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RESULTS OF THE POLLUTION REDUCTION TECHNOLOGY PROGRAM FOR TURBOPROP ENGINES

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ABSTRACT
A program was performed to evolve and demonstrate advanced combustor technology aimed at achieving the 1979 EPA standards for turboprop engines (Class P2). The engine selected for this program was the 501-D22A turboprop manufactured by Detroit Diesel Allison Division of General Motors Corporation. Three combustor concepts were designed and tested in a combustor rig at the exact combustor operating conditions of the 501-D22A engine over the EPA landing-takeoff cycle. Each combustor concept exhibited pollutant emissions well below the EPA standards, achieving substantial reductions in unburned hydrocarbons, carbon monoxide, and smoke emissions compared with emissions from the production combustor of this engine. Oxides of nitrogen emissions remained well below the EPA standards, also.

INTRODUCTION

Three gas turbine combustor concepts were designed and tested in a combustor rig to determine their emissions of unburned hydrocarbons, carbon monoxide, oxides of nitrogen, and smoke at the combustor operating conditions of the 501-D22A turboprop engine.

Concern over air pollution has drawn the attention of combustion engineers to the quantities of exhaust emissions produced by gas turbine engines. Two general areas of concern have been expressed: Urban pollution in the vicinity of airports and pollution of the stratosphere. The principal urban pollutants are unburned hydrocarbons (HC) and carbon monoxide during idle and taxi, and oxides of nitrogen (NOx) and smoke during takeoff and landing. Oxides of nitrogen are also considered to be the most predominant gaseous emission products formed during altitude cruise of an aircraft. NASA Lewis Research Center is engaged in in-house research, university grants, and industry contracts to reduce the levels of these pollutants.

In 1970, the Clean Air Act charged the Environmental Protection Agency with the responsibility to establish acceptable exhaust emission levels of these pollutants for all types of aircraft engines. In response to this charge, the EPA promulgated the standards described in reference 1, with the first compliance date being January 1, 1979. One of the programs generated by Lewis Research Center in response to these EPA standards was the Pollution Reduction Technology Program for Turboprop Engines. The purpose of this program was to evolve and demonstrate advanced combustor technology aimed at achieving the EPA standards applicable to turboprop engines (EPA Class P2). The technology generated from this program is primarily applicable to the commercial sector, but it also has applicability to military turboprop and turboshaft engines. This effort focused on reducing emissions of HC, CO, NOx and smoke, without seriously affecting combustor performance requirements such as combustion efficiency, total pressure loss, exit temperature pattern factor, and altitude relight capability. This paper presents the results of this program.

CONTRACTOR AND ENGINE SELECTION

The contractor chosen for this program through a competitive RFP. The program was conducted by Detroit Diesel Allison (DDA) a Division of General Motors Corporation. The program was a cost sharing contract and was conducted at the DDA facilities at Indianapolis, Indiana. The contract duration was thirteen months, and the various tasks and their duration are shown in table I.

The engine selected for combustor redesign was the Model 501-D22A turboprop. This engine, shown in a cutaway view in figure 1, has a 9.2:1 compression ratio, and utilizes six cylindrical combustor cans in an annulus. The engine is rated at 6800 equivalent shaft horsepower at standard static sea-level conditions. The engines' use in the commercial field is with the L-362 (Hercules) and the L-188 (Electra) aircraft manufactured by Lockheed and used as cargo and passenger transport. Various military aircraft also use this engine.

The major goal of the program was to produce a combustor which, when operated at conditions of the 501-D22A turboprop engine, would exhibit pollutant emissions 25 percent below the EPA requirements for 1979 for turboprop engines. The 25 percent margin was to allow for possible pollutant emission increase during combustor final development and also for possible engine to engine variations. The pollutant goals are shown in table II and are compared with the EPA limits and with current 501-D22A engine data from reference 2. The emission values are in terms of the EPA parameter as specified in reference 1. The current engine requires a substantial reduction in unburned hydrocarbons and smoke emissions. On the other hand, the oxides of nitrogen emissions are well within the goal; so the effort was focused on reducing idle emissions and smoke while minimizing NOx emissions. An increase in NOx emissions might be expected due to higher flame temperatures which are associated with improvements in combustion efficiency at idle.

TEST FACILITY

The 501-D22A combustor operating conditions are shown in table III for the EPA landing-takeoff cycle modes. Excerpt for the taxi-idle mode, the engine runs at constant speed which results in combustor...
which fit within the combustor envelope of the cur- 
mocouple rakes and eleven gas sampling probes al- 
direction, enhancing the recirculating zone and 
combustor sweep air along the liner in the upstream 
detector (FID): a Backman Instruments Model 402 
about 420 K. The procedure of reference 3 was fol- 
ners of operation. Therefore, it was possible to 
measured data at the specific conditions of 
table III without any extrapolation of inlet pressure 
or temperature. The combustor test rig is 
shown in figures 2 and 3. The rig exactly duplic- 
cates a 1/6 annular segment of the 501-D22A engine, 
cluding diffuser, combustor annulus, and turbine 
inlet annulus.

Exhaust instrumentation consisted of ten therm- 
couple rakes and eleven gas sampling probes alter- 
atively spaced as shown in figure 3. Each thermocouple probe had three thermocouples; each 
gas sample probe had four sampling ports. The gas 
sample was steam traced to maintain a temperature of 
about 420 K. The procedure of reference 3 was fol-
lowed in obtaining gas sampling data. The gas sam-
ple was manifolded to one line from the eleven 
probes, and was continuously analyzed by the follow-
ing instruments: carbon monoxide and carbon dioxide 
and carbon dioxide analysis being a product of the nondispersive infrared (NDIR) type (Backman Instruments Model 315A). The 
concentration of oxides of nitrogen was determined by a Thermo Electron Corporation Chemiluminesscent 
Analyzer with NOx converter. The hydrocarbon con-
ent of the gas was determined by a flame ionization detector (FID): a Beckman Instruments Model 402 Hy-
dercarbon Analyzer. Smoke analysis was also per-
domed on gas samples drawn from the same eleven 
gas sampling probes. The smoke sampling procedure as 
recommended in reference 4 was followed.

COMBUSTOR DESIGNS

Three combustor concepts were designed to re-
duce pollutant emissions from the 501-D22A turbo-
prop engine. All of these concepts were burner cans 
which fit within the combustor envelope of the cur-
tent engine. Photographs of the three combustor 
concepts as well as the 501-D22A production combus-
tor are shown in figure 4. These combustors will 
now be briefly described.

A schematic of the production combustor is 
shown in figure 5. The burner is approximately 
14.0 cm in diameter and 62.8 cm long. The main fe-
atures of this design are: dome air-entry holes 
backed by baffles to give the incoming air a swirl-
ing motion; dilution holes not evenly positioned 
around the circumference but placed as required to 
give a suitable gas temperature distribution; pri-
mary-zone air entry holes; and a dual-orifice, 
pressure-atomizing fuel injector.

The first combustor concept, the reverse flow 
combustor, is shown in figure 6. The initial de-
sign plus four modifications of this design were 
tested. The main features of this combustor con-
cept are: the primary zone equivalence ratio was 
increased over the value of the production combus-
tor; decreasing flow through the combustor front; 
and; two reversed louvers in the front end of the 
combustor sweep air along the liner in the upstream 
direction, enhancing the recirculating zone and 
preventing fuel from hitting the wall and passing 
downstream without burning; an air assist fuel no-
zle was used in one configuration; an airblast no-
zle consists of a pressure atomizing pilot and an 
airblast main section. Maximum fuel flow to the 
pilot is 27.2 kg/hr. In two of the reverse flow 
combustor configurations the fuel flow to the pit 
was shut off and all the fuel passed through the 
airblast section.

The second combustor concept, the prechamber 
combustor, is shown in figure 7. The initial de-
sign and five modifications of this design were 
tested. The main features of this combustor con-
cept are: a chamber in front of the combustor pri-
mary zone in which fuel and air is mixed prior to 
combustion (prechamber); the use of remotely oper-
ated variable geometry to alter airflow distribution 
and observe results during testing to obtain opti-

The third combustor concept, the staged fuel 
combustor, is shown in figure 8. The initial de-
sign and six modifications of this design were 
tested. The main features of this combustor con-
cept are: a two-stage in-series combustion system 
consisting of a pilot zone for low-power operation 
and a main combustion zone which is used in combina-
tion with the pilot zone at higher power conditions; 
the fuel for the main zone is premixed with air in 
six equally-spaced tubes and is then air-blast in-
jected into the combustor; advanced wall cooling 
consisting of film and convection cooling, allowing 
more air to be used for quick mixing with hot combi-
ation gases; variable geometry dilution air entry 
ports. Three different fuel nozzles for the pilot 
zone were tested: the production combustor pres-
ure atomizing nozzle, an air assist nozzle, and an 
airblast nozzle which was described previously.

The three combustor concepts vary in complexity 
and in potential for pollutant reduction. The re-
verse flow combustor was simplest in design and the 
staged fuel combustor was most complex with the most 
potential, it was felt, for low pollutant emissions.

COMBUSTOR TEST RESULTS

A total of 19 combustor configurations were 
tested, including the production combustor for di-
rect comparison with the 18 test combustors. An 
abbreviated description of each configuration is 
given in table IV. Over 400 data points were taken 
at the EPA cycle conditions and at idle or takeoff 
with parametric variations of fuel-air ratio, inlet 
pressure, inlet temperature, and reference velocity. 
For a complete analysis of the data, see the final 
report of the program, reference 5.

Pollutant Emissions

The pollutant emissions of the 19 combustor 
configurations are summarized in table V for data 
taken over the landing-takeoff cycle. The gaseous 
pollutants are in terms of the EPA parameter and the 
smoke number is the highest value recorded over all
the landing-takeoff cycle conditions. The three combustor concepts achieved the program goals in 13 of the 18 configurations.

The combustor configurations that exhibited the lowest pollutant emissions for each concept were the reverse flow mod IV combustor, the prechamber mod V combustor, and the staged fuel mod V combustor. The emissions of these three combustors are compared with the baseline production combustor in figures 9 through 12. The hydrocarbon emissions, shown in figure 9, were reduced substantially by the three combustor concepts and are all well below the program goal. The carbon monoxide emissions in figure 10 also show a substantial reduction for the three combustor concepts over the baseline production combustor. Again the emission levels are well within the program goals. The oxides of nitrogen emissions of figure 11 show the expected rise for the three combustor concepts compared with the production combustor, but this increase is very moderate and still remains well below the program goal. Finally, the maximum values of smoke for the three combustor concepts are substantially below the production combustor in figure 12, and are also below the program goal.

Thus, all three combustor concepts produced exhaust pollutant emissions which met the program goals of 25 percent below the EPA standards. Substantial reductions in unburned hydrocarbons, carbon monoxide, and smoke were achieved compared with the production combustor with only slight increase in oxides of nitrogen emissions. From an emissions point of view, all three combustors qualify as candidates for development into the 501-D22A turboprop engine.

Performance

A summary of combustor performance for the three best combustor concept designs is shown in table VI. Pattern factors compare quite favorably with the production combustor for all three combustor concepts. Combustor pressure drop was adequate for all three designs as far as this program was concerned. However, the prechamber mod V and the staged fuel mod V exhibited pressure drop values higher than the production combustor and a further development of these combustors might require reducing these levels. The combustor liner temperatures recorded by skin thermocouples indicate no major problem areas; however, it must be pointed out that more rigorous testing would be required to ensure proper combustor durability and would be part of further development of any of these combustors. Altitude relight tests were not within the scope of this program and were not performed. A complete altitude relight map would be required for further combustor development.

Based on the performance results and on relative combustor complexity, the reverse flow mod IV combustor is judged to be the best candidate for further development into eventual use with the 501-D22A turboprop engine. In this program it has demonstrated pollutant emissions well below the 1979 EPA standards, is quite simple in design, and has shown excellent combustion efficiency, pattern factor, and combustor pressure drop.

CONCLUDING REMARKS

A program was undertaken to evolve and demonstrate advanced combustor technology aimed at achieving the 1979 EPA standards for the 501-D22A turboprop engine. As a result of this program three can-type combustor concepts were designed and tested. Each concept exhibited pollutant emissions well below the EPA standards, achieving substantial reductions in unburned hydrocarbons, carbon monoxide, and smoke emissions from the production combustor of the 501-D22A engine. Based on performance results, pollutant emissions, and combustor complexity, the reverse flow mod IV combustor is judged to be the best candidate for further development into eventual use with the 501-D22A turboprop engine.

ACKNOWLEDGMENTS

This program was performed under NASA contract number NAS3-18561. The author wishes to acknowledge the Detroit Diesel Allison Division of General Motors Corporation for the professional and expert execution of this program. Specific recognition is extended to the DDA Program Manager Mr. J. G. Tomlinson, the Technical Director Mr. R. D. Anderson, and to combustor engineers A. S. Freeman, J. M. Vaught, and A. J. Verdouw for their technical management and support.

REFERENCES

TABLE I. - SCHEDULE FOR THE POLLUTION REDUCTION TECHNOLOGY PROGRAM FOR TURBOPROP ENGINES

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<th>1976</th>
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<th>TASK I</th>
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<td>TASK III</td>
<td>Fabrication</td>
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<td>TASK IV</td>
<td>Combustor screening tests</td>
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<td>TASK V</td>
<td>Reports</td>
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TABLE II. - POLLUTANT EMISSION VALUES

<table>
<thead>
<tr>
<th></th>
<th>EPA limits P2</th>
<th>Program goals</th>
<th>501-D22A engine</th>
<th>Reduction required</th>
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<tr>
<td>Total hydrocarbons</td>
<td>4.9^b</td>
<td>3.7</td>
<td>9.7</td>
<td>62</td>
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<td>Carbon monoxide</td>
<td>26.8^b</td>
<td>20.1</td>
<td>19.0</td>
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<td>Oxides of nitrogen</td>
<td>12.9^b</td>
<td>9.7</td>
<td>5.4</td>
<td>0</td>
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<td>Smoke</td>
<td>29^c</td>
<td>22</td>
<td>55</td>
<td>60</td>
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^a 75% of EPA limits
^b lb/1000 HP-HP-cycle
^c SAE smoke no.

TABLE III. - COMBUSTOR OPERATING CONDITIONS FOR 501-D22A ENGINE

<table>
<thead>
<tr>
<th>Mode</th>
<th>Engine shaft power (kW)</th>
<th>Combustor inlet temperature (K)</th>
<th>Combustor outlet temperature (K)</th>
<th>Combustor inlet pressure (N/cm²)</th>
<th>Fuel-air ratio</th>
<th>Combustor airflow (kg/sec)</th>
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<td>Taxi/idle (out)</td>
<td>116</td>
<td>441</td>
<td>900</td>
<td>37.0</td>
<td>.011</td>
<td>6.80</td>
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<td>Takeoff</td>
<td>3257</td>
<td>610</td>
<td>1322</td>
<td>98.3</td>
<td>.020</td>
<td>14.97</td>
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<td>Clim'out</td>
<td>2931</td>
<td>606</td>
<td>1269</td>
<td>95.8</td>
<td>.0185</td>
<td>15.01</td>
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<td>Approach</td>
<td>977</td>
<td>588</td>
<td>964</td>
<td>84.1</td>
<td>.0096</td>
<td>15.15</td>
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<tr>
<td>Taxi/idle (in)</td>
<td>116</td>
<td>441</td>
<td>900</td>
<td>37.0</td>
<td>.011</td>
<td>6.80</td>
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</table>

^a Single combustor rig operated to these exact conditions.
### TABLE IV. - ABBREVIATED DESCRIPTION OF EACH COMBUSTOR CONCEPT AND THEIR MODIFICATIONS

<table>
<thead>
<tr>
<th>Compressor concept</th>
<th>Mod. I</th>
<th>Mod. II</th>
<th>Mod. III</th>
<th>Mod. IV</th>
<th>Mod. V</th>
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<tr>
<td>Reverse flow</td>
<td>Baseline combustor with airblast fuel nozzle</td>
<td>Baseline combustor with airblast fuel nozzle</td>
<td>Baseline combustor with airblast fuel nozzle</td>
<td>Baseline combustor with airblast fuel nozzle</td>
<td>Baseline combustor with airblast fuel nozzle</td>
</tr>
<tr>
<td></td>
<td>Mod. I - Baseline combustor with airblast fuel nozzle operated with zero pilot flow</td>
<td>Mod. II - Baseline combustor with modified 2nd flow reverse and production airblast fuel nozzle</td>
<td>Mod. III - Mod. II combustor and air assist fuel nozzle</td>
<td>Mod. IV - Mod. II combustor with airblast fuel nozzle with zero pilot flow</td>
<td>Mod. V - Mod. IV combustor with optimum variable geometry settings</td>
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<tr>
<td>Prechamber</td>
<td>Baseline - Initial design with a short prechamber, 100° axial swirler, aft located primary holes, and 14.2 cm² dilution area</td>
<td>Mod. I - A second design with a long prechamber, 200° axial swirler, forward located primary holes, and 14.2 cm² dilution holes</td>
<td>Mod. II - The same combustor as Mod. I but with the dilution adjusted to 12.9 cm²</td>
<td>Mod. III - The baseline combustor modified for improved cooling, and the same dilution area of 14.2 cm²</td>
<td>Mod. IV - The Mod. III combustor with reduced radial swirler flow area</td>
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<td>Prechamber Mod. I</td>
<td>Prechamber Mod. II</td>
<td>Prechamber Mod. III</td>
<td>Prechamber Mod. IV</td>
<td>Prechamber Mod. V</td>
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<td>Prechamber Mod. I</td>
<td>Prechamber Mod. II</td>
<td>Prechamber Mod. III</td>
<td>Prechamber Mod. IV</td>
<td>Prechamber Mod. V</td>
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<td>Staged fuel</td>
<td>Baseline - Initial design of pilot and main combustion chambers in series and a pressure atomizing pilot nozzle and variable-area dilution holes full open</td>
<td>Mod. I - Baseline combustor tested with an air assist pilot nozzle and dilution holes open</td>
<td>Mod. II - Mod. I configuration dilution holes partly closed</td>
<td>Mod. III - Mod. II configuration but with an airblast nozzle and dilution holes open</td>
<td>Mod. IV - Mod. III configuration but with dilution holes partly closed</td>
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<td>Staged fuel Mod. I</td>
<td>Staged fuel Mod. II</td>
<td>Staged fuel Mod. III</td>
<td>Staged fuel Mod. IV</td>
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<td>Staged fuel Mod. II</td>
<td>Staged fuel Mod. III</td>
<td>Staged fuel Mod. IV</td>
<td>Staged fuel Mod. V</td>
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### TABLE V. - SUMMARY OF COMBUSTOR EMISSIONS

<table>
<thead>
<tr>
<th>Compressor concept</th>
<th>EPA Parameter, 1b/1000 Hr-Hr/cycle</th>
<th>Maximum smoke</th>
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<tr>
<td></td>
<td>HC, CO, NOX</td>
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<tr>
<td>Conventional (SOL-D22A)</td>
<td>15.01 63.96 31.46</td>
<td>54.9</td>
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<td>Reverse flow baseline</td>
<td>2.48 4.99 7.80</td>
<td>9.0</td>
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<td>Reverse flow Mod. I</td>
<td>.74 3.53 7.66</td>
<td>8.0</td>
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<td>Reverse flow Mod. II</td>
<td>1.27 9.22 6.83</td>
<td>15.0</td>
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<tr>
<td>Reverse flow Mod. III</td>
<td>1.99 5.55 7.35</td>
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<td>Reverse flow Mod. IV</td>
<td>.99 4.57 7.30</td>
<td>17.0</td>
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<td>Prechamber baseline</td>
<td>1.58 3.99 6.10</td>
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<td>2.27 21.67 6.53</td>
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<td>Prechamber Mod. V</td>
<td>.20 4.71 6.39</td>
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<tr>
<td>Staged fuel baseline</td>
<td>1.92 11.25 8.13</td>
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<tr>
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<td>.42 10.60 8.63</td>
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<td>Program goals</td>
<td>3.7 20.1 9.7</td>
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### TABLE VI. - SUMMARY OF COMBUSTOR PERFORMANCE

<table>
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<tr>
<th>Configuration</th>
<th>Pattern factor</th>
<th>Max wall temp., F</th>
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<tr>
<td>Production</td>
<td>0.18</td>
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<td>.11</td>
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<td>.17</td>
<td>1190</td>
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<td>.22</td>
<td>1083</td>
<td>6.0</td>
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Figure 1. - Cutaway view of the Detroit Diesel Allison 501-D22A turboprop engine.

Figure 2. - Detailed sketch of combustor test rig.
Figure 3. - Overall combustor test rig showing exhaust instrumentation location.
REVERSE FLOW COMBUSTOR

STAGED FUEL COMBUSTOR

50402A PRODUCTION COMBUSTOR

PRECHAMBER COMBUSTOR

Figure 4. Combustors of program.
Figure 5. - Schematic of 501-D22A production combustor.

Figure 6. - Reverse flow combustor design.
Figure 7. - Prechamber combustor design.

Figure 8. - Staged fuel combustor design.
Figure 9. - Comparison of hydrocarbon emissions from best combustor concepts and from production combustor.

Figure 10. - Comparison of carbon monoxide emissions from best combustor concepts and from production combustor.
Figure 11. - Comparison of oxides of nitrogen emissions from best combustor concepts and from production combustor.

Figure 12. - Comparison of smoke emissions from best combustor concepts and from production combustor.