \frac{\text{digital counter reading}}{1410}.$$

14.2.1 With a setting, for example, of 1.3 on the etched glass scale, allow the knockmeter needle to reach equilibrium and record the reading. Then obtain and record knockmeter readings for richer fuel-air ratios by raising the fuel level by 0.1 increments to 1.2, 1.1, . . ., until the knockmeter reading has decreased at least five divisions from the maximum. Reset the fuel level at the position for which the maximum knockmeter reading was obtained, for example, 1.2. Follow the same procedure for leaner fuel-air ratios by setting in turn at 1.3, 1.4, . . ., until the knockmeter reading has decreased at least five divisions from the maximum. Set the fuel level at the position for which the maximum knockmeter reading was obtained, or between the two positions for which the reading was the same, for example 1.25. This is the position for maximum knock. Verify it at least once by settings at levels 0.1 on either side—in the example just given at both 1.15 and 1.35. If higher knockmeter readings are obtained at either of these positions, the setting is in error and the entire procedure must be repeated. For each setting of the fuel level, allow the knockmeter needle to reach equilibrium before recording readings.

14.3 *Sample Cooling*—Cooling of the critical carburetor assembly components is mandatory if there is excessive gasoline vaporization as evidenced by bubbling in the sight glass, fluctuating sight glass fuel level, or uneven engine combustion.

14.3.1 *Standard Coolant*—Jacketed carburetor components are described in A1.12.2 of Annex 1. The circulated coolant (water or a water antifreeze solution) must not be cooler than 33°F (0.5°C) in the carburetor coolant exchangers. This coolant may be circulated when rating any gasoline sample.

14.4 *Final Adjustment of Cylinder Height*—After locating the fuel level for maximum knock, adjust the cylinder height, if required for a knockmeter reading of 50.

14.4.1 *Bracketing Procedure*—Use this cylinder height for the remainder of the test, provided that later observations show that it is within the tolerances specified in 15.9 for the knock rating of the sample■.

14.4.2 *Compression Ratio Procedure*—Allow sufficient time for the engine and knockmeter to reach equilibrium. This time will vary with the fuel■, deposits from the previous fuel■ on which the engine was operated, testing range, and the condition of the equipment. When the engine has reached equilibrium make a final adjustment of the cylinder height, if necessary, so that the knockmeter reading is 50 ± 1.

15. Bracketing Procedure for Rating the Sample

NOTE 4—For compression ratio procedure, go directly to Section 16.

15.1 Bracket or match the knocking tendency of the test sample■ by the knocking tendency of reference fuels■ from one of the fuel systems defined in 3.1 or 3.2.

15.2 *Reference Fuel Blends*—Use specified combinations of the reference materials listed in 7.1 to prepare the

TABLE 12a Guide Table for Standard Knock Intensity at 29.92 In. Hg (101.3 kPa) Barometric Pressure—Motor Octane Numbers for Digital Counter Readings Apply for 1600 to 3300 ft (500 to 1000 m) Altitude (1⁹⁄₃₂ Venturi)
See Table 29 for Corrections for Other Barometric Pressures.

Digital Counter Setting	0	1	2	3	4	5	6	7	8	9	Digital Counter Setting
	Motor (CR) Octane Number										
40					40.0	40.1	40.2	40.3	40.4	40.6	40
50	40.8	40.9	41.0	41.1	41.2	41.4	41.6	41.8	41.9	42.0	50
60	42.1	42.2	42.4	42.6	42.8	42.9	43.0	43.1	43.2	43.4	60
70	43.6	43.8	43.9	44.0	44.1	44.2	44.4	44.6	44.7	44.8	70
80	45.0	45.1	45.2	45.3	45.4	45.6	45.8	46.0	46.1	46.2	80
90	46.3	46.4	46.6	46.7	46.8	47.0	47.1	47.2	47.3	47.4	90
100	47.6	47.8	47.9	48.0	48.1	48.2	48.4	48.5	48.6	48.7	100
110	48.8	49.0	49.2	49.3	49.4	49.5	49.6	49.8	49.9	50.0	110
120	50.1	50.2	50.4	50.5	50.6	50.7	50.8	51.0	51.1	51.2	120
130	51.3	51.4	51.5	51.6	51.8	51.9	52.0	52.1	52.2	52.4	130
140	52.5	52.6	52.7	52.8	53.0	53.1	53.2	53.3	53.4	53.5	140
150	53.6	53.8	53.9	54.0	54.1	54.2	54.3	54.4	54.5	54.6	150
160	54.7	54.8	55.0	55.1	55.2	55.3	55.4	55.5	55.6	55.7	160
170	55.8	55.9	56.0	56.1	56.2	56.3	56.4	56.5	56.6	56.8	170
180	56.9	57.0	57.1	57.2	57.3	57.4	57.5	57.6	57.7	57.8	180
190	57.9	58.0	58.1	58.2	58.3	58.4	58.5	58.6	58.7	58.8	190
200	58.9	59.0	59.1	59.2	59.3	59.4	59.5	59.6	59.6	59.7	200
210	59.8	59.9	60.0	60.1	60.2	60.3	60.4	60.5	60.6	60.7	210
220	60.8	60.9	61.0	61.0	61.1	61.2	61.3	61.4	61.5	61.6	220
230	61.7	61.8	61.9	62.0	62.1	62.2	62.2	62.3	62.4	62.5	230
240	62.6	62.7	62.8	62.8	62.9	63.0	63.1	63.2	63.3	63.4	240
250	63.4	63.5	63.6	63.7	63.8	63.9	64.0	64.0	64.1	64.2	250
260	64.3	64.4	64.5	64.6	64.6	64.7	64.8	64.9	65.0	65.1	260
270	65.2	65.2	65.3	65.4	65.4	65.5	65.8	65.6	65.7	65.8	270
280	65.9	66.0	66.1	66.2	66.2	68.3	66.4	66.4	66.5	66.6	280
290	66.7	66.8	66.9	67.0	67.0	67.1	67.2	67.2	67.3	67.4	290
300	67.5	67.6	67.6	67.7	67.8	67.8	67.9	68.0	68.0	68.1	300
310	68.2	68.2	68.3	68.4	68.5	68.6	68.7	68.8	68.8	68.9	310
320	69.0	69.1	69.2	69.2	69.3	69.4	69.4	69.5	69.6	69.6	320
330	69.7	69.8	69.8	69.9	70.0	70.0	70.1	70.2	70.3	70.4	330
340	70.4	70.5	70.6	70.6	70.7	70.8	70.8	70.9	71.0	71.0	340
350	71.1	71.2	71.3	71.4	71.4	71.5	71.6	71.6	71.7	71.7	350
360	71.8	71.8	71.9	72.0	72.0	72.1	72.2	72.2	72.3	72.4	360
370	72.4	72.5	72.6	72.6	72.7	72.8	72.9	73.0	73.0	73.1	370
380	73.2	73.2	73.3	73.3	73.4	73.4	73.5	73.6	73.6	73.7	380
390	73.8	73.8	73.9	74.0	74.0	74.1	74.2	74.2	74.3	74.3	390
400	74.4	74.4	74.5	74.8	74.8	74.7	74.8	74.8	74.9	75.0	400
410	75.0	75.1	75.1	75.2	75.2	75.3	75.4	75.4	75.5	75.6	410
420	75.6	75.7	75.7	75.8	75.9	76.0	76.0	76.1	76.1	76.2	420
430	76.2	76.3	76.4	76.4	76.5	76.6	76.6	76.7	76.7	76.8	430
440	76.8	76.9	77.0	77.0	77.1	77.2	77.2	77.3	77.3	77.4	440
450	77.4	77.5	77.6	77.6	77.7	77.7	77.8	77.8	77.9	78.0	450
460	78.0	78.1	78.2	78.2	78.3	78.3	78.4	78.4	78.5	78.6	460
470	78.6	78.7	78.7	78.8	78.8	78.9	79.0	79.0	79.1	79.1	470
480	79.2	79.2	79.3	79.4	79.4	79.5	79.5	79.6	79.6	79.7	480
490	79.8	79.8	79.9	79.9	80.0	80.0	80.1	80.1	80.2	80.2	490
500	80.3	80.3	80.4	80.4	80.5	80.6	80.6	80.7	80.7	80.8	500
510	80.8	80.9	80.9	81.0	81.0	81.1	81.2	81.2	81.3	81.3	510
520	81.4	81.4	81.5	81.6	81.6	81.7	81.7	81.8	81.8	81.9	520
530	81.9	82.0	82.0	82.1	82.1	82.2	82.2	82.3	82.4	82.4	530
540	82.5	82.5	82.6	82.6	82.7	82.7	82.8	82.8	82.9	83.0	540
550	83.0	83.1	83.1	83.2	83.2	83.3	83.3	83.4	83.4	83.5	550
560	83.5	83.6	83.6	83.7	83.7	83.8	83.8	83.9	83.9	84.0	560
570	84.0	84.1	84.1	84.2	84.2	84.3	84.3	84.4	84.4	84.5	570
580	84.5	84.6	84.6	84.7	84.7	84.8	84.8	84.9	85.0	85.0	580

TABLE 12a *Continued*

Digital Counter Setting	0	1	2	3	4	5	6	7	8	9	Digital Counter Setting
	Motor (CR) Octane Number										
590	85.1	85.1	85.2	85.2	85.3	85.3	85.4	85.4	85.5	85.5	590
600	85.6	85.6	85.7	85.7	85.8	85.8	85.9	85.9	86.0	86.0	600
610	86.1	86.1	86.2	86.2	86.3	86.3	86.4	86.4	86.5	86.5	610
620	86.6	86.6	86.7	86.7	86.8	86.8	86.9	86.9	87.0	87.0	620
630	87.1	87.1	87.2	87.2	87.3	87.3	87.4	87.4	87.5	87.5	630
640	87.6	87.6	87.7	87.7	87.8	87.8	87.9	87.9	88.0	88.0	640
650	88.1	88.1	88.2	88.2	88.3	88.3	88.4	88.4	88.5	88.5	650
660	88.6	88.6	88.7	88.7	88.8	88.8	88.9	88.9	89.0	89.0	660
670	89.1	89.1	89.2	89.2	89.3	89.3	89.4	89.4	89.5	89.5	670
680	89.6	89.6	89.7	89.7	89.8	89.8	89.9	89.9	90.0	90.0	680
690	90.1	90.1	90.2	90.2	90.3	90.3	90.4	90.4	90.4	90.5	690
700	90.5	90.6	90.6	90.7	90.7	90.8	90.8	90.9	90.9	91.0	700
710	91.0	91.1	91.1	91.2	91.2	91.3	91.3	91.4	91.4	91.5	710
720	91.5	91.6	91.6	91.7	91.7	91.8	91.8	91.9	91.9	92.0	720
730	92.0	92.1	92.1	92.2	92.2	92.3	92.3	92.4	92.4	92.5	730
740	92.5	92.8	92.8	92.7	92.7	92.8	92.8	92.9	92.9	93.0	740
750	93.0	93.1	93.1	93.2	93.2	93.2	93.3	93.3	93.4	93.4	750
760	93.5	93.5	93.6	93.6	93.7	93.7	93.8	93.8	93.9	93.9	760
770	94.0	94.0	94.1	94.1	94.2	94.2	94.3	94.3	94.4	94.4	770
780	94.5	94.5	94.8	94.8	94.7	94.7	94.8	94.8	94.9	94.9	780
790	95.0	95.0	95.1	95.1	95.2	95.2	95.3	95.3	95.4	95.4	790
800	95.5	95.5	95.6	95.6	95.7	95.7	95.8	95.8	95.9	95.9	800
810	96.0	96.0	96.1	96.1	96.2	96.2	96.3	96.3	96.4	96.4	810
820	96.5	96.5	96.6	96.8	96.7	96.7	96.8	96.8	96.9	96.9	820
830	97.0	97.0	97.1	97.1	97.2	97.2	97.3	97.3	97.4	97.4	830
840	97.5	97.5	97.6	97.6	97.7	97.7	97.8	97.8	97.9	97.9	840
850	98.0	98.0	98.1	98.1	98.2	98.2	98.3	98.4	98.4	98.5	850
860	98.5	98.8	98.8	98.7	98.7	98.8	98.8	98.9	99.0	99.0	860
870	99.1	99.2	99.2	99.3	99.3	99.4	99.4	99.5	99.5	99.6	870
880	99.6	99.7	99.7	99.8	99.8	99.9	99.9	100.0	100.0	100.1	880
890	100.1	100.2	100.2	100.3	100.3	100.4	100.4	100.5	100.6	100.6	890
900	100.7	100.7	100.8	100.8	100.9	101.0	101.0	101.1	101.1	101.2	900
910	101.2	101.3	101.3	101.4	101.4	101.5	101.5	101.6	101.6	101.7	910
920	101.8	101.8	101.9	102.0	102.0	102.1	102.1	102.2	102.3	102.4	920
930	102.4	102.5	102.5	102.6	102.6	102.7	102.8	102.8	102.9	102.9	930
940	103.0	103.1	103.2	103.3	103.4	103.4	103.5	103.6	103.6	103.7	940
950	103.8	103.8	103.9	104.0	104.0	104.1	104.2	104.3	104.4	104.4	950
960	104.5	104.6	104.7	104.8	104.9	105.0	105.1	105.2	105.3	105.4	960
970	105.5	105.6	105.7	105.8	106.0	106.1	106.2	106.3	106.4	106.5	970
980	106.6	106.7	106.8	106.9	107.0	107.1	107.2	107.4	107.5	107.6	980
990	107.7	107.8	107.9	108.0	108.2	108.4	108.5	108.6	108.7	108.8	990
1000	108.9	109.0	109.2	109.3	109.4	109.6	109.8	109.9	110.0	110.2	1000
1010	110.4	110.6	110.8	111.0	111.2	111.3	111.4	111.5	111.6	111.8	1010
1020	111.9	112.0	112.1	112.2	112.3	112.4	112.6	112.7	112.8	113.0	1020
1030	113.2	113.3	113.4	113.5	113.8	113.7	113.8	113.9	114.0	114.1	1030
1040	114.2	114.3	114.4	114.6	114.7	114.8	115.0	115.1	115.2	115.3	1040
1050	115.4	115.5	115.8	115.8	116.0	116.1	116.2	116.2	116.3	116.4	1050
1060	116.5	116.6	116.7	116.8	117.0	117.1	117.2	117.3	117.4	117.5	1060
1070	117.6	117.8	117.9	118.0	118.1	118.2	118.4	118.6	118.7	118.8	1070
1080	119.0	119.1	119.2	119.4	119.5	119.8	119.7	119.8	119.9	120.0	1080
1090	120.1	120.2	120.3								

$$\text{Equivalent micrometer reading} = 1.012 - \frac{\text{digital counter reading}}{1410}$$

necessary reference fuel blends for making the knocking tendency comparison required in 15.1. Thoroughly mix all such reference fuel blends before use. Detailed information on the blending procedures is given in Section A2.4 of Annex 2. The specified combinations of the reference materials are as follows (Note 6):

15.2.1 ASTM *n*-heptane and ASTM 80 octane blend.

15.2.2 ASTM 80 octane blend and ASTM *iso*octane.

15.2.3 ASTM *iso*octane and ASTM *dilute* tetraethyllead.

NOTE 5—ASTM *n*-heptane and ASTM *iso*-octane can be used to make a laboratory 80 octane number blend for use in place of the ASTM 80 octane blend specified in 15.2.1 and 15.2.2. However, this practice is *not* recommended.

15.3 *First Bracketing Reference Fuel*—Based on the cylinder height determined in 13.4, make a reference fuel

blend■ near the estimated octane number of the sample■ and pour it into one of the other carburetor tanks. Set the fuel level on this carburetor at the estimated maximum knock position and turn the selector valve to operate on this fuel■. When the knockmeter needle has reached equilibrium, adjust the fuel level for maximum knock as described in 14.2 and record the knockmeter reading.

15.4 *Second Bracketing Reference Fuel*—Make a second reference fuel blend■ that it is expected will bracket the knockmeter reading of the sample■ and that differs from the first reference fuel■ by no more than two octane numbers (9.1.18). Pour this reference fuel blend■ into the third carburetor tank. Set the fuel level on this carburetor at the estimated maximum knock position and turn the selector valve to operate on this fuel■. When the knockmeter needle has reached equilibrium, adjust the fuel level for maximum knock as described in 14.2 and record the knockmeter reading. If the readings for the two reference fuel blends■ bracket that for the sample■, or if the reading for the sample■ matches that of one of the reference fuel blends■, proceed with the test as described in 15.7.

15.5 *Checking Conformance to Standard Knock Intensity*—If the knockmeter readings for the first and second reference fuel blends■ do not meet the requirements in 15.4, estimate the rating of the sample■ from the knockmeter readings obtained. If the cylinder height is within the

TABLE 13 Guide Table for Standard Knock Intensity at 29.92 in. Hg (101.3 kPa) Barometric Pressure—Micrometer Readings for Motor Octane Numbers Apply for Altitudes over 3300 ft (1000 m) (¾ Venturi)

See Table 15 for Corrections for Other Barometric Pressures

Motor Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Motor Octane Number
	Micrometer Setting, in.										
40	1.018	1.018	1.017	1.017	1.016	1.016	1.015	1.015	1.014	1.014	40
41	1.013	1.013	1.012	1.012	1.011	1.011	1.010	1.010	1.009	1.009	41
42	1.008	1.008	1.007	1.007	1.006	1.006	1.005	1.005	1.004	1.004	42
43	1.003	1.003	1.002	1.002	1.001	1.001	1.000	1.000	0.999	0.999	43
44	0.998	0.998	0.997	0.997	0.996	0.996	0.995	0.995	0.994	0.994	44
45	0.993	0.992	0.992	0.991	0.991	0.990	0.990	0.989	0.989	0.988	45
46	0.988	0.987	0.987	0.986	0.986	0.985	0.985	0.984	0.983	0.983	46
47	0.982	0.982	0.981	0.981	0.980	0.980	0.979	0.979	0.978	0.978	47
48	0.977	0.976	0.976	0.975	0.975	0.974	0.974	0.973	0.972	0.972	48
49	0.971	0.971	0.970	0.970	0.969	0.968	0.968	0.967	0.967	0.966	49
50	0.966	0.965	0.964	0.964	0.963	0.963	0.962	0.961	0.961	0.960	50
51	0.960	0.959	0.958	0.958	0.957	0.957	0.956	0.956	0.955	0.954	51
52	0.954	0.953	0.952	0.952	0.951	0.951	0.950	0.949	0.949	0.948	52
53	0.948	0.947	0.946	0.946	0.945	0.944	0.944	0.943	0.943	0.942	53
54	0.941	0.941	0.940	0.939	0.939	0.938	0.937	0.937	0.936	0.936	54
55	0.935	0.934	0.934	0.933	0.932	0.932	0.931	0.930	0.930	0.929	55
56	0.928	0.928	0.927	0.928	0.925	0.925	0.924	0.923	0.923	0.922	56
57	0.921	0.921	0.920	0.919	0.919	0.916	0.917	0.917	0.916	0.915	57
58	0.914	0.914	0.913	0.912	0.912	0.911	0.910	0.909	0.909	0.908	58
59	0.907	0.907	0.908	0.905	0.904	0.904	0.903	0.902	0.901	0.901	59
60	0.900	0.899	0.898	0.898	0.897	0.896	0.895	0.894	0.894	0.893	60
61	0.892	0.891	0.891	0.890	0.889	0.888	0.888	0.887	0.886	0.885	61
62	0.884	0.884	0.883	0.882	0.881	0.880	0.880	0.879	0.878	0.877	62
63	0.878	0.875	0.875	0.874	0.873	0.872	0.871	0.870	0.970	0.869	63
64	0.868	0.867	0.866	0.865	0.865	0.864	0.863	0.862	0.861	0.860	64
65	0.860	0.859	0.858	0.857	0.856	0.855	0.854	0.853	0.852	0.852	65
66	0.851	0.850	0.849	0.848	0.847	0.846	0.845	0.844	0.843	0.843	66
67	0.842	0.841	0.840	0.839	0.838	0.837	0.836	0.835	0.834	0.833	67
68	0.832	0.831	0.830	0.829	0.828	0.828	0.827	0.826	0.825	0.824	68
69	0.823	0.822	0.821	0.820	0.819	0.818	0.817	0.816	0.815	0.814	69
70	0.813	0.812	0.811	0.810	0.809	0.808	0.807	0.808	0.805	0.804	70
71	0.803	0.802	0.801	0.800	0.799	0.798	0.797	0.796	0.794	0.793	71
72	0.792	0.791	0.790	0.789	0.788	0.787	0.786	0.785	0.784	0.783	72
73	0.782	0.781	0.780	0.778	0.777	0.776	0.775	0.774	0.773	0.772	73
74	0.771	0.770	0.768	0.767	0.768	0.765	0.764	0.763	0.762	0.761	74
75	0.759	0.758	0.757	0.756	0.755	0.754	0.752	0.751	0.750	0.749	75
76	0.748	0.747	0.745	0.744	0.743	0.742	0.741	0.740	0.738	0.737	76
77	0.736	0.735	0.734	0.732	0.731	0.730	0.729	0.728	0.726	0.725	77
78	0.724	0.723	0.721	0.720	0.719	0.718	0.717	0.715	0.714	0.713	78
79	0.712	0.710	0.709	0.708	0.707	0.705	0.704	0.703	0.702	0.700	79
80	0.699	0.698	0.696	0.695	0.694	0.693	0.691	0.690	0.689	0.687	80
81	0.686	0.685	0.683	0.682	0.681	0.680	0.678	0.677	0.676	0.674	81
82	0.673	0.672	0.670	0.669	0.668	0.666	0.665	0.664	0.662	0.661	82
83	0.660	0.658	0.657	0.656	0.654	0.653	0.651	0.650	0.649	0.647	83
84	0.646	0.645	0.643	0.642	0.640	0.639	0.638	0.636	0.635	0.634	84

TABLE 13 *Continued*

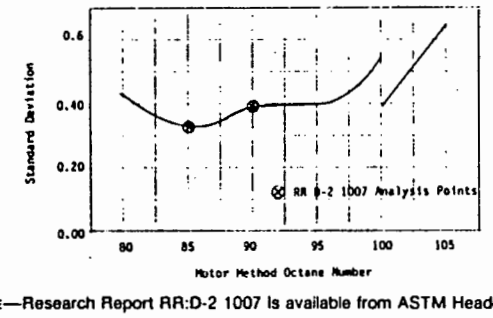
Motor Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Motor Octane Number
	Micrometer Setting, in.										
85	0.632	0.631	0.629	0.628	0.627	0.625	0.624	0.622	0.621	0.620	85
86	0.618	0.617	0.615	0.814	0.813	0.811	0.610	0.608	0.607	0.606	86
87	0.604	0.603	0.601	0.600	0.599	0.597	0.598	0.594	0.593	0.591	87
88	0.590	0.589	0.587	0.586	0.584	0.583	0.581	0.580	0.578	0.577	88
89	0.578	0.574	0.573	0.571	0.570	0.568	0.567	0.565	0.564	0.563	89
90	0.561	0.560	0.558	0.557	0.555	0.554	0.552	0.551	0.550	0.548	90
91	0.547	0.545	0.544	0.542	0.541	0.539	0.538	0.537	0.535	0.534	91
92	0.532	0.531	0.529	0.528	0.526	0.525	0.524	0.522	0.521	0.519	92
93	0.518	0.516	0.515	0.513	0.512	0.511	0.509	0.508	0.506	0.505	93
94	0.503	0.502	0.500	0.499	0.498	0.496	0.495	0.493	0.492	0.490	94
95	0.489	0.488	0.486	0.485	0.483	0.482	0.480	0.479	0.478	0.476	95
96	0.475	0.473	0.472	0.471	0.469	0.468	0.467	0.465	0.464	0.462	96
97	0.461	0.460	0.458	0.457	0.456	0.454	0.453	0.451	0.450	0.449	97
98	0.447	0.446	0.445	0.443	0.442	0.441	0.439	0.438	0.437	0.435	98
99	0.434	0.433	0.432	0.430	0.429	0.428	0.426	0.425	0.424	0.423	99
100	0.421	0.419	0.417	0.416	0.415	0.414	0.413	0.411	0.410	0.408	100
101	0.408	0.407	0.406	0.404	0.402	0.401	0.400	0.399	0.397	0.396	101
102	0.395	0.394	0.392	0.391	0.391	0.389	0.388	0.386	0.385	0.384	102
103	0.384	0.383	0.382	0.381	0.380	0.379	0.378	0.377	0.376	0.375	103
104	0.374	0.373	0.372	0.371	0.370	0.369	0.369	0.368	0.367	0.366	104
105	0.365	0.364	0.364	0.363	0.362	0.362	0.362	0.361	0.360	0.360	105
106	0.359	0.358	0.357	0.357	0.358	0.358	0.355	0.355	0.354	0.353	106
107	0.352	0.352	0.351	0.350	0.350	0.349	0.348	0.348	0.347	0.347	107
108	0.348	0.348	0.345	0.345	0.344	0.343	0.342	0.342	0.341	0.341	108
109	0.340	0.340	0.340	0.339	0.339	0.338	0.338	0.337	0.336	0.336	109
110	0.335	0.335	0.335	0.334	0.334	0.333	0.333	0.333	0.333	0.332	110
111	0.332	0.331	0.330	0.330	0.330	0.329	0.328	0.328	0.327	0.327	111
112	0.328	0.325	0.325	0.324	0.323	0.323	0.323	0.322	0.321	0.321	112
113	0.320	0.320	0.319	0.319	0.318	0.318	0.317	0.318	0.316	0.315	113
114	0.314	0.313	0.313	0.313	0.312	0.311	0.311	0.310	0.309	0.308	114
115	0.308	0.307	0.307	0.308	0.305	0.305	0.304	0.303	0.302	0.302	115
116	0.301	0.300	0.300	0.299	0.299	0.298	0.297	0.297	0.296	0.296	116
117	0.295	0.294	0.294	0.293	0.293	0.292	0.291	0.291	0.290	0.290	117
118	0.289	0.288	0.288	0.287	0.287	0.286	0.286	0.285	0.285	0.284	118
119	0.284	0.283	0.283	0.282	0.282	0.281	0.280	0.280	0.279	0.279	119
120	0.278	0.278	0.277	0.278	...	...	...	...	...	...	120

Tolerance is ±0.020 in. below 85 octane number and ±0.025 in. above 85 octane number.
Equivalent digital counter reading = (1.012 − micrometer reading) 1410.

specified tolerances given in Tables 9 through 14 for the estimated rating of the sample■, proceed with the test as described in 15.6. If not, make the required adjustments to the cylinder height and detonation meter and repeat the procedure in 15.3 and 15.4 as required.

15.6 *Third Bracketing Reference Fuel*—If a third reference fuel blend■ is required to bracket or match the knockmeter reading of the sample■, prepare a blend■ that differs from the second reference fuel blend■ by no more than two octane numbers (9.1.18). Drain the carburetor containing the first reference fuel blend■ and pour the third reference fuel blend■ into the tank of this carburetor. Follow the instructions given in 15.4 to obtain a maximum knockmeter reading on this fuel■.

15.7 *Order of Readings*—At this point, one series of knockmeter readings has been obtained on the sample■ and on the bracketing reference fuels■. With the three carburetor bowls set to give maximum knock, take another knockmeter reading on each fuel■ in the following order (Note 6): (*1*) sample■, (*2*) second bracketing reference fuel■, and (*3*) first bracketing reference fuel■. In taking this series of readings, verify the carburetor settings for maximum knock as described in 14.2. Allow sufficient time after fuel changes for the engine and knockmeter needle to reach equilibrium. The amount of time required for equilibrium readings will vary with the fuel■, deposits from the previous fuel■ on which the engine was operated, testing range, and condition of the equipment.



NOTE—Research Report RR:D-2 1007 is available from ASTM Headquarters.

FIG. 4a Reproducibility Standard Deviation of Motor Method

NOTE 6—The sequence of reference fuel readings is reversed from that followed in the first series. This reversal is helpful in detecting residual deposit effects from the sample■ that delay the obtaining of true knock intensity readings on the reference fuels■.

15.8 *Number of Knockmeter Readings*—For completion of a test, the required minimum number of knockmeter readings is as follows:

15.8.1 Two knockmeter readings on the sample■ and two on each bracketing reference fuel■ constitute a test provided (*1*) the difference in ratings calculated from the first and second series of readings is no greater than 0.3 octane number, and (*2*) the average reading on the test sample■ is within the specified limits of 50 ± 5.

15.8.2 Three knockmeter readings on the sample■ and three on each bracketing reference fuel■ constitute a test provided (*1*) the difference in ratings calculated from the first and second series of readings is no greater than 0.5 octane number, (*2*) the rating calculated from the third series of

TABLE 14 Guide Table for Standard Knock Intensity at 29.92 in. Hg (101.3 kPa) Barometric Pressure—Digital Counter Readings for Motor Octane Numbers Apply for Altitudes over 3300 ft (1000 m) (¾ Venturi)

See Table 15 for Corrections for Other Barometric Pressures

Motor Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Motor Octane Number
	Digital Counter Setting										
40	...	...	...	...	...	...	...	...	...	...	40
41	...	...	0	0	1	2	3	3	4	4	41
42	5	6	7	7	8	9	10	10	11	11	42
43	12	13	14	15	16	16	17	17	18	18	43
44	19	20	21	22	23	23	24	24	25	26	44
45	27	28	28	29	30	31	31	32	33	34	45
46	34	35	35	36	37	38	38	39	40	41	46
47	42	43	44	44	45	45	46	47	48	48	47
48	49	50	51	52	53	54	54	55	58	56	48
49	57	58	59	60	61	62	62	63	63	64	49
50	65	66	67	68	69	70	71	72	72	73	50
51	74	75	78	76	77	78	79	79	80	81	51
52	82	83	84	85	86	86	87	88	89	90	52
53	91	92	93	93	94	95	96	97	98	99	53
54	100	101	102	103	103	104	105	106	107	108	54
55	109	110	110	111	112	113	114	115	118	117	55
56	118	119	120	121	122	123	124	125	126	127	56
57	128	129	130	131	132	133	134	135	136	137	57
58	138	139	140	141	141	142	144	145	146	147	58
59	148	149	150	151	152	153	154	155	156	157	59
60	158	159	160	161	162	164	165	166	167	168	60
61	169	170	171	172	173	174	175	176	178	179	61
62	180	181	182	183	185	186	187	188	189	190	62
63	192	193	194	195	198	197	199	200	201	202	63
64	203	204	206	207	208	209	210	212	213	214	64
65	215	218	217	219	220	221	223	224	225	226	65
66	227	228	230	231	233	234	235	237	238	239	66
67	240	241	243	244	245	247	248	250	251	252	67
68	254	255	257	258	259	260	261	262	264	265	68
69	266	268	269	271	272	274	275	276	278	279	69
70	281	282	283	285	286	288	289	290	292	293	70
71	295	296	298	299	300	302	303	305	307	309	71
72	310	312	313	314	318	317	319	320	321	323	72
73	324	328	327	329	331	333	334	336	337	338	73
74	340	341	343	345	347	348	350	351	352	354	74
75	356	358	360	361	362	364	366	368	369	371	75
76	372	374	376	378	379	381	382	384	386	388	76
77	389	391	393	395	398	398	399	401	403	405	77
78	406	408	410	412	413	415	417	419	420	422	78
79	424	426	427	429	430	432	434	436	438	440	79
80	441	443	445	447	448	450	452	454	456	458	80
81	460	461	463	465	467	469	471	472	474	476	81
82	478	480	482	484	485	487	489	491	493	495	82
83	497	499	501	502	504	506	508	510	512	514	83
84	516	518	520	522	524	526	528	530	532	534	84
85	536	538	540	541	543	545	547	549	551	553	85
86	555	557	559	561	563	565	567	569	571	573	86
87	575	577	579	581	583	585	587	589	591	593	87
88	595	597	599	601	603	605	607	609	612	614	88
89	615	617	619	621	623	626	628	630	632	634	89

TABLE 14 *Continued*

Motor Octane Number	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Motor Octane Number
	Digital Counter Setting										
90	636	638	640	642	644	646	648	650	652	654	90
91	656	658	660	662	664	666	668	670	672	674	91
92	676	678	681	683	685	687	689	691	693	695	92
93	697	699	701	703	705	707	709	711	713	715	93
94	717	719	721	723	725	727	729	731	733	735	94
95	737	739	741	743	745	747	750	752	754	756	95
96	758	760	761	763	765	767	769	771	773	775	96
97	777	779	781	783	785	787	789	791	792	794	97
98	798	798	800	802	804	806	808	809	811	813	98
99	815	816	818	820	822	824	826	828	829	831	99
100	833	836	839	840	842	843	845	847	849	851	100
101	852	853	855	857	860	862	863	865	867	869	101
102	870	872	874	875	876	878	880	882	884	885	102
103	886	887	888	890	891	893	894	895	897	898	103
104	900	901	902	904	905	908	907	908	909	911	104
105	912	913	914	915	918	916	917	918	919	920	105
106	921	922	923	924	925	925	926	927	928	929	106
107	930	931	932	933	934	935	936	936	937	938	107
108	939	939	940	941	942	943	944	945	946	946	108
109	947	948	948	949	949	950	951	952	953	953	109
110	954	955	955	956	956	957	957	958	958	959	110
111	959	960	961	962	962	963	964	965	966	966	111
112	967	968	969	970	971	971	972	973	974	975	112
113	978	976	977	977	978	979	980	981	982	983	113
114	984	985	986	986	987	988	989	990	991	992	114
115	993	994	994	995	997	997	998	1000	1001	1001	115
116	1003	1004	1004	1005	1005	1007	1008	1008	1010	1010	116
117	1011	1012	1012	1014	1014	1015	1017	1017	1018	1018	117
118	1019	1021	1021	1022	1022	1024	1024	1025	1025	1026	118
119	1026	1028	1028	1029	1029	1031	1032	1032	1034	1034	119
120	1035	1035	1036	1038	...	...	...	...	...	...	120

Tolerance is ±28 digital counter units below 85 octane number and ±35 units above 85 octane number.

$$\text{Equivalent micrometer reading} = 1.012 - \frac{\text{digital counter reading}}{1410}$$

readings is between the ratings calculated from the first and second series of readings, and (*3*) the average reading on the test sample is within the specified limits of 50 ± 5.

15.8.3 If the difference in ratings calculated from the first and second series of knockmeter readings is greater than 0.5 octane number, or if the rating calculated from the third series of readings is not between the ratings calculated from the first and second series of readings, discard all readings and repeat the test procedures described in Sections 14 and 15.

15.9 *Checking Conformance to Standard Knock Intensity*—If the requirements of 15.8 are met, make certain that the cylinder height as measured by either the micrometer or digital counter is within ±0.020 in. or ±28 digital counter units below 85 octane number and ±0.025 in. or ±35 digital counter units above 85 octane number of those given in the appropriate standard knock intensity Tables 9 through 14, corrected in accordance with Table 15 for the prevailing barometric pressure, for the octane number of the reference fuel■ that matches the sample■. If the cylinder height is not within these tolerances, adjust it to the correct height and adjust the METER READING controls again to give a 50 knockmeter reading. After these adjustments have been made, repeat the test on the fuel sample■.

15.10 For subsequent testing of fuel samples■, the knockmeter reading is used as a guide for obtaining standard knock intensity by adjusting the cylinder height to obtain a knockmeter reading of 50 at the maximum knock fuel-air ratio for the fuel sample■. At the completion of each test, check for conformance to standard knock intensity as described in 15.9.

15.10.1 If the barometric pressure changes more than 0.2 in. Hg (0.68 kPa) during an operating period when an engine has been standardized in accordance with 13.2, repeat the operations described therein.

15.11 *Calculation:*

15.11.1 Average the knockmeter readings obtained in accordance with the detailed instructions given in 15.8, and Section A3.15 of Annex 3 for the sample■ and the two bracketing reference fuels■.

15.11.2 Use the average knockmeter readings of 15.11.1 and calculate the octane number to the second decimal as in the example in A3.16.1.4 of Annex 3.

15.11.3 Round the calculated octane number of 15.11.2 to the nearest tenth. Any octane number ending exactly in 5 in the second decimal shall be rounded to the nearest even tenth number; for example, round 95.55 and 95.65 to 95.6.

16. Compression Ratio Procedure for Rating the Sample

16.1 *Reading the Octane Number:*

16.1.1 *Reading the Cylinder Height Indicator*—Obtain the micrometer or digital counter reading for the final cylinder height used in 14.4 and correct it to a barometric pressure of 29.92 in. Hg (101.3 kPa) in accordance with Table 15.

16.1.2 *Converting to Equivalent Octane Number*—Using the applicable table, 9 through 14, read the octane number equivalent to the cylinder height indicator reading obtained in 16.1.1.

16.1.3 The octane rating of the sample■ is not acceptable if it differs by more than the appropriate value given below from the octane number of the reference fuel blend■ last used to establish standard knock intensity.

Sample Rating Range in Octane Number	Maximum Permissible Octane Number Difference Between Reference Fuel and Sample
Below 90	2.0
90 to 100	1.0
100 to 102	0.7
102 to 105	1.3
Above 105	2.0

When the difference between the reference fuel■ and sample■ exceeds the listed value, reestablish the standard knock intensity as described in Section 12, but using a reference fuel blend■ with an octane number differing from the sample■ by not more than the listed limits. If the knockmeter reads 50 for this new reference fuel blend■, the sample rating may be accepted. If not, repeat Section 12 with the new reference fuel blend■ and retest the sample■ as described in Section 14.

16.1.4 The standard knock intensity should be reestablished in accordance with Section 12 or 16.1.3 after every fourth sample■ tested in the range below 100 octane and after every second sample■ tested in the range above 100 octane number. More frequent rechecking of standard knock intensity may be required in testing "sensitive" gasolines■ of high-octane numbers or in rating fuels■ covering a wide octane range.

16.2 *Calculation:*

16.2.1 Determine the engine rating (16.1.2) and round this value to the nearest tenth. Any octane number ending exactly in 5 in the second decimal shall be rounded to the nearest even tenth number; for example, round 95.55 and 95.65 to 95.6.

17. Report

17.1 Report the number obtained in 15.11.3 or 16.2.1 as the ASTM – IP motor octane number.

TABLE 15 Corrections to Motor Method Engine Guide Table Conditions to Achieve Standard Knock Intensity at Various Barometric Pressures[A]

Barometric Pressure, in. Hg (kPa)	To determine the compression ratio measure that provides standard knock intensity at a prevailing barometric pressure: SUBTRACT the listed micrometer correction from the guide table micrometer reading in Tables 9, 11 or 13. ADD the listed digital counter correction to the guide table digital counter reading in Tables 10, 10a, 12, 12a, or 14. To convert an observed engine compression ratio measure at the prevailing barometric pressure to that for 29.92 in. Hg (101.3 kPa): ADD the listed micrometer correction to the observed engine micrometer reading. SUBTRACT the listed digital counter correction from the observed engine digital counter reading.										Barometric Pressure, in. Hg (kPa)
		0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	
22.0 (74.5)	Counter Corrections	336	331	327	323	319	314	310	306	302	298	22.0 (74.5)
	Micrometer Corrections	0.238	0.235	0.232	0.229	0.226	0.223	0.220	0.217	0.214	0.211	
23.0 (77.9)	Counter Corrections	293	289	285	281	276	272	268	264	259	255	23.0 (77.9)
	Micrometer Corrections	0.208	0.205	0.202	0.199	0.196	0.193	0.190	0.187	0.184	0.181	
24.0 (81.2)	Counter Corrections	251	247	243	238	234	230	226	221	217	213	24.0 (81.2)
	Micrometer Corrections	0.178	0.175	0.172	0.169	0.166	0.163	0.160	0.157	0.154	0.151	
25.0 (84.7)	Counter Corrections	209	204	200	196	192	186	183	179	175	171	25.0 (84.7)
	Micrometer Corrections	0.148	0.145	0.142	0.139	0.136	0.133	0.130	0.127	0.124	0.121	
26.0 (88.0)	Counter Corrections	166	162	158	154	149	145	141	137	133	128	26.0 (88.0)
	Micrometer Corrections	0.118	0.115	0.112	0.109	0.106	0.103	0.100	0.097	0.094	0.091	
27.0 (91.4)	Counter Corrections	124	120	116	111	107	103	99	94	90	86	27.0 (91.4)
	Micrometer Corrections	0.088	0.085	0.082	0.079	0.076	0.073	0.070	0.067	0.064	0.061	
28.0 (94.8)	Counter Corrections	82	78	73	69	65	61	56	52	48	44	28.0 (94.8)
	Micrometer Corrections	0.058	0.055	0.052	0.049	0.046	0.043	0.040	0.037	0.034	0.031	
29.0 (98.2)	Counter Corrections	39	35	31	27	23	18	14	10	6	1	29.0 (98.2)
	Micrometer Corrections	0.028	0.025	0.022	0.019	0.016	0.013	0.010	0.007	0.004	0.001	
	To determine the compression ratio measure that provides standard knock intensity at a prevailing barometric pressure: ADD the listed micrometer correction from the guide table micrometer reading in Tables 9, 11 or 13. SUBTRACT the listed digital counter correction to the guide table digital counter reading in Tables 10, 10a, 12, 12a, or 14. To convert an observed engine compression ratio measure at the prevailing barometric pressure to that for 29.92 in. Hg (101.3 kPa): SUBTRACT the listed micrometer correction to the observed engine micrometer reading. ADD the listed digital counter correction from the observed engine digital counter reading.											
30.0 (101.6)	Counter Corrections	3	7	11	16	20	24	28	32	37	41	30.0 (101.6)
	Micrometer Corrections	0.002	0.005	0.008	0.011	0.014	0.017	0.020	0.023	0.026	0.029	

[A] To set the digital counter indicator so that the bottom counter reading is compensated to 29.92 in. Hg (101.3 kPa), position the indicator drive knob so that the lower counter is disengaged and then change the engine compression ratio so that the two digital counter readings differ by the value listed in Table 15 for the prevailing barometric pressure. After setting compensation return indicator drive knob to position 1.

Top counter reading must be greater than the bottom compensated reading for pressures numerically less than 29.92 in. Hg (101.3 kPa).

Top counter reading must be less than the bottom compensated reading for pressures numerically greater than 29.92 in. Hg (101.3 kPa).

TABLE 16 Octane Numbers and Engine Acceptance Rating Tolerances for Toluene Standardization Fuel Blends

Octane No.	Rating Tolerance	Composition, vol %		
		Toluene	Isooctane	n-Heptane
57.8	±0.6	50	0	50
66.5	±0.3	58	0	42
74.4	±0.3	66	0	34
78.0[A]	±0.3	70	0	30
81.6[A]	±0.3	74	0	28
85.3[A]	±0.3	74	5	21
88.8[A]	±0.3	74	10	16
92.6[A]	±0.3	74	15	11
96.8	±0.4	74	20	6
99.8[A]	±0.4	74	24	2
100.8	±0.4	74	28	0

[A] Blends recalibrated by the National Exchange Group in 1986. All other blends have O.N. values obtained for the original calibration programs in the late 1950's. These blends are being considered for recalibration also.

17.2 For aviation type gasoline, convert the motor octane number obtained in 15.11.3 or 16.2.1 to an ASTM - IP aviation method rating by use of Table 8 reporting the rating as octane number below 100 and performance number above 100.

18. Precision and Bias

18.1 *Precision*—The precision of this test method as determined by the statistical examination of interlaboratory replicate test results at the two most commonly used octane levels is as follows:

18.1.1 *Repeatability*—At the 85.0 and 90.0 octane levels, the differences between two test results obtained by the same operator with the same apparatus under constant operating conditions on identical test material would, in the long run, in the normal and correct operation of the test method, exceed the values in the following table only in 1 case in 20.

18.1.2 *Reproducibility*—At the 85.0 and 90.0 octane levels, the difference between two single and independent results obtained by different operators working in different laboratories on identical test material would, in the long run, in the normal and correct operation of the test method, exceed the values in the following table only in 1 case in 20.

Average Motor Octane Number Level	Repeatability Limits Octane Number	Reproducibility Limits Octane Number
85	0.3	0.9
90	0.3	1.1

18.2 The above precision limits were calculated from the replicate octane number results obtained by the National Exchange Motor Fuels Group (NEG) participating in cooperative testing programs during October 1979 through July 1983. These data were analyzed by procedures detailed in the "Manual on Determining Precision Data for ASTM Methods on Petroleum Products and Lubricants."[5]

18.3 *Reproducibility*—At the 80, 95, 99, 100.1, and 105 octane levels, the difference between two single and independent results obtained by different operators working in different laboratories on identical test material would, in the long run, in the normal and correct operation of the test method, exceed the values in the following table only in 1 case in 20.

Average Motor Octane Number Level	Reproducibility Limits Octane Number
80.0	1.2
...	...
95.0	1.1
99.0	1.5
100.1	1.1
105.0	1.8

18.4 The above precision limits are given in the interest of maintaining continuity with previous issues of this test method. These values are based on NEG data from 1957 through 1982 for single determinations by each participating laboratory.

18.5 *Standard Deviation*—Extensive data over the years have shown that the reproducibility of fuel ratings among laboratories varies with octane number level. This variation is shown in Fig. 4a, where the Standard Deviation is plotted against Octane Number level. The curve for this figure is based on ASTM National Exchange Group data from 1966 through 1982 with some earlier data for octane levels below 83.

18.6 *Bias*—The bias statement is currently being developed.

[5] Available from ASTM Headquarters. Request Research Report RR: D02 - 1007.

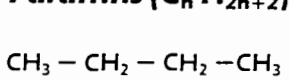
The American Society for Testing and Materials takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, 1916 Race St., Philadelphia, PA 19103.

APPENDIX 1.3

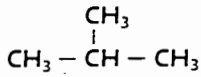
STRUCTURAL FEATURES OF SOME SIMPLE FUEL COMPONENTS

Paraffins ($C_n H_{2n+2}$)



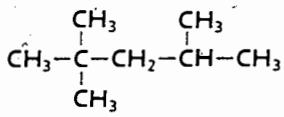
$CH_3 - CH_2 - CH_2 - CH_3$

n-butane ($C_4 H_{10}$)



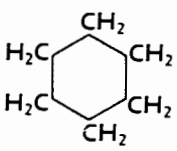
iso-butane ($C_4 H_{10}$)

n-octane ($C_8 H_{18}$)

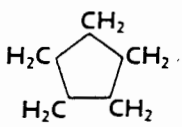


iso-octane ($C_8 H_{18}$)

Cyclo-paraffins ($C_n H_{2n}$)



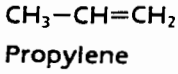
Cyclohexane



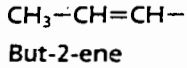
Cyclopentane

Olefins ($C_n H_{2n}$)

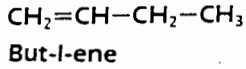
Ethylene



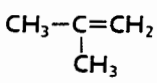
Propylene



But-2-ene

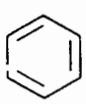


But-l-ene

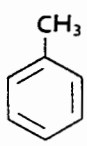


iso-butylene

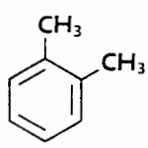
Aromatics



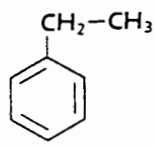
Benzene



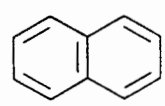
Toluene



Ortho-xylene

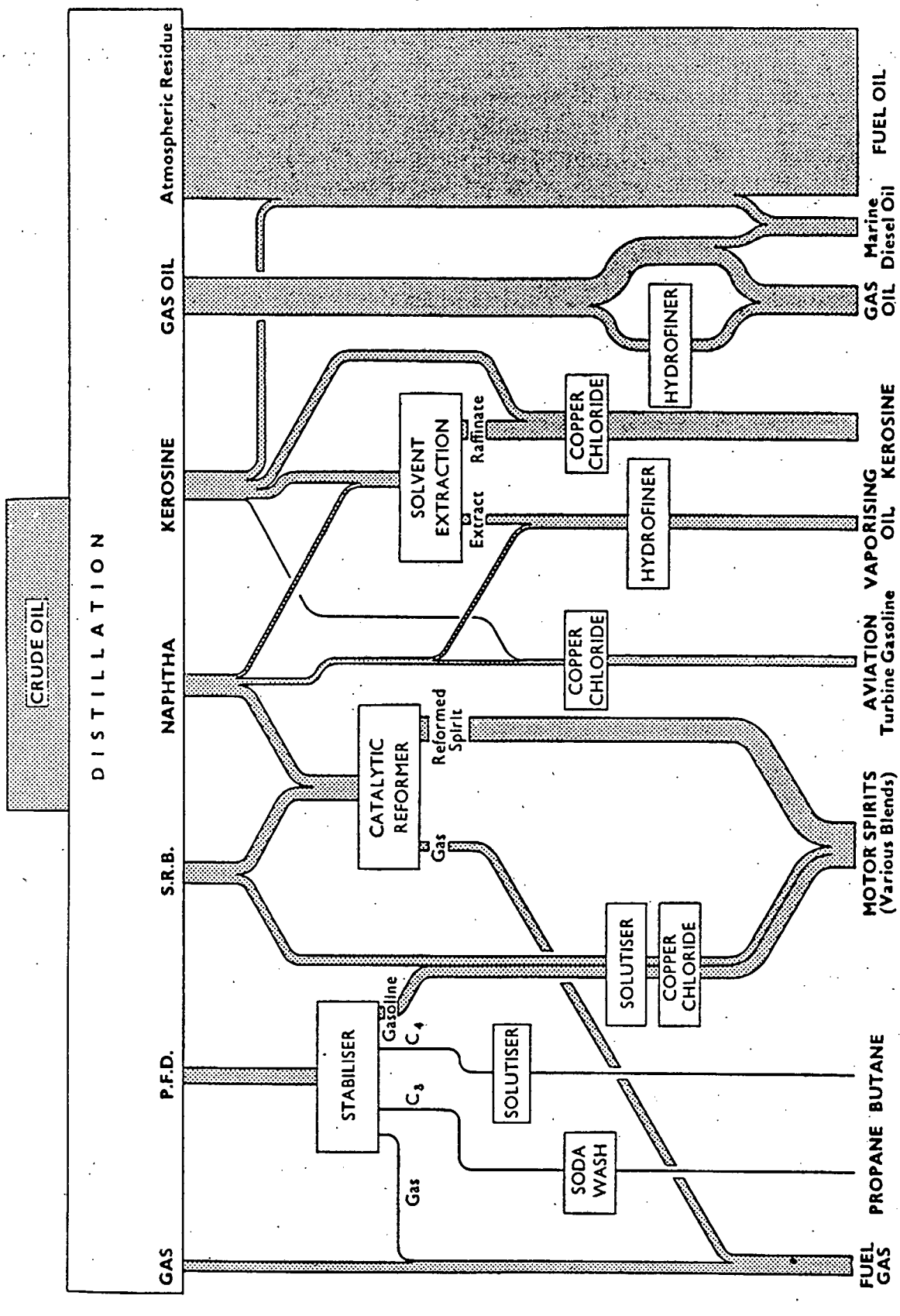


Ethylbenzene



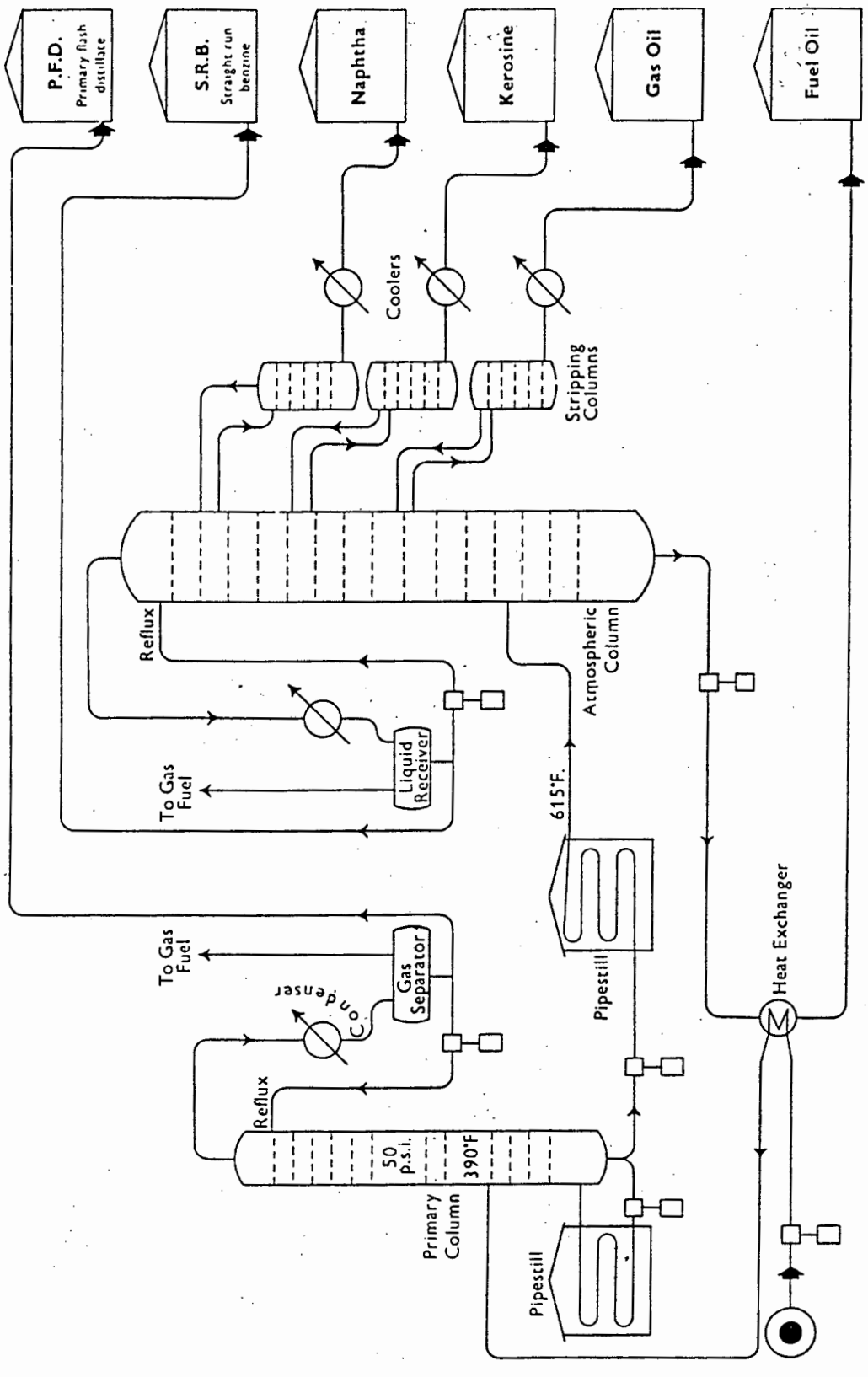
Napthalene

APPENDIX 2.1



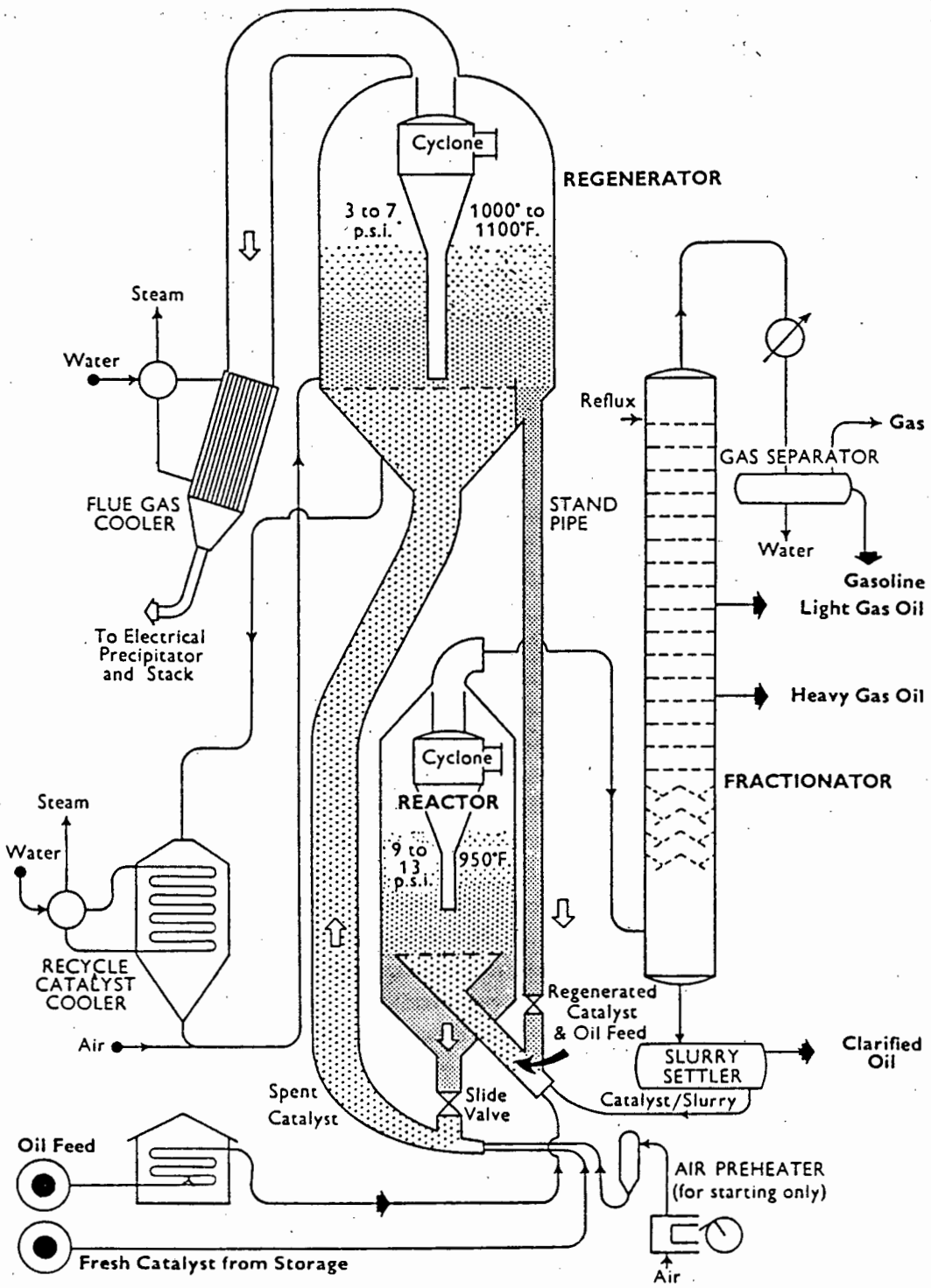
FLOWSHEET FOR SIMPLE REFINERY

APPENDIX 2.2



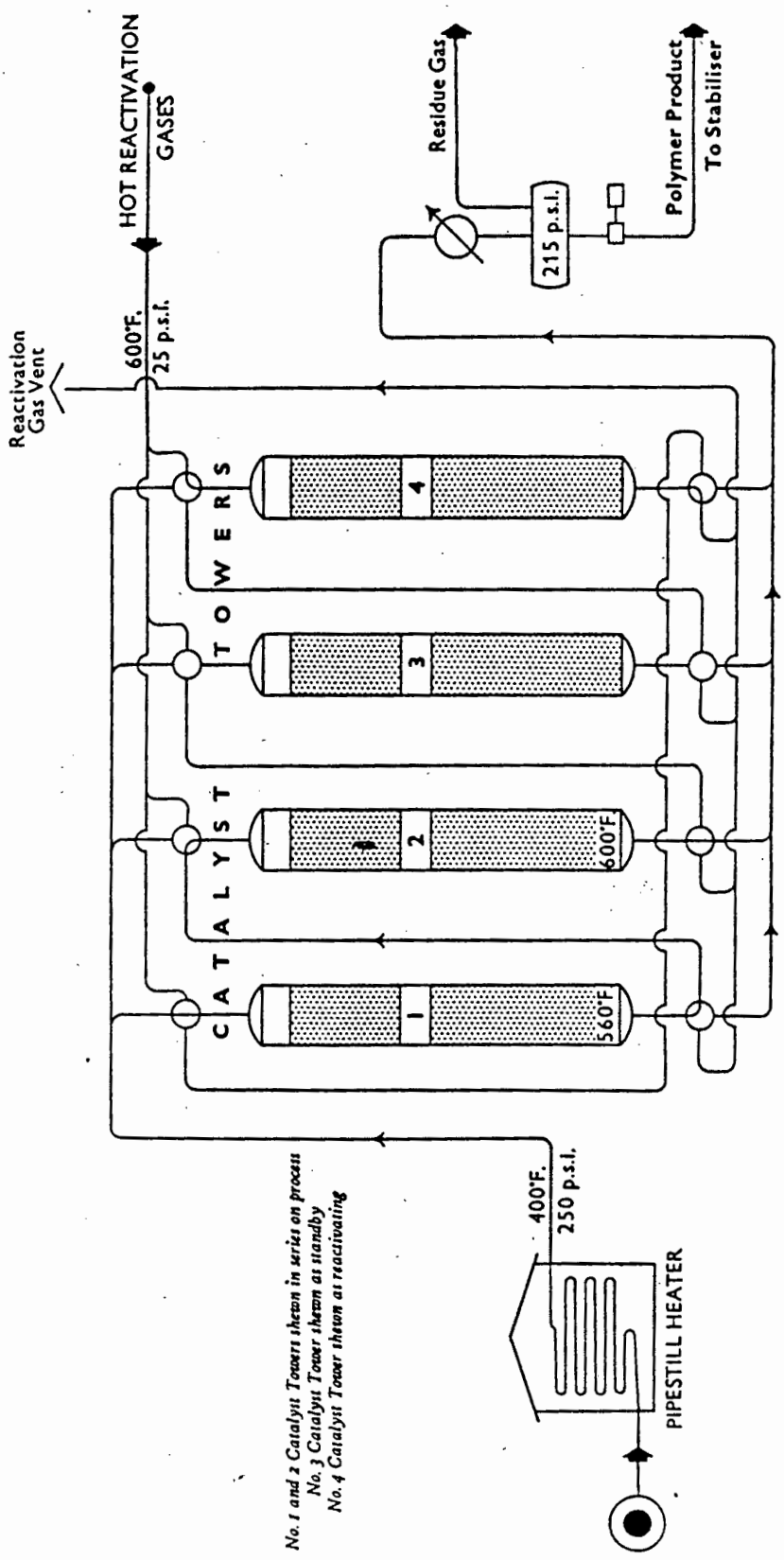
TWO-STAGE CRUDE OIL DISTILLATION UNIT

APPENDIX 2.3



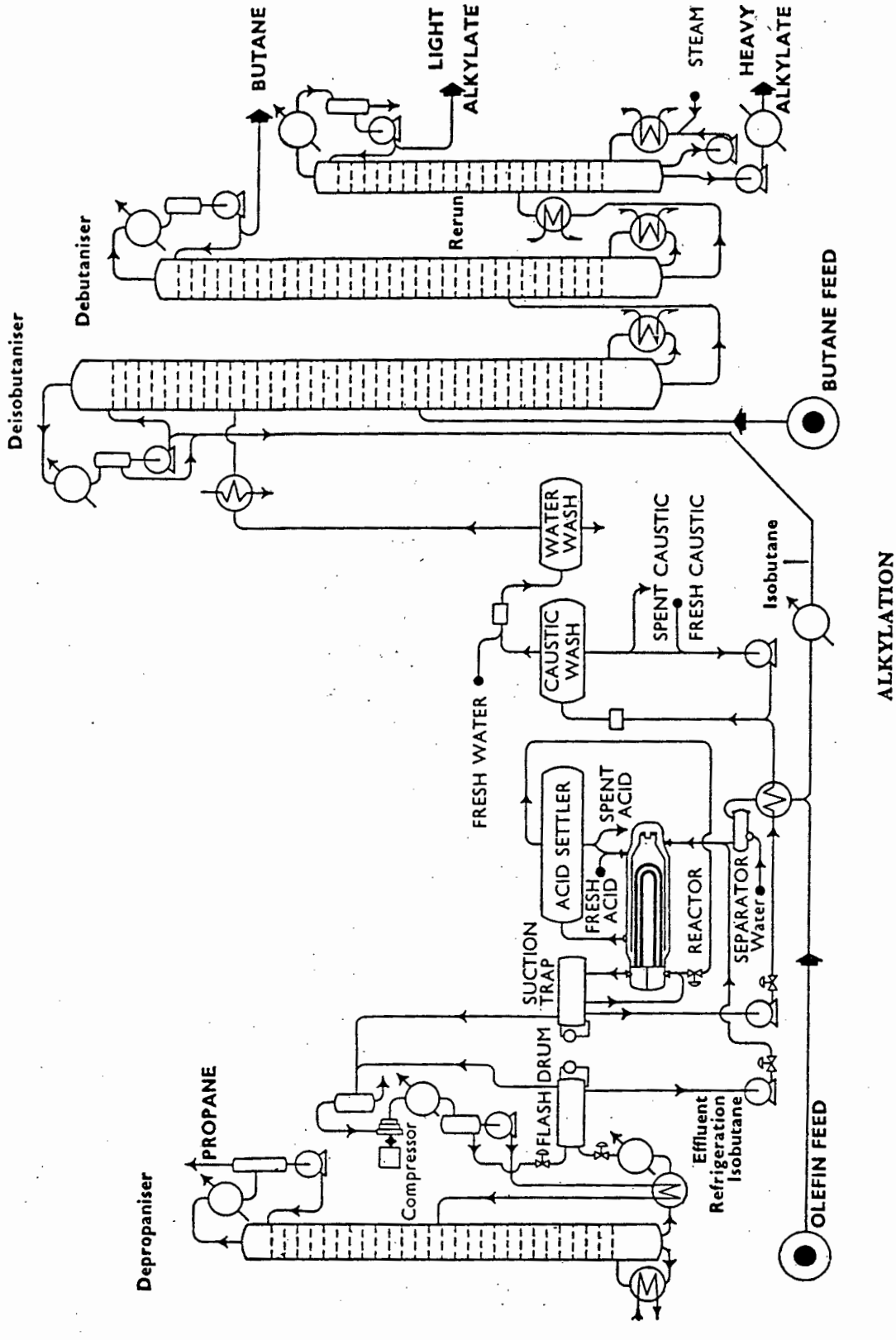
FLUID CATALYTIC CRACKER

APPENDIX 2.4



CATALYTIC POLYMERISATION

APPENDIX 2.5


BUTANE
LIGHT ALKYLATE
STEAM
HEAVY ALKYLATE
Debutaniser
Rerun
Deisobutaniser
BUTANE FEED
WATER WASH
SPENT CAUSTIC
FRESH CAUSTIC
CAUSTIC WASH
Isobutane
FRESH WATER
ACID SETTLER
SPENT ACID
FRESH ACID
REACTOR
SEPARATOR
Water
SUCTION TRAP
DRUM
FLASH
Compressor
PROPANE
Depropaniser
Effluent Refrigeration Isobutane
OLEFIN FEED
ALKYLATION

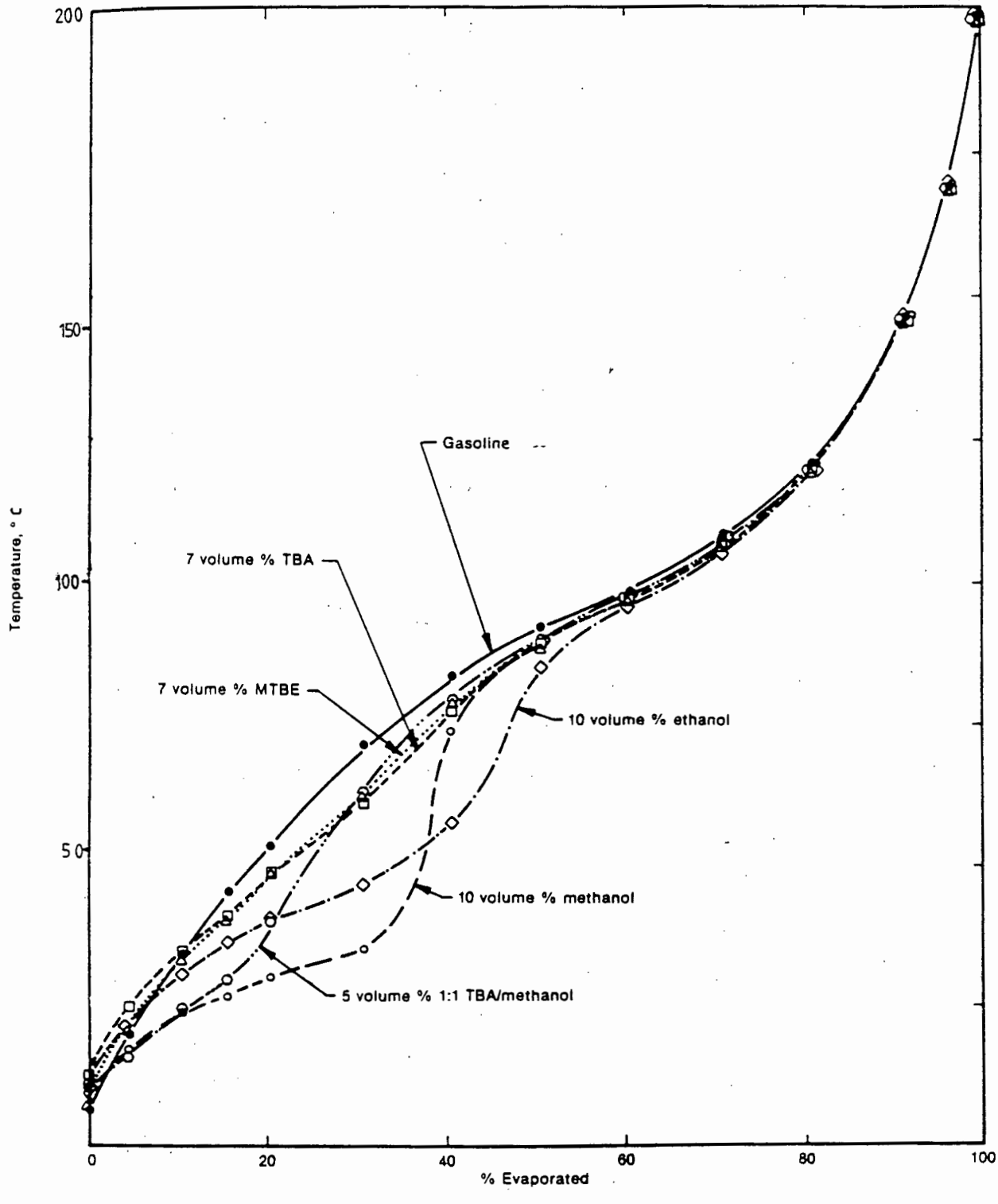
Number of Carbon atoms	Name	Formula	Boiling point at 1 bar (°C)	RON	MON	Flammability		Density at 20°C, 1 bar	Latent heat of vapourisation at 20°C (KJ/Kg)	Calorific value - net (MJ/Kg)	Vapour Pressure @ 37,8°C (kPa)	Auto ignition Temp °C in air	Stiochio-metric air/fuel Ratio (Kg/Kg)
						Lower %	Upper %						
0	Hydrogen	H2	-253			4,0	75	0,090 Kg/m^3		120		560	34
1	Methane	CH4	-162	120		5,0	15	0,716		47,5		515	17,3
2	Acetylene	C2H2	- 81			1,5	80	1,17		48,1		305	13,25
2	Ethane	C2H6	- 88	119		3	14	1,36		47,5		515	17,3
2	Ethene	C2H4	-102			2,75	34	1,26		47,1		425	14,3
3	Propane	L3H0	- 43	112,5		1,9	9,5	2,0	244	46,3	1020	470	15,6
3	Propene	C3H6	- 47			2,0	11	1,92		45,8	1700	450	14,7
4	n-Butane	C4H8	- 0,5	93,6		1,7	9,0	2,5	365	45,6	408	365	15,4
4	Iso-Butane	C4H10	-11,7	102,1		1,5	8,5	2,7	330	45,2	272	408	14,8
5	n-Pentane	C5H12	36,1	62	62	2,2	9,5	0,626 Kg/l	367	45,4	100	290	15,4
5	neo-Pentane	C5H12	9,5	92,3	90	2,4	10,3	0,591	303	45,2	136	458	15,4
6	n-Hexane	C6H14	68,7	24,8	26	1,2	7,5	0,659	368	44,7	34	240	15,2
6	3-Methyl Pentane	C6H14	63,3	74,5	73			0,664	352	44,7			15,2
6	2,3-Dimethyl Pentane	C6H14	57,9	103,5	93	1,1	6,5	0,661	339	44,7	11,0	220	15,2
7	n-Heptane	C7H16	98,4	0	0			0,684	365	44,4			15,2
7	2,2-Dimethyl Pentane	C7H16	79,2	92	93			0,674	323	44,4			15,2
7	2,2,3-Trimethyl Pentane	C7H16	80,9	>100	>100			0,690	319	44,4	3,7		15,2
8	n-Octane	C8H18	125,7	-	-			0,702	365	44,6			15,2
8	2,2-Dimethyl Hexane	C8H18	106,8	72	77			0,695	328	44,6			15,2
8	2,2,4-Trimethyl Pentane (Iso-octane)	C8H18	99,2	100	100	1,0	6,0	0,692	376	44,6		410	15,2

PHYSICAL PROPERTIES OF HYDROCARBONS - PARAFFINS

Number of Carbon atoms	Name	Formula	Boiling point at 1 bar (°C)	RON	MON	Flammability		Density at 20°C, 1 bar	Latent heat of vapourisation at 20°C (KJ/Kg)	Calorific value - net (MJ/Kg)	Vapour Pressure @ 37,8°C (kPa)	Auto ignition Temp °C in air	Stiochio-metric air/fuel Ratio (Kg/Kg)
						Lower %	Upper %						
6	Benzene	C6H6	80	99	91	1,2	8,0	0,880	394	40,2	20,4	550	13,3
7	Toluene	C7H8	110	124	112	1,2	7,0	0,867	364	40,6	6,8	530	13,4
8	o-Xylene	C8H10	145	120	103	-	-	0,880	410	40,6	2,0	460	13,7
8	m-Xylene	C8H10	139	145	124	-	-	0,864	403	40,6	2,1	460	13,7
8	p-Xylene	C8H10	137	146	127	-	-	0,861	400	40,6	2,0	460	13,7
8	Ethylbenzene	C8H10	136	124	107	1,0	7,6	0,867	399	40,6	2,0	460	13,7
9	n-Propylbenzene	C9H12	159	127	129	-	-	0,862	382	40,6	-	-	13,7
9	Iso-Propylbenzene	C9H12	1525	132	124	-	-	0,862	378	40,6	-	-	13,7
9	1,3,5-Trimethylbenzene	C9H102	164	171	137	-	-	0,865	395	40,6	-	-	13,7

PHYSICAL PROPERTIES OF HYDROCARBONS - AROMATICS

APPENDIX 2.7

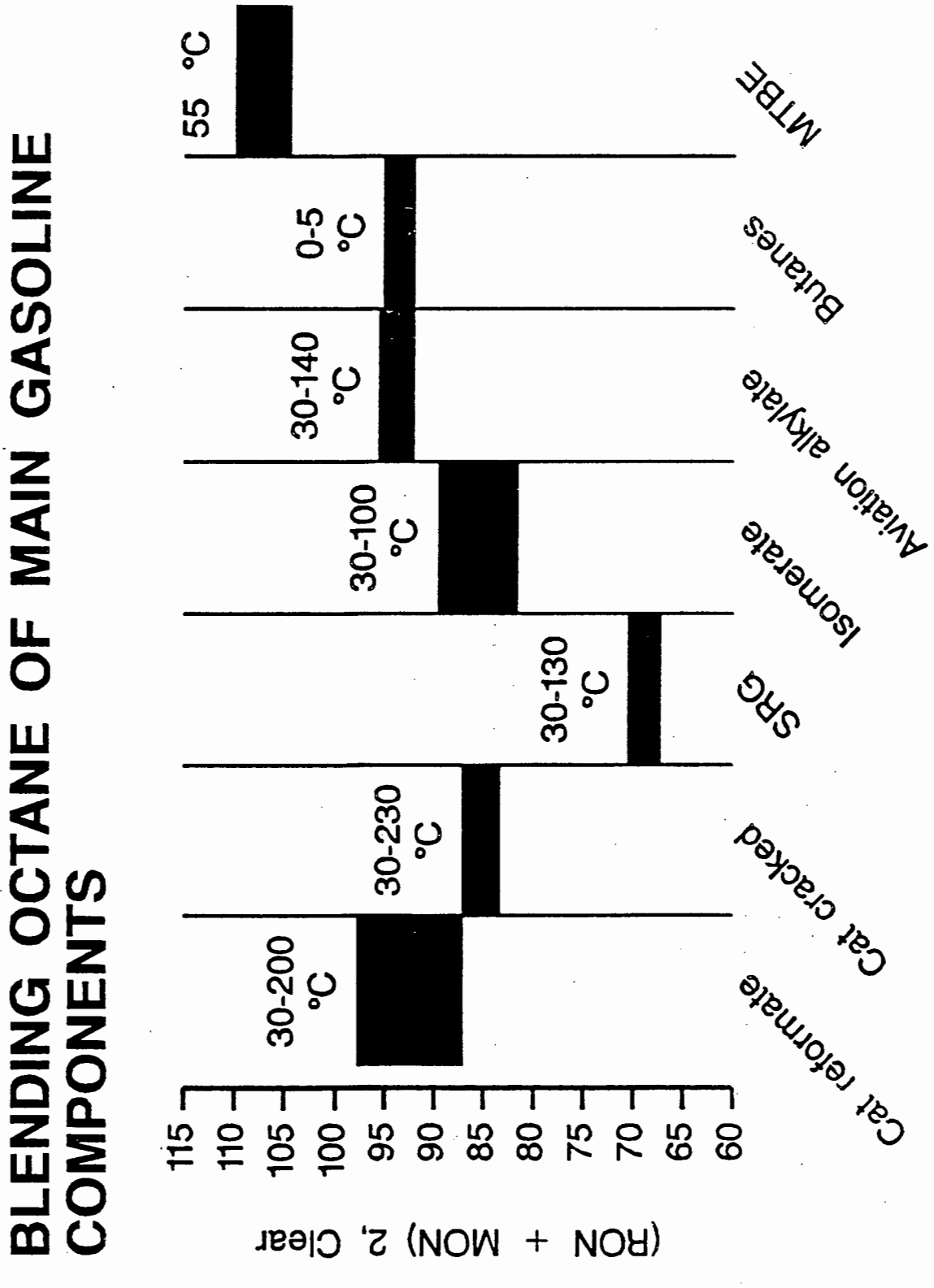


Effect of Oxygenates on Distillation

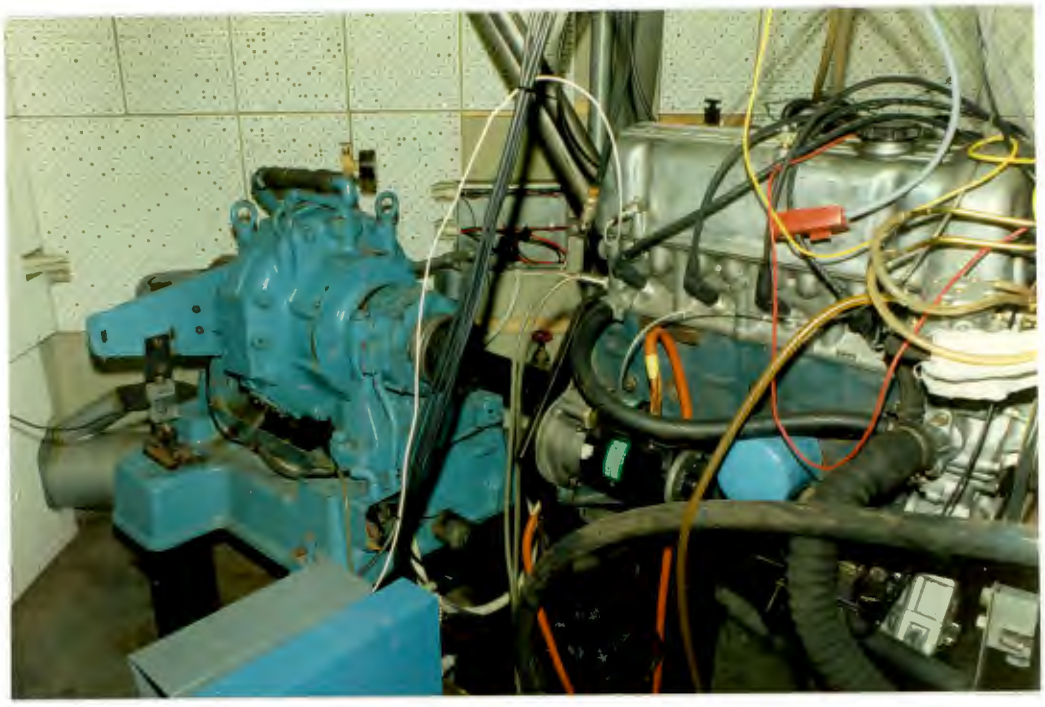
BLENDSTOCK	RON	MON	RVP, kPa @ 37.8°C	Vol.% arom. (FIA)	Vol.% olef (FIA)	Sulfur, wt ppm
Reformate						
Full range	97.7	87.4	33	62.6	0.7	55
Light	82.8	77.5	49	31.1	1.0	10
Heavy	104.9	94.5	8	87.2	0.5	6
St. run naphtha						
Full Range	78.6	76.0	63	9.8	2.2	146
Light	74.1	72.1	83	2.8	0.8	155
Medium/heavy	53.7	54.2	17	10.7	0.2	259
C_5 + isomerate						
Once through	82.3	80.2	90	0.4	0.0	2
Recycle	88.5	85.4	106	1.4	0.7	1
FCC naphtha						
Full range	92.1	80.7	44	29.2	29.1	756
Light	92.6	80.8	62	13.5	39.8	289
Heavy	91.9	81.3	16	60.3	16.5	748
Lt. coker naphtha	82.0	74.5	81	4.5	35.2	2 268
Hydrocrackate						
Light	82.6	79.2	78	2.7	0.2	47
Medium/heavy	0.0	0.0	0	0.0	0.0	0
Alkylate						
Full range	93.2	91.1	49	0.4	0.5	26
Light	93.9	91.2	40	0.6	0.3	44
Heavy	84.0	81.5	0	0.0	0.0	0
Poly gasoline	94.4	81.9	57	0.5	94.6	125
Dimate	95.3	81.2	56	0.1	98.1	5
MTBE	113.9	98.9	58	0.1	0.4	0
Poly gasoline	94.4	81.9	57	0.5	94.6	
Toluene/Xylene	110.3	100.9	7	95.3	0.0	7
Isobutane	0.0	0.0	0	0.0	0.0	0
Normal butane	94.2	89.6	366	0.0	2.7	14
Reaffinates						
Light (B/BT)	68.2	65.2	41	6.7	2.5	5
Heavy (T/X/TX)	54.1	53.1	14	6.6	0.2	0
Whole (BTX)	60.0	59.4	24	6.2	2.5	65
Other						
Aromatic	105.2	94.0	8	90.1	1.5	133
Lt. paraffin	82.5	79.4	108	3.1	1.3	205
Other	90.6	80.8	53	32.6	20.1	47

SUMMER 1989 U.S. GASOLINE COMPONENT PROPERTIES[36]

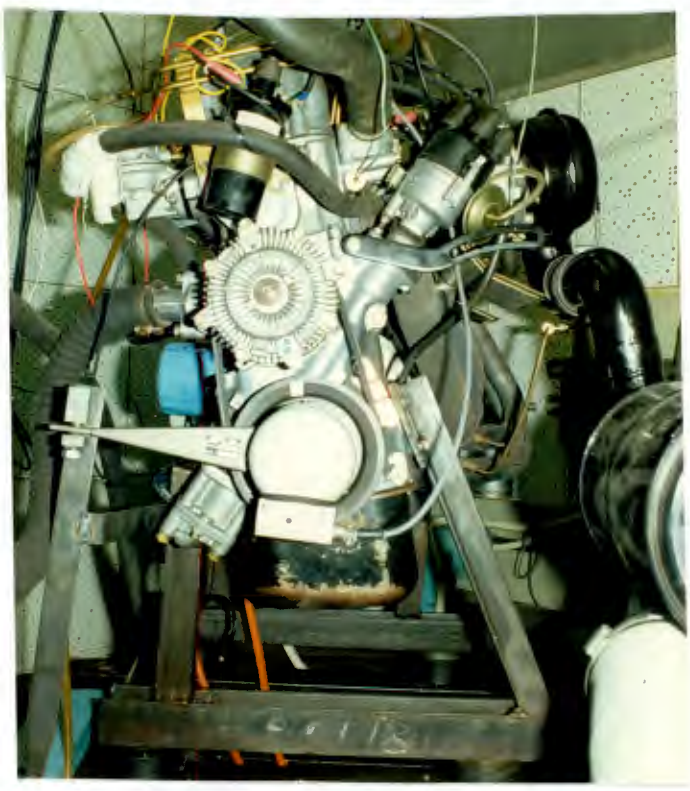
APPENDIX 2.9


BLENDING OCTANE OF MAIN GASOLINE COMPONENTS
(RON + MON) 2, Clear
115
110
105
100
95
90
85
80
75
70
65
60
Cat reformate
Cat cracked
SRG
Isomerate
Aviation alkylate
Butanes
MTBE
30-200 °C
30-230 °C
30-130 °C
30-100 °C
30-140 °C
0-5 °C
55 °C

APPENDIX 4.1



Photograph of the Nissan engine and dynamometer



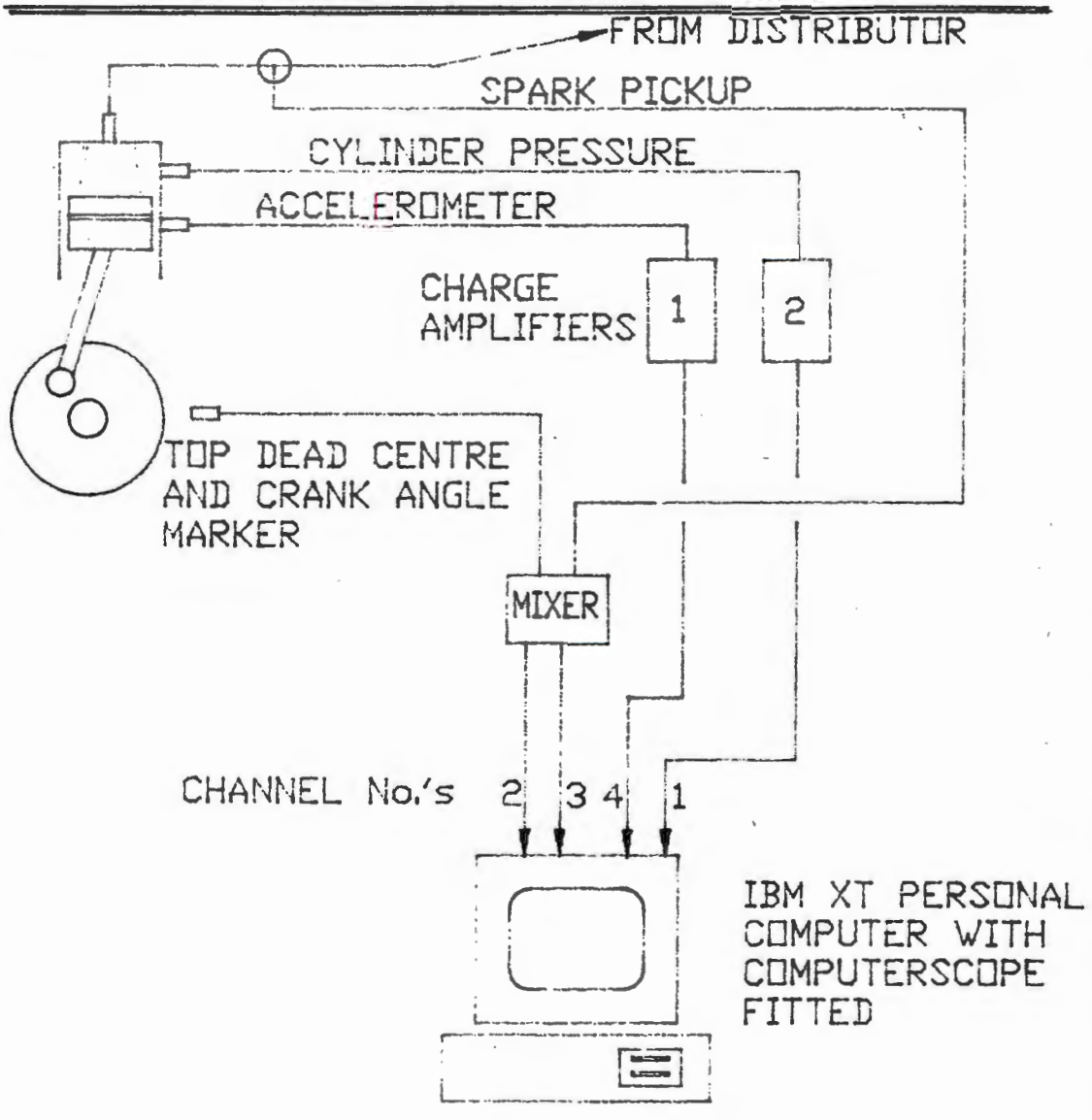
Front view of the Nissan engine showing the crank angle-marker

APPENDIX 4.2

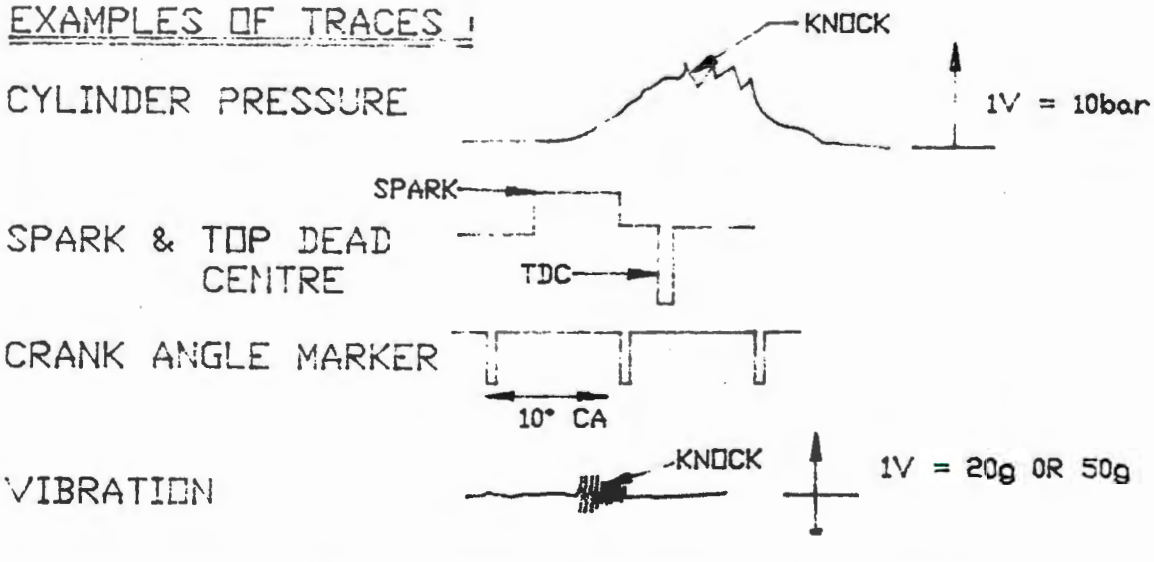
Position of the pressure transducer in the Ford cylinder head

APPENDIX 4.3

SCHEMATIC DIAGRAM OF ENGINE INSTRUMENTATION



EXAMPLES OF TRACES :



APPENDIX 4.4

	UNITS	TEST METHOD	VALUE
Appearance		Visual	Bright & Clear
Knock rating			
Lean mixture			
- Performance No (MON)		IP 236/D.2700	103.4
Rich mixture			
- Performance No		IP 119/D.909	131.3
Research Octane Number		D2699	103.0
Tetraethyl Lead	gPb/l	IP 270/D3341/D2599	0.83
Colour		IP 17	Green
Dyes: Blue	mg/1		1.14
Yellow			1.44
Aniline gravity		IP 2/IP 160	
Product		D.611/D.1298	8298
Density at 15°C	kg/l	D.1298	723
Distillation			
I.B.P.	°C	IP 123/d.86	38.5
10% Evap.			72.0
40% Evap.			96.5
50% Evap.			100.5
90% Evap.			125.5
F.B.P.			159.0
Recovery.	Vol. %		98.5
Residue	Vol. %		1.0
Loss	Vol. %		0.5
R.V.P.	kPa	D.323	45
Freezing PT.	°C	IP 16/d.2386	<-60
Sulphur	Mass %	IP 107/D.1266	<0.01
Existent Gum	mg/100 ml	D.381	Less than 1.0
Copper corrosion 2h @ 100°C		IP 154	1A
Oxidation Stab.			
Potential Gum		IP 138 or D.873	Less than 1.0
PB. Precipitate			Nil
Water reaction			
- Interface rating		IP 298 or D.1094	1B
- Separation rating			2
- Volume change	ml		Nil
Additive	mg/1		19.3

AVIATION GASOLINE 100/130 : TYPICAL ANALYSIS

APPENDIX 4.5

Property	Fuel 1	Fuel 2	Fuel 3
RON	92,2	93,3	95,5
MON	81,4	83,3	84,5
Sensitivity (RON - MON)	10,8	10,0	11,0
Aromatics %	23	18	13
Olefins %	25	30	30
Paraffins	42	42	47
Alcohols %	10	10	10
Density Kg/l at 20°C	0,747	0,741	0,731
R.V.P.	55	51	53

Sasol unleaded petrol/alcohol blend characteristics

APPENDIX 5.1

Knock damage to the Ford piston

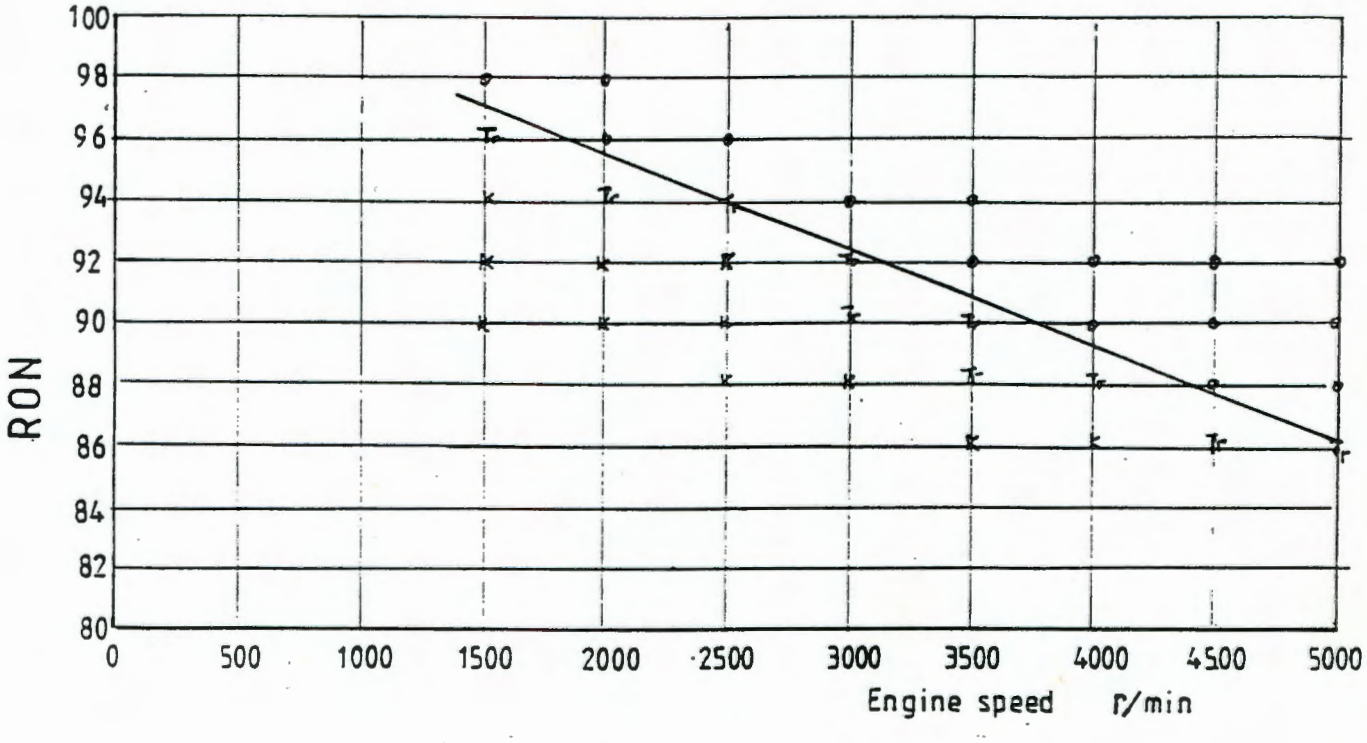
APPENDIX 5.2

Scuffing damage to the Ford piston

APPENDIX 5.3

Catastrophic failure of a Nissan piston due to knock.
This failure occured during an earlier test.

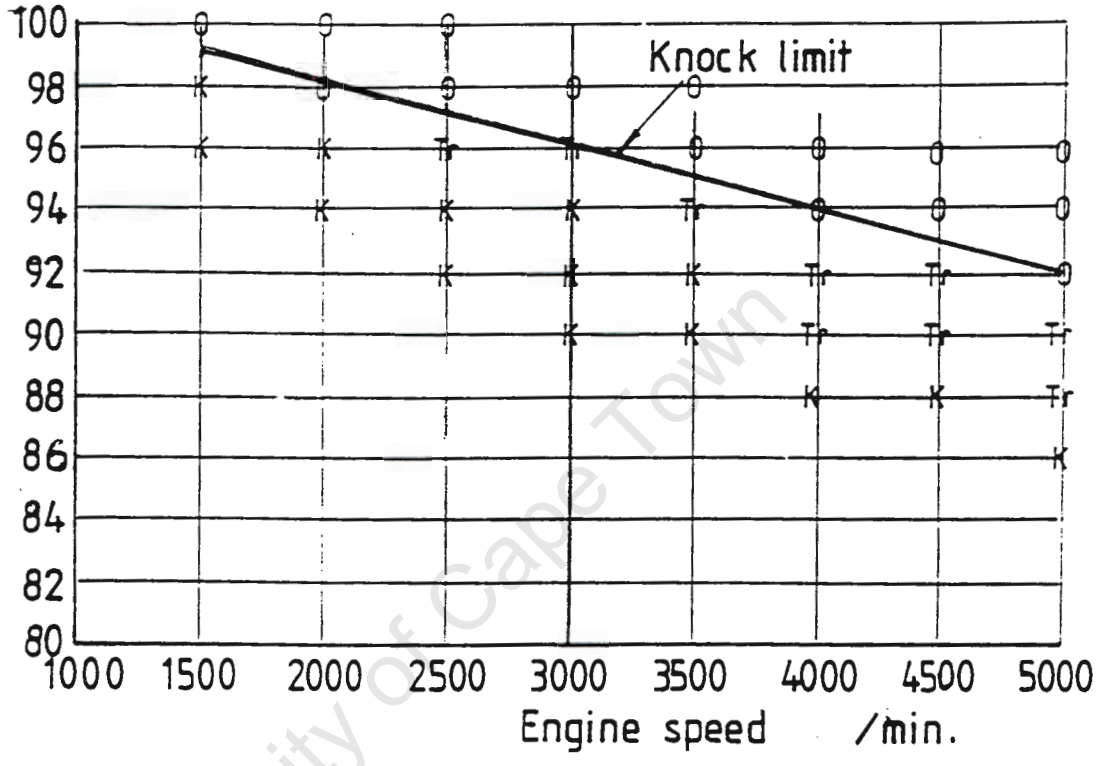
APPENDIX 5.4



O - No knock
Tr - Trace knock
K - Knock

Toyota octane requirement using primary reference fuel.

APPENDIX 5.5

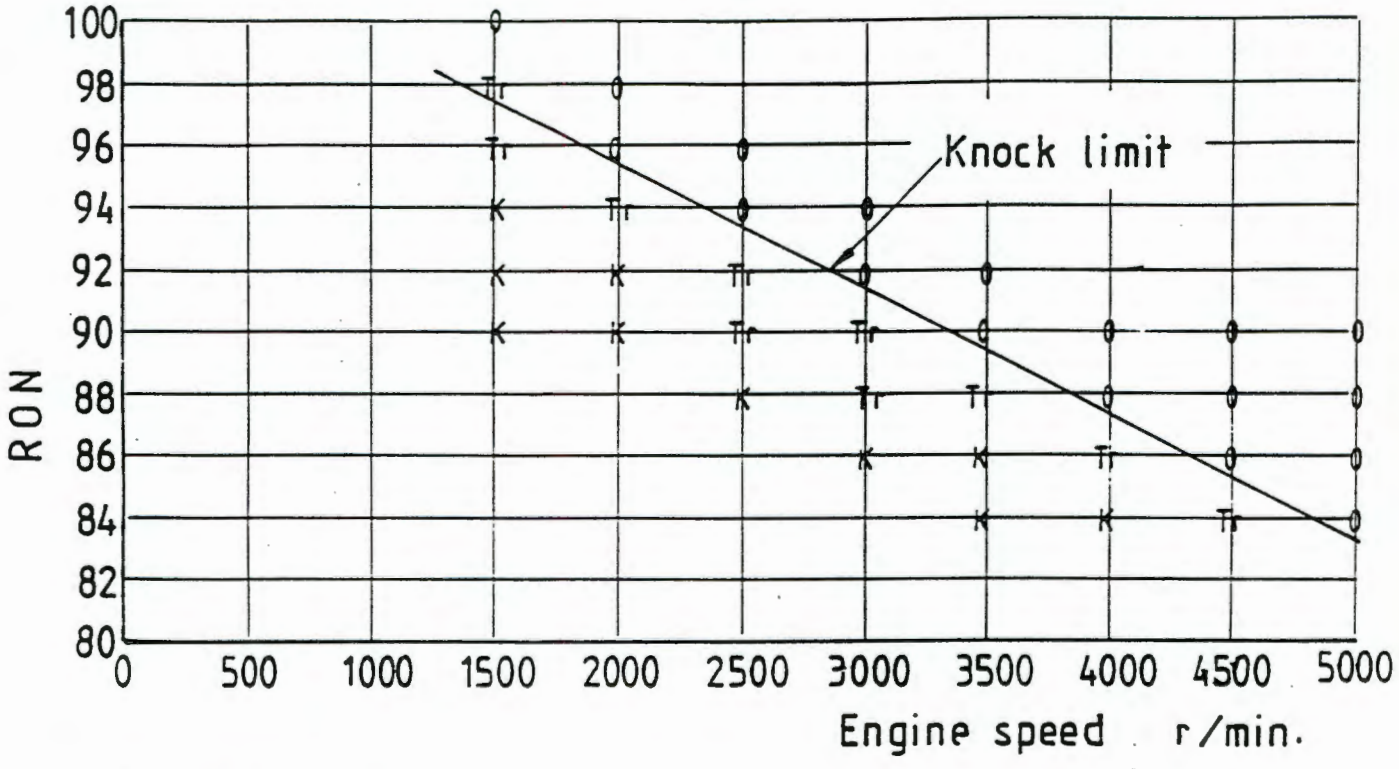


O - No knock
Tr - Trace knock
K - Knock

Volkswagen octane requirement using primary reference fuels.

University of Cape Town

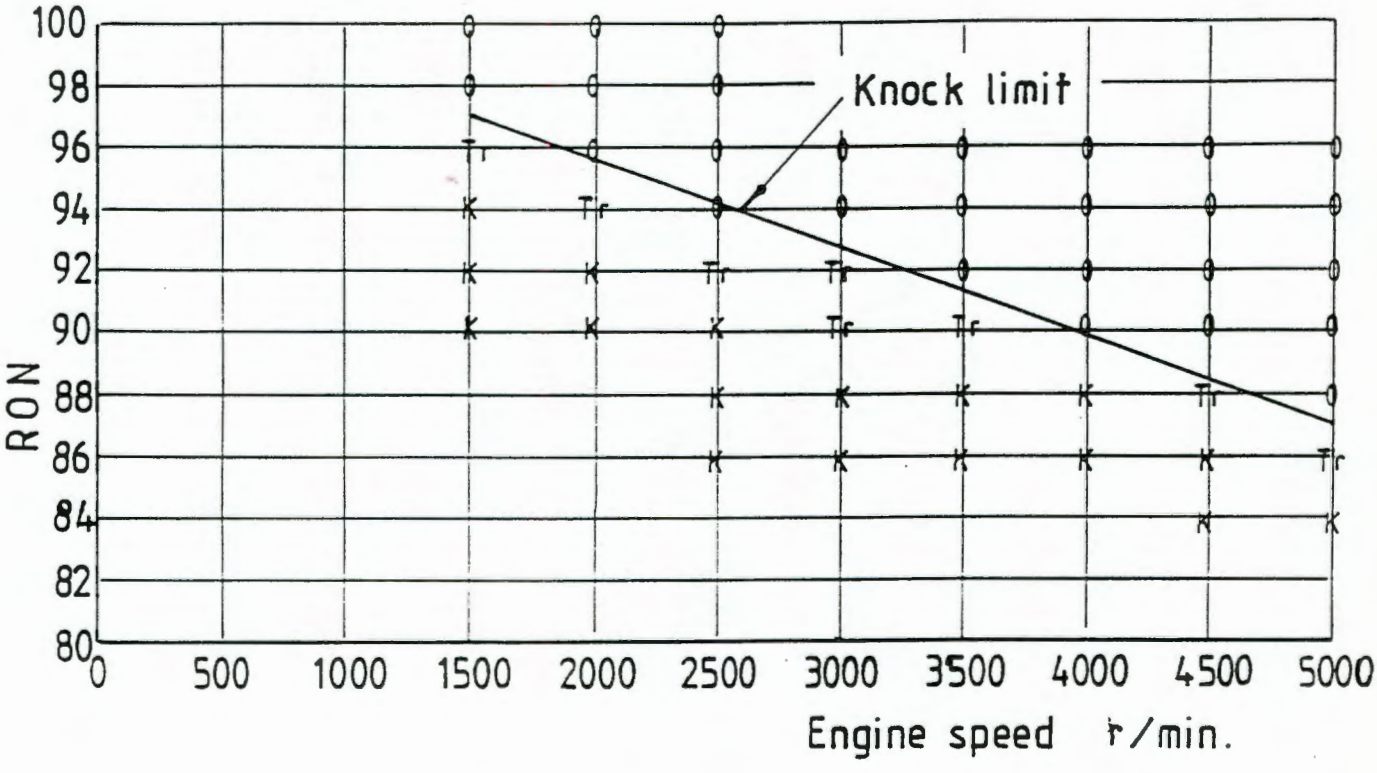
APPENDIX 5.6



O - No knock
Tr - Trace knock
K - Knock

Nissan octane requirement using primary reference fuels.

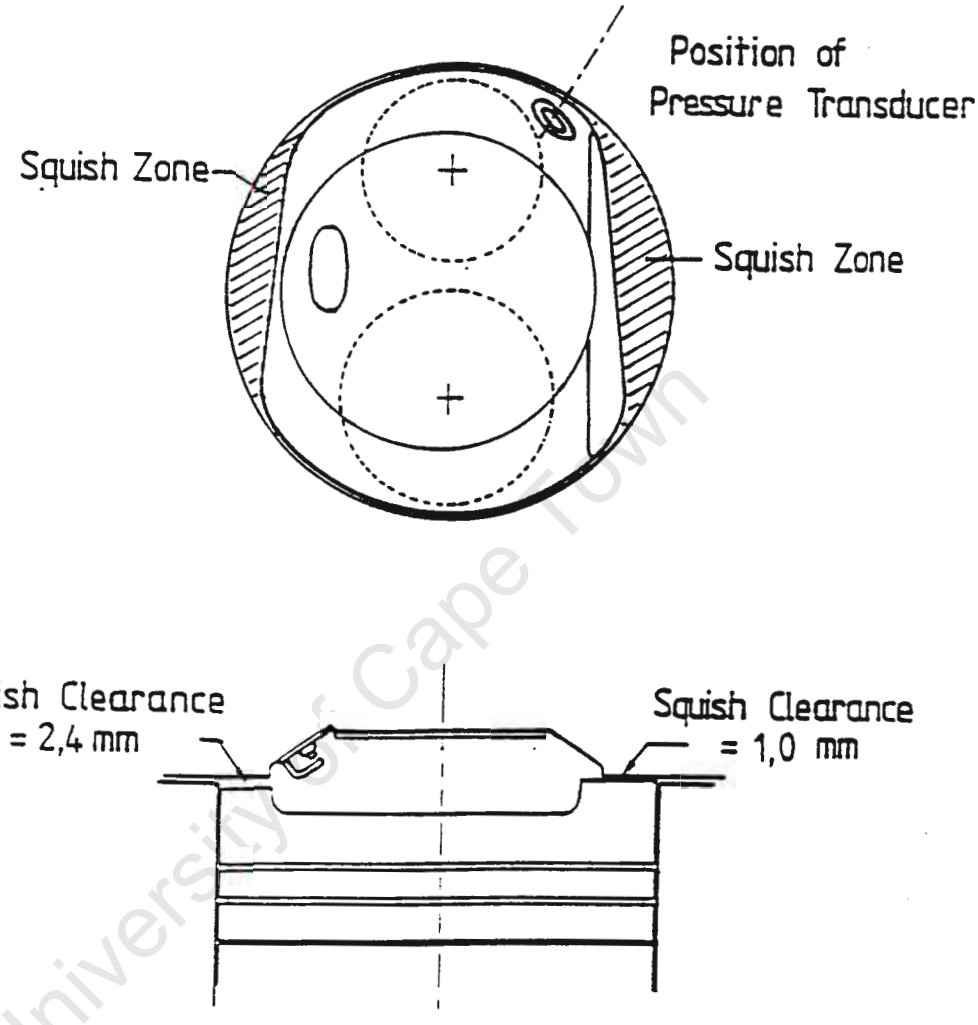
APPENDIX 5.7



O - No knock
Tr - Trace knock
K - Knock

Ford octane requirement using primary reference fuels.

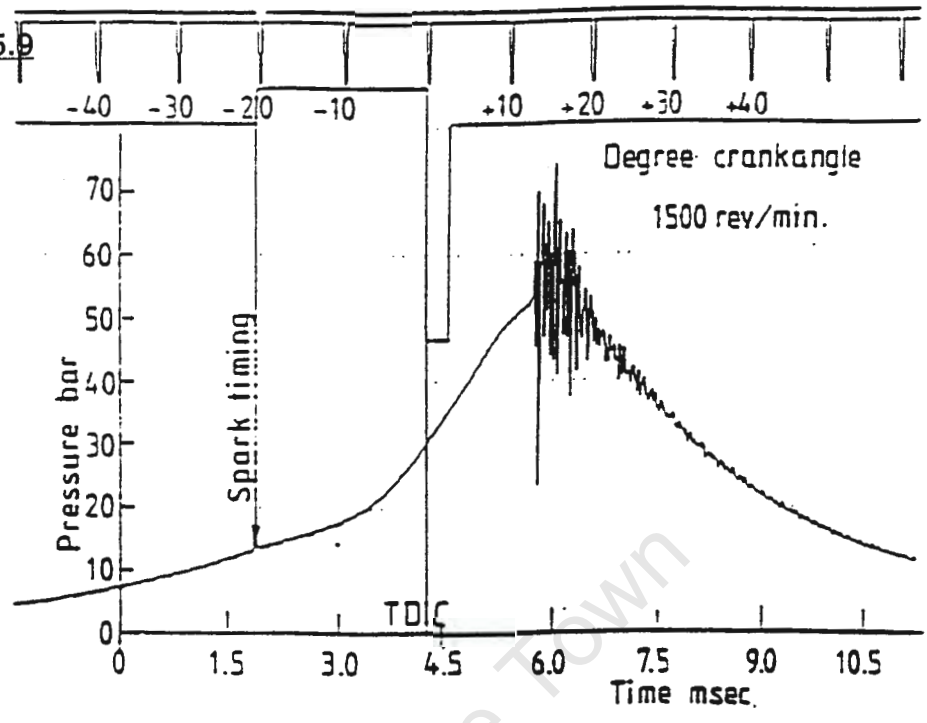
APPENDIX 5.8

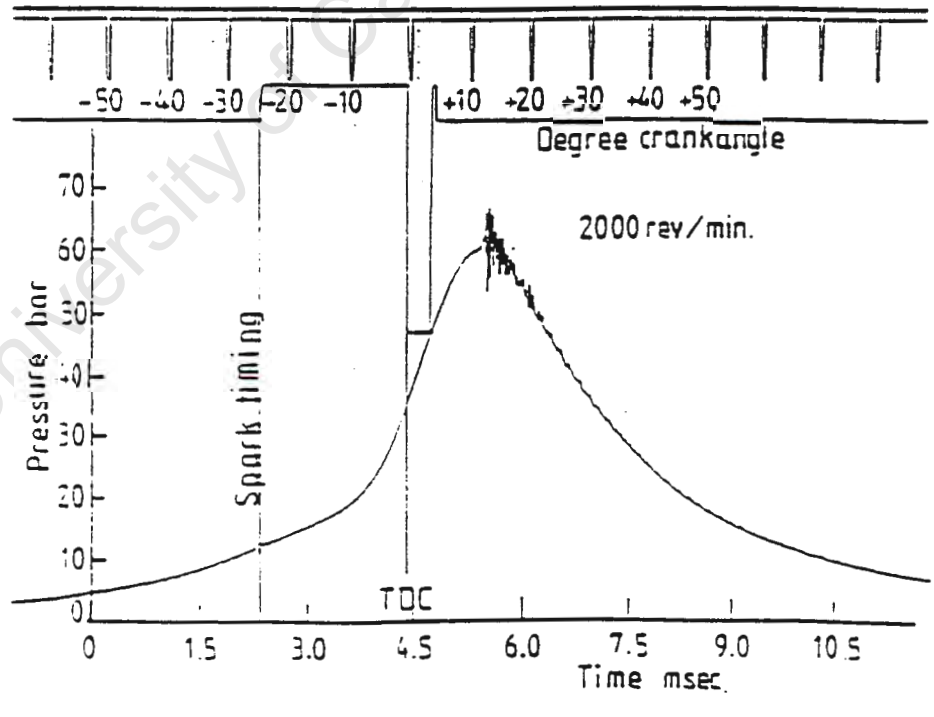


Volkswagen combustion chamber

University of Cape Town

APPENDIX 5.9

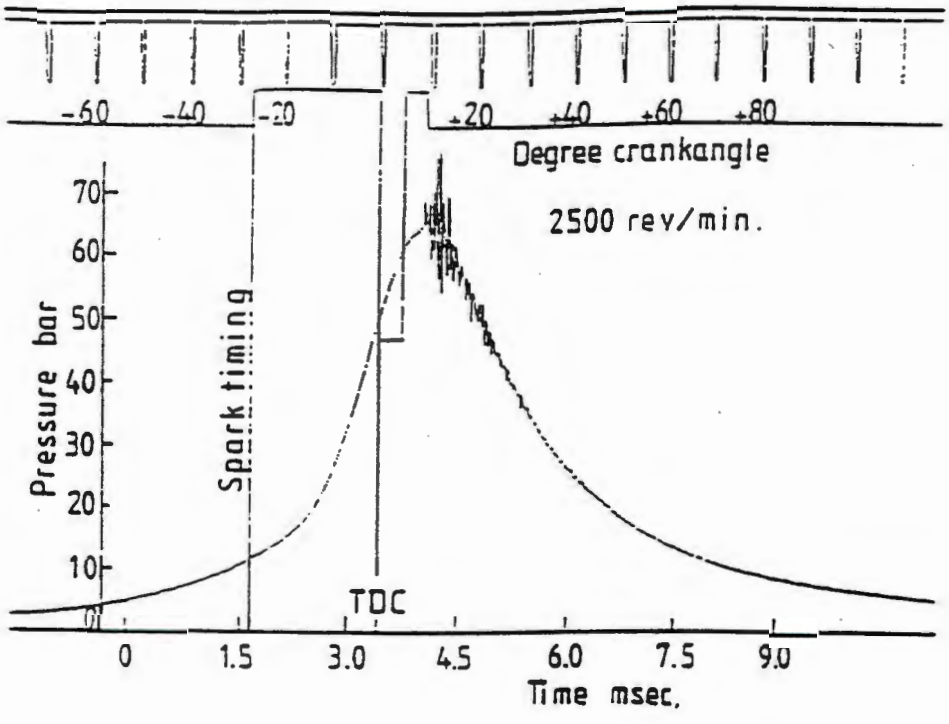


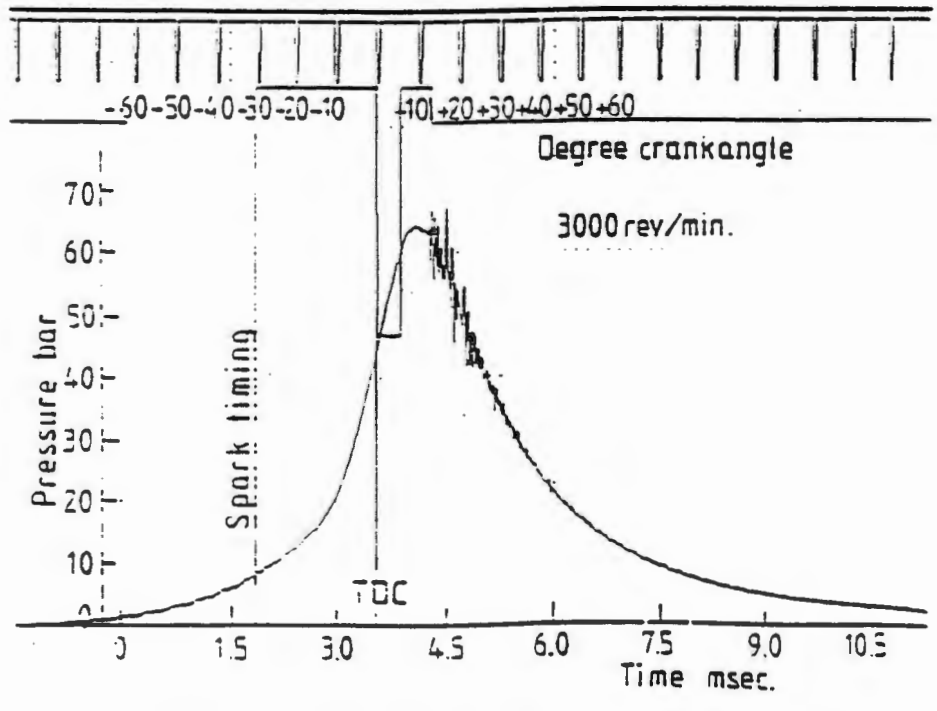


Cylinder pressure diagams at 1500 and 2000 r/min

University of Cape Town

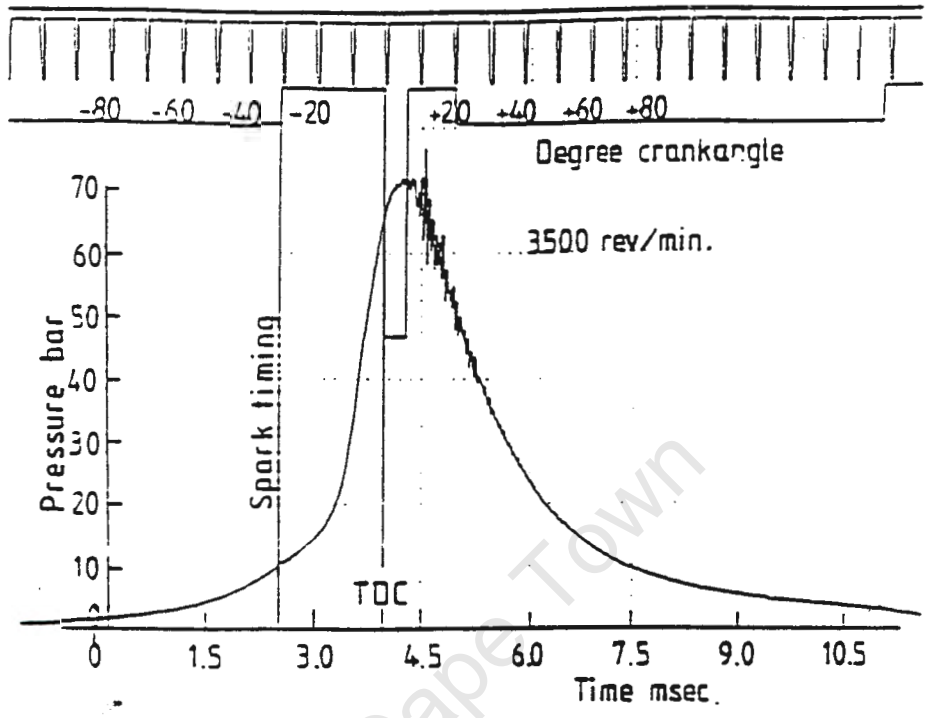
APPENDIX 5.10

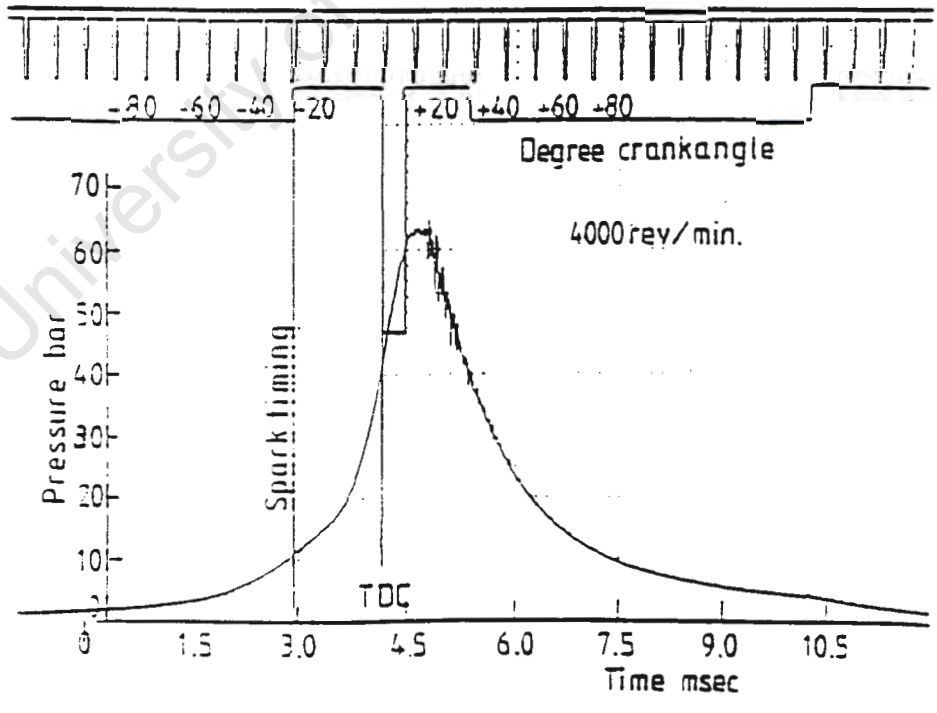




Cylinder pressure diagrams at 2500 and 3000 r/min

APPENDIX 5.11

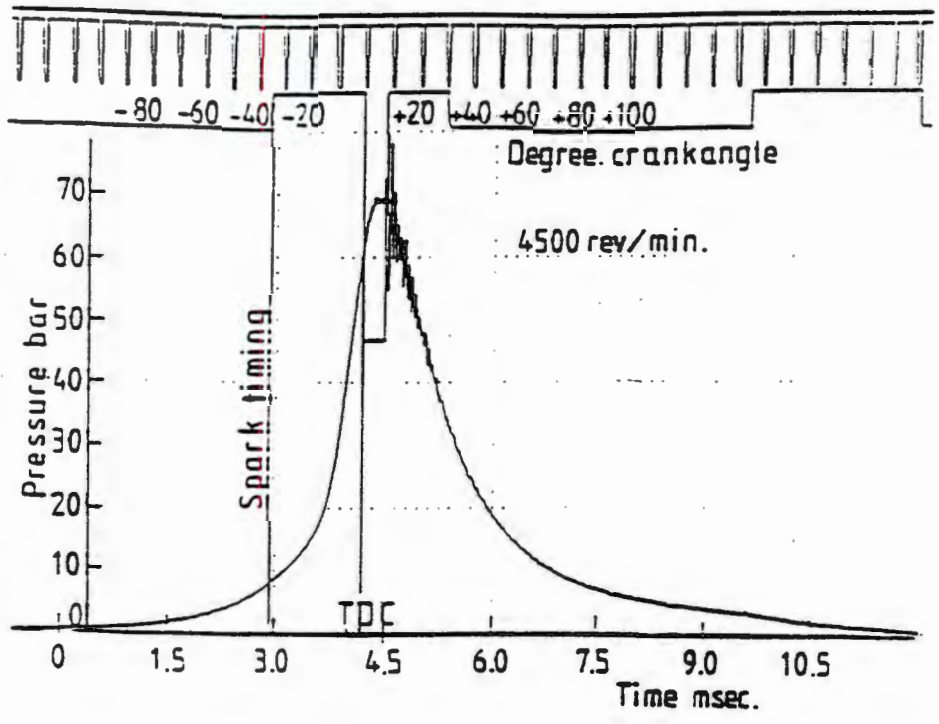


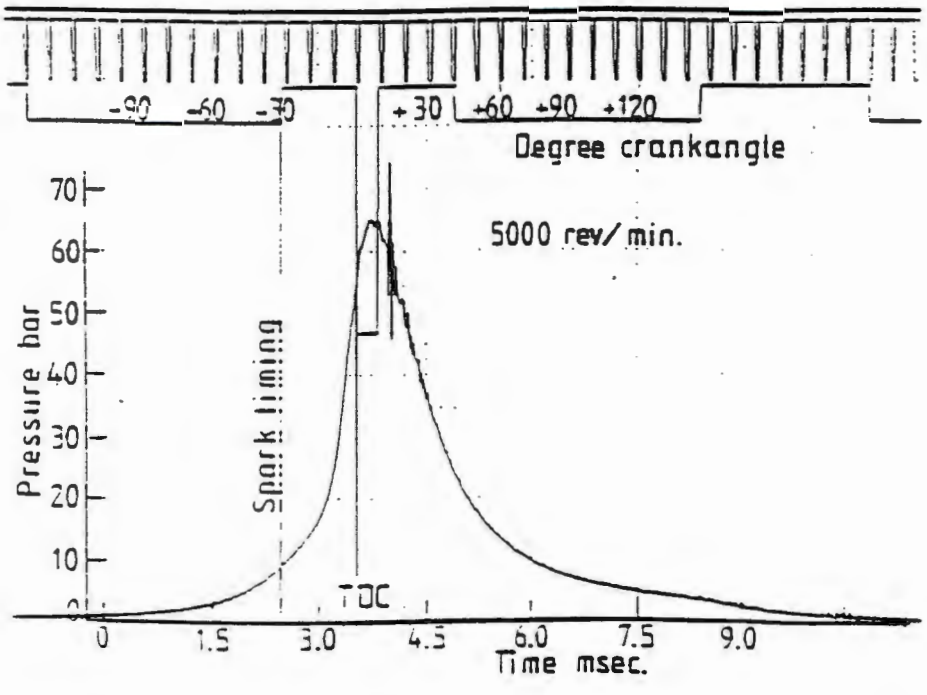


Cylinder pressure diagrams at 3500 and 4000 r/min

University of Cape Town

APPENDIX 5.12





Cylinder pressure diagrams at 4500 and 5000 r/min