Introducing the VRT Gas Turbine Combustor

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ABSTRACT

An innovative annular combustor configuration is being developed for aircraft and other gas turbine engines. This design has the potential of permitting higher turbine inlet temperatures by reducing the pattern factor and providing a major reduction in NOx emission. The design concept is based on a Variable Residence Time (VRT) technique which allows large fuel particles adequate time to completely burn in the circumferentially mixed primary zone. High durability of the combustor is achieved by dual function use of the incoming air. The feasibility of the concept was demonstrated by water analogue tests and 3-D computer modeling. The computer model predicted a 50 percent reduction in pattern factor when compared to a state of the art conventional combustor. The VRT combustor uses only half the number of fuel nozzles of the conventional configuration. The results of the chemical kinetics model require further investigation, as the NOx predictions did not correlate with the available experimental and analytical data base.

1.0 INTRODUCTION

1.1 Future aircraft operating in both the subsonic and supersonic regime will be powered by engines operating at higher cycle efficiencies than current gas turbines. Increases in cycle efficiency of simple aircraft gas turbines require an increase in mean turbine inlet temperatures with disproportionately large increases in peak turbine inlet temperature and NOx formation. To meet these challenges, SOL-3 Resources Inc. proposed an innovative annular combustor concept which is based on a circumferentially mixed vortex flow principle with variable residence time (VRT) for the fuel particles. The salient features of the combustor are:

* Circumferentially mixed vortex flow for low pattern factor.

* Rich-Quench-Lean combustor for low NOx emission.

* Variable fuel residence time for high efficiency at all operating conditions.

* Walls cooled by 60 percent of total available air for liner durability.

* Elimination of compressor exit flow straightening vanes and reduction in the number of fuel injectors and turbine nozzle vanes for a simple engine.

1.2 The Phase I SBIR (Small Business Innovation Research) effort supported by NASA Lewis Research Center was aimed at demonstrating the feasibility of the VRT combustor concept in an annular configuration. A Textron Lycoming engine of the 10 lb/sec class was chosen as host for the combustor to provide a realistic physical boundary envelope. The design operating conditions were based on the Lycoming turbine flow numbers and temperatures and pressures which would be experienced at a supersonic cruise condition of 65,000 feet altitude and Mach 3. The approach used a three-dimensional mathematical model running both cold and reacting flow conditions. The cold flow model was validated experimentally by a clear plastic model in a water analogue rig. The reacting flow conditions will be validated by combustor laboratory tests which are planned for Phase II.

2.0 THE VARIABLE RESIDENCE TIME (VRT) COMBUSTOR

2.1 Description of the Concept

In a conventional gas turbine engine, ambient air is compressed and given axial and circumferential velocities by a compressor. At the exit of the compressor one or more sets of straightening vanes are used to change the swirl velocity into an axial direction. The air then goes through a combustor where it is mixed with fuel, ignited, and its temperature is raised. At the exit of the combustor, a set of nozzle vanes again turns the flow so that the hot gas is directed at the correct angle for entry to the turbine.

The three basic combustor concepts currently in wide use are a) the swirler stabilizer design, b) the vaporizing baffled design and c) the slinger design. The fundamental reason for these concepts is that in a continuous combustion system, the continually injected charge of fuel needs a source of ignition. This is achieved by recirculating the burning hot gases. The recirculation ratio and turbulent flame speed together with combustor inlet pressure and temperature place an upper limit on the through flow velocity in the primary zone.
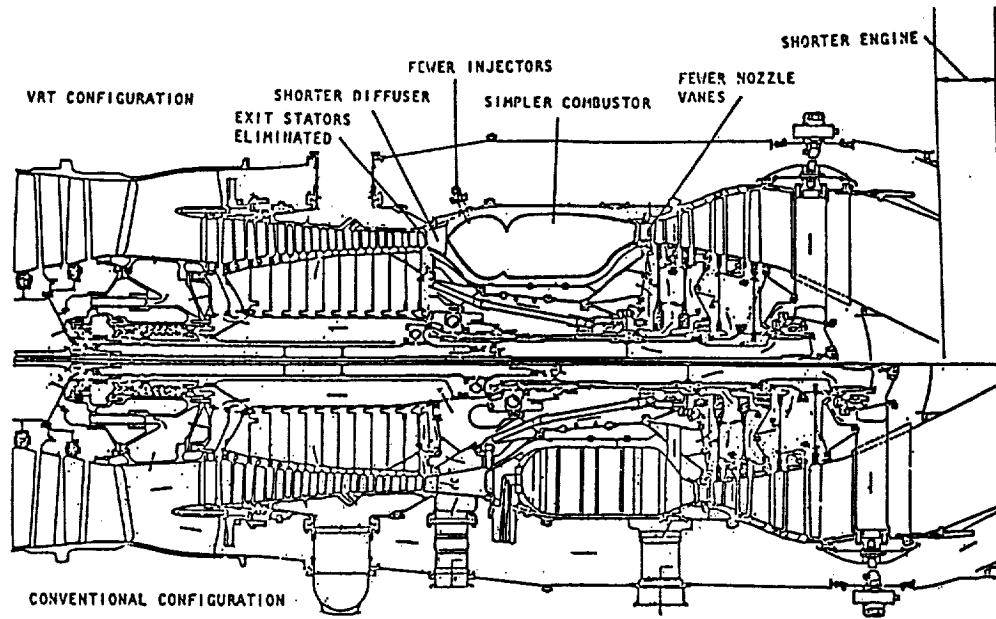
VRT CONFIGURATION SHORTER DIFFUSER FEWER INJECTORS SHORTER ENGINE
EXIT STATORS SIMPLER COMBUSTOR FEWER NOZZLE VANES
ELIMINATED

CONVENTIONAL CONFIGURATION

FIGURE 1 - THROUGH FLOW ENGINE CONFIGURATION

FIGURE 2 - VRT COMBUSTOR MAIN FLOW PATTERN
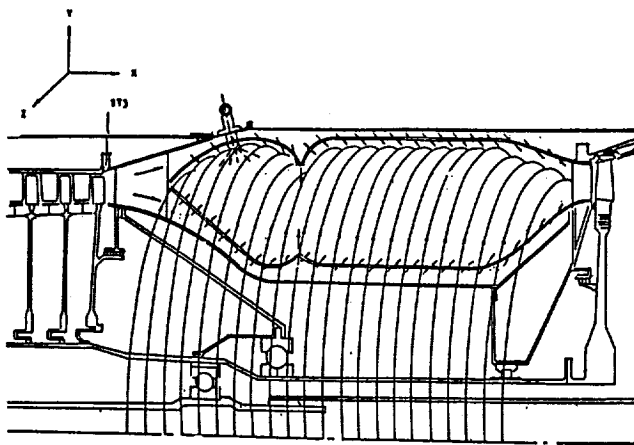

FIGURE 3 - TRANSVERSE FLOW PATTERN IN PRIMARY ZONE

With current designs the mean through flow velocity in the primary zone is of the order of 20 feet per second.

The VRT combustor in a straight through configuration is shown in Figure 1 together with an equivalent conventional design. The noticeable differences are the elimination of compressor exit straightening vanes and a shorter diffuser leading to a shorter engine. Not as obvious are the reduced number of fuel injectors and number of turbine nozzle vanes.

Referring to Figure 2, the air entering the combustor at ST3 has both axial and swirl velocities. Both velocities are reduced in the diffuser section. As the flow path of the air is the resultant vector of the axial and swirl velocities, the diffuser effective angle is smaller than the geometric angle and a shorter diffuser is possible with the VRT configuration because the
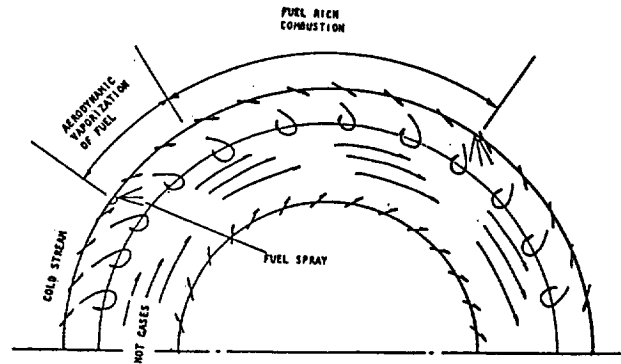
swirl is not taken out. The air enters the primary zone of the combustor through axial slots which maintain the swirl component to provide circumferential mixing. Within the primary zone, a combined vortex is established. Fuel is injected in a tangential direction (i.e. in the plane of the paper) to reinforce the vortex. As the fuel is burnt, there is a natural stratification of the droplets due to the centrifugal effect of the vortex. The heavier fuel droplets are flung to the outer circumference of the toroidal shaped primary zone and the lighter particles remain at the inner circumference. The shape of the waist forces the heavy particles to remain in the vortex until they are burnt and replaced by new heavy particles entering. Opposed air jets in the waist provide rapid quenching of the fuel rich combustion products leaving the primary zone. In the secondary zone, air is introduced by means of tangential slots to maintain the swirl and complete the combustion of unburnt gaseous products. In the dilution zone, air is again introduced by means of tangential slots to tailor the swirl and the radial temperature profile of the combustor exit gases to that acceptable to the turbine.

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Conventional annular combustors are like a number of can combustors placed side by side with the side walls removed. Each injection point has its own flame holding devise and the main flow proceeds axially in the x-direction. Mixing of fuel and air and ignition of freshly injected fuel is by secondary vortices in the x-y plane. Propagation of the flame from injector to injector is at the interface of the two "cans". Circumferential mixing, if any, also occurs at this interface. Acceptable combustor exit temperature distribution is achieved by strict control of the air apertures in the liner and the fuel passages in the injectors.

The mixing process in the primary zone of the VRT combustor is radically different from conventional annular designs. In the VRT configuration, the main flow is a spiral in the y-z plane with its axis in the axial direction. The primary zone can be visualized as a series of curved "can" combustors placed end to end to form a circle. The axis of the fuel spray is in the y-z plane and ignition of freshly injected fuel is by the flame from the preceeding injector. Mixing of fuel and air is by shear layers in the y-z plane enhanced by secondary vortices in the x-y plane (Figure 3). The net effect is a true circumferentially stirred annular combustor. Flow reversal no longer being necessary to ignite the freshly injected fuel, the through flow velocity can be increased substantially.

2.2 Advantages of Concept

The proposed concept has the following advantages over current gas turbine designs:

Aerothermodynamic Advantages

1. The circumferentially mixed vortex flow provides the necessary conditions for a low temperature pattern factor at the exit of the combustor. A reasonable target for the developed hardware is a pattern factor of 0.15 compared to a value of 0.25 for the best conventional combustor.

2. The Rich-Quench-Lean burn technique used in the combustor partitioning has been shown to be one of the effective methods of limiting flame temperatures and thus the formation of NOx. Preliminary calculations indicate that an NOx Emission Index of 5 g/kg is achievable at high altitude supersonic aircraft operating conditions.

3. The Variable Residence Time feature which prevents liquid fuel droplets from leaving the primary zone ensures a broad combustion stability envelope and nearly 100 percent efficiency at all operating conditions. It also provides a true multi-fuel capability.

Mechanical Advantages

1. Elimination of the compressor exit stator and a shorter diffuser in an axial compressor configuration leads to a shorter engine. With a centrifugal compressor, the higher acceptable diffuser exit velocity and elimination of turning vanes leads to a smaller engine diameter

2. Nearly 60 percent of the total available air enters the combustor through tangential total head apertures and will first cool the walls before taking part in combustion or exit temperature control. The effectiveness of any cooling method will be further enhanced by the larger quantity of available air.

3. The circumferentially stirred primary zone is not limited by the need for flow reversal and can therefore be operated at much higher air velocities. The result is a reduction in combustor size and number of fuel injectors.

4. The high velocity, high swirl combustor exit flow conditions will reduce the number of turbine nozzle vanes required. Preliminary calculations indicate a combustor exit swirl angle of 70 degrees at a Mach number of 0.23 for the through flow configuration. For the reverse flow configuration, the swirl angle is 78 degrees and the Mach number 0.38.

3.0 COMBUSTOR PRELIMINARY DESIGN

3.1 Combustor Dimensions

In arriving at the combustor dimensions, two factors were considered to be of paramount importance. The first was the capability of the engine to relight at 30,000 ft altitude. Although the aircraft is expected to cruise at 65,000 ft, it would normally descend to 30,000 ft for relight in the event of an engine flame out. The second factor which was important for this program, was the ability to use the Lycoming test rig without major modifications.

The design methodology for gas turbine combustors is based on semi-empirical correlations developed over the past 40 years. The most widely used loading parameter is Lefebvre's Theta, θ, parameter (Ref. 1) which is an evolution of the kinetic rate formulation and time.

A large base of experimental data has shown that to achieve combustion efficiencies exceeding 95 percent, Theta must equal 73×10^6 (SI units). This level of efficiency at the 30,000 ft windmill condition would virtually guarantee an engine relight. Solving the equation gives us a required liner cross-sectional area of 0.03052 sq m (47.32 sq in). The Lycoming high performance combustor liner has a cross-sectional area of 0.04055 sq m (62.83 sq in). The Lycoming cross-sectional area was chosen for the VRT combustor as this gave us a 33 percent margin and compatibility with the test rig and engine. The remaining combustor dimensions shown in Table 1 were arrived at through geometric considerations, air flow pattern visualization, and engine space compatibility.
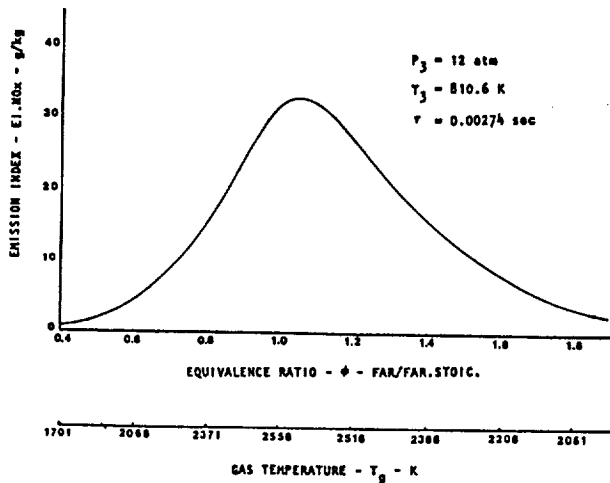
3.2 Supersonic Cruise Operation

The supersonic cruise operating conditions were synthesized by using the Lycoming engine combustor exit flow number, which determined the mass throughput of the engine, and the NASA High Speed Civil Transport Emission Data of Niedzwiecki (Ref. 2), which provided the state of the fluid. The lower end of the range of the NASA data was used as this was considered more realistic of the next generation of gas turbines.

TABLE 1

PHYSICAL DIMENSIONS OF VRT COMBUSTOR LINER (INNER SURFACE)

Overall Length	4.1 in	0.10414 m
Primary Zone Height	2.0 in	0.0508 m
Secondary Zone Height	1.9 in	0.04826 m
Exit Height	0.9 in	0.02286 m
Wall Perimeters		
Outer	5.188 in	0.13178 m
Inner	4.751 in	0.12068 m
Primary Zone	4.501 in	0.11433 m
Secondary Zone	3.125 in	0.07938 m
Dilution Zone	2.313 in	0.05875 m
Cross-Sectional Area, X-Y Plane		
Primary Zone	2.66 sq in	0.001716 sq m
Secondary Zone	2.75 sq in	0.001774 sq m
Dilution Zone	1.30 sq in	0.0008387 sq m
Combustor Volume	0.11214 cu ft	0.003176 cu m

TABLE 2

SYNTHESIZED SUPERSONIC CRUISE OPERATING CONDITIONS

Air Flow, m	5.0176 pps	2.2767 kg/sec
Fuel Flow, m_f	0.1772 pps	0.08036 kg/sec
Gas Flow, $m_{3.6}$	5.195 pps	2.356 kg/sec
Inlet Pressure, P_3	176.4 psia	1.216 MPa
Pressure Drop		
Liner	3.0 %	
Diffuser Exit	0.5 %	
Inlet Temperature, T_3	1459 R	810.6 K
Exit Temperature, $T_{3.6}$	3459 R	1921.7 K
Exit Flow Function	1.795 (ENG)	86.02×10^{-6} (SI)
Hot Residence Time, τ	0.00274 sec	
COMBUSTOR LOADING		
English Units	8.74×10^{6} Btu/hr.cu.ft.atm.	
SI Units	3.90×10^{12} W/hr.cu.m.atm.	

TABLE 3

COMBUSTOR EQUIVALENCE RATIO & AIR DISTRIBUTION

COMBUSTOR EQUIVALENCE RATIO ϕ	
For Emission Index EI.NOx = 5 at Supersonic Cruise	
Overall,	0.62
Primary Zone,	1.72
Secondary Zone,	0.62
AIR PARTITIONING	
Primary Zone,	30.23 percent
Quench,	57.18 percent
Dilution	12.59 percent
PHYSICAL AIR DISTRIBUTION	
Airblast Injectors (8)	2.8 percent
Primary Zone Tangential	27.43 percent
Secondary Zone Radial	40.47 percent
Secondary Zone Tangential	16.71 percent
Dilution Zone Tangential	12.59 percent

FIGURE 4 - PREDICTED NOx EMISSIONS

The pressure drop across the liner was set at 3 percent to match the Lycoming high performance combustor pressure drop. Although the VRT configuration could use a lower pressure drop, this pressure drop also controls the turbine cooling flow. Any changes to the pressure drop would require a redesign of the turbine cooling passages which at this stage of the program would prevent the use of the Lycoming rig and engine.

The resultant synthesized supersonic cruise operating conditions are shown in Table 2. The low residence time of 2.74 millisecond will be a significant factor in reducing the NOx emissions.

3.3 NOx Emissions

The NOx emissions of greatest concern are those occurring at the supersonic cruise altitude of 65,000 ft. This is where the greatest damage to the Earth's ozone layer is likely to occur due to the catalytic action of NOx. The target NOx emission index at these operating conditions has been set at 5 grams NOx per kilogram of fuel. A rich burn, quick quench, lean burn configuration was chosen to minimize the NOx emission.

To estimate the NOx Emissions Index, the correlation derived by Odgers (Ref. 1, Vol. II) was used. Figure 4 shows the estimated emission index versus equivalence ratio at the altitude cruise combustor operating conditions. The curve correlates with the data given by Nguyen et al (Ref. 3). To achieve an EI(NOx) of 5 g/kg, the rich primary zone will have to operate at an equivalence ratio of 1.72 and the lean secondary zone at an equivalence ratio of 0.62. These results together with the required air partitioning are given in Table 3.

3.4 Combustor Air Distribution

The air partitioning calculations show that to obtain a primary zone equivalence ratio of 1.72 will require 30 percent of the available air flow. This air would be divided between the airblast fuel injectors and the tangential apertures in the primary zone.

At this time, a choice had to be made on the number of circumferential sectors and the type of fuel nozzles. The Lycoming configuration has 18 fuel nozzles which flow 16 percent of the total air. The decision was made to go with 8 sectors for the VRT configuration and use available fuel nozzles from the Lycoming ALF 502 engine. Unfortunately these nozzles limit the quantity of airblast to 2.8 percent.
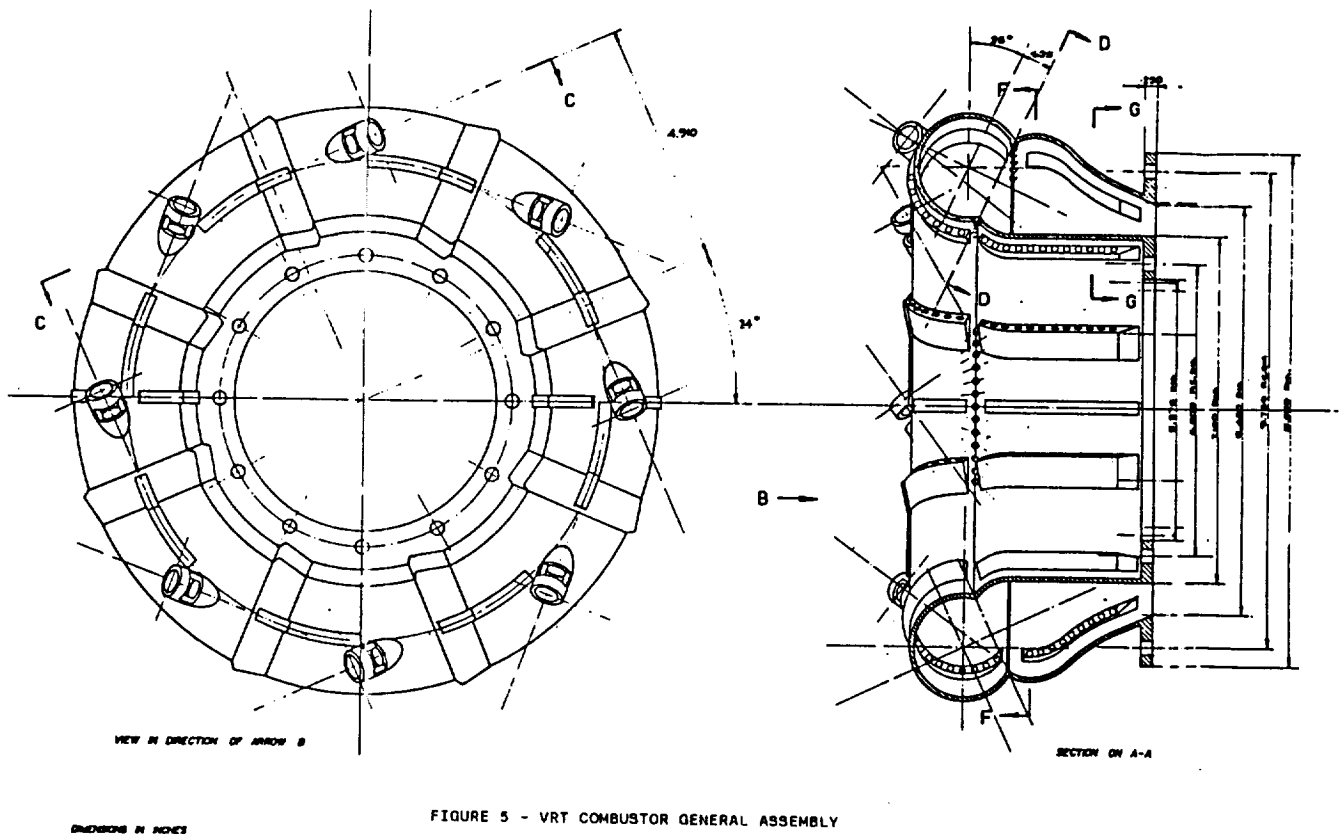
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FIGURE 5 - VRT COMBUSTOR GENERAL ASSEMBLY

The air partitioning calculations also showed that to achieve a transition from an equivalence ratio of 1.72 in the primary zone to 0.62 in the secondary zone would require 57 percent of the total air flow for quenching. This quantity of air was split between the radial jets at the waist (40 percent) and the secondary zone tangential apertures (17 percent). The remaining 12 percent of the available air was allocated to the dilution zone. The detailed physical air distribution is shown in Table 3.

3.5 Liner Wall Apertures

Next, the zone open areas were calculated and converted into physical openings. A number of iterations was needed to obtain an optimum aperture shape, size and spacing. The final VRT combustor configuration for manufacture in plastic is shown in Figure 5.

3.6 Gas Temperatures

For these calculations the combustor was divided into three zones. The rich primary zone is where the fuel and air are intimately mixed and the fuel vaporized. The lean secondary zone is where the gases are quenched and combustion completed. In the dilution zone the remaining air is introduced to reduce the gas temperatures to that acceptable to the turbine. The temperature in each zone is assumed to be the mean between the inlet and exit temperatures of the zone. The temperature rise is obtained from standard charts. The resultant calculated temperatures in each zone is given in Table 4.

TABLE 4

GAS TEMPERATURES

Inlet Temperature, T_3	1459.0 R	810.5 K
Primary Zone Average	2595.6 R	1442.0 K
Primary Zone Exit	3729.6 R	2072.0 K
Secondary Zone Average	3692.3 R	2051.3 K
Secondary Zone Exit	3655.1 R	2030.6 K
Dilution Zone Average	3556.2 R	1976.2 K
Dilution Zone Exit, $T_{3.8}$	3459.0 R	1921.7 K

TABLE 5

COMBUSTOR WALLS MAXIMUM TEMPERATURES

Primary Zone Outer	1653.6 R	918.7 K
Primary Zone Inner	1631.3 R	906.3 K
Secondary Zone Outer	2313.3 R	1285.2 K
Secondary Zone Inner	2176.1 R	1208.9 K
Dilution Zone Outer	2854.0 R	1585.6 K
Dilution Zone Inner	2698.4 R	1499.1 K

3.7 Combustor Wall Temperatures

In a conventional combustor, the wall cooling apertures are distinctly separate from the aerodynamic apertures. The former are designed to provide a wall hugging air blanket, whereas the later are penetrating jets. For the VRT configuration, except for the quenching jets at the waist, the wall cooling and aerodynamic apertures are the same. The air exiting the tangential apertures hugs the wall to provide the cooling and the driving force for the vortex.

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The present VRT combustor was designed with eight fuel injectors. For symmetry, the number of sectors must be a factor of the number of injectors. For simplicity in the first design, the number of sectors was also set at eight. The resultant estimated maximum wall temperatures using the techniques described in Reference 1 are given in Table 5.

3.8 Air Flow Vector Analysis

One of the unique features of the VRT combustor is the circumferential vortex. A preliminary analysis of the expected velocity and swirl angles was performed using the principles of conservation of angular momentum and continuity in the axial direction. The effects of frictional and mixing losses were neglected in these calculations. The results of this cold flow analyses can be compared to the water analogue flow fields and the non-reacting computer model. The results of the analysis are given in Table 6 together with the cold and hot exit Mach numbers.

TABLE 6
COLD AIR FLOW VECTOR ANALYSIS

PRIMARY ZONE MEAN - STATION 3.2

Tangential Velocity, $w_{3.2}$	395.2 ft/sec	120.5 m/sec
Axial Velocity, $u_{3.2}$	6.05 ft/sec	1.8 m/sec
Swirl Angle, $\beta_{3.2}$	89.1 degrees	

PRIMARY ZONE EXIT - STATION 3.3

Tangential Velocity, $w_{3.3}$	395.2 ft/sec	120.5 m/sec
Axial Velocity, $u_{3.3}$	16.0 ft/sec	4.9 m/sec
Swirl Angle, $\beta_{3.3}$	87.7 degrees	

SECONDARY ZONE INLET - STATION 3.4

Tangential Velocity, $w_{3.4}$	395.2 ft/sec	120.5 m/sec
Axial Velocity, $u_{3.4}$	37.5 ft/sec	11.4 m/sec
Swirl Angle, $\beta_{3.4}$	77.5 degrees	

SECONDARY ZONE MEAN - STATION 3.5

Tangential Velocity, $w_{3.5}$	395.2 ft/sec	120.5 m/sec
Axial Velocity, $u_{3.5}$	32.9 ft/sec	10.0 m/sec
Swirl Angle, $\beta_{3.5}$	80.3 degrees	

DILUTION ZONE MEAN - STATION 3.6

Tangential Velocity, $w_{3.6}$	395.2 ft/sec	120.5 m/sec
Axial Velocity, $u_{3.6}$	66.8 ft/sec	20.4 m/sec
Swirl Angle, $\beta_{3.6}$	73.4 degrees	

COMBUSTOR EXIT - STATION 3.7

Tangential Velocity, $w_{3.7}$	395.2 ft/sec	120.5 m/sec
Axial Velocity, $u_{3.7}$	98.6 ft/sec	30.0 m/sec
Swirl Angle, $\beta_{3.7}$	67.3 degrees	

COMBUSTOR EXIT MACH NUMBER - STATION 3.7

Cold Mach Number	0.120
Hot Mach Number	0.166

4.0 WATER ANALOGUE TESTS

4.1 Installation

The Lycoming water analogue test facility consists of a vertical glass testway with a 12 x 24 inch (0.3 x 0.6 m) rectangular test section. Because of the depth limitations of the testway, the model was mounted horizontally and bolted to a collector. The flow approached the model vertically from below, was turned horizontal within the model and returned to the vertical inside the collector. Shop air was available to 25 individually controlled small bore tubes within the testway. A large holding tank and recirculating pump allow a controllable water flow with a maximum rate of over 100 pps.

Observations were carried out at flow rates of 15 pps (Reynolds No. = 0.89 x 10^5) and 30 pps (Reynolds No.= 1.8 x 10^5). Except for the higher flow speed, the flowpaths at the two flow rates were virtually identical.

The model was instrumented with ten 0.040 inch O.D. tubes feeding the apertures shown in Figure 6. Eight fuel nozzles were inserted into the fuel nozzle holders in the header and retained with silicone rubber adhesive. One of the fuel nozzles was instrumented with 0.125 inch O.D. tube to allow feeding air or dye to the main fuel passage.

4.2 Test Observations

The tests consisted of allowing time for the water flow to stabilize and then introducing air bubbles at each of the injection points in turn. Written and video records were made at three series of tests. The observations were as follows:

Test Series 1 - Water flow rate 15 pps

The flow went about 350 degrees in the primary zone. The flow hugged the wall, was temporarily deflected at each fuel nozzle location but reattached itself to the wall. The reattachment after each nozzle was due to a superimposed swirl. The quench jets produced a secondary counter-clockwise swirl in the outer and a clockwise swirl in the inner section of the secondary zone. The flow did one further revolution in the secondary and dilution zones before exiting the combustor. The main flow pattern is shown in Figure 6.
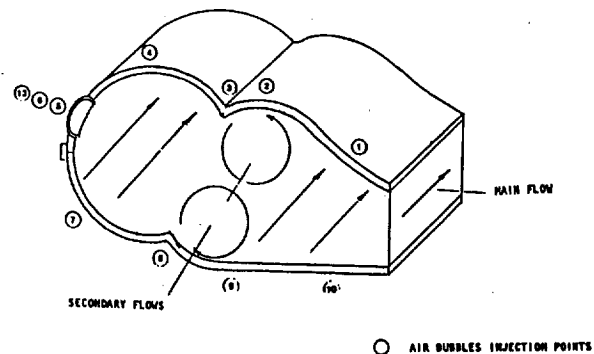

FIGURE 6 - VRT COMBUSTOR WATER ANALOGUE FLOW PATTERNS

Test Series 2 - Water flow rate 30 pps.

The flow pattern was essentially the same as Test Series 1. Turbulence and mixing were increased, and the flow path around the circumference appeared to have increased slightly to 370 degrees.

6

Test Series 3 - Water flow rates 15 pps and 30 pps.

The third series of tests was with red dye being fed into the main fuel passage of the fuel injector. The circumferential flow pattern was essentially the same as seen in Test Series 1, with one complete turn in the primary zone. It took about 90 degrees circumferentially for substantial mixing between the dye exiting the fuel nozzle and the bulk of the primary zone flow entering tangentially. After this initial 90 degrees however, the dye filled the whole cross-section of the primary zone and was totally dissipated by the time it reached the secondary zone.

5.0 THREE-DIMENSIONAL COMPUTER MODEL

This section presents the 3-D computer model analysis conducted by Textron Lycoming under subcontract to SOL-3 Resources. In addition to the performance analysis of the VRT combustor, a comparison was made with the results obtained on a state of the art Lycoming designed combustor of conventional configuration utilizing 18 swirler stabilized fuel injectors.

5.1 Description of the 3-D Combustor Model

The 3-D combustor performance model computer program ("FLUENT") that forms the basis of the present work is described in Reference 4. "FLUENT" is a general purpose computer program that solves steady state continuity, momentum, and energy equations in 2D/3D Cartesian or polar coordinates for laminar or turbulent flows. Turbulence is modeled using the standard two-equation $K-\varepsilon$ model or Algebraic Stress Model (ASM). "FLUENT" also has a six equation radiation model that allows calculation of radiative heat transfer. A single step global chemical reaction is used to model reacting flows. The conservation equations for three chemical species are solved to calculate the local reacting flow field. Four reaction rates are computed at each node point in the flow field; the kinetic reaction rate, and three mixing controlled rates based on the laminar or turbulent diffusion of the three chemical species respectively. The local reaction is then allowed to proceed at the lowest of these four rates.

The liquid spray is modeled using a Lagrangian trajectory technique for groups of droplets based on the computed continuous gas flow field. Effect of turbulence on the trajectories of the droplets is simulated using a stochastic tracking technique which takes into account the local turbulence characteristics as the droplet traverses the flow field. The calculations of the liquid spray and continuous phase are fully coupled so that evaporation and combustion of liquid fuel droplets can be modeled in a realistic manner. A partial equilibrium Zeldovich mechanism is used in the NOx calculation. The NOx reaction sequence is solved under the assumption that it has no impact on the predicted flowfield or temperature field in the combustor.

The NOx reaction sequence is solved decoupled from the flowfield and temperature field in the combustor. It is also assumed that the reaction rates are infinitely fast so that the species concentrations may be obtained via chemical equilibrium. The "CREK" (Ref.5) program is used to solve the conservation equations for the species involved in the NOx production.

The equilibrium assumption reduces the number of kinetic equations to be solved and was used in several premixed combustion systems. However, this assumption may not be quite valid in all regions of a gas turbine combustor.

5.2 Results

The results include velocity vectors, temperature isotherms, species, and emission concentrations. The analysis covers one of the derivatives of the Lycoming combustors and SOL-3 VRT combustor. The cruise condition given in Table 2 was used in the calculations and JP4 fuel was used as a fuel type in the spray calculation.

The VRT Combustor

A 45 degree sector in polar coordinates with cyclic boundary conditions at the repeating planes was used to model the entire combustor. The computational grid comprised 35x36x31 elements in axial, radial, and tangential directions respectively. The fuel spray was modeled with droplets injected at 8 discrete angular positions with 10 discrete drop sizes. Figure 7 illustrates a 3-D view of the fuel droplet trajectories with crosses indicating the point of complete evaporation. This figure also shows that all droplets are fully evaporated within a distance approximately equal to half the circumferential spacing between fuel injectors. The smallest droplets evaporate very near the fuel nozzle while the largest travel a longer distance. The droplets are heated to the vaporizations temperature, at which point they begin to evaporate by convection and diffusion into the gas phase. When the droplet temperature reaches the boiling point, a boiling rate equation governs the mass transfer. As the droplet evaporates, it enters the gas as a chemical species "f" and reacts with oxygen present in the gas. This process creates interphase coupling of heat, mass, and momentum transfer between the gas and liquid phases.

Air Swirl of Fuel Injector

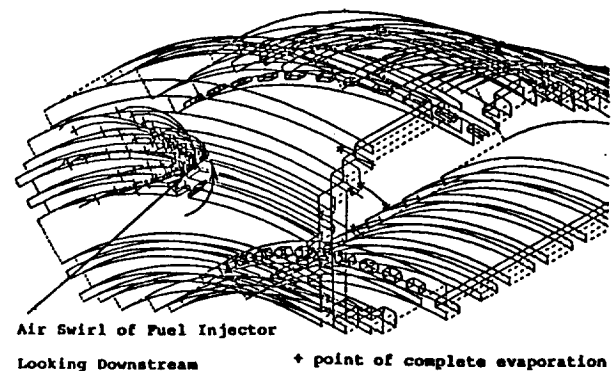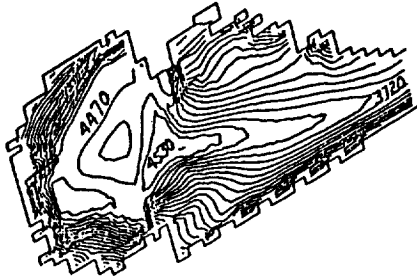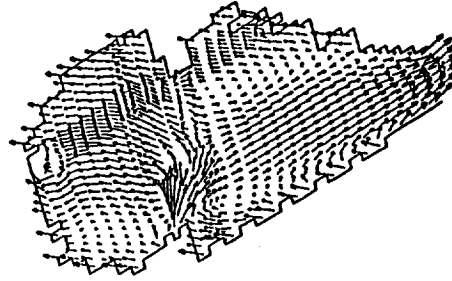Looking Downstream   + point of complete evaporation

FIGURE 7 - VRT COMBUSTOR MEAN DROPLET TRAJECTORIES
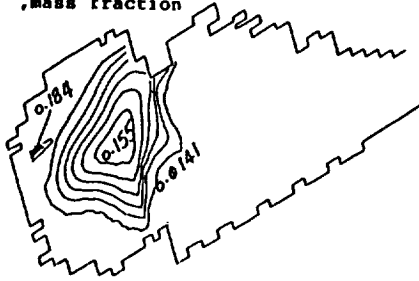
(a) Temperature contours , °R

(b) velocity vectors, 3-D Magnitude & Direction

(c) Unburned fuel contours
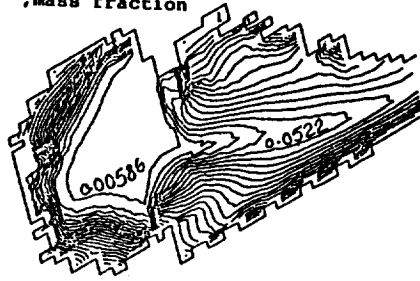   ,mass fraction
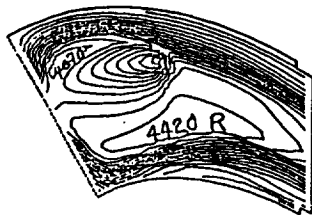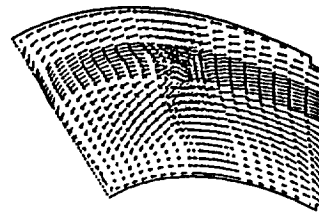
(d) Oxygen
     ,mass fraction

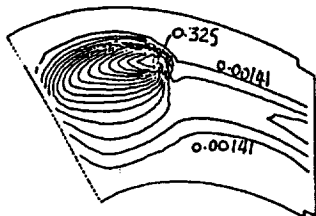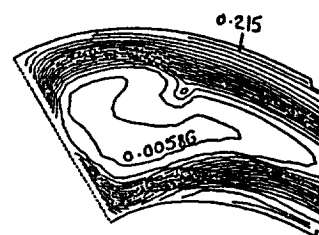FIGURE 8 - VRT COMBUSTOR PREDICTIONS AT AN AXIAL PLANE

(a) Temperature contours , °R

(b) Velocity vectors, 3-D Magnitude & Direction

(c) Unburned fuel contours
     ,mass fraction

(d) Oxygen
     ,mass fraction

FIGURE 9 - VRT COMBUSTOR PREDICTIONS IN PRIMARY ZONE

8

Figure 8 illustrates velocity vectors, contours of temperature, and the concentrations of unburned fuel and oxygen ·n an axial plane intersecting with the fuel nozile centerline at the combustor inlet plane. Maximum gas temperatures occur in the middle of the primary zone. Gas temperature decreases near the air inlets and lower levels of temperature occur in regions close to the liner walls due to the high tangential velocity of the injected air. Figure 8 also shows the contours of the concentration of unburned fuel vapor and oxygen. The distributions of these two quantities are also quite consistent w·th the temperature distribution.

Figure 9 shows velocity vectors, contours of temperature and the concentrations of unburned fuel and oxygen in a vertical plane midway through the combustor primary zone. It can be seen that max temperature and unburned fuel concentration occur just downstream of the fuel nozzle. Gas temperature as well as the fuel concentration decrease in regions between nozzles.

The Lycoming Combustor

A 20 degree sector of the combustor was selected for modeling and divided into 38x33x35 finite difference nodes along axial, radial, and circumferential directions, respectively. In order to concentrate calculation cells near the inlets, a non uniform grid spacing was used in the analysis.

Figure 10 shows a plot of predicted velocity vectors in an axial plane in line with the injector centerline. As can be seen the fuel injector/ swirler that has a swirl number of 0.8 produces a large on-axis recirculation zone that sweeps back burnt gas products to ignite the incoming reactants.

Figure 11 shows the contours of temperature and fuel concentration in line with the injector centerline. Maximum gas temperatures occurs toward the end of the primary zone. The secondary jets that are in line with the injector cause a reduction in gas temperature in this plane. Lower levels of gas temperature occur in regions surrounding the air inlets which is marked by low level of fuel concentration.
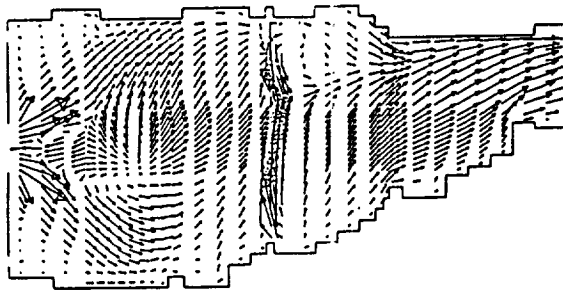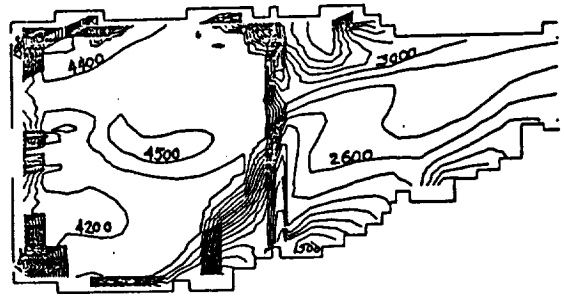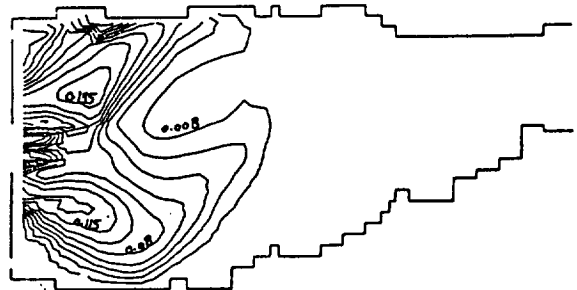
Temperature

Fuel Mass Fraction

FIGURE 11 - LYCOMING COMBUSTOR AXIAL CONTOURS

FIGURE 12 - LYCOMING COMBUSTOR TRANSVERSE VELOCITY VECTORS

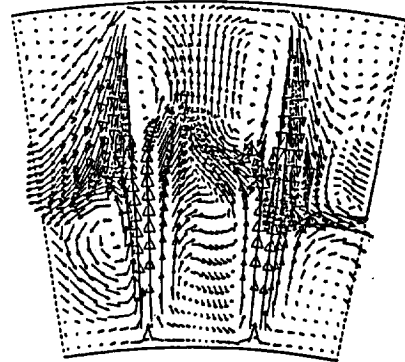
FIGURE 10 - LYCOMING COMBUSTOR AXIAL VELOCITY VECTORS

FIGURE 13 - LYCOMING COMBUSTOR TRANSVERSE TEMPERATURE CONTOURS

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Figures 12 and 13 illustrate the predictions at the axial plane of the primary zone holes. Figure 12 displays the velocity vectors while Figure 13 depicts the temperature contours. It can be seen from these two figures that the primary jets are well impinged and bring the gas temperature down rapidly. Gas temperature decreases in regions between injectors due to primary zone jets and lower gas temperature occur in regions close to the inner wall of the liner.
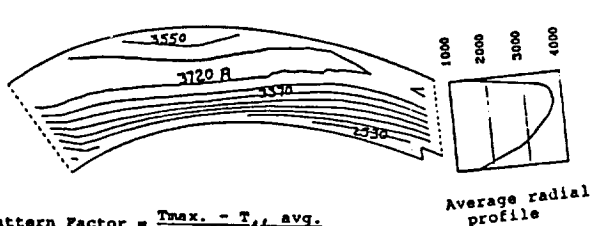

(a) Lycoming Conventional Combustor (Side View)

P.F. = 0.271
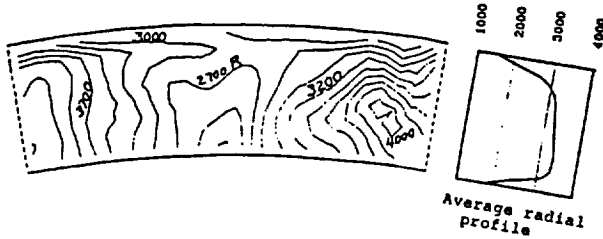
(b) VRT Combustor (Isometric View)

P.F. = 0.131

$$\text{Pattern Factor} = \frac{T_{max.} - T_{4,avg.}}{T_{4,avg.} - T_3}$$

FIGURE 14 - TEMPERATURE CONTOURS AT COMBUSTORS EXIT PLANE

5.3 Comparison Between the VRT and Conventional Combustors

Figure 14 shows the temperature contours at the exit plane of both combustors. The maximum exit temperature is 3720 R for the VRT combustor compared to 4000 R for the conventional combustor. This corresponds to a pattern factor of 0.131 for the VRT combustor compared to 0.271 for Lycoming's conventional combustor.

Figures 15 and 16 show the axial distribution of the mass average values of gas temperature and NOx concentration, respectively. It can be seen from these two figures the strong relation between NOx level and gas temperature. These two figures also show that most of the conventional combustor NOx is formed in the primary zone where the maximum temperature occurs. In the case of the VRT combustor, the NOx is mainly generated in the secondary zone where most of the reaction occurs and produces the maximum temperature.

6.0 DISCUSSION OF RESULTS

6.1 Water Analogue Tests

The water analogue tests clearly demonstrated the predicted flow within the combustor model. In the primary zone, the flow did one complete circumferential circuit. This is equivalent to a
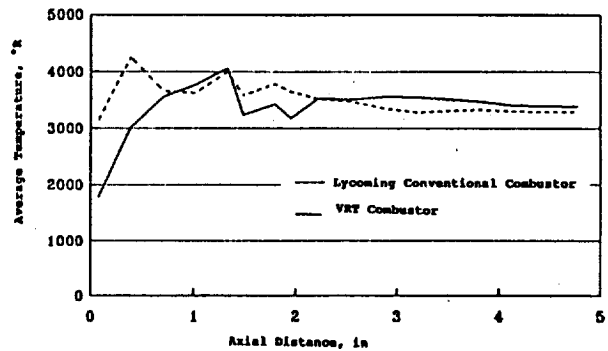

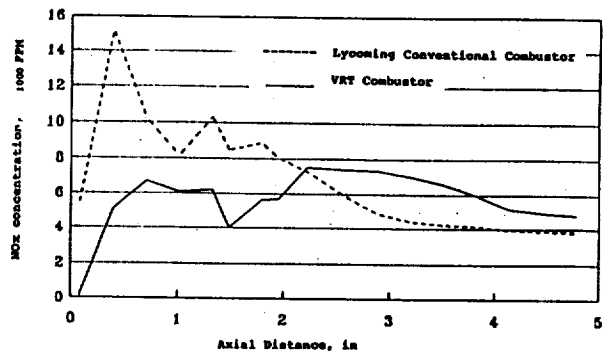FIGURE 15 - AXIAL DISTRIBUTION OF SECTOR AVERAGE TEMPERATURES

FIGURE 16 - AXIAL DISTRIBUTION OF SECTOR AVERAGE NOx

swirl angle of about 87 degrees. The preliminary vector analysis carried out in the design phase, predicted an angle of 89 degrees. The flow did one further circumferential circuit in the secondary and dilution zones before exiting the combustor. This is equivalent to a swirl angle of 85 degrees. The prediction was 80 degrees in the secondary zone and 73 degrees in the dilution zone. The close correlation of the swirl angles also means that the velocity vectors have to correlate by geometric similarity.

In the primary zone, there appeared to be a weak secondary swirl superimposed on the circumferential swirl. The first combustor design required an airblast mass flow of 6 percent. However because of hardware availability, the mass flow was reduced to 2.8 percent. The rate of diffusion of the red dye indicated an inadequacy in the fuel nozzle airblast mass and swirl number. The higher airblast mass flow would have been a superior choice.

In the secondary zone, the radial quench jets set up two strong secondary swirls superimposed on the circumferential swirl. One rotating counterclockwise in the upper half of the secondary zone and the other rotating clockwise in the lower half. These secondary swirls had been observed in the can version of the VRT combustor and were the basis of the predicted quick quench. The secondary zone did demonstrate the vigorous mixing required to go from the rich burn in the primary zone to the lean burn in the secondary zone.

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6.2 Velocity Field

The velocity vectors predicted by the 3-D computer model can be compared to the flow observed in the water analogue tests. The typical example given in Figure 8 shows in some areas exceptionally good correlation. The predicted primary zone flow in the circumferential direction is identical to that observed. The computer model even shows the inferred weak secondary swirl

In the secondary zone, the two models are not quite identical. The computer model shows the circumferential pattern near the walls and the two secondary swirls. However at the center of the secondary zone, the predicted velocity vectors are now axial which is in disagreement with the water analogue flow. It would appear also that the degree of penetration of the radial quench jets is higher in the water analogue than predicted by the computer.

In the dilution zone, the two models are radically different. The computer model shows the flow to be predominantly axial. Whereas the flow in the water analogue is predominantly circumferential. In the water analogue, the circumferential flow path continues into the transition section and can even be seen in the collector. The artificial high numerical diffusion in the "FLUENT" program could well be the cause of the axial/circumferential flow pattern discrepancy between the calculated and observed flows.

6.3 Thermal and Reacting Flows

The thermal results presented in this report were arrived at after some modifications to the input boundary conditions to best depict the flow fields. In the case of the conventional combustor, the swirler flow field in the primary zone was adjusted until the desired recirculation was obtained. For the VRT configuration, the airblast mass flow rate was increased from two to four percent and the inner quench jets moved axially downstream by 0.1 inch. These jets will have to be moved further downstream in future work to meet the intent of the design.

Figure 15 shows the axial distribution of section average temperatures for the conventional and VRT combustors. The maximum average temperature in the VRT combustor is lower and occurs further downstream than the conventional configuration. At the exit, the average temperature of the VRT is nearly 100 degrees R higher than the conventional. This means that either the VRT combustor is more efficient, or that the total air/fuel ratios for the two configurations are slightly different. In spite of this discrepancy, the pattern factor for the VRT combustor is predicted to be 0.131 compared to 0.271 for the conventional configuration.

Figure 14 shows the temperature contours at the exit planes. In the conventional combustor, the isotherms are randomly located with a fairly flat radial profile peaking at 20 percent turbine blade height. In the VRT configuration, the isotherms are more organized with a steep radial profile peaking at 70 percent turbine blade height. Both conventional and VRT combustor exit temperatures would be amenable to developmental

adjustments, with the VRT being the more manageable of the two due to its more regular isotherm pattern.

6.4 NOx Emissions

For conventional combustor configurations, both experimental and analytical data are available for comparison. The data used must be adjusted for the actual pressure, inlet temperature and residence time of our combustor. The predicted emission shown in Figure 4 was obtained from the empirical relationship derived by Odgers in Reference 1 and is based on a large experimental data base. The data given by Nguyen, Bittker and Niedzwiecki in Reference 3 are analytical but have been validated experimentally.

For the conventional Lycoming combustor with a near stoichiometric primary zone, the predicted NOx emissions are:

Source	NOx ppm	EI NOx g/kg
Empirical (Ref 1)	1,040	33
Analytical (Ref 3)	1,076	34
Lycoming Analysis	3,676	117

The empirical and analytical predictions correlate very well, but the Lycoming analysis is high by a factor of 3.5.

Figure 16 shows the axial distribution of sector average NOx concentration for the conventional and VRT combustors. The maximum average NOx concentration in the VRT combustor is nearly half that of the conventional configuration and occurs in the secondary zone.

The NOx predictions provided by the "CREK" model (Ref 8) lack credibility when applied to the state of the art conventional combustor and the VRT configuration. Possible reasons for the discrepancy could be:

1. The simple three equation reaction mechanism. (The analytical model of Nguyen et al uses 102 reactions.)

2. The assumption that the reactions are infinitely fast so that chemical equilibrium is achieved at each node.

3. The decoupling of the NOx chemistry from the hydrodynamics.

7.0 CONCLUSIONS

* The feasibility of a combustor based on the VRT principle was demonstrated by both the water analogue tests and the 3-D computer model. The flow pattern within the combustor was virtually as predicted.

* The VRT configuration showed the feasibility of reducing by half the number of required fuel nozzles when compared to a conventional design.

* The thermal performance analysis conducted by the 3-D computer model on the VRT configuration predicted a 50 percent reduction in pattern factor when compared to a state of the art conventional combustor.

* The results of the chemical kinetics model will require further investigation, as the NOx predictions did not correlate with the available experimental and analytical data base.

* Because of the significant benefits which can derive from the VRT combustor concept and the encouraging results obtained in this Phase I SBIR program, NASA is funding a Phase II which would prove the concept under actual operating conditions in an Allison engine configuration.

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16. Abstract

An innovative annular combustor configuration is being developed for aircraft and other gas turbine engines. This design has the potential of permitting higher turbine inlet temperatures by reducing the pattern factor and providing a major reduction in NOx emission. The design concept is based on a Variable Residence Time (VRT) technique which allows large fuel particles adequate time to completely burn in the circumferentially mixed primary zone. High durability of the combustor is achieved by dual function use of the incoming air. The feasibility of the concept was demonstrated by water analogue tests and 3-D computer modeling. The computer model predicted a 50 percent reduction in pattern factor when compared to a state of the art conventional combustor. The VRT combustor uses only half the number of fuel nozzles of the conventional configuration. The results of the chemical kinetics model require further investigation, as the NOx predictions did not correlate with the available experimental and analytical data base.

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