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Advanced Turbine Systems Program
Conceptual Design and Product Development

Topical Report
April 1995

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Work Performed Under Contract No.: DE-AC21-93MC29257

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Allison Engine Company
Indianapolis, Indiana

DISCLAIMER

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I. INTRODUCTION

Allison has developed and verified key combustion system technologies to satisfy ATS Phase II performance requirements. These activities include the following:

- demonstration test of an ultra-lean premix module meeting the ATS 8 ppm NOx goal using natural gas fuel
- design and fabrication of a second generation premix module for bench test evaluation
- bench test verification of catalytically enhanced combustion
- preliminary design of the transition section that guides the combustor discharge flow from the external combustor to the turbine inlet

Allison has been executing a systematic approach in developing the combustion system technologies to insure that our ATS engine includes the benefits of advanced material and low NOx combustion technologies without placing undue risk on the overall engine development program. New technology is most easily assimilated in discrete evolutionary stages; thus Allison has structured the combustion system development plan with a series of increasingly demanding performance evaluations that demonstrate the suitability of the individual technology. The following discussion summarizes the progress made in bringing advanced combustion technology to the ATS.

II. ALLISON'S ATS COMBUSTION SYSTEM

The preliminary design activity defined the ATS combustion system configuration as an external, silo-type combustion system. The combustor consists of a single cylindrical chamber mounted between the compressor discharge and turbine inlet sections with the combustor's axis of symmetry perpendicular to the engine centerline. The off-centerline combustion system has several advantages over in-line combustion systems. Firstly, the silo combustor arrangement permits the necessary flexibility to develop a low emission combustion system. The silo configuration permits easy access to the combustor, which will allow for periodic maintenance that may be necessary for ultra low emission combustion systems of the future. In addition, the length or volume of the silo combustor is no longer constrained to be within the space between the compressor and the turbine. Additional combustor length is essential for reducing CO and UHC emissions in premixed combustor systems that operate with lower primary zone combustion temperatures to limit NOx temperatures. Finally, the geometrically flexibility inherent in an external silo combustor configuration permits inclusion of either an aerodynamically stabilized ultra-lean premixed combustion with various fuel staging concepts, or catalytically enhanced ultra-lean combustion. The initial steps of evaluating both of these designs were accomplished in Phase II and are discussed later in this report.

A design is envisioned for the catalytically enhanced system; however, the specifics have not been undertaken.

III. ULTRA-LEAN PREMIX MODULE DEVELOPMENT

One method of meeting the ATS emissions requirements is to use an aerodynamically stabilized, lean premixed combustion system. By operating near the stability boundary, NOx emissions are reduced through low combustion zone temperatures.

The combustion system's emission performance will critically depend on the uniform dispersion of fuel within the combustion chamber. Nonuniform mixing results in a range of equivalence ratios that yield a range of combustion temperatures. Those areas that are relatively fuel rich, and thus closer to stoichiometric conditions, will burn much hotter. Since NOx production through the Zeldovich mechanism is exponentially dependent on the local temperature field, these hot zones produce a disproportionate amount of NOx.

As a result, a mixing device is necessary to provide the desired fuel/air mixture that will minimize NOx as well as produce a flow field suitable for flame stabilization. One such device is a radial swirler plus nozzle (RSPN) premixer.

Two RSPN premixer configurations have been evaluated to determine their mixing efficiency and flame stabilization potential. The baseline premixer consists of a fuel distribution manifold, fuel delivery tubes, a radial inflow swirler, a throat section, and a controlled divergent passage. The resultant fuel-air mixture is accelerated through a converging passage with a throat sized to yield a velocity profile that would inhibit flashback. A divergent passage is affixed downstream of the throat which controls the expansion of the flow and produces the proper flow field in the combustor.

The operation of the second module is similar to the baseline unit except that two swirling passages are used.

Testing included mixing studies, flashback propensity, and laser Doppler velocimeter (LDV) measurements.

This study consisted of passing a 8000 ppm mixture of natural gas and air through the fuel circuit as a seed gas. A blower supplied airflow to the radial air swirler and the resultant mixture was sampled at the throat of the module. Sampling of the mixture through a hydrocarbon analyzer produced a fuel distribution by recording hydrocarbon (HC) concentration. Both modules produced similar mixing profiles.

Although a perfectly uniform fuel-air mixture is desired to make combustor temperatures uniform and thereby minimize NOx production, it is not the only consideration in designing a premixer. Another design criterion is to avoid the propensity for flashback while maintaining a stable flame.

A swirling flow is used to stabilize a lean premixed flame. This flow field was determined using Allison's second generation, 2-D, finite element code which utilizes the continuity and momentum equations and a standard K-ε turbulence model. With a swirling flow, the axial velocity at the center of the throat passage is lower than the velocity at other radial positions. As the flow moves axially downstream through the divergent passage, the expansion causes the flow to separate and a recirculation zone to form. This recirculation zone stabilizes the combustion process and provides an ignition source for the remainder of the fuel-air mixture. Provisions must be made to avoid upstream flame propagation at the middle of the throat where velocity is low. Since flame propagation speed is a strong function of stoichiometry, this is accomplished by a small change in the local fuel-air ratio at the throat, which will inhibit flashback into the premixer.

The RSPN module is a very efficient mixer in that the distributed fuel injection and swirling flow combine to produce a uniform fuel concentration profile. Early testing of the modules indicated that the shape of the concentration profile played a major role in defining the flashback characteristics. However, low NOx emissions were not sacrificed as a result of this design.

The propensity of the modules to flashback was evaluated at atmospheric conditions. The flashback sensitivity was evaluated with the module operation at a fuel-air ratio of 0.030. During combusting operation, preheated air was driven through the radial swirler at 100°C (212°F) and natural gas was supplied to the fuel manifold to establish the proper stoichiometry. The reaction was contained in a quartz combustion liner affixed to the discharge of the RSPN module. Flashback was induced within the module by placing a torch within the swirler cavity. After moving the flame inside the module, the torch was removed. Both RSPN modules tested showed flashback resistance by purging the flame from within the module at a fuel-air ratio of 0.030 with pressure drops from 1 to 6%.

A two component laser Doppler velocimeter (LDV) setup was used to determine the velocity along the centerline of the combustion chamber aft of the RSPN throat. The system is driven by a 4 W Argon-ion laser. Simultaneous measurements of the axial and azimuthal velocity were obtained. The multicolored beam was separated into green and blue colors with the fiber drive. Two beams of each color were fed into individual fiber optic couplers. The four fibers were brought to the transmitter which forced these four beams to cross at the probe volume. The light scattered by the seeded flow at this point was collected by the receiver. The resulting fringe pattern (shift) was processed by an FFT signal processor and outputted as velocity components.

The velocity "profiles" for both RSPN swirlers were similar. The axial position represents the distance downstream from the throat. The axial velocity was mapped as a function of the distance from the throat for both the reacting and nonreacting flow situations. The length of the recirculating zone as indicated by the transition from negative to positive axial velocity is slightly longer for the nonreacting flow field. The higher temperatures produced by the reacting flow increase the velocities within the liner and alter the recirculation zone length slightly.

Atmospheric bench testing was followed by high pressure testing at Allison. The baseline RSPN module was mounted on the front of a 4 x 4 in. square cross-section liner and installed in a rig capable of simulating elevated inlet pressures and temperatures. A schematic of this rig is shown in Figure 3-1.

Tests showed that the NOx emissions were not sensitive to pressure changes over a 5 to 10 atmosphere range. However, CO oxidation mechanisms were susceptible to operating pressure with high pressure accelerating CO burnout. The emissions are plotted with the flame zone temperature as the correlation parameter.

In an effort to pursue an alternative swirler stabilized premixer, design work has been completed on another premixer design that employs axial swirlers. Airflow enters through three axial swirler passages to impart a tangential velocity component. The swirling airflow then passes over a fuel injector grid consisting of a series of fuel injector tubes. The resultant fuel-air mixture is accelerated through a throat venturi and then expanded in a controlled divergent passage as in the RSPN modules.

A series of polycarbonate swirlers were procured to adjust the airflow split, swirl angle, and number of swirl vanes. These polycarbonate swirlers could be inserted into the metal nozzle and secured for mixing tests under cold flow conditions.

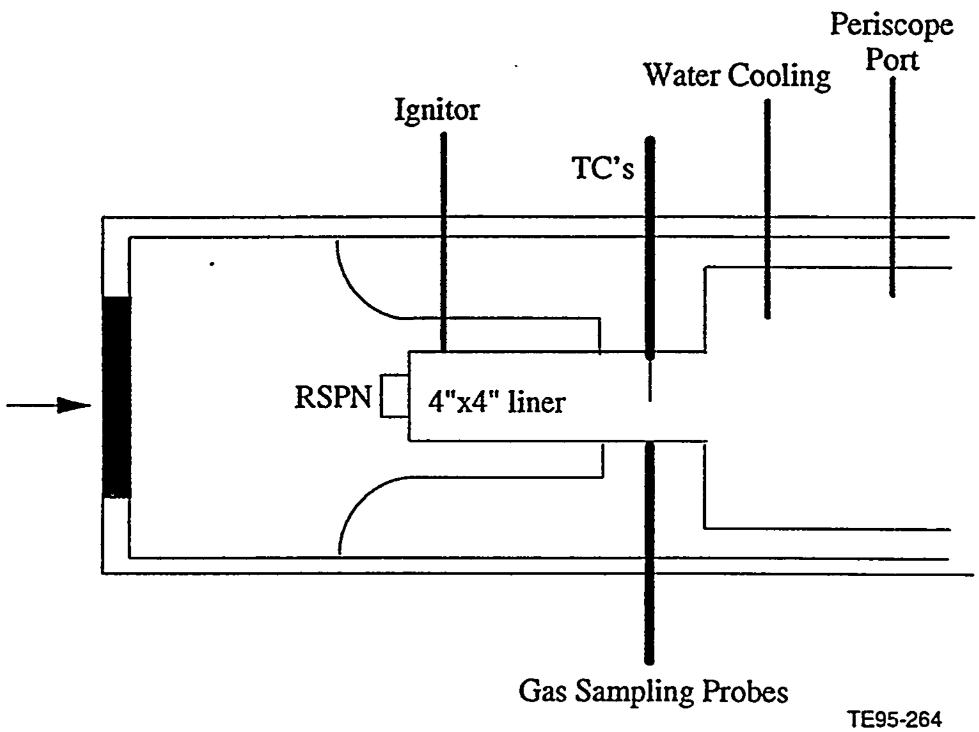

Figure 3-1. Allison 4 in. x 4 in. test rig schematic.

IV. CATALYTIC ENHANCED COMBUSTION

As shown, an aerodynamically stabilized ultra-lean premixed system provides one method for obtaining the ATS emissions goals. An alternative method involves using a catalytic element to enhance combustion. This would extend the lean stability limit encountered with the aerodynamically stabilized system. As a result, Allison initiated a program with Catalytica, Inc., to investigate the benefit of employing a catalytic element to enhance combustion.

In traditional catalytic combustion systems, fuel and air are mixed to a composition required to achieve the target combustor outlet temperature and this mixture is fed to the catalyst, as shown in Figure 4-1. For a sufficiently high fuel/air mixture temperature, the catalytic reaction occurs and the catalytic surface temperature rises rapidly. These high temperatures lead to various durability problems for the catalyst support structure such as thermal sintering of the support surface, thermal sintering, and vaporization of active components such as noble metals, thermal shock fracturing of ceramic supports.

Catalytica's design approach is shown in Figure 4-2. The fuel air mixture to achieve the required combustor exit temperature is fed to the catalyst. If the inlet temperature is sufficiently high, the catalyst promotes a reaction rate sufficient to induce a temperature rise in the catalyst substrate as well as the gaseous mixture. This substrate temperature rise, however, is limited to a relatively low value by the

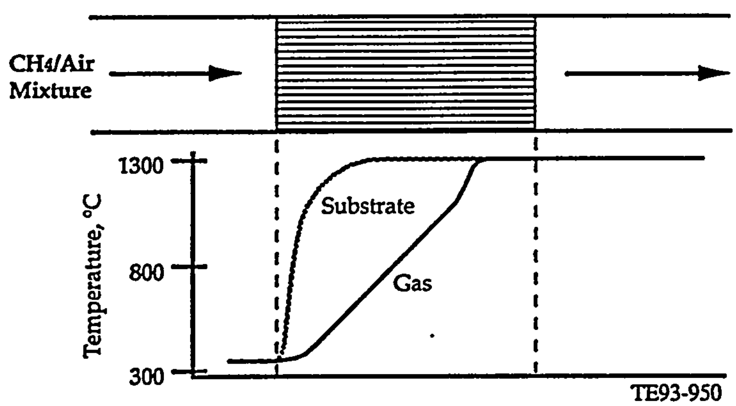

Figure 4-1. Schematic diagram showing the substrate and gas temperature in a traditional catalytic combustor.

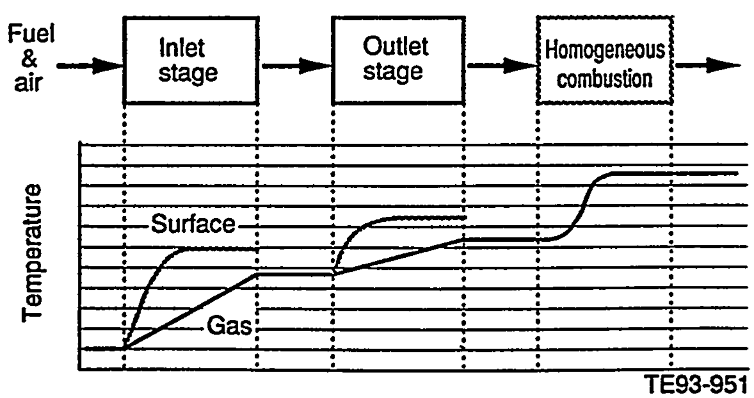

Figure 4-2. Schematic diagram of Catalytica's multistage design approach.

specific (proprietary) catalyst composition. Additional stages may be required to achieve the required catalyst outlet temperatures, however, this was not necessary for the ATS operating conditions. This partially combusted fuel air mixture then enters a post catalyst zone where it spontaneously combusts to complete the reaction and yield the necessary outlet temperature. As a result, the thermally sensitive catalyst substrate does not reach the maximum obtained temperatures. This allows for the use of a metal substrate, which combined with limited temperature gradients, will improve the durability of the catalytically enhanced combustion system.

Catalytica designed and fabricated a catalyst to operate near ATS conditions, and bench tested a 5 cm (2 in.) diameter catalyst in their test facility (see Figure 4-3). The test conditions in the Catalytica reactor were designed to approximate mass flux, catalyst inlet temperature, and combustor exit temperature expected in the Allison ATS machine at full load.

One of Catalytica's first tasks was to specify the required catalyst outlet gas temperature. Catalytica has dedicated a significant effort over the past several years to develop an understanding of the homogeneous combustion reactions that occur immediately downstream of the catalyst. The resulting mathematical models provide estimates of the reaction time required to initiate homogeneous methane combustion in the post-catalyst region and to complete the oxidation of residual carbon monoxide. The model has been refined using in-house measurements such as ignition delay time and CO burnout times under a variety of experimental conditions. It has proven to be especially useful in estimating the outlet gas temperature that must be generated by the catalyst in order to achieve full combustion and emissions burnout within the residence time available. Catalytica has determined that the adiabatic combustion temperature (i.e., equilibrium temperature of a gas given the global fuel-air ratio of the mixture neglecting heat transfer from the reacted products) does not have a large impact on the predicted or measured ignition delay time.

Catalysts were evaluated in the Catalytica test rig (recall Figure 4-3). Several catalysts were designed, prepared, and tested to develop a reactor that would attain the desired balance between the need for the high temperatures to achieve complete combustion with low emissions and the need for low temperatures to preserve the stability of the catalyst.

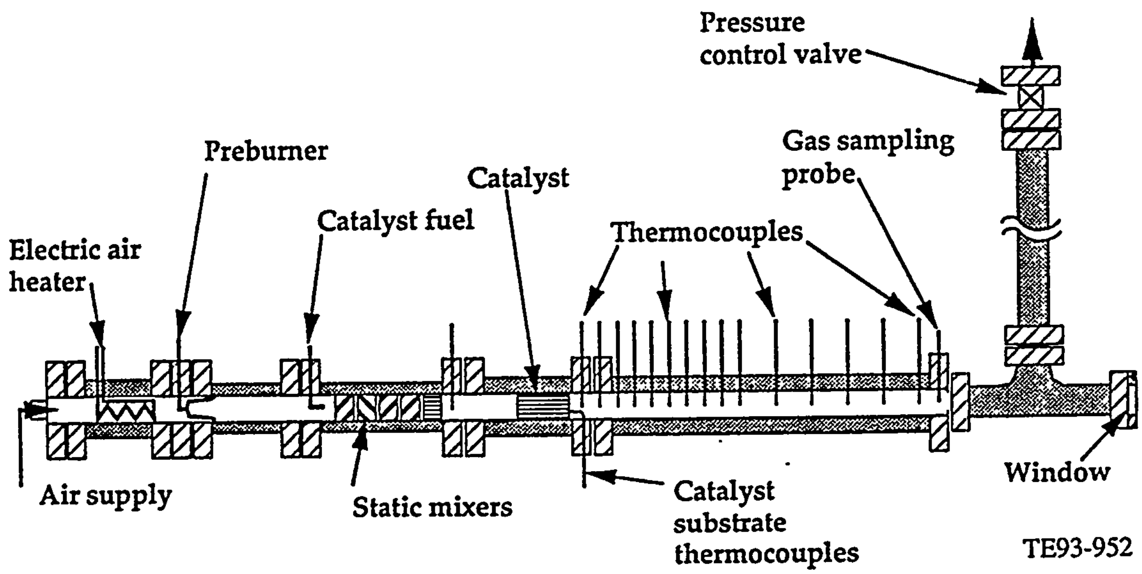

Figure 4-3. Schematic diagram of Catalytica test reactor.

The chosen catalyst design was bench tested by Catalytica. Test consisted of premixing a preheated fuel-air mixture upstream of the catalyst to evaluate the emission performance at conditions representative of ATS engine operation. The catalyst was evaluated at two pressures (13.5 and 20 atm), while maintaining the same outlet temperature.

In addition to evaluating the emissions levels at full power, Catalytica also determined the "operating window" for off load points. The boundaries of the operating window are determined by two constraints on the linear velocity of the gas flowing through the reactor. First, the velocity must be high enough to keep the internal catalyst temperatures below a maximum value of approximately 1000°C (1830°F). Second, the velocity must be low enough to provide sufficient residence time to completely burn the fuel and the residual CO within the combustor volume.

The load cycle data show that the combustor outlet temperature decreases as the power is turned down. If the velocity through the catalyst is kept constant while the combustor outlet temperature decreases (with decreasing load), CO emissions will rise when the reactor drops below the operating window. To maintain low emissions at low combustor exit temperatures, the air velocity throughout the catalyst can be reduced by diverting a portion of the air to bypass the combustion section. This adjustment has two beneficial effects in keeping the catalyst within its operation window: (1) it decreases the gas velocity and (2) it increases the fuel/air ratio in the reactor (and thus, the outlet temperature) since all the fuel still passes through the catalyst.

For the initial testing, the minimum combustion temperature, Tad, (for CO burnout) was assumed to be 1150°C. To determine the operating window, the appropriate properties (fuel and airflow rates, pressure, etc) were set for a given power condition, while the inlet temperature to the catalyst was varied through the use of an electric preheater. The initial value was set as the maximum allowable inlet catalyst temperature with the criteria being that the catalyst wall temperatures must not go above 1000°C. The preheat was then lowered in steps and the CO emissions were measured.

The measured inlet temperature windows for the three different airflows and three different Tad's are shown in Figure 4-4. At any particular Tad, an operating condition of catalyst airflow and inlet temperature that falls within the indicated region of the plot will provide low emissions and an acceptable catalyst temperature.

Figure 4-4 reflects the trade-offs involved in defining an optimal cycle. A low inlet gas temperature will minimize the preburner duty and thus will minimize the NOx emissions produced by the preburner. On the other hand, operating at low inlet gas temperatures necessitates a relatively high Tad in the catalyst in order to achieve low CO emissions under part load conditions. This in turn implies high bleed levels and lower efficiency. The design of an optimal operating cycle will balance the preburner temperature and catalyst activity to achieve the best overall emission signature.

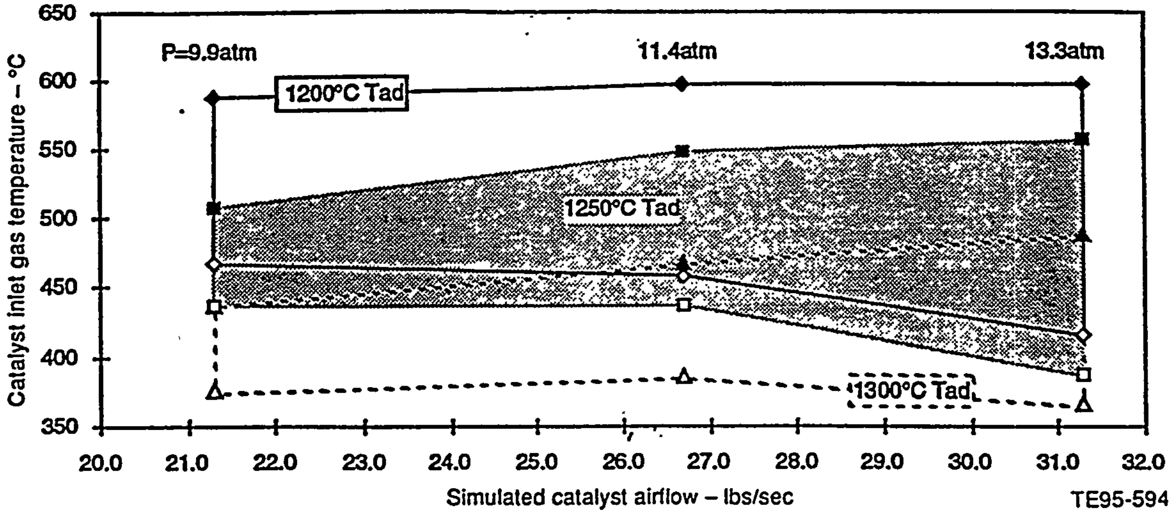

Figure 4-4. Operating windows for different fuel/air ratios in the reactor.

V. COMBUSTOR TO TURBINE TRANSITION DESIGN

As mentioned earlier, the ATS combustor is configured as a single-silo type that is mounted on an axis perpendicular to the centerline of the engine. Although this configuration has considerable flexibility for emission control, the engine airflow must be routed from the annular compressor discharge flow field along the engine centerline, to the off-axis combustor, and then back into the annular flow path along the engine centerline to the turbine. The latter is especially critical to design properly to maintain flow and temperature uniformity into the turbine. Two design iterations have been completed to define the combustor to turbine transition geometry. Figure 5-1 shows the grids for the two designs. These grids represent one-half the flow path because of the combustor centerline axis of symmetry and were used for computational fluid dynamics (CFD) analysis.

The baseline design located the combustor directly above and centered over the turbine distribution annulus with a relatively short combustor exit convergence. The refined design featured a longer combustor exit convergence which protrudes into the combustor discharge flow. A three-dimensional, fully viscous CFD solution was obtained for the two transition designs. The analysis code used for the CFD calculations is a modified version of the NASA Ames Research Center state-of-the-art code OVERFLOW. OVERFLOW is a proven flow code that has undergone extensive code validation. It was initially developed at NASA to handle difficult 3-D problems such as the Space Shuttle and fighter store separation that could not be handled by any other analysis tool. The analysis allows a complex flow field to be decomposed into distinct domains that are solved on individual grids that communicate by interpolation or direct transfer of boundary data. With this approach, the transition piece was decomposed into four regions, and a grid capable of resolving critical flow details was generated for each region. These were combined into a composite mesh and the flow field for the entire transition piece was calculated.

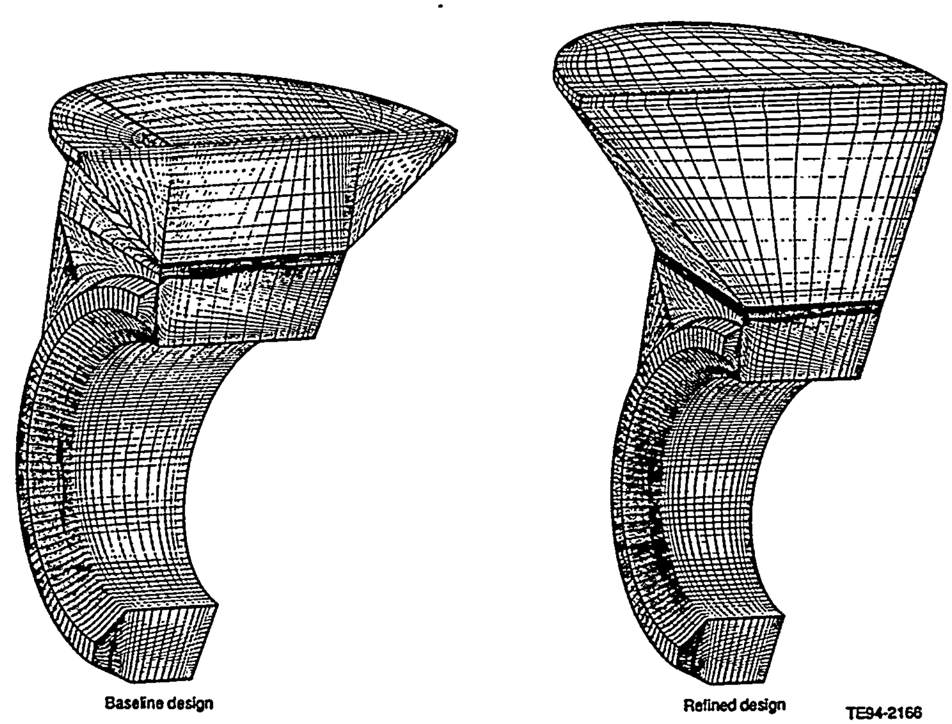

Figure 5-1. Combustor exit to turbine inlet transition grid used for CFD analysis.

The flow solver calculated a fully viscous steady state solution of the Reynolds averaged Navier-Stokes equations with the turbulent viscosity approximated using the 1-equation Baldwin/Barth turbulence model. The equations are solved using an implicit method based on the Beam and Warming algorithm. At all solid surfaces, a no-slip velocity condition was specified. For these first two designs, an adiabatic condition for temperature was enforced with the static pressure extrapolated to the surface. At the inlet to the transition piece, total pressure and total temperature were specified.

Both designs have similar mass flow distributions into the turbine, but the refined design has a better temperature distribution into the turbine. The baseline design produced an unfavorable temperature gradient. At this position, the baseline design generated a hub hot temperature profile that creates high stresses in the rotating turbine airfoils and would lead to premature turbine failure. The revised design is better as it produces a nearly uniform temperature profile across the turbine inlet annulus. The refined design produces a relatively flat profile at all turbine inlet circumferential positions.