NASA Technical Memorandum 105562

NASA's Rotary Engine Technology Enablement Program — 1983 Through 1991

Edward A. Willis
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

John J. McFadden
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

NASA

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Edward A. Willis

SverdrupTechnology, Inc.

Lewis Research Center Group

Brook Park, Ohio 44142

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John J. McFadden

National Aeronautics and Space Administration

Lewis Research Center

Cleveland, Ohio 44135

ABSTRACT

This paper provides a brief review of NASA's Rotary Engine Technology Enablement Program from 1983 through 1991, with primary emphasis on the CFD or Computational Fluid Dynamics approaches used since 1987. The main discussion includes both code development and applications to several particularly difficult internal airflow, fuel-air mixing and combustion-related problems. A summary of the final status of the technology is given.

INTRODUCTION

NASA's original goal in this program was to establish the technology base for superior new powerplants for light aircraft and similar uses. These new powerplants, desirably, would combine some of the better features of reciprocating and gas-turbine engines, so as to simultaneously be fuel-efficient, reliable, light, easy to install and cost-effective. Based on engine and aircraft/mission studies conducted in the early 1980's, Ref. [1]-[3], the rotary (Wankel) engine was perceived to have many of the desired features, including in particular the potential ability to burn jet and other distillate fuels as well as gasoline. It was also judged to be capable of significant further development, since only a limited amount of rotary engine R&D had been accomplished up to that time. Existing automotive rotary engines had by then demonstrated high power outputs in a compact, smooth-running and reliable package, but required high grade gasoline and were less fuel-efficient than comparable reciprocating engines. Accordingly, the basic thrust of the NASA Rotary Engine Technology Enablement Program was to improve the rotary engine's efficiency to a level which would be generally perceived as "competitive". Specifically, this meant a cruise BSFC of no more than 244 g/kwh or 0.40 #/bhp-hr under installed, warranted conditions, while running on Jet-A or other readily available aviation fuels. (This is equivalent to about 213-219 g/kwh or 0.35-0.36 #/bhp-hr under dynamometer-laboratory conditions.)

FIGURE 1 lists the formal technical objectives of the program. These objectives are ambitious but were originally thought to be achievable by the end of FY 1992. The program to be described herein was initially planned on that basis.

A PARTICULAR form of the rotary engine, the so-called stratified-charge rotary engine or SCRE was considered to have the best chance of meeting these objectives. In this embodiment, see Figure 2, the primary structure consists of a triangular rotor which moves in hula-hoop fashion within a trochoidal housing. The rotor's motion, generated by an eccentric crank and timing gears, is such that the rotor makes one complete revolution for three revolutions of the crank, while it's sealed tips maintain contact with the trochoid walls. A combustion pocket is cut into each rotor flank; the pocket typically contains about 50% of the total working volume at top-dead-center (TDC). Thus, each of the rotor flanks defines a sealed working volume in which the familiar strokes of intake, compression, combustion/expansion and exhaust are accomplished. One complete four-stroke cycle is accomplished per crankshaft revolution.

IN COMMON with other versions of the Wankel rotary engine, the SCRE retains the clear virtues of compactness, low weight and vibration, high power and simplicity. It differs, however, from its conventional automotive counterpart, in that it employs diesel-type, timed, high pressure fuel injection, across an ignition source, to maintain a degree of control over the combustion event. With appropriate choices of the ignition and fuel-injection parameters, the combustion process can usually be controlled to the point where fuel octane or cetane numbers have little or no effect. This characteristic clearly points to multi-fuel capability, which was a major program goal. The SCRE also presented some major challenges and opportunities in terms of understanding and optimizing it's novel combustion process. The object of this paper is to describe some of the ways in which these challenges were addressed.

SINCE 1983, the program has been approached via a series of three consecutive contracts with major industries, supported as appropriate by in-house efforts, small industry contracts and University grants. For convenience, it has become customary to refer to Phase I, Phase II and Phase III of the total program, according to the major contract in place at the time. (Phase I--Curtiss-Wright Corp., FY 1983-84; Phase II--Deere & Co., FY 1986-89; Phase III--Deere & Co., FY 1990-91). The same nomenclature will be utilized herein. This paper provides a brief summary of the effort from the viewpoint of eventual applications in the light aircraft or related fields. A parallel paper in this Session discusses many of the same developments from a broad-application point of view, see Ref.[4]. The present discussion touches on all major aspects of the effort, but places primary emphasis on the CFD or Computational Fluid

Dynamics approaches and results of the later stages of the program. Also included is a summary of the final status of the technology as the program approaches a conclusion.

RESULTS & DISCUSSION

PHASE I & II

Objectives: The intent in this early part of the program included four major objectives, as shown below.

1) Design, build and acceptance-test a high-performance   rotary engine test rig capable of sustained running at the   speeds, loads and other conditions identified in the precursory studies.

2) Demonstrate multi-fuel capability.

3) Accomplish initial R&D applications of the rig with   emphasis   on   high-pressure, electronically-controlled fuel   injection.

4) Develop and apply computational-fluid-dynamics (CFD)   methods   to better understand and improve the combustion   process in the SCRE.

Related Events:

THE PHASE I contract was awarded to the Curtiss Wright Corporation in early FY 1983.

CURTISS-WRIGHT sold the rotary engine business to John Deere & Co. in early 1984 and Deere completed the Phase I testing under novation. The Phase II contract was awarded to Deere in FY 1986.

DEERE, NASA in-house and University Grant efforts were also initiated during this period with additional objectives including: a) the development and application of advanced analytical methods such as improved CFD codes to study internal airflow, combustion and related events; and b) the use of laser-optical and related techniques to obtain experimental data for code assessment purposes.

Principal Results: The following major results were accomplished.

IN PHASE I, the rig was built under Contract NAS3-23056, initially with the Curtiss-Wright Corp., but later novated to Deere. See Ref. [5]. Figure 3 illustrates the general arrangement of this very rugged test article. It's internal airflow lines, combustion chamber geometry, fuel injection, ignition and sealing arrangements were identical to those defined in the original studies, but it was structurally beefed-up to withstand limit condition testing and/or accidental overloads. The single rotor design provided a very stiff mainshaft as well a simplified configuration. Acceptance tests showed it was structurally sound and able to meet the maximum speed and maximum load requirements separately, but not simultaneously. As originally built, it could not develop the anticipated maximum rating of 120-150 kw (160 - 200 BHP) ə 9600 RPM due to limitations of the fuel-injector system. Thus, fuel-injection technology was identified as the first major barrier to obtaining the expected levels of power output and efficiency. Review of the Phase I test results nevertheless indicated that the specific-output levels projected in the original studies (180 kw/l or 4 HP / cu.in.) could be attained, provided that some advanced form of high-rate fuel-injection technology could be

obtained to support the necessary fuel flow at the full rated RPM.

MULTI-FUEL capability was demonstrated early on. As Figure 4 suggests, tests with gasoline, diesel, jet and various other fuels all showed substantially the same thermal efficiencies in a given engine. In most cases, there was little or no observable octane or cetane dependence. This was expected since it is inherent in the stratified-charge combustion concept. The fact that the rotary is so well adaptable to stratified-charge is one of it's major advantages. It's ability to tolerate various fuels makes it particularly useful in those parts of the world where fuel availability or quality may be an issue.

IN PHASE II, an advanced, high pressure, electronically controlled fuel-injection system was identified, pro·ured and tested, Ref. 6. Bench tests were successful in terms of flow rates and frequency response. In engine rig testing, the original specific power goal of 180 kw/l or 4 HP/cu.in. was demonstrated with relative ease and a new long range goal of 230 kw/l or 5 HP/cu.in. was adopted by mutual agreement. Unfortunately, the cruise BSFC associated with this technology was initially worse than that of the original configuration. This was attributed to the rate-shape of the fuel injection flow pulse, which had a declining characteristic vs the square or rising characteristic of the original. Subsequent efforts were re-focussed on improving the speed/flow capabilities of the more conventional, mechanical type fuel injection systems.

TURBOCHARGING was found to be a very effective way of improving the best BSFC as well as the maximum power of the SCRE, throughout Phases I, II and III. Work related to turbocharging was initially pursued to provide an increased power density. The results showed not only the expected higher power, but a substantial improvement in BSFC as well. Figure 5 illustrates a typical effect of turbocharging on SCRE economy and equivalence ratio. (These particular results were generated with the Sverdrup Technology (SVT) system/cycle computer code of Ref. 17, but are representative of many experiments throughout the program.) As this data indicates, the BSFC improvement was most evident at the higher powers where it was most needed. As the power increased, the normally aspirated engine's equivalence ratio soon increased to the region (>0.7) that is usually assiciated with less efficient combustion. This effect, working against the normal improvement of mechanical efficiency with load, resulted in a BSFC minimum at about 40 Bhp. Turbocharging resulted in higher airflow and hence lower equivalence ratios, especially at higher powers. This delayed the onset of lower combustion efficiency, so that the low BSFC region became broader, moved downward and shifted to higher output powers.

CFD DEVELOPMENT and related analysis efforts on the SCRE were initiated, first at Deere, and later at Sverdrup Technology and at two of NASA's university grantees. The development of Deere's CFD code, known as REC-1, began ca. 1984. As described in Ref. 8 - 10, it became operational in 1987 and soon led to a highly improved form of the main fuel injection spray pattern. This became known as the "fan" or non-shadowing spray pattern,

Ref. 11. A very beneficial application was also made to the pilot spray, known as the "rabbit-ears" spray or dual-orifice pilot, Ref. 12.

THE PHASE II technical effort was completed at the end of FY 1989. By then, as illustrated in Figure 6, the test rig had demonstrated over 195 kw/l (4.3HP/cu.in.), a cruise BSFC of about 256 g/kwh (0.42 lbs/BHP-hr) on jet fuel, diesel fuel or aviation gasoline and (in terms of computer simulations) the potential to be an effective powerplant for a variety of high altitude applications. The improvement noted in specific power can be primarily attributed to a combination of turbocharging and improved fuel injectors. The BSFC improvement is due largely to the CFD-inspired spray pattern modifications together with continuing optimization of the engine- turbocharger match.

PHASE III

Objectives: The principal thrust of Phase III was to continue, extend and complete the work begun in Phase II to obtain the original major goals of:

        1) 230 kw/l (5 HP/cu.in.) ₃ takeoff;

        2) a cruise BSFC of 216 g/kwh (0.355 lbs/BHP-hr.) or better;

        3) a wear-life potential of at least 2000 hrs. TBO;

        4) a cruise altitude capability of 10 km. (33000 ft.) or more   for a general aviation type mission; while

        5) maintaining multi-fuel capability with all the above.

Principal Results: IMPROVED FUEL-INJECTOR tests with a modified high-speed fuel pump led to meeting the 5 HP/cu.in. specific power goal. In the process, it was observed that the rig was not running efficiently at this power (it was too rich); predictions with a cycle and system simulation code similar to Ref. [17] indicated that an enlarged exhaust port would enable a higher airflow, thus leaning the mixture and providing a major gain in efficiency at maximum power. Two new trochoid housings were procured for later tests: one having a minor (30%) and one with a major (100%) enlargement of the exhaust port area. Figure 7, generated with the Ref.[17] code, illustrates the predicted BSFC changes between the original and a range of enlarged port areas at maximum power. Meanwhile, in the ongoing experimental program, further tests with continuing spray-pattern optimizations and improved engine/turbocharger matching brought the cruise BSFC down to about 244g/kwh (0.40 lbs./BHP-hr.) with the standard configuration.

THE CFD-oriented approach of Phase II was continued with efforts to refine Deere's REC-1 code; efforts to complete an assessment of the SVT CFD code known as AGNI-3D and described in Ref.[19]-[23]; efforts to complete an alternative rotary-CFD project at Carnegie-Mellon University (resulting in three different versions, see Ref.[24]-[26]); and efforts at Michigan State University to obtain experimental data on airflow, spray and mixing characteristics (see Ref.[27]-30]).

TECHNICAL EMPHASIS by then was shifting towards the CFD-aided design of advanced rotor-pocket shapes and related modifications to the trochoid housings. This type of change is potentially more powerful than the simple spray-pattern changes which were investigated in Phase II, but is also more expensive and time-consuming to implement since new patterns and castings are required. Five major iterations of this nature were originally planned for Phase III. These were: 1) the dual-ignition rotor housing, see Figure 8; 2) the enlarged-exhaust-port rotor housing described above; 3) a "reentrant-pocket" rotor; 4) a "leading-deep-recess-pocket" rotor; and 5) a "dual-pocket" rotor. (The latter three items are not illustrated.)

FRICTION REDUCTION and additional work oriented towards further improvements of the fuel-injection system, turbocharging and spray patterns was also undertaken. The results to date from these efforts are described in the following paragraphs, see also Ref. 7.

DUAL-IGNITION housing tests addressed the configuration illustrated in Figure 8 and described in Ref.[13] and [14]. The theory behind this arrangement was based on the observation that the early CFD simulations often showed very non-uniform mixture distributions near TDC. Typically, two combustible regions were separated by a region of overly-rich, slow-burning mixture. With only one igniter, the ignition of the second combustible region was delayed until well beyond TDC. With two igniters, both regions could be ignited at once to enhance the overall rate of combustion. Although the theory was logical, the experimental investigation gave mixed results as noted in Ref.[15] and [16]. At low to medium power, the expected 8%-10% improvements in efficiency or BSFC were not seen, and this would be an accomplishment of some significance for most applications of the rotary engine. Figures 9 and 10 generally illustrate the types of changes that occurred when dual ignition was used. Figure 9 displays a comparison of pressure data computed with the newly-operational SVT AGNI-3D code (Ref.[22]) and data obtained in the Deere experimental program under nominally identical conditions (RPM, 6000; BMEP, 950 kPa (138 psi); equivalence ratio, 0.51). As may be clearly seen, the AGNI-3D computations agree almost perfectly with one of the two transducers reported. Compared with the other transducer, the AGNI results show a slight under prediction of the peak pressure magnitude but still agree very well with the clearly observable trends. From several comparisons such as this (see Ref.[23] of this Session), we conclude that AGNI has reached the point of being a useful and fairly reliable predictive tool within the limitations and cautions that apply to complex CFD codes of this sort. Figure 10 then proceeds to show AGNI predictions of three relevant cases: (1) The solid curve duplicates the dual-ignition results shown in Figure 9, at about 50% power and advanced ignition timing; (2) The dotted curve is for the same conditions except with timing retarded to a value typical of the baseline, single-igniter case; and (3) The original single-igniter case, clearly showing two pressure peaks corresponding to the sequential burning of the two combustible regions.

By comparison of the upper and lower curves, it may be seen that, for given timing, the change from single to dual ignition resulted in a significantly more favorable pressure profile. The transition from a double-peaked trace to a higher, single-peaked trace indicates that the two combustible regions are now burning at the same time. Also, optimization of the ignition timing has it's usual effect (the improvement is indicated by an earlier and still higher peak), as may be seen by comparing the upper two curves in Fig. 10. As a result, the observed BSFC at 50% power improved by 8%-10% as previously noted.

AT HIGH POWER, however, other effects came into play that had not been predicted by either of the CFD codes. Attempts to obtain substantially higher power at the advanced timings represented by the solid curve resulted in a detonation type of combustion instability. This was arguably followed by local overheating, seal lockups, and excessive blowby of hot combustible mixture into the following chamber, which in turn increased the likelihood of detonation in that chamber. (While this sequence of events is admittedly controversial, the authors must point out that similar phenomena can be noted during any test of a gasoline fuelled automotive rotary engine, when the spark is excessively advanced during a high-power run. Several such instances were noted, for example, during the work reported in Ref.[18].) On the other hand, when the spark was retarded, as is normal for high powers, the secondary igniter simply did not light off the mixture. The reasons for this are again not clearly understood at this time and perhaps they are still somewhat controversial. In our view, the most likely explanation is that the higher local "squish" velocity associated with later timing was sufficient to either blow combustible mixture away from the upstream-located igniter, or to simply blow out a weak, incipient flame. In that case, a better location for the second, trochoid-mounted igniter would be downstream of the main injector nozzle, rather than upstream of it. At all events, the experimental performance deteriorated abruptly at higher powers, until it was no better than the previous, single-igniter baseline. The ultimate cause of this, regardless of the details, was the failure of the second igniter to provide consistent ignition at the retarded timings required for high power operation. Thus, although much was learned, there was no improvement from the bottom-line aviation viewpoint where cruise efficiency at 55%-75% power is the dominant requirement.

KEEP IN MIND, however, that the program discussed herein is a research program in which the value of what is learned should (and usually does) exceed the importance of immediate objectives. In this instance we learned that: (1) The trochoid-mounted igniter, when it works properly, has an overwhelmingly powerful effect on the subsequent combustion process and can offer large potential benefits when properly utilized; (2) This concept is a relatively risky one at the present time, due to the absence or inadequacy of currently-available ignition models for CFD codes such as REC-1 and AGNI-3D; (3) The lack of an applicable autoignition/detonation model compounds the problem even further; and (4) Still other code refinements,

such as seal-leakage modelling and a wall-wetting model, would allow us to reproduce and thus fully understand the "vicious circle" described above, which apparently involves detonation, overheating, seal lockup/leakage, and finally, a worse case of detonation.

THE MODIFIED PORT housing, with an enlarged exhaust port area, was incorporated with an increased compression ratio (8.4:1 vs. 7.5:1), the best of the CFD- generated spray patterns and low-friction, low-leakage side and apex seals from the "friction-reduction" element of the program for the final test of the standard or single-ignition configuration. The resulting cuise BSFC was 230 g/kwh (0.375 lbs/BHP-hr.), which satisfied the original project BSFC milestone planned for the end of FY 1991. For reasons which will be discussed below, it is currently unclear how or when the three remaining advanced CFD-pocket rotors will be tested.

Related Events:

DEERE & CO. in September, 1990, announced plans to sell its Rotary Engine Division (REDIV) by November, 1991. This posed some difficulty for NASA, since the effort was being carried out at REDIV and the technical plans and related resources were originally scheduled for completion at the end of FY 1992. NASA responded by first developing plans to complete a worthwhile subset of the original technical effort by November, 1991.

AN ACCELERATION of one full year out of two years remaining could not be accomodated, however, without something being lost. The major losses, as now perceived, are as follows:
1) The three advanced, CFD-defined rotor pocket shapes mentioned above, which reflect the final outcome of many years of NASA-supported CFD research and currently exist in test-ready hardware, may not be evaluated under NASA's sponsorship or to NASA's credit; and also quite significantly, 2) The maximum power and best cruise BSFC will not be demonstrable in a single build of the test rig. A final iteration, incorporating at least one of the CFD-defined rotors and possibly structural modifications for higher peak pressures, would still be required to demonstrate technology readiness in a convincing way. Also needed are tests of further known improvements, such as ceramic seals and coatings and turbo-compounding, which might have been accomplished under the original schedule.

AT PRESENT, it appears that the former REDIV operation has been taken over by a group known as Rotary Power, International or RPI. It is clear that the future of this technology will depend to a great degree on their commitment, resources and technical capabilities.

SUMMARY

PHASE I & II

A TEST RIG reflecting the flow lines and other high preformance features identified in the early studies was designed, built and tested. The initial tests showed: smooth, reliable and repeatable operation over a wide power band; multi-fuel capability; minimum BSFC's in the 305 g/kwh

(0.5 lb./BHP-hr.) neighborhood; about 136 kw/l (3 HP/cu.in.); and no apparent structural deficiencies. Fuel-injection technology was identified as the first major barrier to obtaining the full expected levels of power output and efficiency.

AN ADVANCED, very high pressure, electronically controlled fuel-injection system was then identified, procured and tested. Bench tests were successful in terms of flow rates and response speed. In engine rig testing, the original specific power goal was demonstrated with relative ease and a new long range goal of 230 kw/l (5 HP/cu.in.) was adopted. Unfortunately, the cruise BSFC associated with this technology was no improvement over the original configuration. Subsequent efforts therefore focussed on improving the speed capabilities of the more conventional, mechanical type fuel injectors.

TURBOCHARGING was found to be a very effective way of improving the best BSFC as well as the max power of the SCRE. Work related to high-altitude turbocharging was initiated to support aircraft requirements.

CFD developments and analyses relative to the SCRE were initiated at Deere and at two of NASA's supporting contractors or grantees. Deere's CFD code became operational in 1987 and led rather quickly to some highly significant improvements to the main fuel spray pattern ("fan" or non-shadowing spray) and to the pilot spray as well ("rabbit-ears" or dual-orifice pilot).

THE PHASE II technical effort was completed in FY 1989. By then, the program had demonstrated 195 kw/l (4.3HP/cu.in.), a cruise BSFC of about 256 g/kwh (0.42 lbs/BHP-hr) on jet fuel, diesel fuel or aviation gasoline and (in terms of a design study) the potential to be a very effective powerplant for high altitude applications. Figure 11 summarizes the progress up to that point and later. Early in the program, the cruise BSFC was hovering in the neighborhood of 0.5 and often higher, while the power density was not appreciably better than that of automotive rotaries. By early 1989, high-rate fuel injection together with turbocharging had improved the specific power to and beyond the original target level of 182 kw/l (4 HP/cu.in.), albeit with no immediate BSFC improvement. Towards the end of Phase II, the advent of CFD-driven spray and injector nozzle modifications caused a dramatic improvement in the BSFC criterion.

PHASE III

CFD-ORIENTED approaches of Phase II were continued and extended, with emphasis shifting towards the design of advanced rotor-pocket shapes and related modifications to the trochoid housings. As the right-hand part of Figure 11 indicates, these efforts together with friction-reduction measures and further optimization of the engine/turbocharger match have resulted in meeting the agreed BSFC goal of 230 g/kwh (0.375 lbs/Bhp-hr) for the end of FY 1991.

FRICTION-REDUCTION work and further improvements of the fuel-injection system were also undertaken. Tests with a modified high-speed fuel injection pump led to meeting the 230 kw/l (5 HP/cu.in.) specific power goal. In the process, it was observed that the rig was running too rich at this power ; cycle code predictions indicated that an enlarged exhaust port would result in a leaner mixture and a major gain in efficiency at maximum power.

DUAL-IGNITION housing tests gave mixed results. At low to moderate powers, it gave the expected 8%-10% improvements in efficiency or BSFC and this would be a significant accomplishment for most applications of the rotary engine. At higher powers, however, the performance deteriorated abruptly, until it was no better than the previous, single-igniter baseline. The cause of this was found to be failure of the second igniter to provide reliable ignition at the retarded timings associated with high power operation. Thus, although much was learned, there was no immediate improvement from the bottom-line aviation viewpoint where cruise efficiency at 55%-75% power is the dominant requirement.

FINAL TESTS with the original, single-ignition configuration were aimed at continuing spray-pattern optimization and improving the engine/turbocharger match. These brought the cruise BSFC down to approx. 244 g/kwh (0.40 lbs./BHP-hr.) with the original configuration. The final test with the single-ignition configuration incorporated an enlarged exhaust port, an increased compression ratio (8.4:1 vs. 7.5:1), the best of the CFD generated spray patterns and low-friction, low-leakage side and apex seals from the "friction-reduction" element of the program. The resulting cruise BSFC was 230 g/kwh or 0.375 lbs/BHP-hr. This together with the 230 kw/l (5 HP/cu.in.) demonstration earlier in the year, satisfied the project milestones for FY 1991.

DUE TO THE CHANGE OF OWNERSHIP, some uncertainty exists as to whether, when or how the three advanced rotors which remain untested can be evaluated. Nevertheless, as Figure 12 suggests, there is a clear potential to proceed onwards from what has been accomplished already. We believe that at least one and possibly all of the advanced pocket configurations, when combined with the abovementioned advances, will be capable of meeting our original and very ambitious goal. In addition, obvious further possibilities exist as shown on the last three lines. Serious investigation of these as well as the three advanced pockets is clearly warranted.

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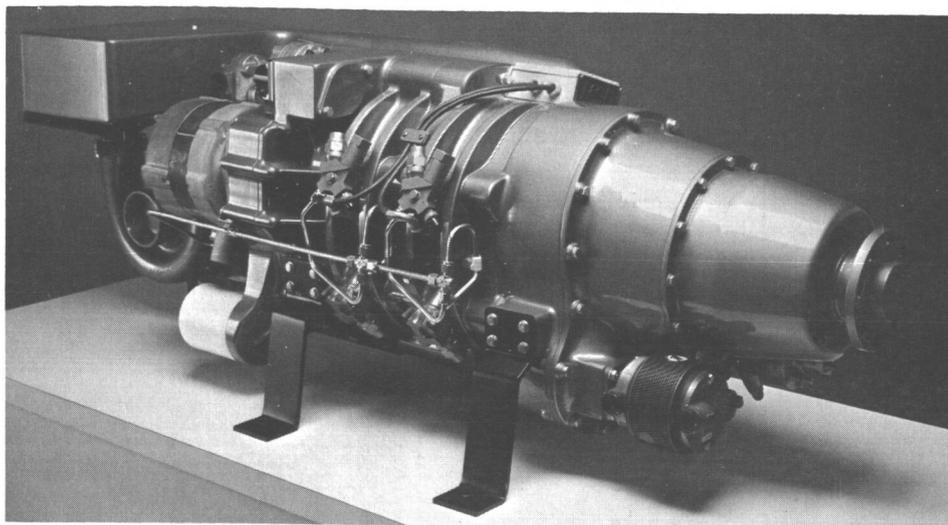
- Multifuel capability (gasoline, jet, diesel, and alcohol fuels).
- Cruise BSFC: 0.36 lb/hp-hr, or better.
- Power density (maximum): 5 hp/in.^{3}, or better.
- 2000-hr durability (TBO).
- Altitude capability: 28 000 ft or more (depends on application).
- Modular design (family-of-engines concept).
- Manufacturing cost competitive with comparable reciprocating engines.

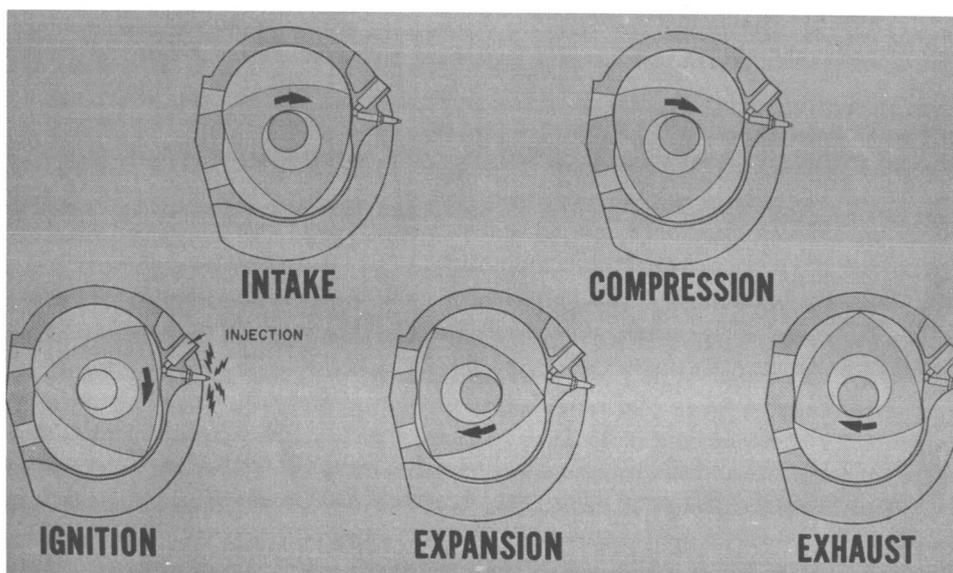FIGURE 1 - OVERVIEW of NASA OBJECTIVES
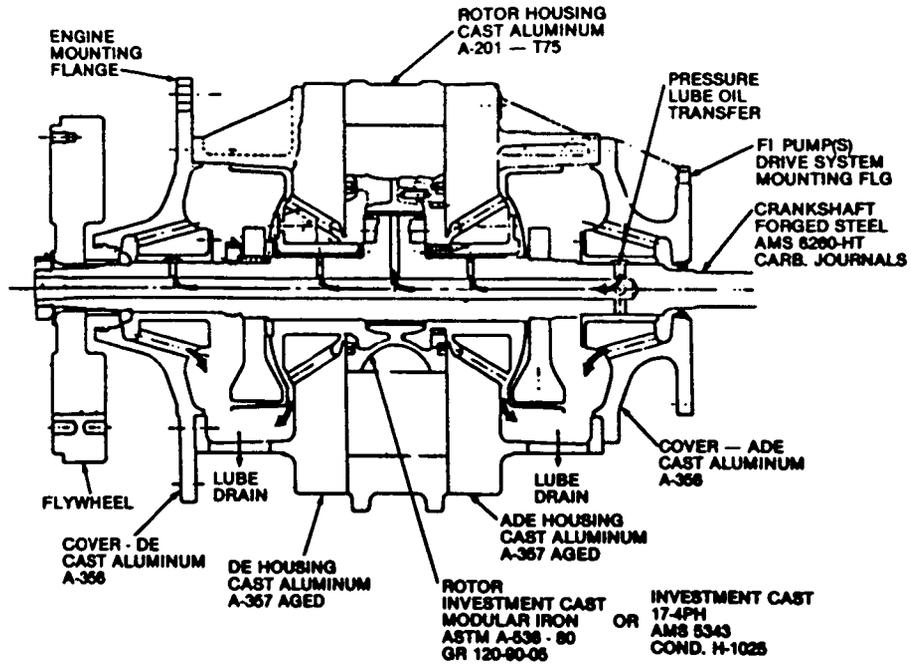

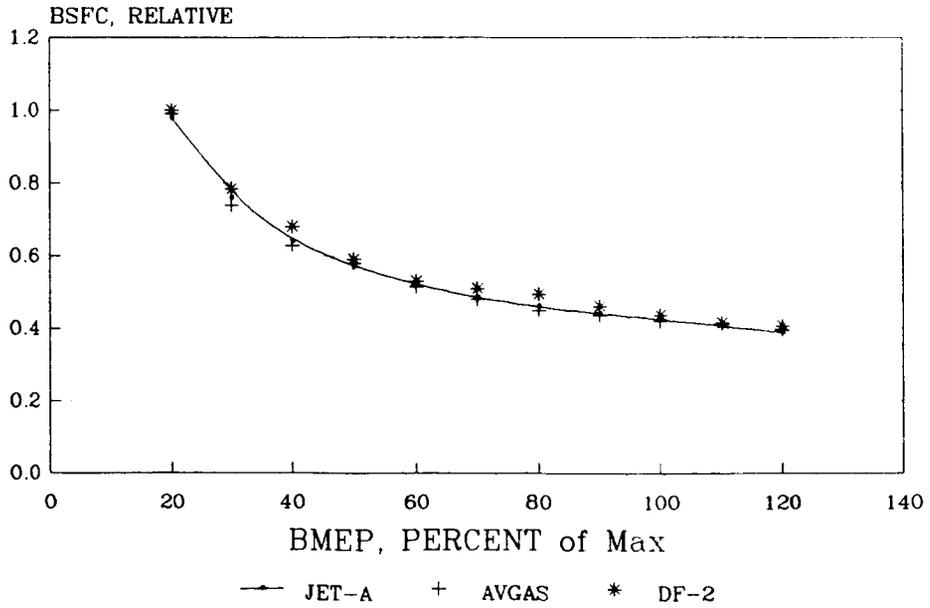FIGURE 2 - STRATIFIED CHARGE ROTARY ENGINE CONCEPT

FIGURE 3 - SINGLE ROTOR TEST RIG

FIGURE 4 - MULTIFUEL BSFC COMPARISON

F/A

0.06
0.04
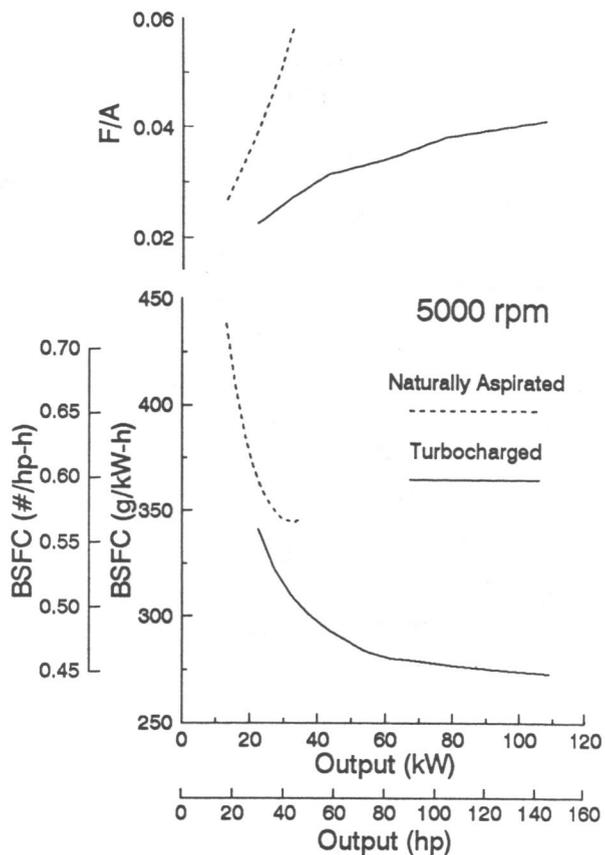0.02

5000 rpm

Naturally Aspirated

Turbocharged

BSFC (#/hp-h)

0.70
0.65
0.60
0.55
0.50
0.45

BSFC (g/kW-h)

450
400
350
300
250

Output (kW)

0 20 40 60 80 100 120

Output (hp)

0 20 40 60 80 100 120 140 160

FIGURE 5 - EFFECT of
TURBOCHARGING

BSFC (lb/hp-h)

0.50
0.49
0.48
0.47
0.46
0.45

BSFC (g/kW-h)

310
300
290
280
270

80 kW (107 hp)
100 kW (134 hp)
120 kW (161 hp)
135 kW (181 hp)

Exhaust Port Area (cm²)

8 10 12 14 16 18
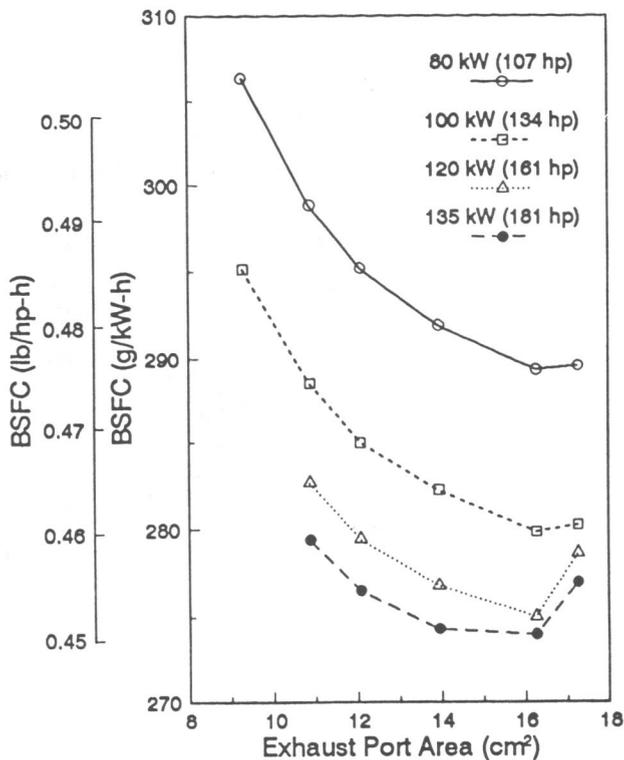
FIGURE 7 - EFFECT of EXHAUST
PORT AREA

Fuel
consumption

0.55 BSFC

0.41

Original objectives:
5 hp/in.^{3}
40% ηt
(0.34 BSFC)

4 hp/in.^{3}

Specific
power

2.5 hp/in.^{3}

CFD studies

Engine tests

1987 & earlier | 1988 | 1989 | 1990 | 1991
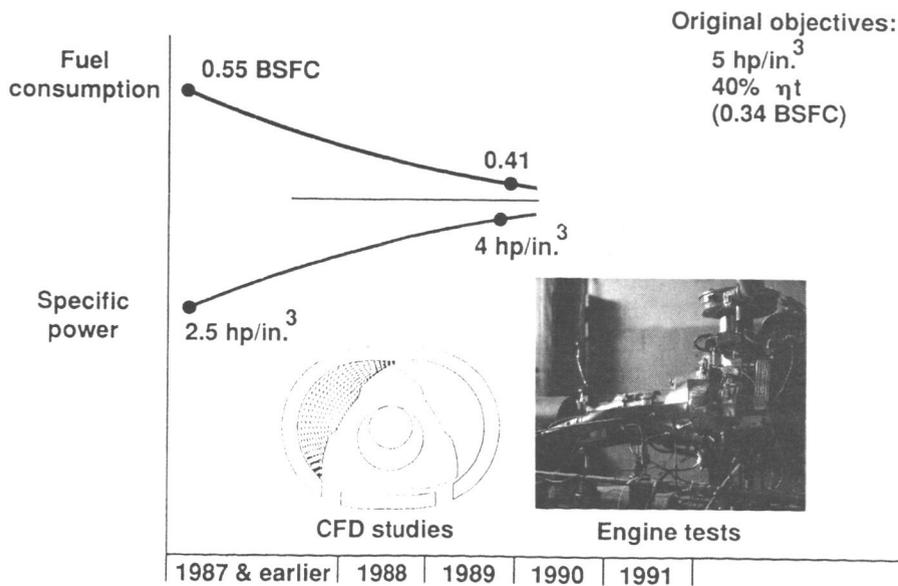
FIGURE 6 - PHASE I and II ACCOMPLISHMENTS

Main nozzle

Auxiliary ignitor

Pilot nozzle

Ignitor

Rotor housing

Combustible mixture

Combustible mixture
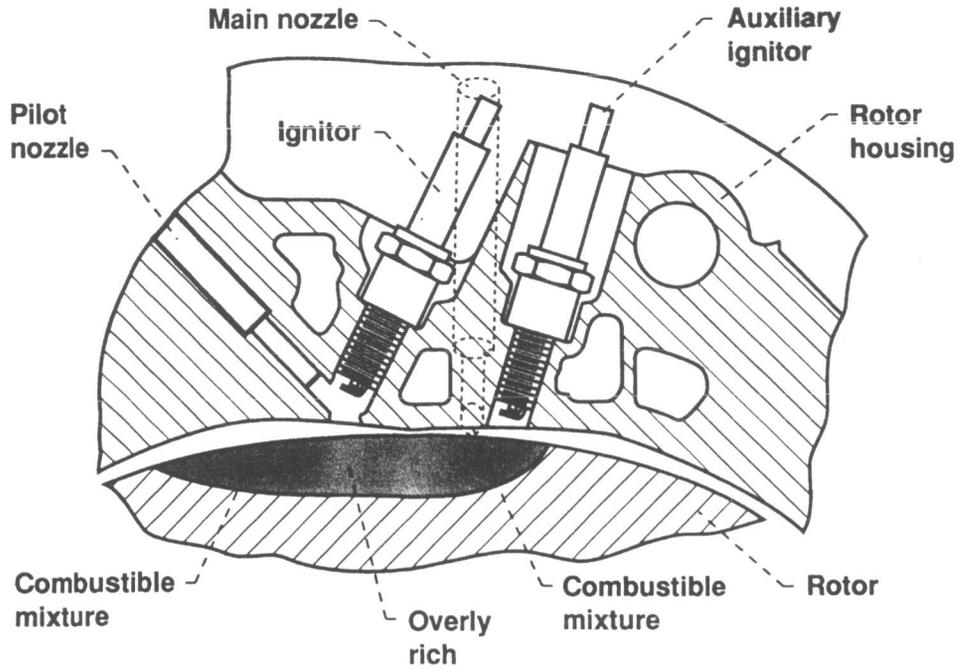
Overly rich

Rotor

FIGURE 8 - DUAL SPARK IGNITION CONCEPT
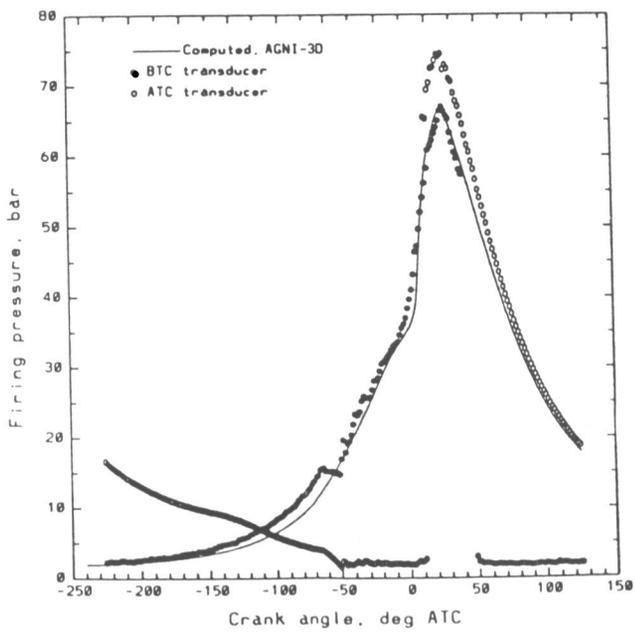
FIGURE 9 - EXPERIMENTAL vs.
COMPUTED FIRING PRESSURES
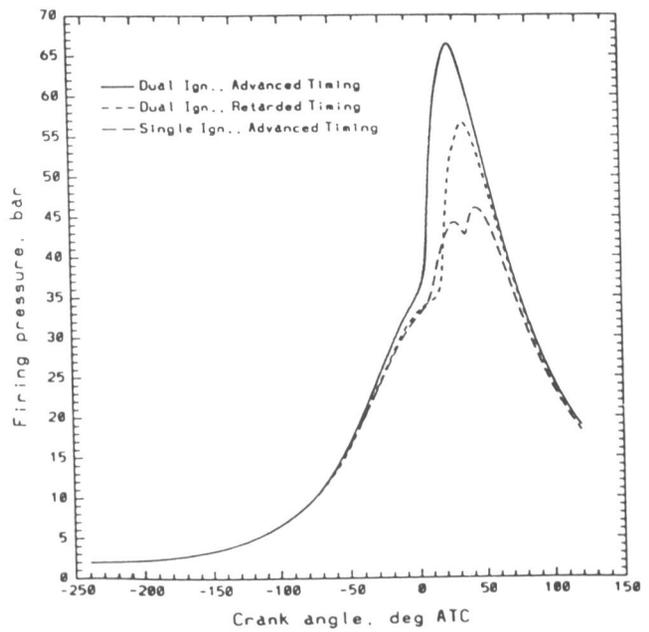
FIGURE 10 - COMPARISON of DUAL
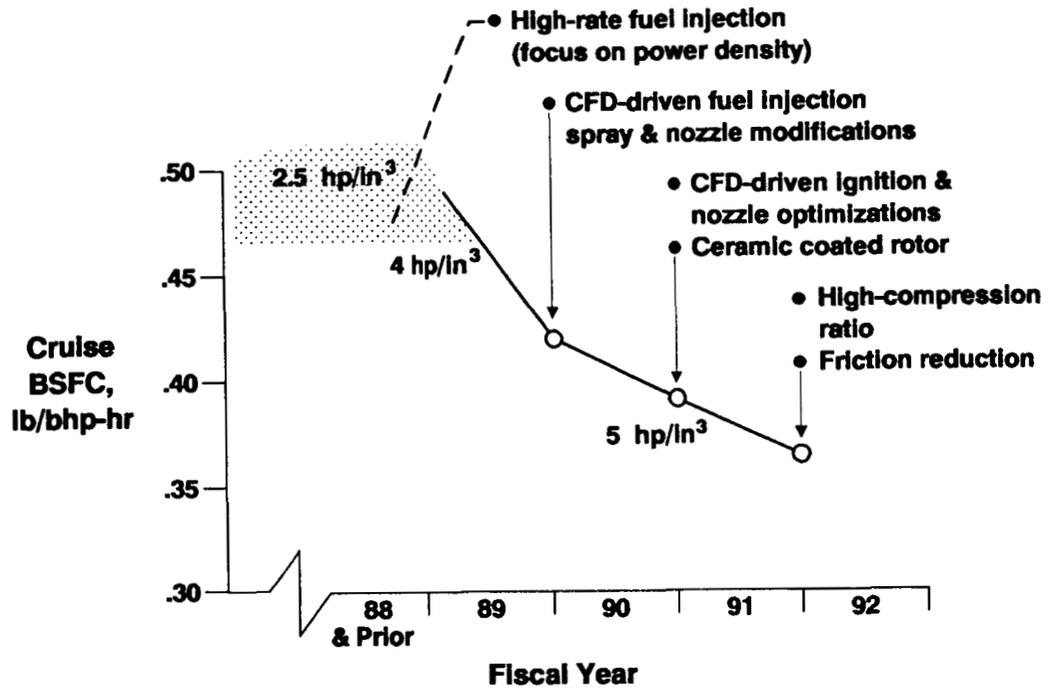and SINGLE-IGNITION PRESSURES

−● High-rate fuel injection
(focus on power density)

● CFD-driven fuel injection
spray & nozzle modifications

● CFD-driven ignition &
nozzle optimizations
● Ceramic coated rotor

● High-compression
ratio
● Friction reduction

Cruise
BSFC,
lb/bhp-hr

.50 — 2.5 hp/in³

.45 — 4 hp/in³

.40

5 hp/in³

.35

.30

88 & Prior   89   90   91   92

Fiscal Year

FIGURE 11 - ROTARY EFFICIENCY IMPROVEMENTS

Original goals

Fan spray main injector	0.42/lb/hp-hr	1989 BASELINE
Dual-Spray pilot	0.39/lb/hp-hr	Jan. 1991
Revised porting & sealing	0.385/lb/hp-hr	May 1991
Higher compression	0.375/lb/hp-hr	Sep. 1991

Future potential

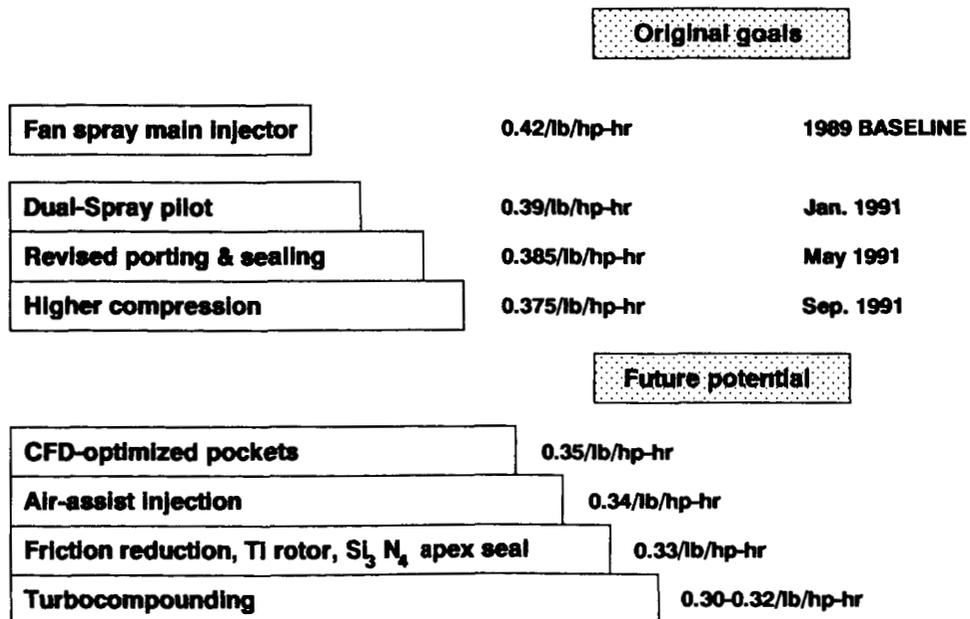|	
CFD-optimized pockets	0.35/lb/hp-hr
Air-assist injection	0.34/lb/hp-hr
Friction reduction, Ti rotor, $Si_3 N_4$ apex seal	0.33/lb/hp-hr
Turbocompounding	0.30-0.32/lb/hp-hr

FIGURE 12 - BSFC IMPROVEMENT STEPS: PAST and POTENTIAL

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	1992	Technical Memorandum

4. TITLE AND SUBTITLE

NASA's Rotary Engine Technology Enablement Program — 1983 Through 1991

5. FUNDING NUMBERS

WU–505–62–12

6. AUTHOR(S)

Edward A. Willis and John J. McFadden

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–6868

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–105562

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 07

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This paper provides a brief review of NASA's Rotary Engine Technology Enablement Program from 1983 through 1991, with primary emphasis on the CFD or Computational Fluid Dynamics approaches used since 1987. The main discussion includes both code development and applications to several particularly difficult internal airflow, fuel-air mixing and combustion-related problems. A summary of the final status of the technology is given.

14. SUBJECT TERMS

Rotary engine; Stratified-charge; Fuel-injection; Computational fluid dynamic (CFD) code

15. NUMBER OF PAGES

12

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	