JPL PUBLICATION 79-75

Ultralean Combustion in General Aviation Piston Engines

J. E. Chirivella

(NASA-CR-163001) ULTRALEAN COMBUSTION IN GENERAL AVIATION PISTON ENGINES (Jet Propulsion Lab.) 246 p HC A11/MF A01 N80-22430
CSCL 21E Unclas
G3/25 18041

December 1, 1979

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract No. NAS7-100.

Here is the ultimate in lightness of weight and power - two hundred and twenty-three horses compressed into nine delicate, fin-covered cylinders of aluminum and steel. On this intricate perfection I'm to trust my life across the Atlantic Ocean.

The inner organs of this engine - its connecting rods, cams, gears and bearings - will be turning over many hundred times each minute - sparks jumping, teeth meshing, pistons stopping and reversing at incomprehensible speeds. And I'm demanding that this procedure continue for forty hours if need be, for all the 3610 miles between New York and Paris. It seems beyond the ability of any mechanism to stand such a strain.....

Charles A. Lindbergh, The Spirit of St. Louis

PREFACE

The report presented herein formalizes the final episode of the NASA/OAST-sponsored "Hydrogen Enrichment for Aircraft Piston Engines Program." This program was undertaken as a part of the effort that the Office of Aeronautical Propulsion of OAST had devoted to improving the efficiency of aircraft piston engines in general aviation.

It was found during the course of the program that the original concept of using hydrogen enrichment to operate engines ultralean, and thus improve their efficiency, had important limitations. The original scope was therefore modified to encompass other successful techniques discovered earlier in the program, and in doing so it was also realized that there was a need for a coherent document which, while summarizing the potentials for fuel economy improvement, would also provide the reader with the minimum background for an in-depth understanding of the subject when present technical, practical and economic issues are taken into account. The major reason for this need was found to be related to the fact that the most important research in aircraft piston engines was conducted during the pre-World War II period and had not been translated into terms used nowadays by the General Aviation community. As part of the program and in an effort to assemble and organize the existing body of knowledge as it affects fuel economy, the open literature was critically reviewed.

It is the opinion of this author that an important need of the general aviation technical community will be fulfilled if a document containing the reviewed material with the gaps closed could be made available to the workers in the field. It was deemed that the presentation of the results of the Hydrogen Enrichment for Aircraft Piston Engines Program was an unusual opportunity for such an attempt in spite of the constraints imposed by the scope of the program.

This document contains then a summary of the body of knowledge in aircraft-engine ultralean operation for fuel economy improvement as well as the results of the technical phases of the program. The material has been presented in a somewhat tutorial form with the intention of making the subject more useful to those in need of data and who lack specialization in the field.

Section II contains a historical background illustrating the struggle of aviation for range improvement with a particular emphasis on engine design parameter development, particularly fuel economy and weight. Section III presents a quick review of the general characteristics of a modern aircraft piston engine in general aviation as well as a functional and anatomic description. Section IV reviews those factors which affect the fuel economy of an engine. Section V elaborates on the procedures and the technical background related to fuel economy improvement by leanout, identifying ultralean operation as the most promising and unexploited technique to achieve fuel economy. Section VI penetrates into the heart of the program and fully describes the original hydrogen enrichment technique for ultralean operation as well as the modified procedure for gasoline only which was successfully tested during the program and which proved to be most gratifying to the aircraft industry. Section VII conducts an assessment of the applicability of advanced ultralean techniques for the engines presently manufactured and in service but from which no experimental data is available to judge their eligibility. Section VIII is in essence a study of the strategy required as well as the logistics involved should ultralean burning be attempted now, and takes into account the existing confusion in the fuel situation, aircraft engine evaluation, and introduction of advanced systems in general aviation. The study also includes highlights of trends in the automobile industry as they may affect further developments in general aviation. A summarized list of conclusions and recommendations is offered in Section IX for convenience.

This document will without a doubt awake controversy and disagreement among some of the engine specialists active in industry and government agencies. It has been the honest attempt of the author to present the findings of the program and his views as principal investigator. It is hoped that other more detailed studies and developments will follow which may verify, clarify, disprove or contradict the claims presented herein, but it is judged that the main objective of the program has been accomplished if the attention of the aircraft industry and government agencies is focused on ultralean combustion as a potential for improving fuel economy in aviation during the transition scenario to alternate fuels.

J. E. Chirivella
Principal Investigator
Hydrogen Enrichment for Aircraft
Piston Engines

ACKNOWLEDGMENTS

The Hydrogen Enrichment for Aircraft Piston Engines Program was initiated and carried on under the direction of the NASA/OAST Office of Aeronautical Propulsion. AVCO-Lycoming Division and Beech Aircraft Corporation were under contract and fully participated during the different program phases.

The author is grateful for support given the program by many individuals and organizations. Key roles were played by the following people:

From the Jet Propulsion Laboratory:

Wesley A. Menard, Supervisor of the Combustion Research Group and former principal investigator of this program, who was instrumental in starting the program and who provided technical direction during Phase I. He was also responsible for the planning of Phase II and later continued to provide technical and administrative guidance. A major portion of the success of the program is credited to him.

Donald J. Cerini, Task Leader for Development of the Hydrogen Generator, who advanced the hydrogen generator technology to the point of making it airworthy for the flight test phase. He operated the hydrogen generator in flight, an arduous task.

Glen H. Haskins, who conducted the integration and installation of the hydrogen generator systems on the engine. His indefatigable dedication to the program is here especially acknowledged.

Jack Rupe, developer of the hydrogen enrichment concept, who was deeply involved in organizing and starting the program.

Philip I. Moynihan, Member of Technical Staff and task leader for the systems analysis conducted in Phase I, who provided the initial evaluation of the merits of the ultralean burn approach.

Jerry L. Brown, from the Procurement Division, who conducted the contractual effort.

Doug Maple, who was responsible for editing the report and whose valuable suggestions have substantially enhanced it.

Richard M. Clayton, who reviewed the final report and provided important suggestions in the organization of the presented material.

From AVCO-Lycoming Division:

Frank Riddell, Vice President of Engineering, for sharing his remarkable engine experience and for the enthusiastic support he gave to the program.

Larry C. Duke, Assistant Chief Engineer, who headed the Lycoming technical team that had responsibility for the test cell phase. Dr. Duke's numerous suggestions contributed to the success of the program.

Roy Meyer, test engineer who conducted the tests and collected the data.

From Beech Aircraft Corporation:

Robert C. Umscheid, who headed the Beech Technical team and was responsible for the flight test phase of the program. Mr. Umscheid contributed very effectively in all phases of the program, providing technical assistance and support as a formidable organizer.

O. W. Scott, Chief, R&D Systems, who enthusiastically supported the program, providing a valuable interface.

Van D. Gregg, project pilot, who skillfully implemented, in flight, the ultralean techniques through a wide range of operating conditions.

L. Johannsen, flight test engineer, who collected and reported the flight test data.

The author wishes in particular to express his gratitude to H. W. Johnson and D. J. Miller of the NASA/OAST Office of Aeronautical Propulsion for their direction, guidance, interest and support.

Finally, but not least, the author expresses his appreciation to his wife, Margaret Chirivella, who assembled and typed the rough draft of this report with no motivation but love.

ABSTRACT

The role of ultralean combustion in achieving fuel economy in general aviation piston engines is investigated. The aircraft internal combustion engine is reviewed with regard to general aviation requirements, engine thermodynamics and systems. Factors affecting fuel economy are also analyzed: in particular, those connected with an ideal leanout to near the gasoline lean flammability limit (ultralean operation). Techniques for achieving ultralean operation are discussed, and the results of the NASA "Hydrogen Enrichment for Aircraft Piston Engines Program" are presented. A Lycoming TIO-541E engine was tested in that program (both in the test cell and in flight). For this engine, the tests showed that hydrogen addition is not necessary to operate the engine ultralean. In turn, 17% improvement in fuel economy was demonstrated in flight with the Beechcraft Duke B60 by simply leaning the engine at constant cruise power and adjusting the ignition for best timing. No detonation was encountered, and a 25,000-ft ceiling was available. Engine roughness was shown to be the limiting factor in the leanout. An assessment for the other general aviation engines is also conducted, and a plan is offered to implement ultralean burning in general aviation, which results eventually in engine digital control by means of a microprocessor.

SUMMARY

Most gasoline aircraft engines of the past as well as the present were designed to burn rich fuel/air mixtures. By doing so, one provides an additional means to cool the engine, and allows it to operate at higher manifold pressures (which means higher power-to-weight ratios). This trend has been inherited by general aviation and has resulted in exhaust gases rich in carbon monoxide and unburned hydrocarbons. The BSFC, even in the best engines, has remained at a relatively high value (about 0.45). The maximum manifold pressure that can be used during takeoff and still prevent detonation has led manufacturers to run the engine at high speed to meet the power requirements. This, unfortunately, has given rise to noisier takeoffs and climbouts.

It is known that if an engine designed for rich operation is considerably leaned out, it will stumble, run unstable, and even misfire. There is experience, however, in the large radial engines used in the fifties, that lean operation is possible by adjusting the spark timing. These techniques were used to increase the range of large transport aircraft.

During the past years, several programs have been underway in the automotive facilities at the Jet Propulsion Laboratory (JPL) to stabilize ultralean burning by means of the hydrogen enrichment. The success of these programs prompted NASA to investigate the applicability of ultralean burning techniques in aircraft piston engines with the use of hydrogen enrichment.

It was found that with the Lycoming TIO-541-E engine selected for this program, no difficulty was experienced in leaning out with gasoline to the low fuel/air mixtures required, if the ignition timing was properly advanced. It was also observed that hydrogen enrichment would always provide better combustion stability. The inherent loss of power associated with ultralean burning was overcome by increasing manifold pressure, which was possible since the engine runs cooler with ultralean mixtures. Altitude checks in the test cell were conducted, and it was demonstrated that fuel economy improvements of about 20% could be obtained using such techniques.

Flight verification tests confirmed most of the test cell findings and demonstrated the feasibility of using, in flight, the ultralean power recovery techniques, while maintaining engine controllability and avoiding detonation. The critical altitude was reduced somewhat, but remained high enough for cruising above weather. A fuel economy improvement of 17% was demonstrated in flight.

It is recommended that those engines with better ratings, (nominally the fuel injection, supercharged engines) be equipped with larger superchargers or turbochargers, and possibly aftercoolers. These engines should also be provided with means of advancing the spark in flight, although it would be desirable that the leanout and spark advance procedures be made automatic or, even better, be incorporated in a single power lever.

More precise techniques for ignition timing and fuel injection will have to be introduced if the engine is to be operated ultralean, mostly at the low power levels. It is recommended that the successful techniques developed in the automotive industry for electronic fuel injection and electronic ignition be incorporated in the aircraft, possibly by means of digital controls and microprocessors. These techniques, however, will have to be introduced using the present systems as a backup for fail-safe mode; and when the electronic system has been proved to have acceptable reliability, the backup system may then be eliminated.

The methods and procedures recommended herein will most certainly increase the cost of the power plant, which will in turn become more efficient. This result is not surprising but it follows rather the general trends observed in the development of stationary and mobile power plants.

As these innovations prove to be successful in the higher quality engines, and their cost is reduced to acceptable levels, the manufacturer may be able to introduce them in the marketing of smaller, lower-rated engines.

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SECTION I

INTRODUCTION

In 1973 an OPEC oil embargo triggered an energy crisis in the U.S. which motivated a large number of studies addressed primarily to two main goals:

(1) Finding new energy sources.

(2) Conserving known energy sources.

Because of the immediacy of the energy crisis (and the resulting increase in oil prices), those concerned with energy conservation critically reviewed the efficiency of existing power plants. The effort benefited significantly by work which was undertaken in the 60's, when a better understanding of basic power plant phenomena was achieved in an attempt to control air pollution. In pursuing this work, many priorities and design tradeoffs developed to reduce air pollutants had to accommodate a new parameter: thermal efficiency.

The general aviation industry was also affected by these events. Although the Environmental Protection Agency (EPA) did not direct attention to general aviation until the early 70's, legislation was eventually passed which led engine manufacturers to investigate specialized fuel management techniques to lower CO and HC emissions near airports. The 1973 oil embargo made an impact on general aviation by affecting the availability of certain fuel grades. The fuel for general aviation, particularly aviation gasoline, constitutes a very small amount of the refinery output, thus creating a logistics distribution problem for the oil companies. It is expected that aviation fuel will continue to increase in price, which in turn will encourage aircraft owners to pay special attention to fuel economy improvement.

As a result of the considerations mentioned above, the Jet Propulsion Laboratory, sponsored by NASA and the Department of Transportation, undertook the challenge to meet the 1977 EPA standards for automobiles. The approach selected by JPL in order to reduce NOx was the operation of engines low in fuel, achieving combustion on the lean side of the exhaust gas temperature (EGT) peak. Since such a NOx reduction was not possible unless the engine operated very lean, small amounts of hydrogen were injected in order to stabilize combustion. For a description of the program, as well as the most important results, see References 1-1, 1-2, 1-3.

The JPL Low Pollution Car Program achieved its goals and demonstrated that by operating ultralean one could also achieve dramatic improvements in mileage. The results interested NASA, and a similar program tailored to the needs of general aviation and undertaken as a joint venture by JPL, Beech Aircraft, and AVCO-Lycoming was funded. JPL provided management and technical direction to the program; AVCO-Lycoming had responsibility for cell tests; Beech Aircraft Co. integrated the theoretical and experimental results in airborne packages and flight-tested it. The program, which was started in 1975, comprised three phases. In Phase I the systems were analyzed and the potentials for fuel economy evaluated. In Phase II the theoretical results were checked by running the engines in the test cell. Phase III was a flight verification.

The results of the program are presented in this document and given in the framework of the struggle of aviation to improve the range of airplanes. It was found that while hydrogen enrichment does not offer any fuel economy improvement, some of the present engines, while operating with gasoline only, with no further modification, can be leaned-out far more than has been attempted, provided that some unorthodox practices are included, such as higher manifold pressures, adequate variable spark advance and, possibly, lower rpm. With such practices it is possible to obtain improvements in fuel consumption of from 10 to 20%, while power level and thermal requirements remain the same or better than the design values.

Presently available engines are reviewed and evaluated in view of these new findings, and an effort is made to assess the potentials for energy savings of the general aviation fleet equipped with gasoline engines. Some recommendations for the general aviation industry are offered, particularly those affecting the requirements for engine controls during ultralean operations.

SECTION II

HISTORICAL BACKGROUND

In reviewing the history of aviation, one does not find a direct drive toward fuel economy improvement as such, or if there was any, it remains hidden in the secret desires of those connected with engine design. The actual feeling that one gets from history is that the priorities imposed on engine design, such as power-to-weight ratio, reliability, cooling, etc., were so overwhelming, that the cost of fuel was never raised as an issue.

It will be seen later that for a given airplane, there is a close relationship between fuel economy, range, and payload to be delivered. From this point of view, although indirectly, there has been indeed a long historical struggle for development of range.

Range has been improved through two methods: (1) increasing the lift-to-drag ratio of the airplane, and (2) decreasing the brake specific fuel consumption of the power plants. While the first approach implies sound applications of the principles of aerodynamics and structures, the latter is achieved by improving engine thermal efficiency, fuel heat content, and propeller efficiency.

A. THE BEGINNING (1800 - 1898)

Although the period prior to the Wright brothers' flight is most fascinating, if nothing else as an exposition of human ingenuity and dedication, hardly any achievements in range are worth mentioning. The problem plaguing the contending devices for powered flight was the absence of a suitable engine that could meet the power/weight ratio required for flight. There were then in existence machines that could have flown with today's engines, but at that time they all depended on the steam engine, which was way too heavy for flight.

Furthermore, even if those machines had left the ground (as some of them did, DuTemple in 1874, Mozahski in 1884, Ader in 1890), the pilots had no means of controlling their machines in the air, and they would return quickly to ground, many times with catastrophic results. The prevailing theory was that the important goal was to get in the air, because once this was accomplished, they would know what to do.

In parallel with the efforts of powered flight, important developments were taking place in Germany, which would contribute largely to the first powered flight. Near Berlin, Otto Lilienthal experimented and learned to fly gliders. He conducted well over 2000 flights and demonstrated that air could support a man in winged flight. He paid the price to fly very dearly, with his own life. On August 9, 1896, in one of his standard flights, a gust of wind stalled his glider and he plunged to the ground from 50 feet, fatally injured. His work inspired another famous flyer, this time a Scotsman, Percy Pilcher, who learned to fly his gliders beautifully and made glides as long as 250 yards. In 1899, he was soaring steadily when a tail-plane brace snapped and he also ended fatally injured. The tragic deaths of these two natural flyers brought a consciousness in the most astute experimenters of powered flight, that they did have to pay more careful attention to the problems of flight control. This period was characterized by a few successful hops (up to 164 feet, Ader). The nonexistence of a suitable engine prevented many visionaries from leaving the ground, although some sound aerodynamic and structural principles were implemented in a few airplanes. A most important achievement was also realized: men were initiated in the art of flying!

B. THE BREAKTHROUGH (1898 - 1903)

In spite of the important developments underway in Europe at the end of the 19th century, it was in the U.S. that the breakthrough was to occur. Two teams were competing for the honor of achieving the first powered manned flight: the Langley Aerodrome and the Wright brothers' powered glider.

When Langley completed his Aerodrome design, he concluded that a gasoline engine offered more promise for powered flight than the steam engine. Since he was not too familiar with gasoline engine state of the art, he turned to Charles M. Manly for assistance. To fill the requirements, Manly modified a gasoline engine designed by Balzer. The engine, a five-cylinder radial engine, produced 53 horse power and its weight came down to 125 pounds, with a weight/power ratio of 2.36, a remarkable achievement for those days. The Manly engine was many years ahead of its time and became the predecessor of modern engines. Unfortunately, it was married to the Aerodrome, in which, although termed an aerodynamic failure by some, it actually was later flown in 1906. The fallacy of Langley's approach was more in the launching technique than in the aerodynamics. Manly almost lost his life in attempting to fly the aerodrome in 1903. In trying to gain the fame of being the first man to achieve powered flight and beat his rivals, some intermediate tests were cancelled and the manned flight ended in catastrophe. Langley is credited with launching the first flying powered machine (unmanned) that flew for 3/4 of a mile after the fuel gave out.

The Wright brothers had all the characteristics that mark the inventive genius: patient, painstaking and methodical, provided with a superb creativity and a magnificent integrity. On top of that, they possessed the skill, imagination and daring to seek control in the air through gliding experiments.

In 1899, having heard of Langley's progress, they asked the Smithsonian for the best books on flying. This was perhaps the most fortunate break for them, since one of the books was Octave Chanute's Progress in Flying Machines. It was the first historical account of the early developments, including the flying experience of Lilienthal and Pilcher. The brothers contacted Chanute, and this was the beginning of a warm relationship which proved most helpful to the young experimenters. Through Chanute and with their own experiments, they learned the art of flying and introduced advanced control techniques such as wing warping and vertical rudder; and after two years of experimenting and flying their gliders and experiencing their share of disappointments, they felt that they had mastered the science of aerodynamics and the art of flying to the point that they could attempt powered flight.

Like Pilcher and like Langley, they found no lightweight gasoline engine in the market. They decided to build their own, and with a superb engineering effort, they created a four-cylinder 12-hp engine with a weight/power ratio of 16. This hardly compares with the Manly engine, but the brothers felt it was light enough.

In December 17, 1903, the Wright brothers executed their first historic flight: 120 feet. Three more flights were conducted on that day, the third lasting 59 seconds and covering 582 feet. This flight was to set a record for 4 years. The limiting factors in their effort were flying ability (loss of control) and poor engine cooling.

C. AVIATION WINS WIDESPREAD POPULARITY (1903 - 1909)

After the Wrights had demonstrated the realities of airp[illegible] flight, more than three years passed before anyone else flew. In the meanwhile, the Wrights had increased their flight up to distances of 25 miles. In spite of their success, the American press and the mil[illegible]ary we[illegible] responsive to their achievements. The initiative was undertaken [illegible] France, where, in 1908, Henry Farman flew 3368 feet in a Voisin biplane. The plane was powered by a 50-hp Antoinette engine. These engines were introduced in France in 1906 by Levavasseur, and were to become the most important power plant in Europe for several years. The Antoinettes were water-cooled V-type and although initially were built with 8 cylinders only, models were eventually offered which had 16 and 32 cylinders. The Antoinettes had inlet port fuel injection and evaporative cooling, and had a weight-to-power ratio of 3 lb/hp, an exquisite achievement. The cylinders were of machined steel using brass water jackets.

In 1908 two other important engines appeared; the 35-hp Renault 8-cylinder air-cooled V-type, and in the U.S., the Curtiss air-cooled V-type 8-cylinder engine. Early Curtiss engines were air-cooled but later the water-cooled approach was adopted for V-8 engines similar to the Antoinette engines, except that cast iron cylinders with monel water jackets were used. Next to the Wright Brothers, Glenn Curtiss was the most important figure in early American aviation history, and many of the modern engines are still associated with his name.

By 1909 four types of airplanes had made flights of more than one-hour duration: Wright, Antoinette, Farman and Bleriot. Bleriot made his famous cross-channel flight on July 25, 1909, with a tractor monoplane equipped with an Anzani 24.5-hp 3-cylinder fan-type air-cooled engine. But from the power plant point of view, the outstanding engine in 1909 was the 50-hp 7-cylinder Gnome rotary radial. This engine was a masterpiece designed by Laurent Seguin. It was made entirely from forged steel machined overall, with integrally machined cooling fins and a master rod system; it anticipated many of the innovations found later in the air-cooled radials. The engine was installed in a cowling with a central air intake with a bottom outlet for the cooling air. The major feature of the rotary engine was efficient cooling and most interesting its method of control; throttling down was accomplished by temporarily cutting the ignition. Another 1909 engine worth mentioning was the Darracq, used by Santos Dumont, one of the first aircraft engines to use mechanically operated inlet valves. This engine used two cylinders placed in the opposed configuration and was water cooled.

D. THE AGE OF THE FLYING ACES - WORLD WAR I (1910-1918)

The years 1910-1918 were characterized by a fairly rapid development in aircraft engines. The early part was dominated by the Gnome air-cooled rotary engine which, with modifications, was built in many countries. The design was eventually made obsolete owing to the limitation on speed imposed by centrifugal stresses and rather strong gyroscopic effects on the airplanes during turns. After the rotary engines, which were air cooled, V-type liquid-cooled engines took the lead.

In 1910, the famous Curtiss OX-5 made its appearance. This engine had an aluminum crankcase with cast-iron cylinders, sheet monel water jackets placed onto the barrels, and overhead valves. The OX-5 was used by the Army and the Navy in trainer airplanes. It was considered very reliable for its day and built up to 90-hp output, but most pilots during the training course experienced forced landings, due to its use of a single ignition, pull-rods for the inlet valves and a defective water pump.

In 1915, the Germans introduced the Mercedes 6-cylinder, 180-hp engine. It used welded-steel cylinder construction which would later be widely copied by most water cooled engines.

In 1917, after the U.S. entered the war, an engine was produced and delivered to the army in a record period of six months. This was the Liberty, which was built in the same style as the German Mercedes engine but with 12 cylinders and up to 420-hp; it had no original features but incorporated the best elements of the state of the art. Large quantities of these engines were produced by automobile companies such as Packard, Ford, Lincoln and some General Motors divisions. It was used in British military airplanes as well as in the U.S. Army Air Service and the Naval Flying Corps. Later it was to power the NC4 Flying Boat, the first aircraft to cross the Atlantic in 1919 and was also used by the Fokker T-2 in 1923, the first airplane to cross the American continent nonstop.

The technical breakthrough in this period was brought about by the Hispano-Suiza V-8 built in Barcelona by a Swiss engineer. It was adapted by French fighters in 1915 and used in the Spad 7 and 13, the best fighters of World War I. The engine design was a block cylinder construction with a cast aluminum water jacket containing steel cylinder barrels with enclosed and lubricated valves and valve gear. By 1917 these engines were built in England, the U.S. and France. The only drawback by the standards of that time was a tendency to burn exhaust valves. The major contribution was that the engine used cast aluminum except for the moving parts and the cylinder barrels.

E. THE PERIOD BETWEEN THE WARS (1918 - 1936)

After 1918 hundreds of new engines appeared, and a review of their development is beyond the scope intended here. The period is marked by three major developments: (1) future development of the liquid cooled engine of the all cast type, mostly for military purposes; (2) the development of the air-cooled radial to a dominant role for every kind of applications except fighters and light airplanes.

A major milestone was accomplished in the Bristol Jupiter, which was introduced and used in large numbers in England and the Continent for military purposes. It was a 9-cylinder air-cooled radial engine with flat steel heads, although it had a severe exhaust valve cooling problem due mostly to poor contact of the exhaust valve with the cylinder head.

In 1922, the Jaguar 2-row radial made its appearance using the Gibson-Heron type of cylinders. This engine used aluminum heads with two rows of 7 cylinders in radial configuration.

Other developments of air-cooled engines with aluminum cylinders and steel liners were undertaken in the U.S. by Lawrence. By 1921 the Lawrence J-1, using a 9-cylinder radial configuration and 200-hp engine appeared in the market. In 1922, the Lawrence Company was absorbed by the Wright Aeronautical Corporation and produced the models J-3, J-4, and J-4B, all with the Lawrence cylinder design. The J-5 type was produced shortly after, and became one of the most reliable engines of that time. In 1927, Charles Lindbergh used it for his nonstop flight across the Atlantic. However, this engine, the Wright J-5, was a Lawrence-type engine with Heron-type cylinders. It was one of the best engines produced and won the Robert Collier trophy award in 1927.

Also at this time the Pratt & Whitney Aircraft Company was founded and a new engine was produced, the famous Pratt and Whitney Wasp 425 hp. This engine looked very close to engines developed in the 1950's; it had 9 cylinders, a centrifugal gear supercharger, fully enclosed valve gear with rocker boxes integral with cylinder head, a forged and machined crankcase with a domed head and 2-valve cylinders of the Heron design. The crankpin was divided and had a one-piece master rod.

The liquid-cooled engines continued development following the lines of the Hispano-Suiza engines. The Curtiss company issued successive 12-cylinder designs that eventually produced the D-12 in 1922. The D-12 had aluminum heads with valve seats embedded directly in them. These Curtiss engines were much used to power racing airplanes (first to exceed 200 miles an hour). The Rolls Royce Company developed D-12 engines of a similar type. In 1927 the Kestrel generation of engine was initiated, and was to power racing airplanes for years to come. The Kestrel was followed by the Rolls Royce Merlin.

By 1930 the Kestrel R, with an astonishing specific power output and weight-power ratio, was well introduced into the market. The Kestrel was followed by the Rolls Royce Merlin that powered the Hurricanes and Spitfires - victors in the Battle of Britain.

German power plant developments were descendants of the Hispano Suiza and the Curtiss. Outstanding were the Daimler Benz and Junkers V-12 liquid cooled engines. In both of these the valves were seated in inserts in the aluminum head with excellent valve cooling. The basic structure consisted of a cast aluminum crankcase with in-block water jackets and cylinder heads also of cast aluminum.

Although more modest in its performance, the most important engine for General Aviation appeared in 1931. This was the Continental A-40 engine which used 4 cylinders. It was the forerunner of the contemporary horizontally-opposed light plane engines. Engines of this type built by Continental Engines Corp., the Lycoming Division of the AVCO Corp., and Franklin, have nowadays been developed to a unique degree of reliability and performance.

F. WORLD WAR II (1936 - 1945)

By the time World War II was started the air power in the nations involved in the war had been built primarily on engines whose design had been set forward during the intense research and development of the 1930's. Perhaps the main development during the war period was the introduction of the Pratt & Whitney 2800 series and the Wright Cyclone R-1880. In England the Packard Merlin was developed, perhaps the last of the liquid-cooled engines. All the famous airplanes in World War II used some variation of the engines referred to above, although significant improvements in reliability in extreme regimes of speed and high temperature were achieved. It was during this period that long-range bombers were developed, and although the range and payload capability were the result mostly of sound airframe design, fuel tankage and fuel systems, enough was known about the thermal efficiency of these engines to attempt range increases by substantially reducing brake specific fuel consumption. It is known that some B-29s were provided with special instructions during the leanout in order to achieve very low fuel consumption. The latest development in power plants in Germany were oriented toward the jet and the rocket engines. England concentrated on jet engines while the U.S. was credited with the only notable achievements in piston engines.

G. POST-WAR PERIOD (1945 - PRESENT)

Toward the end of the war, the long-range military bombers were using the most advanced radial engines, such as the Pratt & Whitney 1200, R-200, and R-2800, and the Wright Cyclone R-1820 and R-1830. By 1945, jet engine technology was developing rapidly, but fuel consumption was high and eliminated them from consideration as power plants of long range bombers and airliners. Airlines did not wait for further jet engine developments, and the Pratt & Whitney 4360 and Wright Turbocompound R-3350 were developed to power the three most popular airliners of the fifties, the Boeing Stratocruiser, the Lockheed Superconstellation and the Douglas DC-7. These engines had the best performance of commercial aircraft piston engines, although they never showed the reliability of the Pratt & Whitney R-2800. The advent of jet engines put an end to the large funding allocated to the research and development of the piston engine, and there is no doubt that further improvements would have appeared if the jet engine introduction had been delayed a few years. There is still a large amount of piston engine work and information which awaits a go-ahead by engine manufacturers. How much of this information is applicable to the horizontally opposed cylinder configuration used nowadays by general aviation is not clear, but there is strong evidence of multiple commonalities.

H. SUMMARY OF ENGINE DEVELOPMENT

The early development of power plants for aircraft was characterized by a broad variety of approaches and designs for engines to drive the propeller, which was at that time the only propulsive element available. Some of those early designs were seen for a short period, but 20 years after the first flight of the Wright brothers only the gasoline and diesel engines survived as competitive power sources. Although the diesel engine proved to be an adequate and reliable machine, it was overwhelmed by the success of the gasoline engine due primarily to the better power-to-weight ratio, which is most important in aviation.

The first 20 years of the development of the aircraft gasoline engine were mostly characterized by perfecting design details and manufacturing procedures. The motivation to increase the engine power-to-weight ratio brought about a wide variety of cylinder arrangements around the crankshaft. For large engines this culminated in the powerful (3500-hp) radial air-cooled engines of the type produced by Pratt & Whitney and the Wright Aeronautical Corporation.

In the late twenties, the demands for larger power plants for takeoff and altitude performance, triggered the introduction of supercharging. In the 30's the evolution of aircraft piston engines was marked by a great increase in power output from engines of a given size. This effort required considerable redesign and endurance testing, which even to this day is the method used in engine development. These great increases in power and constraints in engine sizes resulted in formidable engine cooling requirements. The pioneering work that NACA conducted in the study of cowl and pressure baffles is worth mentioning here. This gave rise to what is presently known as cooling drag. Other achievements during the same period were improvements in lubrication, valve mechanics, fuel injection, and water injection at takeoff.

In the 40's and 50's, the radial gasoline engine had become highly perfected, and had conquered the challenge of reliability and power-weight ratio (about 1-hp/lb). Then the new challenge was to lower specific fuel consumption to meet the requirements of the long-range strategic bombers and the transatlantic nonstop air liners, such as the B-29 and the DC-7. Further development on the large radial engines lowered cruise brake specific fuel consumption (BSFC) to 0.42 lb/hp/h. The efficiency loss required for crankshaft geared superchargers can be reduced if the supercharger is driven by a turbine powered by the exhaust gases. This is the concept of turbocharging, and although it was used in large engines during World War II (the Boeing Super-Fortress), its real significance at that time was superseded by the role it played in the development of the jet engine. Turbocharged piston engines gave rise to the efficient turbocompound radial, the Wright Turbocompound R-3350. This is a turbocharged engine where the excess power in the turbine shaft is delivered to the propeller. The turbocompound engines produced the best power-weight ratio and the lowest BSFC (0.38 lb/hp/h) of all radial piston engines in the late fifties, but their price was very high and their performance was obscured by dramatic developments underway in jet engine technology. At this point, the costly R & D supporting the large gasoline engines came to an end, and, in a matter of 10 years, the gasoline engine became a power plant exclusively for general aviation.

Table 2-1 shows a list of engines and specifications which summarizes the engines of historical importance mentioned above. Table 2-2 gives an outline of the contribution to engine development by each country and the aircraft where it was tested, as well as the type of engine innovation. Figure 2-1 presents a comprehensive view of engine genealogies and their interrelationships. The information has been selected from References 2-1, 2-2 and 2-3.

I. HISTOGRAM OF DEVELOPMENT OF ENGINE PARAMETERS

Figure 2-2 (from Reference 2-1) presents a set of engine development curves which show at a glance the improvement in engine performance parameters throughout the years. It is clear from the figure that the introduction of superchargers during the 30's remarkably improved specific fuel consumption as well as specific power output. This was accomplished by working at increasingly higher mean effective pressures, which was made possible by use of better cooling techniques, sounder structural design and fuels of higher resistance to detonation. The reliability of the engine was increased continuously, as is reflected in the longer overhaul periods. The maximum piston speed remained practically constant after 1935. The improvement in aviation fuels is shown in Figure 2-3 (Reference 2-1). Not shown in the figure is the constant increase of heat content per unit weight of the fuel, which also translates into better aircraft ranges.

From the brief historical review given above it is evident that considerable knowledge and experience were gained on aircraft piston engines during those 40 years of development, and that has resulted in the great reliability and performance of modern general aviation engines. It is also obvious that the introduction of a power plant based on a different thermodynamic cycle will necessarily have to compete in reliability with the present piston engines for similar application. Such a power plant must also demonstrate that the gasoline engine technology has come to an end; that it is not able to cope with present challenges of aviation: to reduce exhaust emissions, to lower noise, and to decrease fuel consumption.

Most gasoline aircraft engines of the past as well as the present were designed to burn rich fuel/air mixtures. This provided a means to cool the engine and to operate at higher manifold pressures (which means higher power-to-weight ratio). This trend has been inherited by general aviation and has resulted in exhaust gases rich in carbon monoxide and unburned hydrocarbons. The BSFC, even in the best engines, has remained

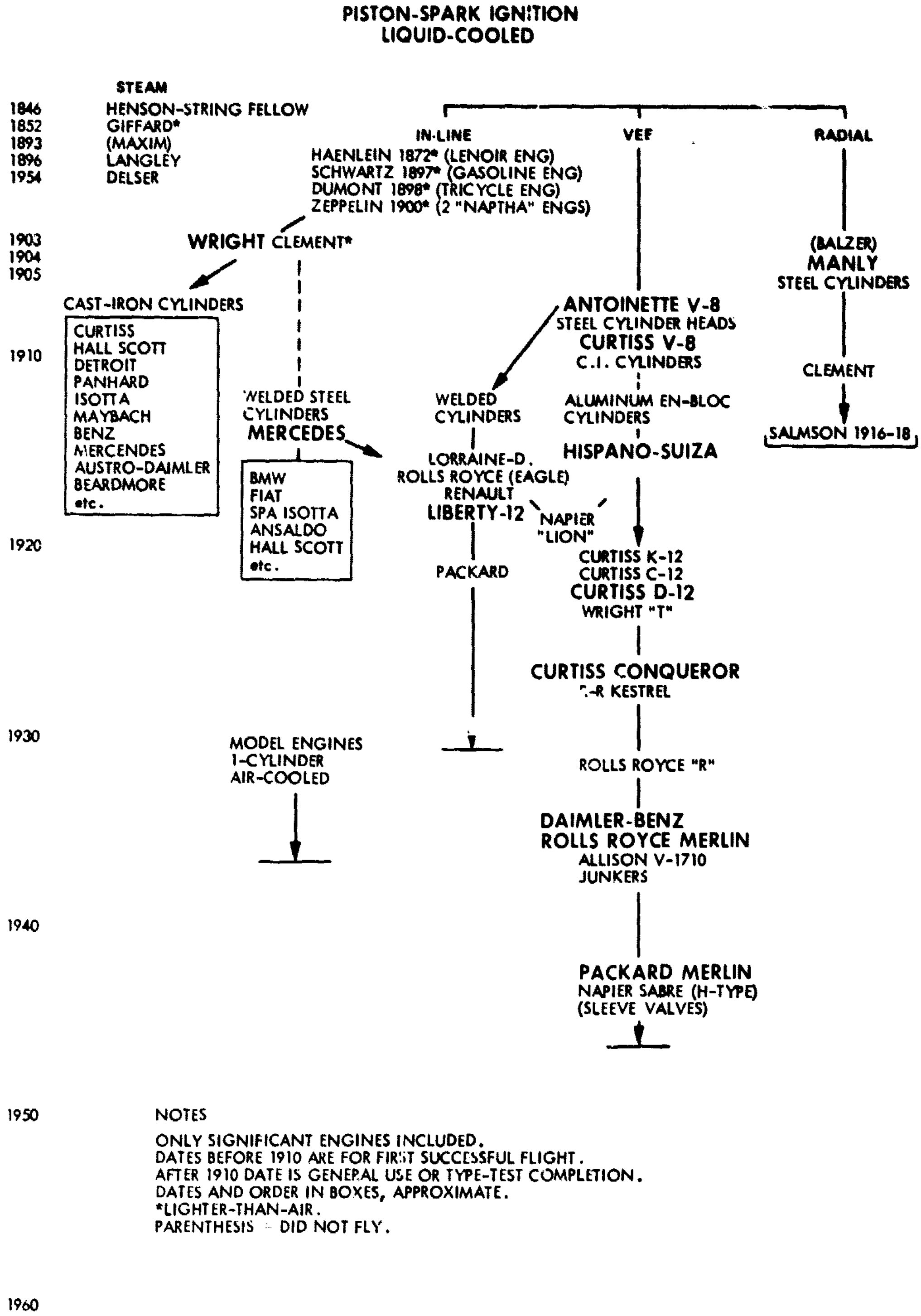


Figure 2-1. Family Tree of Aircraft Engines

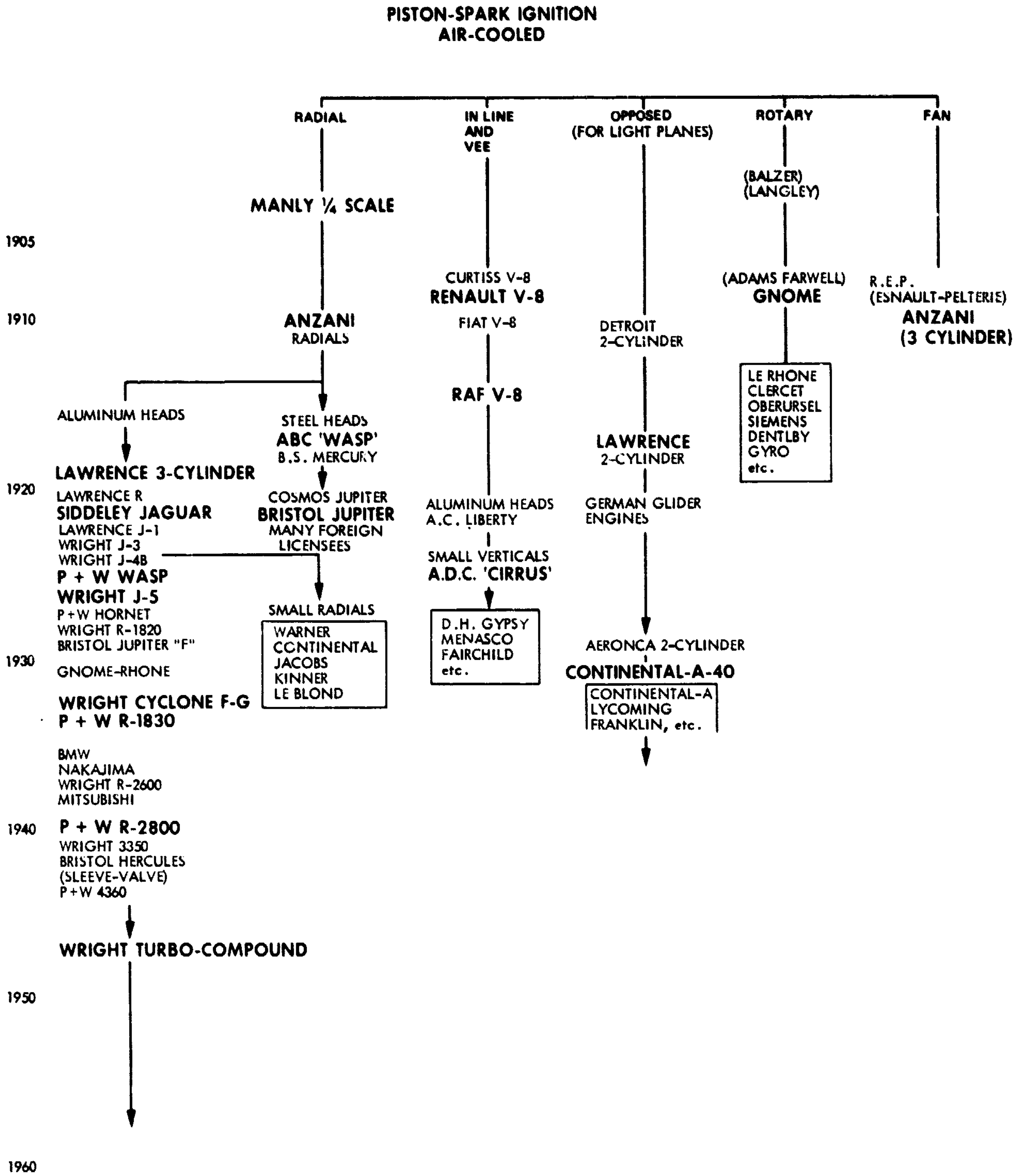


Figure 2-1. Family Tree of Aircraft Engines (Continued)

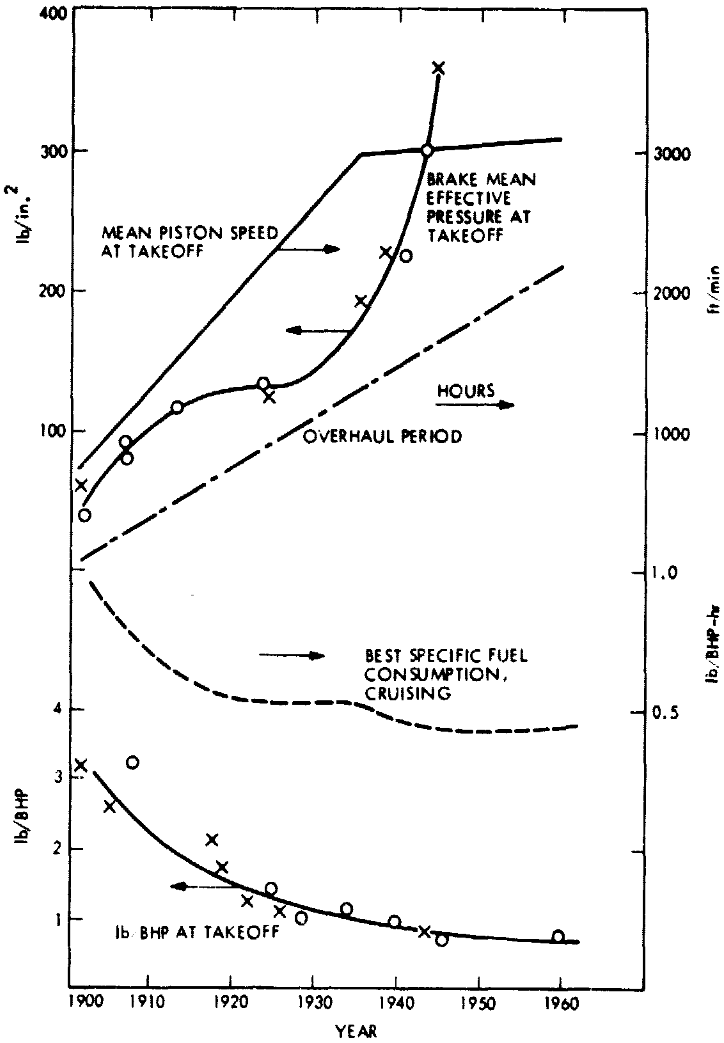


Figure 2-2. Engine Development Curves. Typical performance characteristics of military and large commercial airplane piston engines, 1903-1960. From 1930 on, these curves apply to supercharged engines; unsupercharged engines, except as regards overhaul period, remain at approximately the 1930 levels.

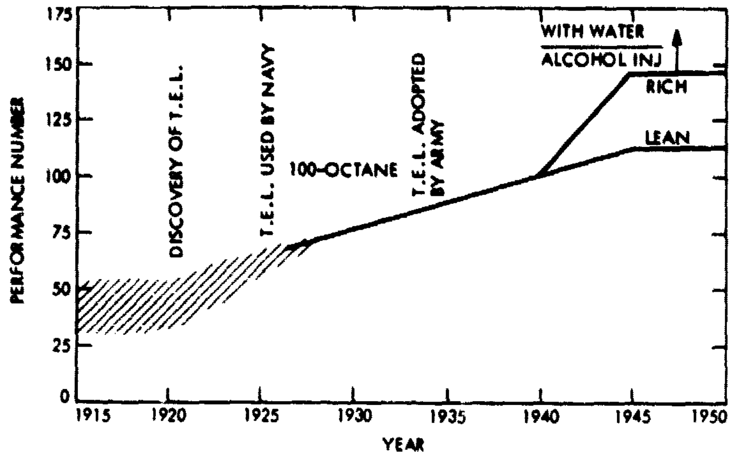


Figure 2-3. Increase in Aviation Fuel Performance Number with Respect to Time. The improvement was due both to additions of tetraethyl lead (T.E.L.) and to improved refining methods. Performance number is ratio of knock-limited power to that with pure iso-octane (x100).

at a relatively high value (about 0.45). The maximum manifold pressure that can be used during takeoff and still prevent detonation has led manufacturers to run the engine at high speed to meet the power requirements. Unfortunately, this has given rise to noisier takeoffs and climbouts.

It is known that if an engine designed for rich operation is considerably leaned out, it will stumble, run unstable, and even misfire. There is experience, however, in the large radial engines used in the 50's, which indicates that lean operation is possible by adjusting the spark timing. These techniques were conducted to increase the range of large transport aircraft: those using the Wright R-3350 engine, for example. These aircraft were equipped with torquemeters, gas analyzers, and two spark advance settings; the pilot had to actually tune the engine in flight to improve efficiency and meet mission range objective. Most of these techniques were known before the war, as shown by the excellent historical paper presented by Hersey in 1939 on "Fuel-Economy Possibilities of Otto-Cycle Aircraft Engines" (Reference 2-4).

Table 2-1. Engines of Historical Importance

Engine	Year[a]	Type	No. cyl.	Bore, in.	Stroke, in.	Displacement cu.in.	Horse power[b]	RPM	Weight[c] lb	Weight[c] lb/hp	BMEP, psi	Piston Speed, ft/min
Water-Cooled[d]												
Langley	1901	Radial	5	5	5.5	687	52	950	135	2.6	63	870
Wright	1903	Horizontal	4	4	4	200	16[d]	1090	179	11.2	58	725
Antoinette	1906	V	8	3.15	3.15	196	32	1400	93	2.9	91	735
Darracq	1909	Opposed	2	5.2	4.72	194	24	1500	121	5.04	65	1180
Curtiss OX-5	1910	V	4	4	5	503	90	1400	320	3.55	101	1170
Mercedes	1915	Vertical	6	5.51	6.3	901	160	1400	618	3.86	100	1470
Hispano-Suiza	1915	V	8	4.72	5.11	718	150	1450	467	3.1	114	1235
Liberty	1917	V	12	5	7	1650	420	1700	856	2.04	118	1985
Curtiss D-12	1922	V	12	4.5	6	1145	325	1800	704	2.16	125	1800
Rolls Royce Kestrel VI.	1930	V	12	5	5.5	1296	560	2500	992	1.77	137	2290
Rolls Royce Merlin I	1936	V	12	5.4	6	1650	1030	3000	1320	1.28	165	3000
Packard-Merlin	1945	V	12	5.4	6	1650	2250	3000	1740	.78	360	3000
Air-Cooled												
Langley (model)	1901	Radial	5	2.06	2.75	46.5	3.2	1800	7	2.2	30	825
Anzani	1909	Fan	3	4.13	5.12	206	24.5	1600	145	5.9	59	1360
Renault	1908	V	8	2.76	4.72	226	35	1400	242	6.9	88	1100
Gnome	1909	Rotary	7	3.93	3.93	335	50	1150	165	3.3	103	753
Jupiter	1920	Radial	9	5.75	7.5	1753	400	1650	700	1.75	109	2060
Jaguar	1922	2-row-radial	14	5	5.5	1512	360	2000	910	2.53	94	1830
Lawrence J-1	1922	Radial	9	4.5	5.5	787	200	1800	476	2.38	112	1650
Pratt & Whitney wasp	1926	Radial	9	5.75	5.75	1344	425	1900	650	1.53	132	1820
	1930	Radial	9	6.13	6.88	1823	575	1900	940	1.64	...	2180
Wright 1820	1945	Radial	9	6.13	6.88	1823	1525	2750	1376	.90	245	3150
Continental A-65	1938	Opposed	4	3.88	3.63	171	65	2350	155	2.38	128	1420
Pratt & Whitney	1940	2-row-radial	18	5.75	6.0	2804	2000	2700	2300	1.15	209	2700
2800.	1945	2-row-radial	18	5.75	6.0	2804	2800	2800	2327	.83	305	2800
Pratt & Whitney 4360.	1948	4-row-radial	28	5.75	6.0	4363	3500	2700	3470	.99	235	2700
	1941	2-row-radial	18	6.13	6.31	3347	2000	2400	2848	1.43	197	2550
Wright 3350	1955	2-row-radial	18	6.13	6.31	3347	3700	2900	3560	.96	302	3070

[a]Refers to year of first general use (except for Langley engine). Where two dates are given, they refer to typical early and late models of the same basic engine.
[b]Maximum rated, or takeoff power.
[c]Radiator, cowling, and coolant are not included in the weight of liquid-cooled engines. Cowling is not included for air-cooled engines.
[d]Dropped to 12 hp after 1 min.

All liquid-cooled engines later than Curtiss D-12 are supercharged. All air-cooled engines later than Lawrence J-1, except Continental, are supercharged.

Table 2-2. Credits, by Country, for Engine Development

First Manned Flight	Engine	Aircraft	Year
Austria			
Internal combustion engine	Lenoir gas engine	Haenlein (dirigible)	1872
Denmark			
Fixed radial engine air-cooled	Ellehammer	Ellehammer	1906
England			
With gear-driven centrifugal supercharger	Armstrong Siddeley	Armstrong Siddeley	1917
Transatlantic nonstop	Rolls-Royce Eagle	Vickers Vimy	1919
Automatic constant-speed propeller	Bristol Jupiter	Gloster Grebe	1928
Turbo propeller engine	Rolls-Royce Trent	Meteor	1945
France			
Steam engine	Steam	Giffard (dirigible)	1852
Electric motor	Electric motor	Tissandier (dirigible)	1883
Air-cooled Otto-cycle engine	Tricycle engine	Santos-Dumont (dirigible)	1898
Helicopter	Antoinette V-8	Cornu helicopter	1907
Rotary radial engine	Seguin Gnome	Voisin	1909
More than 8 cylinders	Levavasseur Antoinette 16-cylinder	Antoinette	1910
Propeller reduction gear	Renault V-8	Farman	1910
Inlet-port fuel injection	Antoinette	Antoinette	1906
Seaplane (floats)	Gnome	Heurig Fabre	1910
Turbosupercharger	Rateau	R.A.F. 4D	1918
Germany			
Rocket engine	von Opel	Opel-Sander Rak-1	1929
Diesel engine in commercial transport	Junkers 2-cycle opposed piston	Junkers G-38	ca.1936
Jet engine	von Ohain	Heinkel He-178	1939
Axial flow jet engine	Junkers Ju-004	Messerschmitt 262	1944
Rocket engine in military service	Walter	Messerschmitt 163	1944
Spain-Switzerland			
Aluminum cylinder structure	Hispano-Suiza	Spad 7	1914
United States			
Airplane	Wright	Wright	1903
Seaplane (flying boat)	Curtiss	Curtiss	1912
Over 400 hp	Liberty	DeHavilland-4	1918
Transatlantic with 2 stops	4 Liberties	Navy-Curtiss NC-4	1919
With fuel antiknock	Liberty	DH-4 (McCook Field)	1921
Metal propeller	Reed	Standard J-1	1921
Controllable-pitch propeller	Hispano-Suiza	Curtiss JN-4 (McCook Field)	ca.1921
Over 200 mph	Curtiss D-12	Curtiss racer (Detroit)	1922
Crankless engine	Caminez	Fairchild	1926
Roots supercharger[a]	Liberty	DH-4 (NACA)	1927
Diesel engine	Packard	Stinson Detroiter Monoplane	1928
Cylinder fuel injection with spark ignition	Pratt and Whitney	Ford or Fokker	1931
With pendulum-type vibration absorber	Wright 1820	Wright Experimental	1935

[a]The British two-cycle NEC engine used a Roots-type scavenger blower, but this was not a supercharger in the sense that it was used for altitude compensation.

SECTION III

THE AIRCRAFT SPARK-IGNITED PISTON ENGINE: A REVIEW

A. GENERAL CHARACTERISTICS

The power plant for most modern light and medium general aviation airplanes is still the spark-ignited piston engine. Although the size and price of small turbine engines have been reduced considerably during the past decade, there is, at present, no acceptable substitute for aircraft engines at power levels below 400 BHP. The situation could change, however, if the turbine engine should enter the extensive automotive market and thus develop a technological interest in small, low-cost turbines, since it is believed that the reliability of turbine engines could be even higher than that of the present piston aircraft engines.

The most important basic requirements of an airplane engine are (1) adequate power, (2) low weight-power ratio, and (3) high specific power output.

1. Adequate Power

When designing an airplane required to meet a certain performance, the engineer is usually confronted with estimating the installed capacity required for the power plant. This installed capacity will have to be provided with a reserve capacity for takeoff or high-performance flight. In general aviation, the maximum power required is determined by the takeoff performance. General aviation airplane owners often desire to land on poorly maintained short fields, some of them located at considerable altitude. Manufacturers are aware of these needs and offer an assortment of airplanes with such a takeoff performance. Later, during cruise, the pilot adjusts the engine controls to 75% power (fast cruise), 65% power (nominal cruise), or even 55% power (economy cruise), power needed to overcome the parasite drag combined with induced drag and propeller characteristics. Using some simplifying assumptions, one can state that the power required by an airplane in level flight is

$$BHP_R = \frac{\rho}{\rho_0} \frac{C_{D_f} S V^3}{146,600} + \frac{0.332}{(\rho/\rho_0)e} \left(\frac{W}{b}\right)^2 \frac{1}{V} \qquad (3-1)$$

where ρ is the actual density, C_{D_f} is the parasite drag coefficient, S is the wing area, e is the airplane efficiency factor (also known as Oswald's factor, and which accounts for the variation of parasite drag with the angle of attack and for the departure of the lift distribution from the elliptic one), W is the airplane weight, b is the wing span, and V is the true air speed (Reference 3-1). Equation 3-1 enables the designer to estimate the power necessary for level flight at several speeds, and Figure 3-1 shows the variation of maximum speed with installed brake horsepower per square foot of wing area for a number of general aviation airplanes using piston engines. The data, that have been compiled from References 3-2 and 3-3, can

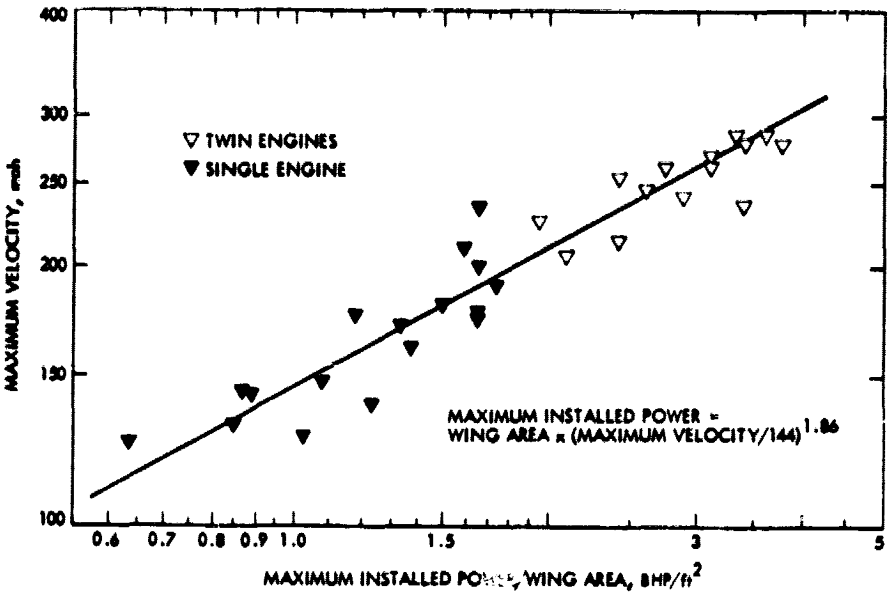


Figure 3-1. Maximum Installed Power/Wing Area as a Function of Aircraft Maximum Velocity for Various Light Aircraft

be approximately represented by a straight line in double logarithmic scales. The slope of this line is 1.86 and can be easily represented as

$$BHP_{max} = S\left(\frac{V_{MAX}}{144}\right)^{1.86} \qquad (3\text{-}2)$$

2. Low Weight-Power Ratio

The requirement for a low weight-power ratio is perhaps one of the most genuine for aircraft engines. Any unnecessary weight will be carried with the airplane for its entire life and will therefore drastically affect the performance of the airplane. All performance items suffer by an increase in weight: flight speed is reduced by an increase in weight, more so at cruising speeds than at high speeds; the rate of climb and the required takeoff and landing distances are unfavorably changed by an increase in weight.

But perhaps the most significant, although hidden, impact of the weight-power ratio occurs in the airplane-life integrated total fuel consumption, since it is estimated that weight change on an airplane has even more far-reaching effects on performance than a change in parasite drag. Under long-range operations, based on maximum allowable takeoff weight, it is possible to find that for every pound of weight added to the empty weight, approximately one pound of additional fuel is required, resulting in an unnecessary increase of 2 pounds in takeoff weight. Figure 3-2 shows the weight-power relationships for some representative

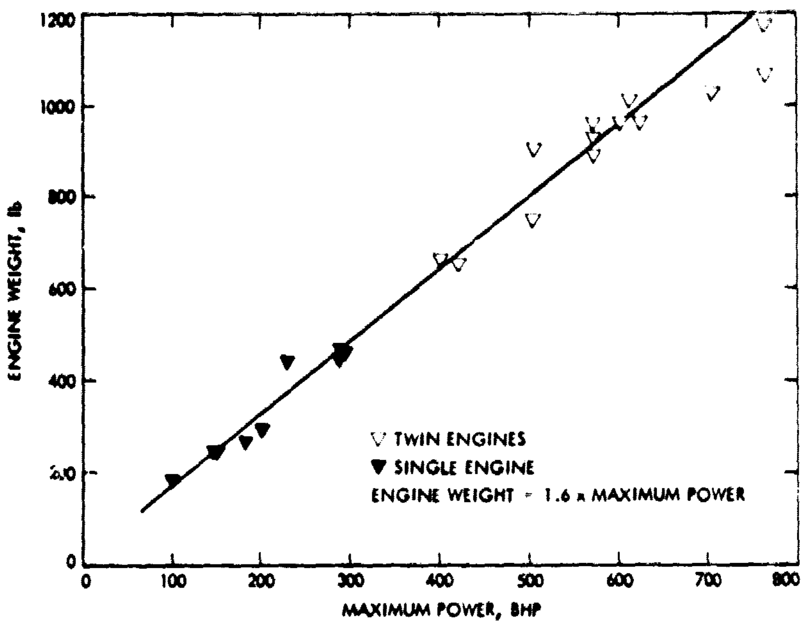


Figure 3-2. Engine Weight as a Function of Maximum Power for Various Light Aircraft

general aviation airplanes, and Figure 3-3 shows the weight of engines in terms of gross weight of the airplane. Power loadings, defined as the installed power-airplane gross weight ratio, are given in Figure 3-4. In Figure 3-5 is shown the power loading versus maximum speed. These illustrations are indicative of the present trends of the manufacturers in diminishing the parasite drag and the engine weight-power ratio. Representative points departing severely upward from the mean should be indicative of the need for further improvements.

In summary, the author believes that the ongoing efforts of manufacturers to improve the engine-power ratio and reduce parasite drag will greatly benefit the overall fuel consumption in general aviation, although it is difficult to obtain a quantitative estimate. Furthermore, the implementation is straightforward: the weight and drag reduction occurs at the factory, and requires no effort on the part of the pilot.

3. High Specific Power Output

The specific power is defined as the engine power-volume ratio. The useful power output from an engine can be expressed as

$$BHP = \frac{BMEP \times L \times A \times N \times \eta_p}{33{,}000} \qquad (3\text{-}3)$$

where BMEP is the brake mean effective pressure (psi), L is the piston stroke (inches), A is the piston area (square inches), N is the

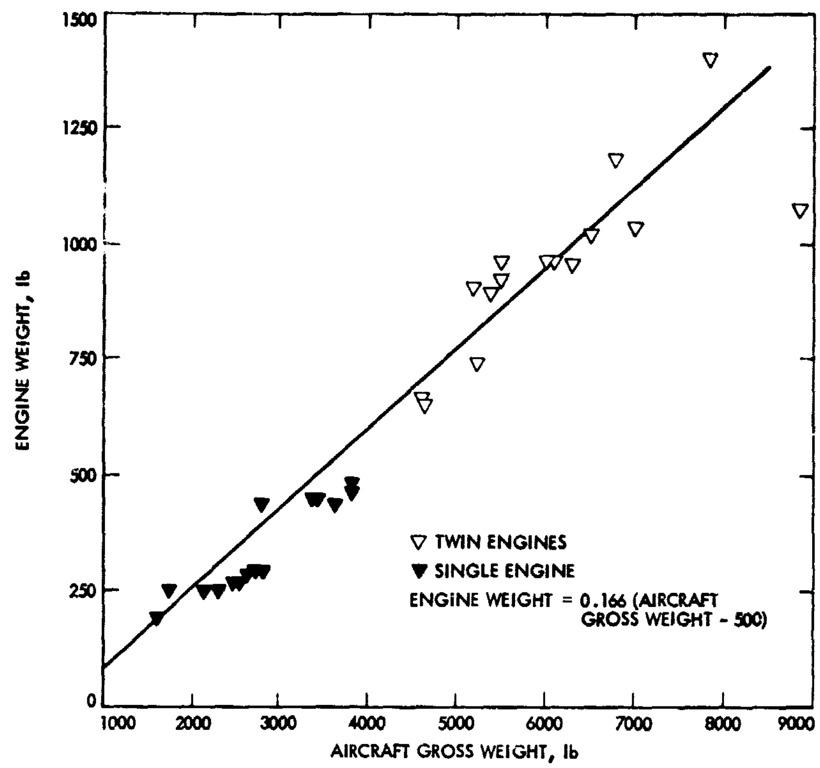


Figure 3-3. Engine Weight as a Function of Gross Aircraft Weight for Various Light Aircraft

engine speed (rpm), and η_p is the propeller efficiency. From Equation 3-3, it is obvious that an increase in working pressure (BMEP) is one of the most valuable methods in increasing the power output. The way to increase BMEP is to increase the compression ratio, which impacts on the fuel octane requirements, although greater increases are still possible by supercharging. The speed of the engine is limited by the propeller efficiency, and in this sense reduction gears are used where added complexity and cost is warranted. Even with reduction gears the speed is limited by the valve gear, crank pin loadings, high specific oil consumption, and engine life. Figure 3-6 shows the engine weight versus BMEP and fuel octane number for several general aviation airplanes (where applicable, supercharged engines are indicated). This figure shows how manufacturers take advantage of the availability of different octane fuels to achieve high specific power output. In some cases, one can see that a good combustion chamber design and adequate cooling can render high BMEPs for low octane numbers. In any case, the effect of supercharging should be considered as being limited by the octane number since, at the very end, supercharging is equivalent to an increase in compression ratio if the engine does not possess an after-cooler.

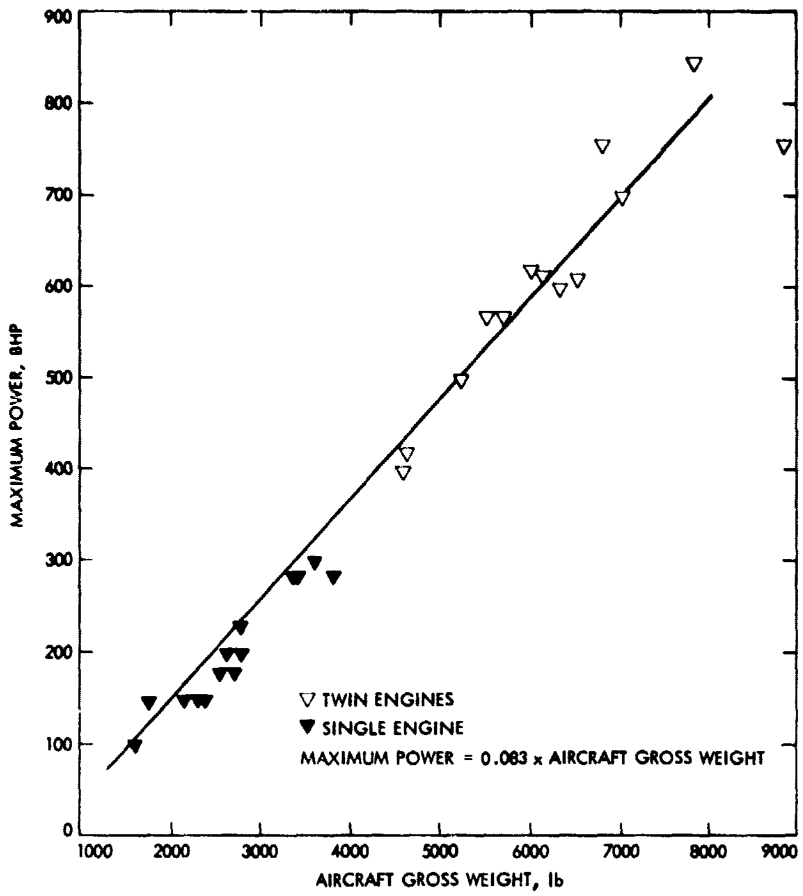


Figure 3-4. Maximum Power as a Function of Gross Aircraft Weight for Various Light Aircraft

4. High Thermal Efficiency

Thermal efficiency is the inverse of the specific fuel consumption, and good fuel economy is important in aviation not only because it affects the direct airplane operating costs, but also because the effect is cumulative. Fuel economy is very tightly related to range, which has been, and is, a prime performance item as mentioned previously in Section II. There have been great improvements in the aircraft piston engine to reduce the specific fuel consumption. Many of these improvements have to do with engine block design, intake manifold development, and the use of high-temperature materials, but the most important variable affecting fuel consumption resides in the ability of the engine to burn very lean fuel-air mixtures, while maintaining an acceptable degree of combustion stability.

5. Reliability

Engine reliability is of crucial importance; human lives are at stake. The Federal Aviation Agency (FAA) has been particularly effective

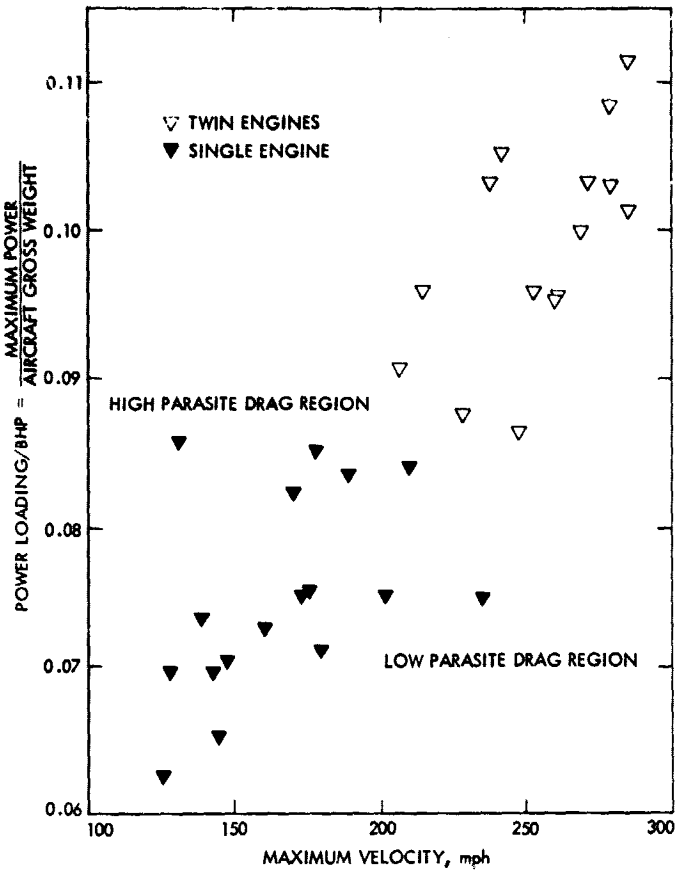


Figure 3-5. Power Loading as a Function of Maximum Velocity for Various Light Aircraft

as a regulatory agency, coordinating with NASA, engine manufacturers, and airplane manufacturers, in developing the remarkable reliability and safety features of modern general aviation airplanes. This issue is perhaps least understood by those concerned with the implementation of noise and air pollution regulations and who may lack experience in the cockpit: air pollution, noise abatement, and fuel economy are extremely important but are secondary to reliability. Whereas general aviation traffic allegedly offends the environment near airports (i.e., the ground operations, takeoff, climb, approach, and landing) presenting thus certain incompatibilities with safely conducting traffic operations, a fuel economy issue primarily affects the airplane cruise and climbing modes, where the traffic density is low, there is a safe altitude, and the crew has a comfortable opportunity to implement fuel economy procedures.

6. Compactness

If the engine block, systems, and appurtenances are maintained to a high degree of compactness, the parasite drag will be low, although certain limitations are imposed by air-cooling requirements. Since the

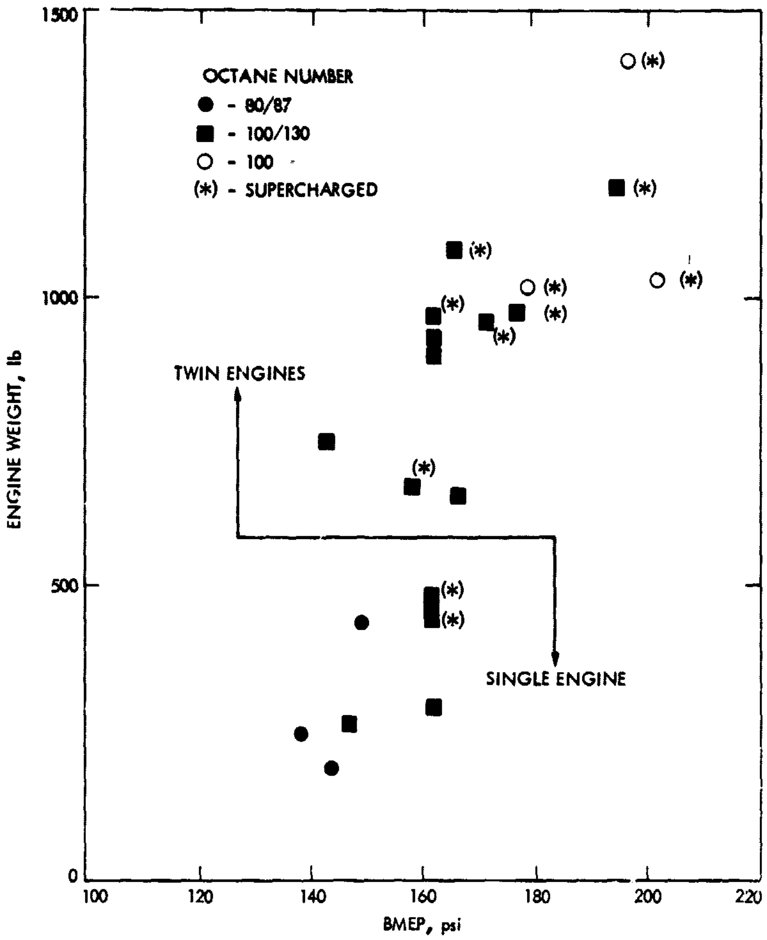


Figure 3-6. Engine Weight as a Function of Brake Mean Effective Pressure (BMEP) and Octane Number for Various Light Aircraft

thermal efficiency is about 35%, 65% of the fuel energy must be dissipated. The radial engine configuration has, in this respect, an advantage over the modern opposed-cylinder configuration, although in practice the differences become negligible for the small-sized engines used in general aviation. An improvement in thermal efficiency will also reduce the air cooling drag, the total engine size, and therefore the parasite drag.

7. Low Maintenance Cost

The cost of maintenance is determined by simplicity in design, the use of standard parts, and interchangeability of parts on like engines, as well as the size of the repair parts inventory.

8. Engine Lifetime

Operating life between overhaul periods directly affects the economy of the aircraft. It is greatly related to pilot practices during flight (unintentional overheating, oil starvation, etc.) and, most important, to periodic service and maintenance in accordance with the airplane manufacturer's instructions. Operating life is also substantially affected by the particular use to which the airplane is committed (operating life is directly connected with the number of takeoffs and landings per logged hop time). In this respect, an airplane engine used for pilot training will have a much shorter lifetime than an airplane engine involved in long-range passenger and light cargo transport and operated by professional pilots.

9. Low Initial Cost

Most of the cost of an engine is not in the materials but in the fabrication, which is in turn tightly connected with the complexity of design. This is, perhaps, together with weight reduction, the area where the engine manufacturers have had more pressure from their clients (the airframe manufacturers) in meeting certain costs. The economic factors that drive general aviation are, in a certain way, similar to those of the high-quality automotive industry (top-of-the line passenger cars, sport cars) and, therefore, the cost of a candidate engine will be one of the first questions that an airplane designer will address when investigating the market needs.

10. Operation Under a Wide Range of Conditions

Because of the worldwide distribution of airplanes, the mobility of an airplane, and the diverse weather conditions that may be encountered during a climb or descent, the aircraft engine must be reliably operated under a broad spectrum of adverse conditions. This is notably reflected in the FAA requirements for dual ignition, special carburetors, and other features which are not encountered in automobile engines.

11. Industry Constraints

When all these requirement and limitations are taken together, and when one realizes that the general aviation market is very small compared with other engine markets in the world (the automobile industry manufactures more engines in two or three days than the general aviation industry has produced in the last 20 years), one is impressed by the extraordinarily narrow corridor in which the general aviation industry operates, and it is no surprise that there are only two engine manufacturers left in the world (AVCO-Lycoming and Teledyne Continental Motors) in the active market. Furthermore, and in spite of limited competition, top-of-the line engines, particularly those provided with supercharging and fuel injection, are excellent machines, the result of extensive research and development effort and widely tested in the field. Even though the advent of the jet engines for heavy transports put an end to the research in piston engines by the giant engine manufacturers, Lycoming and Continental have excelled in adapting such knowledge to general aviation modern needs and have substantiated every change with considerable research and development. In this respect, therefore, the author wants to acknowledge the difficulty in improving these engines significantly by means of limited resources. This report documents the efforts to achieve an improvement in fuel economy, the results obtained during such an effort, and the prospects for practical implementation in the near future.

B. THERMODYNAMICS

The modern aircraft piston engine for general aviation airplanes is the four-stroke, spark-ignited, gasoline-powered Otto cycle engine. Figure 3-7a shows the thermodynamic processes in the P-V diagram correlated with the different piston strokes. During an Otto cycle, fresh air is admitted into the cylinder through the inlet valve (inlet stroke). After the inlet valve is closed, the piston is moved inward by an external force, and the gas is compressed adiabatically and reversibly from point 1 to point 2 (compression stroke). Heat is then added at constant volume to increase the pressure to point 3. Reversible adiabatic expansion causes the piston to return to the original volume at point 4 while pushing against an external force (expansion stroke). The exhaust valve is now opened and the air is exhausted and cooled down to the original point 1 (exhaust stroke). This cycle is also known as the constant-volume air cycle and is described in detail in Reference 3-4, but some fundamental definitions will be given here for the convenience of the reader:

Thermal Efficiency, η_t: Ratio of the net cycle work to the heat released into the system during the process.

Compression Ratio, r: Defined as the relation $r = \frac{V_1}{V_2}$

Adiabatic Index, k: Gas specific heat ratio.

Mean Effective Pressure, MEP: Work done on the piston during one cycle divided by the displacement volume $V_1 - V_2$.

Power Output, HP: Defined as the work given by the cycle times half the engine angular speed:

$$HP = MEP \times (V_1 - V_2) \times \frac{n}{2} \qquad (3\text{-}4)$$

Brake Mean Effective Pressure, BMEP: Same as MEP but measured at the shaft.

Brake Horsepower, BHP: Same as HP, but measured at the shaft.

$$BHP = HP \times \eta_m \qquad (3\text{-}5)$$

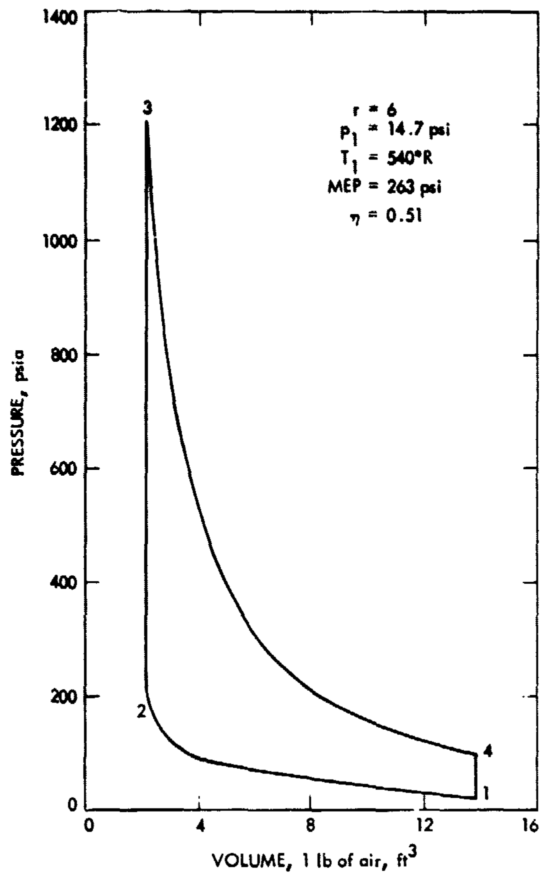


Figure 3-7a. Otto Cycle in P-V Diagram

where η_m is the engine mechanical efficiency.

An analysis of the engine air cycle shows that

$$\eta_t = 1 - \left(\frac{1}{r}\right)^{k-1} \qquad (3\text{-}6)$$

which shows the effects of the compression ratio on thermal efficiency.

The actual thermodynamic cycle differs somewhat from the discussed ideal air cycle (see Figure 3-7b.) The major departures are due to:

(1) Finite heat release rates due to fuel/air mixture combustion characteristics.

(2) Heat losses to the piston, cylinder heads, and walls.

(3) Fuel/air mixture properties.

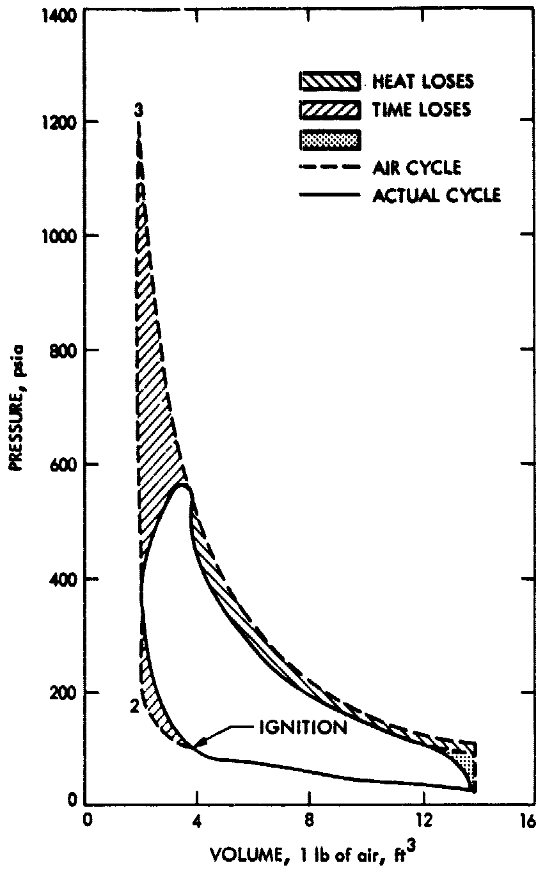


Figure 3-7b. Actual Cycle and Losses

(4) Combustion product properties.

(5) Cycle corners roundoff due to engine speed, valves, and ignition timing.

Of particular interest is the specific fuel consumption, SFC, defined as the inverse of the thermal efficiency, expressed in pounds of fuel per hour divided by HP, which is a figure of merit of the efficiency of the engine. Of still more use to the engineer is the brake specific fuel consumption, BSFC, which is the same as SFC but with the power output measured at the shaft:

$$BSFC = \frac{\text{pounds of fuel per hour}}{\text{BHP}}$$

A detailed description of the thermodynamics of the actual cycle can be found in Reference 3-4. The specific fuel consumption is greatly influenced by the compression ratio, fuel octane number, optimum timing for a particular engine regime, manifold pressure, and, most of all, by the leanest fuel-air mixture compatible with the required performance of the engine. More on the subject will be given in a later section.

C. ENGINE SYSTEMS

The aircraft piston engine is provided with specialized systems which serve two major functions:

(1) To control the thermodynamic variables and have the engine operating under a specific indicated cycle.

(2) To deliver and condition the power for specific flight requirements.

Most of these systems are similar to those present in automobile engines but because of the special needs and environment of the aircraft, these systems differ somewhat from other applications. It is customary to classify spark-ignited piston engines as air induction, fuel, ignition, cooling, and lubrication systems.

1. Air-Induction System

The air-induction system comprises the air inlet, the throttle, the intake manifold, and the inlet valves. If the engine is supercharged, a compressor is installed upstream of the throttle valve. The air inlet position in the engine cowling varies with the particular design of airframe, but in general it takes advantage of the ram pressure existing behind the propeller and is enhanced by the aircraft air speed.

An air filter is usually placed in the proximity of the air inlet to protect the engine from dust particles and accidental debris encountered during ground operations, and a vent, which is operated from the cockpit, allows the air to bypass the filter and be routed through a heat exhanger, thus providing a carburetor heat system if the engine requires it (see Figure 3-8).

In supercharged engines, a compressor of the centrifugal type is installed to keep the desired engine power output constant up to a certain altitude for that particular power. The compressor can be driven by a turbine (turbocharger) or can be mechanically coupled to the engine. In the first case, the turbine is operated by the engine exhaust gases and in the second case the compressor receives its shaft power through a multiplicative gear box driven by the crankshaft.

The throttle is a butterfly-type valve mechanically coupled to the cockpit throttle lever. The intake manifold has been designed to distribute the air flow uniformly throughout all the cylinders. Although such a distribution is adequate at some power levels, it may not be adequate at different engine speeds and throttle positions. The design of the intake manifold is still an art and is greatly responsible for the variations from cycle to cycle in the different cylinders. The inlet valves have been designed to provide the cylinders with the maximum volumetric efficiency. The controls for the air-induction system for naturally aspirated engines are limited to the actuation of the throttle in a similar manner as in an automobile engine. In supercharged engines with a geared compressor, the compression ratio is directly coupled to the

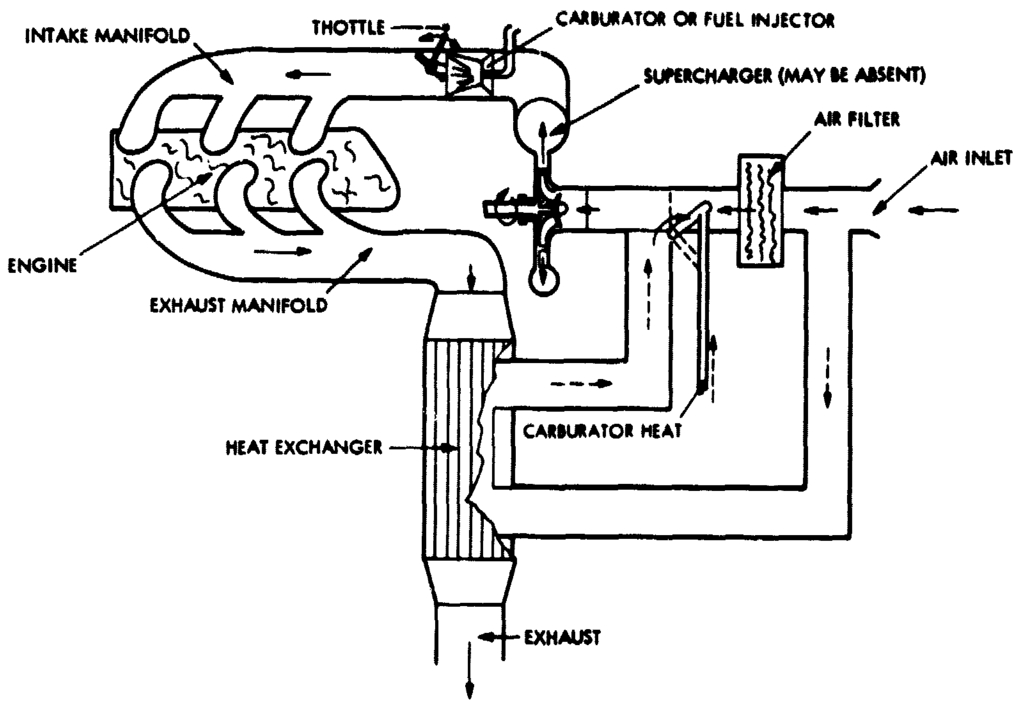


Figure 3-8. Air Induction System. Some components may be missing in certain types of engines

engine speed, and again the only control available is the throttle valve. In modern turbocharged engines, the control of air flow is by far more sophisticated (see Figure 3-9). The compressor speed is equal to the turbine speed which is, in turn, controlled by the flow of the exhaust gases. The amount of exhaust gases which expand through the turbine can be varied from zero to a full load by means of a waste gate valve. The position of the waste gate valve is, in turn, determined by a controller that senses the manifold pressure. The desired manifold pressure at any altitude is requested from the cockpit by positioning the throttle valve at a certain angle. This angle is mechanically transmitted to the controller and compared with the signal from the manifold pressure sensor, resulting in the proper activation of the waste gate valve. If the aircraft is pressurized, the pressurization air is bled from a nozzle located on the compressor discharge side.

In some engine models, because of the increase in manifold temperatures with increasing compression ratio, an air after-cooler is provided in order to bring the manifold temperature down to levels that will not be detrimental to the volumetric efficiency.

2. Fuel System

The fuel system consists of fuel tanks, fuel strainers, fuel pumps, carburetor or fuel injectors. The fuel tanks are vented to the atmosphere

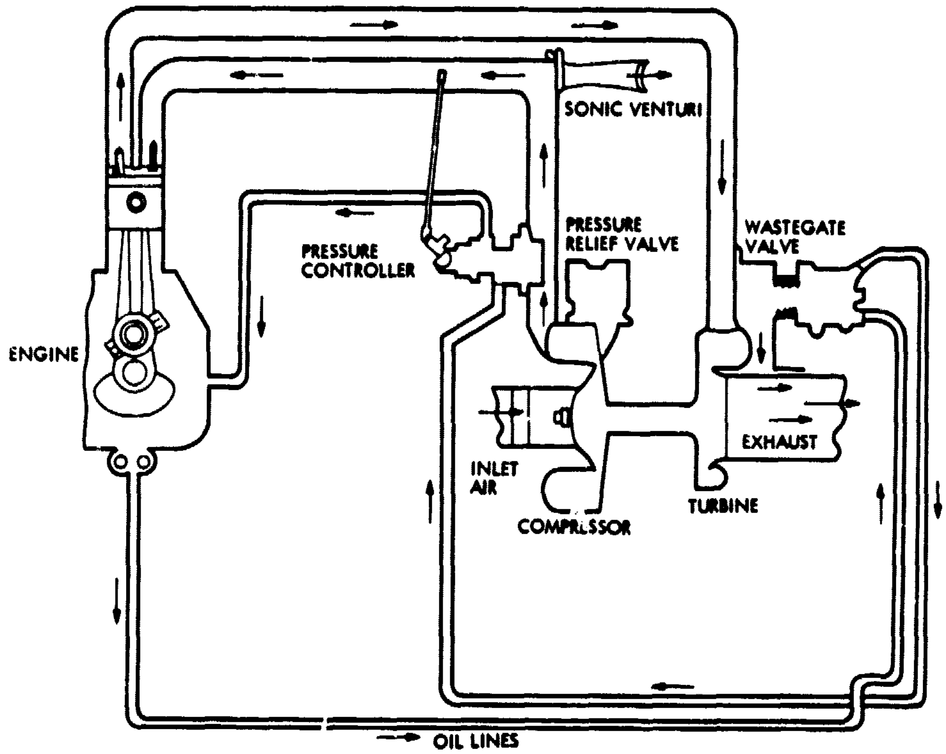


Figure 3-9. Modern Engine Equipped with Turbocharger. Wastegate valve operated with engine oil pressure (as offered by Airesearch Industrial Division)

and are integrated with the wings. These tanks are usually provided with individual fuel strainers to clean the fuel from contamination and water condensation that could have been deposited on the bottom. The fuel is transferred to the engine by means of fuel lines which are interconnected to provide the engine with an additional fuel strainer and priming capabilities (see Figure 3-10). Except in the case where the fuel is fed into the engine by gravity, a mechanical fuel pump directly driven by the engine transfers the fuel from the tank to the carburetor or fuel injector as applicable. This pump is supplemented in some cases by an electric booster pump submerged in the tanks, which is turned on during critical operations such as takeoff, landing, and taxiing. In many light airplanes, the fuel is introduced into the intake manifold by means of a carburetor, although the general trend in all modern engines is to use fuel injection. There are many reasons for this trend, but the most important one is the ability of the fuel injector to provide an accurate fuel schedule and a uniform fuel distribution through all the cylinders; moreover, the fuel injector is not subjected to the dangers of carburetor icing which have caused so many fatalities in the history of aviation. Although the term "fuel injection" has been used to designate such systems, they are not fuel injectors in the proper sense of the word, since the fuel is not actually injected into the cylinder (as in Diesel engines) but, rather, is injected at different locations upstream of the inlet port, depending on the engine model. The

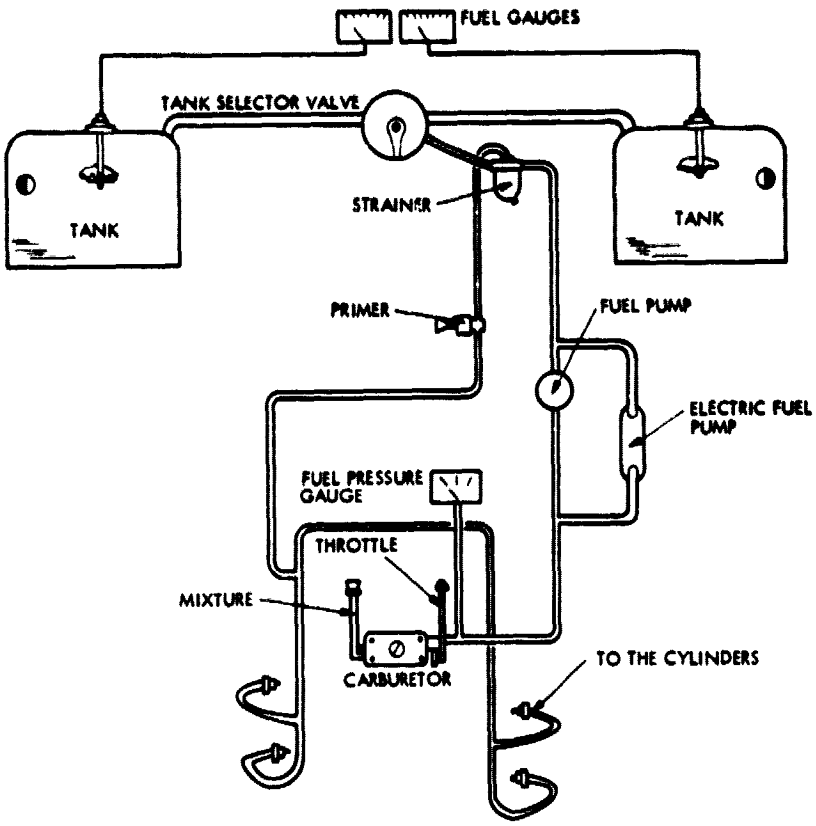


Figure 3-10. Fuel System for Piper Cherokee Cruiser. The general arrangement varies considerably from model to model

most extensive practice in modern engines is to manifold the fuel to the different cylinders and inject the fuel into the air-intake manifold a few inches from the inlet valve. The fuel distribution throughout the cylinders as well as the above-mentioned air distribution, are the two most important factors in the ability to operate an engine smoothly near the lean flammability limit and very fuel rich. They are also responsible for the quality of an engine as regards fine crankshaft balance, vibrations, and low specific fuel consumption.

3. Ignition System

The ignition system in aircraft engines is designed with the philosophy of complete electrical independence from the rest of the electric system in the airplane: As long as the engine turns, there is a guarantee of a spark in the cylinder. FAA regulations require that every spark-ignited piston engine be equipped with dual ignition. This can be accomplished with two independent magnetos independently geared to the engine (twin magneto) or with a dual magneto with single gear. This dual ignition is instrumental in assuring an efficient combustion of the mixture in the cylinders for any engine regime and in preventing catastrophic engine failure by malfunction of one of the two systems, and it is indeed well known that the engine loses some power when the pilot intentionally switches to single left or right magnetos during the engine runup check. The magnetos are wired to ignite the mixture at a certain fixed advanced timing. This feature is different from the variable timing that automobile engines are provided with. The reason for this resides mostly in simplicity and the fact that the engine regimes in an airplane are not subject to drastic changes during flight. The optimum timing is selected for inhibiting detonation during takeoff power situations. No attempt is made later on to vary the timing for cruise power. The magnetos are provided with an additional breaker for easy engine startup which is about 5° before top dead enter (BTDC). This last timing is achieved by a multivibrator or an impulse coupler. The normal timing varies somewhat from engine to engine, but is on the order of 20° BTDC. The spark plugs are of the long penetration type, located in the cylinder head to assure complete combustion and, like the rest of the ignition harness, electrically shielded to avoid interference with the aircraft radioelectric instrumentation.

4. The Cooling System

The cooling system in these engines is without exception an air-cooled system. An opening at the front of the cowling serves as intake of ram air, which is later deflected inside of the cowling by means of baffles in order to provide sufficient convective heat transfer throughout the fins of the cylinders. The amount of air is regulated in some models by means of movable gills located near the fire wall. This air-cooling flow causes an increase in the aircraft drag (cooling drag), particularly during takeoff and climb operations. Engine manufacturers are presently undertaking an effort to minimize the cooling drag by providing a better design of the cylinder fins, and the air frame manufacturers are constantly seeking more convenient engine-cowling configurations which will minimize the cooling drag (see Fig. 3-11).

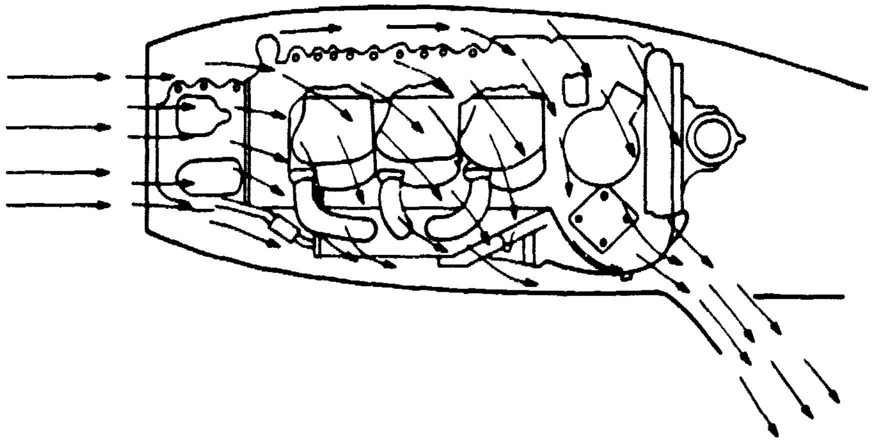


Figure 3-11. Air Cooling Circulation in Engine Cowling

5. Lubrication System

The lubrication system is provided by means of forced circulation of oil. In the past, such systems were of the dry sump type, but modern engines use the wet sump arrangement. The oil is forced by means of a mechanically driven oil pump. Sometimes the oil pressure is used to actuate some engine hydraulic components. The lubrication system is also used to cool certain internal parts of the engine; to remove this heat a small oil cooler is often installed in the forepart of the engine. Oil temperature and pressure are two variables of utmost concern to the pilot, since they are one indication of the mechanical status of the engine. Specific oil consumption is also a good indication of the mechanical condition of cylinder and piston assemblies. Greater than normal oil consumption is usually a sign of loss of compression in some cylinders.

D. MECHANICAL

We will not discuss here any of the details concerning the requirements for a sound mechanical design of an aircraft piston engine. The interested reader can find some information in other treatises pertaining to aircraft engine design (Reference 3-5). We will, however, give the essence of the general problem with which the designer of the aircraft engine is confronted, and will point out as well those important aspects in the mechanical design which arise from changes in the thermodynamic cycle.

The pressure forces exerted by the combustion chamber gases onto the piston are transferred to the crankshaft by means of the connecting rods. In this manner, piston displacement is transformed into the crankshaft angular rotation and, therefore, a linear force into a torque at the engine shaft. Because of the need to obtain a high specific power output while avoiding detonation, several cylinders are arranged to contribute to the total torque. Without exception, the modern general aviation industry uses opposed cylinder arrangements in numbers of 4, 6 and 8. The cylinder firing order is sequentially arranged in such a way that for every two crankshaft revolutions, each one of the cylinders has completed a cycle. In addition to the resultant crankshaft torque, the crankshaft experiences severe torsional and flexural vibrations which are dependent on the engine speed. These vibrations, if allowed, would readily destroy the crankshaft bearings, the reduction gear box, and the propeller, and the engine designer eliminates them by installing balancing weights on the crankshaft. This technique would eventually eliminate any sensitive vibration if enough weights are installed in precise points on the crankshaft for a complete static and dynamic deflection balance (such is the case in the best automobile engines), but because of the low weight requirements of an aircraft engine, there is a limit to the amount of crankshaft balancing that an aircraft engine can utilize. By using movable counterweights, the top-of-the-line engines sometimes improve the balancing characteristics without increasing the engine weight. It is not surprising, therefore, that any small variation from cycle to cycle resulting from poor fuel/air distribution ignition defaults, or cylinder decompression may result in vibrations which are very noticeable in flight. To the flyer, aircraft engine roughness is more evident than the same level of roughness in an automobile.

The same weight considerations mentioned above force the designer to select lightweight materials and small cross sections for the crankcase, cylinder walls and heads, pistons, and connecting rods. The crankcase is usually manufactured out of reinforced aluminum alloy castings. The cylinder barrels are machined from chrome and nickel steel forged alloys, and the interior of the barrel is nitrided to enhance hardness. The cylinder heads are made from aluminum casting. The connecting rods are forged from steel alloys. The pistons are machined from aluminum alloys, and the gears, if any, are hardened to insure precision and long life.

It is not a surprise that any premature malfunction of the engine caused by lack of tuneup or other slight malfunction is immediately translated into engine roughness that can be detected by an experienced pilot (incipient roughness) or any passenger (moderate roughness). Modern FAA-approved pilot training schools do not sufficiently emphasize these powerful means of engine default diagnosis which are so intuitive for an experienced pilot and so useful for the novice pilot. Everyone should learn to listen to the engine in taxiing, idling, magneto checkup, takeoff, and flight and should learn to distinguish between engine noise variations due to engine and aircraft attitude, and those due to cycle malfunction or loose mounting bolts.

The crankshaft resultant torque profile along two revolutions is transmitted to the propeller. The cross sections of the engine have a safety factor which, in most cases, will absorb severe roughness, and it is usually the state of the stresses on the propeller that is the pacing item for determining maximum rpm and maximum level of roughness tolerable for a sustained period of time. One of the advantages of the opposed cylinder configuration is the ease of balancing of the crankshaft, which is one of the reasons why general aviation uses exclusively such an arrangement.

SECTION IV

FACTORS AFFECTING FUEL ECONOMY AND POTENTIAL FOR IMPROVEMENT

The challenge of improving fuel economy in aircraft piston engines is being revisited within the new technological framework of the 1970s. When discussing fuel economy in gasoline-powered engines, one cannot ignore the present hydrocarbon fuel scenario. Social, political, and economic reasons have led the United States to depend heavily on petrochemical fuels for its economy. This situation has been aggravated by the fact that the low prices enjoyed by the American society in their oil supply have encouraged a gigantic consumption which, if carried over at the present rate, will either exhaust the present reserves or drive the prices to prohibitively high levels. The oil-dominated energy scenario is further threatened by increasing dependence on foreign oil. A discussion of the social, political and economic issues will not be attempted here: the reader is directed to some other recent studies on the subject (see Reference 4-1).

General aviation is feeling the consequences of the present crisis, perhaps more than other government and public sectors. First of all, the priorities assigned to general aviation during a crisis are very low, and second, the highly specialized specifications for aviation gasoline present an economic and logistics problem to oil companies. The refineries have to make space for a very small customer who demands complex processing and who needs to be served throughout more than 10,000 airfields distributed across the nation. This last consideration is perhaps the largest threat to piston-driven general aviation airplanes.

When discussing fuel economy within the present industrialized society, one has to take the systems approach and start from the original barrel of oil. In this respect aviation gasoline, which is composed of a narrow fraction of the distillate, has a narrow tolerance for its fractions, sulfur content and other residual contents, and requires highly energy-intensive processing at the refinery. To meet the octane requirements of engines presently in use, the different AVGAS ratings worsen the situation. One can see that any attempt to simplify AVGAS and/or compromise its specifications will contribute to a significant energy savings if engine designers maintain the same engine lifetime and specific fuel consumption presently existing with specialized fuels.

Figure 4-1 shows the distillate curve for automotive gasoline and a representative AVGAS. It is important to notice the broad distribution in molecular weight content of automotive gasoline, contrasted to the narrow composition of AVGAS. Because of the higher content of volatiles in automotive gasoline, one may experience better engine start characteristics than with AVGAS, but as the airplane gains altitude unless special arrangements have been made in the fuel system of the airplane, one is likely to encounter the insidious problem of vapor lock

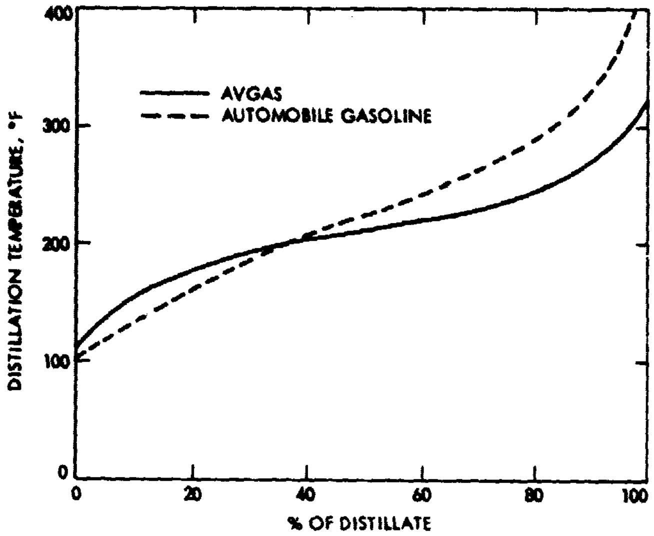


Figure 4-1. ASTM Distillation Curves for AVGAS (——) and Summer Automobile Gasoline (---) (Reference 4-2)

and corresponding engine failure. Aircraft engines, as opposed to automobile engines, are also run at full power during takeoff, which demands a high octane fuel to inhibit detonation. Thus, even though some airplane owners use automotive gasoline in their engines, engine manufacturers do not recommend the use of any fuel other than that rated for the engine.

It is the opinion of the author that this is an area worth looking into, although borrowing from past experience, one is expected to lose in specific fuel consumption part of the refinery energy process gains obtained when lowering the specifications. In the past, when such high octane fuels were not available, success was experienced by cooling the engines and safeguarding from detonation by means of water injection at takeoff. This could probably be reconsidered by engine manufacturers if an effort to lower the octane number is undertaken.

Finally, but not less important in aviation, the energy density content Q of the fuel should be high, as can be seen from its relationship to thermal efficiency η_t and specific fuel consumption SFC

$$SFC = 1/(Q\,\eta_t) \qquad (4\text{-}1)$$

In order to familiarize the reader very briefly with some practical aspects of engine design as it relates to thermal efficiency, a brief review of design parameters and operating conditions is offered here, together with a review of the methods and potentials to achieve a quantum step in energy savings.

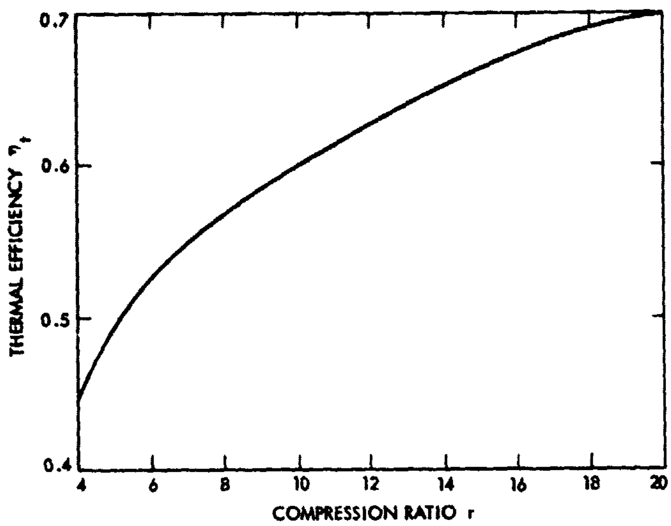


Figure 4-2. Air Cycle Thermal Efficiency vs Compression Ratio

A. IDEAL AIR CYCLE

When considering the ideal cycle described in Section III, the first points to be fixed in the cycle are the compression ratio, the displacement, the BMEP, inlet and exhaust pressures and temperatures, as well as fuel/air ratio. It has been mentioned that for the ideal air cycle the thermal efficiency is a function only of the compression ratio (see Figure 4-2), but when the presence of the fuel in the engine charge is taken into account, the properties of the mixture during the different parts of the cycle are highly modified. If one assumes chemical equilibrium, and the same idealizations as in the air cycle, one obtains what is known as the fuel/air cycle.

B. FUEL-AIR CYCLE

In this cycle, the fuel-air mixture admitted by the cylinder is characterized by the equivalence ratio (defined as the fuel-air ratio/stoichiometric fuel-air ratio). As in the air cycle, the mixture is adiabatically compressed followed by constant volume combustion which ends with a certain mixture composition (combustion products). As it expands to outlet pressure, the composition of the mixture changes, but it is assumed to be in chemical equilibrium at each point.

Table 4-1 shows those design factors that affect the thermal efficiency. The compression ratio has an effect similar to that observed in the air cycle (see Figure 4-3a). The inlet pressure has a negligible effect on the thermal efficiency except for stoichiometric mixtures, when it is near or equal to the exhaust pressure (Figure 4-3b). The equivalence ratio ϕ has, together with the compression ratio, the most striking effect on thermal efficiency (Figure 4- 3c). For lean mixtures (ϕ less than 1), the thermal efficiency decreases as equivalence ratio increases because the higher temperatures encountered after combustion increase the specific heat of the gases.

Table 4-1. Effects of Cycle Parameters on Thermal Efficiency η_t for the Fuel-Air Cycle

	Lean Mixtures	Rich Mixtures
Compression ratio r	Increase r → increase η_t	Increase r → increase η_t
Equivalence ratio ϕ	Increase ϕ → decrease η_t	Increase ϕ → decrease η_t
Inlet pressure p_1	negligible effect on η_t	negligible effect on η_t
Inlet temperature, T_1	Increase T_1 → decrease η_t	Increase T_1 → decrease η_t

The maximum combustion temperature is reached at $\phi = 1$, and it decreases for $\phi > 1$ due to the formation of CO. CO formation lowers the specific heats, but it also increases the number of molecules and the specific enthalpy of the combustion gases, resulting in an overall decrease of thermal efficiency. In summary the thermal efficiency is a monotonic decreasing function with ϕ for this cycle. It approaches asymptotically, on the very lean side, the value obtained for the ideal air cycle. The inlet air temperature T_1 (see Figure 4-3d) also increases the combustion temperatures with a resulting detrimental effect on the thermal efficiency.

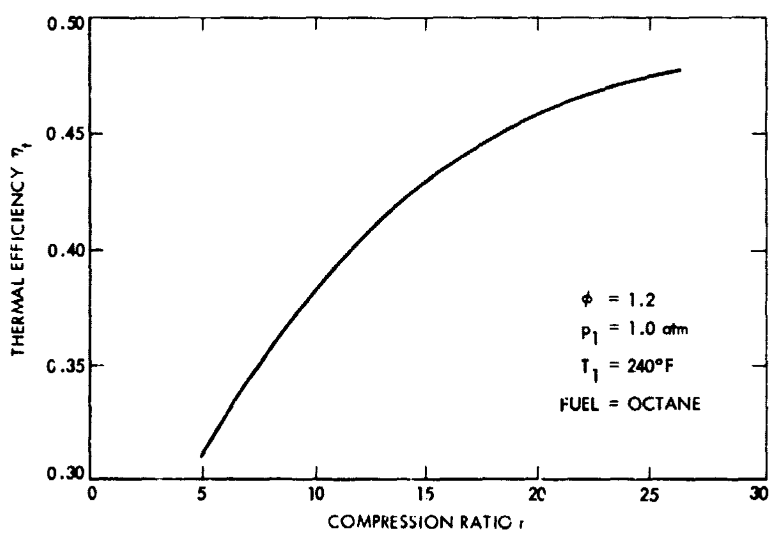


Figure 4-3a. Thermal Efficiency as a Function of Compression Ratio for a Fuel-Air Cycle

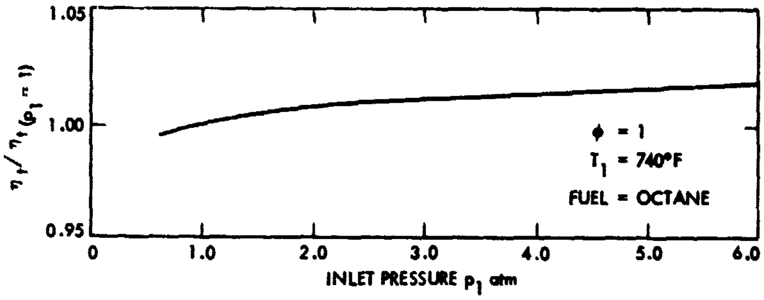


Figure 4-3b. Thermal Efficiency as a Function of Inlet Pressure for a Fuel-Air Cycle

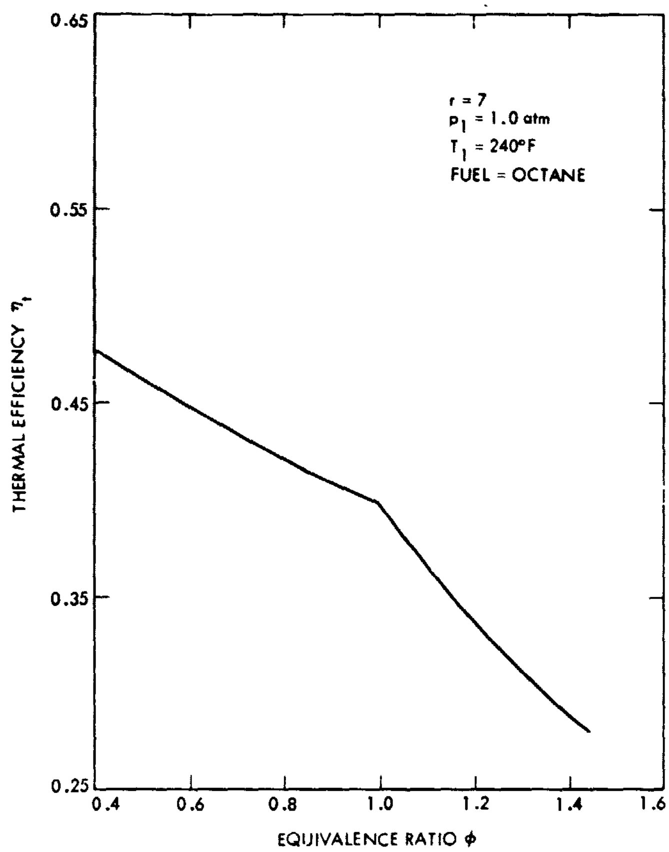


Figure 4-3c. Thermal Efficieny as a Function of the Equivalence Ratio for a Fuel-Air Cycle

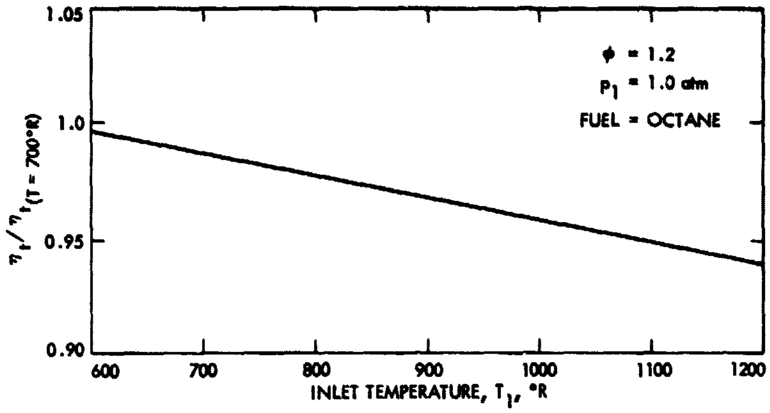


Figure 4-3d. Thermal Efficiency as a Function of Inlet Temperature for a Fuel-Air Cycle

C. ACTUAL CYCLE

The actual cycle of an engine departs considerably from the fuel/air cycle due to the irreversibilities encountered by the working fluid when practically implemented. Some of the losses which the engine designer has to minimize in order to meet a good efficiency compatible with the performance requirements are reviewed here. These losses can be classified as thermodynamic losses and mechanical losses.

1. Mechanical Losses

Among the mechanical losses, one can cite the losses due to leakage of gases from the combustion chamber to the crankcase through the piston rings and cylinder walls. This leakage is very small in a well-maintained engine working at a reasonable speed, but can be noticeable at lower speeds in poorly maintained engines. A crankcase breather is provided to eliminate such gases. The rest of the mechanical losses comprise the losses of power due to the conversion of the linear motion of the piston to torque at the propeller shaft, and they increase with engine rpm. Both types of losses are presently minimized in existing engines and any worthwhile improvement in this area is not expected.

2. Thermodynamic Losses

The thermodynamic losses can be grouped into time losses, heat losses, combustion losses and exhaust losses.

a. Combustion Losses. Combustion losses can in turn originate from two different sources, incomplete combustion and progressive burning. Incomplete combustion is due to the fact that the mixture has undergone incomplete mixing and also to the finite reaction rates experienced in the chamber. These effects are coupled in what is called combustion efficiency, which is very near 1 for fuel/air mixtures not near the flammability limits,* although the contribution to smoke and smog due to incomplete combustion may be very important even if the losses are insignificant. The combustion efficiency, however, is drastically lowered as one approaches the fuel flammability limits. All the aviation engines in use nowadays are designed to operate at equivalence ratios of 1.1 up to 1.4. One can thus see that they are well within the safe limits unless the pilot forgets to follow the manufacturer's leaning procedures during climbout or takeoff from high-altitude airfields (engine will loose power and run rough). A well-designed combustion chamber/inlet valve arrangement will result in an optimum turbulence level which will assure complete combustion even when approaching the engine lean or rich limit.*

Progressive burning results from the fact that the mixture burns at a finite speed when ignited at certain specific points (ignition). As was discussed in Section III, FAA regulations require dual ignition for all general aviation engines. Under ideal circumstances one would desire an instantaneous combustion, which can be achieved only if the mixture is ignited simultaneously at very many points. This of course is impractical and one has to withstand the limitations of having a few ignition sources, with the combustion taking place at several flame fronts. Once the location of the ignition sources has been fixed, the bulk flame speed is dependent on local turbulence level, local fuel/air mixture, combustion pressure (under normal circumstances the pressure throughout all the points of the cylinder is approximately the same), and local temperatures. In order to obtain best power or best efficiency, there is a certain synchronization that one has to achieve by properly timing the ignition. The ignition timing to achieve the best power (maximum torque) is sometimes incompatible with the occurrence of detonation. General aviation engines use fixed ignition timing, which yields the rated takeoff power while staying away from detonation. This usually implies a moderately advanced timing (one practical way to control detonation would be to vary the timing to a less advanced position). Further aspects of detonation are not dealt with here, although it is known to be the most important consideration to be taken into account at takeoff (high power) or high-altitude flying (cylinder head cooling defective due to the low air density). For more information on the subject see Reference 4-3. General aviation engines are operated thus at a constant ignition timing, which is not the optimum timing to achieve best engine efficiency. More on this subject will be offered in later sections.

b. Time Losses. This type of loss is due to the fact that the piston moves during the combustion process and the combustion does not take place at constant volume. It is primarily responsible for the roundoff of the peak pressure in the thermodynamic cycle, but this is partially compensated by having a better expansion process efficiency.

c. Heat Losses. The heat losses during the compression stroke are negligible, but that is not the case during the expansion stroke. The thermodynamic transformation during the expansion is polytropic rather than isentropic. There is a certain amount of heat loss during combustion

*Defined and discussed in Section V.

which contributes also to lowering the peak pressure. It is often difficult to separate the heat losses from the time losses.

d. Exhaust Losses. Exhaust losses are the losses due to the exhaust valve opening before bottom center. In most cycles, this loss is a rational compromise for the gain incurred by minimizing the exhaust stroke loss. Engine designers therefore select a certain valve timing to optimize volumetric efficiency and an efficient exhaust stroke at take-off, and the engines usually run with a certain valve overlap; that is, for an instant both the inlet and exhaust valves are simultaneously open. There is a certain black art in selecting such a valve overlap, and it is believed that the valve timing has a definite effect on HC exhaust emissions during idling and taxiing, and most possibly on thermal efficiency. Efforts are presently under way elsewhere to provide variable valve timing in order to optimize the valve overlap at different regimes (Reference 4-4). The results of such an effort are still uncertain, but the mechanism to achieve valve overlap introduces an additional complexity to the mechanical aspects of the engine which will most certainly impact weight, price and reliability.

D. THE MULTICYLINDER ENGINE

The appearance of detonation with increasing cylinder size, together with the requirement of high power density, can be handled by designing an engine with a cluster of cylinders properly arranged to provide the total power required. The fuel/air mixture has then to be manifolded to the cylinders and the exhaust gases of each cylinder are also manifolded and collected out to the exhaust pipes. The air flow into the engine therefore has a transient character; there is a pulsating flow superimposed on the average air flow into the engine. This pulsating flow increases in amplitude as one approaches the inlet valve of each cylinder, and it is not unusual to find, at certain rpm, a pattern of strong standing acoustic waves set up in the intake manifold. This pulsating flow causes a nonuniform volumetric efficiency in each cylinder, which in turn is aggravated by the fact that the fuel which has been injected into the airstream is vaporizing in the manifold while the pulsating flow is in progress. The overall effect is a nonuniform fuel/air distribution throughout the cylinders.

Engines provided with carburetors usually have more problems in this respect than those using fuel injectors. The nonuniform fuel distribution can be improved if the evaporation process is accelerated. This can be done by increasing the temperature in the manifold (which diminishes the volumetric efficiency and increases the chance for detonation) or using a fuel with a higher fraction of volatiles (which diminishes the available power). In those engines using carburetors, the altitude also affects the fuel distribution by causing condensations in the manifold, which is another reason for selecting fuel injectors. For these reasons, the trend in modern engines is to move to air-flow-controlled fuel injection with an assortment of injection schemes. Intermittent injection for each cylinder has been tried, but it presents some mechanical complexity and has been shown to offer little advantage over continuous injection.

E. SUPERCHARGING

As mentioned earlier, supercharging at constant altitude has an effect similar to increasing the compression ratio; therefore, it should apparently increase the efficiency. On the other hand an increase in inlet pressure or, what is the same, manifold pressure, causes higher BMEP and peak pressures, resulting in greater heat and time losses. In general, if the manifold pressure is larger than the exhaust pressure (mechanically driven superchargers), the thermal efficiency should be lower. The situation is much improved when turbochargers are used. The designer then has the opportunity to map the gas flow through the engine and turbocharger for each altitude and operating condition, which results in a significant improvement in thermal efficiency.

F. CONCLUSION

With this background on the factors affecting thermal efficiency, we can classify such factors into two groups: (1) those inherent to the mechanical design of the engine, which cannot be changed without considerable amount of research and development, and (2) those pertaining to engine operating points, which can be implemented by the engine operator or by a very slight modification in engine systems. We will focus our attention on the latter group and explore some procedures to obtain higher thermal efficiencies. In particular, we will fix all engine parameters except manifold pressure, engine rpm, ignition timing, fuel air ratio and environmental conditions such as ambient pressure and temperature.

SECTION V

FUEL ECONOMY IMPROVEMENT BY LEANING-OUT TECHNIQUES

As stated in Section IV, our interest will focus on those techniques that have a potential for fuel economy improvement which can be implemented in the present state of the art without substantially affecting assembly line engine production techniques. It is obvious that the schemes that can cause a major impact on fuel economy improvement are those which incorporate leaning-out procedures. Modifications which the engine designer undertakes to safely operate the engine with very lean mixtures depend on the particular scheme selected, the operating design conditions and the specified tolerances on the engine and its systems. In this section we will review the presently existing leaning techniques in general aviation, analyze the thermodynamics of lean mixtures, and introduce the reader to the phenomena of lean flammability limits and ultralean combustion. Three schemes for ultralean operation of engines will be briefly discussed: stratified charged combustion chamber, hydrogen enriched fuels, and improved conventional engines.

A. LEANOUT PROCEDURES IN GENERAL AVIATION

It has been mentioned that aircraft engines, whether equipped with carburetors or fuel injectors, have the capability of varying the fuel/air ratio by operating a mixture lever located at the cockpit. This lever is also used as an idle cutoff control for stopping the engine. The checklist of procedures for engine start, idling, taxiing, engine runup, takeoff, climb and approach require the lever mixture to be in the full rich position, which corresponds usually to an equivalence ratio of $\phi \geq 1.4$. The pilot may override some of these instructions when operating from airfields located at high altitudes or when roughness is encountered during climb. Most pilots will also go to full rich every time they vary the power settings, although the engine manuals only require full rich when power is increased. Once the cruise altitude has been reached, the mixture lever is moved to a leaner position according to instructions that vary for different engine models or aircraft. The reason for leaning during cruise is twofold: the aircraft, when flying at cruise speed, does not require more than 75% of the rated power while the dynamic pressure available for cooling the engine is quite high. This allows the engine to run with leaner mixtures than at takeoff, resulting in fuel savings. The same leanout will also give an increase in power and smoother engine operation.

B. INSTRUCTIONS FOR LEANING-OUT THE LYCOMING IGO-540 ENGINE

The leanout procedures can be better understood by following the instructions for a specific engine. Figure 5-1 has been taken from Reference 5-1 and shows how to lean-out a Lycoming IGO-540 engine. Figure 5-1 also indicates what are known as the best power and best economy points. The leanout instructions are as follows (quoted from Reference 5-1):

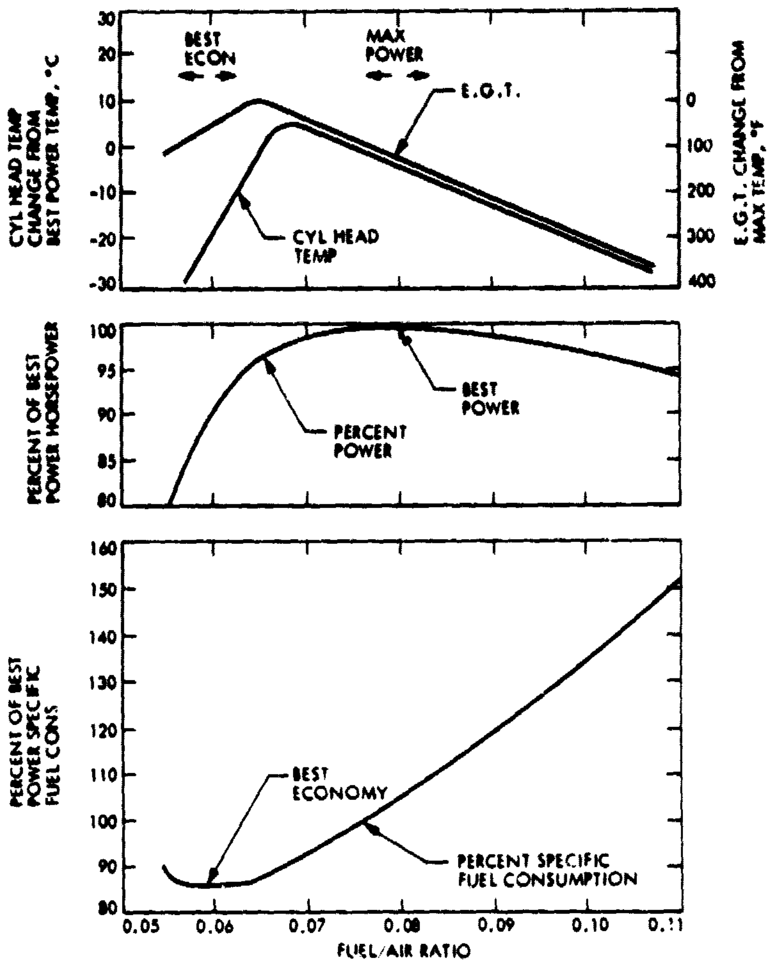


Figure 5-1. Representative Effect of Fuel/Air Ratio on Cylinder Head Temperature, Power and Specific Fuel Consumption at Constant rpm and Constant Manifold Pressure at Cruise Range Operation (Reference 5-1)

<u>Manual Mixture Control Leaning Procedure</u> - Opinion varies among operators regarding leaning procedures to obtain most economical fuel-air ratios with a certain margin of safety. Improper fuel and air mixtures take their toll in high replacement parts in the form of cracked cylinder heads, burned pistons, warped piston ring lands and warped and failed valves. The procedures set forth in the following paragraphs for "leaning out" an Avco Lycoming engine have proven to be the most economical, both in low fuel consumption and low parts replacement rates, and it is recommended that all Avco Lycoming engine operators adhere to these procedures.

CAUTION

Never operate an engine in excess of the maximum cylinder head temperature specified.

The mixture control should remain in the "Full Rich" position for takeoff, normal rated operation and climb power settings. During climb, if roughness or loss of power is noted due to over richness, it is permissible to lean only until engine operates smoothly.

NOTE

IGSO-540 Series - Manual Leaning Procedures

a. Not equipped with a Fuel Flow Meter or Exhaust Gas Temperature Gage.

(1) Supercharged engines should not be manually leaned without the aid of an approved flow meter or exhaust gas temperature gage.

b. Equipped with an Exhaust Gas Temperature Gage (EGT).

(1) 75% cruise power - Never lean beyond 150°F on rich side of peak EGT. Monitor cylinder head temperatures.

(2) 65% cruise power and below - Operate at peak EGT, or if desired, drop 50°F on rich side of peak EGT.

NOTE

Operation on the lean side of peak will result in slightly better fuel economy but may cause unstable engine operation.

C. THERMODYNAMIC NATURE OF THE LEANOUT CURVES

Taking into account that the curves shown in Figure 5-1 have been obtained at constant engine rpm and manifold pressure and recalling that the specific fuel consumption is, except for conversion factors, the inverse of the thermal engine efficiency, the behavior of the leanout curves can easily be explained in light of what was said in Section IV. For equivalence ratios larger than 1, the cylinder heads and exhaust gas temperatures decrease as one enriches, due mostly to the lowered equilibrium combustion temperatures obtained; that is, the engine is being cooled by an excess of fuel. Also in this region the engine efficiency is unfavorably affected when enriching because of the presence of larger and larger amounts of CO and H_2 in the exhaust, resulting in an increase in the BSFC. The power output decreases somewhat when enriching, due to the fact that the power output is proportional to the efficiency and to the fuel-air ratio, giving a maximum power at an equivalence ratio slightly above 1. If the equivalence ratio is larger than this value the efficiency decreases faster than linearly and the power output drops. For equivalence ratios near 1 the equilibrium combustion temperature reaches a maximum, the same as the specific heats and the thermal losses of the engine, which is the reason why cylinder head and exhaust gases temperatures are very high, although these temperatures peak at equivalence ratios slightly less than 1, due mostly to thermal losses. When leaning to equivalence ratios less than 1, the BSFC keeps improving because of the favorable effect of lower specific heats (caused by lower combustion temperatures) on the efficiency.

The thermal losses are also smaller and for equivalence ratios less than 0.9, the engine temperatures begin to drop down very fast. A pronounced decrease in power output can also be observed in this region when leaning out due to the decrease in fuel-air ratio. This line of reasoning could be carried out to fuel air ratios ridiculously small, but two new effects, the mixture lean flammability limit and the decrease in flame speed, appear, causing the BSFC to level off and go through a minimum while the power output and engine temperatures continue decreasing as before. These regions are indicated in Figure 5-2.

D. FLAMMABILITY LIMITS

More than one pilot has experienced roughness, engine misfiring, backfiring, or simply a slight missing when leaning out beyond the recommended values of fuel/air ratio during cruise. Although the physical reasons for such engine behavior are varied, they all are associated with the characteristics of lean combustion. We will briefly analyze some of the salient features of lean burning that one needs to take into account in order to understand the lean burning engine.

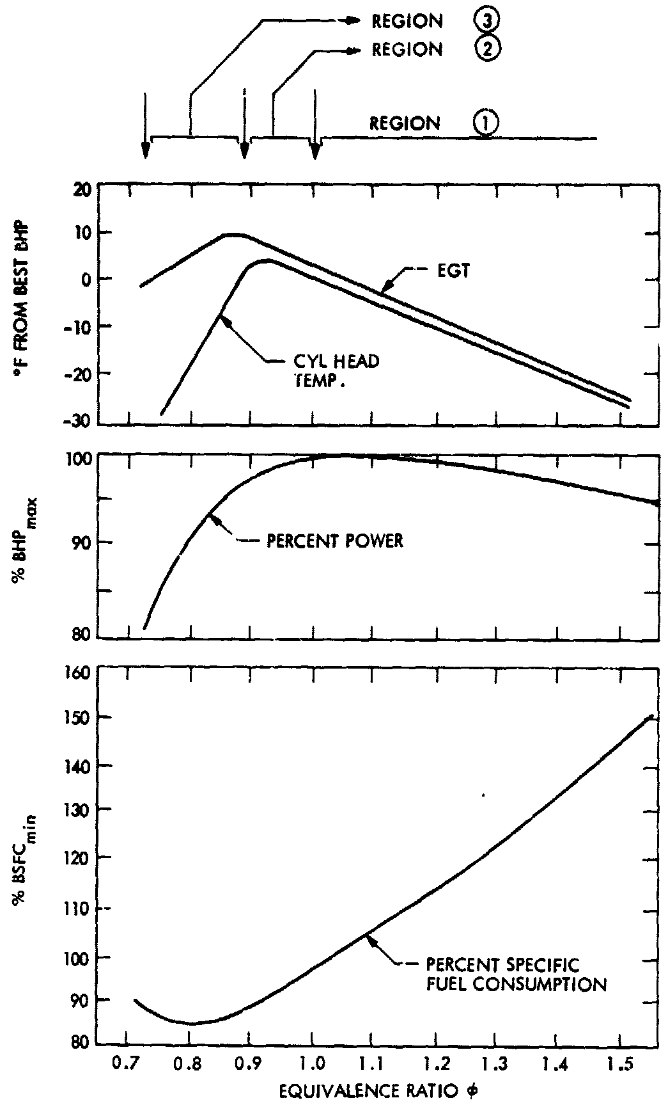
1. Flammability Limits of Fuel/Air Mixtures - Lean Limits

Let two reactants A and F form an explosive mixture and assume that they are intimately mixed at the molecular level; the reaction can proceed via deflagration or detonation. Explosion is a term which implies a rapid heat release (or pressure rise). An explosive mixture will react very rapidly as opposed to other reactions which proceed slowly and at a lower temperature. Whether the combustion wave, or flame, is a deflagration or a detonation depends on many other parameters not discussed here, but it is a well-known fact that certain explosive mixtures will not propagate a flame under any circumstances. Consider for simplicity the one step reaction

$$A + F \longrightarrow P \qquad (5\text{-}1)$$

and assume there is an excess of reactant A over the chemically correct (stoichiometric) ratio of A to F. There are mixture ratios which will not support a flame after the ignition source is removed, and one speaks of such mixtures being outside the flammability limits. The leanest and richest concentration which will just self-support a flame are called, respectively, the lean and rich flammability limits. In Reaction 5-1, the lean limit will be reached when reactant A (the oxidizer) reaches a maximum value.

The most comprehensive experimental determination of flammability limits and recollection of their bibliography was conducted by Coward and Jones (Reference 5-2). These authors have also standardized the apparatus and procedures for determination of flammability limits. Table 5-1 shows the lean limits for several gasoline/air mixtures



REGION	PHENOMENA
① $\phi > 1$	CO AND H_2 PRESENT IN EXHAUST ⟶ HIGH BSFC LOW SPECIFIC HEATS
② $\phi < 1$	HIGH SPECIFIC HEATS IN EXHAUST GAS THERMAL LOSSES IMPORTANT
③ $\phi < 1$	LOW SPECIFIC HEATS IN EXHAUST THERMAL LOSSES SMALL, POOR COMBUSTION: THE LEAN LIMIT IS NEAR

Figure 5-2. Leanout Curves Showing the Distinct Regions Encountered During a Leanout Procedure

(Reference 5-2, page 118). The lean flammability limit thus obtained is somewhat affected by the vessel dimensions, pressure (very slight effect), temperature and turbulence. The measurement of such limits has been conducted with the purpose of establishing safe industrial standards. One should not expect to find a flammable mixture in the cylinder of a piston engine capable of sustaining a flame anywhere near the lean flammability limits seen in Table 5-1.

Table 5-1. Lean Flammability Limits for Three Different Gasolines (Reference 5-3)

Sample	Octane Rating	Specific Gravity at 60/60°F	Vapor Pressure, mm Hg at 250°C	Lean Limits of Flamability: Open Tube by volume %	Lean Limits of Flamability: Closed Tube by volume %
1	73	0.7136	200	1.50	1.40
2	92	0.7061	182	1.50	1.45
3	100	0.7161	168	1.45	1.40

The cylinder temperature, the combustion chamber turbulence, and the ignition source, as well as the fact that the combustion is not proceeding at a constant volume, will contribute to raise the lean limit.

The physics of combustion near the lean flammability limit are not well understood. In addition to the experimental work described in Reference 5-2, some theoretical efforts have been conducted in trying to predict the flammability limits. Spalding (Reference 5-3) has assumed that the lack of flammability in a mixture is due to a heat loss caused by conduction and radiation, which causes quenching of the flame and stops its propagation. One should also suspect that strong flame instabilities induced by differential diffusion and large-scale turbulence may cause the collapse of a flame while quenching by the cylinder walls is also under way.

2. Flame Speed Near the Lean Flammability Limit

There are several theories that try to predict the flame speed of combustible mixtures, some of them more elaborate than others, but none of them is able to reliably predict the flame speed in all circumstances. One of the simplest theories was set forward by Mallard and Le Chatelier and can be found in Reference 5-4, page 67. Mallard and Le Chatelier give a simple formula to predict the laminar flame speed

$$S_L \sim (\alpha \times RR)^{1/2} \qquad (5\text{-}2)$$

where S_L is the flame speed, α is the thermal diffusivity and RR the reaction rate. From Formula 5-2 one can see that since the reaction rates depend exponentially on the temperature by the Arrhenius law: the higher the temperature, the higher the flame speed, which is the reason for having lower flame speeds when leaning a mixture since combustion temperature decreases with the equivalence ratio. Figure 5-3 illustrates the flame velocity vs equivalence ratio for pentane (Reference 5-5). As one can see, the flame speed has dropped to less than 40% when one nears the lean flammability limit and becomes zero (by definition) at the limit. This behavior is typical also of gasolines and other hydrocarbons. For hydrogen the diffusivity in Formula 5-2 is so large that it begins to play an important role in the flame speed curve. In general, the flame speed presents a peak near stoichiometric ratio.

3. Engine Lean Flammability Limit

The values of the lean flammability limits previously shown in Table 5-1 correspond to fuel/air ratios of 0.039 by weight, that is, an equivalence ratio of $\phi = 0.57$. One has to keep in mind, however, that these values have been obtained in a standardized tube and ignited with an alcohol flame from one end. This situation is very different from that existing in the combustion chamber of an internal combustion engine at the end of the compression stroke.

There have been some attempts to measure the lean flammability limits under conditions which simulate the internal combustion engine, and the most successful has been the one conducted by Halstead and others from Shell Research Laboratories (Reference 5-6), who obtain an extremely low lean limit for gasolines bracketed between the values of 0.40 and 0.48. The machine that they employed simulated a "rapid adiabatic compression" followed by a spark ignition with the fuel prevaporized and premixed with air. These conditions, however, are still far from simulating those encountered in a real engine, and for more practical values for the lean limits one should go to a review of the most recent work in lean burning engines.

Reference 5-7 contains an excellent brief summary review of such work together with a bibliography. The most important contributions have been tabulated and shown in Table 5-2 from Reference 5-7. From this table, one can see that a substantial amount of research has been conducted with the AME-CFR (Committee for Fuel Research) engine, which consists of a single cylinder engine with variable compression ratios and some other variable engine parameters. The table shows results also for multicylinder engines equipped with an assortment of modifications on the engine systems. Notice that after some improvement the best lean limits have been obtained on CFR engines and as low as $\phi = 0.61$.

One word of caution should be advanced here in explaining how the investigators defined the lean limit. On leaning out an engine, and when approaching the gasoline flammability limit, one will observe in a CFR engine certain pressure variations from cycle to cycle whose frequency and excursion interval increase as one approaches the flammability limit until occasional misfiring is observed. The CFR lean limit misfire is defined as that equivalence ratio at which 5% of the times one obtains cycle misfiring. If one observes the indicated thermal efficiency obtained from a CFR engine when leaning out, a curve such as that one shown in Figure 5-4 is observed. This figure has been extracted from Reference 5-8 and is

Table 5-2. Summary of Significant Lean Mixture Engine Testing (Taken from Reference 5-7)

Engine	Displacement	Combustion Chamber	Baseline max. A/F	Engine Modifications	Modified max. A/F	Equipment Lean Limit Extension, %
CFR	-	Disk	19.5	Manifold, fuel injection, dual spark plugs, spark plug location	25.0	28.2
CFR	-	Hemi	19.5	Atomized/vaporized fuel, vaned intake valve spark plug gap and projection, spark energy and duration (Texaco ignition system)	24.0	23.1
CFR	-	Bowl	19.5	Vaporized fuel, spark plug location, combustion chamber shape	24.0	23.1
4-cyl.	96.7 CID	-	15.1	Fuel injection, spark plug, variable F/A and spark advance (optimizer)	23.5	55.6
4-cyl.	1982 CC	Heron	18.4	Spark plug gap and projection, spark energy, vaned intake valve, combustion chamber shape, intake air temperature	21.0	14.1
4-cyl.	1800 CC	-	18.0	Heat pipe vaporization	21.0	16.7
4-cyl.	91 CID	-	20.2	Vaporized fuel	22.5	11.4
6-cyl.	-	-	17.8	Vaporized fuel	22.5	26.4
V-8	318 CID	-	18.0	Induction system, spark energy	23.6	31.[illegible]

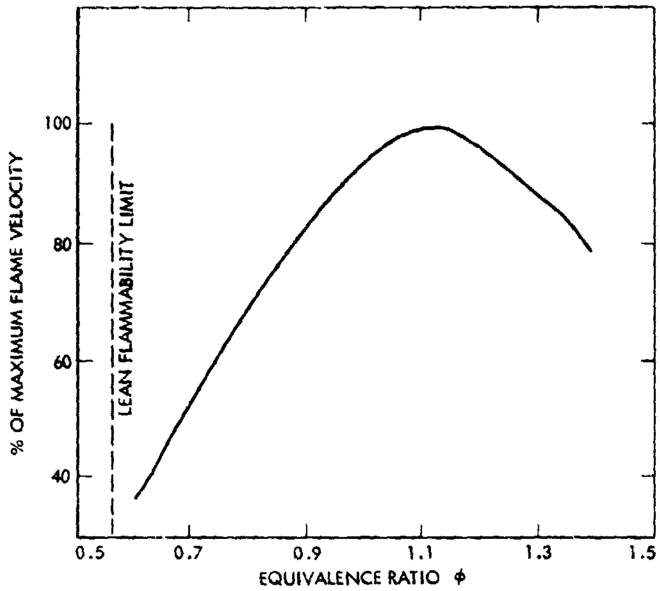


Figure 5-3. Change in Relative Flame Velocity for Pentane, with Equivalence Ratio at 25°C and 1 Atmosphere

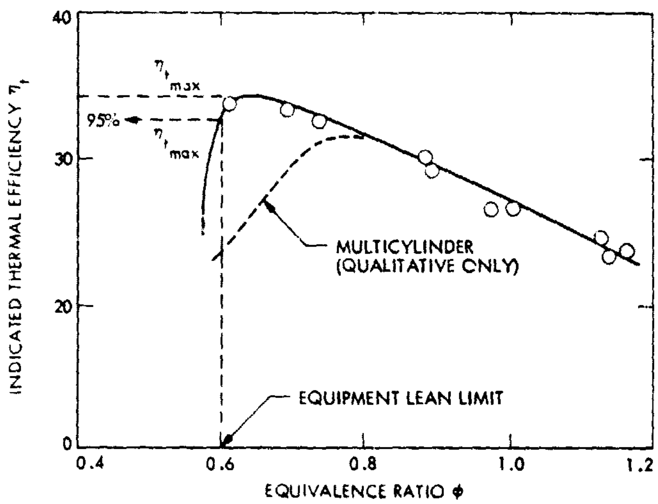


Figure 5-4. CFR Measured Thermal Efficiency for Gasoline. Also given is the Qualitative Behavior of the Multicylinder Engine

typical of the behavior of the thermal efficiency near the lean limit when one approaches the limit carefully. Notice that after the thermal efficiency undergoes a maximum, it falls catastrophically if an attempt is made to lean any further. The equipment lean limit is defined as the equivalence ratio ϕ at which the thermal efficiency is 95% of the peak efficiency and on the leaner side.

Before proceeding to a multicylinder engine configuration, we will briefly review those factors which affect the operating quality of a single cylinder engine near its lean flammability limit. These factors are:

Mixture Homogeneity. This will affect the local equivalence ratio through which the flame will propagate in the combustion chamber. It is desirable to have the mixture as homogeneous as possible (complete mixing at a molecular level); otherwise the flame may encounter leaner pockets which may inhibit its further progress. Lack of homogeneity is also a source of pressure variations from cycle to cycle. A good atomization followed by complete vaporization and maximum mixing length will favor homogeneity.

Scale and Intensity of Turbulence. Turbulence in the combustion chamber is most important, but near the lean limit it requires a different intensity and scale distribution in different points of the combustion chamber. Very small eddies are desired in the region of the spark to assure a turbulent flame without blowout. In the rest of the chamber larger eddies and more intensity are desired, except near the walls if heat transfer losses and quenching are to be minimized.

Ignition Characteristics. The spark plug characteristics and design are very important. The timing should be matched to the engine speed and flame propagation speed. The spark plug should be located in a hot spot and submerged, if possible, in a rich pocket in which the mixture has accumulated an excess of fuel. The spark should be of long duration or, as an alternative, of the shower type; long penetration, narrow electrodes and wide gap are also desired.

Wall Effects. The cylinder wall, acting as a quenching agent of the combustion process, will have to be kept at fairly high temperatures, although in so doing, the volumetric efficiency is lowered and the specific power output drops even if the thermal efficiency increases.

For multicylinder engines, the intake manifold is responsible for assuring a uniform mixture distribution throughout all cylinders. Because of different engine regimes and operating conditions, it is difficult to design a manifold which will provide a uniform distribution (same equivalence ratio) to all the cylinders and even more difficult, if not impossible, to design a manifold that can accomplish satisfactory results when coupled to different types of engines. Figure 5-5 shows the equivalence ratio in different cylinders obtained for a stock Chevrolet V-8 engine and a modified lean burn engine with the standard deviations for the different cylinders (Reference 5-9). These engines were equipped with carburetors, and such distribution can still be improved if individual fuel injectors are used.

The multicylinder engine has a lean limit that is somewhat higher than the single cycle engine for identical conditions, since its limit is being paced by those cylinders that run leaner. This results in a more gentle slope on the leaner side of the thermal efficiency curve, since

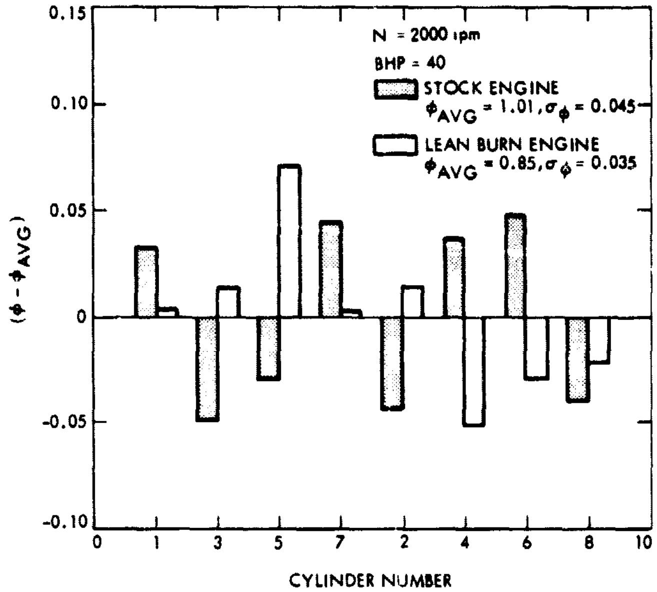


Figure 5-5. Cylinder-to-Cylinder Equivalence Ratio Distribution (taken from Reference 5.9)

combustion is still being supported by those cylinders which run richer. (See Figure 5-4).

The engine lean flammability limit is defined herein as the lean limit misfire as observed in the leaner cylinder. If fuel economy is the only drive factor in operating an engine lean, one would like to use the equivalence ratio that gives the maximum efficiency, and thus have a comfortable margin of operation between such an equivalence ratio and the engine lean limit. However, it should now be emphasized and later furtherly discussed, that the engine lean limit still depends on three variables which may affect it significantly: type of fuel (H_2, alcohols, hydrocarbons), compression ratio (in supercharged engines one can have a similar effect by varying the pressure), and appurtenances (fuel system, ignition system, valves and vanes).

E. COMBUSTION CHARACTERISTICS IN ULTRALEAN OPERATIONS OF ENGINES

By ultralean operation we mean the operation of engines near the lean flammability limit. The combustion under such circumstances is characterized by two main factors: (1) instability of the flame because of its propagation through mixture pockets near or below the lean flammability limit, and (2) the adverse effect on the thermal efficiency of lower flame speeds encountered during the operation. The salient phenomena connected with lean limits have already been discussed above, and it has been seen that the thermal efficiency increases when leaning out and then decreases sharply after going through a maximum. On the other hand, the flame speed has a detrimental effect on the thermal efficiency. If one defines effective combustion interval as the angle comprised between the first significant pressure rise due to combustion until the peak pressure in the cylinder is reached, it has been observed that, with other things equal, the shorter combustion intervals give higher thermal efficiency. The combustion interval is highly dependent on flame speed and ignition timing. Because of the low flame speeds, it is advisable to operate with large spark advance angles, but it is also imperative to maintain the flame speed as high as possible without increasing the overall equivalence ratio. An account of the effects of combustion interval on the thermal efficiency is given in Reference 5-7.

As indicated above, those interested in fuel economy will be concerned with operation of the engine at peak-thermal-efficiency-equivalence ratio, but because of the stringent EPA regulations for NOx, some may find it desirable to lean further and meet the standards with some sacrifice in fuel economy. This is the case for automobile lean engines. The exhaust emissions during leanout are qualitatively shown in Figure 5-6. One can see that the emissions of NOx and CO follow very closely those obtained from equilibrium after reaching the combustion temperature. The HCs, however, begin to rise sooner than the BSFC, owing to the quenching effects by the cylinder walls. More in this respect will be said later, but it is important to notice here the two operating points A and B in Figure 5-6 and the difference in performances and emissions obtained in each case. The general aviation industry does not have a stringent requirement for NOx, and there is no need to operate leaner than point A. It should be remarked that the EPA automobile standards for HCs are very hard to meet with "lean burning," and the automobile industry has had a very difficult challenge in compromising the NOx and HC requirements when using lean burning schemes, which is the reason why most of these schemes have incorporated reactors to further treat the exhaust and thus meet the standards.

F. SCHEMES FOR OPERATING ENGINES ULTRALEAN

What has been said so far applies in general to any lean burn engine, but keeping in line with our near-term application philosophy, only those schemes which can be implemented by the general aviation industry with reasonable adaptability of their production assembly lines will be addressed here. These schemes have been classified:

(1) Stratified charge engine.

(2) Hydrogen-enriched fuels.

(3) Improvements on controls and systems of unmodified engines.

1. Stratified Charge Engine

The stratified charge engine concept involves a redesign of the combustion chamber. By establishing a local fuel-rich mixture zone near the spark plug, it is possible to ignite mixtures well beyond the lean ignition capabilities of the conventional spark plug. Figure 5-7 shows a

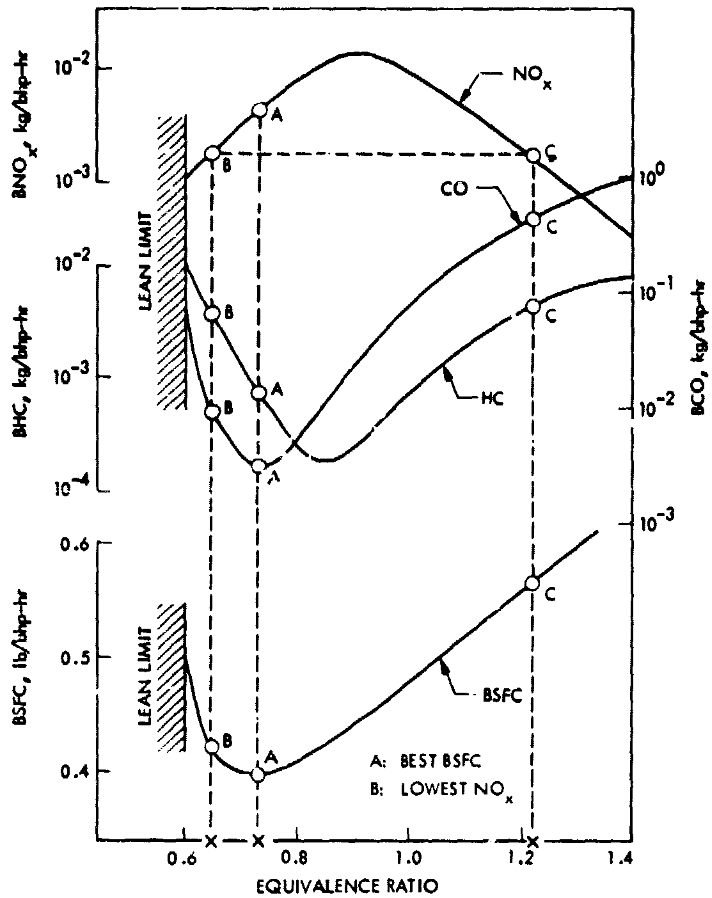


Figure 5-6. Brake Specific Fuel Consumption (BSFC) and Normalized Exhaust Emissions (BCO, BHC, BNOX) for a Typical 6-Cylinder A/C Piston Engine, Constant RPM; Locked Throttle. Note the differences between the two operating points A and B

one-dimensional simplified version of the flame propagation across the combustion chamber. By adopting suitable means of fuel injection and flow stabilization, gradients in the equivalent ratio can be established throughout the chamber from a rich zone near the spark plug to remote zones near the cylinder walls which are practically at the lean flammability limit.

The stratified charge engines can be grouped into two classes, open chamber and divided chamber. The open-chamber configuration consists of a single combustion chamber in which the local fuel-rich mixture near the spark plug is obtained by means of a combination of air inlet swirls and a high-pressure, properly timed combustion chamber fuel injection. The divided chamber engine consists of two adjacent chambers. Some designs use a small prechamber that communicates with the main combustion chamber, and for this type of engine the prechamber volume is about 5% of the total combustion chamber volume. During operation, a small quantity of fuel-

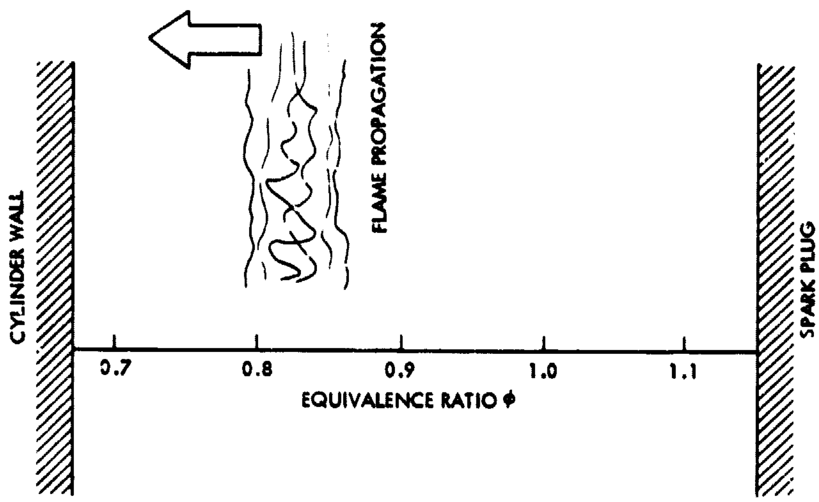


Figure 5-7. One-Dimensional Illustration of the Flame Propagation in the Stratified Combustion Chamber

rich mixture is applied to the prechamber, while a very lean mixture is applied to the main combustion chamber. The powerful flame expanding from the point of ignition within the prechamber serves then to ignite the very lean main chamber fuel/air mixture. Other divided combustion chamber designs utilize two chambers of approximately the same volume separated by a dividing orifice. Fuel is supplied only to the primary combustion chamber, where it ignites and burns; the combustion products expand rapidly into the secondary chamber, which contains only air, where they are quenched.

The thermodynamics cycle of the stratified charge engine is somewhat of a hybrid between the Otto cycle and the diesel cycle (see Figure 5-3). The distinct feature of such a cycle is that heat is added both at constant volume first and later at constant pressure. This type of cycle does not present the inconvenience of large cross sections required by the diesel engine since the cycle is pressure-limited, but it has the advantages of the diesel engine in burning very lean mixtures and presenting versatility in fuel requirements.

The stratified charge engine has been under development for many years at several university and industrial laboratories. A good review of the various techniques and progress for automobile applications was given by Menard in Reference 5-10, and an evaluation of their applicability to aircraft engines was conducted by Rezy and others (Reference 5-11). It should be said that most of the research in this area has been focused on lowering emissions, although fuel economy was often at stake. For completeness, three major company developments are given here:

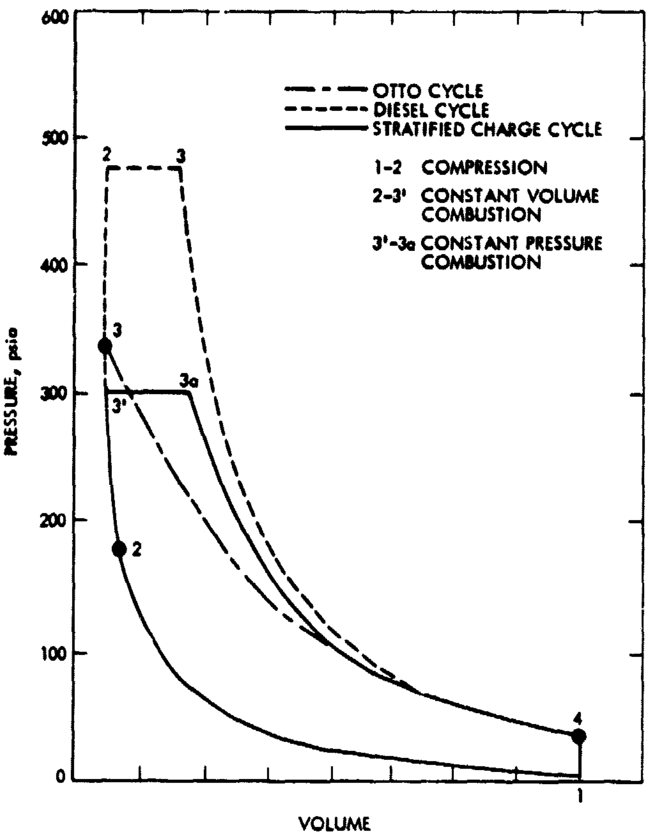


Figure 5-8. Theoretical Air Cycle for the Stratified Charge Engine. Also shown are the Otto cycle and the Diesel cycle

a. Texaco Control - Combustion System (TCCS). This system is shown schematically in Figure 5-9 (Reference 5-12). It is of the open chamber type and involves a coordination of air swirl, fuel injection and positive ignition. Flow control is obtained by regulating the duration of fuel injection with full load duration corresponding roughly to one air swirl. The overall equivalence ratio varies thus from very lean at lower power to stoichiometric proportions at full power. More on the subject can be found in Reference 5-10. This design has been evaluated in Reference 5-11 for its application to aircraft engines and characterized as follows:

Pros:

Limited air throttling requirements.

Low octane fuel requirements.

Multifuel capability with comparable performance and emissions.

Easily turbocharged.

Good specific fuel consumption.

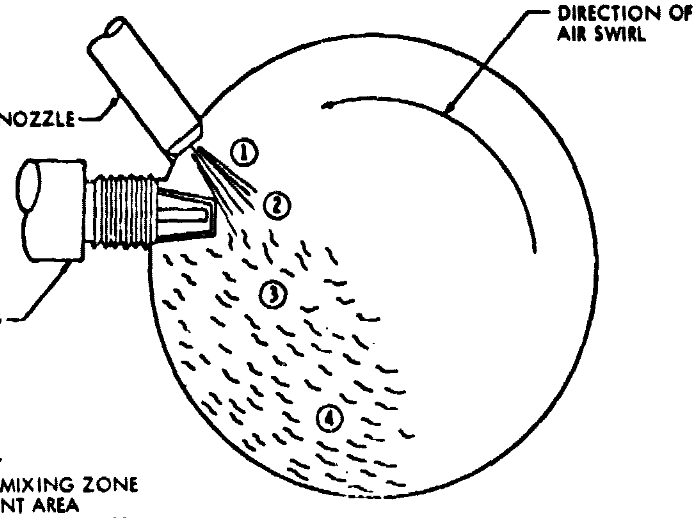


Figure 5-9. Texaco Controlled-Combustion System (TCCS) (Reference 5-12)

Good starting characteristics.

Low wall quenching potential.

Low HC and CO emissions for aircraft emission cycle.

Cons:

Incomplete air utilization.

Limited speed range.

Implementation problems.

Poor performance.

Expensive.

High NOx emissions for aircraft emission cycle.

b. Ford Programmed Combustion Process (PROCO). Research and development at Ford's Stratified Charge Engine Laboratories have been carried out since 1966 and there are an assortment of designs. The best known is the PROCO design, which consists of an open-chamber type similar to the Texaco engine. The intake port is shaped to impart a swirl in the cycle (see Figure 5-10, of Reference 5-13). The fuel is injected during the compression stroke and the swirling charge with an overall 15:1 air/fuel ratio is compressed into a cup-in-piston combustion chamber with a 65% squish area. The fuel injector provides a soft, wide-angle spray which results in a rich mixture at the center, surrounded by a leaner

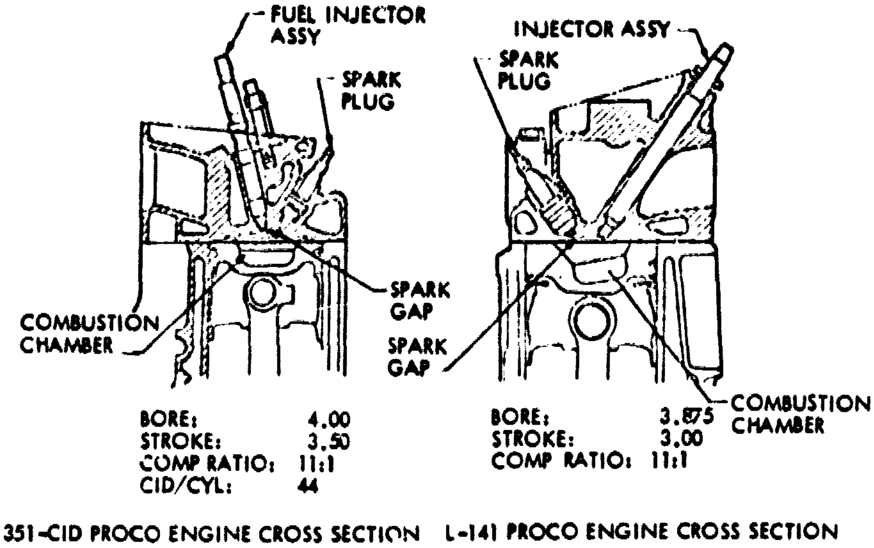


Figure 5-10. Ford PROCO Engines (Reference 5-13)

mixture and excess air. The mixture is ignited near the top dead center (TDC) by a spark plug located in the proximity of the bore centerline. The combustion progresses rapidly in the rich zone and the flame travels into the leaner regions stabilized by the intake swirl and the toroidal movement imparted to the mixture by the squish action. Load control is achieved by throttling the air intake, operating thus at constant equivalence ratio. Because of the need to coordinate the fuel injector timing and spark timing, this engine needs a new fuel injection system which incorporates ignition distributor, fuel air control, and governor. The system has also been evaluated for aircraft applications (Reference 5-11):

<u>Pros</u>:

Low HC and CO emissions for aircraft emission cycle.

Good specific fuel consumption.

<u>Cons</u>:

Octane-sensitive.

Not easily turbocharged.

Implementation problems.

Air throttling required for low emissions.

High NOx emissions for aircraft emission cycle.

Expensive.

c. Honda Compound Vortex Controlled Combustion (CVCC). In the fall of 1971 Honda Motor Company of Japan announced publically the development of an engine featuring compound vortex controlled combustion (CVCC) which would meet the 1975 Federal Emission Standards for Automobiles without after-treatment devices such as thermal reactors or catalysts. EPA conducted confirmatory tests in December 1972 and further developments have since taken place and are described in detail in Reference 5-10. The CVCC engine is of the divided chamber type and achieves stratification by means of a small prechamber. Two separate intake valves are used on each cylinder of the engine. One valve is located in the prechamber and the other in the main chamber. The valves are operated from a single overhead camshaft. A divided carburetor is used on the Honda engine which supplies a rich mixture to the prechamber. Honda describes the combustion sequences of the CVCC engine as follows (Reference 5-14 and Figures 5-11 and 5-12):

(1) A large amount of lean mixture and a small amount of rich mixture, which makes the overall mixture lean, is applied.

(2) At the end of the compression stroke, the following occur: (1) a rich A/F mixture around the spark plug, (2) a moderate A/F mixture in the vicinity of the outlet of the prechamber, and (3) a lean A/F mixture in the remainder of the main combustion chamber is stratified into three different conditions. This mixture stratification is to be made without high resultant turbulence in the cylinder.

(3) Rich mixture in the auxiliary combustion chamber is assured to be ignited by the spark plug. The mixture burns fast and completely (keeping CO emissions down).

(4) Burning of moderate A/F mixture around the outlet of the auxiliary combustion chamber assures the combustion of lean mixture in the main combustion chamber.

(5) Lean mixture continues to burn slowly.

(6) Temperature of burned gas is kept relatively high for a long duration.

Since combustion proceeds at a slow pace at fairly high temperatures, HC emission is inhibited. At the same time, however, the temperature is still kept below the danger point for NOx formation. It is interesting to notice that the air/fuel ratio varies slightly with the operating mode, engine load is met by air throttling, and emissions were not sensitive to the fuel type. The fuel economy of the Honda vehicles was considerably lower than other similar vehicles tested by EPA, although it was most probably due to power/vehicle weight ratio rather than thermal

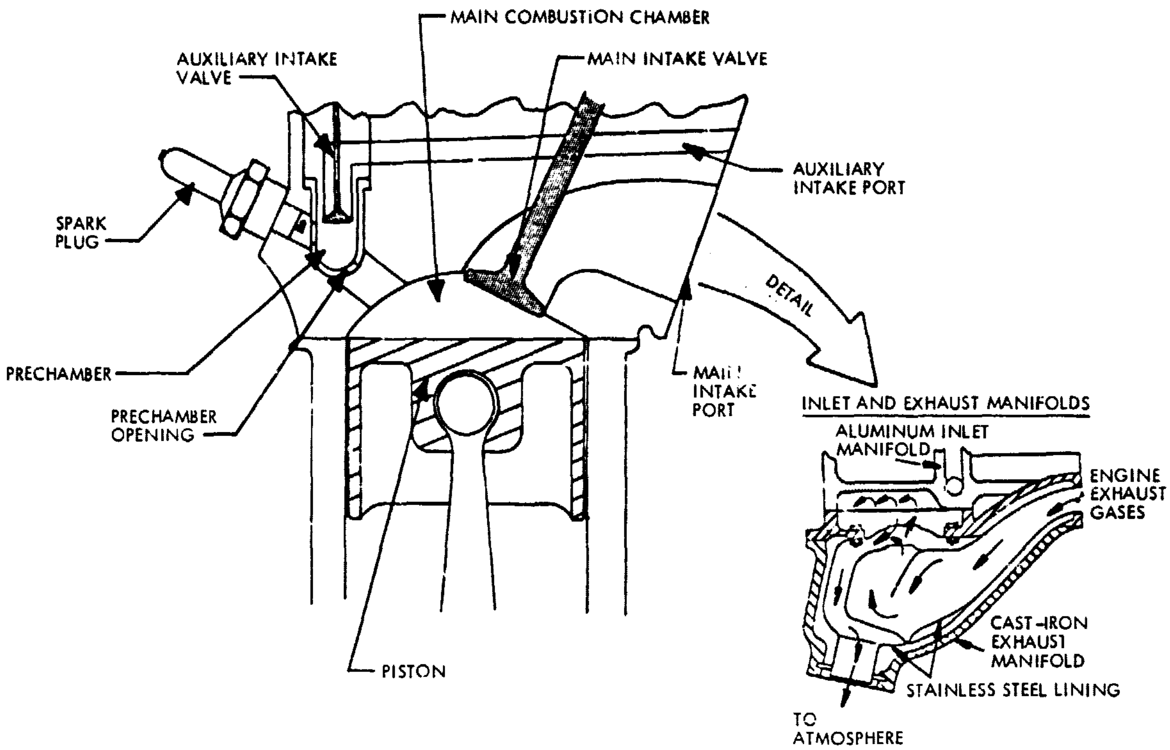


Figure 5-11. Honda CVCC Engine Concept (Reference 5-11)

efficiency of the engine. Reference 5-11 has evaluated this engine for aircraft applications:

Pros:

Good specific fuel consumption.

Stable combustion assured.

Good operational characteristics.

Low octane fuel requirements.

Low emissions for aircraft emission cycle.

Cons:

Possible cooling problems.

Hardware complexity.

High surface-area-to-volume ratio.

High rate of pressure rise at rich mixtures.

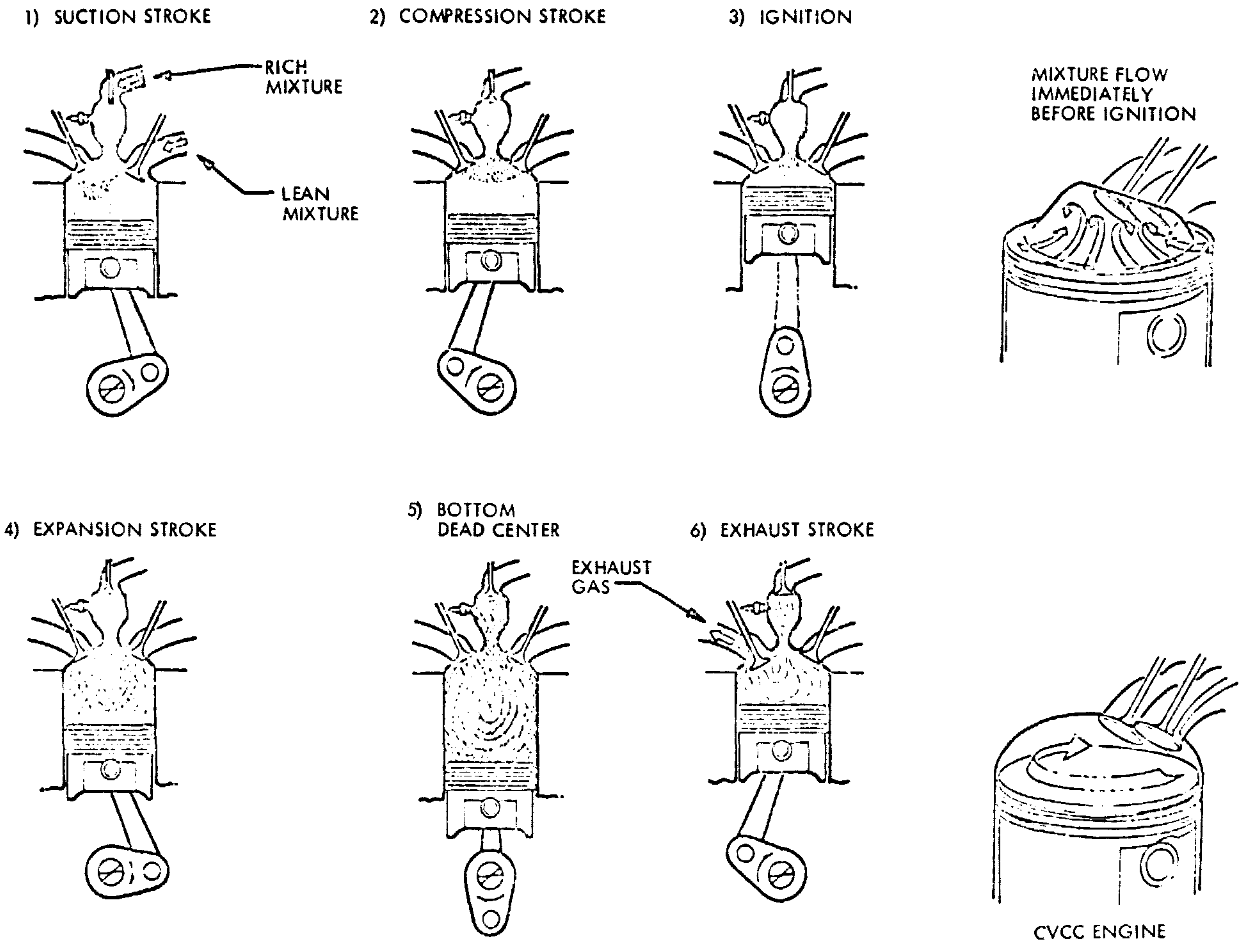


Figure 5-12. Combustion Sequences of CVCC Engine (Reference 5-14)

Implementation problems.

Increased weight.

Expensive.

Increased maintenance.

c. Conclusion. The stratified charged engine has thus demonstrated an ability to operate engines lean but could hardly qualify as an ultralean engine since the overall equivalence ratio is seldom lower than .85, except in some models at very low power levels. This lack of ability to operate them ultralean is due to the inherent low turbulence which such an engine requires to keep a stratified mixture. These engines need, in addition, a redesign of the combustion chamber, fairly sophisticated fuel systems, elaborate ignition systems, and in some instances additional valving. They do not appear to offer an extremely good promise for fuel economy if a high specific power output and simplicity is required, but let's not forget the mild requirements on fuel specifications which could be a most decisive factor in general aviation applications, as was discussed in Section IV. When compared with the diesel engines, they offer also some of the same advantages, such as fuel adaptability and low emissions, without incurring in any severe weight penalties. When all these different aspects are taken into account one should conclude that the stratified charged engine still has a place as a serious candidate for solving the fuel problems in general aviation, although studies such as Reference 5-11 have not scored this design very highly, as will be later discussed.

2. Hydrogen Enriched Fuels

Hydrogen has the lowest flammability limit of any gas or vapor. Amounts as low as 4% in volume have been consistently burned in the laboratory. This ability to ignite and burn at low concentrations has been a matter of concern for those responsible for safety in facilities where hydrogen is handled. Consideration of hydrogen as a fuel for internal combustion engines is not new by any means. Reference 5-15 reports the use of hydrogen in the diesel engines which were to propel hydrogen-filled dirigibles to increase the range somewhat, instead of venting it out to the atmosphere. This event and other sporadic attempts were always accidental and peripheral to the central issue of looking at hydrogen as a fuel. This was due to the fact that hydrogen was, and still is, an exotic, expensive fuel and troublesome to handle. Hydrogen was also utilized as an additive to gasoline during the years when most of the research in internal combustion engines was focused on suppressing knocking at high compression ratio. Ricardo refers to hydrogen (Reference 5-16) as an additive which may allow very lean operation of engines and suppress knocking. Gasoline engines were later operated with pure hydrogen for very specialized applications (research and development for the military), but it was never taken seriously as a near-term solution. The first significant use of hydrogen blended with gasoline with the specific purposes of lowering emissions and increasing the thermal efficiency was conducted by Lee and Wimmer (Reference 5-17). These authors also addressed the logistics of the availability of hydrogen and recommended partial oxidation of the gasoline by means of an onboard reactor in order to meet the small amounts required for their lean burning scheme. CIT-JPL personnel (Shair, Rupe, McKay, Reference 5-18) made contact with these researchers and discussed the scheme as a means of simultaneously decreasing the NOx emission and fuel consumption in automobiles. Rupe (Reference 5-19), following up Lee's and Wimmer's ideas, developed the theoretical aspects of the combustion in hydrogen-enriched fuels and organized a program for hydrogen-enriched fuel in lean burning engines which constituted the technological base for the JPL Low Pollution Car Program that was initiated by Breshears and others (Reference 5-20). The program has undergone profound transformations since its implementation and more about its development will be said later in this report.

The fundamental principle that underlines the hydrogen enrichment concept is contained in the already mentioned document by Coward and Jones (Reference 5-8), which contains a compilation of the original work advanced by Le Chatelier (Reference 5-21). Le Chatelier's empirical formulation for the study of lean limits of mixtures of flammable gases and vapors goes as follows:

Let two gases A and B form a mixture C. N_A and N_B are the lean limits of gases A and B in air by volume. Assume n_A and n_B to be the percentages by volume of each gas in the mixture of the two gases in air. The formula used by Le Chatelier for the mixture to be in the lean limit is

$$\frac{n_A}{N_A} + \frac{n_B}{N_B} = 1 \qquad (5\text{-}3)$$

Assuming that a similar relationship exists for the rich flammability limits, one can display Equation (5-3) graphically and bracket the flammability region (see Figure 5-13). The Le Chatelier law has been tested for many mixtures, and although its applicability has been proved, it should not be applied indiscriminately and should be verified experimentally when considering new applications. Its validity for studying lean combustion of gasoline/ hydrogen mixtures has been tested by Houseman and others (Reference 5-22). Their results are presented in Figure 5-14. The experimental points were found to be within 10% of the theoretical prediction. The lean limits for gasoline and hydrogen are 1.4 and 4 volume percent in air. If a mixture in air contains 3.5% gasoline and 2% hydrogen, one obtains a lean limit mixture. The way to look at these results from the point of view of an investigator in hydrogen-enriched fuels is that the lean flammability limit of gasoline has been extended by the addition of hydrogen. However, because of the very low density of hydrogen relative to gasoline vapors (1:48), small amounts of hydrogen can substantially extend the lean flammability limit of a gasoline/air mixture. The results shown in Figure 5-14 have been plotted as hydrogen/ (hydrogen + gasoline) mass ratio vs the overall equivalence ratio, which is displayed in Figure 5-15 (taken from Reference 5-22) and found more convenient when discussing hydrogen enriched fuels.

At the time of Le Chatelier, combustion phenomena were not looked upon from the modern point of view of kinetics, and empiricism was the exclusive method of attack for most physical-chemical phenomena. Nowadays, and as a consequence of the momentum imparted by Von Karman to the science of combustion, very powerful and analytical methods are available to the researcher and the theory of lean flammability limits should be analyzed again in terms of such current techniques. The lean flammability limit phenomenon has not been systematically reviewed because of lack of support for fundamental research. Only very meager theories are available, and they are not reliable for prediction of lean limits and foster a suspicion of a lack of understanding of such phenomena. A heuristic explanation of the extension of the lean flammability limit by the presence of hydrogen could be attempted. The higher molecular diffusivity of hydrogen may, by differential diffusion in the flame front, compensate the quenching term of conduction heat losses originated by the diffusion of O_2 away from the flame front and into the premixed fuel-air mixture. In other words, sources are brought in precisely

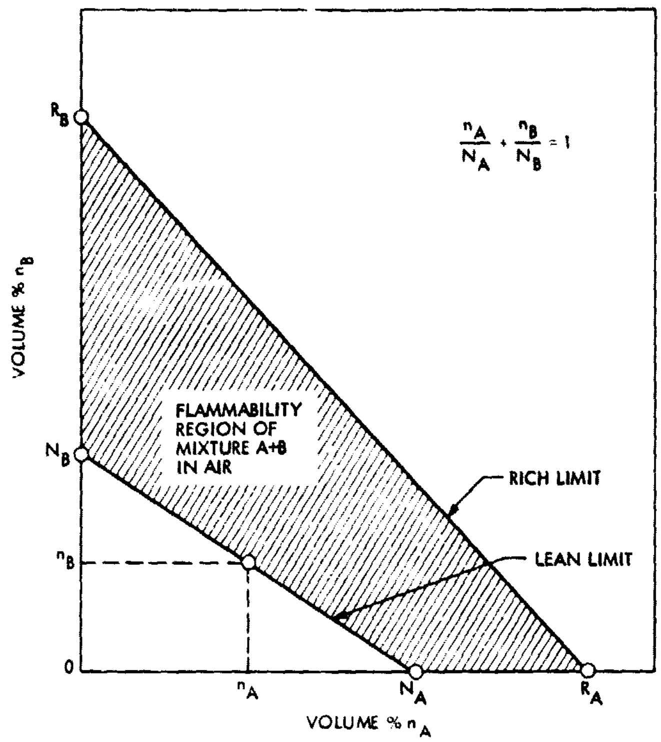


Figure 5-13. Le Chatelier Formula for Mixtures of Gases in Air

to the point where there is a starvation of fuel due to the oncoming differential diffusion of O_2. This explanation is offered based on the model for single fuel/air mixtures advanced by Spalding (Reference 5-3). It has not been investigated theoretically or experimentally but it should be worth pursuing.

Since such small additions of hydrogen to a gasoline/air mixture extend the flammability limit considerably, this approach seems to be ideal for operating internal combustion engines ultralean. This scheme has an advantage over the stratified charge engine since the hydrogen-enriched mixture has been premixed at the molecular level (or at least that is the prevailing desire), and the overall equivalence ratio can be brought down to low values, much lower than the 0.85 used by those other schemes. Furthermore the turbulence scale and intensity in the combustion chamber do not have to be restricted, since no stratification is here required, thus considerably improving the flame propagation. The original approach advanced by Rupe in Reference 5-19, and which constitutes the original JPL patent, can be understood by referring to Figure 5-6, which is also applicable to automobile engines:

> The strategy set forward by the U.S. automobile industry to meet the exhaust emission standards for HC and NOx consists in operating at equivalence ratios larger than one in order to have the NOx below a certain level (Point C). At this equivalence ratio the NOx, CO and HC levels are determined for a well tuned engine by the combustion

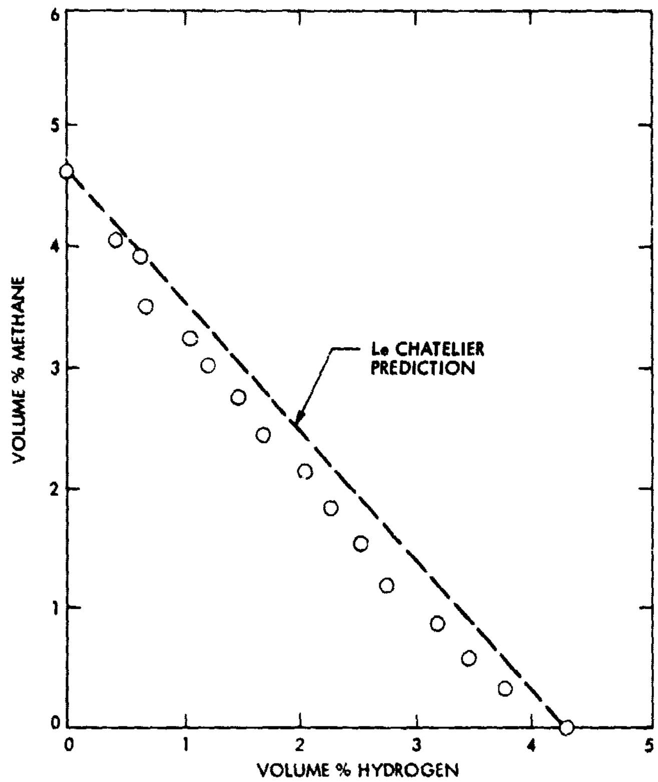


Figure 5-14. Verification of Le Chatelier Formula for Methane-Hydrogen/Air Mixtures (Reference 5-22)

temperature, and a well-known tradeoff exists between CO and NOx. The automobile manufacturers further lowered the prohibitively high CO and HC emissions at Point C by installing "catalytic incinerators" in the exhaust pipes. With this strategy the U.S. standards were barely met but a substantial reduction in mileage resulted from operating so rich. Rupe suggested operation at Points A and B (ultralean region), where a reduction in NOx is accomplished by operating at the other side of the peak of the NOx curve and thus avoiding the typical tradeoff between CO and NOx, since the CO levels decrease drastically for such substantial leanouts. A further benefit can be quickly noticed by observing the Brake Specific Fuel Consumption in the ultralean region. The JPL patent emphasized NOx reduction with simultaneous increase in thermal efficiency and low CO emissions. The HC was also hopefully expected to be low.

Since the days of the JPL preliminary investigations much has been learned about the practical aspects of combustion efficiency, lean burning and kinetics contribution to the exhaust in an internal combustion engine (see References 5-9, 5-23, 5-24, and 5-25). The combustion efficiency near the lean flammability limit is widely dominated by the kinetic effects which come into evidence because of the slowing down of the flame. In other words, the lean limits as defined above and as given by Coward and Jones are limits of flammable mixtures in the sense that a flame will

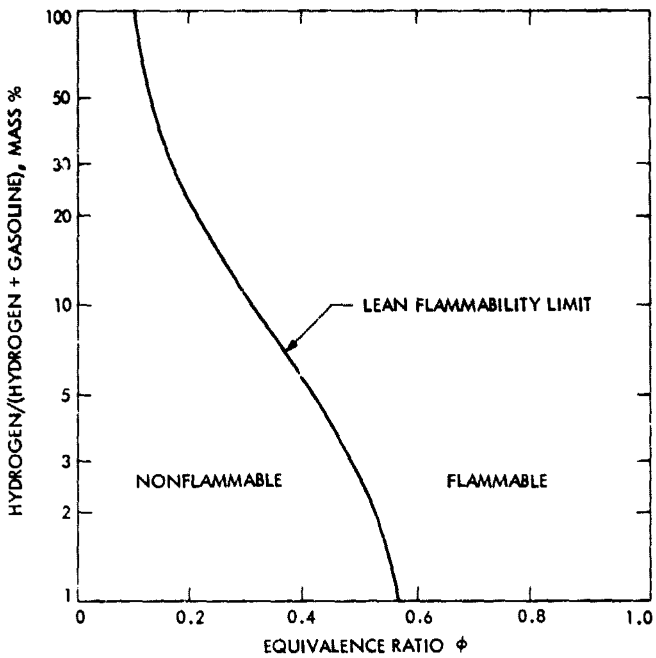


Figure 5-15. Hydrogen-Gasoline/Air Mixtures - Flammable Regions

self-propagate, but there is no indication of the percentage of fuel that will remain unburned. This is due most probably to experiencing, in a perfectly premixed fuel/air mixture, a molecular migration of the fuel toward certain regions of the combustion chamber along which the flame will propagate. This differential diffusion, which is driven by thermal gradients, can affect the flame path because of the flame speed being so low, as low as the diffusion velocities of the fuel. It is this lack of combustion efficiency which hampers the Rupe scheme of exhaust emissions in the ultralean region and whose kinetic production of CO and HC brings back the typical tradeoff between NOx and CO.

In any event one can still use catalytic reactors in the exhaust for eliminating the prohibitively high levels of CO and HC in the same manner as was done in the rich region by the automotive manufacturers. The benefit of higher thermal efficiency in the ultralean region remains still to be explored and, if confirmed when compared to the thermal efficiency in the rich region, could justify operating the automobile ultralean if the higher weight, cost, and complexity of the hydrogen enrichment system is compensated by the fuel savings. The logistics of supplying hydrogen to the gasoline/air mixture were resolved by the development of a hydrogen generator which would inject into the mixture a hydrogen rich stream of gases. Those gases were obtained by the partial oxidation of gasoline.

The fundamentals as discussed up to here constitute the state of the art of technology at the time that the Hydrogen Enrichment for Aircraft Piston Engines Program was undertaken, which is presented and widely discussed in Section VI.

3. Improvement on Systems and Control of Unmodified Engines

The scheme of achieving ultralean combustion in engines is what we should call the "naive approach." This approach consists in operating a conventional aircraft piston engine, attempt leanout until the lean misfire limit is encountered, investigate the cause for premature cycle-to-cycle pressure variations and/or misfiring, and improve the faulty condition. If the faulty condition is due to a poorly designed engine, the engine model should be discarded as a candidate for the ultralean operation. If the faulty condition is identified with some of the engine systems and/or controls, they should be redesigned, improved or substituted for until the faulty condition is removed and leanout is continued to reach ultralean operation. This procedure, of course, will increase the complexity of engine systems and controls, and consequently the overall price, unless there is a fortunate coincidence in that very slight modifications result in substantial improvements. It is obvious that on proceeding along these lines one can probably have more success with top-of-the-line engines than with low-cost, low-power engines.

From present understanding of ultralean burn engines, it is possible to separate certain desirable features whose introduction results in favorable trends towards achieving ultralean burning. Some of these innovations have already been recognized and evaluated by workers conducting research in aircraft piston engine exhaust emissions, but their effect on fuel economy has always been observed through a window warped by the concern of lowering emissions. We will list here those approaches which may affect the fuel economy.

a. Variable Valve Timing. This procedure provides an adequate valve overlap for different engine regimes. It may reduce emissions when taxiing and idling and during approach, but this impacts very slightly the overall fuel expenditure from block time to block time. Its impact on fuel economy is judged very small and its increase in weight, complexity, and cost does not seem to justify its introduction.

b. Ultrasonic Fuel Atomization. This system applies only to carbureted fuel systems. Its only objective is to provide a spray with a much smaller initial droplet size, which will thus relax the required length for total vaporization. It consists of a piezoelectric device which emits acoustic waves from 20 Hz to 40 Hz and is located near the venturi of the carburetor. Since it favors early vaporization, a more homogeneous mixture will be maintained near the intake manifold which will render a more uniform equivalence ratio distribution, thus allowing leaner operation. This system is worth considering when dealing with carbureted engines.

c. Thermal Fuel Vaporization. There are several variations on this scheme but they all involve transferring heat from the engine coolant or from the engine exhaust pipe into the intake manifold. This promotes quick vaporization of the fuel and prevents its condensation on the manifold walls during certain steady-state engine conditions or transients. This scheme is often combined with some modification in the air induction system which promotes turbulence during the mixing length and/or the use of plenum chambers that serve the purpose of small surging tanks, fuel droplet collectors, flow stabilizers, etc. One should also include here the intake turbulator valves which have been successfully demonstrated as favoring ultralean burning in Reference 5-7. These turbulators increase combustion chamber turbulence, although it is well known that the turbulence level in aircraft engines is much higher than in automobiles, and the impact of such turbulators in aviation may be considerably lower than experienced in automobiles. They have a detrimental effect on volumetric efficiency.

d. Individual Fuel Injection. This system ideally consists of a different fuel system for each cylinder. Every injector is independently controlled to assure that all the cylinders are running at the same equivalence ratio. The system has not been proposed in aviation, but Mercedes Benz has in the past tried individual injectors in some diesel engines. Whether the injectors are air-flow-controlled or electronically driven by some sort of a microprocessor will be left for later discussion.

e. Fuel Injector or Carburetor Upstream of the Supercharger. This system has been used by Lycoming in some of its engines for purposes other than improving leanout. The system was abandoned since no benefit was observed when operating rich. Additionally, the compressor discharge region is mixed with fuel vapors, and therefore not available for cabin pressurization. More will be said about it later in view of some new findings.

f. Spark Plugs. The most desirable spark plug for ultralean burning is one which will produce a strong stable flame kernel. Long spark penetration, wide electrode gap and a small electrode area are desirable characteristics. Of special significance in this respect is the plasma spark plug developed and tested at JPL by Fitzgerald (Reference 5-26), who was successful in producing a plasma discharge highly stabilized by a magnetic field induced by a coil. The plasma discharge grows in the form of a highly stable toroidal spark with deep penetration into the combustion chamber. The spark plug size is conventional and its modification is considered minimal. The discharge is very energetic and utilizes a capacity system. The drawback is the unproved reliability and the electromagnetic shielding requirements to protect the aircraft communication and navigational equipment. This approach is highly recommended for ultralean operation.

g. Spark Plug Pulse Control. This technique plays a very important role in ultralean combustion. Desirably, one would like to have available a high-energy, long-duration pulse, but it is hard to find any practical magnetos which could provide such an energetic discharge. The alternative solution is a multisparked discharge system which gives a series of high-energy, fast-rise sparks over some time interval, instead of a single slow rise spark of decreasing magnitude and shorter interval. There is a good system manufactured by Autotronic Controls Corporation which has been tested with success in ultralean automotive applications at JPL (Reference 5-7). Its application in general aviation should be investigated.

h. Ignition Timing. When operating ultralean, ignition timing is very critical. Besides selecting a very advanced spark and matching the low flame speed, corrections for manifold pressure and engine speed are also helpful in successfully operating the engine at low loads and during transients. Some modifications of existing magnetos will be necessary, but considerable experience in ignition systems in automobiles is available and the aviation industry can easily adapt it.

i. Controls. Depending on the degree of sophistication needed to operate an engine in the ultralean region, the engine controls may range from the purely mechanical to electrical or may incorporate microprocessors. More on this subject will be offered in the later sections of this report.

j. Conclusions. The three schemes for achieving ultralean engine operation discussed in Section V-F have been analyzed previously for consideration as serious contenders in aircraft engines applications. Rezy and others (Reference 5-11) have conducted an analysis and selection of emission reduction schemes for aircraft piston engines. The criteria for screening and selection were divided into three major groups:

Dominant:

- Emissions
- Safety
- Performance
- Cooling
- Weight and size
- Fuel economy
- Cost

Secondary:

- Reliability
- Technology
- Operational characteristics
- Maintainability and maintenance

Minor:

- Integration
- Material
- Productibility
- Adaptability

The following concepts were analyzed:

- Improved cooling combustion chamber
- Improved fuel injection system
- Air injection
- Multiple spark discharge system
- Ultrasonic fuel atomization
- Variable timing ignition system
- Thermal fuel vaporization
- Hydrogen enrichment
- Texaco CCS

Two-stroke diesel
Ford PROCO
Variable camshaft timing
Honda CVCC
Four-stroke diesel, open chamber

The results of the screening of concepts and selection criteria are presented in Table 5-3 taken from Reference 5-11, where engine candidacy for ultralean operation has not been taken into account. These results, although not directly applicable to our main objective, are very meaningful because they reflect the impact of important criteria on the selection of schemes which have been recommended in this section as strong candidates for ultralean operation. Each scheme has been ordered from 1 to 14 by the results of the scoring algorithm. If we suppress those schemes that are not eligible for our purposes (flagged as **********) and the issue of emissions is floated, Table 5-3 brings to attention several options previously discussed in this section. Notice the preferent places occupied by the improved fuel injection systems, the variable timing ignition systems, the ultrasonic fuel atomization system, and the multiple spark discharge system. Interestingly enough, hydrogen enrichment, which qualifies so well in fuel economy, appears as a weak contender because of the scoring in other criteria. Notice also that in spite of the good scoring in fuel economy the stratified charge schemes have, their scoring in safety, performance, weight, size, and cost places them in a very disadvantageous position. One seems to conclude from such analysis that the "naive scheme" proposed in Section V-3 is the one recommended first followed by hydrogen enrichment and stratified charge. We point out that because of lack of information and experience, there is an uncertainty associated with each scheme incorporated in the scoring algorithm. The places occupied in the scoring could be sustantially altered if (1) emissions are floated, (2) ultralean operation is desired, and (3) the bulk of experience from automobile applications is extended experimentally and translated in terms of aircraft engines.

Table 5-3. Concept Rank Ordering vs Criteria Importance

Concept	Criteria													
	Dominant					Secondary					Minor			
	Safety	Performance	Cooling	Weight and Size	Fuel Economy	Cost	Reliability	Technology	Operational Characteristics	Maintainability and Maintenance	Integration	Materials	Producibility	Adaptability
Improved cooling combustion chamber ****	1	6	1	1	6	6	3	2	1	1	6	3	2	4
Improved fuel injection systems	2	1	14	2	5	7	4	1	6	2	4	2	7	6
Air injection *****	5	8	9	6	14	1	5	3	3	5	2	6	1	1
Multiple spark discharge system	3	5	7	3	12	2	6	4	2	3	1	1	5	2
Ultrasonic fuel atomization, autotronic	4	9	11	5	10	4	1	5	5	4	10	4	4	7
Variable timing ignition system	6	3	8	4	11	5	7	7	9	6	3	5	6	3
Thermal fuel vaporization, ethyl	7	10	13	7	9	3	2	6	4	7	9	7	3	5
Hydrogen enrichment, JPL	14	7	4	8	1	12	8	9	12	8	7	14	8	8
Texaco CCS	8	12	2	10	2	10	12	13	10	13	11	13	11	11
Two-stroke diesel, McCulloch ****	11	2	6	13	4	13	9	11	13	9	13	12	13	14
Ford Proco	9	13	3	11	3	9	11	14	11	14	12	9	12	12
Variable camshaft timing *****	13	4	10	9	13	8	14	8	8	10	5	8	9	9
Honda CVCC	12	11	12	12	8	11	13	10	7	11	8	10	10	10
Four-stroke diesel, open chamber ****	10	14	5	14	7	14	10	12	14	12	14	11	14	13

SECTION VI

HYDROGEN ENRICHMENT FOR AIRCRAFT PISTON ENGINES

The potentials described in Section V for fuel economy improvement by operating ultralean were recognized by NASA and prompted the NASA-OAST Office of Aeronautical Propulsion to sponsor a program to investigate the possibilities offered by piston aircraft engines in general aviation. Hydrogen enrichment was selected as the baseline scheme for achieving ultralean operation.

A. OBJECTIVES

The objective of the program was to investigate the fuel economy improvement obtained by operating piston aircraft engines ultralean, stabilizing combustion by means of hydrogen enrichment.

B. APPROACH

The program was undertaken as a joint venture by the Jet Propulsion Laboratory of the California Institute of Technology; AVCO Corp., AVCO-Lycoming Division; and Beech Aircraft Corp and it was divided into three phases. Phase I consisted of a systems analysis study to estimate the possible improvements in fuel economy and exhaust emissions to be gained. Phase II was a laboratory verification of these estimates, and in Phase III flight tests were conducted. JPL provided management and technical cognizance and hydrogen systems hardware to the program. AVCO-Lycoming had the responsibility of conducting the laboratory verification of the results of Phase I in its experimental facilities at Williamsport, Pennsylvania. Beech Aircraft conducted the flight tests of the engine-system configuration which was finally selected as a result of the analytical and experimental efforts of Phase I and Phase II.

The hydrogen enrichment scheme requires the injection of hydrogen-enriched gases into the engine cylinders. The operational problems associated with supplying hydrogen onboard were overcome by incorporating a hydrogen generator as part of the air induction system. The hydrogen is generated by partial oxidation of small amounts of aviation gasoline used in the conventional propulsion system (see Figure 6-1).

C. THE AIRCRAFT

The aircraft used in the program was a Beech Model B60 Duke, Series P-3. A photograph of the airplane in flight is shown in Figure 6-2, and a three-view drawing can be seen in Figure 6-3. The Beechcraft Duke B60 is a pressurized, all-weather aircraft with two turbocharged engines, cruising up to 278 mph and flying up to 35,800 feet. The airplane has a 6-seater cabin and offers all the comfortable options typical of a modern business executive aircraft, and it was therefore considered a good representative of the top-of-the-line general aviation

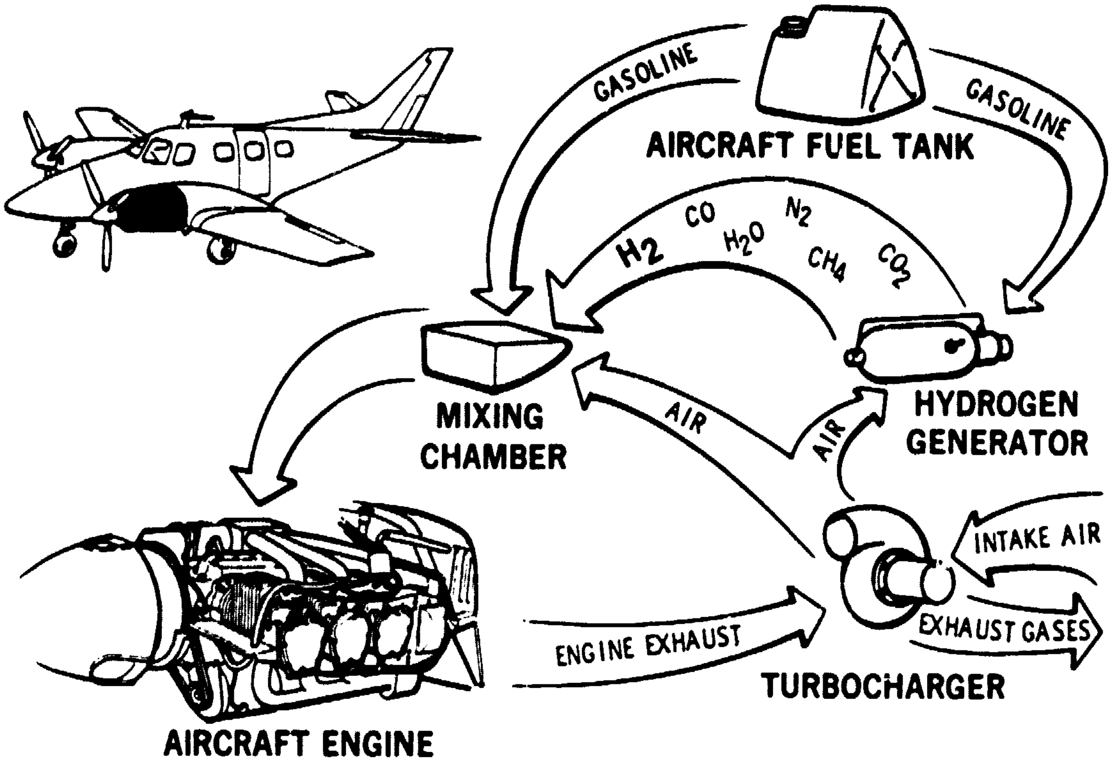


Figure 6-1. Hydrogen Enrichment Design Concept

Figure 6-2. The Beechcraft Duke B60

aircraft, which made it especially suited for this program, and highly convenient, since it was available from past Beech experimental programs.

A summary of the aircraft specifications is given in Table 6-1. The Duke is powered by two 6-cylinder Lycoming turbocharged fuel-injected engines rated at 380 horsepower. The control center of the turbocharger system is the variable absolute pressure control which simplifies turbocharging to one control -- the throttle. Once the pilot has set the desired manifold pressure, virtually no throttle adjustment is required with changes in altitude. The turbocharger maintains the manifold pressure called for by the throttle setting. The Duke uses standard three-bladed, full-feathering, constant-speed propellers. These propellers are equipped with deicing and antifreezing devices to secure propeller feather or change of pitch at any altitude and temperature. A complete description of the aircraft is found in the Duke Pilots Operating Manual (Reference 6-1) while manufacturer commercial information has been taken from Reference 6-2.

D. THE ENGINE

The engine tested was a Lycoming TIO-541-E. The initials stand for turbocharged, fuel injection, opposed cylinders. Other aircraft applications of the same engine series are found in the Mooney airplane, and other variations in the series such as the TIO-540 and TIGO 541 and 540 have been installed in the Piper Pressurized Navajo, Turbo Navajo, Navajo Chieftain, Turbo Aztec F, Cessna 421, etc. More and more models are using this type of engine or equivalent. Testing this engine was considered appropriate since it seems to follow the prevailing design trends for general aviation.

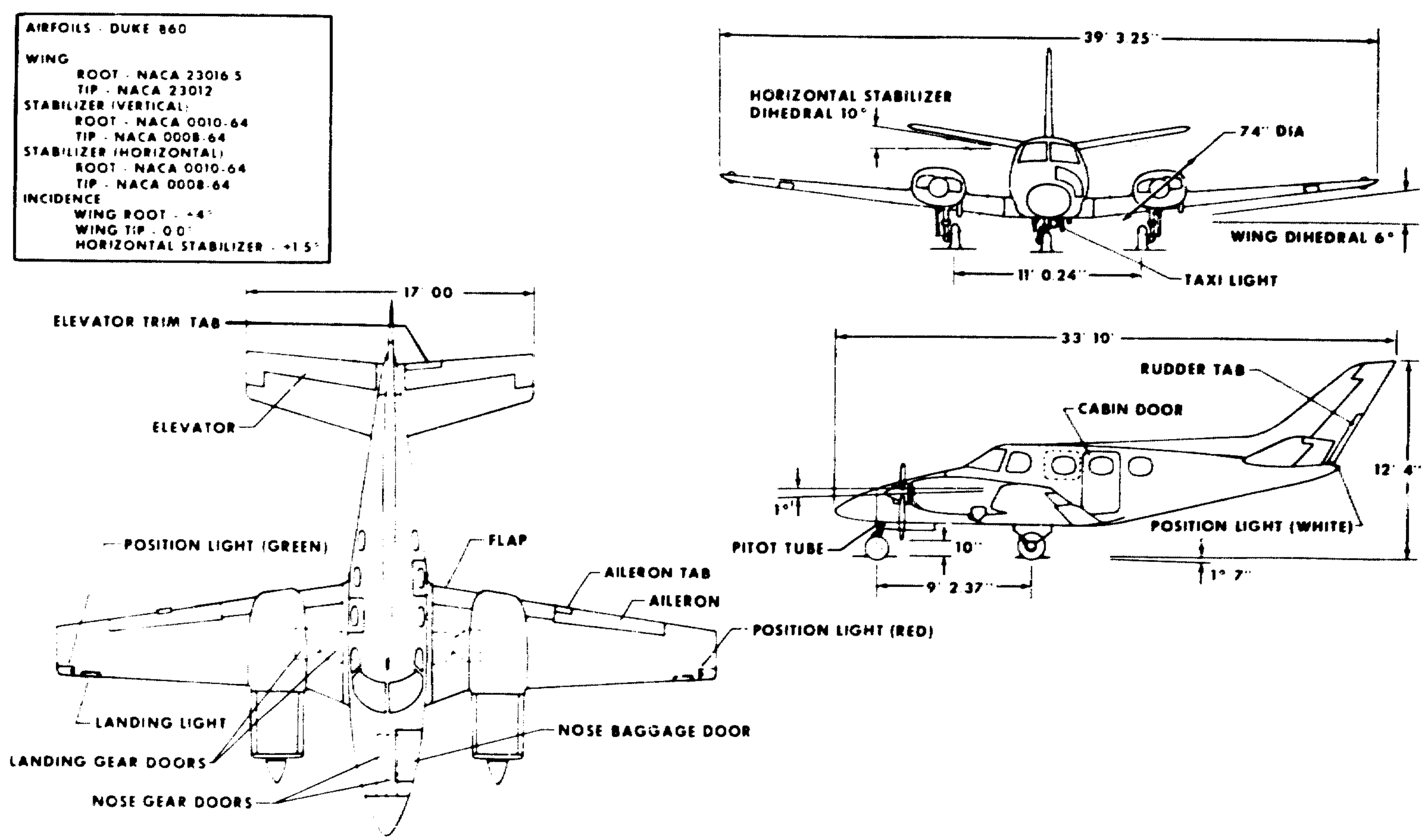


Figure 6-3. Three-View Drawing of the Duke B60 Model

The AVCO Lycoming TIO-541 aircraft engine (Figure 6-4) is a six-cylinder, direct drive, horizontally opposed, wet sump, fuel-injected, turbocharged, air-cooled model with side-mounted accessories and incorporating piston cooling oil jets in the crankcase. It has a displacement of 541.5 cubic inches and develops 380 brake horsepower at 2900 rpm and a manifold pressure of 41.0 inches of mercury (absolute).

Relative to this study certain engine components require particular attention to construction and operation. These individual units are detailed in the following paragraphs.

1. Cylinders

The cylinders are of air-cooled construction with the two major parts, head and barrel, screwed and shrunk together. The heads are made from an aluminum casting with a fully machined combustion chamber. The cylinder barrels are machined from chrome-nickel molybdenum steel forgings with deep integral cooling fins. The barrel bore is nitr.ded, requiring the use of chrome-plated piston rings.

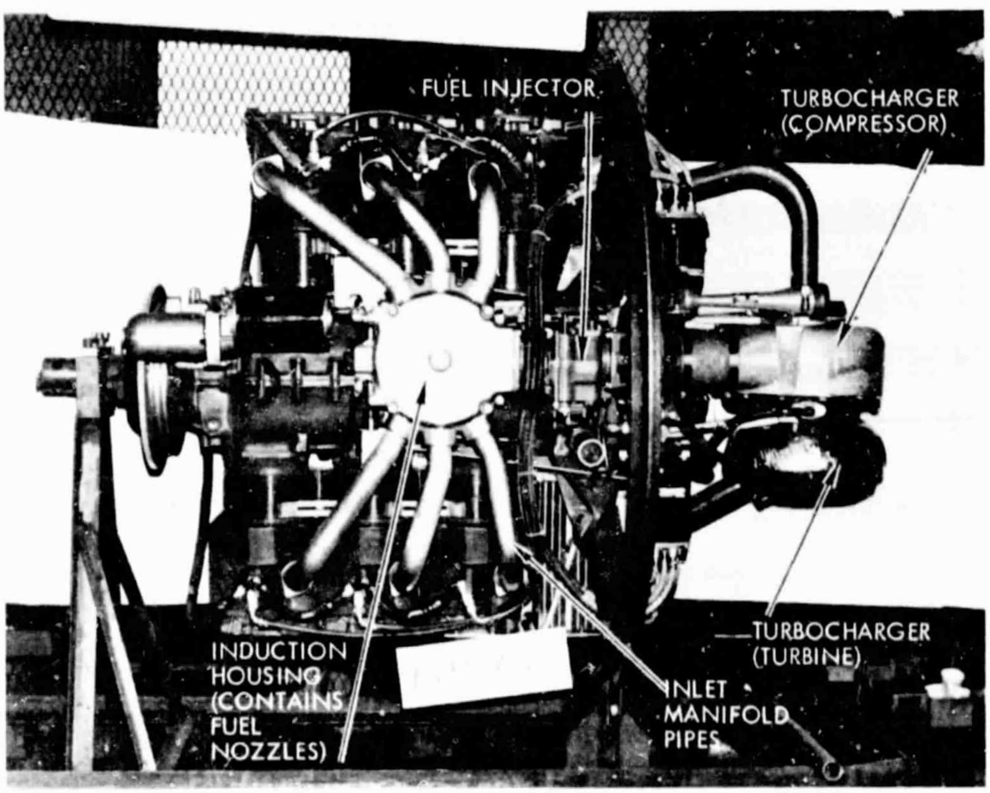


Figure 6-4. The Lycoming TIO-541-E Series Engine

Table 6-1. Duke B60 Performance

Maximum ramp weight	6819 lb
Gross weight	6775 lb
Empty weight (includes unusable fuel and standard avionics)	4275 lb
Useful load (standard airplane)	2544 lb
Cruise speed (65% power @ 25,000 ft)	222 kts (255 mph)
High-speed cruise (@ 23,000 ft)	248 kts (286 mph)
[a]Range (75% power @ 25,000 ft)	1005 nm (1157 sm)
[a]Range (65% power @ 25,000 ft)	1118 nm (1287 sm)
[a]Range (45% power @ 20,000 ft)	1227 nm (1412 sm)
Rate-of-climb (two engines)	1601 fpm
Rate-of-climb (single engine)	307 fpm
Service ceiling (two engines)	30,800 ft
Service ceiling (single engine)	15,100 ft
Takeoff distance (sea level) Over 50-ft obstacle	2626 ft
Landing distance (sea level) Over 50-ft obstacle	3065 ft

[a]Range figures are based on 232 gallons usable and includes start, taxi, takeoff, climb and 45-minute reserve at 45% power.

2. Induction System

This engine employs a Bendix RSA type fuel injection system. This fuel injection system is based on the principle of measuring air flow and uses the air flow signal in a diaphragm-type regulator to convert the air pressure into a fuel flow, making fuel flow proportional to air flow. A manual mixture control and idle cutoff are provided.

3. Turbocharger System

The turbocharger system is mounted as an integral part of the engine. Its turbine utilizes the engine exhaust gases to drive a compressor which furnishes air to the engine induction system and cabin pressurization system. Bleed air to the cabin for pressurization at altitude is controlled by a sonic nozzle that limits the flow of air to the cabin. The variable pressure controller senses the compressor discharge pressure (deck pressure) and regulates the oil pressure controlling the position of an exhaust bypass valve located on the engine exhaust. The desired compressor discharge pressure is determined by moving of the throttle control, which is linked to the pressure setting controller cam. Engine oil pressure is utilized as the "muscle" for this control system. The action of the turbocharger control system is automatic and modulates continuously to maintain engine power as altitude is varied. However, the regulation of manifold pressure by modulation of the exhaust gas flow to the turbocharger is limited. This limitation, called the critical altitude, is that condition existing when the exhaust bypass valve (wastegate) is completely closed and diverting the entire exhaust gas flow through the turbine section of the turbocharger. Transferring this condition into performance (Figure 6-5) indicates that rated power (380 BHP at 2900 rpm) can be maintained to 15,000 feet. Or, conversely, at rated power, the critical altitude is 15,000 feet. At lower power settings, for example 300 BHP at 2750 rpm (Figure 6-6), higher critical altitudes are possible.

4. Ignition System

Dual ignition is furnished by two Scintilla 1200 series magnetos. The S6LN-1208 magneto is a retard breaker magneto providing a fixed retard and a long-duration spark for easier starting. The S6RN-1209 is a conventional magneto which is grounded out at the time the engine is started. A source of dc power and a starting vibrator are required to complete the installation. The 1200 series magnetos incorporate an integral feedthru capacitor and require no external noise filter in the ground leads. Other than the retarded timing for starting, the spark advance for this engine is fixed at 20° BTDC.

Further engine performance and specification details are contained in Table 6-2 (References 6-3 and 6-4).

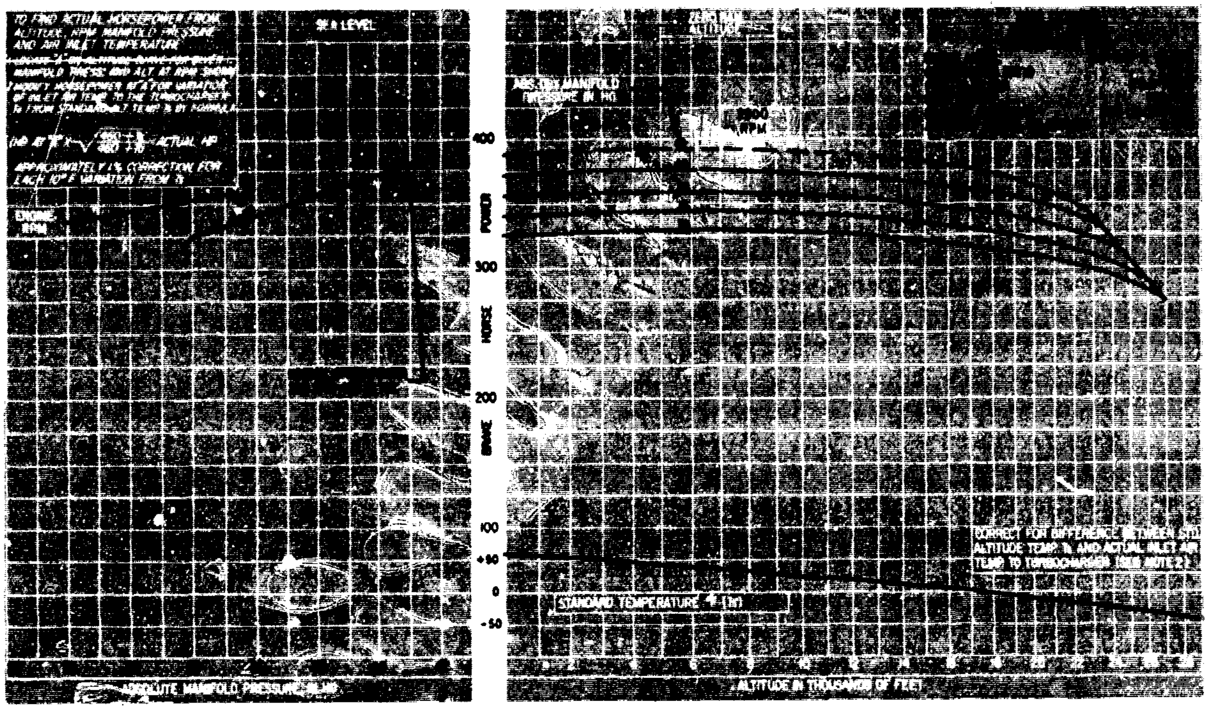


Figure 6-5. Sea Level and Altitude Performance: Engine Speed 2900 rpm

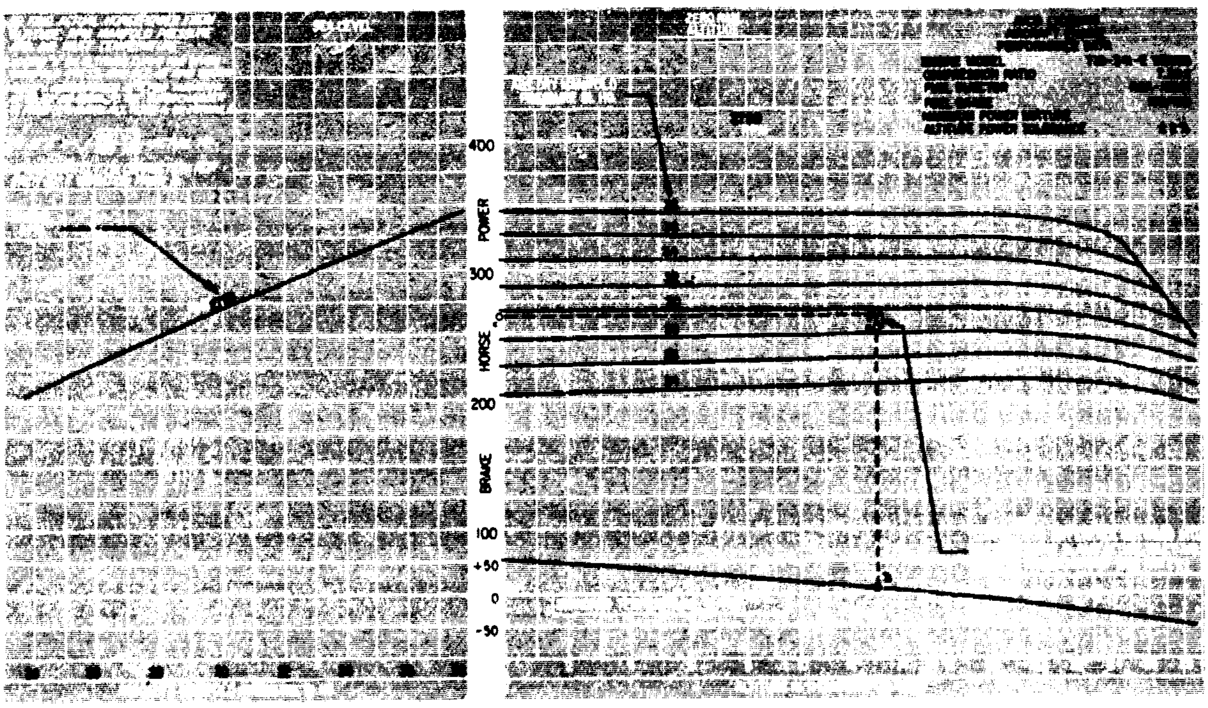


Figure 6-6. Sea Level and Altitude Performance: Engine Speed 2750 rpm

Table 6-2. Engine Specifications - AVCO-Lycoming TIO-541-E

FAA type certificate	E10EA
Rated horsepower, alt.	380 @ 2900/15,000 ft
Performance cruise horsepower rpm alt.	300 @ 2750/21,000 ft
Economy cruise, horsepower, rpm	247 @ 2650
Bore, in.	5.125
Stroke, in.	4.375
Displacement, cu in.	541.5
Compression ratio	7.3:1
Fuel injector, Bendix type	RSA-10DB1
Magnetos (1) Scintilla (right)	S6RN-1209
Magnetos (1) Scintilla (left)	S6RN-1208
Firing order	1-4-5-2-3-6
Spark occurs, deg BTC	20
Valve rocker clearance (hydraulic lifters collapsed), in.	0.040-0.105
Dimensions:	
Height, in.	25.17
Width, in.	35.66
Length, in.	52.07

E. THE HYDROGEN ENRICHMENT SYSTEM

In order to supply a uniform and homogeneous charge of hydrogen to the engine cylinders, a hydrogen-injection system was integrated with the engine. This system was intended to accomplish the following functions:

(1) Manufacture hydrogen-rich gases from gasoline and air (partial oxidation).

(2) Mix the hydrogen-rich gases with the air and additional gasoline in the intake manifold.

(3) Provide sufficient mixing length to assure a homogeneous mixture and uniform distribution throughout all the cylinders, while maintaining the manifold temperature down to acceptable levels to assure a good volumetric efficiency.

(4) Regulate the hydrogen-rich gas flow rate as required for efficient operation of the engine/hydrogen enrichment system.

1. The System

A schematic diagram of a functional hydrogen enrichment system is given in Figure 6-7. The diagram indicates also the conventional operation of the engine and the modification when hydrogen enrichment is incorporated. Air from the compressor discharge is injected into a hydrogen generator by means of an auxiliary air pump. As the compressor discharge pressure varies for different engine regimes, the air flow into the hydrogen generator is regulated by means of a throttle. A certain fuel flow from the gasoline tank is diverted into the hydrogen generator by means of a fuel pump and a fuel metering valve. The hydrogen generator output consists of a mixture of gases rich in hydrogen which are injected into a mixing chamber where they mix intimately (ideally at molecular level) with the intake manifold air. Also, depending on engine design, a heat exchanger may be necessary to lower the resulting manifold temperature, since the hydrogen generator output is of the order of 800°F. This heat exchanger is cooled by the cowling ram air, but may be absent if the distance from the hydrogen injection point to the cylinder intake ports is long enough to allow cooling, eliminating an unnecessary piece of hardware. Notice that the hydrogen generator air pump hardly draws any power, since it has only to overcome some of the pressure drop in the generator. The pressure drop across the engine throttle is in most cases sufficient to maintain the necessary air flow through the generator. The system (Figure 6-7) is also provided with a three-way valve downstream of the generator, which is actuated during the start and stop operations of the system. A specific implementation of this system will be shown in later paragraphs.

2. Hydrogen Generator

The fundamental principle of the hydrogen generator used here is the partial oxidation of hydrocarbons. When gasoline and air are completely reacted at

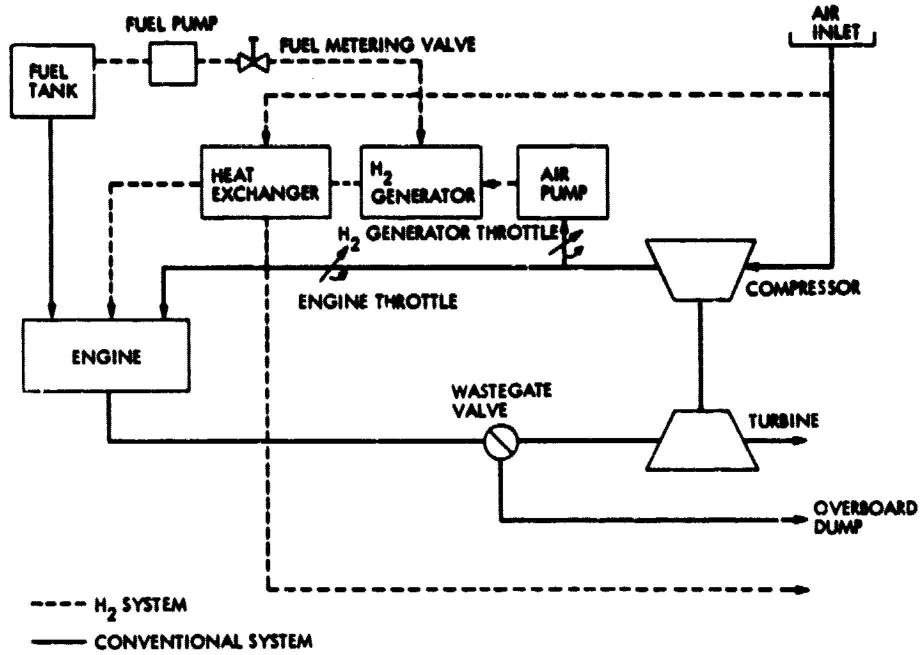


Figure 6-7. Schematic Flow Diagram of Hydrogen Enrichment System

an equivalence ratio of $\phi = 2.75$, the reaction yields a product gas consisting of 21% H_2, 23% CO, 52% N_2 and 4% other species (by volume). A more complete listing of the product composition is shown in Figure 6-8, where the hydrogen produced as a function of fuel flow rate input is also shown. It has been found that this equivalence ratio corresponds to the optimization of hydrogen output relative to the fuel input, although small variations of ϕ for constant fuel flow have not been shown to affect the hydrogen output significantly. As shown in the figure, approximately 8.5 pounds of fuel are consumed to generate one pound of hydrogen. The reactions of these rich fuel/air mixtures are very hard to drive thermally due to a tendency to produce soot. To avoid this pitfall, which could seriously hamper engine operation, a catalyst is used to drive the reaction at the equilibrium temperature, which is about 2000°F. The catalyst consists of a ceramic structure (pellets or monolith) coated with nickel. A more complete description of the catalytic hydrogen generator can be found in Reference 6-5, and more details about the generators used in this program will be found later in this section.

F. PHASE I - A SYSTEM ANALYSIS ASSESSMENT

The objective of this phase was to conduct a study to determine the feasibility of the hydrogen enrichment concept by characterizing the overall system efficiency in aircraft performance. Analytical representations of an aircraft piston engine system were formulated, including all essential components required for onboard hydrogen generation. To assist in the study, the services of AVCO Lycoming and Beech Aircraft were obtained through contracts with JPL. JPL developed the analytical

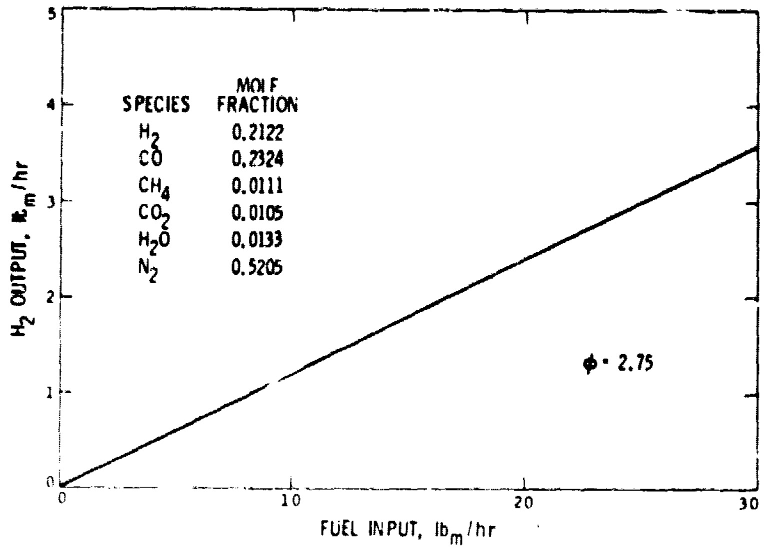


Figure 6-8. Hydrogen Generator Product Gas

modeling and calculated the operational characteristics of the integrated generator/engine system, Lycoming determined the critical altitude, and Beech computed the aircraft performance. The results were formally published by Menard and others in Reference 6-6. The aircraft performance calculations were published by Umscheid in Reference 6-7, and a detailed account of the analysis and results are given in Reference 6-8.

1. System Description

The aircraft used in this analysis has been described in Section VI-C; the engine utilized for the study was an F model, which is a variation of the TIO-541-E engine model described in Section VI-D. At the time the study was undertaken, the only hydrogen generator available was the one described in Reference 6-5 that was developed for automobile applications. This generator performance has been described in Section VI-E; it was recognized that some generator development had to be undertaken later on in the experimental phase. Integration of the hydrogen generator with the engine is illustrated schematically in Figure 6-9, which is a simplified version of the system under study. The functional relationships of the different elements shown in Figure 6-9 have been treated in Section IV-E and do not require further explanation. In the analysis, the thermodynamic state conditions were computed throughout the system, and detailed balances of mass, pressure, and energy were established to determine the impact of adding the hydrogen generator. In assessing the aircraft performance, it was assumed that the hydrogen generator would be installed on top of the engine, requiring a nacelle modification which would translate into a slight increase in aerodynamic drag.

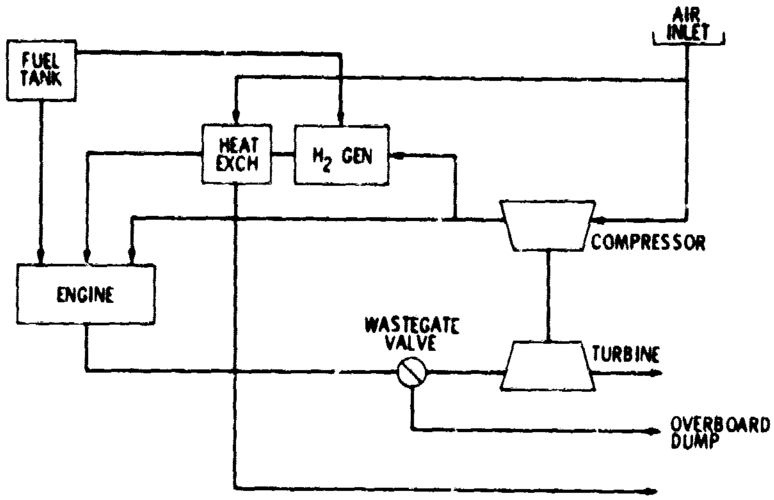


Figure 6-9. Schematic Flow Diagram of Hydrogen Enrichment System

2. Engine-Generator Assembly Analysis

The performance and fuel consumption characteristics of the engine/generator assembly were studied for various operating conditions. The brake horsepower, BHP, and brake specific fuel consumption, BSFC, were calculated as a function of engine speed, operating altitude, intake manifold pressure, and hydrogen flow rate. A parametric study was conducted and wherever possible empirical data were utilized. The analysis will not be repeated here. The reader is referred to the above References 6-7 and 6-8 for further information, but the fundamental equations used in the modeling will be given in condensed form for a critical discussion in view of the findings from Phase II and III:

$$BHP = IHP - FHP \tag{6-1}$$

where IHP is the indicated horsepower and FHP the friction horsepower, which is a function of the engine rpm and includes the power required to drive the accessories.

$$IHP = \frac{\eta_t}{J}\left[\left(\dot{m}_{g(eng)}\ h_g\right) + \sum\left(\dot{m}_i\ H_i\right)\right] \tag{6-2}$$

where η_t is the engine indicated thermal efficiency, J is Joule's coefficient, $\dot{m}_{g(eng)}$ is the mass flow of gasoline supplied to the engine, and h_g is the heat of combustion of gasoline. The terms in the summation account for the energy content of the hydrogen generator output, which flows to the engine as additional fuel. In order to produce these gases, the generator consumes $\dot{m}_{g(gen)}$, and one defines the system BSFC as:

$$BSFC = \frac{\dot{m}_{g(eng)} + \dot{m}_{g(gen)}}{BHP} \qquad (6\text{-}3)$$

Empirical information available from previous work that JPL had conducted with hydrogen-enriched fuels for the automobile program showed that the thermal efficiency was a function of the hydrogen mass flow rate $\dot{m}_{H_2}$, engine rpm, manifold pressure P_{man}, and equivalence ratio ϕ.

In functional form

$$\eta_t = f_1(\dot{m}_{H_2}, rpm, P_{man}, \phi) \qquad (6\text{-}4)$$

The gasoline flow rate to the engine can be written as

$$\dot{m}_{g(eng)} = \zeta_g \left[\phi(\dot{m}_{a(eng)} + \dot{m}_{dil}) - \dot{m}_{a_s}\right] \qquad (6\text{-}5)$$

where ζ_g is the stoichiometric fuel/air ratio for gasoline, $\dot{m}_{dil}$ is the diluent mass flow rate (N_2, CO_2, and H_2O) and $\dot{m}_{a_s}$ is the stoichiometric air mass flow rate for the generator product gas, which is a function only of $\dot{m}_{H2}$. This relationship also applies to $\dot{m}_{dil}$. Further relationships are found in Equations 6-6, 6-7, and 6-8:

$$\dot{m}_{a(eng)} = \eta_v \frac{rpm}{C_1} V \frac{P_{man}}{T_{mix}} - C_2 \frac{\dot{m}_p}{\overline{M}} \qquad (6\text{-}6)$$

$$\eta_v = f_2(P_{man}, T_{mix}, \phi) \qquad (6\text{-}7)$$

$$T_{mix} = \frac{\dot{m}_{a(eng)} C_{p_a} T_c + \dot{m}_p C_{p_p} T_{gen}}{\dot{m}_{a(eng)} C_{p_a} + \dot{m}_p C_{p_p}} \qquad (6\text{-}8)$$

where η_v is the volumetric efficiency, T_{mix} is the temperature of the mixture of induction air and generator product gases, C_1 and C_2 are conversion factors, V is the engine displacement, $\dot{m}_p$ is the product mass flow rate, $\overline{M}$ is the mean molecular weight, $C_{p(a)}$ and $C_{p(p)}$ are the specific heats of the air and product gas, T_{gen} is the generator output temperature, and T_c is the compressor discharge temperature.

The solution of these equations was conducted by means of a computer program, which also calculated thermodynamic conditions, pressure losses, and energy balance. The computations involve some complexity, but the physics are straightforward. We want, however, to emphasize the two areas which required empirical information: one of them, the volumetric efficiency (Equation 6-7), was calculated from Lycoming engine performance measurements conducted in the past, resulting thus in a high degree of confidence in its estimation. The other one, and this is the most important point in the study, was the indicated thermal efficiency η_t.

The functional form of η_t was estimated from measurements conducted by Houseman and Cerini (Reference 6-5) which gives the basis for such an estimate. Figure 6-10 displays the indicated thermal efficiency of a Chevrolet V-8 engine with a displacement of 350 cubic inches, as a function of the equivalence ratio for various amounts of hydrogen enrichment. Unfortunately, the data shown was obtained for an engine operational cycle specified for EPA automotive emission standards, and due to the fact that several engine parameters were varying, the effect of hydrogen enrichment on η_t was not clearly isolated, although it was believed that if constant rpm and locked throttle were maintained, one would ideally obtain a qualitative behavior as shown in Figure 6-11. Owing to this interpretation of the previous results, two cases were considered in the calculations: a conservative case and an optimistic case. These were thought to bracket the engine thermal efficiency

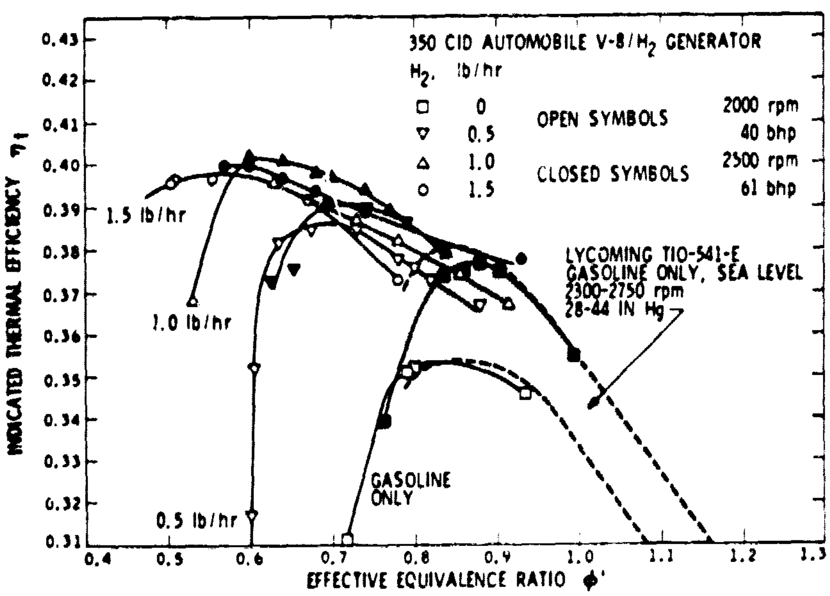


Figure 6-10. Indicated Thermal Efficiency vs Equivalence Ratio for a Chevrolet V-8 Engine with Hydrogen Enrichment. The Indicated Thermal Efficiency of the TIO-541 is also shown for comparison

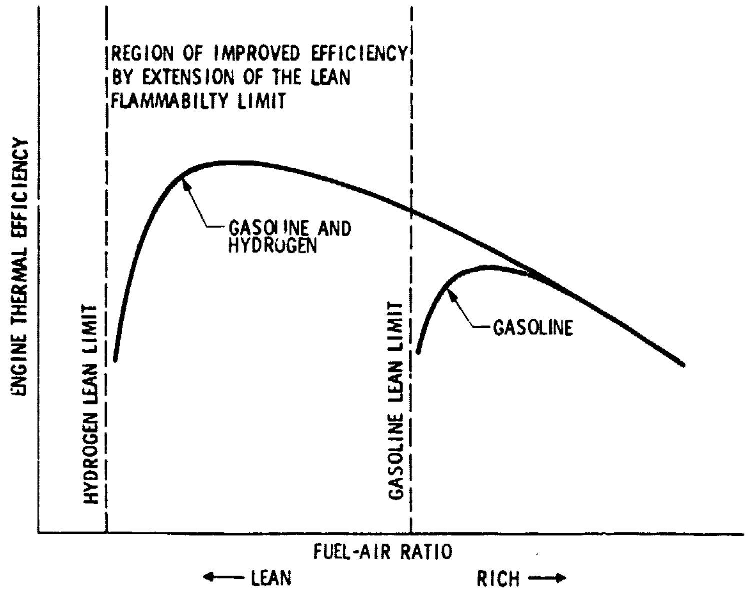


Figure 6-11. Effect of Hydrogen Enrichment on Indicated Thermal Efficiency

in the ultralean region. Actual engine data for equivalence ratios larger than one were available from the manufacturer.

Although not shown in the set of equations (6-1) to (6-8), the engine thermal behavior was studied by means of an independent assessment; the energy availability in the exhaust gases was incorporated in the program for energy balance purposes. Borrowing from experience in the JPL automotive program, the analysis team convinced themselves that when operating ultralean with hydrogen the engine would run considerably cooler, and very important aspects in aircraft engines such as cooling and detonation were therefore excluded by default from the study. In observing Figure 6-10, notice that the spark timing was variable for each data point shown, as well as the throttle position. It will be shown later, that the state of the art in hydrogen enrichment has evolved considerably since those early days, and we will reserve modern findings for later discussion.

3. Results

With the above analysis techniques, engine performance was calculated for a wide range of operating conditions and hydrogen flow rates. Figures 6-12 and 6-13 show BSFC and BHP versus the equivalence ratio for a certain engine speed, altitude and manifold pressure. Figure 6-12 indicates the BSFC estimated for gasoline only (based on what was known about the actual performance of the engine) and the conservative and optimistic cases with 2 lb/hr of hydrogen. Figure 6-13 shows the BHP obtained for different hydrogen flow rates. From these results, it was estimated that the critical altitude for the standard engine was reduced

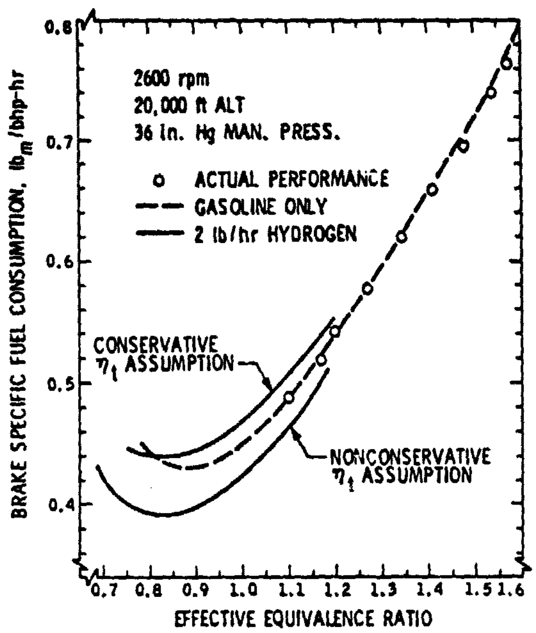


Figure 6-12. Sample Results of Brake Specific Fuel Consumption, With and Without Hydrogen Enrichment

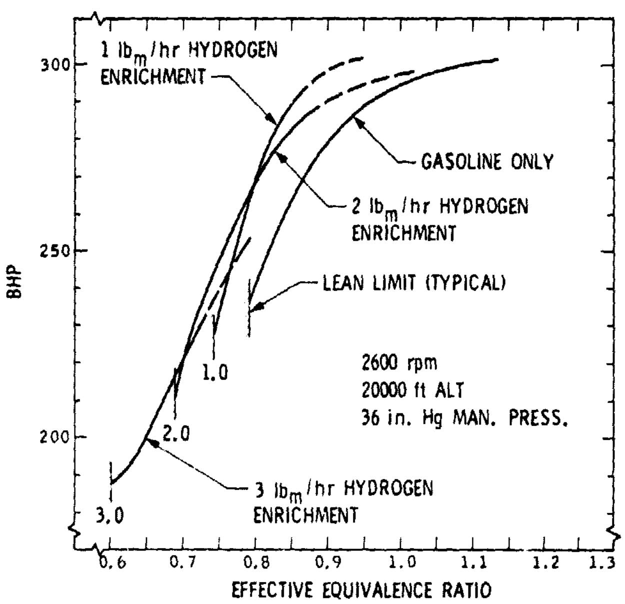


Figure 6-13. Sample Results of Brake Horsepower With and Without Hydrogen

from 30,000 to 25,000 feet because of the power loss penalty incurred when operating the hydrogen generator. BSFCs below 0.4 lb/BHP/hr were obtained for power settings as high as 85% rated power (note that no further check was conducted on engine temperatures). Because of heat losses to the ram air, the hydrogen generator has a fuel conversion efficiency of 80% and a tradeoff analysis showed that for most power settings, 1.5 lb/hr of hydrogen enrichment should result in the simplest technique to achieve optimum fuel economy with constant generator output. The results of Phase I as they apply to the engine/generator assembly are summarized in Table 6-3. We will return later to this Table for final discussion.

4. Aircraft Performance

A Beechcraft computer program was utilized. The program used the engine/generator assembly performance predictions and corrected them for installation losses (accounting for inlet temperature rise, accessory power, engine cooling drag, propeller efficiency, and a specific flight condition). The resulting data were then used in a second Beechcraft program, which combined engine and aircraft characteristics and calculated

Table 6-3. Summary of Results in Phase I

Engine/Generator Assembly
System BSFC's less than 0.4 were found for cruise and climb.
Power could be maintained when leaning at constant rpm and P_{MAN} with hydrogen enrichment.
System critical altitude was reduced from 30,000 ft down to 25,000 ft.
1.5 lb/hr of H_2 could accomplish an almost optimum BSFC at cruise and climb (H_2 generator with constant output).
Engine exhaust temperatures were considered to be cooler than normal when utilizing H_2 enrichment.
Detonation was not determined to be a concern.
Aircraft Performance
Short-range flights showed 24% improvement in fuel economy.
Long-range flights achieved 21% improvement in fuel economy.
Maximum savings were found during climb mode.

aircraft performance. Consideration was given in this program to aircraft weight, aerodynamics and fuel load.

A given flight was separated into four segments: takeoff, climb, cruise and descent. Hydrogen enrichment was not considered during takeoff because of maximum rated power requirements. Substantial fuel savings were estimated during climb with the engine operating at 85% power. The aircraft was assumed to arrive at the desired altitude, level off and cruise at 75% power. It later was assumed to descend at 45% power and shut down. An example of the range profile calculations is given in Figure 6-14. The results illustrated in the figure represent the integration of the aircraft performance characteristics over a given flight envelope. In a typical short flight the standard aircraft has used 100 gallons of fuel against 76 gallons for the hydrogen-enriched aircraft, showing a total savings of 24%. In a long flight a standard aircraft has used 202 gallons while the same flight is achieved with 160 gallons by the hydrogen-enriched aircraft, a 21% savings. The dashed lines show an alternative way to show the results, that is, an increase in range for the same amount of fuel.

5. Exhaust Emissions

Using the results observed for automotive engines, an attempt was made to estimate the emissions for a hydrogen-enriched engine. The emissions were calculated for the 5-mode cycle as specified in the Federal Register of July 17, 1973. It was concluded that the standard engine, when operated in the usual manner, could not meet the standards while the hydrogen-enriched configuration could do so comfortably. Table 6-4 summarizes the results.

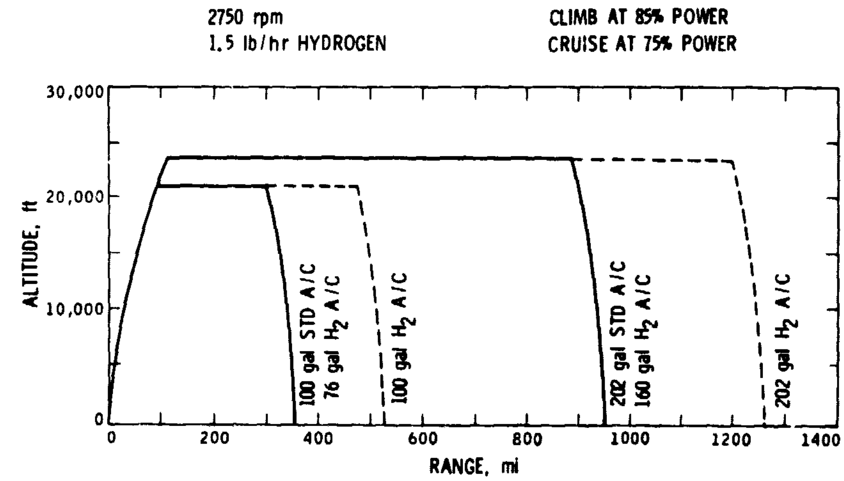


Figure 6-14. Range Profiles With and Without Hydrogen Enrichment

Table 6-4. Emission Estimate for a T10-541 Engine With and Without Hydrogen Enrichment

A. Standard Engine

Mode	Air/Fuel Ratio	ϕ	Emission Rate, g/ihp-h			Pollutant Produced, g		
			NO_x	HC	CO	NO_x	HC	CO
Taxi-Idle (out)	8.7	1.66	.36	26	340	2.92	210.9	2757
Takeoff	10.6	1.36	2.3	3.1	120	4.90	6.6	256
Climbout (rich)	10.4	1.39	1.9	3.5	135	52.6	96.8	3735
Approach	8.7	1.66	.36	26	340	7.21	520.5	6807
Taxi-idle (in)	8.4	1.72	.25	70	400	.60	166.6	952
Total Pollutant Produced/Cycle, g						68.2	1001.4	14,507
Fraction of Allowable Standard						0.26	3.06	2.00

B. Engine With Hydrogen Enrichment

Mode	Air/Fuel Ratio	ϕ	Emission Rate, g/ihp-h			Pollutant Produced per Mode, g		
			NO_x	HC	CO	NO_x	HC	CO
Taxi-Idle (out)	24.1	0.6	1.2	4.0	7.4	9.73	32.4	60
Takeoff	10.6	1.36	2.3	3.1	120.0	4.90	3.1	256
Climb (option)	20.6	0.7	6.0	3.0	4.5	166.0	83.0	125
Approach	24.1	0.6	1.2	4.0	7.4	24.0	80.1	148
Taxi-idle (in)	24.1	0.6	1.2	4.0	7.4	2.9	9.5	18
Total Pollutant Produced/Cycle, g						207.5	208.1	607
Fraction of Allowable Standard						.80	.64	.08

6. Naturally Aspirated Aircraft

Hydrogen enrichment schemes for naturally aspirated aircraft were also analyzed. It was found that no major obstacles were encountered in hydrogen enrichment application to this type of engine. Fuel savings comparable to those obtained for the turbocharged engine were calculated, although a reduction in power was encountered for each throttle setting because of the operation of the hydrogen generator, which translated in reduced altitudes and speeds.

7. Summary

We would like to end this discussion of Phase I by pointing out that the results obtained in this assessment were encouraging enough to justify proceeding to Phase II of the program. There were, however, very important assumptions that had to be verified experimentally.

G. PHASE II - EXPERIMENTAL INVESTIGATION IN THE TEST CELL

The overall objective of this phase of the program was to experimentally investigate and verify with test cell experiments the results obtained in Phase I. The specific objectives set at the beginning of Phase II were:

(1) Establish, as a baseline, the power and fuel consumption characteristics of the AVCO-Lycoming-TIO-E1A4 engine when conventionally operating.

(2) Install and operate a laboratory model hydrogen generator

(3) Install and operate a high-performance, compact, lightweight hydrogen generator (designed and fabricated by JPL) that is capable of integration into the aircraft/engine structure and suitable for flight testing, and evaluate the influence of hydrogen enrichment on specific fuel consumption and performance of the engine/generator assembly system in flight configuration. This generator design was also intended for use in Phase III flight tests.

(4) Examine the influence of hydrogen enrichment on exhaust pollutant output.

(5) Investigate ultralean burning with gasoline only.

During this phase of the program, the emphasis was placed on exploring the potential of hydrogen enrichment for fuel economy improvement. The early stages of this phase were characterized by a fast learning rate, and the experimental activities were frequently tailored to accomplish the objectives with the benefit of accumulated experience. In the later stages of Phase II, the engine/generator assembly in flight configuration was firmed up and underwent flight qualification, anticipating the imminent move to Phase III.

The results of Phase II have been published previously in References 6-9, 6-10, 6-11. For a broad and detailed description of the facility and methods, Reference 6-10 is recommended. A full discussion of the results is presented in Reference 6-9, while the point of view of the airframe manufacturer can be seen in Reference 6-11.

1. Experimental

The experiments were conducted in the AVCO-Lycoming facility in Williamsport, Pennsylvania. A Lycoming TIO-541-E1A4 engine was equipped with a JPL hydrogen generator and tested on dynamometer and flight stands.

a. Engine. The engine has been described in Section VI-D.

b. Hydrogen Generators. For the purpose of this program, two hydrogen generator models were designed, fabricated and tested. One type was strictly a laboratory generator; the other was a flight model. The laboratory generator was based on a previous JPL design and required minimal development. It was used for the dynamometer experiments. While such experiments were in progress, two lightweight flight generators were built and qualified for the upcoming flight program of Phase III. Some features of the hydrogen generators can be found in References 6-9 and 6-10, and detailed descriptions are given in References 6-12 (laboratory generator), 6-13 (flight generator) and 6-14.

The laboratory generator was designed for independent control of air and fuel flow, with the capability of producing as high as 3-1/2 lb/hr of hydrogen output. The flight generator version was developed to provide the required hydrogen enrichment rate for the flight phase of the program. It consisted of a cylinderlike body 10 inches in diameter and 14 inches long. The generator weighed 30 lb and the lines and valves associated with it an additional 25 lb. This generator could deliver up to 3 lb/hr of hydrogen with a pressure drop of about 2.5 psi across it. The salient feature of the flight generator was the use of monolith catalyst, never tried before for these purposes, and introduced here in an attempt to overcome the undesirable effects of engine vibration on pellet-type catalysts.

c. Laboratory Generator/Assembly. The engine and the laboratory generator were coupled in a configuration that would allow systematic evaluation of the merits of hydrogen enrichment techniques. A simplified schematic diagram of the arrangement can be seen in Figure 6-15. The air to run the generator was bled from the sonic nozzle located near the compressor discharge. An auxiliary compressor and heat exchanger were used to make up for the pressure losses inherent in the generator system. Fuel to run the generator was taken from the fuel line to the engine, between the fuel meter and the engine fuel pump. The heat

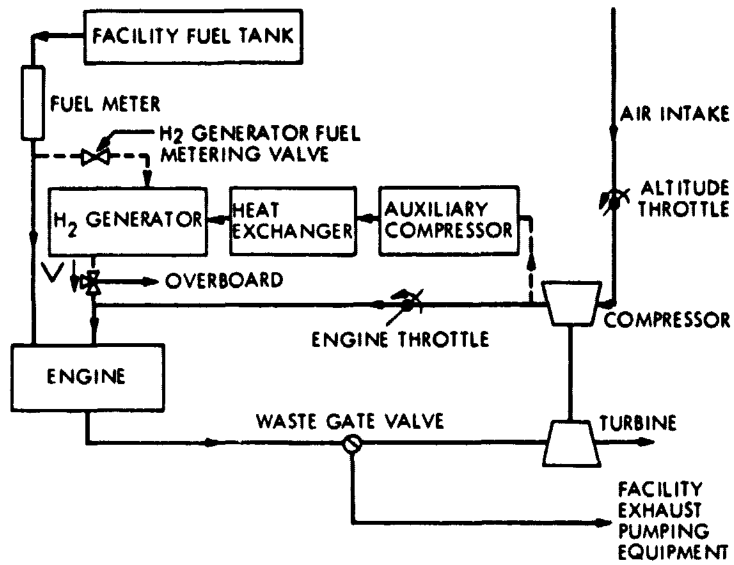


Figure 6-15. Schematic Flow Diagram for the Laboratory Generator-Engine Setup on the Dynamometer Stand

exchanger was required to cool the air at the exit of the auxiliary compressor unit. The generator product gases were introduced into the engine by means of a specially designed auxiliary spider that fits on top of the engine intake manifold and distributes the hydrogen-enriched gases evenly to each cylinder. The generator output was injected into each intake pipe a few inches downstream of the intake manifold. A fine screen filter with a low pressure drop was positioned between the generator and the engine for the purpose of capturing fines washed down from the generator catalyst bed by the product gases. The valving system was used to divert the generator product gases into the engine or out to the test cell room as desired.

The engine was installed on the dynamometer stand in the conventional manner. The generator was located in a rack in the test cell, a few feet away from the engine. The generator was monitored and operated by a control console fabricated by JPL, and its product gases analyzed by a gas chromatograph located in proximity to the cell. The Lycoming facility has the ability to simulate pressure altitude at the engine intake and exhaust ports. The engine is cooled by means of forced convection provided by a hood installed on the engine which receives forced air from a fan. During steady-state operation, the facility fuel meter indicated the total fuel flow to the generator and the engine, and analogously, the facility air flow meter registered the total amount of air going through the engine and the generator. Additional instrumentation allowed individual fuel and air readings for the generator. For the purpose of isolating the effects of hydrogen enrichment when the engine was operated with gasoline only under ultralean conditions, air would be diverted from the main stream, passed through the generator, and on to the engine. This procedure practically reproduced the same pressure profile through the system when running with or without hydrogen.

Modification of the spark advance was accomplished by physically pulling the magneto breakers out, rotating them to the desired angle, and then refitting them back into the magneto. This was an awkward method and, indeed, it considerably limited the operational procedures but, within the scope of the program, it was considered satisfactory for the purpose of investigating the ignition timing effects.

d. Engine/Flight Generator Assembly. The flight generator was coupled to the engine in the flight configuration and the whole assembly installed on the flight test stand. This facility is similar to the dynamometer facility in many respects. The main differences are that a propeller has been installed on the engine and the power is measured by means of a torquemeter. Figure 6-16 shows a schematic diagram of the assembly as well as the location of the controls to operate the generator and the instrumentation to monitor it. Notice that the pressure gradient in the air system necessary to operate the generator was obtained from the pressure drop across the engine throttle, eliminating the need for an auxiliary air pump. However, the generator fuel atomizer was activated by a small, electrically operated air pump which bled air from the generator intake system, then pressurized and injected it into the atomizer. Notice also that the engine exhaust gases could be diverted by means of valve EV, into the generator intake system, for the purposes of warming up or cooling down the generator. This flow circuit was activated by simultaneously closing the air valve AV1 and opening the exhaust valve EV. For steady-state operation of the engine, the engine throttle was set at an angle which established a pressure difference across it. As the air valve AV1 was opened, air was diverted into the generator and regulated by the generator throttle. This air was injected into the generator through two different ports as controlled by the 3-way valve AV2 and determined by the desired amount of preheat in the air/fuel mixture. The air was then passed into a mixing duct containing the fuel atomizer, where a homogeneous mixture was formed. The mixture was then diverted via distribution ducts to the top of the generator and into the catalyst bed where it finally exited the generator through the bottom outlet. The path of the generator products (either to atmosphere exhaust or to the engine) was controlled by valves PV1 and PV2, which were coupled together for their operation. A relief valve located at the top of the generator protected the system from overpressures. The generator fuel system consisted of a flow metering valve, a flow meter and a solenoid valve FV. Some modifications in the exhaust pipe and engine mount were necessary to accommodate the generator. The valves and plumbing were mounted on the engine by means of auxiliary brackets, and a screen filter was introduced into the generator product spider for protecting the engine from catalyst fines.

e. Instrumentation. The standard Lycoming instrumentation for the characterization and calibration of engines was used for this program, see Reference 6-10. It is worth mentioning, however, that the torquemeter used in the flight test stand experiments was calibrated against the dynamometer, and, during certain critical detonation checks, specialized Lycoming detonation equipment was installed on the engine to monitor incipient or severe detonation. Emission measurements conducted on the flight test stand were obtained with Lycoming

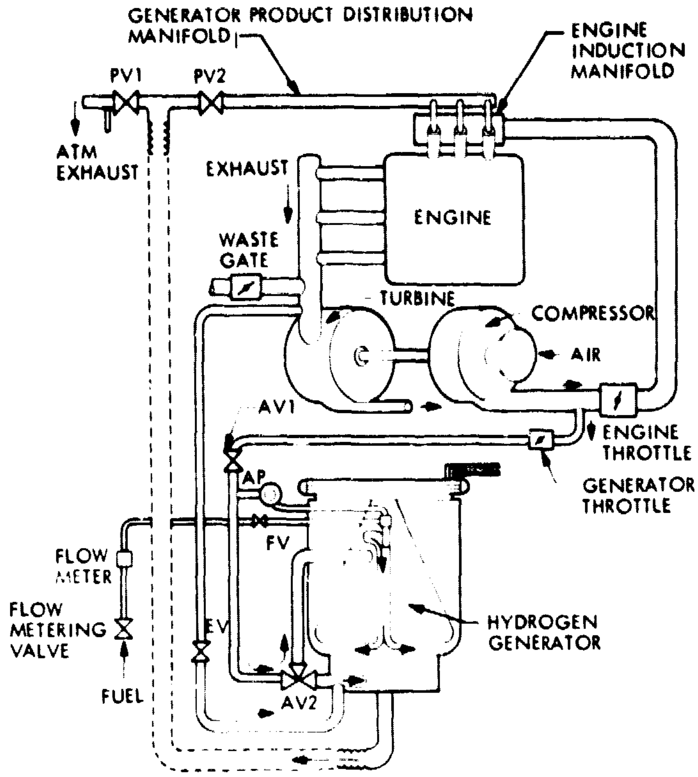


Figure 6-16. Schematic Diagram of the Flight Generator-Engine Assembly

emissions equipment which measured NOx, CO, HC, O_2, and CO_2. The hydrogen generator was equipped with adequate instrumentation to monitor the pressure and temperature field of the generator and its interface with the engine. The amount of hydrogen injected in the engine was calculated from the measured fuel/air flow rates and was verified by gas chromatograph measurements. Automatic data acquisition systems were not available at Lycoming, and all the readings were taken by hand using Lycoming standard procedures. Over 80 different parameters were recorded for every engine operating point.

2. Results

With the dynamometer test stand setup described above, a matrix of cases was investigated that unraveled the essence of the ultralean burning and hydrogen enrichment effects. Baseline data for the engine was obtained to serve as a frame of reference for all the subsequent investigations. To bring out the salient features of ultralean burning, leanout curves were obtained at constant engine speed and manifold pressures. A typical leanout curve is shown in Figure 6-17. The figure shows a plot of the BSFC, brake horsepower, and turbine inlet temperature vs the equivalence ratio. These curves in particular were obtained with the unmodified engine. The engine would be started, warmed up, and set at a predetermined

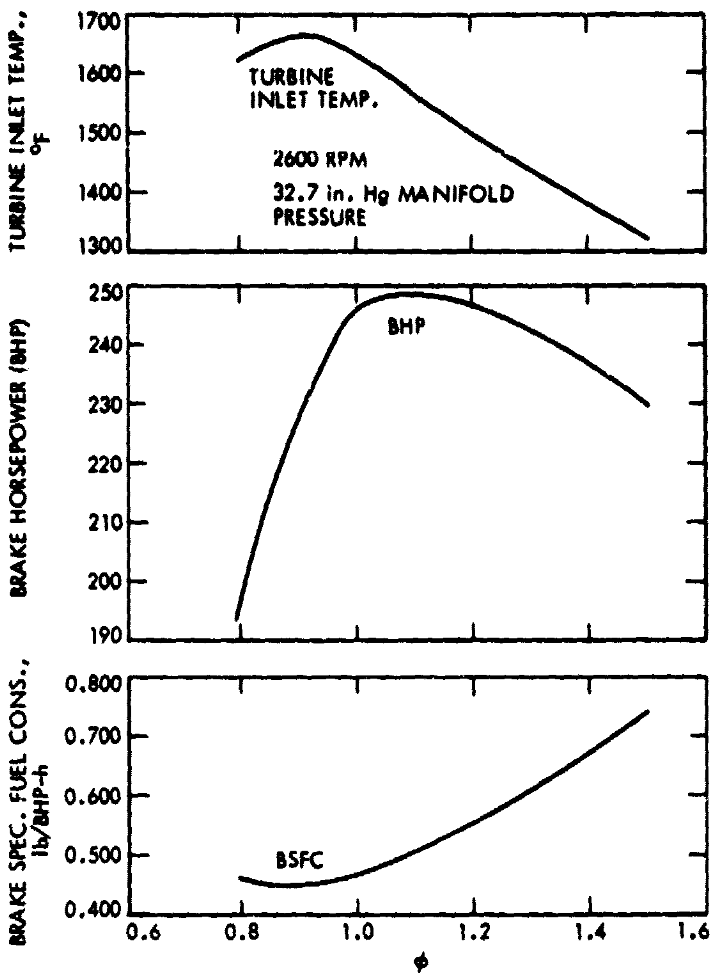


Figure 6-17. Brake Specific Fuel Consumption CBSFC, Brake Horsepower, and Turbine Inlet Temperature Leanout Curves for the Unmodified Engine at 2600 rpm and 32.7 in. Hg Manifold Pressure at Sea Level

speed (2600 rpm), a full-rich mixture setting, a certain manifold pressure (32.7 in. Hg), and a certain altitude (sea level in this case). Locking all the controls, the mixture control lever would be operated and the mixture leaned until engine misfiring was evident. These leanout curves were described typically by five operating points, although under certain conditions where overheating was a problem it was necessary to lean quickly through the peak Turbine Inlet Temperature (TIT) region (around equivalence ratio 1.0), and no data were recorded.

Table 6-5 gives a summary of the engine regimes explored thoroughly, and which were selected because they describe well-established operating conditions where a large amount of experience in present engines is available. Only a partial set of results will be given here. A more comprehensive reporting of the data can be found in Reference 6-10.

Table 6-5. Range of Explored Variables

Hydrogen enrichment flow rate, lb/hr	1.0	1.75	2.0	3.0		
Manifold pressure, in. Hg	32.7	36.0	38.0	39.0	41.0	
Spark advance, °BTC	20	30	35			
Engine speed, rpm	2600	2750				
Altitude, ft	3000	6000	8000	9000	11000	16000
Emissions	CO	HC	NO_x			

Figure 6-18 shows a set of leanout curves for an engine speed of 2750 rpm, a manifold pressure of 39 in. Hg (corresponding to the standard 85% rated power setting), 20° spark advance (standard), with gasoline only (solid line), and with 1.75 lb/hr of hydrogen enrichment (dashed line). During the leanout, the redline temperature of the turbine (1650°F) was reached and the data recording had to be interrupted to be resumed on the lean side until misfiring occurred at an equivalence ratio of about 0.7. It was noticed that misfiring was notably retarded when hydrogen was used. Note in the figure, that on the rich side of the BSFC curves, hydrogen enrichment shows a higher value than with gasoline only, and this behavior is maintained all the way to and beyond the minimum BSFC , where the hydrogen enrichment curve crosses below the gasoline-only curve because of its flatter valley. It is also evident the in the minimum BSFC region the turbine inlet temperature reaches its maximum, which makes it impossible to operate the engine at that point for long periods of time.

Figure 6-19 shows the same conditions with 30° spark advance, and Figure 6-20 compares the gasoline-only cases of Figures 6-18 and 6-19. From Figure 6-19, it can be seen that advancing the spark has displaced the minimum BSFC to leaner equivalence ratios and has lowered its value. This effect can be best observed in Figure 6-20, where the power and turbine inlet temperature curves are also shown for convenience. Power is improved with spark advance in the ultralean region, and the turbine inlet temperature has decreased considerably while its peak remains at $\phi = 0.9$. In Figure 6-18, one can appreciate that, with hydrogen enrichment, lower power, higher BSFC and lower turbine inlet temperatures are obtained. In Figure 6-21 are displayed the cylinder

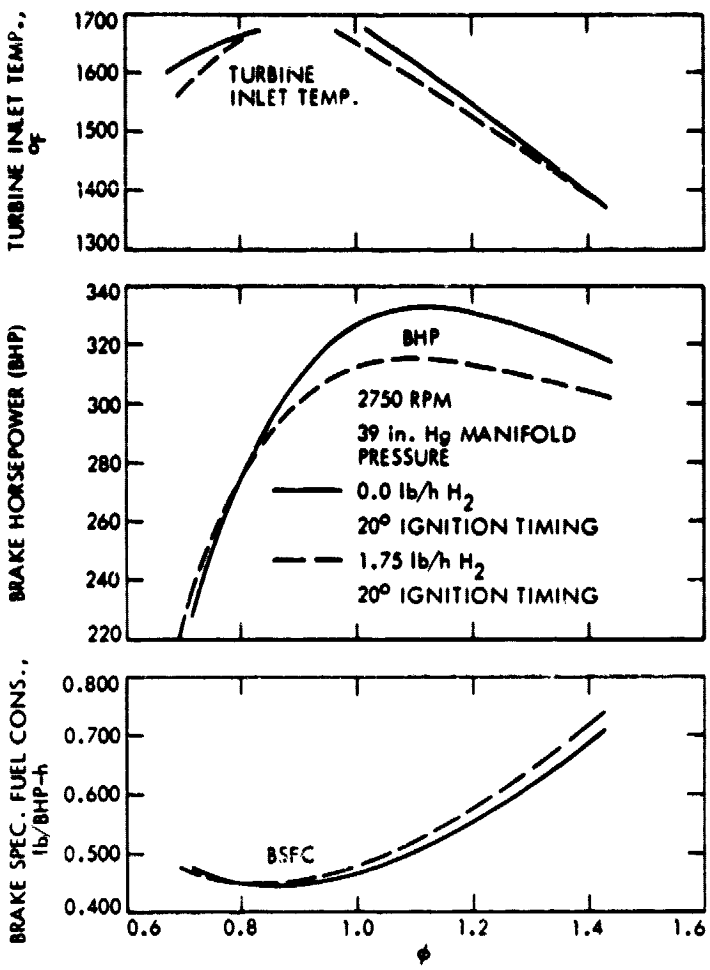


Figure 6-18. Leanout Curves for 2750 rpm, 20° S.A. and 39 in. Hg Manifold Pressure for Gasoline Only and for 1.75 lb/hr Hydrogen Enrichment

head temperatures for the four cases just described, and it is obvious, as expected, that increased spark advance gives higher cylinder head temperatures than those at 20° in the ultralean region. These curves were obtained keeping all other parameters equal, and they eloquently illustrate the phenomenological aspects of ultralean combustion on engine temperature with and without hydrogen enrichment and with variable spark advance.

Experiments with a manifold pressure of 36 in. Hg were similarly performed (Figures 6-22 through 6-25) and the results behave in the same manner as the ones just described. Notice that because of the lower manifold pressure setting, the engine overheating is not as severe in the turbine inlet temperature peak region, which remains at $\phi = 0.9$. Figures 6-25 through 6-29 show comparison for 32.7 in. Hg manifold pressure at 2600 rpm with 20° and 30° spark advance.

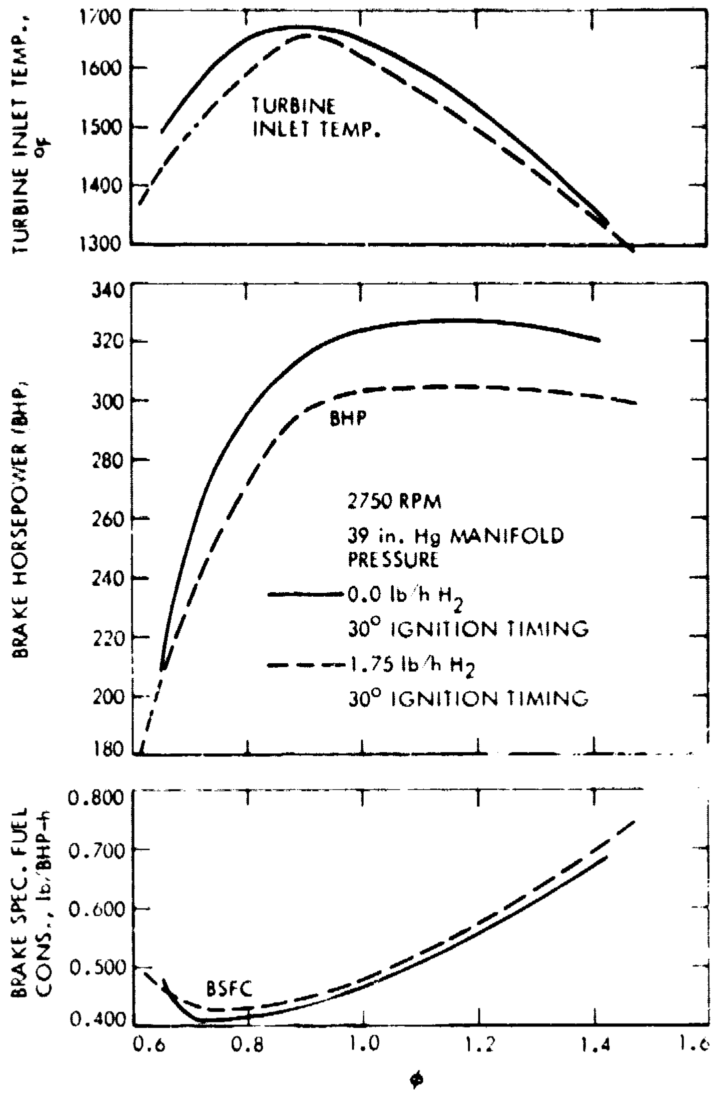


Figure 6-19. Leanout Curves for 2750 rpm, 30° S.A. and 39 in. Hg Manifold Pressure for Gasoline Only and for 1.75 lb/hr Hydrogen Enrichment

The most promising feature observed was that advancing the spark shifted the minimum BSFC toward leaner regions than the peak of cylinder head and turbine inlet temperatures, providing then a possibility to operate at the best economy point without overheating the engine. Except for misfiring at equivalence ratios lower than the minimum BSFC point, no difficulties were encountered while operating the engine ultralean. The laboratory hydrogen generator performed smoothly under steady-state condition. but was difficult to control during the air and fuel flow transients introduced when engine conditions were changed. On two occasions the generator Inconel liner was overheated and damaged.

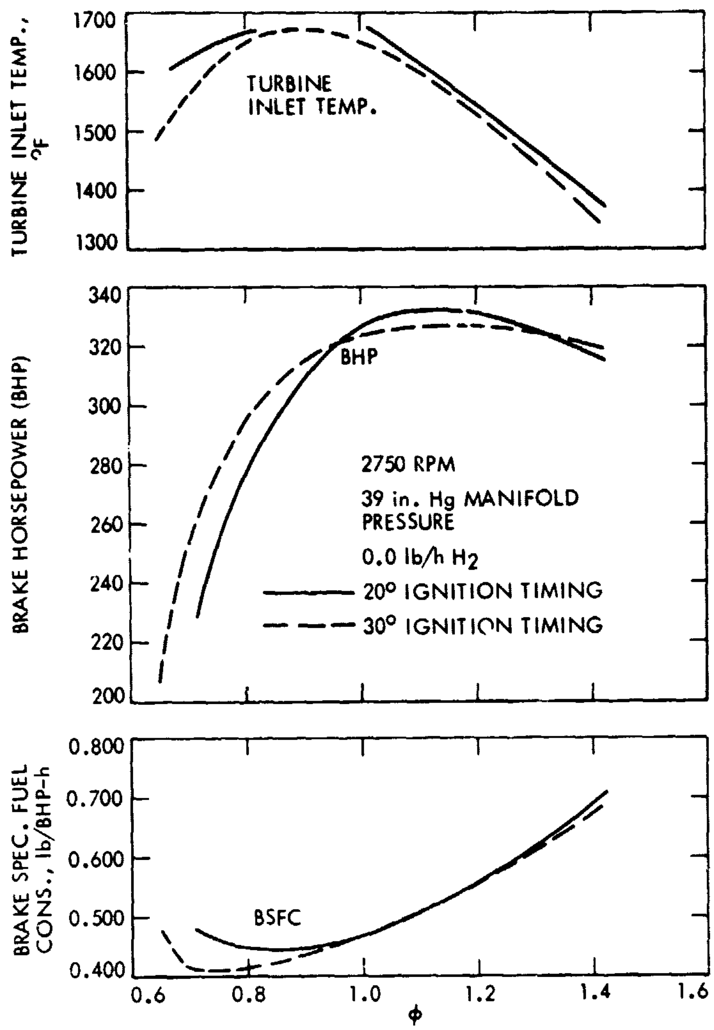


Figure 6-20. Leanout Curves for 2750 rpm, 39 in. Hg Manifold Pressure with Gasoline Only for 20 and 30° S.A.

While conducting the experiments, it became evident that there was no difficulty in leaning the engine with gasoline only down to an equivalence ratio as low as 0.65. This made it most attractive since it was also found that the minimum BSFC with gasoline only was coming to be lower than the one obtained with hydrogen enrichment, while all the other variables were kept equal.

One problem still remaining to be overcome was the loss in power experienced when operating at the minimum BSFC with the correct spark advance. To this end, and taking an engine speed of 2600 rpm as a representative case, the leanout curves shown in Figure 6-28 were repeated at 36 in. Hg. The results are shown in Figures 6-30 and 6-31. The most interesting feature is that the BSFC at 36 in. Hg almost coincides with the BSFC at 32.7 in. Hg, while the power curve is considerably higher. The cylinder head and turbine inlet temperatures have increased slightly, but

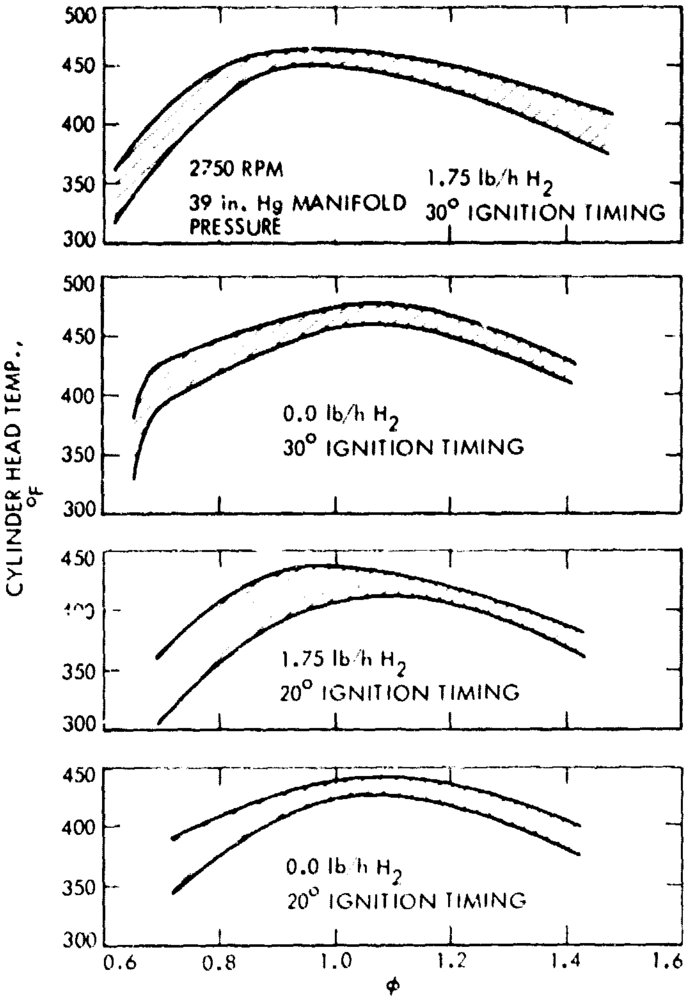


Figure 6-21. Cylinder Head Temperatures for the Cases Shown in Figures 6-18 and 6-19

they are still at reasonable levels at the minimum BSFC point. This behavior suggests a technique for recovering power during ultralean operation.

If the engine conditions at the minimum BSFC point are compared with the equal power point used on the rich side, where the engine presently operates, the difference is a substantial improvement in BSFC of nearly 20%, and equal or lower temperatures. The only disadvantage is the running of the engine at higher manifold pressure, which, while it does not constitute any difficulty at sea level (notice that all the curves described above were obtained at sea level), will impact the critical altitude. In addition, the higher operating manifold temperature and pressure could possibly cause difficulties in cooling the engine at altitude. Several simulated altitude checks were conducted to verify the capability of the turbocharger to cope with the power recovery techniques

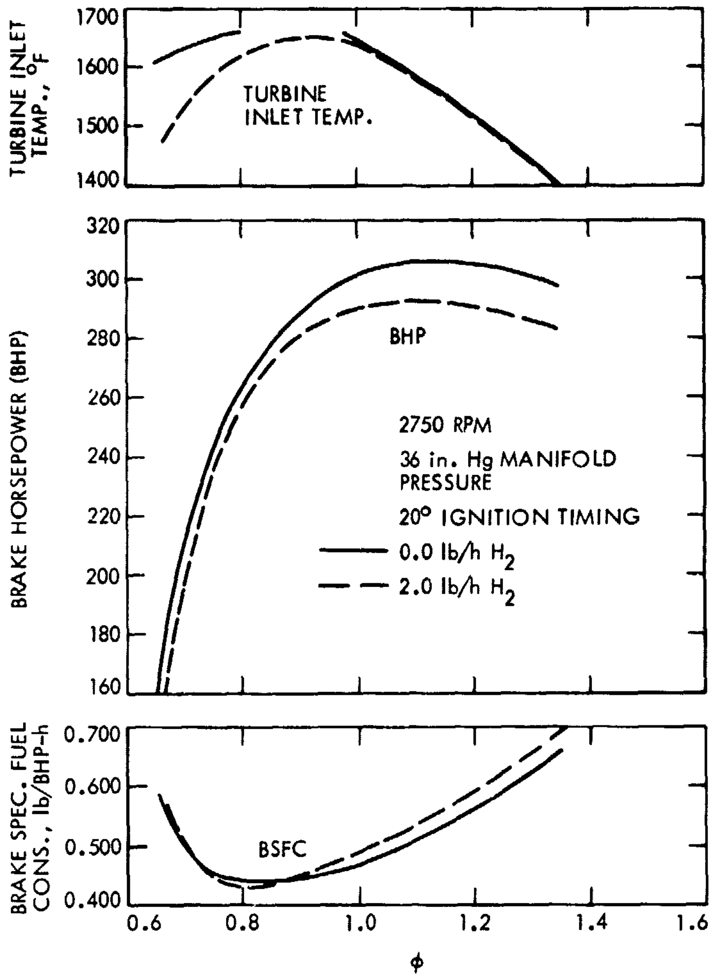


Figure 6-22. Leanout Curves for 2750 rpm, 20° S.A. and 36 in. Hg Manifold Pressure for Gasoline Only and 2.0 lb/hr Hydrogen Enrichment

described above, as well as the temperature excursions with altitude. Representative results are shown in Figures 6-32 and 6-33. The figures illustrate the results at 16,000 ft of leaning-out the engine at 2600 rpm, with a 30° spark advance, and 39.9 in. Hg manifold pressure. While the performance of the engine at the minimum BSFC was acceptable, some detonation was induced when leaning-out through equivalence ratio 1.0. This detonation was suspected of causing damage to the engine during the few seconds that it was exposed to this severe operation.

Further experiments were conducted on the flight test stand to qualify the hydrogen generator flight model assembly, obtain engine performance data and get some emission measurements. A 15-hr endurance test was performed on the hydrogen generator. At the end of the test the integrity of the hardware was considered adequate for the follow-on

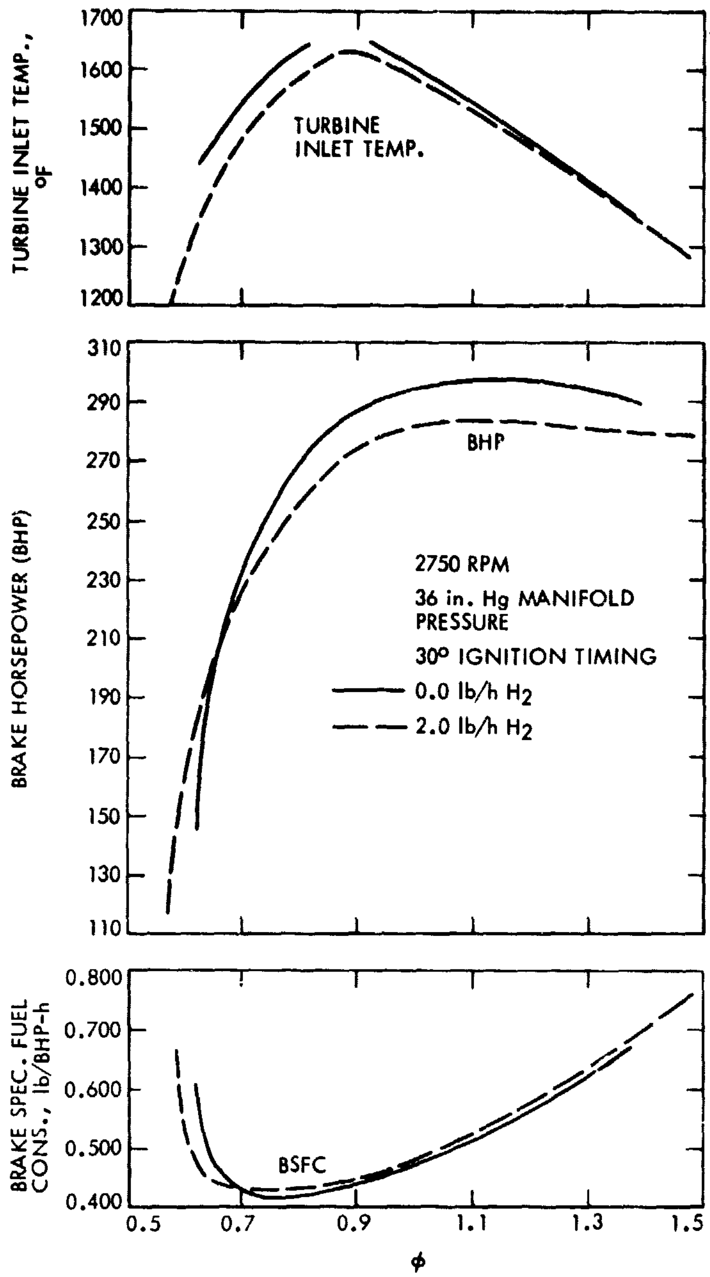


Figure 6-23. Leanout Curves for 2750 rpm, 30° S.A. and 36 in. Hg Manifold Pressure for Gasoline Only and 2.0 lb/hr Hydrogen Enrichment

flight test phase of the program. The monolithic catalyst of the generator, however, was damaged by soot accumulated because of malfunction of thermal controls when the generator was operated at too rich fuel/air ratios.

The endurance test was followed by exhaust emissions and engine performance measurements. Some of the results are shown in Figures 6-34

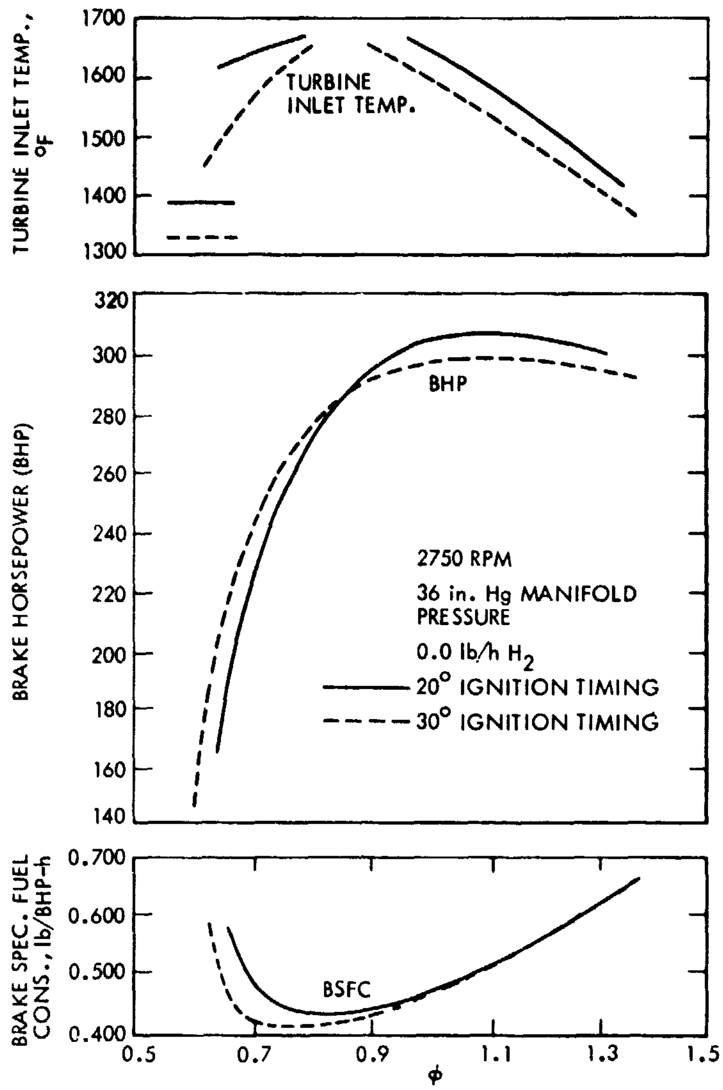


Figure 6-24. Leanout Curves for 2750 rpm, 36 in. Hg Manifold Pressure with Gasoline Only for 20 and 30° S.A.

and 6-35. The figures illustrate a case in which the engine was operated at 2600 rpm with different spark advances and two different manifold pressures. One set of data taken with hydrogen enrichment is also shown. The same features observed in the dynamometer stand can be seen now in Figure 6-34, except that the minimum BSFC reaches as low as 0.391 lb/bhp-h, while the power level goes as high as 69% of the rated takeoff power. Notice that the temperatures are in all cases kept below the redline levels in the ultralean region. Observe that the emissions, as normalized by the brake horsepower, are fairly well correlated until the ultralean region is reached. In this region the curves change their pattern and the CO and HC values begin to increase. The NOx curve does not decrease in the lean region as fast as would be expected from past automotive

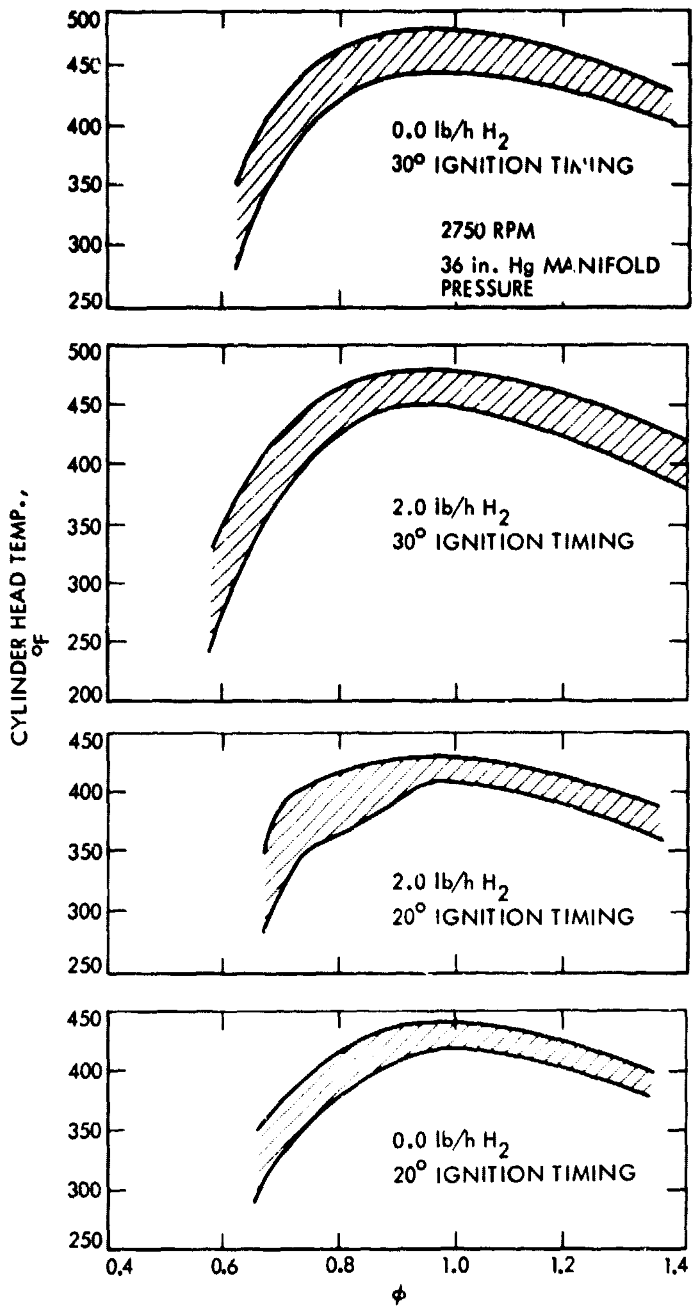


Figure 6-25. Cylinder Head Temperatures for the Cases Shown in Figures 6-22 and 6-24

experience (Reference 5-9). Notice also that the HC curves are the most sensitive to the ignition timing. The behavior for the hydrogen enrichment curve is quite similar to the others except for a lower contribution to CO and the higher HC reading, which is similar to the results obtained in automotive work (see Reference 5-24).

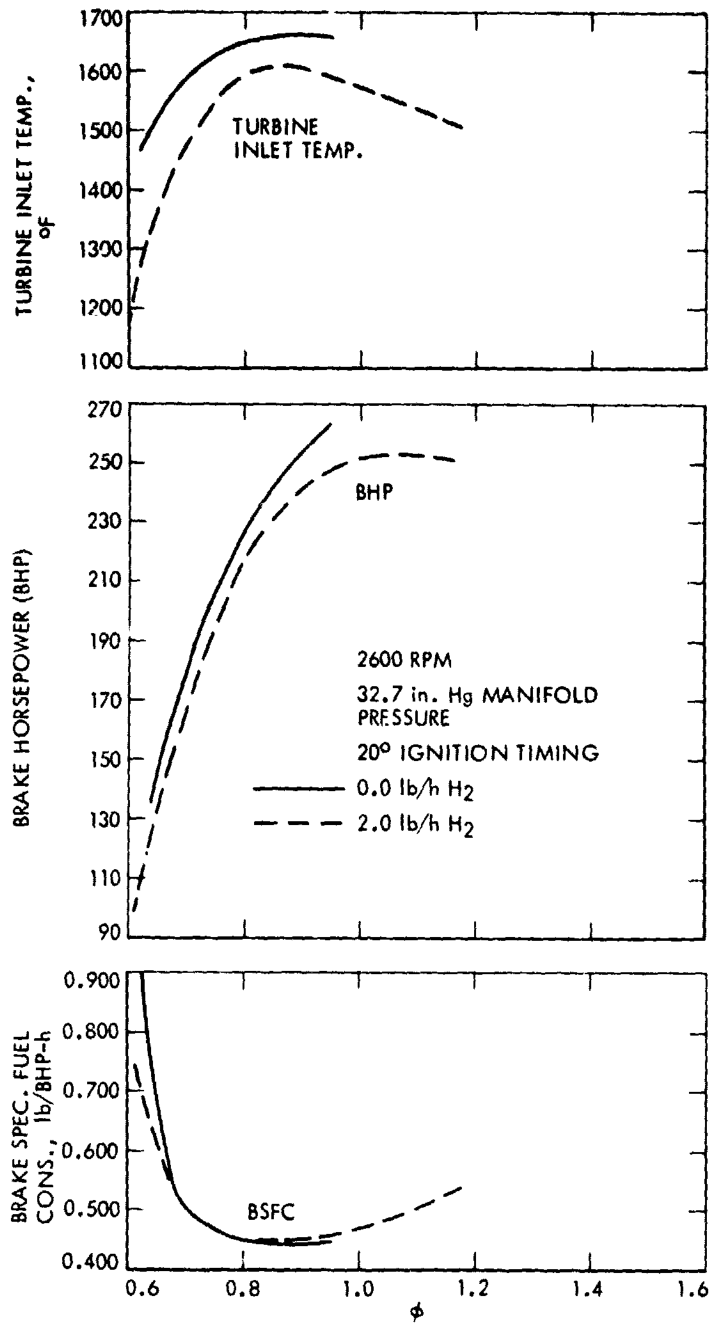


Figure 6-26. Leanout Curves for 2600 rpm, 20° S.A. and 32.7 in. Hg Manifold Pressure for Gasoline Only and 2.0 lb/hr Hydrogen Enrichment

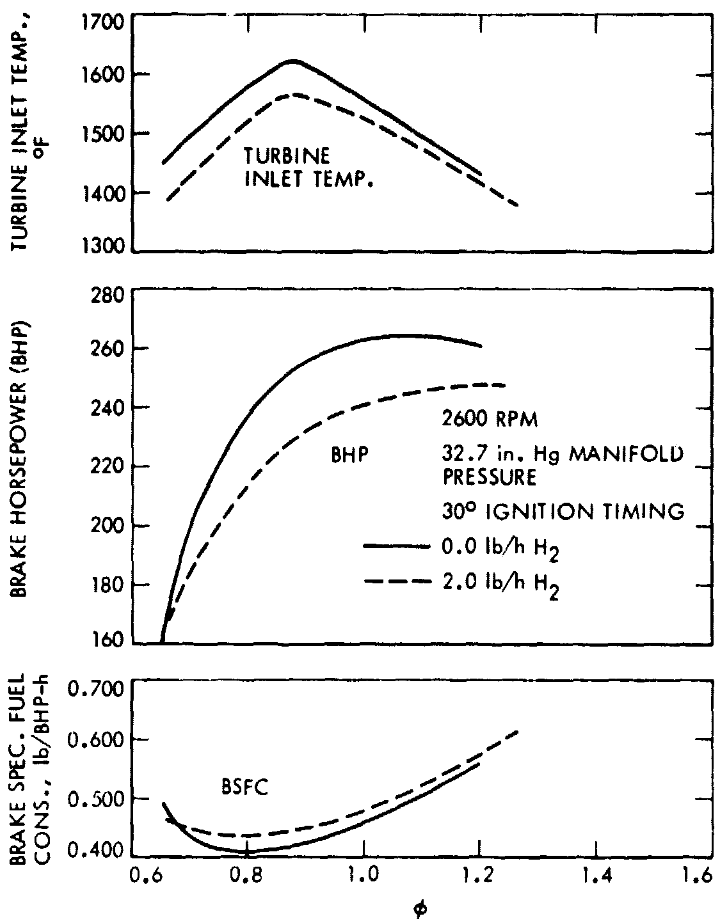


Figure 6-27. Leanout Curves for 2600 rpm, 30° S.A. and 32.7 in. Hg Manifold Pressure for Gasoline Only and 2.0 lb/hr Hydrogen Enrichment

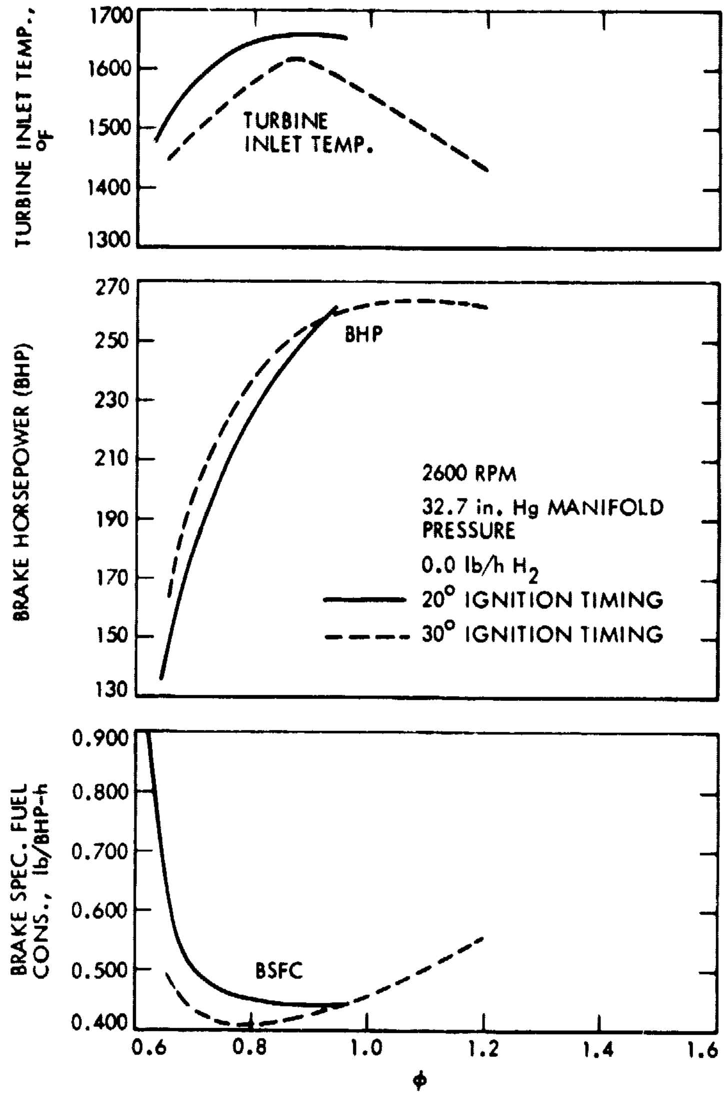


Figure 6-28. **Leanout Curves for 2600 rpm, 32.7 in. Hg Manifold Pressure** with Gasoline Only for 20° and 30° S.A.

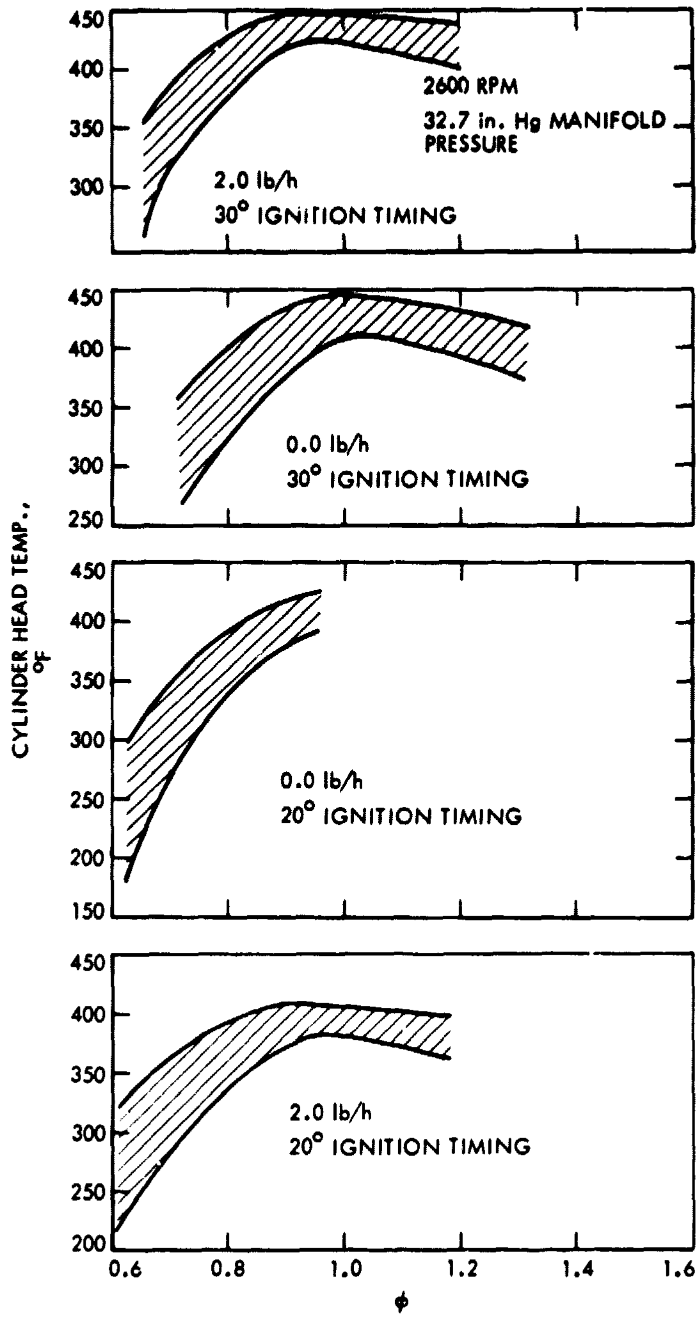


Figure 6-29. Cylinder Head Temperatures for the Cases Shown in Figures 6-26 and 6-27

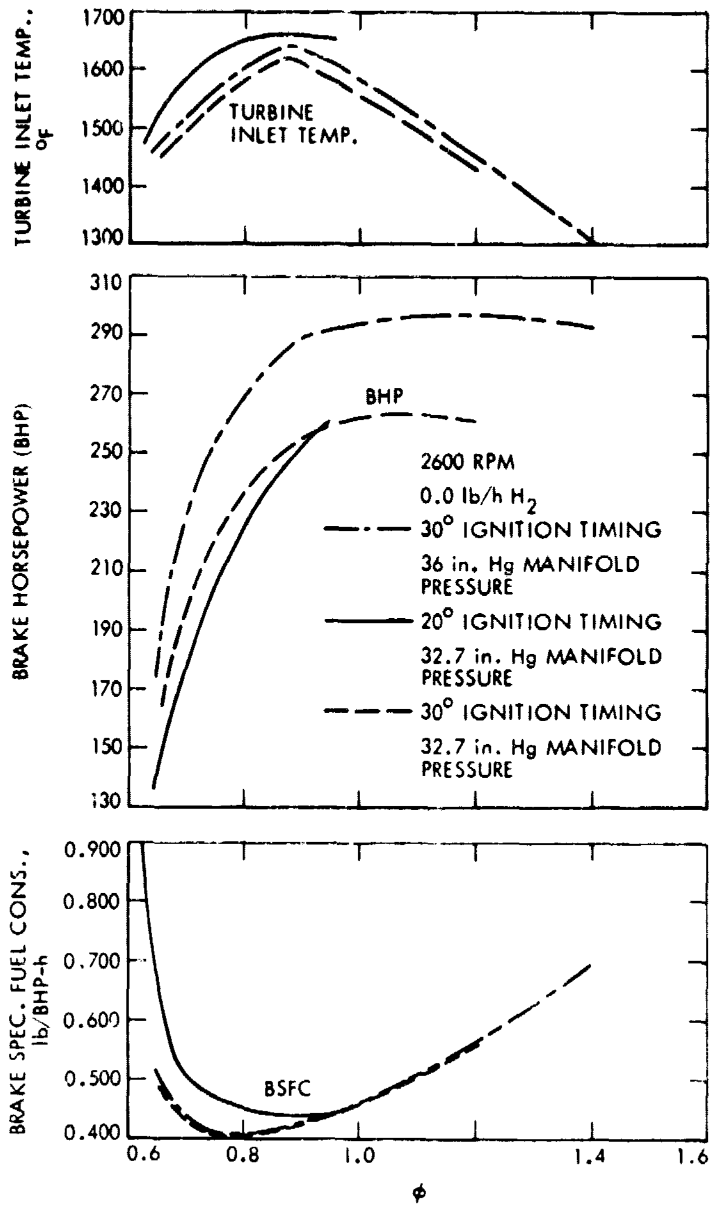


Figure 6-30. Leanout Curves for 2600 rpm, 36 in. Hg Manifold Pressure, 30° S.A. with Gasoline Only. The Results of Figure 21 Are Also Shown for Conver ence

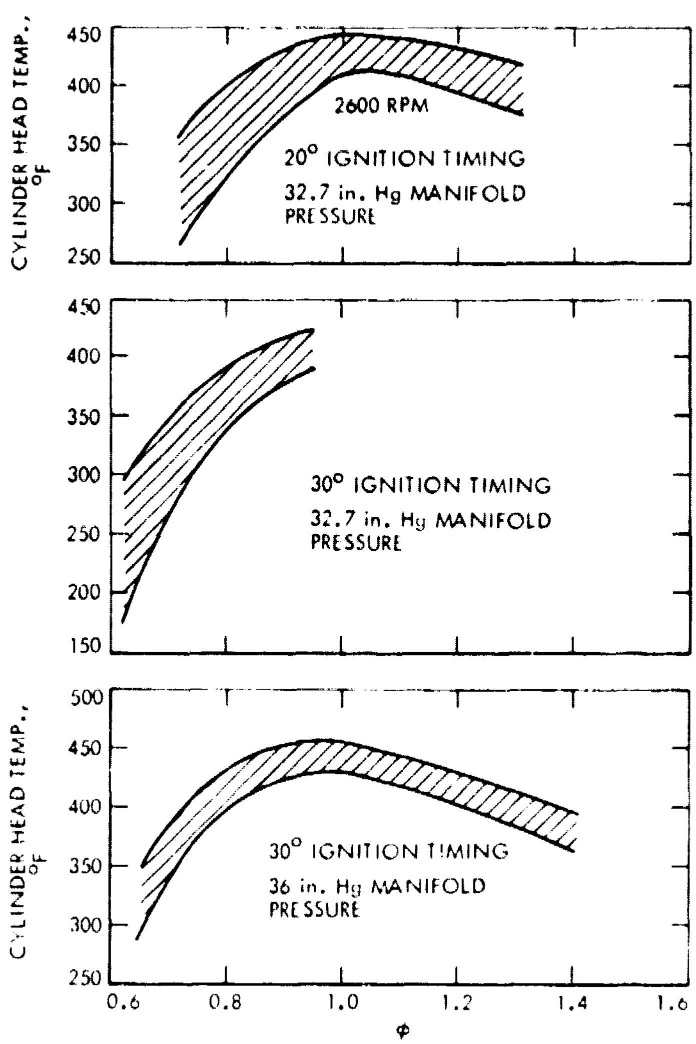


Figure 6-31. Cylinder Head Temperatures for the Case Shown in Figure 6-30

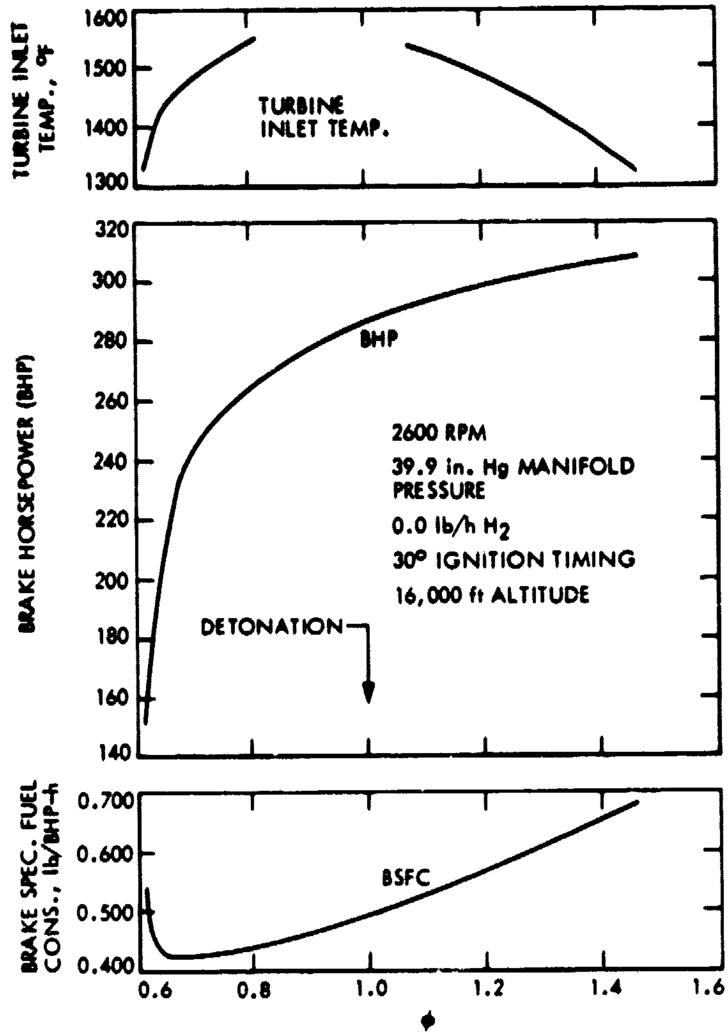


Figure 6-32. Leanout Curves for 16,000-ft. Altitude, 2600 rpm, 39.9 in. Hg Manifold Pressure and 30° S.A. for Gasoline

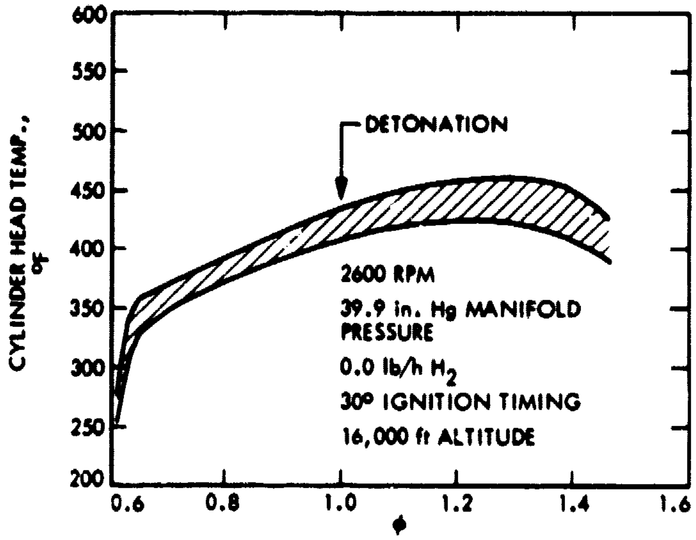


Figure 6-33. Cylinder Head Temperatures for the Case Shown in Figure 6-32

3. Discussion of Results

The results obtained in this laboratory investigation, although not as conclusive as results from a flight demonstration, do show several interesting characteristics of ultralean combustion, and suggest new capabilities for present engines. In the first place, it was found that the engine tested could be leaned out considerably further than was believed possible with gasoline only, if the proper spark advance was used. As has been discussed, spark advance will increase the residence time of the flame in the cylinders, and thus increase cylinder head temperatures (see in Figures 6-21, 6-25 and 6-29). On the other hand, since the combustion is more nearly completed before the exhaust stroke, the exhaust gas temperature will decrease when the spark is advanced. This effect can also be observed in Figures 6-20, 6-26, 6-28 and 6-29. Of special significance is the very low BSFC values obtained in the ultralean region when the spark timing is advanced, as well as the remarkable decrease in turbine inlet temperatures and reasonably low cylinder head temperatures (see Figure 6-36).

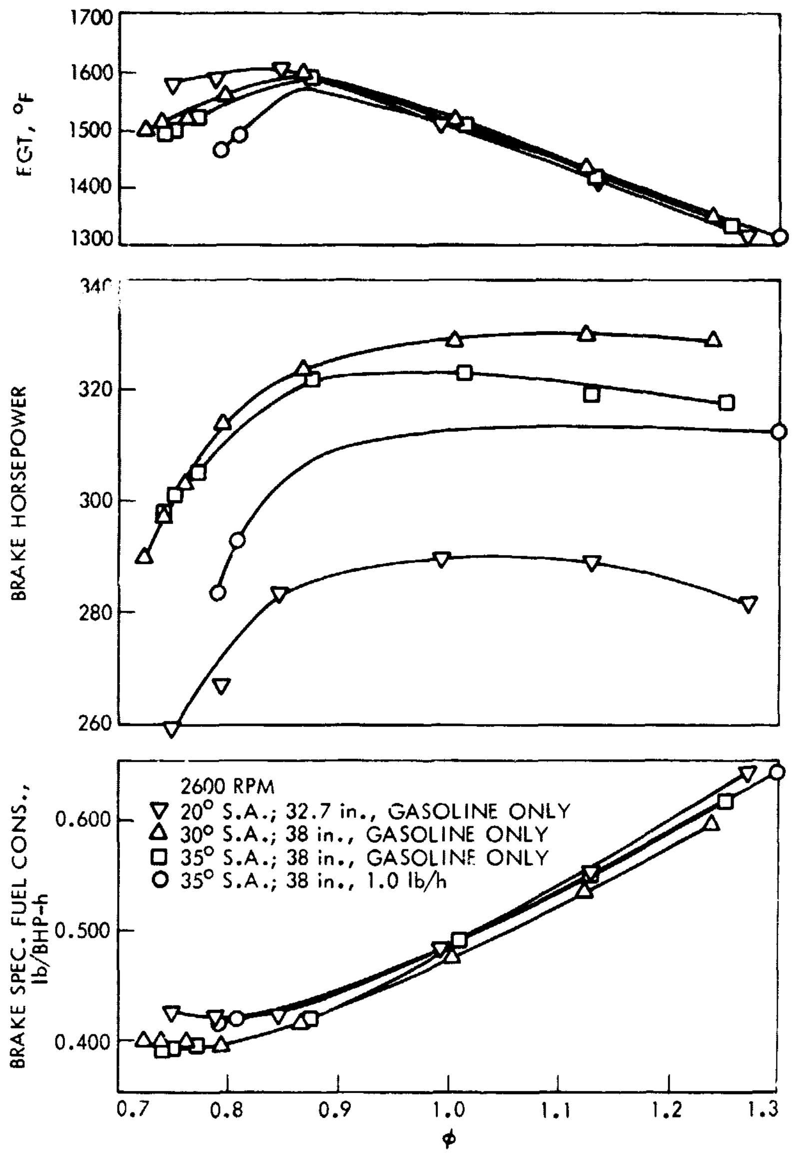


Figure 6-34. Leanout Curves for 2600 rpm, 20, 30, and 35° S.A., 32.7 and 38 in. Hg Manifold Pressure for Gasoline Only and 1.0 lb/hr Hydrogen Enrichment

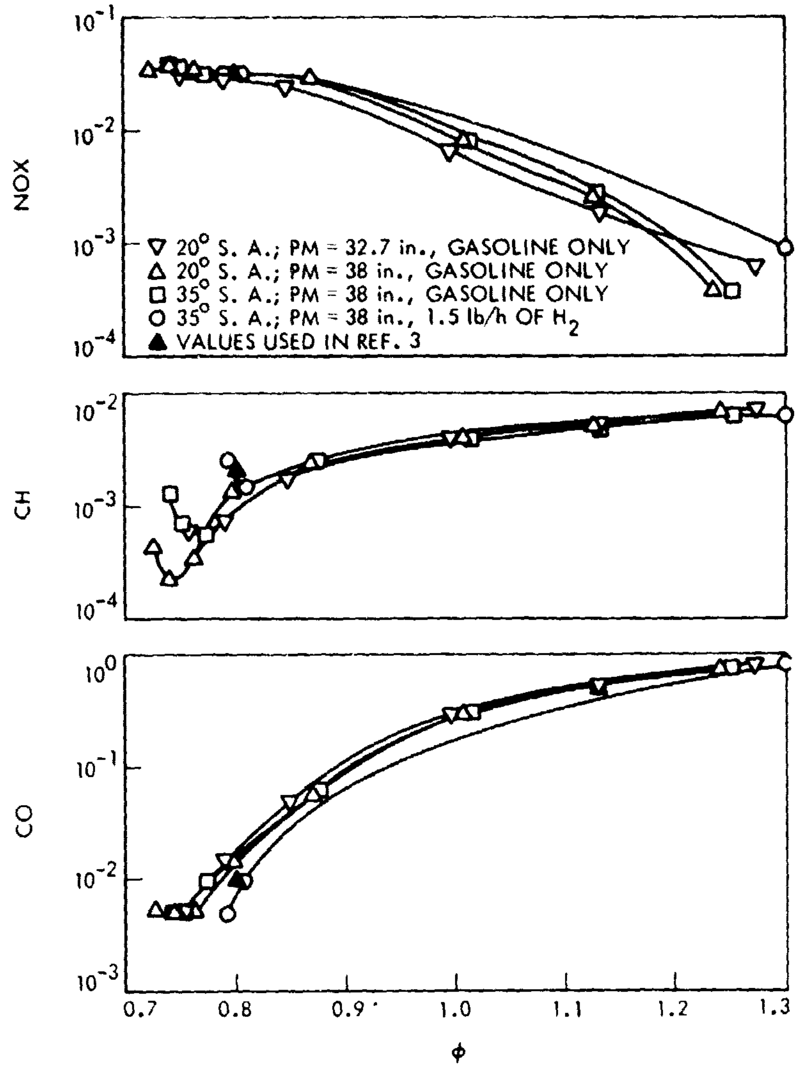


Figure 6-35. Emission Measurements for the Curves Shown in Figure 6-34

The effect observed by adjusting the spark advance was the type of behavior expected when leaning out with hydrogen enrichment. It was assumed that aircraft engines would suffer severe roughness and misfiring at equivalence ratios under 0.8, and on the basis of this judgment it was postulated that hydrogen enrichment would be required to stabilize the combustion and allow the engine to be leaned out to the minimum BSFC point. As a matter of fact, this kind of phenomenon is observed in Figures 6-18, 6-22, and 6-26 at equivalence ratios lower than those that give the minimum BSFC. Where fuel economy is the leading consideration, there is no interest in operating the engine in this region. The reason for the delay in the beneficial effects of hydrogen enrichment originates in the initial handicap that the hydrogen generator engine system has in the rich region with respect to the unmodified engine. This handicap is the 20% loss of energy in the fraction of fuel burned in the generator

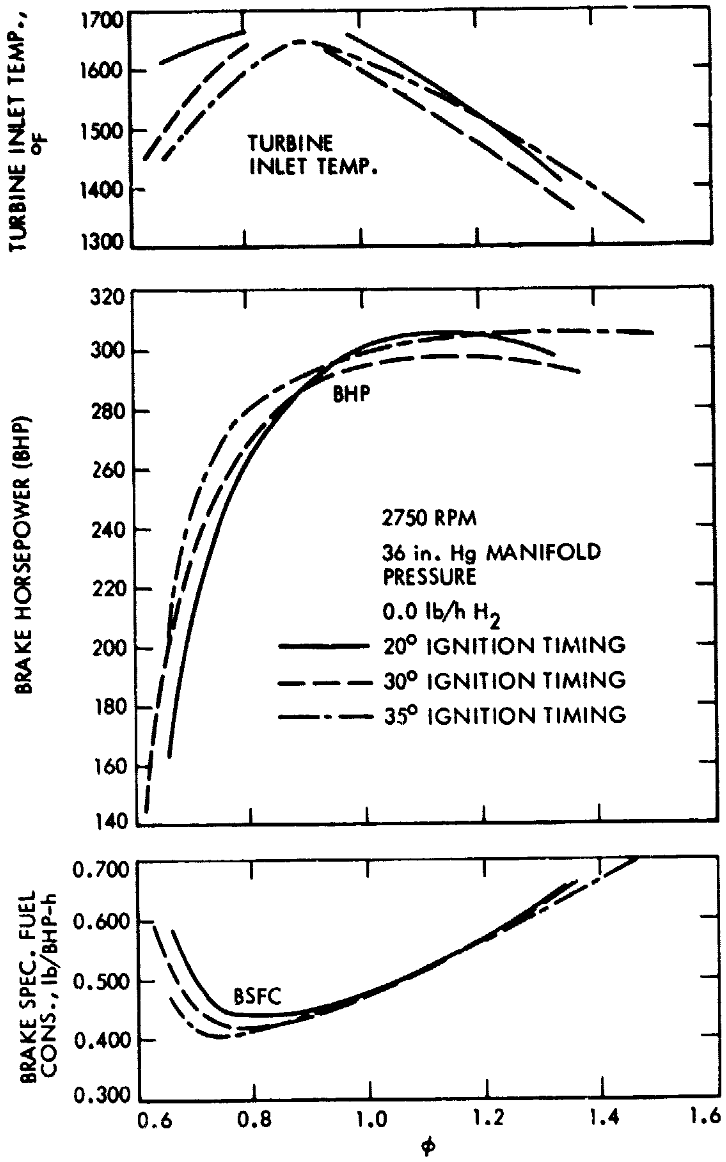


Figure 6-36. Effect of Spark Advance on Ultralean Operation of the Engine for Gasoline Only, 2750 rpm and 36.0 in. Hg Manifold Pressure

to produce the product gas. This loss is imposed because the Otto cycle does not benefit from the increase in sensible enthalpy of the product gas. The flatter valley for the minimum BSFC when hydrogen enrichment is applied gives an indication of the higher stability of combustion. It is also noted that the higher hydrogen flow rates increase BSFC, but further improve combustion stability at the lowest equivalence ratios. The power loss obtained with hydrogen enrichment is a result of the energy loss mentioned above, and this also accounts for the observed lower turbine inlet and cylinder head temperatures.

From past related work on hydrogen enrichment it has been found that one of the most important parameters for the effective use of hydrogen as a means to stabilize ultralean combustion is good premixing (References 6-15 and 6-16). To this end, two tests were conducted to evaluate the hydrogen distribution throughout the cylinders, as provided by the spiders and mixing chamber. In the first test, one pound of hydrogen per hour was injected through the spider as in the standard configuration. In the second test the same amount of H_2 was injected upstream of the compressor while all other parameters were kept the same and the mixing chamber inlet was covered and sealed. The results are presented in Figure 6-37, where one can see that the effective mixing introduced by the compressor impeller is reflected in an improvement of BSFC in the far ultralean region. This improvement, however, will not affect the results shown in this report, since the GSFC curves coincide for both cases until the minimum is reached. Thus the hydrogen distribution achieved by the spider was considered adequate for out purposes.

It appeared, therefore, that if engines similar to the one tested here could be operated in the ultralean region by simply adjusting spark advance, there was no reason to use hydrogen enrichment. There was still a possibility, however, that in the flight test phase of the program, roughness or other difficulties might still be encountered. It was decided to continue the program as originally planned by conducting a few hydrogen enrichment experiments in flight, but to shift the emphasis to gasoline-only with adjusted spark advance. Hydrogen enrichment could still be necessary for other engines of lower performance, because some of these are known to run rough prematurely even during the conventional leanout procedures currently recommended by the manufacturers.

The power recovery techniques described in the last paragraph cause two side effects on the engine: (1) an increase in manifold temperature due to the higher compression ratio of the turbocharger, and (2) a distortion of the indicated cycle diagram. The increase in manifold temperature becomes worse as such techniques are practiced at higher altitudes, and could eventually cause cylinder head overheating and perhaps induce detonation. This manifold temperature increase would also adversely affect the volumetric efficiency of the engine, causing a decrease in specific power output. If difficulties were to be experienced in cooling the engine at altitude, or the volumetric efficiency were to become too low, it might be necessary to install a heat exchanger after the supercharger. This would increase system weight, and increase the pressure drop through the air intake manifold. It should be noted, however, that there are engines (Continental) currently equipped with such aftercoolers, which are justified only on the basis of improving volumetric efficiency. As far as the effects of higher manifold pressures and temperatures over the thermodynamic cycle are concerned, it is known that the BMEP (brake mean effective pressure) is the same in the ultralean region as in the rich region, where the engine is presently operated, since the manifold pressure is set to produce the same torque. Unfortunately, a cycle indicator diagram was not obtained and it is not known how much higher the peak pressure has become. It is felt, however, that at least for 65% rated power, the 36 in. Hg manifold pressure does not cause an unusual stress on the engine.

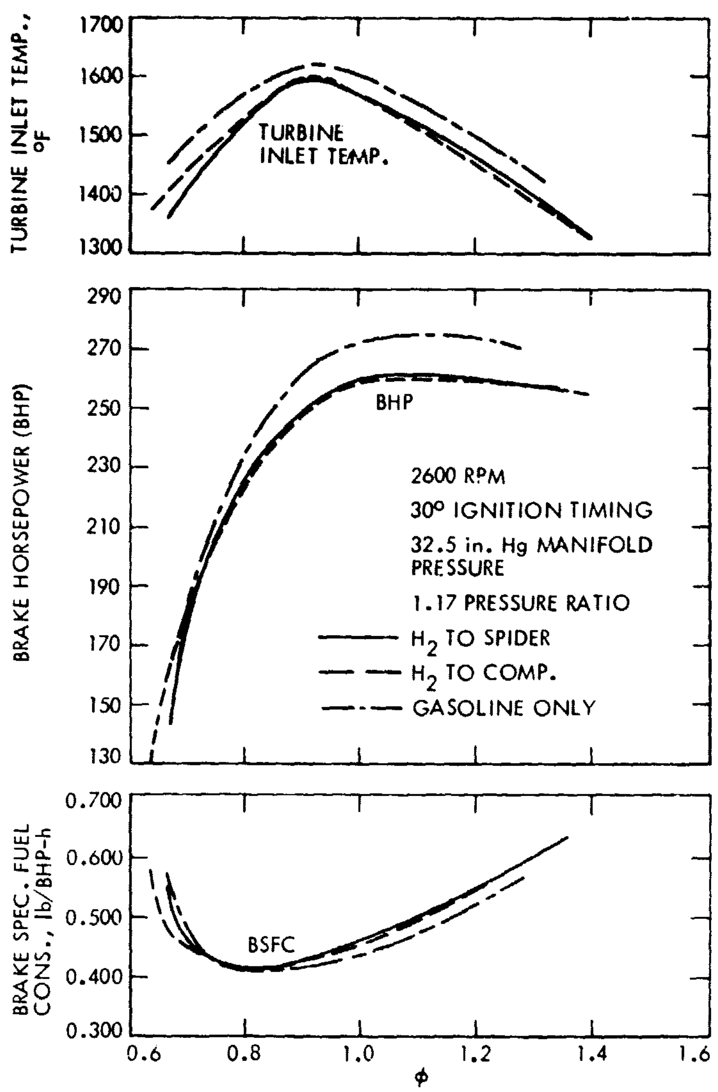


Figure 6-37. Hydrogen Premixing Impact on Engine Performance

The engine was observed to behave very smoothly when operated at the ultralean point and with higher manifold pressure, particularly on the flight test stand. The engine only misfired when leaning further down to an equivalence ratio of 0.65. During the earlier test series on the dynamometer stand, the engine lost compression, and after checking the individual cylinders it was found that two of them had been severely damaged. By the time the problem was detected, the damage had extended to the crankshaft and camshaft bearings, and a major remanufacture of the engine was required before proceeding with the program. An analysis of the incident showed that the engine was exposed to severe heating from detonation or preignition during some part of the test. It was also found that a substantial amount of catalyst fines had reached the cylinders, passed on to the lubrication system and had gone as far as the crankshaft bearings. It is not known whether the fines were directly responsible for preignition, overheating, and eventual detonation, or if the leanout procedures used in this investigation were too stringent when the engine was operated at simulated altitude, with large spark advance, and near the stoichiometric mixture where the flame speed is large. For a detailed description of these incidents see Reference 6-10.

With respect to the objective of this research, that is, the improvement in fuel economy by burning ultralean, the results appear very promising. Table 6-6 has been obtained by comparing operating points at high and intermediate power levels (cases 1, 2, 3) with three different techniques: conventional, ultralean with gasoline only, and ultralean with hydrogen enrichment. The table presents three representative cases. In case 1, the engine is set at 2750 rpm and three operating points are compared. Note that the conventional operating point produces 80% rated power at 36 in. Hg manifold pressure, but its BSFC of 0.5 is limited by the value of the turbine inlet temperature. For the same limiting values of turbine inlet temperature while operating ultralean, one has a lower BSFC of 0.41 for gasoline only and 0.43 for 1.75 lb/hr of hydrogen enrichment, giving fuel economy improvements of 18 and 14%, respectively. The power levels, however, are slightly lower, 72 and 71%, even with manifold pressures of 39 in. Hg. It is believed that further leanout and higher manifold pressures would produce the same power and temperatures, with equal or better BSFC.

Case 2 shows a high-power case (87%), with BSFC limited by temperature, as in previous case 1. It should be noticed that the ultralean techniques in case 2 are mostly limited by lack of capacity of the turbocharger in providing manifold pressures high enough for power recovery and they have been extrapolated from measurements. The turbine inlet temperatures will also be somewhat marginal. If these operating points could be met, improvements of 20 and 16% would be obtained as a result of operating ultralean with gasoline only or with 1.75 lb/hr by hydrogen enrichment, respectively.

Case 3 consists of a comparison at a lower engine speed, 2600 rpm. The conventional point in this case is producing, at the best power point, 76% power, and is not temperature-limited (1500°F). The ultralean operating point with gasoline only, at the same temperature with higher manifold pressure, renders 80% power and a 21% lower BSFC. The hydrogen enrichment of 1 lb/hr results in the conventional power of 76% but at lower temperature (1450°F) and 16% lower BSFC.

It is obvious from this table that hydrogen enrichment is not required in order to operate engines ultralean for the purpose of achieving an improvement in fuel economy. Ultralean operation with gasoline only with proper engine tuning and power recovery is a superior technique. At the time these results were being obtained, the JPL Low Pollution Car Program arrived independently at similar conclusions (see References 6-17 and 6-18). Figure 6-38 (from Reference 6-18) shows a relationship between NOx emissions and mileage improvement for hydrogen enrichment and gasoline only. Although the results have been integrated through a federal driving cycle, it is obvious that if one floats emissions (see Figure 6-38), the ultralean technique with gasoline only will give a better mileage improvement; on the other hand, if very low NOx emissions are desired (required by EPA standards), hydrogen enrichment is needed

Table 6-6. Summary of Results

	Case Number	Conventional	Ultralean (gasoline only)	Hydrogen Enrichment
Engine speed, rpm	1	2750	2750	2750
	2[a]	2750	2750	2750
	3	2600	2600	2600
Turbine inlet temperature, °F	1	1600	1600	1600
	2[a]	1600	Over 1600	Over 1600
	3	1500	1500	1450
Spark advance, °BTC	1	20	30	30
	2[a]	20	30	30
	3	20	30	30
Hydrogen injection rate, lb/hr	1	0.0	0.0	1.75
	2[a]	0.0	0.0	1.75
	3	0.0	0.0	1.0
Fuel/air ratio	1	0.077	0.052	0.057
	2[a]	0.080	0.052	0.057
	3	0.073	0.053	0.057
Manifold pressure (in. Hg)	1	36	39	39
	2[a]	39	6	6
	3	32.7	38	38
Power level (% rated power)	1	80	72	71
	2[a]	87	87	87
	3	76	80	76
BSFC (lb/BHP-hr)	1	0.500	0.41	0.43
	2[a]	0.515	0.41	0.43
	3	0.495	0.391	0.415
Percentage improvement in BSFC	1	-	18	14
	2[a]	-	20	16
	3	-	21	16
Cylinder head temperature (°F) (maximum)	1	440	435	450
	2[a]	442	450?	460?
	3	400	375-425	375-425

[a] Case 2 ultralean data obtained by extrapolation of measurements.

[b] Above turbocharger capacity.

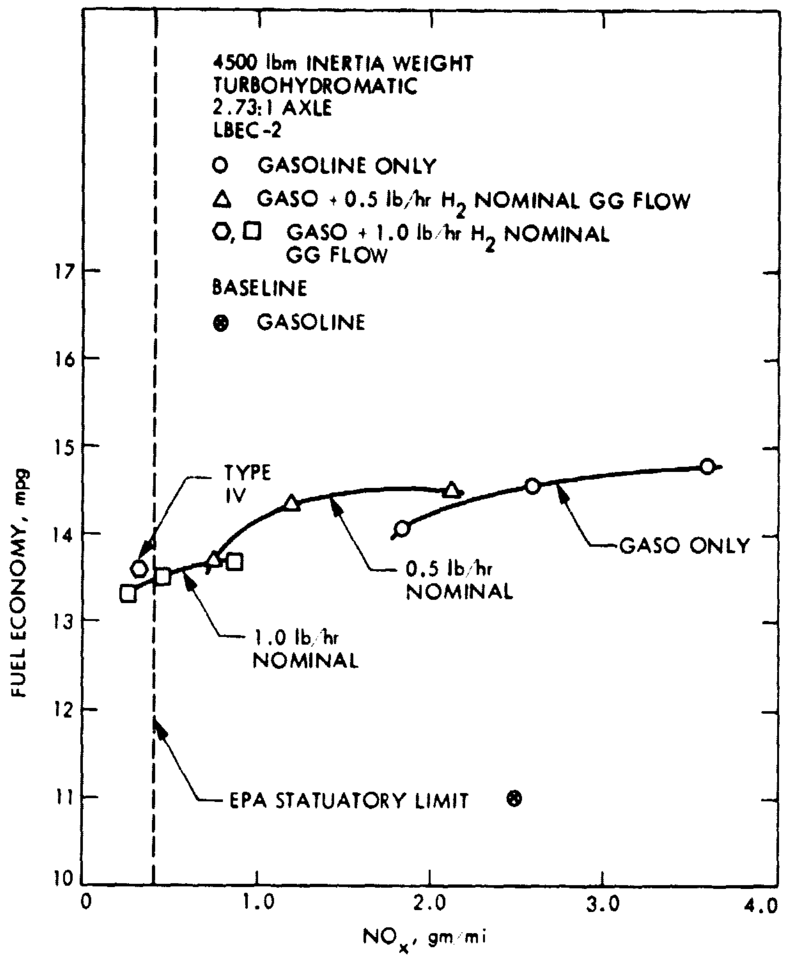


Figure 6-38. NOx - Fuel Economy Tradeoff: 4500 lbm Inertia Weight

but a penalty in mileage improvement is incurred. If these results are translated into our leanout curves, they show that for best fuel economy one would like to operate at point A (see Figure 5-7), and if lower NOx are desired, one would have to operate at point B, which is leaner than the engine misfire limit for gasoline only and therefore requires hydrogen enrichment. For the purposes of this effort there is no interest in operating leaner than point A, and therefore hydrogen enrichment is not required.

The exhaust emissions obtained during the leanout on the flight test stand are not very sensitive to ignition timing and hydrogen enrichment to the rich side of the ultralean region. The reason for this lies in the fact that the production of NOx, CO, and to some extent HC, are combustion-temperature-dominated, and it is only near the lean flammability limit that chemical kinetic effects become important. This behavior is best illustrated by the HC emission, which is very sensitive to ignition timing (see Figure 6-35). CO oxidation begins to be rate-limited at about the same point where BSFC is minimized. NOx should begin to decrease at this point, but for this engine it remained higher than expected. It seems that HC emission is a convenient parameter for judging the ultralean combustion characteristics of the engine and it is a good indicator of the location of the minima of the BSFC curve.

Figure 6-35 shows some representative data (▲) used in Phase I (Reference 6-6) to evaluate the potentials for reducing emissions in the ultralean region. As can be seen, the estimates previously used agree fairly well with the measurements obtained in this phase. The limited amount of data obtained during the present series of experiments suggests that if the present techniques can be implemented during taxi, idle, and approach, the engine could possibly pass the federal standards in effect at the time this work was done. The major problem caused by general aviation emissions has been identified by EPA as CO emissions. It is worth noting from Figure 6-35 that ultralean CO emissions are two orders of magnitude lower than those produced when operating the engine full rich, and HCs are over one order of magnitude lower. NOx shows an increase but may still not present a problem. One should also notice that with hydrogen enrichment CO attained its lower value while HC was the highest. Its effect on NOx production does not seem to be any different than for gasoline only.

There were some doubts about the controllability of the engine in the ultralean region owing to the high-power gradients with respect to fuel flow. It was actually observed during ultralean operation of the engine on the flight test stand that some oscillations in manifold pressure and rpm were sustained, even when the hydrogen generator system was decoupled from the engine. This was attributed to the fact that during ultralean operation the open-loop controllers (e.g., the propeller, governor, fuel injector Venturi, and differential controller for the turbocharger) become close-loop coupled.

4. Conclusions

The conclusions reached from the results of this investigation are:

(1) The feasibility of operating the engine under ultralean conditions with hydrogen enrichment rates from 0.0 to 3.0 lb/hr was demonstrated.

(2) When the engine was operated ultralean with spark advances from 30 to 35°, the minimum BSFC underwent an improvement ranging from 18 to 20%.

(3) The spark advance mentioned in (2) displaced the minimum BSFC to leaner equivalence ratios, which in turn allowed cooler operation of the engine.

(4) The lower temperatures at the ultralean operating point described in (3) allowed the manifold pressure to be increased to recover power.

(5) The increase in manifold pressure described in (4) did not affect the low minimum BSFC obtained in (2) and did not produce engine overheating.

(6) The methods just described were tested at altitudes up to 20,000 ft, but a decrease in the original critical altitude was obtained because of limited turbocharger capacity.

(7) The engine investigated did not need hydrogen enrichment to run ultralean and improve fuel economy.

(8) Rough engine running was not experienced when leaning out to the minimum BSFC condition with or without hydrogen enrichment.

(9) The limited emission measurements obtained indicate that if these techniques can be implemented during taxi, idle, and approach, it may be possible to meet the 1980 Federal Emission Standards (as in effect during the period of this work).

(10) The hydrogen generator technology was significantly advanced during this phase of the program. Although most probably not needed for ultralean operation of this engine, it might be required on other lower rated engines.

5. Summary

The objectives of Phase II were accomplished, although as new information was obtained, intermediate goals were reestablished several times. Hydrogen enrichment was found to be unnecessary for the engine tested. It was found that under no circumstances will hydrogen enrichment compete in efficiency with ultralean operation with gasoline only. These results agree with the results obtained in 1976 by the JPL Low Pollution Car Project. As an alternative, a combination of spark advance, higher manifold pressures and slowdown of engine speed was seen to offer a very promising and simple procedure for ultralean operation of current engines.

H. PHASE III - FLIGHT TESTS

During this phase of the program the engine/flight generator assembly and systems were installed in the left cowling of a Duke B60 model and flight-tested. The right engine was unmodified and was used as the primary power plant of the airplane during the flights, providing sufficient power to tightly control air speed. The systems and assembly followed the design which was prequalified for flight at the Lycoming facility during Phase II. Several activities were undertaken in Phase III which allowed some final conclusions to be made regarding the flight quality and performance of new techniques for ultralean burning and fuel economy improvement. These activities included aircraft modification, engine/generator installation, flight instrumentation development, installation of special magnetos, specialized instrumentation and airborne data acquisition systems, flight testing, data reduction and reporting. The flight tests were limited to a total of 50 hours, but in spite of the short flight time, it was possible to develop the new pilotage techniques, investigate relevant flight parameter effects, and evaluate on practical terms the new techniques advanced during Phase II.

The ultimate purpose of this phase was to conduct a flight verification of the results obtained at the test cell during Phase II, giving special emphasis to aircraft systems limitations, safety, air worthiness, flight quality and new piloting techniques. Specifically, the flight tests were set originally to verify:

Gasoline only - spark advance - power recovery flight

(1) Potentials for fuel economy improvement using advanced ultralean techniques.

(2) Exercise spark advance.

(3) Exercise power recovery techniques.

(4) Investigate effects of altitude on performance when conducting (1), (2) and (3).

(5) Investigate engine cooling characteristics.

(6) Investigate detonation hazards when exercising (1), (2), and (3).

(7) Identify limitations imposed on aircraft performance due to turbine inlet temperatures (TIT), cylinder head temperatures (CHT), and turbocharger capacity when exercising (1), (2), and (3).

(8) Monitor general controllability of the aircraft/engine systems when operating with ultralean techniques.

(9) Investigate conditions under which engine roughness appears in exercising (1), (2) and (3).

(10) Conduct a fuel economy improvement demonstration flight by comparing left and right engines.

Hydrogen enrichment - spark advance - power recovery flights

(11) Test hydrogen generator system operating procedures during flight.

(12) Investigate potential fuel economy improvement.

(13) Compare with gasoline-only/ultralean burning.

(14) Observe hydrogen enrichment effect on engine roughness.

The objectives listed above were originally set in light of the results obtained during Phase II. Notice in particular that the emphasis had shifted toward ultralean burning with gasoline only. Most of these objectives were accomplished except for the fuel economy demonstration flight, which was cancelled because of the unexpected difficulties encountered during the development of the operating procedure for the hydrogen generator in-flight. This Phase III effort was coordinated by JPL, while Lycoming played the role of observer and consultant, giving technical assistance to Beech Aircraft in the areas of engine operation and instrumentation. JPL personnel operated the hydrogen generator in-flight. Beech Aircraft conducted this phase as an in-house activity which required the coordination of the Engineering Flight Test, Instrumentation Group, Data Systems Group, and Experimental Department. The details of Phase III activities and results have been documented in two Beech Aircraft reports, References 6-19 and 6-20.

1. Aircraft

The actual aircraft assigned to the program was a Beech Model 60 Duke P-3. The aircraft was available from past programs and had to be put into flyable condition and pass the required inspections to be relicensed as an experimental aircraft. A photograph of the aircraft is shown in Figure 6-39. Arrangements were made to have the test pilot fly the airplane from the left seat; the right seat was empty and the rest of the cabin was made available for the instrumentation and equipment control racks which were operated by the flight engineer from a jump seat located behind the pilot.

Figure 6-39. Beech Model 60 Duke, S/N P-3

2. **Engine Modifications and Installation**

The engine tested at Lycoming was shipped to the Beech Aircraft facility at Wichita, Kansas, satisfactorily inspected and installed into the left nacelle of the engine. The only engine system that underwent some modification was the ignition. It was noted during Phase II that because of the lack of capability to change the spark advance during a leanout, a few seconds would often be spent operating the engine with very advanced timing, high manifold pressure and equivalence ratio ϕ near one, which are the ideal conditions for occurrence of detonation. Furthermore, since the effect of spark advance became a primary objective in this phase of the program, it was expected that a lengthy and tedious task would have to be undertaken every time a new spark timing was desired, because conventional magnetos operate with fixed timing. To overcome these difficulties and implement a simple and reliable method to change the timing in flight, the conventional engine magnetos were replaced by specialized magnetos.

A Lycoming TIO-541-E engine uses magnetos made by Scintilla, a Division of Bendix Corporation. The conventional installation of these magnetos for twin engines is shown in Figure 6-40, where one can distinguish, as major elements, the magnetos, the starting vibrator, starting motors, battery, starter relays and the combination starter and ignition switches. Notice that each engine has two magnetos (left and right), one starter and ignition switch, one starter relay and one starter motor. The starting vibrator and battery are shared by both engines. This installation wiring using two magnetos, starting vibrator, combination starter and ignition switch, starting relay and starting motor, is shown in more detail in Figure 6-41 (taken from Reference 6-21, which also provides instruction regarding installation, maintenance and service of those magnetos).

In Figure 6-41, with the combination ignition and starter switch in the START position, the right magneto is grounded and starter solenoid L1 is energized, closing its relay contact R1. Battery current flows through the vibrator points V1, coil L2, through the switch and through main and retard contact assemblies of the left magneto to ground. The magnetic field built up around coil L2 causes the vibrator points V1 to open. Current flow ceases through coil L2, causing the magnetic field to collapse and vibrator points to reclose. This allows coil L2 and L3 to energize and vibrator points V1 to again open. When the engine reaches its normal advance firing position, the main contact assembly opens. However, the vibrator current is still carried to ground through the retard contact assembly, which does not open until the starting retard position of the engine is reached. When the retard contact assembly opens (main contact assembly is still open), the vibrator current flows through the primary of transformer T1, producing a magnetic field around the coil. Each time the vibrator points V1 open, the current flow through the primary of transformer T1 ceases. This causes a high voltage to be induced in the secondary which fires the spark plug. A shower of sparks is thus produced at the spark plug due to the opening and closing of the vibrator points V1 while the main and retard contact assemblies are open.

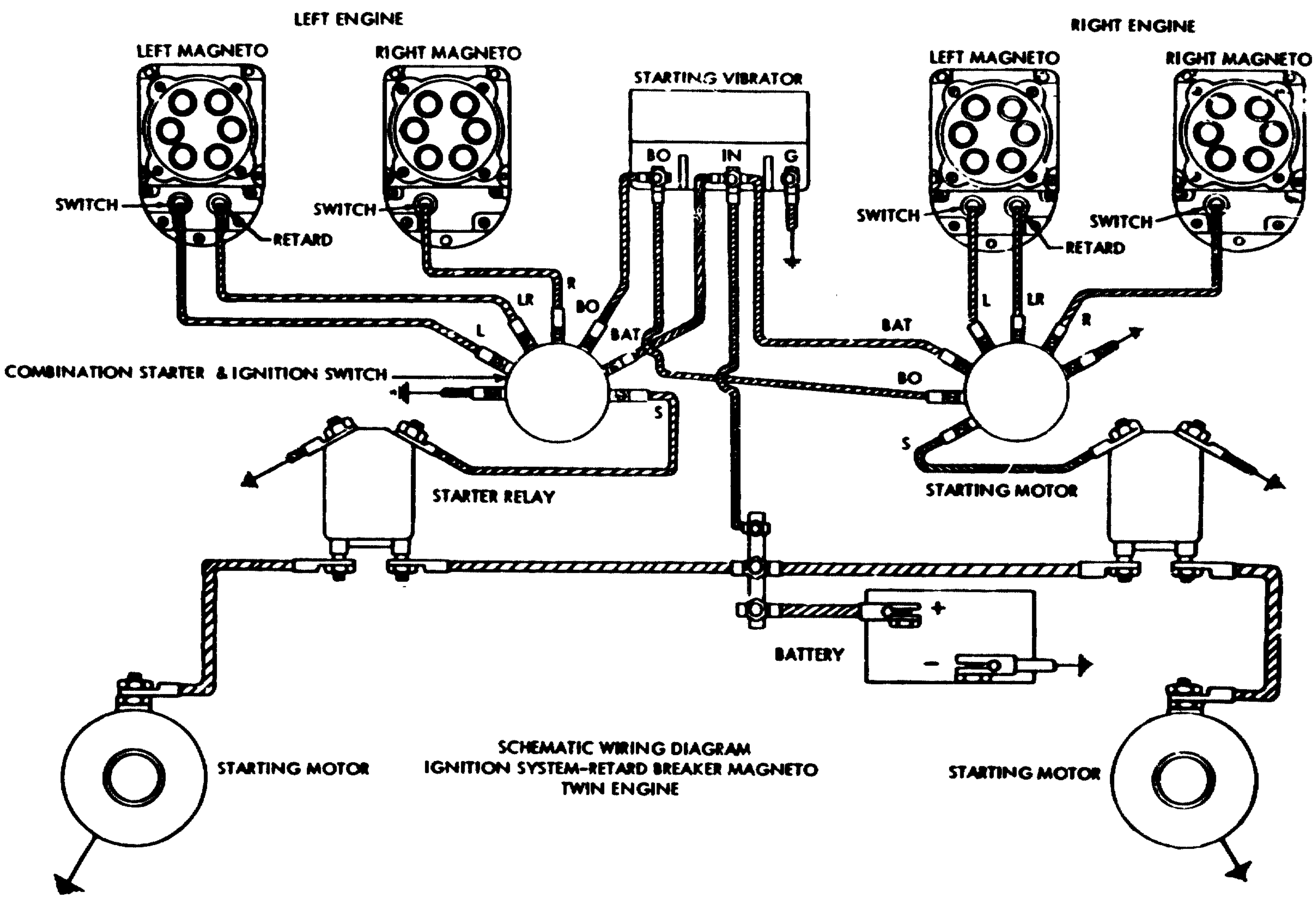


Figure 6-40. Lycoming TIO-541E Conventional Ignition System

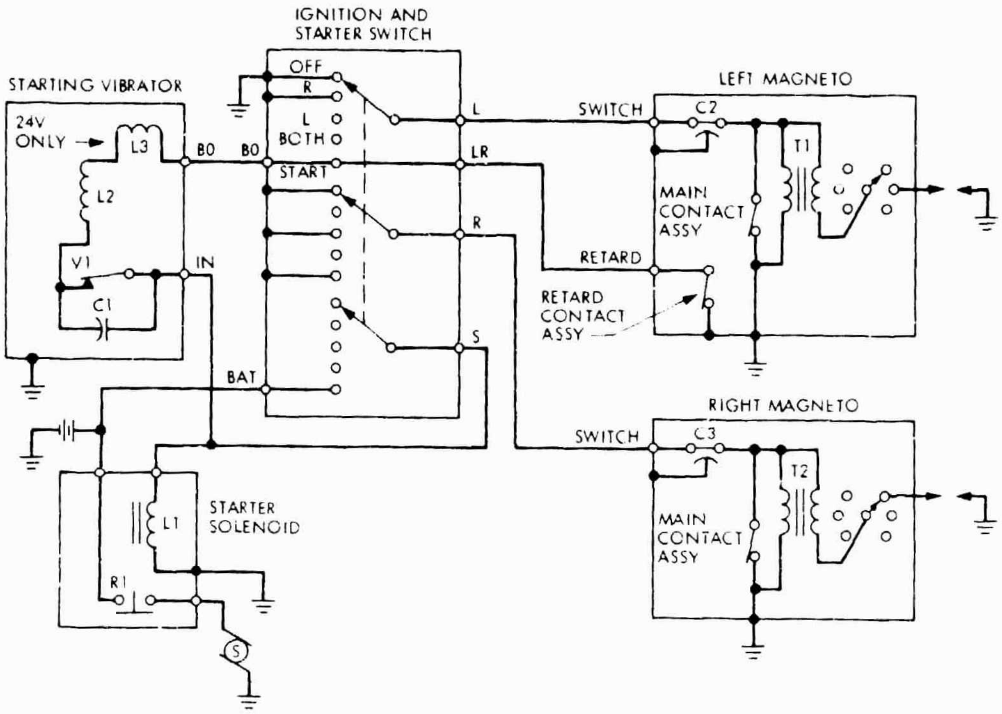


Figure 6-41. Schematic Diagram of Magneto Circuit and Starting Vibrator Without Relay (Reference 6-21)

When the engine fires and begins to pick up speed the switch is released and returns to the BOTH position, rendering the vibrator circuit and retard contact assembly circuit inoperative. The single contact assembly (right) magneto is no longer grounded; therefore, both magnetos are simultaneously firing in full advance.

The rotating magnet is of a four-pole design. As the magnet is turned the polarity continually changes, producing flux reversals in the magneto coil core. The number of flux reversals during one complete revolution of the magnet is equal to the number of poles on the magnet.

With the contact assembly points closed, the flux reversals cause a current to be generated in the primary winding of the magneto coil. The flow of current through this coil produces a magnetic field around the coil. When the contact assembly points open, the magnetic field around the primary tension winding collapses, causing a high-tension current to be induced in the secondary winding of the coil. This high tension current is conducted to the distributor gear electrode by means of a carbon brush, to terminals in the distributor cover, to high-tension contact springs and through high tension cables to the spark plugs.

The combination ignition and starter switches used with the magneto system have five positions actuated by either a key or a lever. They are as follows:

(1) Off - both magnetos not operating.

(2) R - right magneto operating; left off.

(3) L - left magneto operating; right off.

(4) Both - both magnetos operating.

(5) Start - Starter solenoid is operating and vibrator is energized causing current to flow through retard breaker on left magneto while right magneto is grounded to prevent advanced ignition.

Some other type of magnetos incorporate impulse coupling with a single contact assembly rather than the starting vibrator. The purposes of impulse coupling is to (1) rotate the magnet between impulse trips faster than engine cranking speed, thus generating a more energetic spark for starting the engine; (2) automatically retard the spark during engine cranking; and (3) act as a drive coupling for the magneto. With this technique, a spark advance of about 7° BTDC is obtained for ease of engine starting. This is accomplished by turning the ignition switch to start position, which causes grounding of one of the magnetos (no impulse coupling), and a strong retard spark from the other magneto.

The two systems described above show fundamentally the same features. In each engine one of the magnetos is provided with two timers: an advance timing for normal engine operation (about 20° BTDC), and a retard timing for starting the engine (approximately 7° BTDC). The other magneto uses single timing. For the purposes of this program's Phase III, two specialized magnetos were requested which incorporate some common design characteristics from the two systems just described. The two magnetos were fundamentally the conventional magnetos from the 1200 series but modified with a new plate of breakers. The magnetos were identified as L-17640-5 and were similar to the 10-349310-4 (type 1 drive) for the left magneto and to the 10-349370-11 for the right magneto (type 14 drive), with an impulse coupling added for the right magneto. Both magnetos were provided with two breakers, retard and advanced breaker. The retard breaker was an insulated breaker which was grounded by applying 24 volts to a TRIAC by means of a switch (see Figure 6-42). When 24 volts dc is applied to the retard terminal the breaker will open at 20°. With the 24 Vdc removed from the retard terminal, the magneto will operate in advance position 30° BTDC. Besides these two breakers, the right magneto is equipped with an impulse coupling whose timing is set to retard from points opening at 20° BTDC with 24 volts applied. This coupling will produce a spark at 5° BTDC.

Figure 6-43 shows a schematic diagram of the wiring of both magnetos to the starter solenoid for the start position, and Figure 6-44 the same wiring for engine run condition. To start the engine, 24 volts must be applied to the magneto retard terminal (BOTH) by closing switches S1 and S2. The engine can be started by the operation of the conventional combination starter and ignition switch. This will crank the engine by activating the starter and shorting out the left magneto at the magneto switch terminal (capacitor connection) through the R terminal on the ignition switch. With 24 volts connected to right and left magneto retard

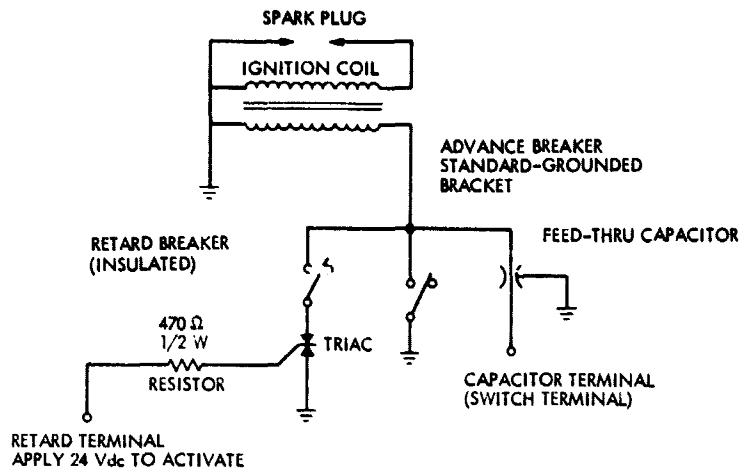


Figure 6-42. Magneto Wiring Diagram (Two Spark Settings)

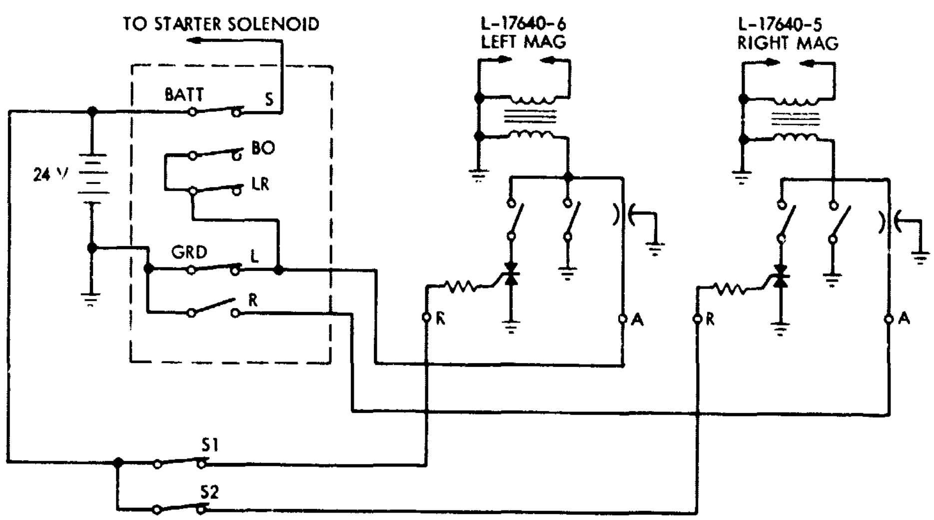


Figure 6-43. Specialized Magnetos Wiring. Start Condition

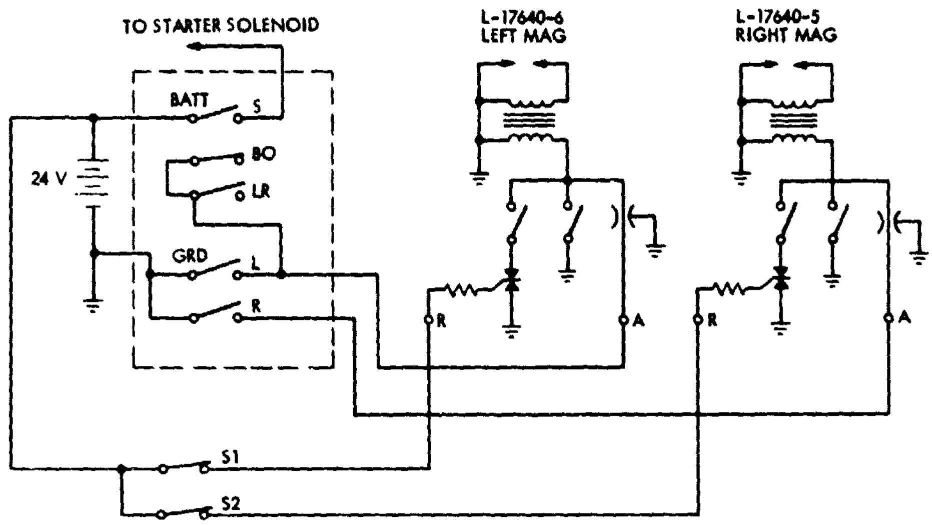


Figure 6-44. Specialized Magnetos Wiring. Run Condition

terminals as stated above, the ignition switch is wired with BO and LR not connected, while the switch terminals are connected with L and R. With this wiring the engine starts, and when the ignition switch is released and left in the BO position, the engine will run in the normal 20° BTDC position. When the 24-Vdc supply is disconected from the magneto retard terminals, a 30° BTDC position will be obtained. With this arrangement, magneto drop check can be conducted as usual.

This type of arrangement for the ignition system was to greatly simplify the flight operations, make them safer, and speed up the experiment. Notice that the retard and advance breakers differ in 10°, and for each flight condition two spark advances can be obtained by simply flipping on and off switches S1 and S2. If other timings are desired, engine retiming should be conducted during preflight operations by actually rotating the magneto housing, but the new timings obtained will still differ by 10°, for example 25° BTDC and 35° BTDC.

3. Installation of Flight Generator Assembly

The flight generator assembly which was prequalified on the flight test stand at AVCO Lycoming during Phase II was installed with the engine in the nacelle. The assembly was functionally identical to the tested configuration and described already in Figure 6-16 with some additional instrumentation added. The generator was placed on an already existing bracket (Figure 6-45), which is usually reserved for the air-conditioning compressor unit, although engine mount rerouting was necessary because of interference with the generator. Some of the generator assembly components had to be moved to different locations from those initially tested in order to optimize compactness and enclose the whole assembly inside the unmodified nacelle. The generator gas output line was relocated in such

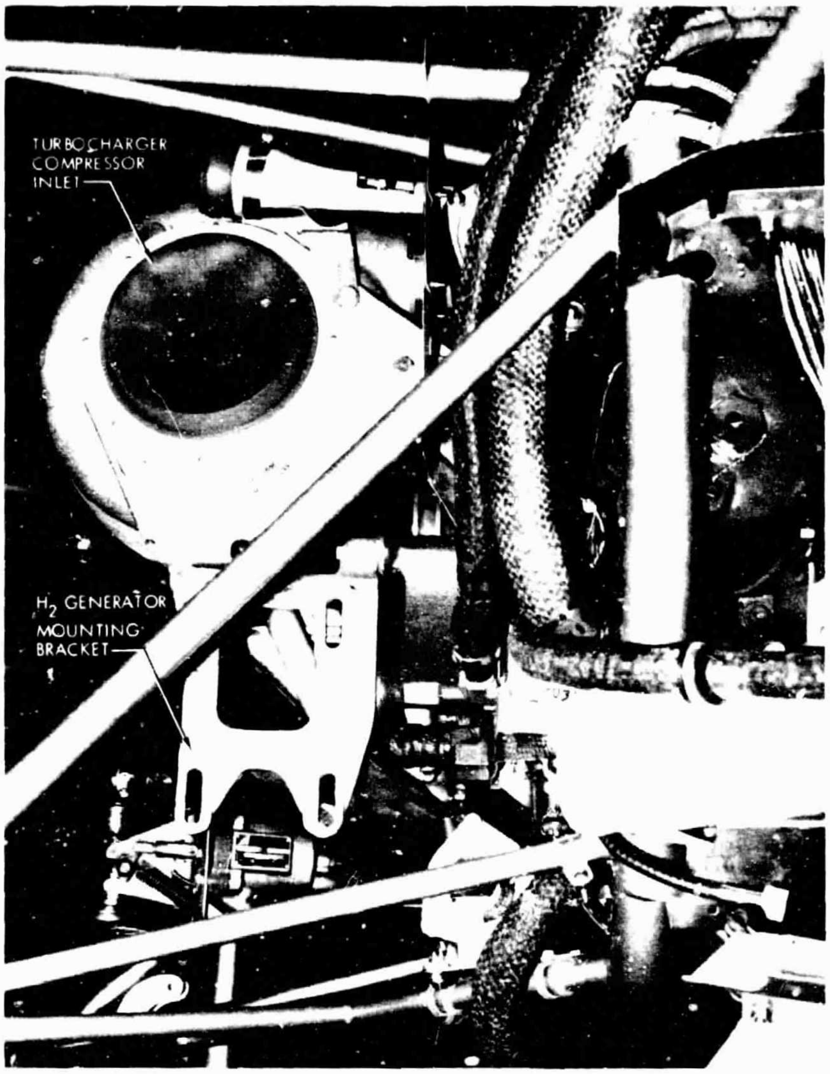


Figure 6-45. Generator Mounting Bracket

a way that the gases were injected into the hydrogen spider in a direction opposite to that originally tested. This allowed a gain of a few inches from the engine top, eliminating the need for a lump on top of the nacelle as originally planned (see Figure 6-46). It was also found that valves PV-1 and PV-2 (Figure 6-16), which were attached on the bottom rear section of the engine, interfered with the cowl flap. During those flights conducted with gasoline only, these valves were removed and the cowl flap operated conventionally, with the open pipes of the assembly capped. The valves were removed for the hydrogen enrichment flights and the cowl flap secured in the full open position. For purposes of this experiment, however, the additional cooling that the engine would experience during the hydrogen enrichment flights was not an issue, and this arrangement was considered satisfactory.

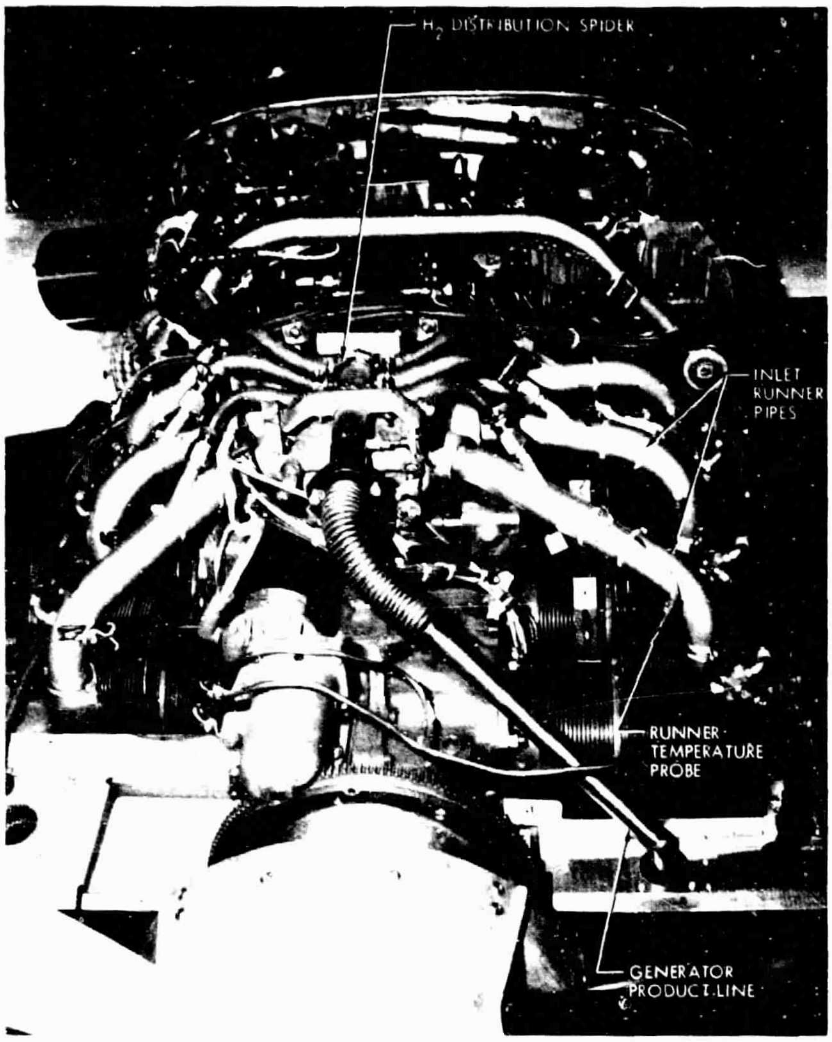


Figure 6-46. Engine Top (Looking Aft) and Hydrogen Injection Manifold

A view of the generator installed in the engine is shown in Figure 6-47, and a photograph of the lower left side of the engine is shown in Figure 6-48, displaying the cluster of valves PV-1 and PV-2 mentioned earlier. This cluster of valves had the function of providing a two-way path for the generator output. This capability was used during the generator start, procedure that called for dumping overboard the product gases during the initial stabilization period of the generator. Figure 6-48 also shows the overboard dump pipe, and Figure 6-49 indicates how the overboard dump pipe was rerouted out of the nacelle, run parallel to the lower wing surface near the landing gear flap, and discharged at the trailing edge. With these arrangements, and after the 15-hour prequalification test, the hydrogen generator assembly was considered safe enough to carry out the experiment.

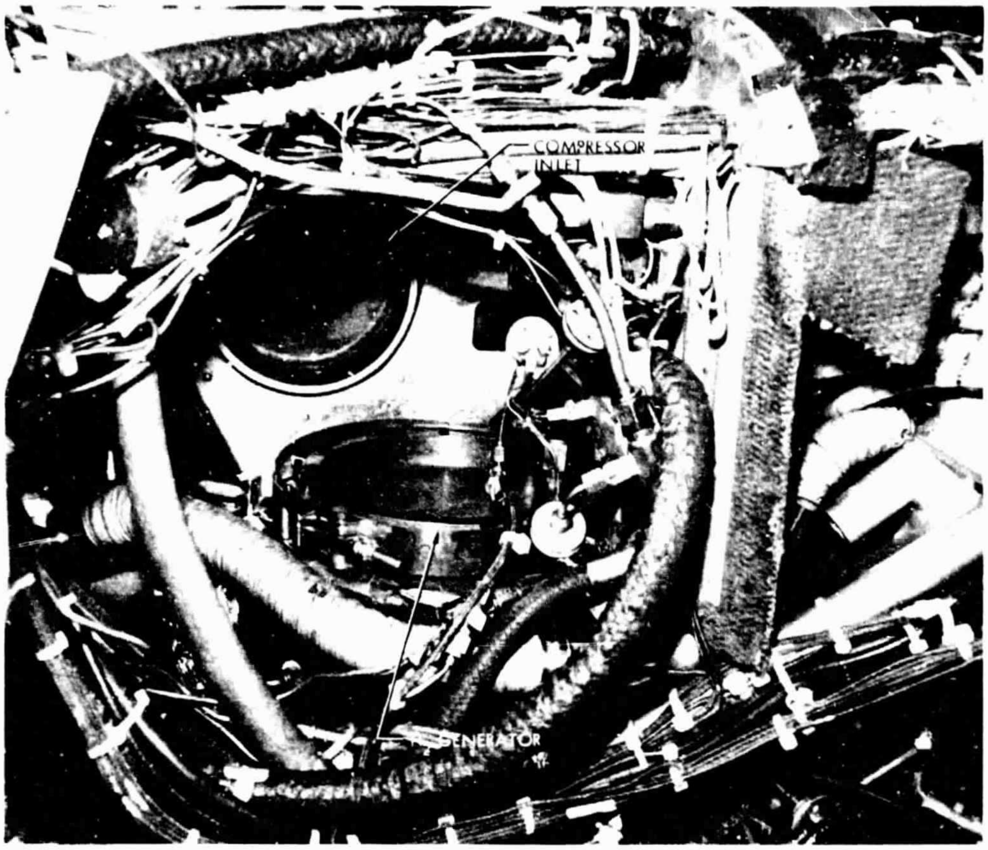


Figure 6-47. Hydrogen Generator Installed on Engine

4. Flight Instruments and Controls

The flight instruments conventionally displayed to the crew were also available in the aircraft. In addition, the pilot had the magneto timing switches S1 and S2, which were described above and shown in Figures 6-43 and 6-44. A photograph of the arrangement for the pilot's panel is shown in Figure 6-50. The flight engine controls were conventional and no high-precision levers were judged necessary for the crew to conduct the leanout and power-recovery techniques. When the left engine was manipulated, the aircraft speed was controlled by selecting different power settings in the right engine and compensating yaw with rudder. In summary, the arrangements for the pilot were almost conventional as to instrumentation and controls. A list of recorded flight parameters is given in Table 6-7. These parameters were also displayed to the pilot (see Table 6-8).

5. Engine Instrumentation and Controls

The engine was equipped with thermocouples and pressure taps installed throughout the engine and inside the nacelle in order to provide a complete set of data for diagnosis. Table 6-9 lists the recorded engine

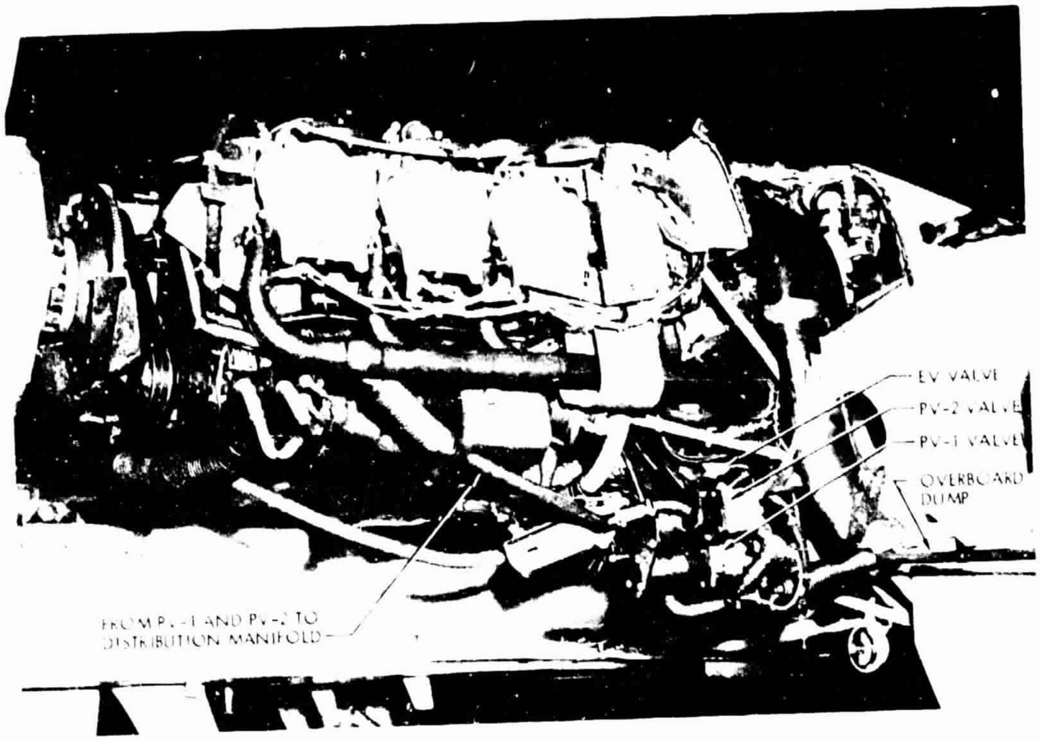


Figure 6-48. Lower Left Side of Engine Showing Valve Cluster Assembly

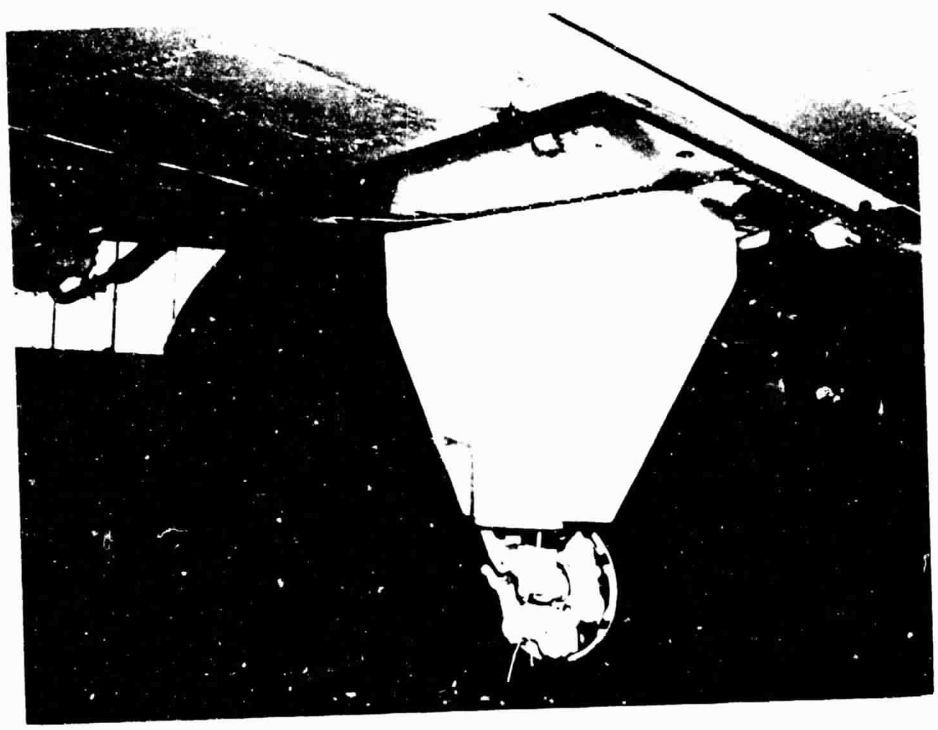


Figure 6-49. Overboard Hydrogen Dump

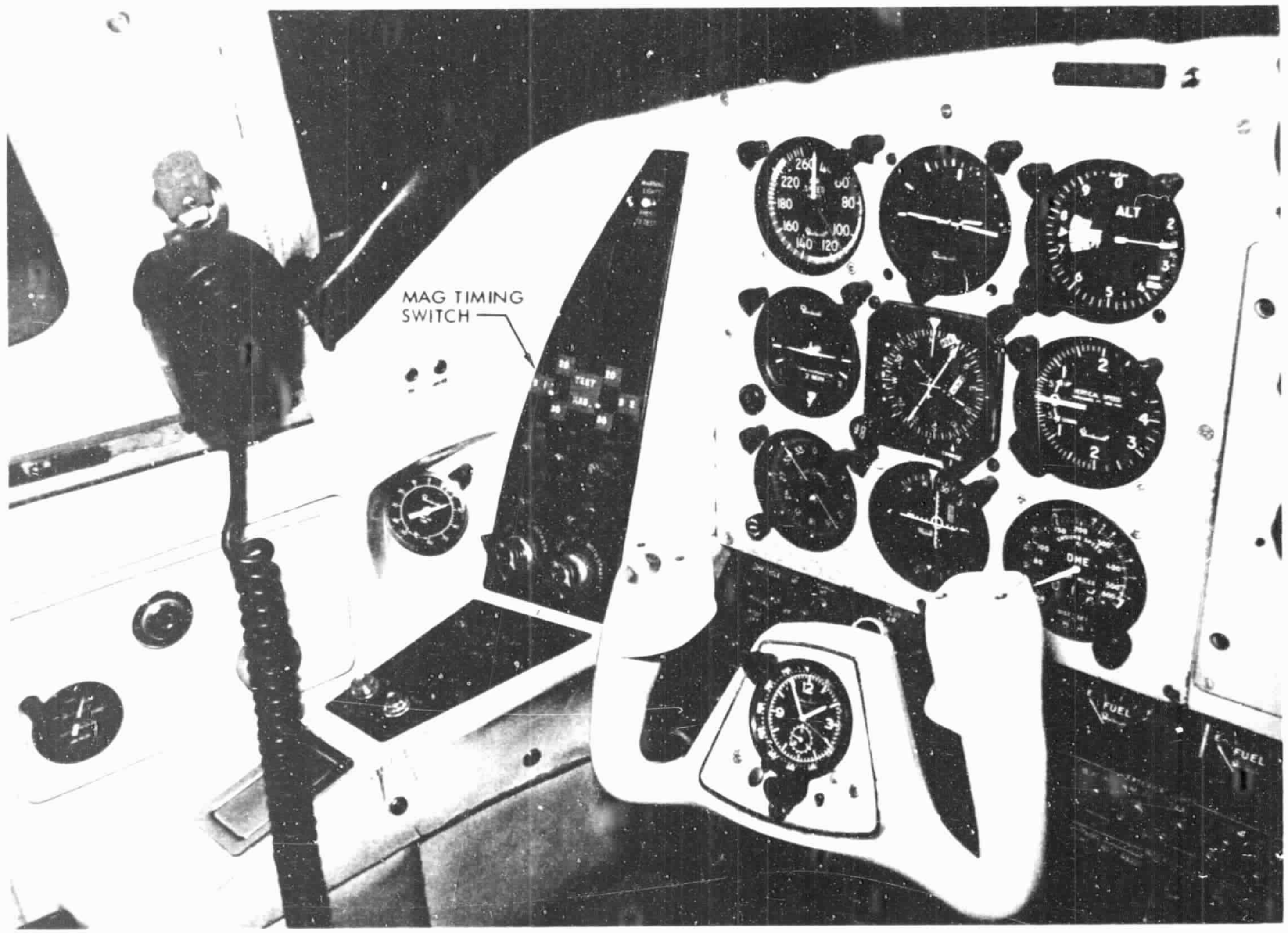


Figure 6-50. Pilot's Instrument Panel

Table 6-7. Recorded Flight Data Variables

Parameter	Unit
Airspeed	knots
Altitude	ft
Engine speed	rpm
Manifold pressure	in. Hg
Time	hrs, min, sec, msec
Oil temperature	^{o}F
Fuel pressure	psia
Fuel flow	lb/hr
Outside air temperature	OAT, ^{o}F

Table 6-8. List of Parameters Displayed to the Pilot and Flight Engineer

Airspeed, kts S/N 510

Altimeter, ft, S/N 6061604

Dual M.A.P., in.Hg, S/N 1018

Dual tachometer, rpm, production gage

Turbine inlet temperature gage (TIT), ^{o}C (This probe was located about an inch from the production probe which provided the temperatures for the tape.)

Fuel flow, lb/hr

Cylinder head temperatures, ^{o}F (each cylinder head was selected using a rotary switch. The same thermocouples provided data to the tape system.)

Table 6-9. Recorded Engine Parameters

Parameter	Unit
Oil Cooling Data	
Temperature of air into oil cooler	°F
Temperature of air out of the oil cooler	°F
Static pressure forward of the oil cooler	in.H_2O
Static pressure aft of the oil cooler	in.H_2O
Compressor Data	
Compressor inlet pressure	in.H_2O
Compressor outlet pressure	in.Hg
Compressor inlet temperature	°F
Ccmpressor outlet temperature	°F
Manifold air temperature	°F
Engine Power Data	
Engine torque	lb-in.
Torquemeter temperature	°F
Exhaust Data	
Exhaust temperature of each cylinder	°F
Turbine inlet temperature	°F
Turbine outlet temperature	°F
Turbine inlet pressure	in.Hg
Turbine outlet pressure	in.Hg
Engine Cooling Data	
Temperature of each cylinder head	°F
Static pressure above cylinder (U tube)	in.H_2O
Static pressure below cylinders (U tube)	in.H_2O
Four temperatures in cowling plenum above engine	°F
Six temperatures in compartment below engine	°F

parameters. Some of these parameters were also available to the pilot and flight engineer for instant display (see Table 6-8). During the progress of the experiment, additional temperatures were added to this list; others were deleted as they were not considered necessary.

The engine was equipped with a Lebow torquemeter, model 1239-101, S/N 108, which was calibrated by AVCO Lycoming using a dynamometer and standard procedures in their facility. The torquemeter readout was a Daytronic 9010 main frame with model 9530 readouts for torque in in.-lb and internal torquemeter temperatures in °F.

AVCO Lycoming furnished test detonation equipment which has been designed especially for use in flight. AVCO Lycoming has developed a technique which indirectly monitors the pressure oscillation in each cylinder by means of individual sensors affixed to the spark plug using a special adaptor. The sensors are vibrationally activated and survey the detonation process by external, nonpenetration means. From past surveys of various Lycoming engines the magnitude of the external cylinder vibration to the pressure oscillation within the cylinder has been correlated. Transformation of the vibration signals into meaningful data is accomplished by a signal conditioning instrument developed by AVCO-Lycoming and displayed to the flight engineer or observer by means of a small scope. In this manner, incipient detonation not perceivable by the human ear is indicated early by the appearance of intermittent flashes in the scope. As the detonation becomes more perceivable, the frequency of these flashes increases. Further information about the detonation instrumentation is proprietary to AVCO-Lycoming.

Notice that the temperatures recorded permitted a diagnosis of the heat transfer characteristics at different sections in four different streams: engine air, engine fuel, engine oil, and engine external cooling air. These temperatures were complemented by pressure measurements.

The engine controls were conventional except for the magnetos (described in Section VI-H-2) and a resetting of the manifold pressure controller, which was set to provide higher pressure during the hydrogen enrichment flights.

6. Hydrogen Generator Instrumentation and Controls

The hydrogen generator assembly, as described in Figure 6-16, was equipped with a set of thermocouples and pressure taps which were used to monitor and operate the generator. A list of instrumentation is given in Table 6-10. These parameters were recorded during the hydrogen enrichment flights and some of them (marked with an asterisk) were also displayed visually to the flight crew. A variable position thermocouple probe which was used during Phase II to monitor the temperature in the reactivity zone of the generator (see Reference 6-10) was replaced by a set of six thermocouples distributed throughout the catalyst bed and spaced about 1 inch apart. The airflow was monitored by a Sierra Hot Wire anemometer-type air flow meter. The fuel was routed through an electric fuel metering valve to a flow meter with electric output.

Table 6-10. Recorded Hydrogen Generator Parameters

Parameter	Unit
* H_2 generator air flow	lb/hr
* H_2 generator fuel flow	lb/hr
* Pressure at inlet of H_2 generator	psia
Air gap pressure (at top of generator)	psia
Pressure at outlet of H_2 generator	psia
Atomizer air inlet pressure	psia
Fuel pressure to H_2 generator	psia
Air temperature into generator	^{o}F
* Generator air gap temperature	^{o}F
Air temperature out of the H_2 generator	^{o}F
* H_2 generator distribution manifold temperature	^{o}F
* H_2 generator catalyst temperatures (six thermocouples spaced about 1 inch apart in core of catalyst	^{o}F
* H_2 generator air preheat	^{o}F

Parameters marked with an asterisk were also displayed visually to the flight crew.

The generator assembly controls were operated from the cockpit. Some of the controls had an electric link with the controlling element (fuel metering and solenoid valves). Others had a mechanical link (generator air throttle and preheat mechanism, operated by cable), and others a hydraulic link (PV-1, PV-2, and AV-1 operated by engine oil pressure).

A functional description of the generator assembly, as well as the role played by each component, can be found in References 6-9 and 6-10.

7. Data Systems

The instrumentation listed comprises 18 pressures, 37 temperatures, three flow meters, and one torquemeter. The number of pressures and temperatures changed slightly during the different stages of this effort.

a. Pressures. Without exception, the pressure was obtained by the installation of pressure tap lines from the point of interest. These pressure lines would be routed to the cockpit and from there branched off to a gage display or to pressure transducers for input in the data system and/or digital readout display. The aircraft air speed and pressure altitude were treated by the same method. In an effort to reduce the number of pressure tap lines from the engine to the cockpit, use was made of a 24-port scani-valve which sampled the following pressures:

Port No.	
1	Pressure forward of oil cooler
2	Pressure aft of oil cooler
3	Compressor inlet pressure
4	Static pressure above engine (U tube)
5	Static pressure below engine (U tube)
6	Aircraft static pressure (from pitot-static systems)

The scani-valve was referred to the aircraft pressure system, and changed ports every 0.125 seconds. The scani-valve was located inside the engine nacelle and can be seen in the photograph shown in Figure 6-51.

b. Temperatures. Most of the temperature sensors consisted of thermocouples whose wire leads had to be conducted to the cold reference junctions located in the cockpit. The output from the cold reference junctions could be displayed to the crew and/or sent to the data systems.

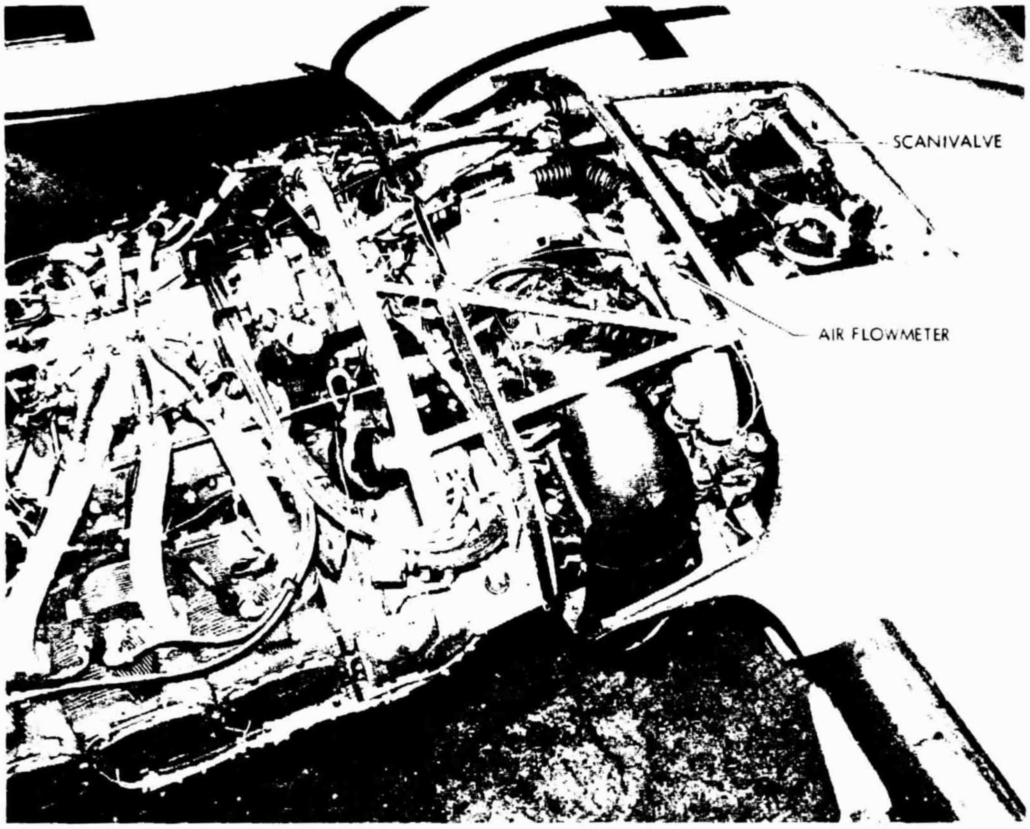


Figure 6-51. Installation of Scani-Valve and Hydrogen Generator Air Flow Meter in Engine Nacelle

c. Torquemeter. This torquemeter consisted essentially of a set of strain gages mounted on a disc which was positioned on a coupling between the engine shaft and the propeller spinner. The currents from the strain gages were balanced with bridges located in the torquemeter module in the cockpit together with the torquemeter indicator which had a signal input to the data systems.

d. Signal Conditioners. The signals described above were conditioned and formatted for compatibility with the data acquisition system. The signal conditioners include cold reference junctions, potentiometers, amplifiers and digitizers.

e. Data Acquisition Systems. The data acquisition system was a pulsed-conditioned modulator (PCM) combined with a magnetic recorder which produced a digital magnetic tape output. The PCM has a sampling rate of 8 records a second, which is much higher than was needed for this program. During a specified interval of 7.5 seconds, 60 samples were recorded and averaged, except for those pressure handled by the scani-valve, each one of which was sampled 10 times before the next port was cycled into position.

f. Flight Engineers Console. This console was specifically manufactured for the purpose of facilitating control of the requirements of the experiment to the flight engineer. The console contains the indicators and controls necessary to monitor and operate the engine/generator system in-flight. It also contains the start and stop controls for the data acquisition system and tape recorder.

g. Power Supplies. These units provided power to the signal conditioners, data acquisition system and tape recorder, flight engineer's console, and instrumentation.

The thermocouple wires, pressure taps, cables and other wiring from different points in the engine were collected in an umbilical cord, fed through the nacelle firewall and through the wing root and routed into the cockpit. Figure 6-52 shows a schematic diagram of the installation of the engine, the routing of the wiring, and the cockpit arrangements for the flight console, power supplies and signal conditioners, and data acquisition system and tape recorder. Figures 6-53 and 6-54 show photographs of those consoles in the cockpit.

8. Procedures

For the purpose of obtaining the information set forward for this phase and described earlier in this section, a number of flights were undertaken. Under normal circumstances four cases were explored during a flight, namely, one leanout at constant manifold pressure, one leanout at constant power, and two spark settings. The following procedures were observed for each flight:

a. Leanouts for Gasoline Only.

(1) Thirty minutes prior to flight, the torquemeter indicator was allowed to warm up using a commercial ac power source.

(2) The engines were started and allowed a 15-minute warmup period.

(3) The left engine was shut down and the torquemeter calibrated per Lebow instructions.

(4) The left engine was restarted and the magnetos set at the retarded timings.

(5) The airplane taxied, took off and climbed to the desired altitude.

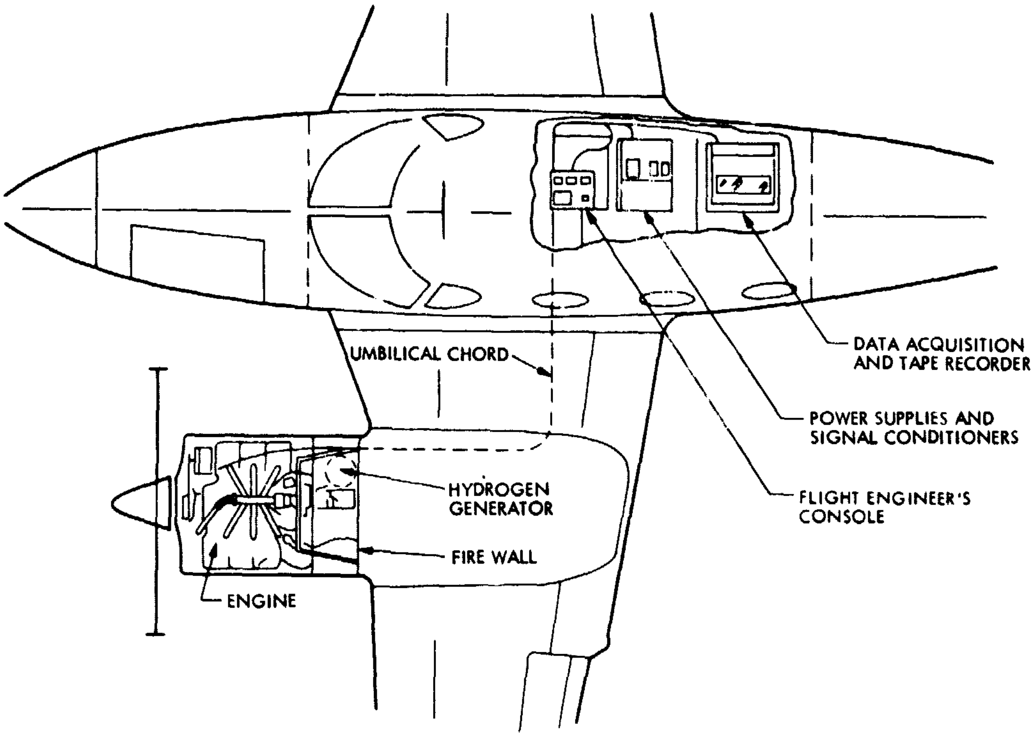


Figure 6-52. Instrumentation and Data System Arrangements in the Aircraft

(6) Once the desired altitude was established, an air speed was selected (its air speed was kept approximately near 140 KIAS throughout all the flights).

(7) The left engine speed was adjusted to desired rpm.

(8) The left engine manifold pressure was set to meet the approximate power setting desired on the rich zone per standard aircraft manual instructions.

(9) The mixture was then leaned by reducing the engine fuel flow until the best torque was indicated by the torquemeter indicator.

(10) The indicated torque was then compared to the nominal torque as given by the manual, and the manifold pressure and fuel flow were again adjusted, if required, until the indicated torque equaled the nominal torque at the best power fuel flow.

(11) The power of the right engine was then adjusted to maintain 140 KIAS air speed.

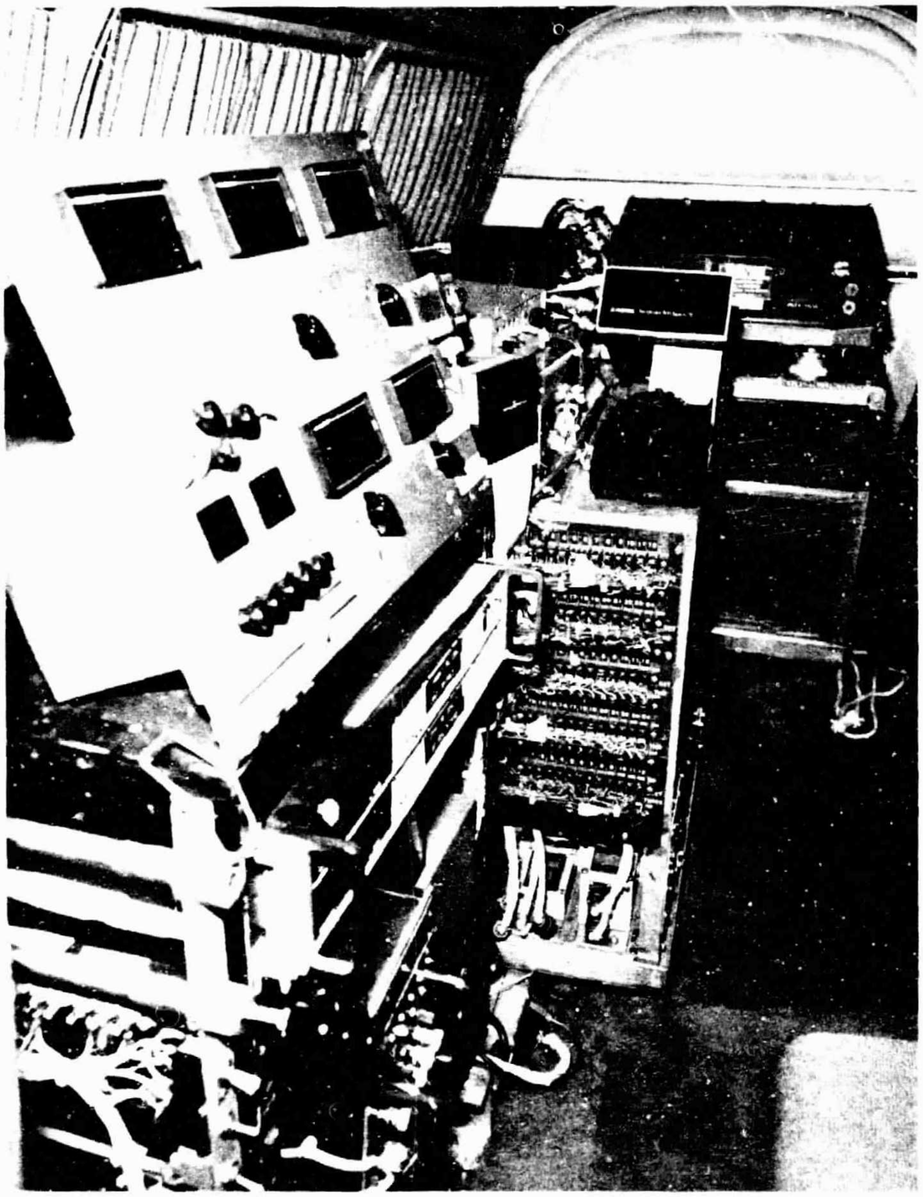


Figure 6-53. Arrangement of Consoles Inside Cockpit (Looking Aft)

(12) The left engine electrical generator was turned off so that the aircraft electrical load would not affect the power output of the left engine. The left cowl flap was closed as much as possible. (At high power settings, however, the left cowl flap was opened further and the fuel boost pumps turned on to assure a steady fuel flow).

(13) The scani-valve was turned on, the PCM tape activated and a run number set on the record counter.

Figure 6-54. Flight Engineer's Console, Power Supplies and Signal Conditioner

(14) A start and stop time was then noted on the flight data sheet to encompass a 2-minute sampling period. During this time a set of parameters was manually recorded (see Table 6-11).

(15) For the constant manifold pressure leanout cases, and starting from the best power operating point, the pilot initiated a leanout by operating the fuel lever, while all the other parameters of the left engine were kept equal.

(16) For the constant power leanout cases the pilot initiated a leanout by operating the fuel lever and maintaining constant power in the left engine by boosting the manifold pressure while all the other parameters were kept constant.

(17) After obtaining the leanout curves for the retarded spark setting (say 20° BTDC) the switches S1 and S2 located at the cockpit were set to the advanced position and two more leanout curves were obtained using the same procedures described in (15) and (16).

Table 6-11. List of Parameters Recorded Manually by the Flight Engineer

Aircraft fuel flow
OAT from aircraft gage
KIAS
M.A.P
RPM
Fuel flow
Turbine inlet temperatures from aircraft gage
Magneto setting
Average torque
Hottest cylinder head temperature
Compressor outlet temperature (after flight 254)
Qualitative analysis of engine operation

(18) During the initial flights and at high power settings, detonation equipment was used to monitor the engine operation. The procedures in (15), (16), and (17) were slightly different as some caution was exercised to protect the engine from unintentional detonation. It was soon realized that the techniques used to gather the experimental data were not detonation-limited. The detonation equipment was then removed from the aircraft and the procedures expedited to those described in (15, (16), and (17).

(19) The qualitative analysis of the engine operation was made by the pilot, who characterized every operating point by three ratings: (a) engine operation normal, (b) perceivable engine roughness, (c) unacceptable engine operation (due to severe roughness, engine misfiring, etc.).

(20) The leanout curves were characterized by a set of operating points or runs which were obtained by leaning the mixture in increments until engine roughness precluded the gathering of further data. The data from each one of these points was recorded automatically and manually for a period of 2 minutes, using the procedures described in (14). Once the set of four

leanout curves was obtained, the flight would be terminated or resumed to explore another set of four cases, as desired.

b. Leanouts with Hydrogen Enrichment.

(1) Preheat hydrogen generator catalyst to 700°F.

(2) Start generator per manual instructions (Reference 6-13).

(3) Set generator controls to obtain an output of 1.5 lb/hr of hydrogen flow rate.

(4) Steps (1), (2), and (3) were conducted as the preflight, takeoff and climb activities were in progress as described above under Gasoline-Only Flights. The generator output was at this time dumped overboard, while the flight crew conducted steps identical to those undertaken from (1) to (12) for the gasoline-only cases.

(5) When the crew was ready to start a leanout curve, the hydrogen generator output was diverted into the engine.

(6) Further adjustments on the engine generator assembly were conducted to regain the best power point after system stabilization.

(7) The rest of the steps would be resumed analogously to steps from (13) to (20) for the gasoline-only cases.

(8) Once the leanout curves were completed, the generator would be shut down under set standard procedures.

(9) As a safety measure, part of the exhaust gases from the engine would be diverted into the generator for cooling purposes, to assure that the generator engine assembly temperatures were at safe levels at the time of airplane landing. This was achieved by operating valve EV (see Figure 6-16).

c. Limitations. During the flight tests the following boundaries were used as engine limitations:

(1) Turbine inlet temperature (TIT), 1697°F.

(2) Cylinder head temperature (CHT), 475°F.

(3) Turbocharger turbine speed limit, expressed as a difference between the compressor outlet temperature (COT) and compressor inlet temperature (CIT) as given by:

TIT = 1697°F, COT - CIT = 350°F.

TIT = 1650°F, COT - CIT = 400°F.

(4) Maximum RPM = 2900.

(5) Maximum manifold pressure = 41 in.Hg.

The hydrogen generator, being an experimental component, had inherent problems derived from its interface with the aircraft engine systems. A few of these problems were encountered when starting the generator. Originally, the generator was designed to be started electrically by means of a high-temperature heater, but during the prequalification of Phase II, the electrical heater was discarded because of frequent failure due to engine vibrations. Arrangements had also been made to heat up the catalyst by using the engine exhaust gases. Although it was estimated that this procedure would be sufficient to start the generator in-flight, it became evident in Phase II that such a procedure was very marginal, although it remained as a primary method to be further explored in Phase III.

Another method that proved to be successful in Phase II for starting the generator consisted in heating up the catalyst by means of an external flow of hot air. A portable electric heater mounted on a cart was fabricated. The generator was started on the ground during the preflight activities and the whole generator assembly system allowed to warm up to a steady-state condition. These activities were initiated one hour before flight. Shortly before starting the left engine for takeoff, the generator was shut down and restarted during climbout before the catalyst had a chance to lose the residual heat.

While the generator was actually started once using the first method, it took 1-1/2 hours of flight to achieve it. Attention was then diverted to using the second method, which proved to be straightforward.

The required generator output of 1-1/2 lb/hr could not be accomplished by the system shown in Figure 6-16 because of the limitation of air flow through the generator. To overcome this, the manifold pressure controller was reset for boosting the compressor discharge pressure while simultaneously controlling engine air flow and pressure drop across the generator by means of the engine and generator throttles.

9. Safety Considerations

During the course of the program in-flight safety was of prime importance and never compromised. This was reflected in the design features incorporated in the hydrogen generator system (shown in Figure 6-16) such as continuous monitoring of the internal and external temperatures in the hydrogen generator system, isolation valves to separate the generator system from the engine, and periodic ground leak tests to assure plumbing integrity. Vibration tests on the generator were also conducted at JPL and AVCO Lycoming for verification of the mechanical integrity of the mounting system, plumbing and catalyst bed.

During Phase III, additional measures were added to the safety of the program; in those flights with gasoline only, the generator system was disconnected and the lines capped. JPL technical personnel were brought in during the hydrogen enrichment flights and operated the generator equipment in-flight. The aircraft was kept close to Beechcraft Airfield during the hydrogen enrichment flights. Ground-to-air contact was maintained during those flights. The surroundings of the generator were monitored by a system of engine compartment thermocouples to detect abnormal heat radiated from the generator.

10. Results

a. Matrix of Flights. Following the procedures described above, a series of flights were undertaken to cover the ranges of interest in altitude, power, manifold pressure and spark advance timing. Table 6-12 summarizes the leanout curves. Notice that four altitudes were explored: 5,000 15,000, 22,000, and 25,000 ft. Each flight covered two ignition timings, and two sets of leanout curves were obtained during each flight: one at constant manifold pressure, the other at constant power. The constant manifold pressure leanout curve was obtained at the manifold pressure which produces the power of interest for that specific flight, when operating the engine at the best power point. The leanout curves at constant manifold pressure are of special interest for two reasons: (1) they allow duplication of the leanout curves obtained during Phase II, the thermodynamics of which are well understood; (2) they are used as monitors for the constant power leanout curves with respect to flying techniques, instrumentation, and detection of accidental errors. It is also seen that several power levels were explored. The lower levels (45 and 55% rated power) were investigated because of the absence of data at these low power settings during Phase II, and to provide a stepping stone for higher power levels at the beginning of the flight test series, when there was uncertainty about the detonability of the mixtures during the leanout. Four spark advances have been studied, but unfortunately, and as described under VI-H-8, only two timings could be exercised during each flight. This made it impossible to obtain a sequence of leanout curves for each of the four timings, keeping all the other parameters constant. More about this point will be said later under discussion of results.

b. Data Reduction. A Fortran program was used to reduce the recorded data to a usable form. After the averaging procedures described in Section VI-H-8, a series of calculations were conducted to translate the recorded flight and engine variables into the correct physical magnitudes. Details on the data reduction are given in Reference 6-20. Most of the recorded parameters were used only in a monitoring function, and the essence of the flight experiments is given by the leanout variations of the BSFC, power, manifold pressure, cylinder head temperatures, and turbine inlet temperature. To bring into evidence the phenomenology of combustion, the variation during the leanout has to be expressed as a function of equivalence ratio. We encounter a difficulty here, however: while the fuel flow was accurately measured, no attempt was made to measure the air flow through the engine. Reference 6-19 describes the calculation of the air flow based on the engine rpm, displacement, manifold pressure, and manifold temperature. These calculations were

Table 6-12. Summary of Leanout Curves

Altitude, ft	Power, % rated	Manifold Pressure, in. Hg	Timing, °BTDC	Flight No.
5000	45%	----	20-30	254
5000	---	25.4	20-30	254
5000	45%	----	25-35	260
5000	---	24.1	25-35	260
5000	55%	----	20-30	250
5000	---	27.3	20-30	250
5000	55%	----	25-35	261
5000	---	27.5	25-35	261
5000	65%	----	20-30	252
5000	---	29.3	20-30	252
5000	65%	----	25-35	264
5000	---	28.8	25-35	264
5000	75%	----	20-30	268
5000	---	31.1	20-30	268
5000	75%	----	25-35	265
5000	---	31.9	25-35	265
15000	55%	----	20-30	251
15000	---	27.1	20-30	251
15000	55%	----	25-35	257
15000	---	27.0	25-35	257
15000	65%	----	20-30	249
15000	---	28.3	20-30	249
15000	65%	----	25-35	263
15000	---	28.9	25-35	263

Table 6-12. Summary of Leanout Curves (contd)

Altitude, ft	Power, % rated	Manifold Pressure, in. Hg	Timing, °BTDC	Flight No.
15000	75%	----	20-30	253
15000	---	31.6	20-30	253
15000	75%	----	25-35	262
15000	---	31.5	25-35	262
22000	75%	----	20-30	267
22000	---	32.4	20-30	267
22000	75%	----	25-35	266
22000	---	33.0	25-35	266
25000	65%	----	20-30	269
25000	---	30.6	20-30	269
25000	65%	----	25-35	256
25000	---	29.6	25-35	256
25000	75%	----	20-30	255
25000	---	28.7	20-30	255
15000	65%	----	30	272[a]
15000	---	28.7	30	272[a]
15000	65%	----	30	273[b]
15000	---	30.6	30	273[b]
15000	65%	----	30	276[c]
15000	---	30.5	30	276[c]

[a]Baseline with gasoline only and hydrogen generator system installed.
[b]Undetermined small amount of hydrogen into the engine.
[c]Hydrogen generator system injecting 1-1/2 lb/hr of hydrogen into the engine under known controlled conditions.

modified using air flow correlation factors observed at the test cell during Phase II under nearly equal conditions. Notice though that all the data obtained during Phase II was at constant manifold pressure, and a large uncertainty is left about the true value of the air flow during the constant power leanouts.

c. Gasoline-Only Flights. The results from Phase III, given in Reference 6-19, have been plotted here in condensed form, specifying four ignition timings in each plot. In the following paragraphs a set of two figures is given for each altitude and power setting. One figure corresponds to the constant power manifold pressure leanouts, the other to the constant power leanouts. The engine roughness conditions encountered in each case are indicated in the figures (* = incipient; ** = severe).

1) 5000-Ft Altitude. Figures 6-55 through 6-62 recap the results obtained at 5000 feet. Figure 6-55 shows the constant manifold pressure case at 45% best power, and 2400 rpm. Figure 6-56 shows the constant power case for the same conditions. Notice in Figure 6-55 the wide variation between BSFC curves and manifold pressures obtained during Flights 254 and 260. This difference is also noticeable in the turbine inlet temperature curves. The same trend can be seen in Figure 6-56. Figures 6-57 and 6-58 show the 55% power settings for the same conditions. As with the previous case, it can be observed that there is a definite variation between the BSFC, manifold pressure and turbine inlet temperature curves for Flights 250 and 261, but the difference is not as pronounced as in the previous case. Figures 6-59 and 6-60 give the 65% power settings displaying similar differences in BSFC, manifold pressure and turbine inlet temperature for the two Flights, 252 and 264. Figures 6-61 and 6-62 show the results for the 75% power settings case; the same anomalous differences are seen for Flights 268 and 265, although this time such differences are only noticeable in the manifold pressure.

2) 15,000-Ft Altitude. Figures 6-63 to 6-68 show the results from 15,000-ft-altitude flights. Figure 6-63 shows the leanouts at constant manifold pressure for 55% power settings, and Figure 6-64 the constant power leanouts for the same conditions. Notice that in this case there are no such marked differences in BSFC, manifold pressure and TIT during Flights 251 and 257. Figures 6-65 and 6-66 show the 65% power settings case. It is again noticed that there are significant differences for Flights 249 and 263. Figures 6-67 and 6-68 show the results for 75% power settings; the data was obtained during Flights 253 and 262 and no marked differences are noticed.

3) 22,000-Ft Altitude. At this altitude, 75% power settings were explored. The data was obtained during Flights 266 and 267, and the results are shown in Figures 6-69 and 6-70. Notice that there is consistency in the BSFC and TIT, but, in Figure 6-69, the manifold pressures for one flight are slightly above the other. Figure 6-70 shows no peak in cylinder head temperature as the engine is leaned and the manifold pressure is increased in an attempt to keep constant power.

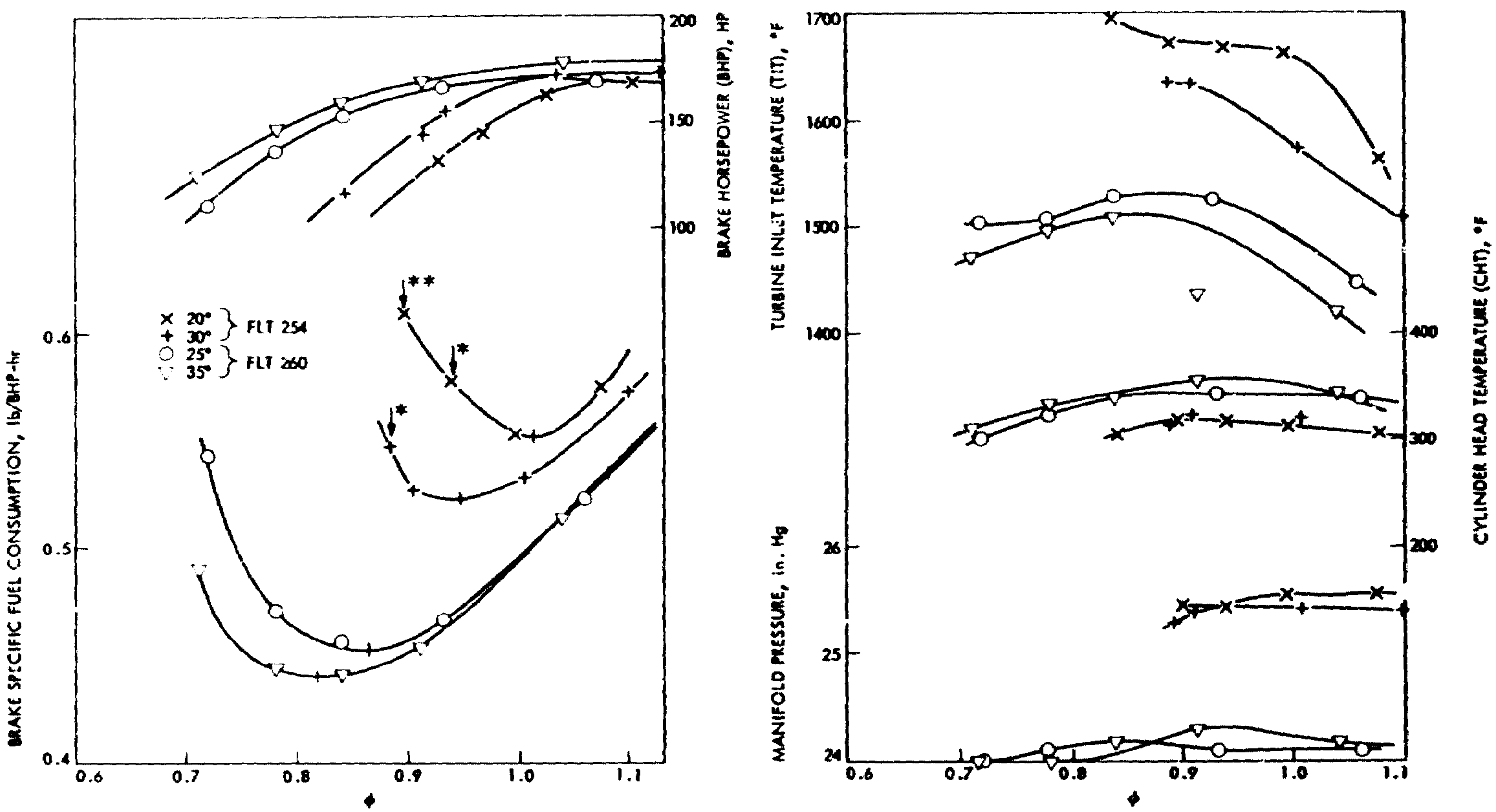


Figure 6-55. Leanout Curves for 2400 rpm, at 5000 ft, Constant Manifold Pressure = 25.5 in. Hg, and Several Ignition Timings

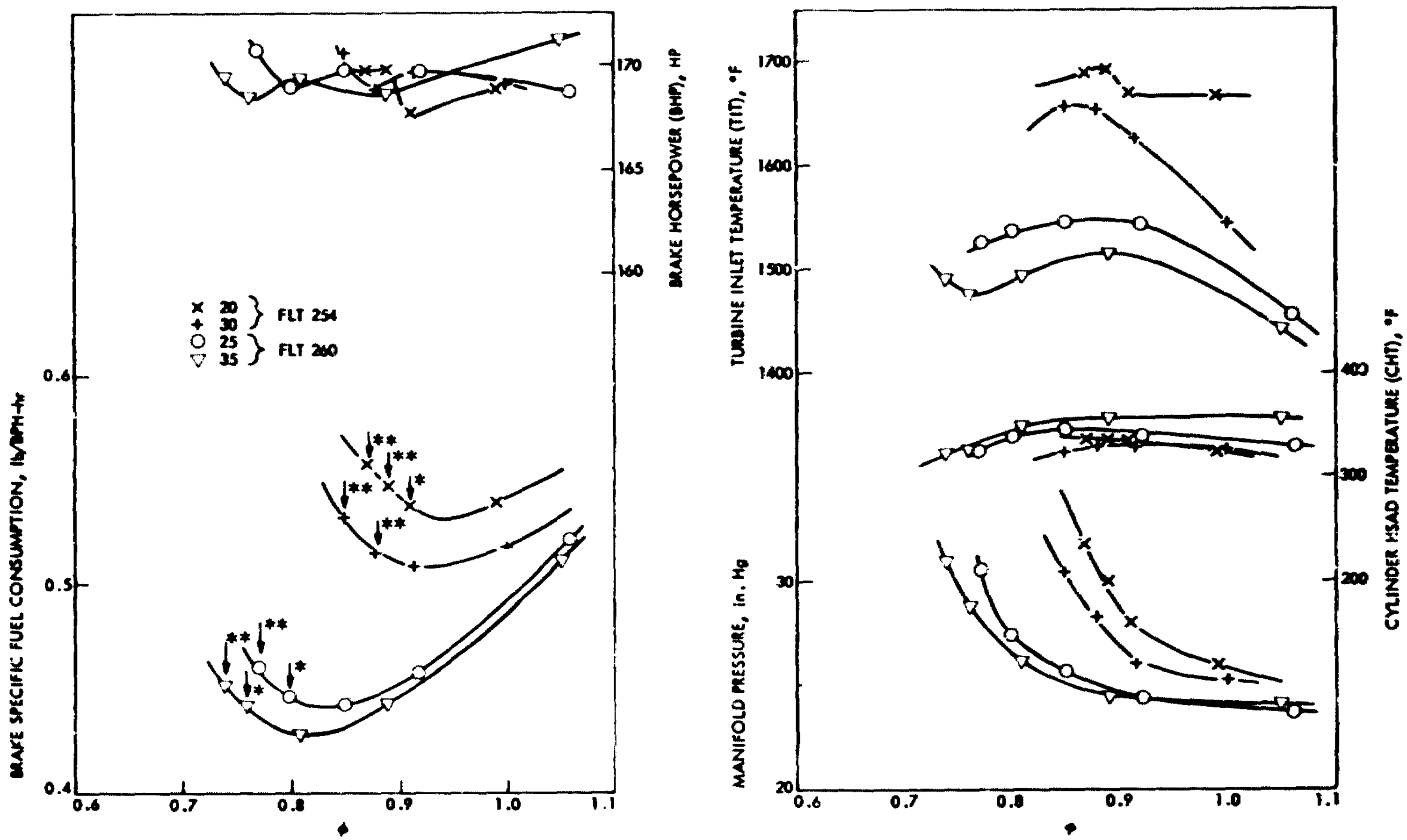


Figure 6-56. Leanout Curves for 2400 rpm, at 5000 ft, Constant Power = 45%, and Several Ignition Timings

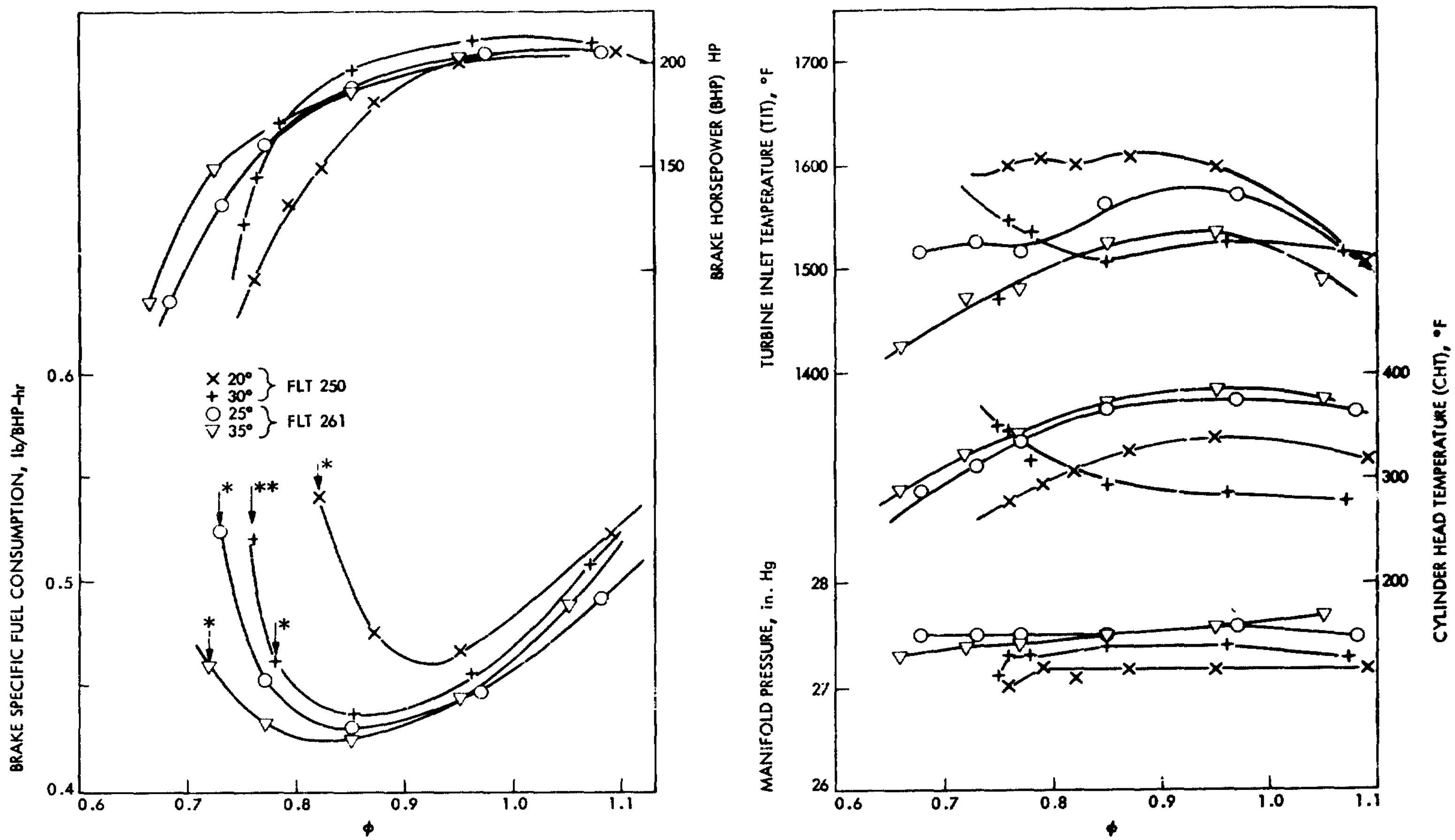


Figure 6-57. Leanout Curves for 2400 rpm, at 15,000 ft, Constant Manifold Pressure = 27 in. Hg, and Several Ignition Timings

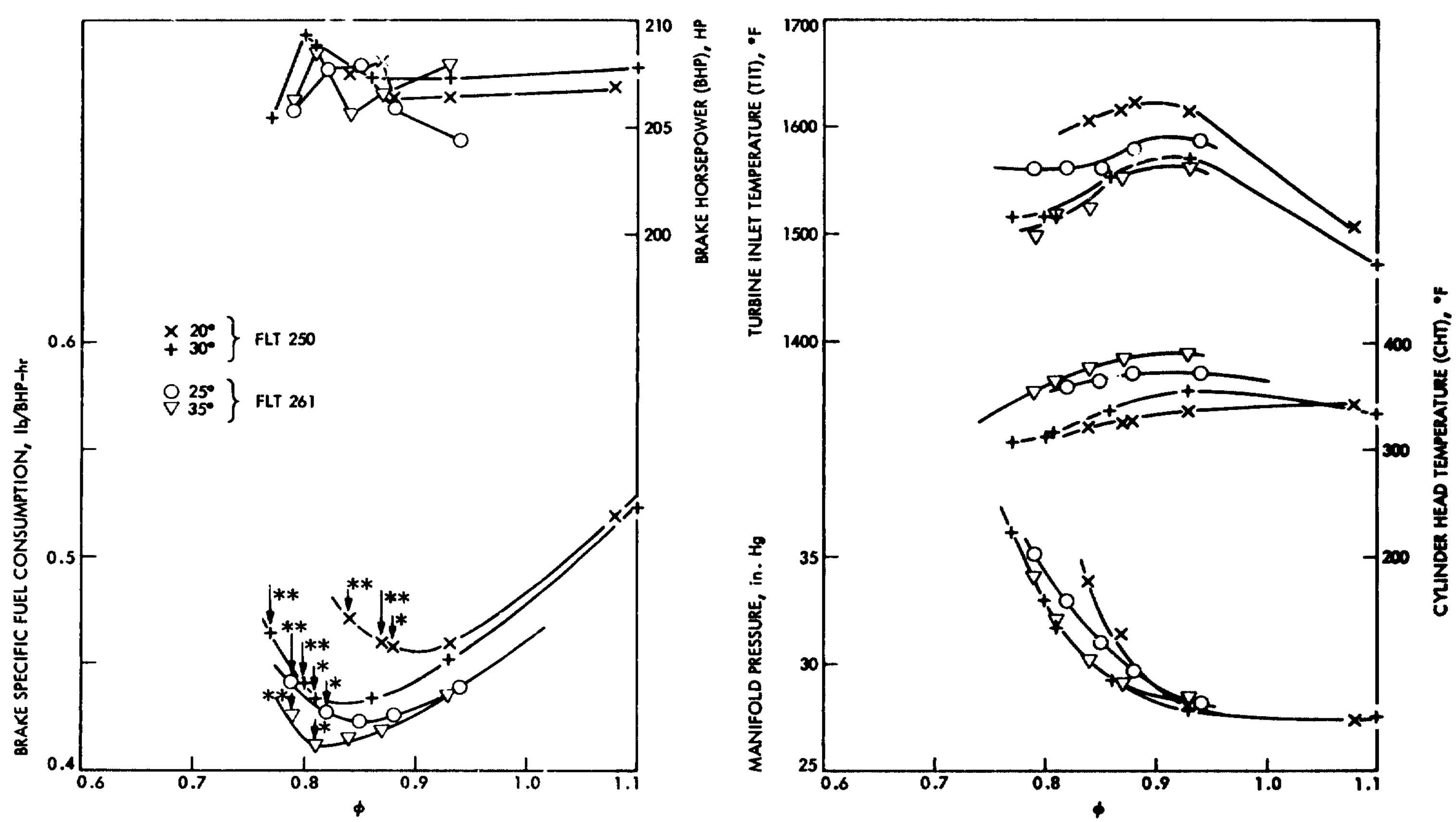


Figure 6-58. Leanout Curves for 2400 rpm, at 15,000 ft, Constant Power = 55%, and Several Ignition Timings

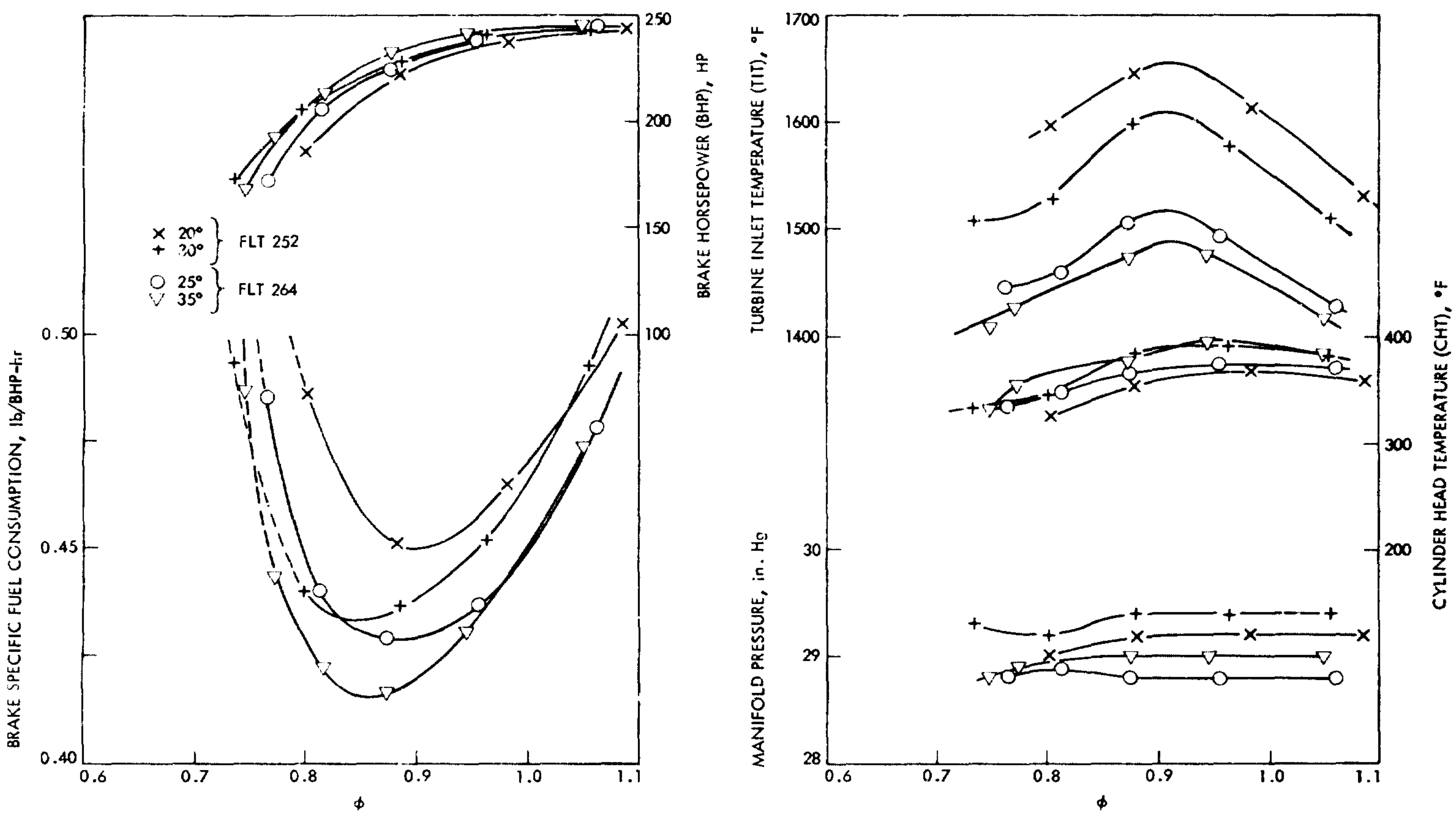


Figure 6-59. Leanout Curves for 2600 rpm, at 5000 ft, Constant Manifold Pressure = 29.3 in. Hg, and Several Ignition Timings (---Unstable Operation, Roughness)

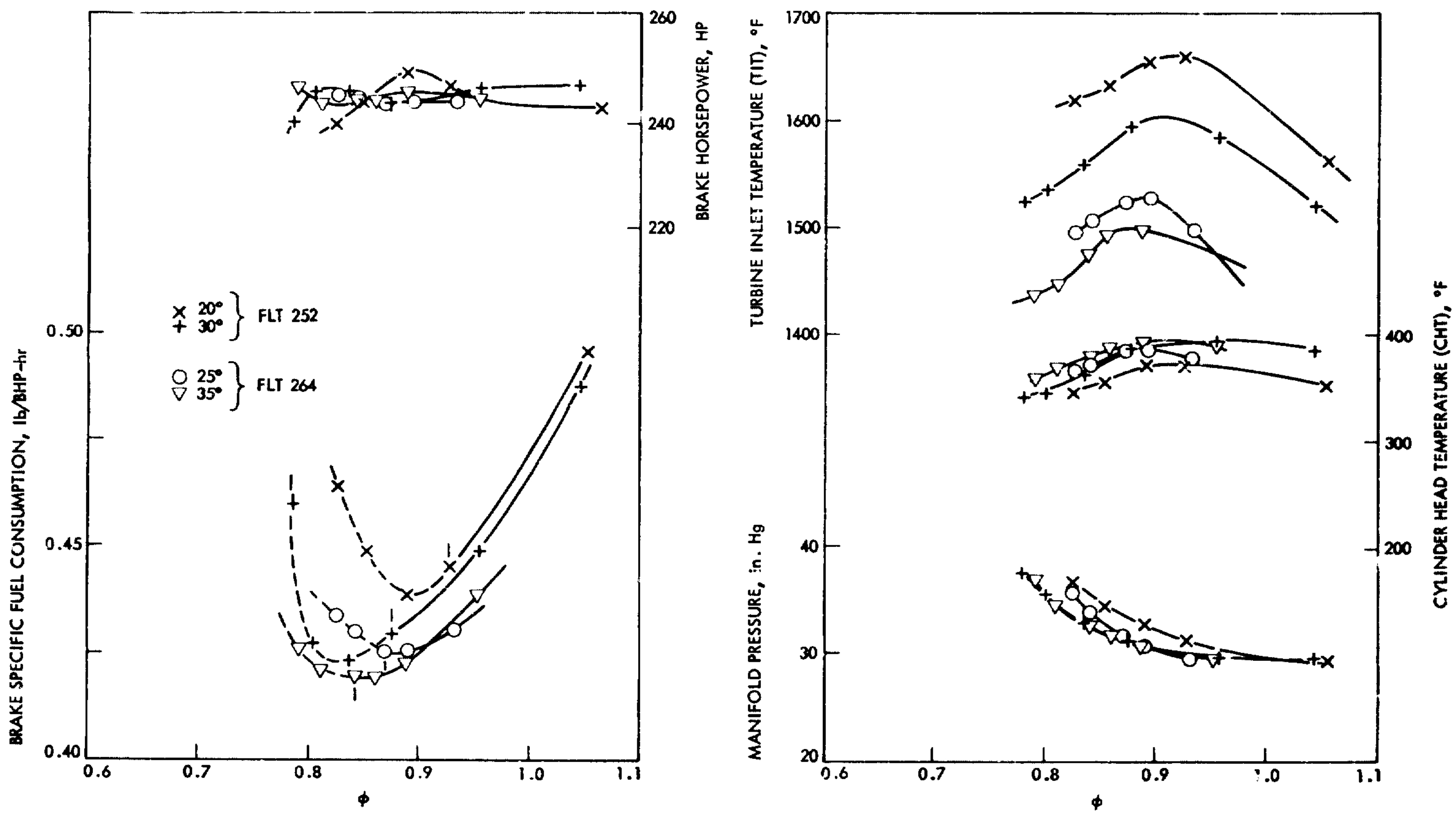


Figure 6-60. Leanout Curves for 2600 rpm, at 5000 ft, Constant Power = 65%, and Several Ignition Timings

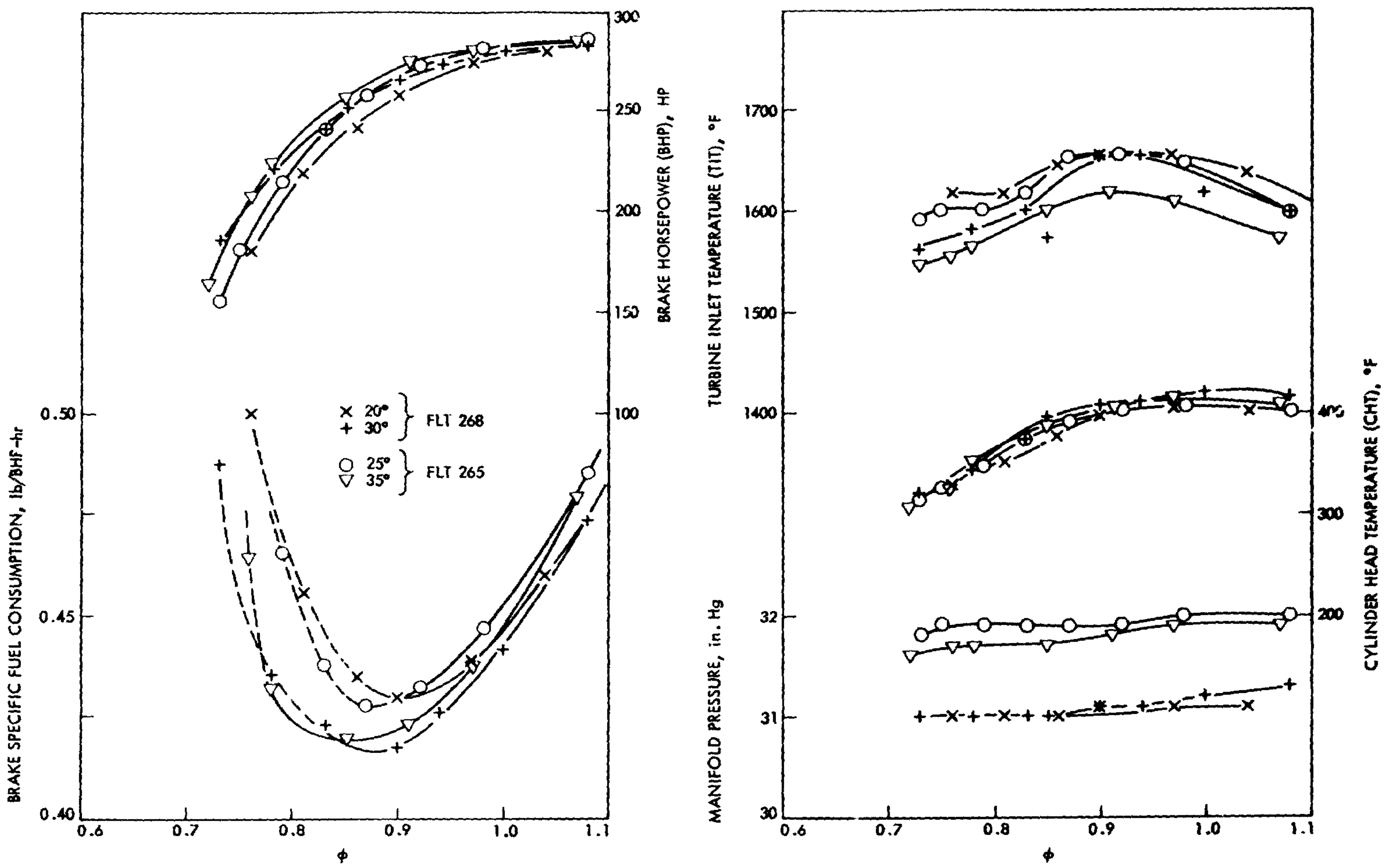


Figure 6-61. Leanout Curves for 2750 rpm, at 5000 ft, Constant Manifold Pressure = 31.5 in. Hg, and Several Ignition Timings (---Unstable Operation, Roughness)

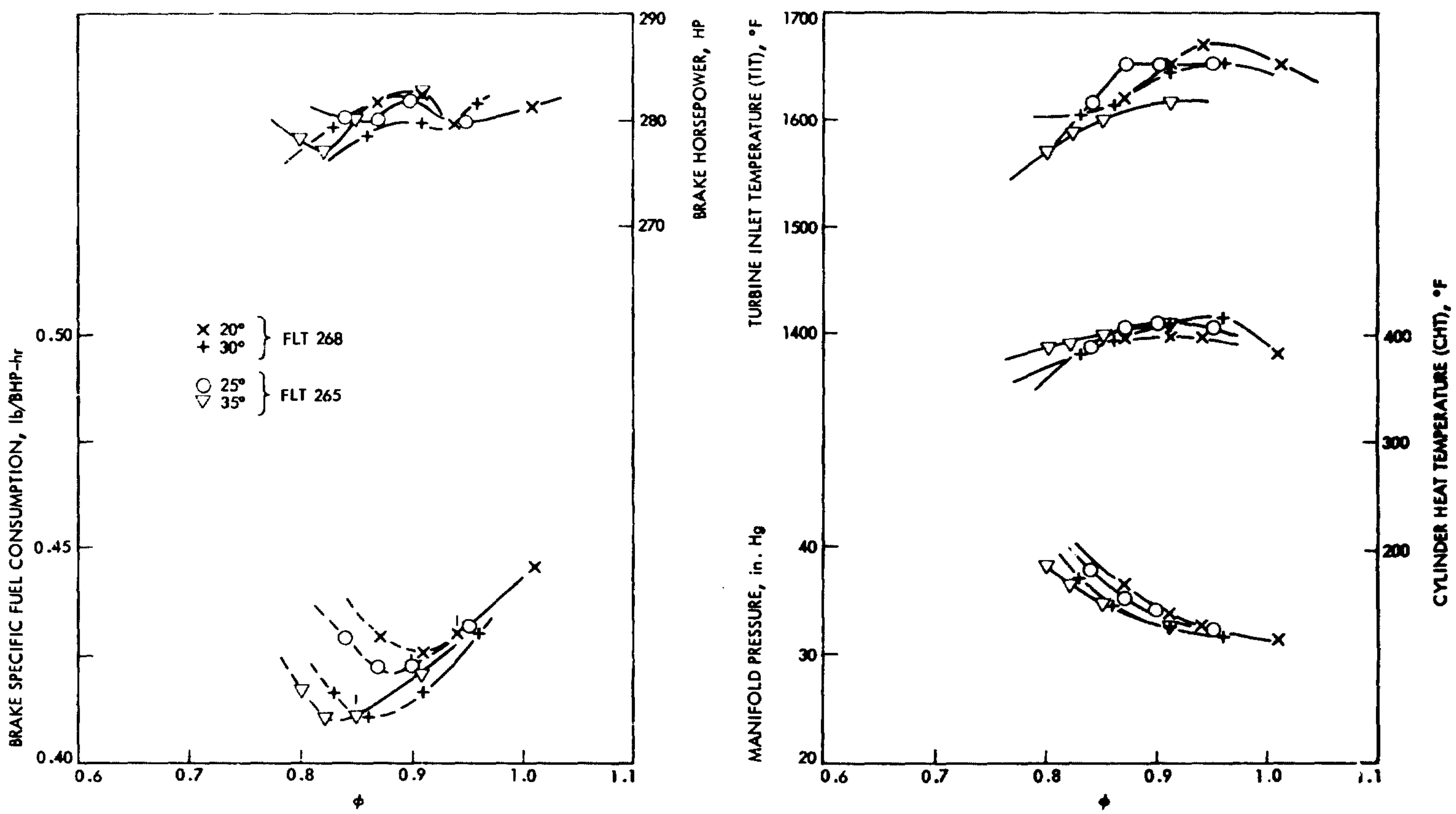


Figure 6-62. Leanout Curves for 2750 rpm, at 5000 ft, Constant Power = 75%, and Several Ignition Timings (---Unstable Operation, Roughness)

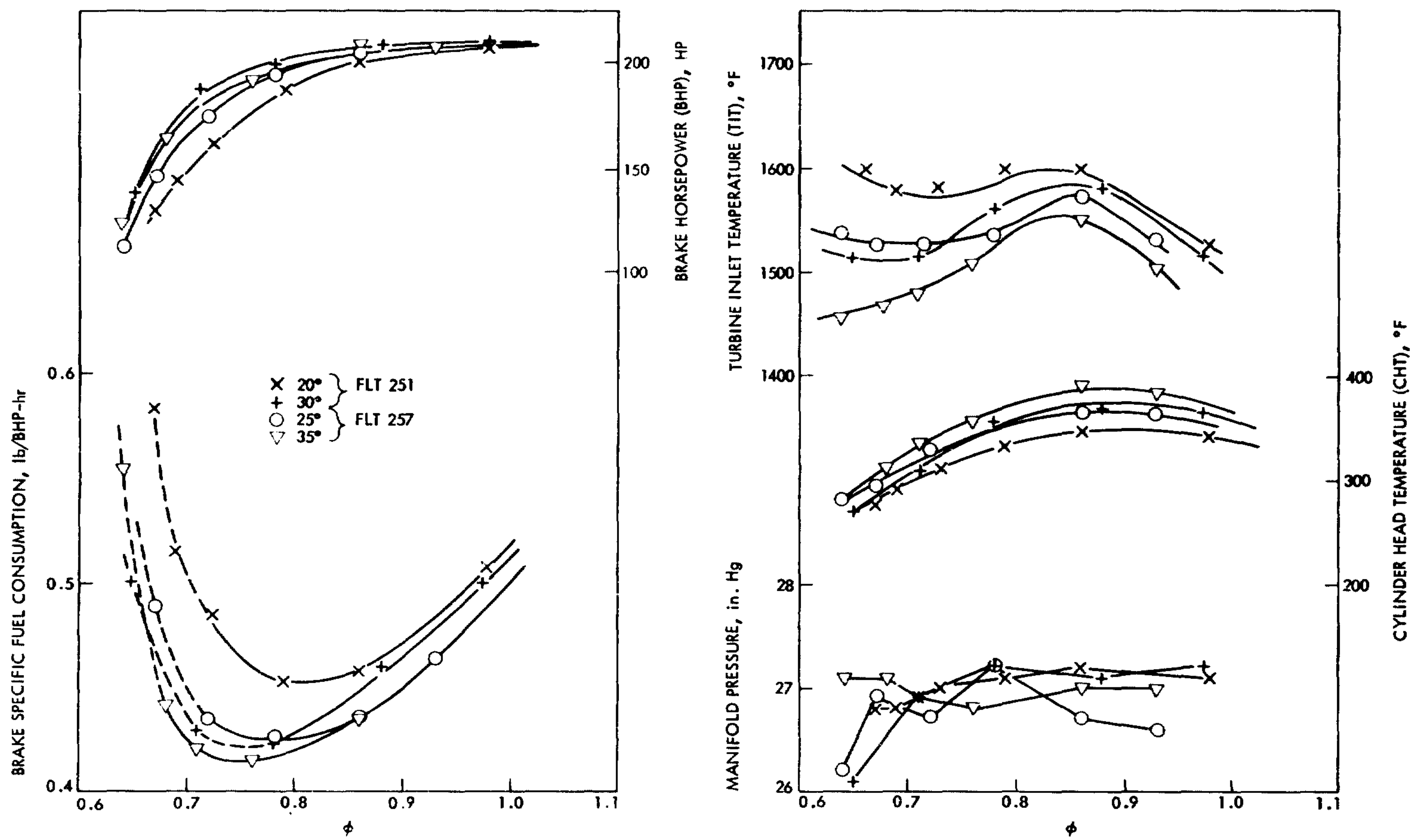


Figure 6-63. Leanout Curves for 2400 rpm, at 15,000 ft, Constant Manifold Pressure = 27 in. Hg., and Several Ignition Timings (---Unstable Operation, Roughness)

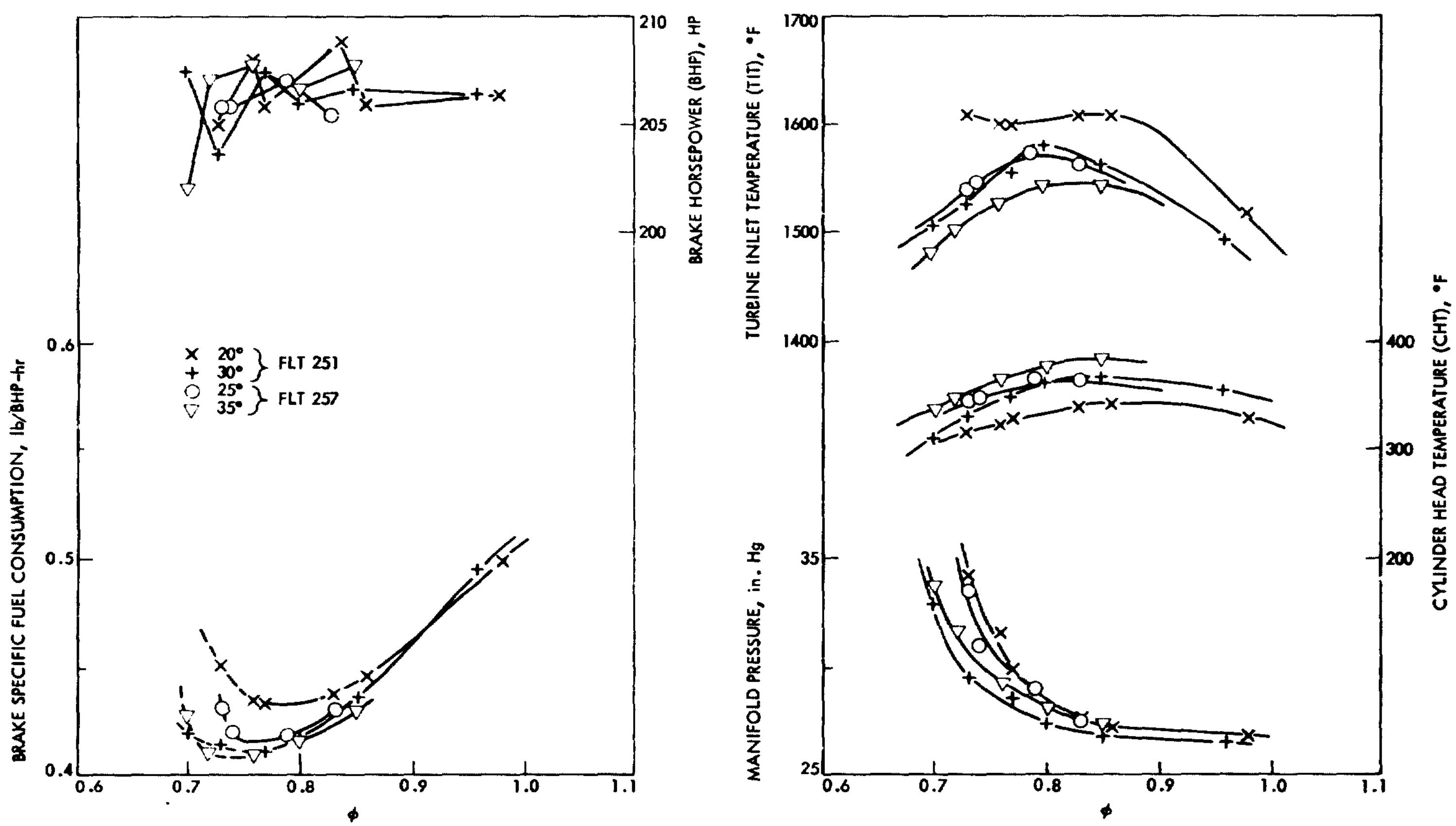


Figure 6-64. Leanout Curves for 2400 rpm, at 15,000 ft, Constant Power = 55%, and Several Ignition Timings (---Unstable Operation, Roughness)

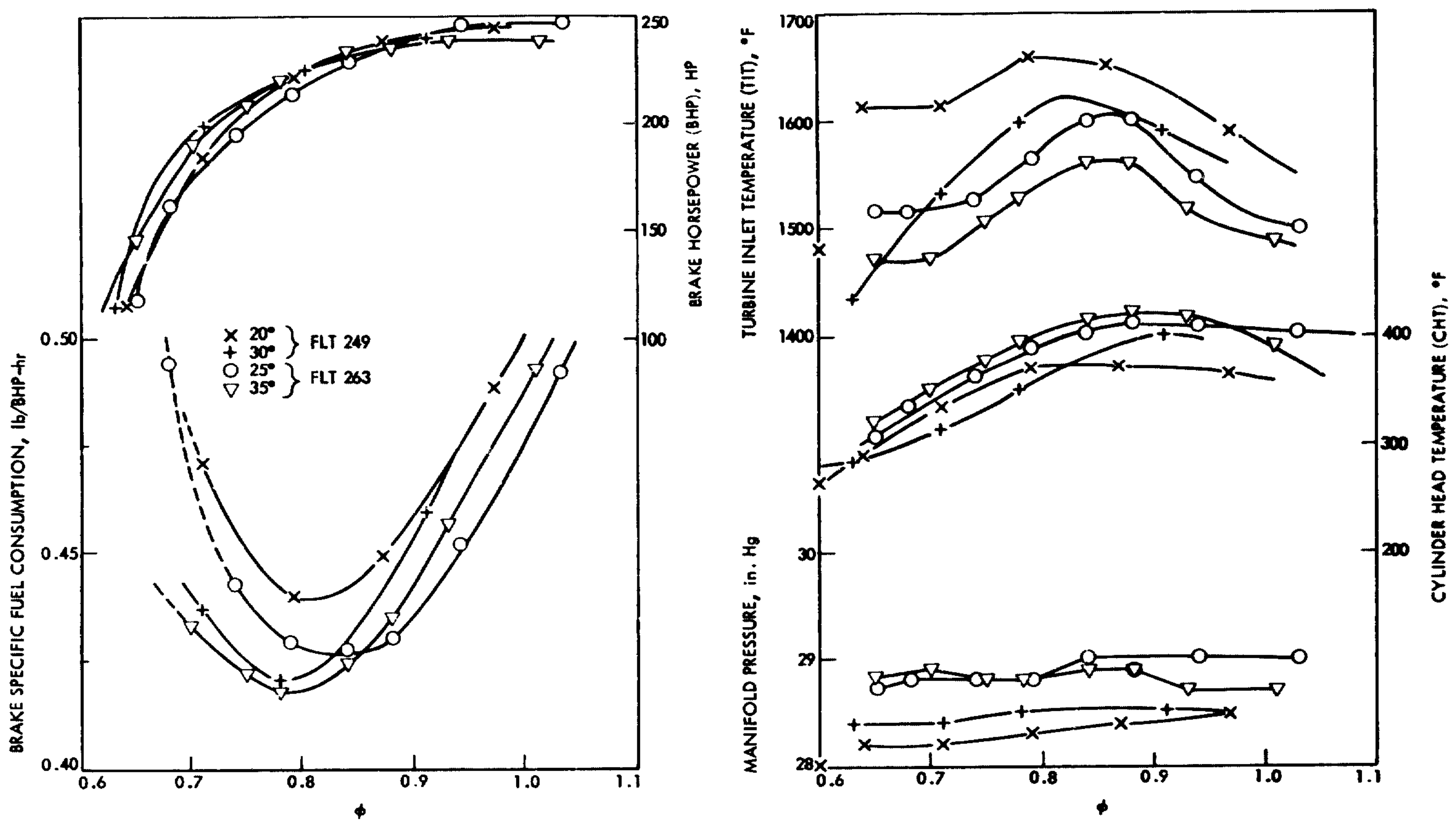


Figure 6-65. Leanout Curves for 2600 rpm, at 15,000 ft, Constant Manifold Pressure = 29.3 in. Hg., and Several Ignition Timings (---Unstable Operation, Roughness)

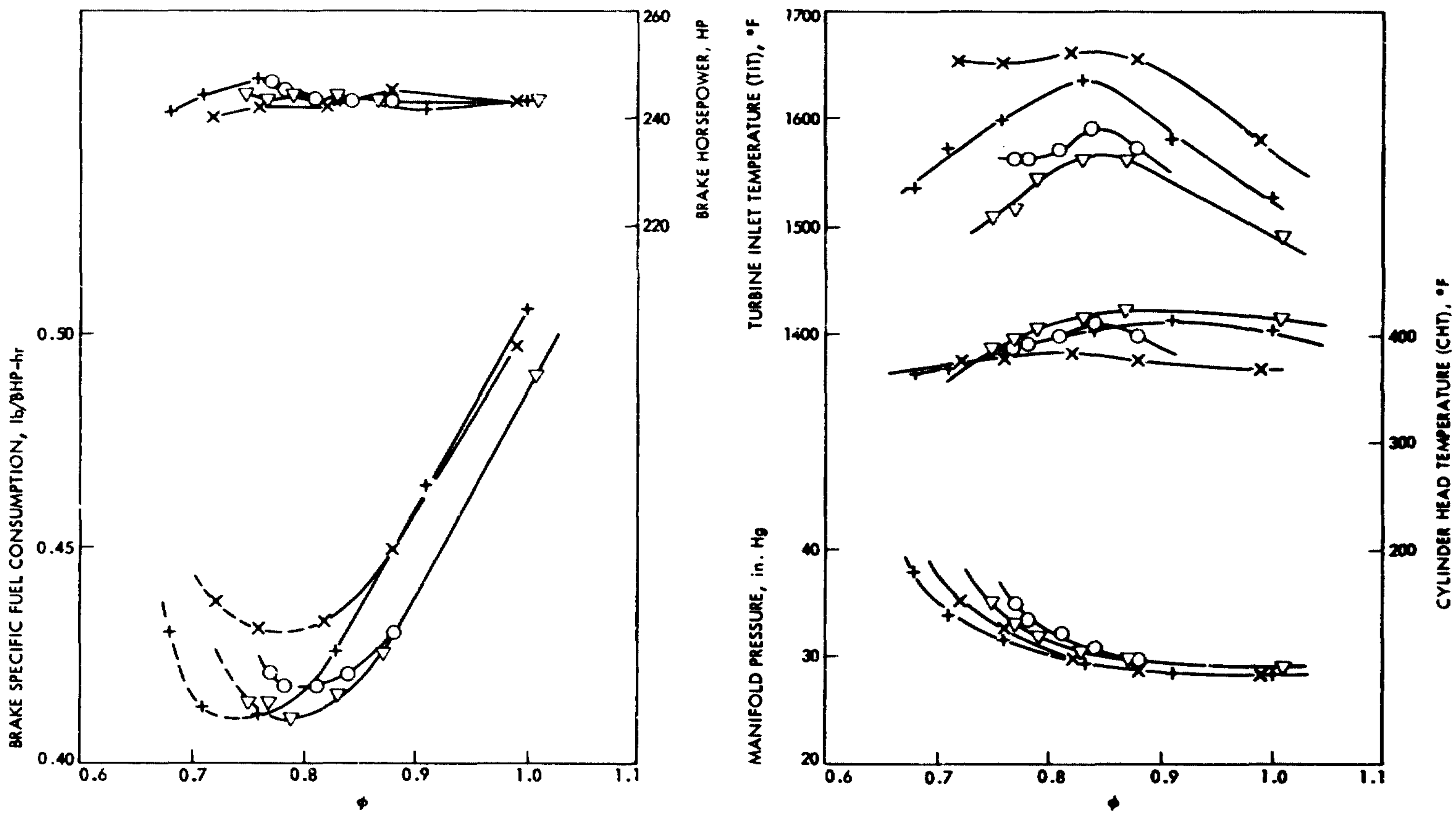


Figure 6-66. Leanout Curves for 2600 rpm, at 15,000 ft, Constant Power = 65%, and Several Ignition Timings (---Unstable Operation, Roughness)

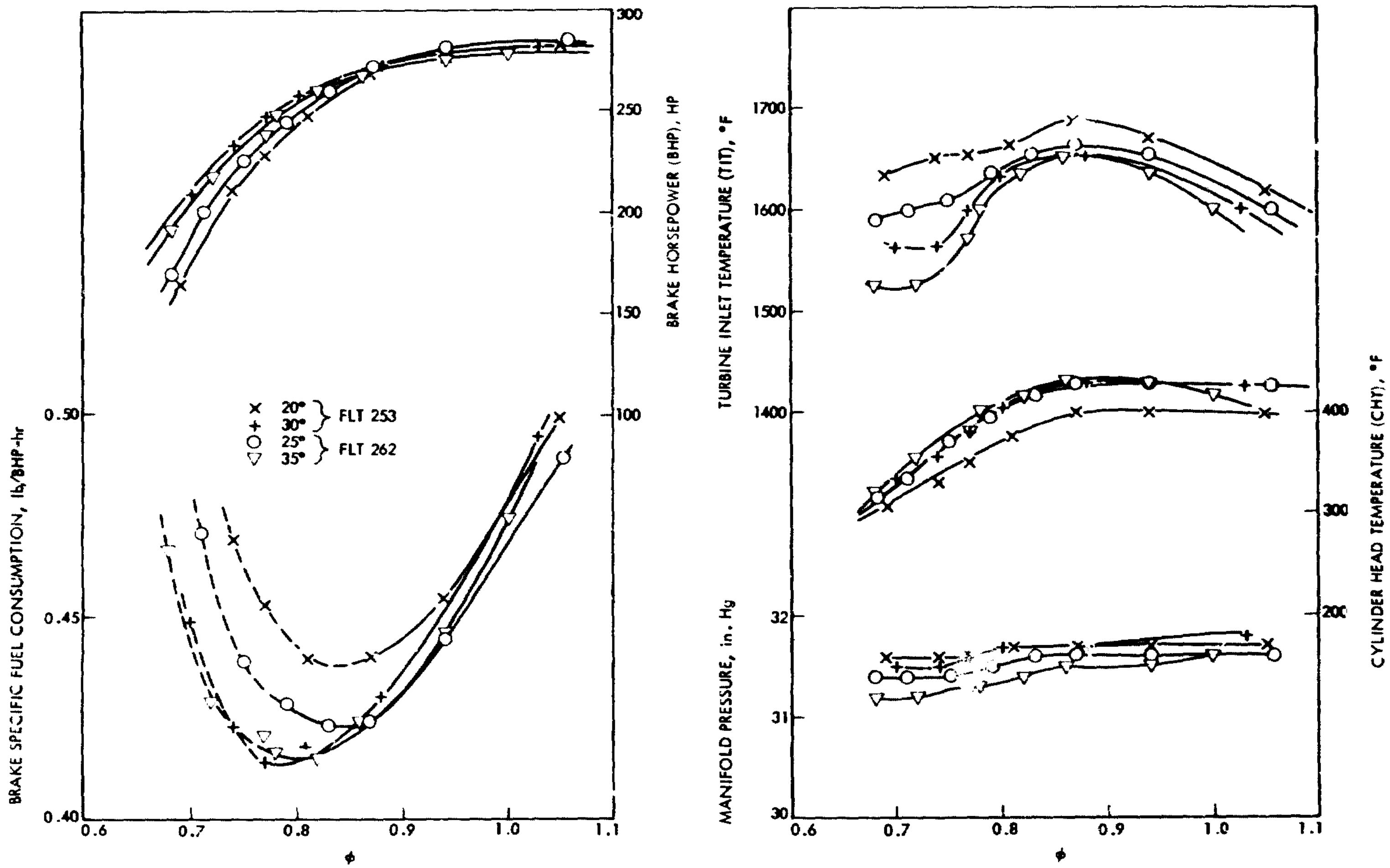


Figure 6-67. Leanout Curves for 2750 rpm, at 15,000 ft, Constant Manifold Pressure = 31.5 in. Hg., and Several Ignition Timings

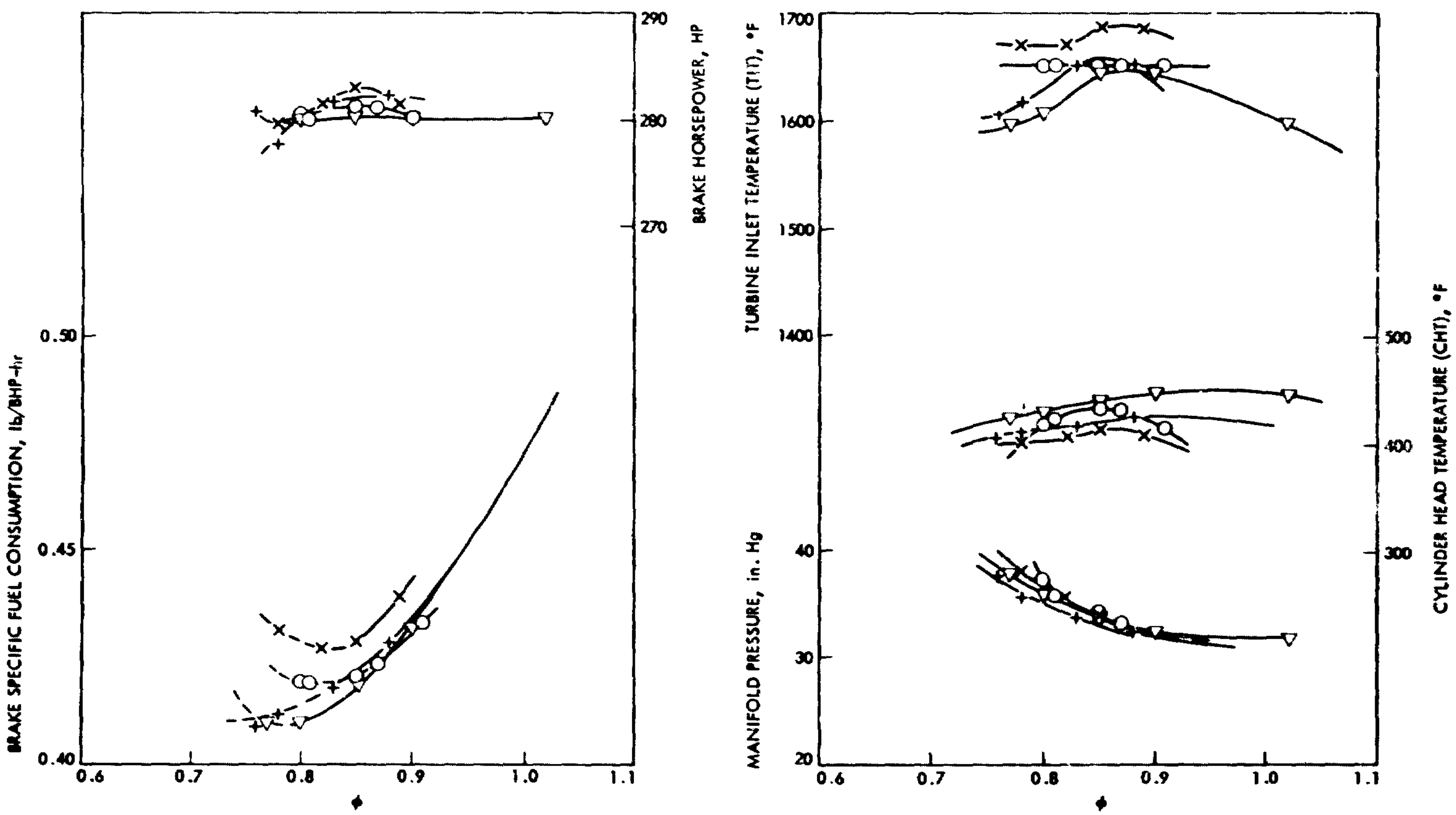


Figure 6-68. Leanout Curves for 2750 rpm, at 15,000 ft, Constant Power = 75%, and Several Ignition Timings (---Unstable Operation, Roughness)

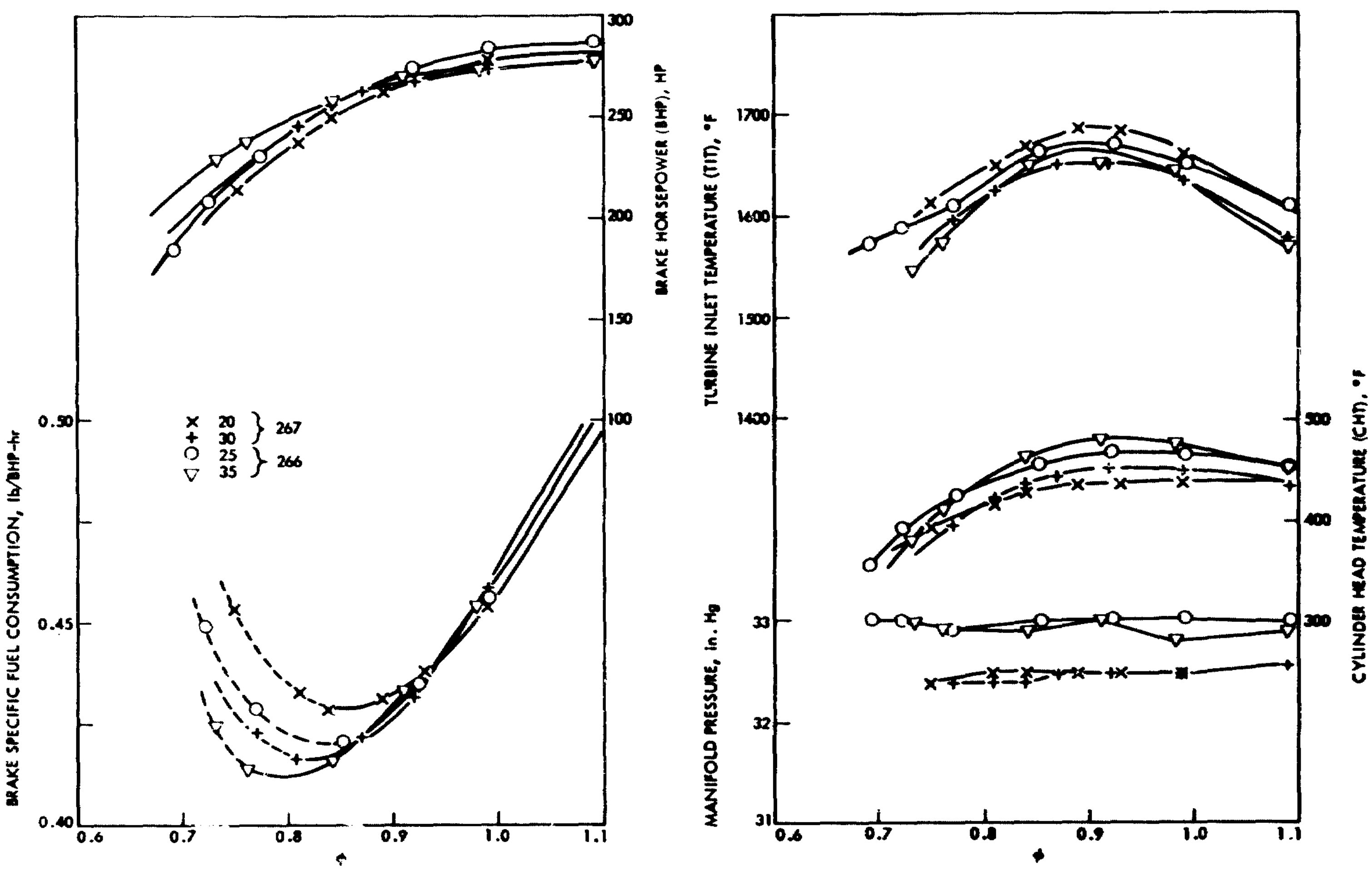


Figure 6-69. Leanout Curves for 2750 rpm, at 22,000 ft, Constant Manifold Pressure = 32.5 in. Hg, and Several Ignition Timings (---Unstable Operation, Roughness)

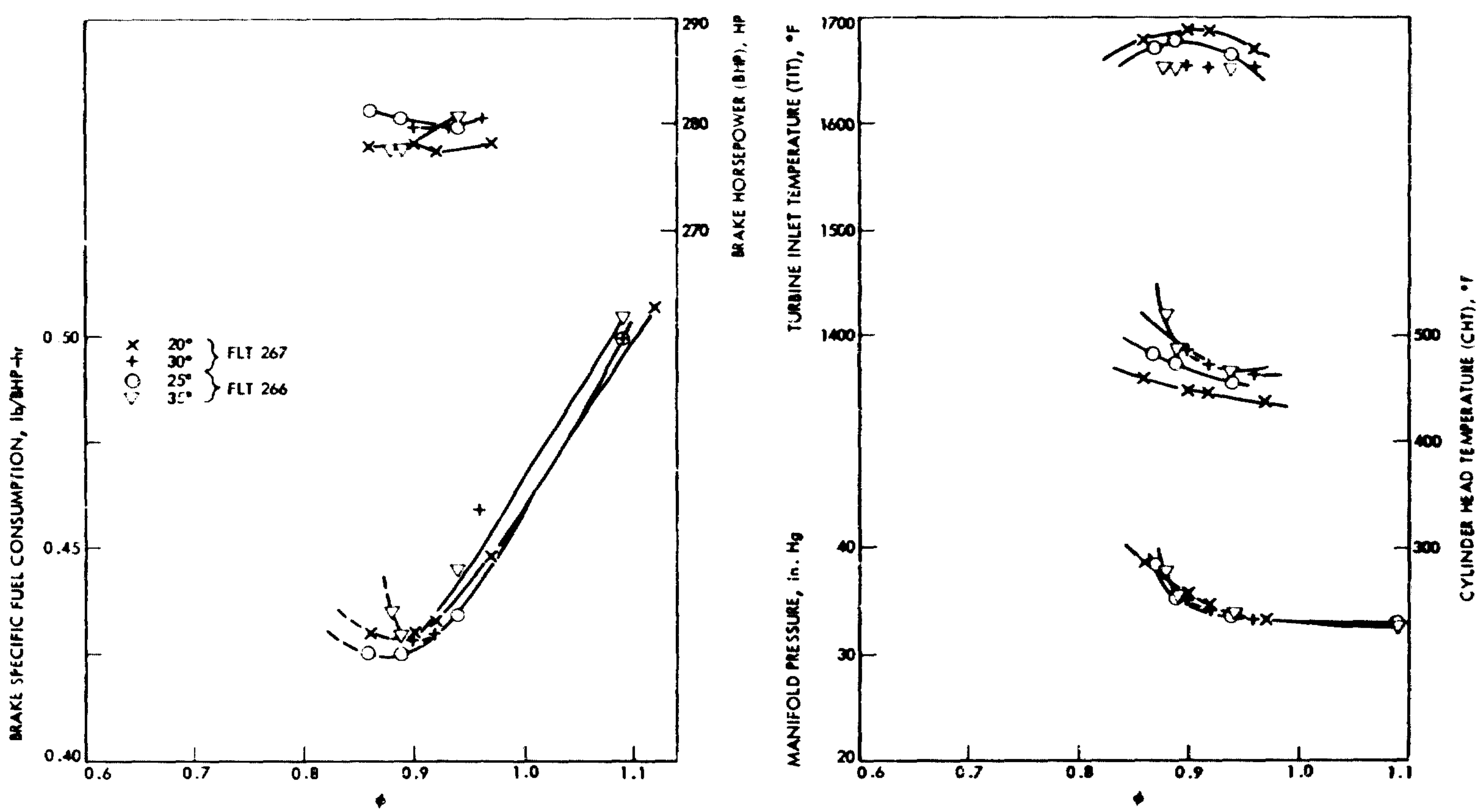


Figure 6-70. Leanout Curves for 2750 rpm, at 22,000 ft, Constant Power = 75%, and Several Ignition Timings (---Unstable Operation, Roughness)

4) <u>25,000-Ft Altitude</u>. Figures 6-71 and 6-72 give the results for a 65% power settings case. The results obtained in Flights 269 and 256 show good consistency in BSFC and TIT, but one can still see small manifold pressure differences in Figure 6-71. Figure 6-72 shows an attempt to leanout at constant power. Notice the reversing of the BSFC curves and the rapid increase in manifold pressure below equivalence ratio 0.9 while the temperatures continue increasing without going through a peak. A further case not shown here was flown at 75% power settings with the purpose of verifying the absence of detonation and the capability of the turbocharger to supply enough air through the engine during the constant power leanouts, the main goal being to obtain a critical altitude for the engine.

d. <u>Hydrogen Enrichment Flights</u>. The hydrogen enrichment flights were all conducted at 15,000 ft and 65% power settings. A gasoline-only flight with the hydrogen enrichment system configuration hardware was first conducted for the purpose of comparison (Flight 272). This flight was followed by Flight 273, in which an undetermined amount of hydrogen flowed into the engine, and Flight 276, in which the hydrogen generator system injected 1-1/2 lb/hr of hydrogen into the engine under known control conditions. Cases 272 and 276 were flown for the same conditions except that the hydrogen generator output in Flight 272 was dumped overboard. All flights were conducted with a spark advance of 30°.

The results of Flights 272 and 276 are presented in Figures 6-73 and 6-74. Figure 6-73 shows the constant manifold pressure comparison and Figure 6-74 the constant power curves. The relative positions for the BSFC curves for both cases are consistent with what was found at the test cell, but notice that the engine roughness appearance has been delayed considerably during the leanout in the hydrogen enrichment flight. The manifold pressure measurement was not obtained in Flight 276 because of malfunction.

11. Discussion of Results

The results just described have been analyzed, and for the purpose of discussion, the relevant features are summarized in Table 6-13. The table compares a series of operating points which have been obtained by the constant power leanouts throughout the flight test program. The table shows the operating points classified by altitudes and power levels (left two columns). Within each row of the table three different operating points are compared at a determined altitude and power level. The first operating point, from left to right, is described as "conventional best power point." This point corresponds to the best power point obtained at 20° BTC spark advance, with manifold pressure adjusted to produce the desired power level. The second operating point is labeled "minimum BSFC at 30° BTC" and corresponds to the operating point obtained during the leanout at the indicated constant power level that results in the minimum BSFC. The third point is shown as "minimum usable BSFC at 30° BTC" and is the point obtained utilizing the same procedures as in the previous case, but stopping the leanout when incipient or severe roughness is encountered. Incipient roughness is labeled with (*) and severe roughness with (**). The column in the far right of the table give the fuel

C-3

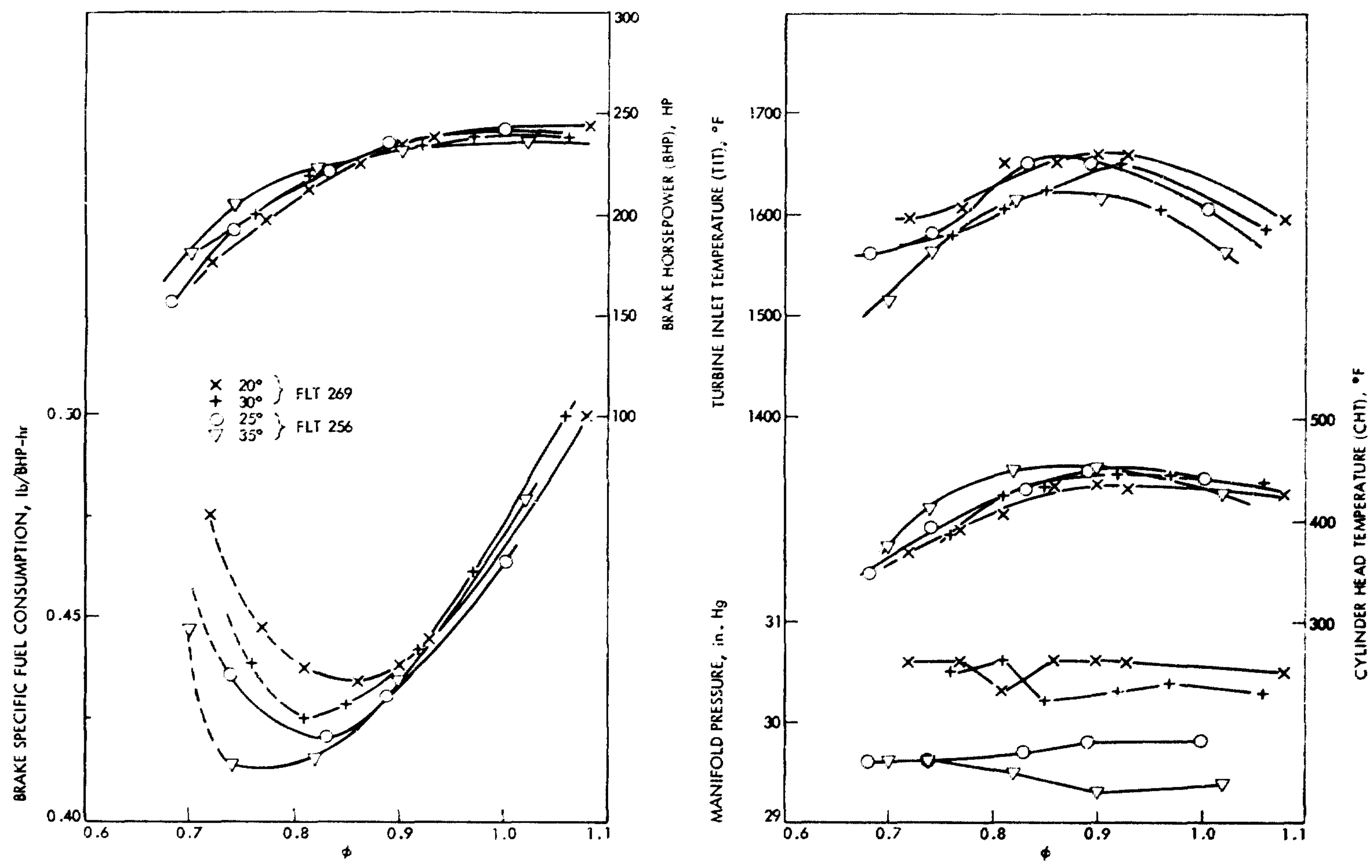


Figure 6-71. Leanout Curves for 2600 rpm, at 25,000 ft, Constant Manifold Pressure = 29.3 in. Hg, and Several Ignition Timings (---Unstable Operation, Roughness)

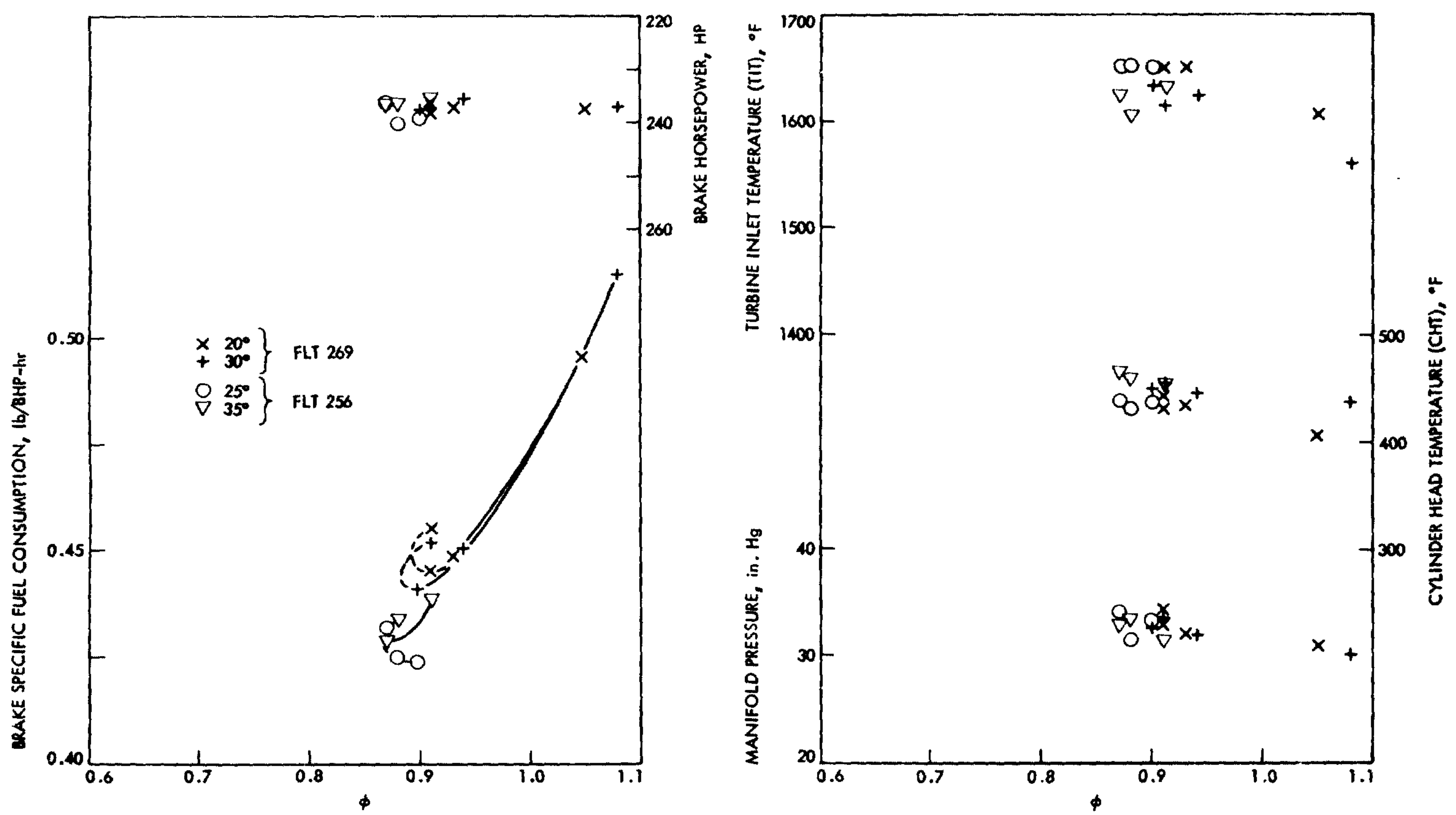


Figure 6-72. Leanout Curves for 2600 rpm, at 25,000 ft, Constant Power = 65%, and Several Ignition Timings (---Unstable Operation, Roughness)

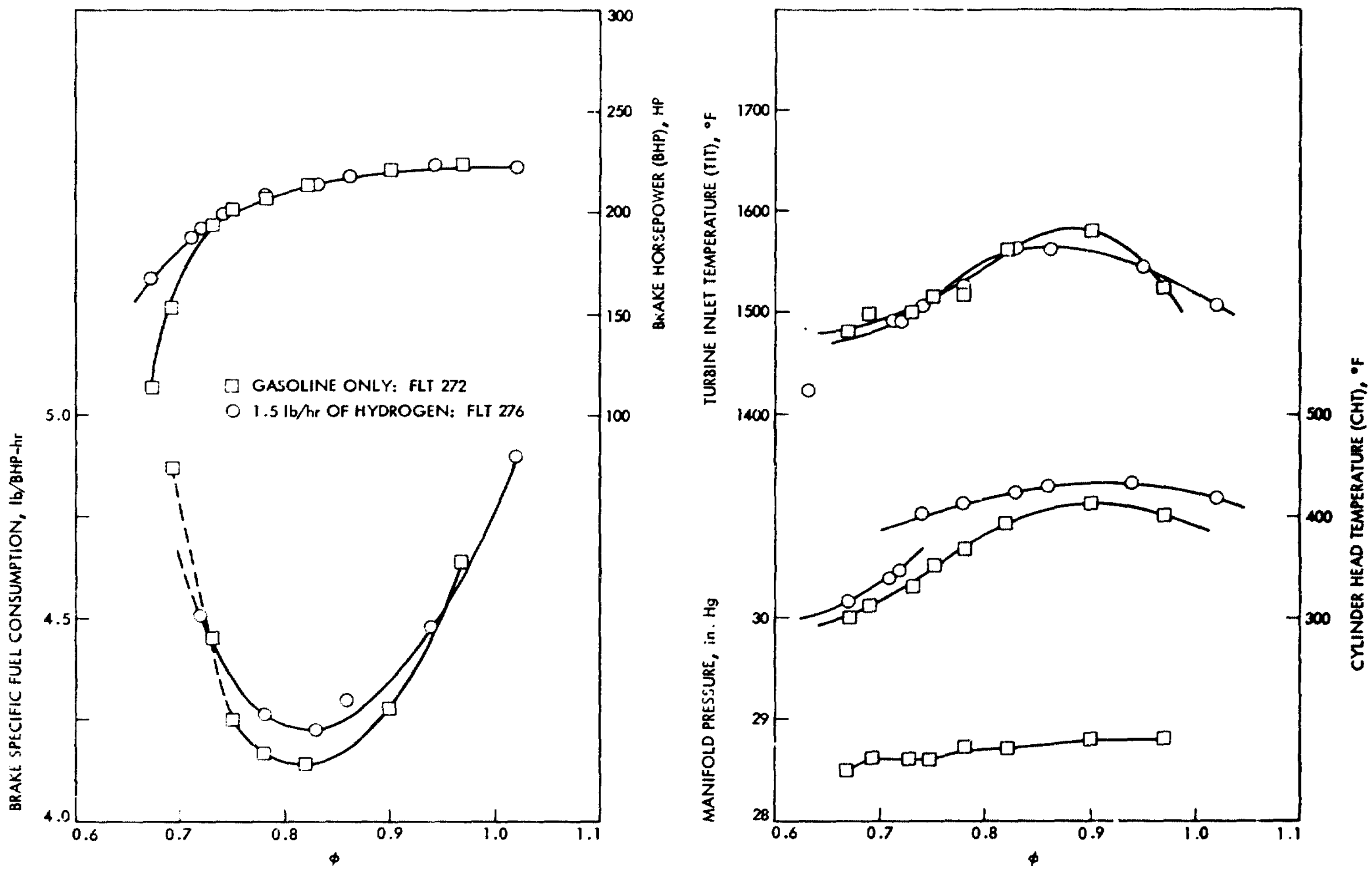


Figure 6-73. Leanout Curves for 2600 rpm, at 15,000 ft, Constant Manifold Pressure = 28.5 in. Hg, 1-1/2 lb/hr of Hydrogen and 30° Spark Advance (---Unstable Operation, Roughness)

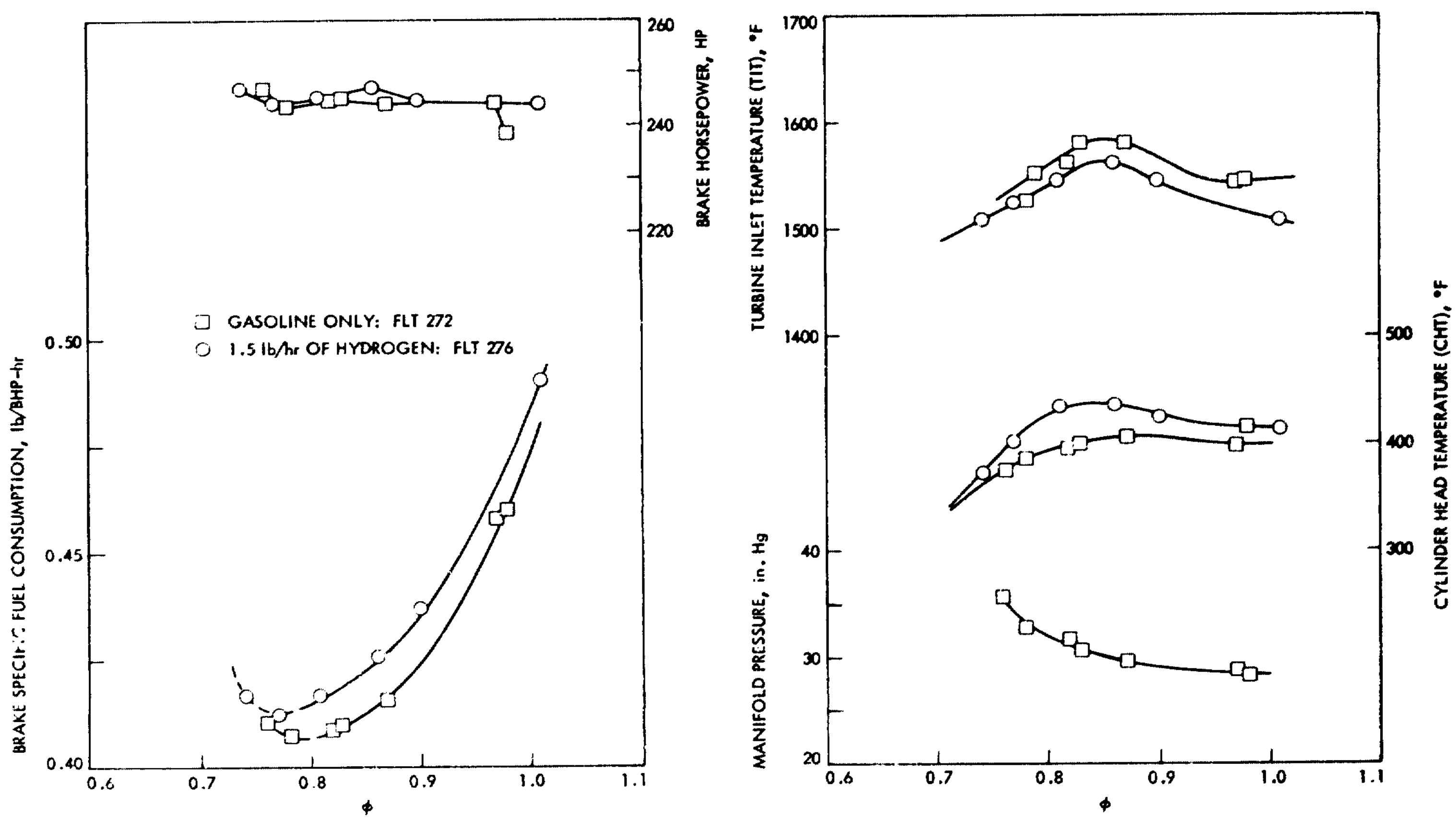


Figure 6-74. Leanout Curves for 2600 rpm, at 15,000 ft, Constant Power = 65%, 1-1/2 lb/hr of Hydrogen and 30° Spark Advance (---Unstable Operation, Roughness)

Table 6-13. Summary of Constant Power Results (fuel economy improvements are shown in right column)

Altitude et	Power, %	Conventional Best Power Point, BSFC/BHP/TIT, °F	Minimum BSFC at 30° BTC, BSFC/BHP/TIT, °F	Minimum Usable BSFC at 30° BTC, BSFC/BHP/TIT, °F	% Fuel Economy Improvement, min/usable, %
5000	45	0.576/169.8/1543†	0.508/169.6/1583†	0.508/169.6/1583†	11.8/11.8
5000	55	0.524/205.6/1443	0.433/208.8/1476	0.434/207.3/1509	* 17.4/17.1
5000	65	0.503/243.9/1530	0.423/245.3/1559	0.449/245.8/1584	* 15.9/10.7
5000	75	0.519/281.3/1505	0.411/278.4/1565	0.430/281.5/1615	* 20.8/17.1
15,000	55	0.465/207.3/1456†	0.410/207.8/1534†	0.416/206.6/1540†	* 11.8/10.5
15,000	65	0.489/246.2/1511	0.412/246.5/1541	0.426/243.5/1570	15.7/12.8
15,000	75	0.500/282.0/1559	0.409/280.2/1568	0.428/282.2/1562	** 18.2/14.4
22,000	75	0.507/279.7/1544	0.428/279.3/1627	0.428/279.3/1627	15.6/15.6
25,000	65	0.502/244.8/1500	0.441/242.7/1585	0.441/242.7/1585	12.1/12.1
15,000	65	30°BTC; H_2 Baseline 0.458/244.3/1580	0.408/244.9/1579	0.410/244.9/1625	* 10.9/10.5
15,000	65	30°BTC; 1-1/2 lb/Hr of H_2 0.490/244.0/1536	0.411/244.9/1569	0.425/247.2/1627	* 16.1/13.2
--	--	--	--	--	10.2/7.2

†TIT Gage Producing questionable readings.

economy improvement of the second and third operating points with respect to the first and expressed as a percentage. Each operating point is defined for the sake of simplicity by three quantities: BSFC, BHP and TIT, which give a quick comparison reference. The last two rows of the table show the results for the hydrogen enrichment cases. One of them is taken as a baseline with gasoline only, the other with hydrogen going into the engine. The numbers in the lower-right-hand corner of the table show the comparison of the gasoline-only operating points with hydrogen enrichment and the conventional operating point of the baseline when running at 30° BTC spark advance. This table will form the basis for the discussion to follow.

a. Gasoline Only Flights

1) Fuel Economy. The main objective of the program, investigation of fuel economy improvement, is here discussed in two steps. First it is instructive to compare the results obtained during the investigation to a well-defined point which is independent of small instrument errors or long-term drifts. The best power point has been adopted here for such a purpose. There is some other fundamental reason for this, and it is that the "best power point" is an engine condition well known to pilots and easy to reach. Furthermore, and in spite of the power settings offered by the manufacturer for airplanes provided with TIT and fuel flow gauges, most pilots do like to operate the engine at such a point because of the safe margin in TIT and/or the absence of engine roughness. Using this comparison, Table 6-13 often shows improvements from 11.8 up to 20.8% if severe roughness is allowed. The numbers become limited to 17.4% if only incipient roughness is tolerated. If on the other hand the engine is not allowed to operate with any trace of roughness, the best fuel economy improvement is identified as 14.4% at 15,000 ft altitude and 75% rated power. Notice also that the TIT at this operating point is 1562°F as opposed to 1568°F for the best power point. These results confirm what was speculated during Phase II: When leaning out at constant power the engine temperatures do not necessarily become higher than those obtained at the best power point if one is able to lean sufficiently to the left of the TIT peak. This is a particularly important point not often understood by workers in the field, and is due to the fact that, when adjusting the ignition timing during the leanout for maximum torque, the TIT peak does not move to a different equivalence ratio, while the minimum BSFC becomes lower and leaner. This occurrence allows the recovery of power to the original "best power point" value by boosting manifold pressure while still remaining below or close to the TIT value at the best power point.

The airframe manufacturer's aircraft operating manual presents a table of instructions for the pilot, so that the airplane can be operated at the altitude and air speed of interest, while taking most advantage of the engine. Table 6-14 is an example of the power setting for the Duke 60 and A60 and has been extracted from Reference 6-22. Notice that the table gives a series of operating points at different altitudes for three atmospheric models and 65% maximum continuous power. All the conditions recommend a fixed rpm (2500) and a fixed fuel flow per engine (112 except for the last two altitudes). Each air speed is then achieved at each

Table 6-14. Duke 60 and A60 Operational Data

Cruise Power Settings

65% maximum continuous power (or full throttle)

Press Alt.	ISA-36°F (-20°C)							Standard Day (ISA)							OSA +36°F (+20°C)						
	OAT	Engine Speed	Main Press	Fuel Flow per Engine		TAS		OAT	Engine Speed	Main Press	Fuel Flow per Engine		TAS		OAT	Engine Speed	Main Press	Fuel Flow per Engine		TAS	
FEET	°C	RPM	IN HG	PPH	GPH	KTS	MPH	°C	RPM	IN HG	PPH	GPH	KTS	MPH	°C	RPM	IN HG	PPH	GPH	KTS	MPH
SL	- 5	2500	28.9	112	18.6	173	199	15	2500	29.8	112	18.6	177	204	35	2500	30.6	112	18.6	180	207
2000	- 9	2500	28.9	112	18.6	176	203	11	2500	29.8	112	18.6	180	207	31	3500	20.7	112	18.6	183	211
4000	-13	2500	29.0	112	18.6	179	206	7	2500	29.8	112	18.6	183	211	27	2500	30.9	112	18.6	186	214
6000	-17	2500	29.0	112	18.6	182	209	3	2500	29.9	112	18.6	186	214	23	2500	31.0	112	18.6	190	219
8000	-21	2500	29.2	112	18.6	185	213	-1	2500	30.0	112	18.6	189	218	19	2500	31.1	112	18.6	193	222
10000	-25	2500	29.2	112	18.6	188	215	-5	2500	30.2	112	18.6	193	222	15	2500	31.2	112	18.6	197	227
12000	-29	2500	29.2	112	18.6	192	221	-9	2500	30.3	112	18.6	196	225	11	2500	31.4	112	18.6	200	230
14000	-33	2500	29.2	112	18.6	195	224	-13	2500	30.4	112	18.6	200	230	7	2500	31.5	112	18.6	204	235
16000	-37	2500	29.3	112	18.6	199	229	-17	2500	30.5	112	18.6	204	235	3	2500	31.6	112	18.6	208	239
18000	-41	2500	29.3	112	18.6	202	233	-21	2500	30.6	112	18.6	207	238	- 1	2500	31.7	112	18.6	212	244
20000	-44	2500	29.4	112	18.6	206	237	-24	2500	30.6	112	18.6	211	243	- 4	2500	31.8	112	18.6	216	249
22000	-48	2500	29.5	112	18.6	211	243	-28	2500	30.8	112	18.6	216	249	- 8	2500	32.0	112	18.6	221	254
24000	-53	2500	29.8	112	18.6	215	247	-33	2500	31.1	112	18.6	220	253	-13	2500	32.0	111	18.5	224	258
26000	-57	2500	30.0	112	18.6	219	252	-37	2500	31.3	112	18.6	225	259	-17	2500	32.0	109	18.2	227	261
28000	-61	2500	29.9	110	18.3	222	256	-41	2500	29.9	105	17.5	223	257	-21	2500	29.9	100	16.7	223	257
30000	-64	2500	26.4	94	15.7	210	242	-44	2500	26.4	91	15.1	210	242	-24	2500	26.4	88	14.7	206	237

NOTES

1. Full throttle manifold pressure settings are approximate.
2. Actual brake horsepower for full throttle conditions (above critical altitudes may be determined by entering the graph of full flow vs. brake horsepower at the appropriate fuel flow.
3. Shaded area represents operation with full throttle.

altitude by varying the manifold pressure. Notice that this procedure is equivalent to a limited constant power leanout at 20° BTC spark advance. The BSFCs obtained by using the values of Table 6-14 are 0.453 and can be obtained also from the constant power leanout curve at 20° BTC if one does not operate the engine at the best power point but rather at a leaner point compatible with the TIT value and/or the presence of roughness, whatever comes first. It is worth noticing here that two gauges, TIT indication and a fuel flow meter, are necessary to determine such a point, and even so customers complain of an inability of the engine to operate smoothly at those points. Indeed it has been found in this program that roughness appears prematurely when the constant power leanout is conducted at 20°.

The reader is perhaps inclined to compare the results expressed in Table 6-13 with those shown in Table 6-14, although the rpm are different. From those results one obtains fuel economy improvements that vary from 1 to 11.2%, although one should properly qualify this comparison: the results from Table 6-13 have been obtained with 50 hours of flight, a substantial portion of which was spent in learning the new operating techniques, and under handicap conditions such as the lack of capability in continuously adjusting the spark for each equivalence ratio, rpm and manifold pressure in order to obtain the optimum torque. The results of Table 6-14 have been obtained by means of an extensive program under well controlled conditions and using practices well-established for the last 20 years, and with different torquemeters.

2) Spark Advance. By now it is obvious that those flights conducted at 25° and 35° spark advance have been deliberately left out of the discussion, the reason being that the results obtained in flights under supposedly equal conditions for 20°, 25°, 30° and 35° spark advance differ from those studied in the test cell during dynamometer and flight test stand testing. In brief, it was expected that the minimum BSFC would be a monotonic decreasing function with spark advance during constant manifold pressure leanouts, as was found in Phase II and in some of the flights in Phase III. An inspection of Figure 6-69 obtained with Flights 266 and 267 shows exactly such a trend. On the other hand, Figure 6-59 shows the anomalous result of a lower BSFC at 25° than at 30°. Notice also that the curves for 20° and 30° spark advance keep the same relative position as those at 25° and 35° BTC. In observing the manifold pressure variations in Figure 6-59 one should be aware of the higher manifold pressures used for Flight 252 and those for Flight 264. With other things equal, it seems that the engine was being operated at higher power in Flight 252 than in Flight 264. This speculation is confirmed when the TIT leanout curves are observed. If one uses the same rationale for analyzing Figure 6-69, one sees some differences in the manifold pressure, but hardly any difference in the TIT curves and no anomaly in the BSFCs.

As a final point, Figure 6-59 was obtained by conducting two flights (252 and 264) which were several weeks apart, while Figure 6-69 contrasts two flights (266 and 267) conducted in sequence. Notice that the power readings in both figures at the best power point are the same for different spark advances, which shows the accuracy of the flight crew in reproducing the torquemeter readings. From all this, one concludes that the torquemeter experienced drifts during the flight tests, since it was calibrated at the start of the program. It is therefore not much use to compare the 35° BTC runs with the 20° BTC runs, but within each flight the torquemeter indications are considered accurate enough to make comparative studies among the data points obtained for that particular flight. This procedure has been followed in constructing Table 6-13, but it is felt that if the torquemeter had provided faithful readings, the BSFCs at 35° would have been improved to equal those values obtained at the test cell, that is, 24%. The constant manifold pressure leanout curves were requested in this program in order to monitor anomalies that often plagued flight testing due to instrument errors and, as demonstrated here, they have proved to be excellent tools in understanding the state of the instrumentation as well as engine operation, although the final results of testing the ultralean techniques can be provided only by the constant power leanout curves.

3) Lean Operation. The results shown in the leanout curves (Figures 6-55 through 6-72) show minimum BSFCs occurring at equivalence ratios richer than those observed during Phase II at the test cell. The reader should remember that the air flow during Phase II was accurately measured while it has only been estimated for Phase III.

It is also noticeable that in several instances the TITs do not peak at the same equivalence ratio (see, for example, Figure 6-65). The cause for these anomalies is undoubtedly the procedure from which the air flow was computed, in which no attempt was made to use the volumetric efficiency, which is in turn a function of the manifold pressure and temperature equivalence ratio and rpm. Perhaps the most relevant indication of difficulties in estimating the air flow is the fact that the TIT, as well as the gas exhaust temperatures, peak at equivalence ratios of .925 regardless of the manifold pressure, rpm, spark advance or atmospheric conditions. This point was already noticed by Moynihan et al. (Reference 6-8) during Phase I of this program and verified during Phase II at the test cell, and may be used from now on as the best account for spark-ignited internal combustion engines to verify the air flow through the engine when an accurate fuel flow reading is available. Moynihan also conducted a brief account of the volumetric efficiency of this type of engine during Phase I. He and his associates correlated the air flow data from Lycoming with a variety of operating conditions and proposed a method to compute the air flow through an engine as given by

$$\dot{m}_a = 0.02293 \times \frac{N \times V_d}{2} \times \frac{P_{man}}{T_{man}} \times \eta_v \qquad (6\text{-}9)$$

where m_a is the air flow through the engine, N is the engine rpm, V_d is the engine displacement, P_{man} and T_{man} are the manifold pressure and temperature, and η_v is the volumetric efficiency. The volumetric efficiency is computed from Figures 6-75, 6-76 and 6-77, using the following procedure:

(1) Determine the effective manifold pressure (P_{man}) from Figure 6-77.

(2) Compute the manifold density as given by

$$\frac{\rho_{man}}{\rho_0} = 17.373 \frac{P_{man}}{T_{man}}$$

where, as usual, the pressures are given in inches of Mercury and the temperatures in degrees Rankine.

(3) With the obtained P_{man} and density ratio, compute the volumetric efficiency from Figure 6-75, and $\dot{m}_a$ flow from Equation (6-9).

(4) From $\dot{m}_a$ use the measured fuel flow rate to compute the equivalence ratio ϕ.

(5) From Figure 6-76 compute the correcting factor for the volumetric efficiency, C_ϕ.

(6) With this value of volumetric efficiency iterate, using Equation (9), until the desired accuracy is achieved.

This procedure has been used to recalculate the air flow obtained for Figures 6-65 and 6-66 (see Figures 6-78 and 6-79). Notice that the BSFC curves have shifted now toward the richer side and the peaks of TIT are obtained at an equivalence ratio of .95 as predicted. The same result has been obtained in Figure 6-79 for the constant power leanouts. Although the corrected values seem satisfactory, the situation is still far from being physically accurate. The corrections on the volumetric efficiency shown in Figures 6-75 through 6-77 were obtained for a limited set of data available from Lycoming, since the conventional engine operating envelope is ordinarily restricted to a fixed set of operating conditions. The corrections would therefore be suspect for equivalence ratios less than .85 and manifold pressures above the maximum recommended values at each rpm. Thus the corrected data shown in Figures 6-78 and 6-79 should be trusted above $\phi = 0.85$, but caution should be exercised below this equivalence ratio. In observing Figure 6-75, notice that the constant manifold pressure curves are limited by an envelope (dashed line). That does not mean that all those curves peak and become tangent to the envelope, but rather, the dashed line ends the region where experimental data is available. The figure shows the regime which is outside normal operation, and another zone is also shown as a shadow region indicating the additional operating regime for the constant power leanouts when operating ultralean. Since this region is utilized during

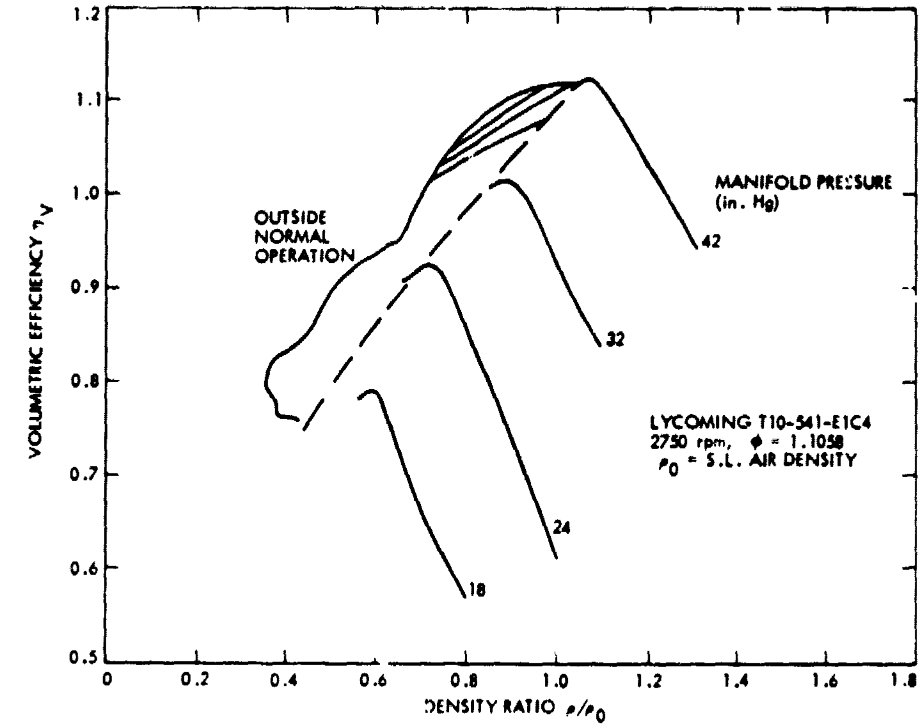


Figure 6-75. Volumetric Efficiency vs Manifold Density for Several Manifold Pressures, at 2750 rpm and ϕ = 1.1058

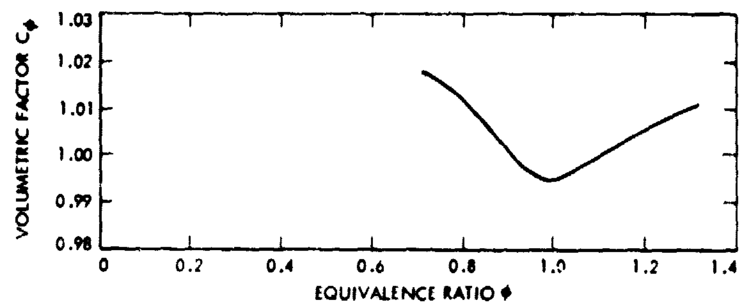


Figure 6-76. Volumetric Factor as a Function of Equivalence Ratio

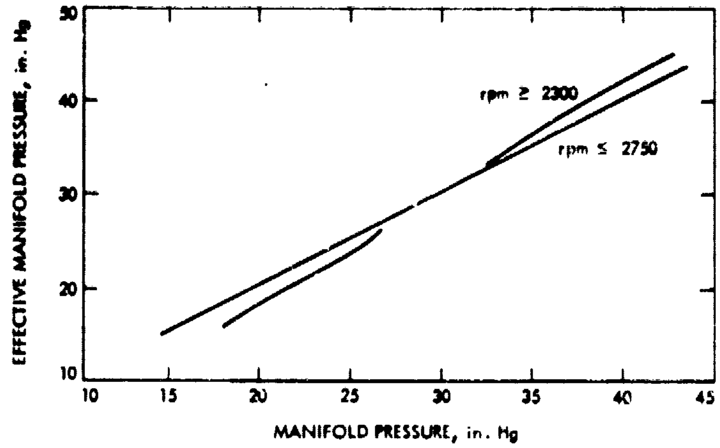


Figure 6-77. Effective Manifold Pressure for Several rpm

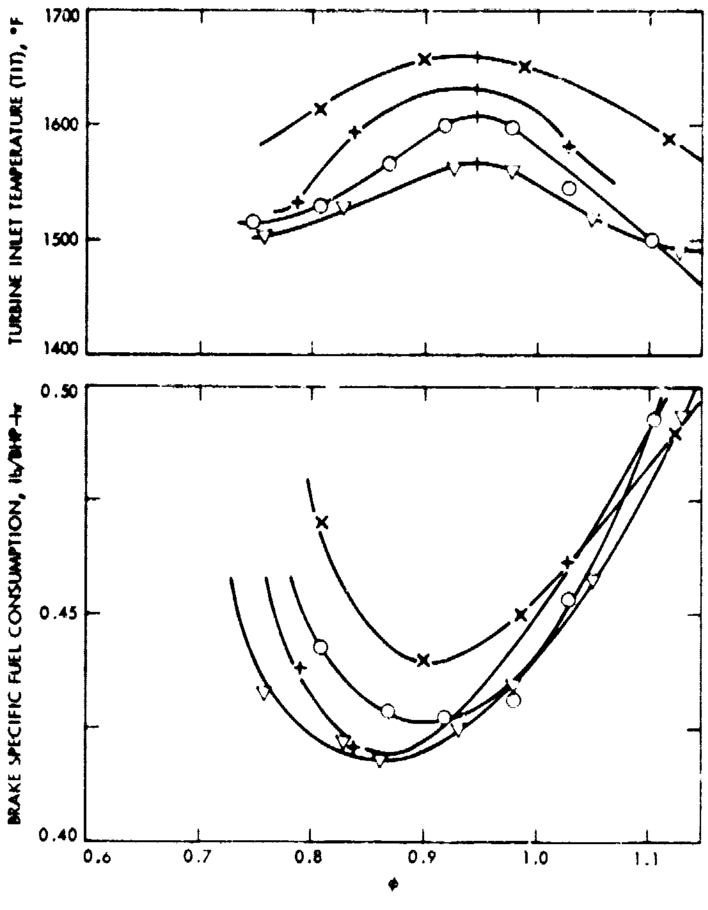


Figure 6-78. Results Corrected for Volumetric Efficiency for Conditions Shown in Figure 6-65

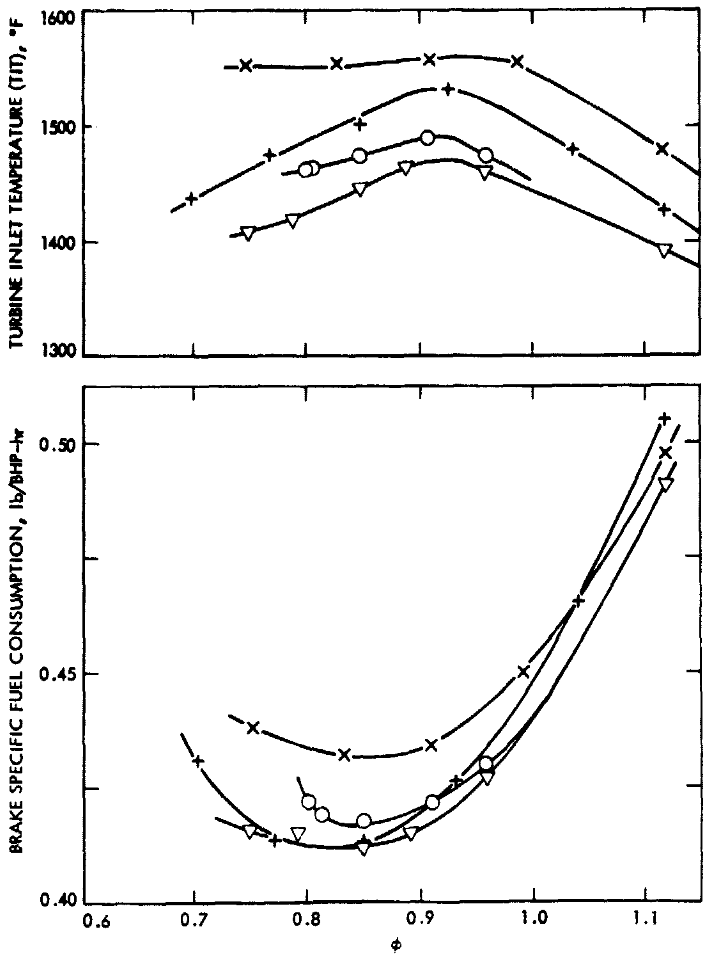


Figure 6-79. Results Corrected for Volumetric Efficiency for Conditions Shown in Figure 6-66

power recovery, the position of the constant power leanout curves of Figure 6-79 should also be suspect as regards equivalence ratio when operating below $\phi = 0.9$.

4) Critical Altitude. The ultralean techniques, utilizing higher manifold pressure than those encountered in conventional operations, left an open question on the critical altitude that the engine could sustain at moderate and high powers because of the size limitations of the turbocharger. During the flights at 25,000 feet, the volumetric flow rate through the turbocharger was adequate to maintain the necessary manifold pressure for achieving 75% power at 2750 rpm.

Data at the same altitude and for 65% power is given in Figures 6-71 and 6-72. While the data at constant manifold pressure seems consistent with that obtained at lower altitude, the constant power leanout curves of Figure 6-72 show a reversal during the leanout. This can be explained in terms of more refined calculations of the air flow, but although the manifold density was seen to increase during power recovery, the manifold temperature became unusually high because of the combined effect of altitude and power recovery.

In spite of this high value, detonation was not observed, but the BSFC throughout the leanout was found to be significantly higher than for lower altitudes. The ultralean techniques at higher altitudes therefore seem to be limited only by the high values of manifold temperature. The possible need of an aftercooler to keep the manifold temperature down to reasonable levels was indicated during Phase II, and has been widely confirmed during Phase III. Continental Motors offers turbocharged engines with aftercoolers, and the Lycoming TIO-541F experimental engine also has provisions for an aftercooler. This technology seems very much at hand and its introduction in general aviation seems doubly justified in terms of better volumetric efficiency and lower operating temperatures. The small pressure losses due to the heat exchanger of the aftercooler seem more than compensated by the beneficial effects mentioned above.

5) Roughness. Throughout this program the term "roughness" has been used to designate anomalous engine vibration caused by pressure variations from cycle to cycle (see Section IV); during the leanout the engine was never allowed to operate lean enough to induce misfiring. Those not experienced with flight testing are surprised at the great sensitivity of the air frame in flight to pressure variations from cycle to cycle (roughness in flight). Engines that show smooth operations when tested on the dynamometer or with simulated engine mounts often show severe roughness in flight due to the lightweight structures used in airframes. This situation is very different from that encountered in automobiles, where engine roughness felt in the car usually is indicative of very severe engine damage or malfunction. The same type of discomfort in an airplane is usually a mild malfunction that can be corrected by adjusting the fuel/air ratio as required. Even anomalous pressure variations from cycle to cycle, hardly detected with Kistler transducers, can be felt by a well-trained test pilot. This type of roughness has been referred to here as "perceivable roughness or incipient roughness." Higher levels of pressure variations that could be felt by the passengers have been termed "severe roughness."

Although the pressure variations from cycle to cycle are mostly due to the nonuniform distribution of fuel/air ratio, there are other factors that affect its appearance. Manifold and cylinder turbulence structure is also connected with the roughness phenomenon. The cylinder turbulence before ignition and after ignition is affected by the pressure buildup during combustion, and the pressure buildup is in turn related to ignition timing and cylinder head temperatures. Thus, it is not surprising that roughness can be delayed when leaning farther if the proper spark advance is being used. To make the subject more confusing, the appearance of roughness is not predictable and the same engine can be operated under the same atmospheric conditions with identical power setting several days apart and show different degrees of roughness or no roughness at all.

Elimination of roughness will allow use of the minimum of BSFCs referred to in Table 6-13, but in addition, it will indirectly "clean-up the engine" resulting in an additional decrease in BSFC. This area has not been systematically studied in the automotive industry and requires extended research.

6) Engine Controllability. One of the concerns raised at the end of Phase II was the ability to operate the engine in flight under tight control conditions with ultralean techniques. This concern arose from the fact that the operation of the engine near the best power point is relatively insensitive to off-design operation because of the flatness of the power curve. In ultralean operation, the power curve at constant manifold pressure is steep; that is, the change in power due to fuel/air ratio variations is over one order of magnitude higher than that experienced near the best power point. Sustained oscillations were observed at the test cell due to the coupling of the governor controller, fuel injector controller, and manifold pressure controller. This did not occur in flight, showing the adequacy of conventional controls in ultralean operation. On the other hand, the constant power leanout curves with variable spark advance proved to be awkward and presented some problems during the first few flights. Owing to the continuous adjustment in the opposite direction of the manifold pressure throttle and fuel lever it is hard to imagine this procedure implemented in general aviation unless it is reserved only for cruise and practiced by experienced pilots. If this procedure is implemented during climb, cruise and approach, some means of automation must be introduced. The following section presents some ideas in this regard. The mechanical and thermodynamical control of the engine was proven successful, but some difficulties related to power control were experienced by the pilot.

7) Low Powers. The data obtained at 45% power showed higher BSFCs for conventional and ultralean operation than those observed for higher powers. This could be attributed to the low rpm which offsets the valve overlap design for high power and takeoff conditions. However, the ultralean techniques are still applicable and also show improvements worth implementing. Notice that no attempt was made to operate the engine ultralean during idling and taxiing (neither at takeoff or 85% power), the reason being that one does not anticipate using, for such conditions, ultralean techniques during the first implementation step in general aviation. Should one be interested in operating ultralean during these modes, it may be found that such operation presents more of a problem than originally expected. Although the principle of ultralean operation applies also at these low power levels, the fuel/air ratio control is provided by the air flow, which happens to be very low, giving a very unstable fuel control. This could be improved, however, if the controls are changed to electronic devices similar to those already used in automobiles.

In addition, the response of the engine during the transients, when idling and taxiing, is important. Fast engine response in general aviation is seldom an issue during flight, except in specialized occasions such as agricultural aviation, air firefighting, etc., but during ground operations and interface with airport traffic, transient response is at stake when crossing runways, executing immediate takeoff clearances, go-around, and the like. Implementing ultralean operation during the transients will be an additional challenge.

8) <u>Structural and Thermal</u>. The structural and thermal conditions of the engine when practicing ultralean techniques are different than during conventional operation; although the TIT are practically the same, the cylinder head temperatures are higher because of the larger spark advance used. However, the value reached by the CHT is not high enough to cause thermal fatigue, nor does it relate to detonation. The engine cylinder heads can be effectively cooled without using additional engine cooling drag, and the equivalence ratio is too low to induce detonation or auto ignition. This occurs in spite of the higher manifold temperatures and pressures used in this program.

A concern is that the use of higher manifold pressures will eventually result in higher cylinder peak pressures. Notice that the mean effective pressure (MEP) remains the same since the rpm and the power remain constant. Figure 6-80 shows a relationship between manifold pressure and engine rpm, where the envelope for conventional operation and the region in which the engine is never operated can be seen. The shadowed area indicates the additional regime used during ultralean operation. As one can see, the manifold pressures never exceed those applied during takeoff or climb, which proves that ultralean techniques can be implementd without beefing up the engine structural cross sections.

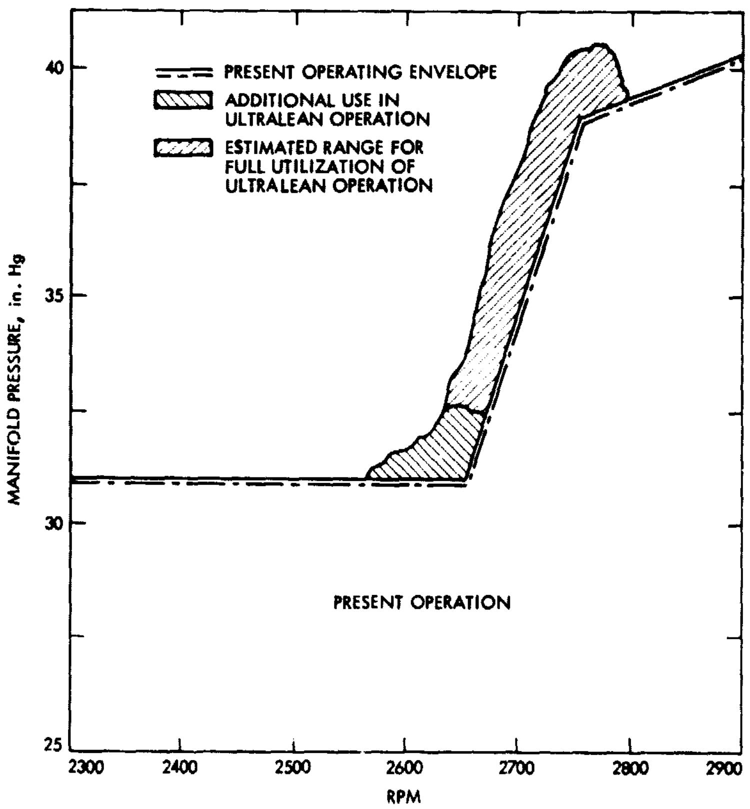


Figure 6-80. Manifold Pressure Range vs Engine Speed

b. Hydrogen Enrichment Flights. Although at this point it was certain that hydrogen enrichment was not needed for ultralean operation, it was decided to undertake a few flights for the sake of completeness and technological interest. A flight was conducted with the hydrogen enrichment systems connected, the hydrogen generator operating and the products being dumped overboard. The flight was followed by a hydrogen enrichment flight that had to be abandoned owing to the inability of the system to inject a substantial amount of hydrogen into the engine, due to the pressure drop limitations across the throttle. This was eliminated by biasing the manifold pressure controller to boost the compressor outlet pressure. The required manifold pressure was then obtained by further closing the throttle, with the final result of a larger pressure drop across the throttle or, what is the same, across the hydrogen generator. The flights were conducted at 15,000 feet, 65% power, and 30° spark advance, and were plagued by hydrogen generator problems that originated mostly during its startup.

1) Fuel Economy. The results, given in Table 6-13, show the same characteristics of those observed with gasoline only. If 1-1/2 lb/hr hydrogen enrichment constant power leanout is compared with the baseline with gasoline only, one obtains the same trends observed in Phase II; for ultralean conditions, operation with gasoline only yields lower BSFC than hydrogen enrichment. The benefits of hydrogen enrichment are only seen on the lean side of the bucket portion of the BSFC curve.

2) Roughness. Although no benefits are seen from hydrogen enrichment as far as fuel economy is concerned, hydrogen enrichment noticeably delayed the appearance of roughness (see Figures 6-73 and 6-74). This is undoubtedly due to the higher diffusivity of hydrogen, which translates in a more uniform distribution of the effective equivalence ratio throughout the cylinders. This delay caused by hydrogen enrichment does not seem to have any practical value. Engine roughness is not well understood, and can possibly be more effectively suppressed by simpler means such as redesign of intake manifolds and more "smart" fuel injection systems.

3) Hydrogen Generator System. It was demonstrated that the hydrogen generator system accomplished its function--except for the hydrogen generator itself--which was shown to be far from any commercial design stage. In spite of some difficulties, however, it fulfilled its objective, and this is a milestone in aviation history: no spark-ignited internal combustion engine had been operated before in-flight using hydrogen as the primary or secondary fuel. This constitutes a very important part of the program. it is in itself a technological advancement.

The state of the art of the hydrogen generator was significantly advanced during this program and brought forward to the point where it was possible to evaluate the merits of catalytic generators. An inherent drawback of any catalytic reactor is the attrition of the catalyst by normal operation. This attrition results in catalyst fines being introduced into the engine, partially exhausted with the gases and partly absorbed in the engine oil. The possibility of incompatibility between the catalyst and the engine oil at operating engine temperatures was cause for concern, but proved not to be the case when a test was undertaken under simulated conditions. When exposed to nickel catalyst, the oil was found to have excellent stability. In any event (in spite of claims that special catalysts can be manufactured which are insensitive to attrition), the fines in the cylinders will affect engine life in the same manner as engines operating in dusty environments with defective air filters are affected, and experience shows that engine life under such conditions is severely limited.

This type of problem was a nuisance during Phase II when catalyst pellets were used, twice resulting in additional expenditures for engine remanufacturing. In Phase III, however, engine integrity proved to be acceptable because of drastic reduction in fines emission from the monolith catalyst used in the flight testings and the limited number of hours assigned to the hydrogen enrichment flights. The monolith catalyst was overheated, and visual inspection at the end of the program showed melted areas and cracks. This condition was probably caused by the absence of diagnostics thermocouples which became inoperative during the flight. The generator operator had to depend on air and fuel flow readings for generating the desired output.

If a hydrogen generator is ever to be used commercially for reasons other than fuel economy in applications for piston engines, gas turbines, or any other engine, the use of thermal generators is recommended. Thermal generators do not exist yet, even in the research stage. The operation falls within the realm of rich combustion, where flame blowout and sooting dominate the phenomena. If thermal generators are ever developed to a degree where sooting is eliminated and the operation reliably controlled, they may become useful tools for implementing hydrogen enrichment in commercial applications, if so desired.

12. Conclusions

In view of the analysis of the results and the rationale behind them, the following conclusions are offered.

(1) The feasibility of operating the engine ultralean in-flight for several altitudes and power levels, with and without hydrogen, has been demonstrated.

(2) It was confirmed that hydrogen enrichment is not needed to reach ultralean operation.

(3) The best fuel economy was obtained for gasoline-only employing ultralean techniques, while leaning at constant power for spark advances as large as 35°. A conservative result has been set at 11.2% when ultralean techniques were matched against the best conventional operation techniques achieved by the airframe manufacturers in tests conducted by their test pilots. The estimated practical value when matched against conventional techniques conducted by the average pilot is from 17 to 20%, as allowed by engine roughness.

(4) Engine roughness appears to be a limiting factor.

(5) Constant power leanouts at high altitudes were limited by manifold temperature and demonstrated up to 25,000 feet and at 75% power.

(6) Controllability of the engine is mechanically and thermodynamically acceptable but is vulnerable to human errors.

(7) Ultralean techniques have been proved to be limited below 75% when conventional rpm is used.

(8) No detonation was detected during the whole series of flight tests.

(9) The spark advance at 35° BTC was still showing improvements of BSFC, which seems to indicate further benefits at larger spark advances.

(10) The hydrogen generator proved to be an effective research tool but still far from a commercial design.

(11) A historical milestone was achieved: For the first time a piston engine was operated in-flight using hydrogen as one of the fuels.

(12) For the first time a hydrogen generator had been coupled and integrated with an engine and operated under practical requirements.

13. Recommendations

Further flight testing of ultralean techniques should incorporate the following recommendations:

(1) Use a variable electronic ignition suitable for continuous adjustment from the cockpit for optimum engine torque.

(2) Explore lower engine speeds and higher manifold pressures to achieve high powers during ultralean operation.

(3) Obtain an indicated cycle of the engine during ultralean operation with variable spark advance adjusted for optimum torque at several power levels.

(4) Use electronic fuel injection (individual fuel injection in each cylinder for best results) to reduce engine roughness, and monitor results with Kistler gauges.

(5) Use special caution in closely monitoring the torquemeter driftout after each flight, recalibrating it if necessary.

(6) Develop accurate methods to estimate air flow in-flight.

(7) Integrate fuel level, throttle, and rpm in a single power lever.

(8) Conduct flight demonstration of fuel economy using conventional techniques followed by ultralean techniques to assess net gains.

14. Summary

The objectives of Phase III have been achieved and very important milestones have been demonstrated in-flight. The first important milestone has been the demonstration of ultralean technology as a primary means of fuel economy improvement using, at full air flow capacity, the engine weight carried by airplanes as determined by takeoff power requirements. This milestone is most promising when one realizes that straightforward techniques result in improvements in fuel economy as large as 20%, although the saving drops to 11.2% if the airframe manufacturers' specifications are indeed practiced by the average pilot. It has been demonstrated that hydrogen enrichment to improve fuel economy is not a thermodynamically sound approach. The full impact of ultralean technology in general aviation will be fully felt when engine roughness can be delayed by better designs of intake manifolds and fuel injection systems, introduction of aftercoolers downstream of the compressor, and the mechanical linking in a single power lever of rpm, variable-spark-advance, fuel lever, and throttle.

SECTION VII

ASSESSMENT OF ULTRALEAN TECHNIQUES FOR OTHER ENGINES

The results obtained in Section VI apply only to the particular engine tested, that is, a Lycoming TIO-541-E engine series. In view of the promising results, one may ask what are the prospects for all the other engines available in the market. As was mentioned in Section IV, when one deals with engines, it is not possible to infer much about other engine designs from the results available from a single engine. For all we know, other engines belonging to the same series as the tested one could very well present wide dispersion in their performance when operating ultralean.

The only approach that could successfully provide reliable statistical data for ultralean burning operation would be testing several randomly selected engines within each series, as is common practice in the qualification of new engines. While this approach is beyond the scope of a government-sponsored program, it could be undertaken by the manufacturers as a phase of testing that an engine undergoes during qualification and verification after manufacturing.

In this section we will attempt to obtain a rough qualitative feeling about the eligibility of the engines offered in the market for ultralean operation. A simple methodology will be applied to each engine, allowing its classification according to a "quality factor".

The engines available have been obtained from Lycoming and Continental catalogs (Refs. 7-1 through 7-4).

A. METHODOLOGY

Each engine has been classified by three of its characteristics: (1) air induction system, (2) fuel system, (3) tolerances. After examining each one of these characteristics, a scoring factor is obtained for each one of them, ranging from 0 to 2. The final quality factor is obtained by weighing each of these characteristics as indicated in Table 7-1 and applying the rating formula

$$K = \alpha \times 0.2 + \beta \times 0.5 + \gamma \times 0.3 \qquad (7\text{-}1)$$

where K is the engine ultralean quality factor, and α, β, and γ are the scoring factors obtained for the air induction system, fuel system and tolerances, respectively.

1. Air Induction System

Table 7-1. Determination of the Engine Ultralean Quality Factor: Characteristics and Scoring Factors

Engine Characteristic	Scoring Factor (weight)	Range
Air induction system	α(20%)	From 0 to 2
Fuel System	β(50%)	From 0 to 2
Tolerances	γ(30%)	From 0 to 2

Quality factor $K = \alpha \times 0.2 + \beta \times 0.5 + \gamma \times 0.3$

The air induction system relevance has been weighed with a factor of 20% as shown in Equation 7-1. The scoring factor is in return obtained by analyzing the following parameters: number of cylinders, supercharging/naturally aspirated systems, and the presence of aftercoolers. The scoring factors for each one of these parameters are given in Table 7-2, and the resulting air induction scoring factor is obtained by the rating formula

$$\alpha = n \times 0.4 + s \times 0.5 + t \times 0.01 \qquad (7\text{-}2)$$

where n is the scoring resulting from the number of cylinders, s is the scoring resulting from the fact that the engine is supercharged or naturally aspirated, and t is the result of incorporating an aftercooler.

(1) Number of Cylinders. Ultralean operation is enhanced by a uniform distribution of air throughout the cylinders. This is accomplished by means of the intake manifold, and under equal circumstances such uniformity is more challenging the higher the number of cylinders. In this respect smaller cylinders would be easier to handle than larger engines. The scoring factors of 0, 1, and 2 have been assigned to engines provided with 8, 6, and 4 cylinders, respectively. This engine parameter is being evaluated within the air induction system with a 40% weight factor.

Table 7-2. Scoring Factor for the Air Induction System

Air Induction Parameter	Scoring Factor (weight)	Range
Number of cylinders	n (40%)	8........0 6........1 4........2
Supercharging	2 (50%)	Turbocharged....2 Supercharged....1.5 Naturally aspirated.......0.0
Aftercooled	t (10%)	Yes......2 No.......0

Air induction system scoring factor $\alpha = n \times 0.4 + s \times 0.5 + t \times 0.1$

(2) Supercharging. Although the ultralean techniques are not exclusively applicable to supercharged engines, they can be effectively implemented and result in ceilings up to 25,000 feet for present supercharged engines. The naturally aspirated engine have, on the other hand, a ceiling penalty. This design characteristic is assigned a scoring factor from 0 to 1 if the engine is naturally aspirated. For geared supercharged engines a scoring factor of 1.5 is applied, reserving the maximum scoring of 2 for the turbocharged systems; this further distinction between supercharged and turbocharged engines arises from the better overall efficiency that the turbocharged engines exhibit. A 50% weight factor has been assigned to this characteristic.

(3) Aftercooling. The presence of the aftercooler allows operating ultralean at high altitude without incurring in exaggerated manifold temperatures which limit in turn the power output. The presence of the aftercooler scores 2; its absence 0. This design parameter is weighted with a 10% factor.

2. Fuel System

The fuel system that has been weighted 50% in the total evaluation (see Equation 7-1) is perhaps the most important system that the designer must consider for good stability in ultralean operation. The evaluation of the fuel system comprises an examination of the carburetion method (see Table 7-3).

Table 7-3. Scoring for the Fuel System

Fuel System Parameters	Scoring Factor	Range
Carbureted systems	β	0 - 0.5
Fuel injection near inlet port	β	2
Fuel injection from a central distributor	β	1.5
Fuel injection from other points	β	1

(1) Carbureted Systems. Those engines using carburetors present usually worse fuel distribution throughout the cylinders due mostly to the incomplete vaporization of the fuel at the branching points of the air intake manifold. Although heat addition to the air intake manifold, immediately downstream of the carburetor, may alleviate the problem, there is a limit to such techniques imposed by the deterioration of the volumetric efficiency. Updraft carburetors have shown in this respect slightly better performance than downdraft carburetors, and taking this into account, a scoring factor from 0 to 0.5 has been assigned to carbureted engines.

(2) Fuel Injection Systems. The modern trend in engines is to incorporate fuel injection in the majority of the series. If the fuel is injected at each inlet port immediately upstream from the inlet valve, a scoring factor of 2 is assigned to the system. If the fuel is injected from a central distributor located at the branching point of the intake manifold, with individual jets directed to the inlet ports, the system scores 1.5. If the fuel is injected by other means, the scoring factor is 1.

3. Tolerances

Under this characteristic, the manufacturing and design quality of each engine series is brought into the picture by means of a scoring factor from 0 to 2. The series corresponding to the top of the line score 2, the medium price series a factor of 1, and the popular small engines, or old technology engines, a factor of 0. The tolerances influence the final evaluation (Equation 7-1) with a factor of 30%.

The relevance of the tolerances in ultralean burning have been discussed in Section IV, but for the present evaluation only those tolerances which affect the air and fuel passages are included, from the air inlet and fuel pump, to the combustion chamber. These tolerances will also affect the dispersion from engine to engine to be observed within each series. The engine designer who is interested in obtaining excellent ultralean operation should take special care in defining the manufacturing tolerances pertaining to the alignment of intake manifold pipe runners, inlet valve and combustion chamber geometries, orientation and cross section of fuel jets, temperature distribution in the intake manifold, and mating accuracies within the air induction system upstream of the manifold spider, which produce separation in the boundary layer and later affect the distribution of air through the manifold. The orientation of the throttle hinge plays a most important role in the even distribution of air, and therefore its adjustment deserves special attention.

B. ASSESSMENT

The methodology described in Section VIII-A was applied to the engines offered by the manufacturers and resulted in the evaluation shown in Table 7-4. The table shows the results for each design characteristic as well as for the engine. Also shown is the approximate number of engines sold from that series during 1975. Although the total number of engines sold in 1976 and 1977 has increased, the relative population of engines has remained practically unchanged. This relative population reflects the more advanced technology of recent years and does not fully show the possibilities offered by the existing fleet, which are somewhat lower.

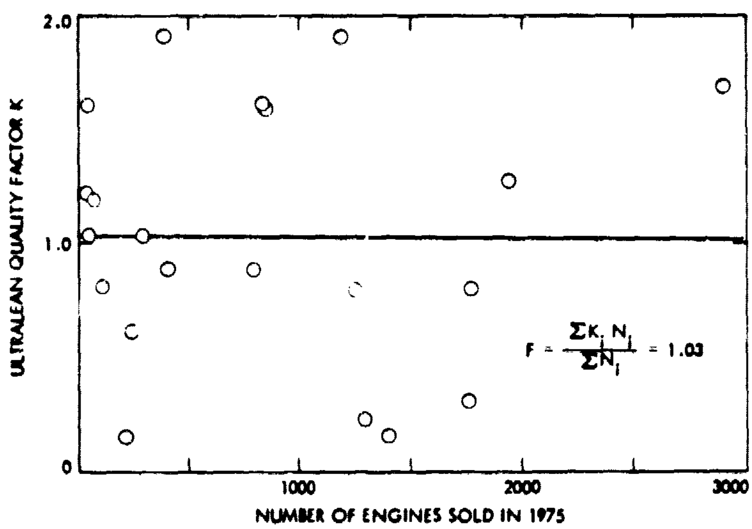


Figure 7-1. Ultralean Quality Factors vs Engine Population as Sold in 1975

Table 7-4. Results of Assessment of Ultralean Operation in Engines Manufactured in 1975

Engine No.	α	β	γ	K	Population
1	0.0	0.8	0.0	0.16	----
2	0.0	0.8	0.0	0.16	1400
3	0.0	0.8	0.0	0.16	215
4	0.0	0.4	0.5	0.23	1300
5	1.0	0.8	0.0	0.81	120
6	1.0	0.8	0.5	0.81	----
7	0.0	0.8	0.5	0.31	1755
8	1.0	0.4	1.0	0.88	403
9	1.0	0.8	0.5	0.81	1775
10	2.0	1.5	1.0	1.60	847
11	0.5	0.4	1.5	0.78	1255
12	1.0	0.4	1.5	1.03	286
13	2.0	1.5	1.5	1.7[illegible]	----
14	0.0	1.0	0.0	0.[illegible]	----
15	1.0	1.2	1.0	1.03	50
16	2.0	0.4	2.0	1.68	2903
17	2.0	1.6	2.0	[illegible].9[illegible]	1190
18	2.0	1.6	2.0	1.92	380
19	0.5	0.4	1.0	0.63	247
20	0.5	0.4	1.5	0.78	890
21	1.5	0.4	1.5	1.28	1930
22	1.5	1.4	1.5	1.48	----
23	1.5	1.4	2.0	1.63	835
24	1.5	1.4	2.0	1.63	50
25	1.5	1.0	1.5	1.40	----
26	1.0	1.2	1.5	1.18	80
27	1.0	0.6	2.0	1.22	55

Figure 7-1 shows a plot of the scoring factors of each engine vs its population as given by Table 7-4. From the figure a scoring factor is obtained which is representative of all the engines sold in 1975. This factor has been obtained by Equation (7-3).

$$F = \frac{\sum K_i \times N_i}{\sum N_i} = 1.03 \qquad (7\text{-}3)$$

where K_i is the quality factor for each engine series and N_i is its population.

In observing Table 7-5, it should be pointed out that the Lycoming TIO-541-E engine tested as described in Section VI scored K = 1.63. If 17% is accepted as a figure which represents the fuel economy improvement for such an engine, the average fuel economy expected from the engines sold in 1975 is estimated from

$$\text{fuel economy (\%)} = \frac{17 \times F}{1.63} = 10.74\% \qquad (7\text{-}4)$$

C. CONCLUSION

After this rough assessment based on scarce data and a crude methodology, one concludes that at the end of the 1970s the engines of the existing fleet can achieve a 10% reduction in aviation gasoline if one could implement ultralean techniques by methods and equipment as simple as those used in Section VI when operating with gasoline only. If such an implementation were undertaken, it would be possible to save over 50 million gallons of aviation gasoline a year at the beginning of the 1980s, and as much as 200 million gallons per year by the end of the 1990s.

D. RECOMMENDATIONS

The results of this assessment should be encouraging enough for the manufacturers to include in the routine engine testing some characteristic leanouts at constant power and assess the potential offered by their engines, correcting if necessary any defects so as to enhance ultralean operation.

SECTION VIII

IMPLEMENTATION OF ULTRALEAN BURNING IN GENERAL AVIATION

From the previous chapters it has become evident that the top-of-the-line piston engines used in general aviation are indeed very suitable to be operated ultralean if the techniques investigated and tested in Section VI are utilized. The results of the investigation are indeed very promising and encouraging. The key issue that remains to be discussed is how the nation can take advantage of these findings. The strategy for implementation of these techniques in general aviation is not exclusively a technical issue but depends heavily on developments underway in aviation fuel and on automobile industrial trends such as the introduction of alternative technology engines (diesels, gas turbines, lean burning, microelectronics, etc.).

A. AVIATION GASOLINE

As discussed previously, general aviation is finding increasing difficulties in securing the different octane gasolines with which present piston engines operate. The most probable trends in the near term will be toward the utilization of a common gasoline (probably high octane) which will mostly be defined by the requirements of supercharged engines. This of course would result in higher operating costs for light airplanes, contradicting the desirable effects of fuel economy improvement. Another scenario could be the relaxation of specs in octane in order to bring a commonality between automobile and aviation gasolines. This situation could be handled without too many changes by naturally aspirated engines, but will present formidable obstacles in highly supercharged engines unless new techniques or designs are implemented, such as water injection at takeoff, ultralean burning at takeoff, etc. A third possibility can be envisioned wherein top-of-the-line engines employ high octane aviation gasoline and the lighter airplanes are converted to automobile gasoline.

B. TRENDS IN THE AUTOMOBILE INDUSTRY

Trends in the automobile industry are tightly directed by the low emission requirements imposed by environmental controls and improved fuel economy as derived from a worldwide awareness of the need to conserve energy. Since 1973, the solution to NOx emissions has been to operate rich (equivalence ratios larger than 1) and reduce CO and HC emissions by means of catalytic reactors. These measures contributed dramatically to improve emissions, but did not help too much in improving fuel economy. More recent developments such as the 3-stage Volvo catalytic converter allowed operating near stoichiometric, while keeping emissions at a very low level. In any event, the final solution has been a decrease in dynamic performance. There are currently very intense efforts in introducing lean burning engines, but the industry lacks a good understanding of engine dynamic conditions in lean burning. Most inputs in this area are described from static performance mapping and empirical data. Industry does recognize, though, the need for accurate engine control during lean burning to fully take advantage of lower NOx with simultaneous fuel savings.

Intense R & D work (mostly proprietary) is presently underway in the three major manufacturing companies. This research includes areas such as electronic ignition, electronic fuel injection, heavy use of sensors, microprocessors and actuators. This technology is expected to be introduced in the market immediately. Diesel engines have also made their appearance, although only with a modest penetration and at very high prices. Furthermore, the availability of diesel fuel is still restricted to major truck routes. It is difficult at the moment to predict the future of the diesel in automobiles, but it should be recalled that although diesel engines have made their presence felt for quite a long time in high priced automobiles, their population has remained at a low level. This could continue indefinitely in the coming years, and it wouldn't be surprising if the diesel engine never makes a strong penetration in the market. The reason for this is simple: diesel engines are very expensive and produce high particulate emissions.

Looking to the midterm future, one can ask about the possibility of new engines underway. We have already witnessed some attempts such as the rotary and stratified charged engines. One of them, the rotary engine, still presents severe problems in the wearing of the seals of the combustion chambers, impacting engine life. The stratified charged engines have so far shown good results in lowering emissions, but their fuel economy has not been very impressive.

A recent study for the Ford Foundation conducted by the Jet Propulsion Laboratory (Ref. 8-1) recommended the Stirling engines and gas turbines as the engines for the automobile industry in the last decade of this century. Both of these represent a quantum step from present technology. These engines show promise in emission reduction, fuel economy and fuel adaptability. It is expected, though, that unless important developments in technology are crystallized, the prices of these engines are going to be high, perhaps higher than most people can pay. But it is also possible that at that time, sociological developments and advanced mass transportation systems may reduce dependence on the automobile. The regulating elements which drive developments in the automobile industry are complex. The future of the automobile engine, beyond 15 years from now, is very difficult to predict, since we presently are living in an age of options and decisions in the energy and transportation arenas.

C. CANDIDATE ENGINES FOR FUTURE GENERAL AVIATION AIRCRAFT

A number of engines are being developed under programs sponsored by the government and private industry that are designed to compete with or replace the aircraft piston engine presently in use, not only for the heavier twin-engine airplanes but also for the lighter, single-engine type, and even for trainers. At the present only three engines have substantially penetrated the general aviation market: piston engines, turboprops and turbojets. The turbojets are beginning to be replaced by more efficient turbofans. At present it is uncertain whether the turboprop or small turbofan will be more utilized in the market. The turbofan has been shown to be superior for high-performance airplanes flying at high altitudes and high speeds. The turboprop has found its place in the market for planes flying at moderate speeds and altitudes. In an effort to make it more competitive and to capture a larger proportion of the market, developments in the turbofan engine have been directed toward lower speeds and lower altitudes, while the same reasons have directed torboprop manufacturers toward higher speed and altitude applications. This type of competition between the small turbofan and turboprop engines has not affected the piston engine market, since the latter covers the lower range of altitudes and speeds with the supercharged and the naturally aspirated engines.

This situation could be drastically changed, as was pointed out in Section VIII-A, if aviation gasoline becomes very scarce. Turboprops and turbofans use kerosene-like fuels, the distribution of which throughout the main airports is assured by the presence of civil aviation aircraft. The question of availability of kerosene-like fuels or aviation gasoline in the smaller airports remains to be resolved, and the substitution of piston engines by small turboprops or turbofans does not seem to remedy or alleviate the fuel situation in small airports. The only sources of fuel near small airports are those installations which supply automobile gasoline, again indicating the desirability of having automobile gasoline for the very light general aviation airplanes.

Other engines are being seriously considered for light airplanes. One of these is the Stirling cycle, with the major benefits of this engine relying on its multifuel capability and high thermal efficiency. The Stirling suffers, however, three severe drawbacks: high cost, high weight, and a lengthy FAA certification, since it represents substantial modification and departure from other proven aircraft engines. Its multifuel capability does not seem to justify such a radical change, even if the fuel situation deteriorates very badly.

Another engine being proposed is the diesel. It is not new in aviation and was, in the early days of heavier-than-air flight, a remarkable machine. It was soon overwhelmed by the success of the gasoline engine due primarily to the better power-to-weight ratio, which is most important in aviation. As with automobiles, its penetration in the market is not expected to be very substantial, although it may be the right answer for specialized applications such as in agricultural aviation, where much of the machinery relies on diesel fuels and/or kerosene. The price of diesel engines is also higher than gasoline engines, although not as high as gas turbines.

The final candidate is the rotary engine (diesel or Otto cycles). This type of engine has long been advertised as the ideal solution for aviation because of its high power-to-weight ratio and low mechanical vibration. It has already made its commercial appearance in automobiles with meager success. Its major problem for aeronautical applications resides on its unproved reliability and overhaul cycle, with FAA certification representing a substantial effort for reasons similar to the Stirling engine. To make up for the lack of good fuel economy shown by rotary engines, there are some suggestions to introduce the stratified charge scheme with the rotary approach.

One can see then, that there is a wide variety of schemes and gimmicks being considered, but they all suffer from one common failing: they try too hard. As in the automotive market, any revolutionary innovation in general aviation will be treated by the customer with caution and apprehension. The only innovations which have proved to effectively penetrate the market are the evolutionary ones, that is, those innovations which have required only a small incremental implementation and which most of the times have had a fail-safe backup. This is particularly true in the light twin- or single-engine airplanes. It is possible to see in the future a further polarization of the trainers, single and twin engines, caused by increasing prices, FAA regulations and deterioration of the fuel situation, but it seems definite that the piston engine is here to stay for many years to come, even if technological breakthroughs in the competitive engines area capture a portion of the market.

From what has been said, it appears that the general aviation market in piston engines aircraft is, in spite of the precarious situation of aviation gasoline, following similar trends as the automotive industry, if for different reasons. It is expected therefore that we are going to contemplate in the near future progressive refinements and innovations in the systems associated with the engine, with perhaps some room in actual engine block modifications and (who knows?) perhaps in the actual cycle (turbo compound approach). The obvious fundamental preliminary step, as proved in Section VI, is the introduction of ultralean burning, since it offers advancement in two major areas of general aviation: emissions and fuel economy. Unfortunately, the stable ultralean operation of engines requires fine engine tuning and control that the present systems cannot cope with. Other systems will have to be introduced (as in the automotive industry) which will provide enough sophistication to adequately burn ultralean. These systems will, of course, impact the initial cost of the engine and probably also its maintenance costs, and its introduction in the market will only be justified if it offsets such costs.

D. FUTURE ULTRALEAN BURNING SYSTEMS FOR GENERAL AVIATION

From the experience accumulated along the course of the hydrogen enrichment program at JPL, an implementation strategy and an evolutionary introduction of engine systems of increasing capability will be presented in this section. The discussion will end with some projections and comments on the optimized integrated system for ultralean burning, which represents a target for such an evolution. Whether or not such a system will ever appear in the market depends on a variety of scenarios, some of which have been already mentioned in the preceding section.

1. Implementation Strategy

The implementation of ultralean burning in general aviation will have to be triggered by the users. The motivation for ultralean burning springs from the increase in range and fuel savings, with other factors still unexplored awaiting in the future (operation at low rpm during takeoff and climb, as well as a potential reduction in octane number). The actual structure of general aviation has not yet brought the effects of fuel costs on the direct operating costs. This is in part due to the psychology of the light airplane owner and the economic environment set for the fixed-base operators. There is, however, an increase in consciousness related to fuel savings. Corporations and government agencies have made the country aware of the necessity of national energy conservation, but this awareness has not yet made its impact in the overall market. The attitude of the users, however, is very different when fuel saving is presented to them in terms of an increase in range. Range is a primary performance parameter, and it is at a premium. It is presumed that an effective public education campaign will motivate the airframe manufacturers to offer ultralean burning to their customers as an important and marketable item.

Once the airframe manufacturer has decided to implement ultralean burning the engine manufacturer will respond by offering effective incremental innovations which will allow testing of such an approach in the market grounds. One can speculate then that the first engines selected as candidates for testing ultralean burning will be at the top of the line, and for several reasons. First, innovative ultralean techniques will have to be FAA-certified and the cost of the certification will have to be absorbed by the first batch of engines equipped with the innovation. The relative cost of the certification, as will be seen below, will be lower for the top-of-the-line engines, and therefore the percentage increase in price will be very moderate and acceptable to the customer who is in turn seeking a sophisticated and reliable engine. Besides the FAA certification, the engine manufacturer will have to worry about providing the guarantee and field services. The population of the top-of-the-line engines is the lowest and this fact, together with the professional approach this type of customer has in the maintenance and service of the aircraft, reduces the logistical problems in servicing the new systems. This is particularly important to the engine manufacturer (from the point of view of economic risk incurred in the innovation), since it could result in recalling for modification a high percentage of engines equipped with such systems, with the corresponding economic impact.

2. Incremental FAA Certification

The FAA certification of new systems for ultralean burning will at first be a modest effort and undertaken as a small engine incremental certification with very limited options, such as a single ultralean operating point for cruise, with conventional backup system in case of failure. As demonstrated in the JPL program, it is highly probable that most of the top-of-the-line engines can be leaned-out and enjoy a fuel savings of over 10% with a simple change in ignition timing: <u>it is</u>

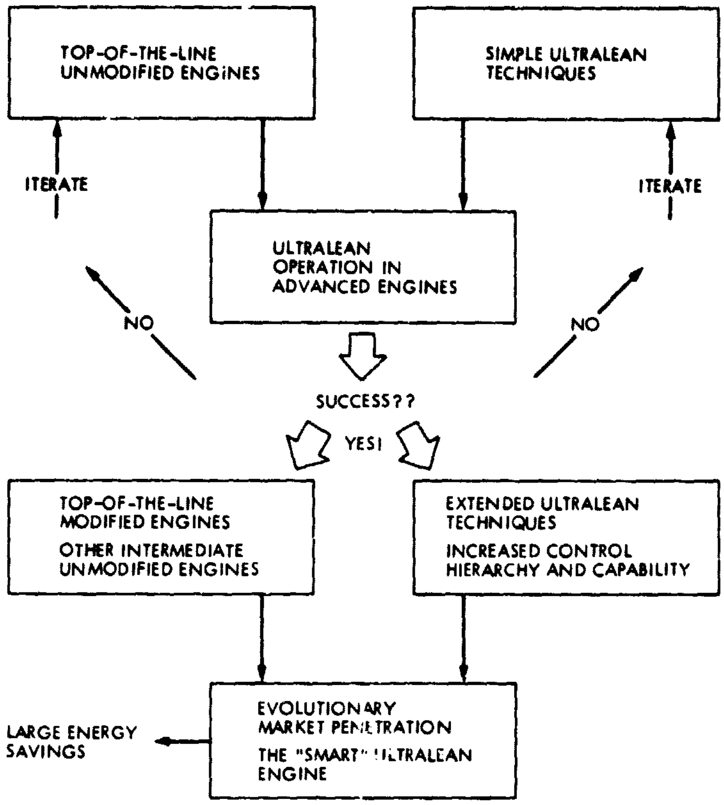


Figure 8-1. Implementation Strategy of Ultralean Burning Techniques in General Aviation

therefore expected that the top-of-the-line supercharged engines will be the commercial testing grounds for ultralean burning (see Figure 8-1).

As the simple ultralean options are proved in the market, more sophisticated systems may be introduced which will further enhance the ultralean capability of the engines. Some of these introductions have already been mentioned and will be recalled here for continuity:

> Individual electronic fuel injection for each cylinder: an accurate fuel schedule will be automatically sent to each cylinder with the purpose of equalizing the fuel/air ratio in each cylinder and delayed roughness in flight.

> Electronic ignition timing: this ignition system will provide the exact timing for each fuel/air ratio, power level and engine speed.

These two systems, which are very familiar in automotive applications, will not be regarded as elementary by the FAA, and will most probably require intensive certification with a fail-safe return mode to the presently used conventional system.

The higher requirements imposed on these systems by the demonstration of high reliability in flight in every conceivable weather condition, is in part balanced by the fact that the dynamic response of the engine during transients has very mild requirements when compared to the automobile. Engine acceleration and deceleration without hesitation are required only as a minimum for taxiing and go-around maneuvers, and for the entire part of its life, the engine is operated in a quasi-steady-state. Furthermore, the time in which the engine is operating in a transient mode is negligible and contributes little to the emissions and fuel economy.

The approach to designing simple sophisticated engine systems for ultralean operation is to assume the engine to be represented by a static model that can be obtained when mapping the engine under steady-state conditions, as is the present practice. The situation is very different from the challenges that the automobile manufacturers are confronted with. The state of the art of very sophisticated engine control systems in automobiles is at a standstill because of the lack of a dynamic model for the engine.

3. Introduction of Electronics

At the present, and without exception, all the engine control systems rely on mechanical and hydraulic actuators which are activated in open loop by the pilot (cable coupling) or close loop by certain pressure and temperature sensors (hydropneumatic coupling). The introduction of analog electronic controls will allow substantial improvement of the state of the art in two of the most important systems in ultralean burning: the fuel management system and the ignition system.

4. Introduction of Fluidics

A potential competitor to analog electronic controls is offered by fluidics. The increasing reliability in fluidics and the variety of off-the-shelf modules available bring its application in the controlling of the new engine systems for ultralean burning. Whether this will happen or the application will be in conjunction with electronic controls, depends in part on other related events and developments in which general aviation doesn't play much of a role, such as those occurring in other areas which use similar controls (orthopedics, robotics, etc.)

5. Digital Techniques

If one is to evaluate the conditions under which ultralean burning can be accurately controlled and optimized, one must think in terms of the modern developments in digital control systems. Some of these techniques have been applied already in advanced control systems for automobile engines at an experimental level, and there are plans to introduce them for control in high-performance fighter turbojet planes (see Reference 8-2). Its introduction in other areas of aviation, however, has been confined to navigation and flight instruments and, to a limited extent, to flight controls. The conservatism of the engine manufacturers and the attitude of FAA officials

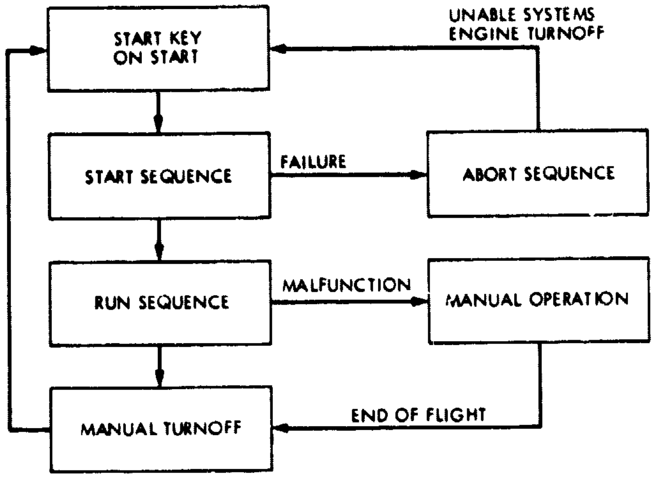


Figure 8-2. Simplified Engine Control Diagram

toward the aircraft power plants have been reflected in the absence of such techniques for engine controls.

Leaving aside reliability, the state of the art in instrumentation, electronics and microprocessing is such that once the control algorithms are established (or what is equivalent, once the engine model is established for control purposes), the implementation is straightforward. As an example and with the main purpose of fixing a base for discussion, a schematic digital control system is offered here for controlling ultra-lean operating in an aircraft engine.

Figure 8-2 is a simplified diagram of the fundamental sequences and functions of such a control, regardless if it is digital or analog. With the switch key in the "on" position a "start sequence" is initiated by the controller. If its detectors show any trouble, (failure or insufficient inputs), the controller will exit from the close loop and will operate an automatic abort sequence which terminates the start operation, de-enables the systems, and sets the engine ready for a new start with a visual display of the critical indicators. If the start sequence is successfully completed, the controller sets the engine in a run sequence. The run sequence results in the control of the engine at the power level required by the operator. If a malfunction is detected in any step, the controller switches itself in an open loop which will allow manual operation of the engine. When in manual operation, the engine can be run in the conventional way (and this reflects the fail-safe mode requirements by using conventional, well-proved backup systems). If the engine malfunction is corrected while the engine is manually operated, it can be reset, and set back to an automatic mode. If the engine malfunction is not corrected, the flight may be continued with the engine in the manual mode, and after landing and taxiing to the parking spot, the engine can be manually turned off with the systems ready for an automatic start sequence.

The engine controller is fairly complex to implement using analog techniques, but its implementation with digital circuitry is trivial. Furthermore, since aircraft engines are not subjected to high acceleration or deceleration, the logic in the sequence operations and the arithmetic of the control algorithms can easily be conducted by conventional microprocessors.

An example of an engine digital electronic control is shown in Figure 8-3. One can distinguish the basic elements of a close loop controller, i.e., sensor-signal processor-actuator. The particular operating point for the controller is set by external inputs and sensors. The inputs are usually introduced by the pilot, and during operation inflight should be reduced to one, that is, the power lever. All the other parameters such as altitude, humidity, and OAT are introduced in the controller as a set of signals from sensors. These signals can later be corrected by the microprocessor to find the true physical quantities for further processing or display to the pilot. Engine parameters such as manifold pressure, manifold temperature, throttle position, engine speed, fuel flow, air flow, individual exhaust temperatures and oxygen exhaust concentration are detected by means of appropriate sensors. The signals from these sensors, as well as the inputs, are passed through signal conditioners and transcribed in a uniform format. These signals are then input into a high-speed multiplexer and then to a digitizer. They are finally fed to a microprocessor data bank. The microprocessor has been programmed with specific instructions for that particular engine, and executes control by activating a set of power drivers which activate the proper actuators to shift the engine parameters. The power drivers stage also carries the override logic. This logic is used during the open loop operations for the start, stop, and failure sequence. A set of indicators completes the package. The power drivers are energized by a power supply, which can be directly linked to each engine or form part of a centralized system in the aircraft. The override logic allows manipulation of the actuators by mechanical means during engine malfunction in a similar manner to present practices.

a. <u>Sensors</u>. An examination of Figure 8-3 shows the criticality of the sensors in the control system. This situation is not different from other ground-based applications, but it is worsened in aircraft applications because of the severe environmental requirements that exist in an aircraft engine nacelle. A development program will have to be initiated to provide reliable, low-cost accurate sensors for this type of application. If low-cost maintenance is also desired, the sensors must be of low cost and easily inspected.

b. <u>Microprocessor</u>. The state of the art in microprocessing is so advanced that one can practically find any microprocessor to suit these requirements. As opposed to an analog processor, in which the tolerance imposes a limit to the complexity of operations, a digital microprocessor tolerance is only a function of the word length. A 12-bit-word-length microprocessor has been shown to handle successfully some complex engine control operations in automobile applications.

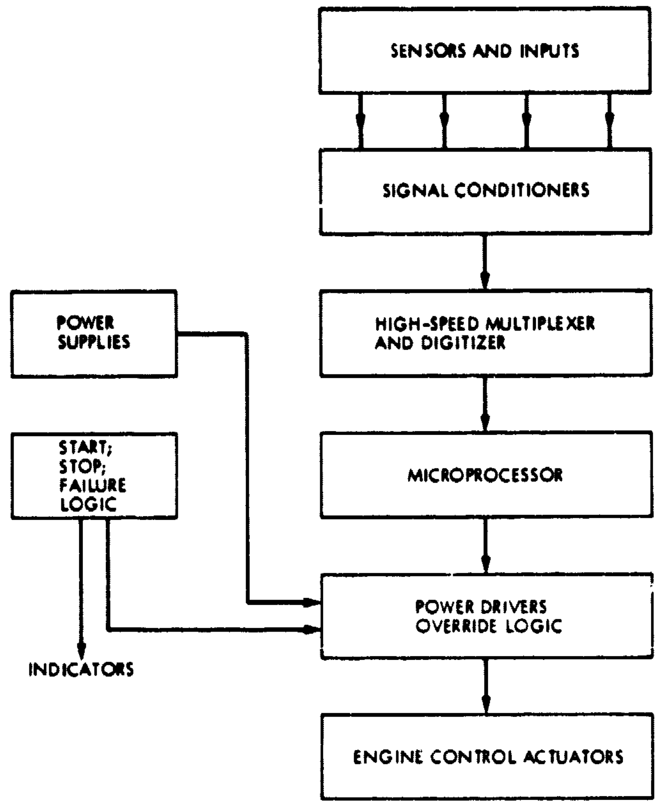


Figure 8-3. Engine Digital Electronic Control

c. Actuators. The power drivers and actuators are straightforward, and they do not represent any unusual challenge other than being limited to a lightweight type.

d. Wiring Harness. After the reliability of the sensors, the wiring harness presents the biggest challenge. It is also subjected to inside nacelle environment, with the wire size selected exclusively by mechanical considerations; teflon insulation seems appropriate, as demonstrated by present engine wiring harness. The connectors are subjected to high temperature in the nacelle, and because of the number of pins required for these types of applications, they are expected to be expensive. For this type of application one would possibly have to develop a specialized low cost connector.

6. Conclusions

Once a microprocessor has been installed onboard for engine control and automatic sequencing, it is cost-effective to extend its functions to assist other aircraft systems. A portion of the microprocessor can be reserved for certain housekeeping functions such as real-time indication of the status in the critical landing gear components, tire pressure, flight control hydraulics, mechanical tolerances, and unacceptable outworn level. Other functions could also be traced by the microprocessor, relieving the pilot of unnecessary stress during departure and approach maneuvers, such as true air speed, true altitude, heading, check list sequences, etc. But perhaps the most interesting application of the microprocessor lies in the fact that it can be used as an aid in preventive and mandatory maintenance, speeding up the routine inspections. Although the more advanced technology may impose more costly inspections, the cost may be offset in part by the ease of conducting maintenance, inspection and diagnosis when using digital computerized techniques. Some parallel attempts along these lines have been introduced by a few automobile manufacturers.

While the total integrated digital techniques for controlling ultralean burning appear very ambitious, their introduction in general aviation is by far easier than in automobiles, if only from the technical point of view. On the other hand, the reliability that they have to demonstrate in aviation is much more demanding than in automobiles. The latter requirements may considerably slow their introduction in the market.

SECTION IX

CONCLUSIONS AND RECOMMENDATIONS

Numerous issues, conclusions and recommendations were raised throughout this report. For convenience and easy reference they are assembled here and catalogued according to the subject matter under which they were discussed.

A. CONCLUSIONS

1. Aircraft Design

The optimum lift-to-drag ratio (L/D) of the airplane in cruise configuration is often compromised to allow for other aeronautical performance parameters such as good climb characteristics, acceptable crosswind landing behavior, etc. This type of compromise is common in homebuilt airplanes and the rest of the general aviation fleet, but there is another factor that severely impacts the airplane L/D: it is the arrangement for cockpit and cabin accommodations which marks the difference between the homebuilt aircraft designs (of highly aeronautical appeal) and the commercial general aviation market, which must appeal to an ever growing non-aeronautical but important customer group: casual flyers (flying for pleasure) and business people. These customer need easy-to-handle airplanes and a certain degree of comfort. An analysis of designs from the past, however, shows that these requirements do not exclude a good L/D in cruise configuration.

2. Engine Installation

The airframe manufacturer can improve the aircraft fuel economy by assuring that the engine installation features provide the optimum power utilization while achieving the required engine cooling, and with minimum drag penalty.

3. Future of the General Aviation Engine

(1) It is difficult to assess the future role of any engine in general aviation.

(2) Further divergence in engine choice for popular single engine and advanced twin engine aircraft is expected.

(3) The piston engine, with 75 years of success in aviation, including moments of crisis, will play a major role in the next 20 years of general aviation.

4. Aviation Fuels

Fuels are expected to become polarized in two groups: kerosene-like fuels and automotive-type fuels.

5. Aircraft Piston Engine Design

From all the engine factors affecting fuel economy, those affecting the leanout procedures are the most promising and cost-effective.

6. Ultralean Operation Methods

From the three methods which allow ultralean operation, it is concluded that:

(1) Ultralean burning with gasoline only, using advanced techniques in conventional piston engines, gives, under equal circumstances, the best fuel economy while simultaneously keeping the cost low.

(2) Hydrogen enrichment yields the smoothest and leanest operation, while being the most costly to implement.

(3) Stratified charge gives the least efficient combustion because of the restricted turbulence in the combustion chamber, resulting in an inherent limitation in the lean limit when compared with the other two options.

7. Results from the Hydrogen Enrichment for Aircraft Piston Engines Program

(1) System Analysis Assessment: The results were encouraging enough to proceed to the experimental phase.

(2) Experimental Investigation in the Test Cell:

(a) The feasibility of operating the engine under ultralean conditions with hydrogen enrichment rates from 0.0 to 3.0 lb/h was demonstrated.

(b) When the engine was operated ultralean with spark advances from 30 to 35°, the minimum BSFC underwent an improvement from 18 to 20%.

(c) The spark advance mentioned in (b) displaced the minimum BSFC to leaner equivalence ratios, which in turn allowed cooler operation of the engine.

(d) The lower temperatures at the ultralean operating point described in (c) allowed the manifold pressure to be increased to recover power.

(e) The increase in manifold pressure described in (d) did not affect the low minimum BSFC obtained in (b) and did not produce engine overheating.

(f) The methods just described were tested at altitudes up to 20,000 feet, but a decrease in the original critical altitude was obtained if the turbocharger capacity is not increased.

(g) The engine investigated did not need hydrogen enrichment to run ultralean and improve fuel economy.

(h) Rough engine running was not experienced when leaning out with or without hydrogen enrichment.

(i) The limited emission measurements obtained indicate that if these techniques can be implemented during taxi, idle, and approach, it may be possible to meet the 1980 Federal Emission Standards.

(j) The hydrogen generator technology was significantly advanced during this phase of the program, and although probably not needed for ultralean operation of this engine in flight, it might be required on other lower rated engines.

(3) Flight Tests

(a) The feasibility of operating the engine ultralean in flight for several altitudes and power levels, with and without hydrogen, has been demonstrated.

(b) Hydrogen enrichment was confirmed not to be needed to reach ultralean operation.

(c) The best fuel economy was obtained for gasoline-only employing ultralean techniques, while leaning at constant power for spark advances as large as 35°. A conservative result has been set at 11.2% when matching ultralean techniques against the best conventional operation techniques achieved by the airframe manufacturers as conducted by their test pilots. The estimated practical value when matched against conventional techniques conducted by the average pilot is from 17% to 20% as allowed by engine roughness.

(d) Engine roughness appears to be a limiting factor.

(e) Constant power leanouts at high altitudes were limited by manifold temperature and demonstrated up to 25,000 feet at 75% power.

(f) Controllability of the engine is mechanically and thermodynamically acceptable but is vulnerable to human errors.

(g) Ultralean techniques have been proven to be limited below 75% power level when conventional rpm is used.

(h) No detonation was detected during the whole series of flight tests.

(i) The spark advance at 35° BTC was still showing improvements of BSFC, which seems to indicate further benefits at larger spark advances.

(j) The hydrogen generator proved to be an effective research tool but still far from a commercial design.

(k) A historical milestone was achieved: For the first time, a piston engine was being operated in flight using hydrogen as one of the fuels.

(l) For the first time a hydrogen generator had been coupled and integrated with an engine and operated under practical requirements.

8. Assessment of Ultralean Techniques for Other Engines

After a rough assessment based on scarce data and a crude methodology, it is concluded that at the end of the 1970s, the engines of the existing fleet are able to achieve a 10% reduction in avaition gasoline if ultralean techniques could be implemented by methods and equipment as simple as those used in Section VI, when operating with gasoline only. If such an implementation were undertaken, it would be possible to save over 50 million gallons of aviation gasoline per year at the beginning of the 1980s, and as much as 200 million gallons per year by the end of the 1990s.

9. Implementation of Ultralean Burning in General Aviation

Whie the total integrated digital techniques for controlling ultralean burning appear very ambitious, their introduction in general aviation is far easier than in automobiles, if only from the technical point of view. On the other hand, the reliability that must be demonstrated for application in aviation is much more demanding than in automobiles. The latter requirements may considerably slow their introduction in the market.

B. RECOMMENDATIONS

1. Aircraft Design

It is recommended that airframe manufacturers improve the L/D of the general aviation fleet, even if this implies a certain sacrifice in comfort, since it substantially affects fuel consumption.

2. Engine Installation

Engine installation can be improved without significant engine power sacrifice by analyzing the available methods of cooling the engine with minimum cooling drag penalty.

3. Future of the General Aviation Engine

(1) Continue to develop alternate technological options to the conventional general aviation piston engine.

(2) Develop advanced systems to exploit at its most the potentials of conventional general aviation piston engines.

4. Research

Conduct research in low specification aviation gasolines leaving automotive gasoline-type specifications as an alternate goal.

5. Aircraft Piston Engine Design

(1) The engine manufacturer should continue to improve engine efficiency by optimizing all factors affecting fuel economy, while being compatible with other requirements, such as reliability, cost, weight, etc.

(2) Special attention should be paid to the introduction and design of systems which contribute to a smooth and far leanout.

6. Ultralean Operation Methods

Ultralean burning in conventional piston engines using advanced techniques is recommended.

7. Results from the Hydrogen Enrichment for Aircraft Piston Engines Program

If the program is to be continued for further flight testing, the following recommendations are made:

(1) Use a variable electronic ignition suitable to be continually adjusted from the cockpit for optimum torque.

(2) Explore lower engine speeds and high manifold pressures to achieve high powers during ultralean operation.

(3) Obtain an indicated cycle of the engine during ultralean operation for variable spark advances adjusted for optimum torque at severl power levels.

(4) Use electronic fuel ignition (individual fuel injection in each cylinder for best results) to fight engine roughness, and monitor results with Kistler gauges.

(5) Special caution should be exercised in closely following the torquemeter driftout after each flight, recalibrating it if necessary.

(6) Develop accurate methods or estimate air flow in flight.

(7) Integrate fuel lever, throttle, and rpm in a single power lever.

(8) Conduct flight demonstration of fuel economy using conventional techniques followed by ultralean techniques to assess net gains.

8. Assessment of Ultralean Techniques for Other Engines

The results of the assessment are encouraging enough for the manufacturers to include in routine engine testing some characteristic leanouts at constant power and assess the potential offered by their engines, correcting, if necessary, any defects in order to enhance ultralean operation.

9. Implementation of Ultralean Burning in General Aviation

Implementation of ultralean burning techniques in the general aviation fleet is recommended, starting with top-of-the-line engines and incrementally introducing the techniques until fully integrated digital control systems are achieved in the medium priced engines.

EPILOGUE

Since completion of the program in November 1977, NASA has continued work related to fuel economy for piston aircraft engines as part of the effort in general aviation engines at the NASA Lewis Research Center. The engine manufacturers are active participants in the program, and it is hopefully expected that a prompt implementation of ultralean techniques for general aviation will result.

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