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Design of a High-Performance Rotary Stratified-Charge Research Aircraft Engine

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DESIGN OF A HIGH-PERFORMANCE ROTARY STRATIFIED-CHARGE RESEARCH AIRCRAFT ENGINE

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Abstract

The power section for an advanced rotary stratified-charge general aviation engine has been designed under contract to NASA. The single-rotor research engine of 40 cubic-inches displacement (RCI-40), now being procured for test initiation this summer, is targeted for 320 T.O. horsepower in a two-rotor production engine. The research engine is designed for operation on jet-fuel, gasoline or diesel fuel and will be used to explore applicable advanced technologies and to optimize high output performance variables. Design of major components of the engine is described in this paper.

Introduction

The industry need for a new generation of General Aviation engines that can offer increased operating economies, improved performance and reliability, and the ability to efficiently burn a variety of fuels, including jet A, has generated a number of studies on the part of NASA. Starting in 1973, NASA Lewis reviewed intermittent-combustion propulsion systems exhaust emission characteristics in response to a proposed EPA aircraft emissions standards.

One of the engines tested was a prototype Rotary gasoline (carbureted) aircraft engine, the RC2-75. The encouraging emission results, weight and fuel consumption led to a NASA Lewis Rotary Engine test program at their facility and parallel NASA-sponsored design studies of the direct combustion chamber injected Stratified Charge technology that was then being developed for the U.S. Navy/U.S. Marine Corps in a larger (350"^3/rotor) military engine.

The stratified charge configurations, defined during 1973-1976 Independent Research and Development programs (IR&D) had demonstrated, in a 60"^3/rotor rig, multi-fuel capability, promising emission potential and fuel economy equal to or better than automotive diesels [1]*, which was the application focus at that time. These results were confirmed on the larger 350"^3/rotor military engine in 1978.

*Numbers in parentheses designate references at end of paper.

The power density for these naturally aspirated stratified charge engines was currently competitive but did not match the projected levels for the most advanced of the alternative future concept engines. During these design studies for NASA (2, 3) it was hypothesized that the涡轮增压 potential, high volumetric efficiency by virtue of unthrottled operation and no valves, and the observed trend of higher thermal efficiency when operating at the leaner end of diesel engine air-fuel ratio - the performance of these higher powered engines were shown, in studies by Cessna (4) and Beech (5), to be extremely attractive on a total aircraft systems basis.

The feasibility of simultaneously achieving both high power output and thermal efficiencies in the same range as direct injected diesel engines by turbocharging was demonstrated in parallel IR&D programs on the 60"^3 and 350"^3 single rotor rig engines during 1980 to 1982 (6). As a consequence of all these inputs, NASA awarded a contract in December 1982 to design, build and conduct an operational check-out on a technology enablement research single rotor rig engine, representative of the power section that would be used in a 320 hp twin rotor General Aviation engine of the early 1990’s. The prime purpose of the research engine would be to thoroughly map combustion, performance and technology parameters and to provide the data for trade-off studies of sealing effectiveness and durability; heat rejection and thermal/structural loading; the interrelations of peak pressures as a function of burning rate, compressor pressure ratio and engine compression ratio; engine speed vs. IMEP; improved materials; adiabatic approaches; lighter weight concepts and other related technology. Towards this end, a research rig module size was chosen which could provide the basis for an engine family which could satisfy both general aviation aircraft needs and other advanced applications. The design emphasis was on rugged construction to permit exploration beyond the anticipated production aircraft engine limits, rather than to demonstrate flight-weight engine goals at this stage.

The work reported in this paper was performed under NASA contract No. NAS3-23056. The contract was originally awarded to Curtiss-Wright (C-W) but will be
1. Specific engine choices for general aviation

The NASA Advanced Rotary Combustion Aircraft Engine Design Study objectives included cruise SFC of 0.38 lb/hr-ft., or better, at 250 hp and 25,000 feet minimum altitude. Two liquid-cooled engines were selected to meet the program objectives. Both were twin rotor machines, representing a compromise between minimum weight, favored by more roto/r, and low cost, generally pointing to less roto/r. The larger of the two, an RC2-47, represents a less ambitious technology projection, noted as "Advanced," while the smaller machine, the RC2-32, would require a larger development effort to meet the same timing goals and is designated "Highly Advanced." The key difference between the two is that the "Highly Advanced" engines include a further increase in BMEP and speed, the latter possibly requiring reduced contact force or retracting apex seals, and more emphasis on advanced weight reduction materials and manufacturing techniques. The "Highly Advanced" engine assumes use of a variable area turbine in the turbocharger system but other design approaches are also possible. The specific fuel consumption prediction for the RC2-32 is shown in Figure 1.

The RC2-32 BMEP is 211 psi at the 320 hp take-off power and 198 psi at 250 hp cruise. The 9420 engine RPM gives the same apex seal velocity as 7850 rpm for the RC-50 and RC-75 trochoid sizes. Both the RC-60 engines and the wider rotor RC-75 series have run to this sliding velocity. The cruise RPM is 7850 which is equivalent to 5875 for the RC-60 and derivative (60, 75 & 90) geometries. Corresponding values for the RC2-47 are 191 psi BMEP at 320 hp take-off, 197 psi at cruise, 7030 R.O. RPM (6000 "equivalent") and 5860 RPM cruise RPM (5000 "equivalent"). The rotor width proportions for both engines (width/eccentricity ratio) are the same as the RC2-75 aircraft engine prototype and the 350"3 rotor military engines.

The comparison of cruise SFC and overall dimensions with the selected current reciprocating baseline engine, the TSIO-550 is shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>TSIO-550</th>
<th>Advanced RC2-47</th>
<th>Highly advanced RC2-32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, in.</td>
<td>69.2</td>
<td>62</td>
<td>48.6</td>
</tr>
<tr>
<td>Width</td>
<td>33.4</td>
<td>16.5</td>
<td>16</td>
</tr>
<tr>
<td>Height</td>
<td>19.2</td>
<td>16.5</td>
<td>16</td>
</tr>
<tr>
<td>Weight-flyable, lb</td>
<td>585</td>
<td>348</td>
<td>255</td>
</tr>
<tr>
<td>Specific fuel consumption at cruise (lb/hr-ft)</td>
<td>.446</td>
<td>.371</td>
<td>.355</td>
</tr>
</tbody>
</table>

The RC2-32 installation longitudinal layout is shown in Figure 2. To achieve a small frontal area (a 16-inch square), most of the accessories are mounted at the anti-propeller end and the turbocharger spaced even farther aft. For improved packaging and to minimize the number of drives and associated gearing, the coolant and oil pumps (scavenge and pressure) are coaxial mounted on the same shaft. Drives are included for an air conditioning compressor, vacuum pump and hydraulic pump, but the weights given include only the accessories needed to run the engine.
While only one engine size is shown for each of the two levels of technology, a number of other engine possibilities, all representing the same degree of "advancement" were defined and compared via the Cessna Aircraft Company analytical model before the choices were made. In either category, improved BSFC can be realized, for the same IMEP level, by either reducing the engine speed, going to a larger displacement single rotor engine, or both. In all cases analyzed, however, the Cessna aircraft analysis programs indicated more sensitivity to weight and size than to the projected SPC improvement. Figure 3 provides an excerpted example (6) of how the baseline twin compares with the rotary engine installations.

To put the projections in perspective, while the BMEP's assumed are not high relative to turbocharged diesel engines and are on the order of only about a third higher than has been run in developed rotary homogeneous charge engines which have demonstrated durability at sustained high output, they have not been demonstrated in stratified charge/rotary engine as of this point. The bulk of RC-350 engine testing and all of the cyclic endurance testing have been run naturally aspirated where both BMEP and peak cycle pressure are about half as high as planned for the NASA rig engine. Homogeneous charge rotary engines have been performance tested to these levels but operation at periods longer than a 24-hour race has been limited. The "best compromises" to attain projected goals, both technical and economic, cannot be evaluated on paper but requires testing to successively increasing BMEP and speed levels with each new plateau yielding both new inputs and new solutions — this is, of course, what the NASA research engine is expected to do.

2. Rig engine sizing

The size of the research engine was chosen was 40.4"³/rotor. This represents a balance where results can be considered representative of both sizes studied and, at the same time, possibly permit earlier flight test without dependence on the more advanced technologies. If future testing data proves this choice too conservative the options are to increase the power output or else to scale down to a smaller displacement. The selection had been coordinated with NASA and production aircraft representatives.

The RC-40 research engine rig characteristics are compared to those of the study engine in Table II. The comparison shows all three sizes at the same T.O. rating of 160 hp/rotor. The "equivalent RC-75 rpm" indicates the speed of the aforementioned carbureted RC2-75 aircraft engine prototype to obtain the same apex seal sliding velocity. The 75"³ engine has been run to 7000 rpm and the same rotor size, in the narrower 60"³/rotor width, has run to 9500 rpm motoring and 8000 rpm firing. While this 160 hp T.O. rating is the nominal output, the rig has been designed to explore speeds to 9600 rpm with the present rotor seal design and to both peak and BMEP pressures beyond those anticipated for the RC2-32. However, this will be done in stages, with instrumentation to confirm the combustion pressures, temperatures, and thermal loadings versus projections at each successive level.

### Table II

<p>| Location (in³/| Advanced | Highly | SCHC-40-XL-7 | Research Rig |</p>
<table>
<thead>
<tr>
<th>chamber</th>
<th>Technology</th>
<th>Technology</th>
<th>Displacement, in³</th>
<th>T.O. Rating, HP</th>
<th>T.O. RPM, Crankshaft</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.4</td>
<td>31.9</td>
<td>40.4</td>
<td>7030</td>
<td>9423</td>
<td>8000</td>
</tr>
<tr>
<td>160</td>
<td>140</td>
<td>160</td>
<td>7000</td>
<td>7050</td>
<td>6646</td>
</tr>
<tr>
<td>199.6</td>
<td>211.7</td>
<td>195.9</td>
<td>29.3</td>
<td>33.4</td>
<td>31.3</td>
</tr>
<tr>
<td>220.1</td>
<td>244.6</td>
<td>227.2</td>
<td>.392</td>
<td>.372</td>
<td>.382</td>
</tr>
<tr>
<td>.64</td>
<td>.261</td>
<td>.607</td>
<td>.889</td>
<td>.689</td>
<td>.637</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Location (lb/HP-Hr)</th>
<th>Linear Scale Factor, Rel. RC-75</th>
<th>Y-150</th>
</tr>
</thead>
<tbody>
<tr>
<td>.296</td>
<td>.281</td>
<td>.280</td>
</tr>
</tbody>
</table>

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Figure 3

Baseline twin - fixed engine size, variable airframe, and fixed payload range. Gross weight, 1650 lb; span, 44.5 ft; aspect ratio, 11.0.

Figure 3

Rotary twin - fixed engine size, variable airframe, and fixed payload range.
From the "Linear Scale Factor" it can be seen that all basic dimensions are 91% as large as the 75"/rotor engine and 49% as large as the 350"/rotor engine counterparts. Testing of the 60°/rotor and of 90°/rotor rig engines, both of which use the same trochoid size as the 75°/rotor engines, as well as the 350°/3 stratified charge engines (7, 8) has shown that there are only thermodynamically and, therefore, significant problems of scaling are not anticipated for the RCI-40.

II. DESIGN INPUT DATA

Analysis of the power section components requires data input giving a pressure time history within the combustion chamber and heat transfer/thermal loading conditions at the component surfaces. These in turn can be used to calculate the pressure forces, temperatures and thermal gradients which, with the inertia force loading, can be used for structural design analysis.

Since a stratified charge rotary engine has not yet been run to the peak BMEP levels for which the RCI-40 has been designed, the only path to extract the relatively limited high power stratified charge engine data is to use this data base. An instrumented RCI-350 turbocharged engine was run to higher power to obtain pressure data and heat flux. This engine was run as high as 182 BMEP when further testing was halted by a turbine output. Engine failure which unfortunately restricted data accumulation. Analytical techniques were used to supplement the experimental data in order to estimate peak heat fluxes at the high heat zones.

In addition, another RCI-350 engine was instrumented with strain gauges in tested to refine the rotor housing stress analysis model of this particular stratified charge design from which the RCI-40 rotor housing was derived. The strain gaged engine was tested at high and low power for each of 3 speeds and with normal and half clamping bolt load, the latter variation to evaluate side housing friction effects.

The RC-350 engine design effort had added to the structural analysis base that had been developed prior to this engine. This "energy program", dating back to the 1960's, had demonstrated ability to calculate rotor housing operating deflections and stresses, and has correlated well with experimental measurements, under thermal, gas pressure and end-housing transmitted loads. This was extended by supplementary finite element analyses to evaluate thermal stresses and temperature distributions, using stress, strain gage, thermocouple inputs and friction resistance inputs. Use of a two-bearing shaft increases end housing loads and provided the impetus to develop a sophisticated finite element and housing analysis, supplemented by static and firing engine strain gage measurements, and the increased shaft deflections provided experimental input at higher shaft slopes at the bearings. This end housing analysis and a detailed rotor finite element analysis had been initially motivated by rotor and end housing casting quality problems during the 350°/3 program, as well as subsequent growth considerations and more precise definition of the loading differences peculiar to the stratified charge engine. Computer analysis for the timing gears, bearing design, dynamics and geometry, shaft stresses, vibratory analysis, etc. have remained unchanged.

This is not to say that further refinements are not desirable, and they will be pursued during the follow-on NASA programs, but this data bank and the operating experience with rotary engines hereover the preceding 26 years provided a resource which was reflected in the RCI-40 design.

One of the distinguishing characteristics of the RCI design series, which started with the RCI-60 design in 1958, was low friction HP. The basic FMEP of this design series (9) is considered to reflect improved sealing as a consequence of particular attention to minimal operating deflection/distortion of the housing and rotor gas sealing contact surfaces, in addition to detailed attention to the seal elements themselves. The motors significant contributing elements are the structural and cooling details of the rotor and rotor housing. On the basis of prior results and the similarity of the RCI-40 cooling and structure to the prior engines in this series, the motorizing (friction) HP projection was estimated as shown in Figure 4. This curve reflects improvements to be developed on the rig and is slightly lower than anticipated for initial test.

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**Figure 4**

**SCRCI-40-XI-T**

**TURBOCHARGED STRATIFIED CHARGE ROTARY COMBUSTION ENGINE ESTIMATED MOTORIZING HORSEPOWER**

(PROJECTED TO TECHNOLOGY ENABLEMENT COMPLETION)

<table>
<thead>
<tr>
<th>CRANKSHAFT SPEED (rpm)</th>
<th>0</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
<th>5000</th>
<th>6000</th>
<th>7000</th>
<th>8000</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRICTION (MOTORING HP)</td>
<td>30</td>
<td>20</td>
<td>15</td>
<td>12</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

---

4
Similarly the estimated indicator card, in this case extrapolating RCl-350 engine data, is shown in Figure 5 for a 7.5:1 compression ratio rotor. Based on RCl-60 data, where it was shown that peak metal temperatures and pressures can be reduced with lower compression ratios (10), a 6.5:1 rotor will also be tested. The projected indicator diagram for this rotor is shown in Figure 6.

III. MECHANICAL DESIGN

1. Arrangement

The rig engine was designed to operate with slave (test stand) oil and water pumps, for maximum flexibility of varying flow and temperature testing, and an accessory gear box drive for fuel injection pump and ignition system drives, again to allow use of different systems and speed relationships.

Two outboard bearings, in addition to the two main bearings, are used to help divorce lubricating oil transfer from bearing performance and to control shaft deflection within the bearings during extreme high pressure and/or high speed testing.

The engine power section arrangement is shown in Figure 7. The inertia cooled rotor, which can supplement bearing oil spill with an oil jet from the shaft, is similar to prior RC engine designs, although there are differences in detail. The investment cast steel rotor is a new approach, intended to improve casting quality in the rotor central web. The other materials noted, with the exception of the rotor housing material, are conventional commercial casting alloys, although "premium" quality specifications have been established to insure sound pieces, particularly in high stress regions. The rotor casting alloy, A-201, is a more recent material developed for high temperature strength. This aluminum alloy has been used in the later RCl-350 turbocharged IR&D testing.
2. Rotor

A cross-section of the rotor (Figure 8) shows that the inserted plugs will be used to dynamically balance the rotor, although it is anticipated that the final production rotor will use cast bosses which will be machined for balancing and weight control. The gear is I.D. piloted to the rotor hub, accommodating the differential thermal expansion by minute rotation about the centroidal axes of the circumferentially continuous gear section. The axial "web hub," located radially inboard of the oil seals, and formed by the end face of the gear as well as the proud "ring" on the anti-gear side, acts as a thrust bearing to centrally position the rotor between the two end housings and also serve as a rough oil scraping seal.

The rotor combustion pocket was derived from the RC-350 engine experience and is expected to be compatible, notwithstanding the reduction to approximately half-size, with the RC-350 scaled location of main and pilot nozzles and spark plug (8). The rotor radial ribs, which are essential for the inlet thermal conductivity and a higher modulus of elasticity, as compared to nodular iron, is compensated by the strength increase. The frictional compatibility of the rotor slots with the apex seals, for this new material, will be evaluated.

The rotor housing overview sketch is shown in Figure 9. Again, for clarity, only the coolant divider ribs are shown. With the exception of additional external structure, in keeping with the exploratory rig nature of this design, the design approach is similar to prior Curtiss-Wright RC engine designs. The cooling passes, however, have been particularly tailored to the boss locations of the stratified charge engine and represent carefully balanced flow velocities within each pass as well as a distribution of passes to match the heat input distribution both circumferentially and axially. The established "stitch flow" cooling system (9) whereby the series flow is turned at each end housing has been arranged to both enter and leave at the top of the engine, but locates the higher flux zone closer to the exit. In this way the absolute pressure will be lower, giving the minimum temperature drop between coolant saturation temperature and hot spout metal surface during nucleate boiling. At lower power settings, the cooling is entirely convective and coolant velocities and paths have been established to be effective in this mode and to also insure circulation when the cooling mechanism locally reverts to nucleate boiling for the higher heat flux operation. A circumferentially developed plot of the calculated metal temperatures, using projected maximum heat flux extrapolated as mentioned, is shown in Figure 10. One of the purposes of the test program is obviously to determine these values under varying test conditions.
The peripheral porting shown can be supplemented or replaced by side porting, with its inherent lower overlap. Initial results with the RC1-60 have indicated the peripheral port to be preferable but testing at the higher turbocharging pressure ratios to be explored in this program will determine the trade-offs as a function of turbocharger match and different operating conditions.

The rotor housing has several possible failure modes which include high cycle fatigue and local low cycle fatigue crack propagation, as well as other less serious types of failure. All of these possible failure modes have been examined and the design considered to have adequate margin for the intended application. In the case of low cycle fatigue, which can result from localized plastic flow at hot spots, known design modifications will be evaluated by test.

3. End Housings

The design is conventional with the exception of relocated divider rib locations as shown in Figure 11 for the anti-drive end housing and Figure 12 for the drive end housing.
5. Sealing

Gas and oil sealing are conventional. The trochoid wear surfacing is detonation gun applied tungsten carbide in a cobalt matrix (87/13%), which has been proven on the RC engines since 1960. Since apex seal wear against this coating, which has been relatively low for powers tested to date, is an unknown at the 200+ BMEP and associated pressure-time histories, one of the purposes of the test program is to determine if the combination of this coating and conventional iron-based apex seals remains acceptable. If the results show it is not, then alternate candidate materials, many of which have already been screened on a wear/compatibility rig (1) and others to be screened, will be evaluated.

In addition there are several high speed concepts which involve reduced contact force or minute retraction from the trochoid surfaces, which will be tested later in the Technology Enablement Research Program. In addition to the growth in power density possible by the increased engine speed which these concepts will permit, they are of particular interest for reduced cooling ("adiabatic") rotor housing designs where the trochoid surface could reach temperature levels above conventional lubricating limits.

6. Turbocharger Installation

The turbocharger and aftercooled test rig installation are shown in Figures 13 and 14. The Garrett AlResearch unit will be evaluated with various inlet housings and other basic variations, depending on initial test results, will be evaluated as well. Previous turbocharging tests have shown compressor selection to be relatively straightforward but turbine selection has failed to exploit the large pulse energy available in the exhaust.

The gas and centrifugal loading of the shaft, similar to the end housing bearing support, upon which it reacts is amenable to relatively straightforward analytical techniques, uncomplicated by the addition of thermally induced loading.

4. Crankshaft (or Mainshaft)

Shaft stresses for rotary engines are generally lower than those of reciprocating piston engines, and the shafts are usually designed on the basis of allowable deflections rather than stresses. In this rig engine, with four bearings, the shaft stresses allow a conservative margin even at the anticipated higher loadings. The prime concern will be the allowable slope within the bearings and the test results are expected to add to the relevant body of knowledge in this regard.

The gas and centrifugal loading of the shaft, similar to the end housing bearing support, upon which it reacts is amenable to relatively straightforward analytical techniques, uncomplicated by the addition of thermally induced loading.

The side inlet ports, which are not cored through to the sealing surfaces, shown in these figures will be left closed for initial peripheral port (rotor housing) testing.

The end housing loads, which result from centrifugal and gas pressure forces acting on the rotor are more readily predictable than those of the rotor housing and rotor where thermal loadings and temperature gradients are significant. The end housings were designed for high cycle fatigue and have a positive safety factor considered ample for the anticipated test range.

The diagram on the page shows the layout of the components described in the text.
7. Fuel Injection

An injection system with demonstrated capability to run up to the planned test limit of 9600 rpm, with controllable injection pressures to 15,000 psi and provide an essentially "square" injection trace is not currently available. However, there are experimental prototypes and units now under development which show promise of meeting these requirements during the early stages of Technology En- ablement testing of the RC1-40, and they are currently being pursued. For initial engine verification, existing production 4-plunger distributor pumps are being modified to use 2 pumps, one for the pilot and one for the main, both running at 1/4 engine speed and with all plungers active. This will suffice initially, but more flexible systems will be required, early in 1985, to maintain research testing momentum.

IV. CONCLUSION

1. Numerous studies have identified the stratified charge rotary engine as the best choice for future light aircraft.

2. A Technology Enablement Program was established and contracted with NASA to explore and optimum directions.

3. The resulting RC1-40 research engine will go to the test stand late this summer. After initial check-out and evaluation has been completed, the work effort for the current NASA contract will be ful- filled.

4. It is anticipated that the future testing of this valuable research tool, starting in late 1984, will lead to promising configurations and commercialization of aircraft as well as other engine applications.

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