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(Statement A)

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DESIGN, FABRICATION AND TEST OF A FULL SCALE COPPER TUBULAR COMBUSTION CHAMBER

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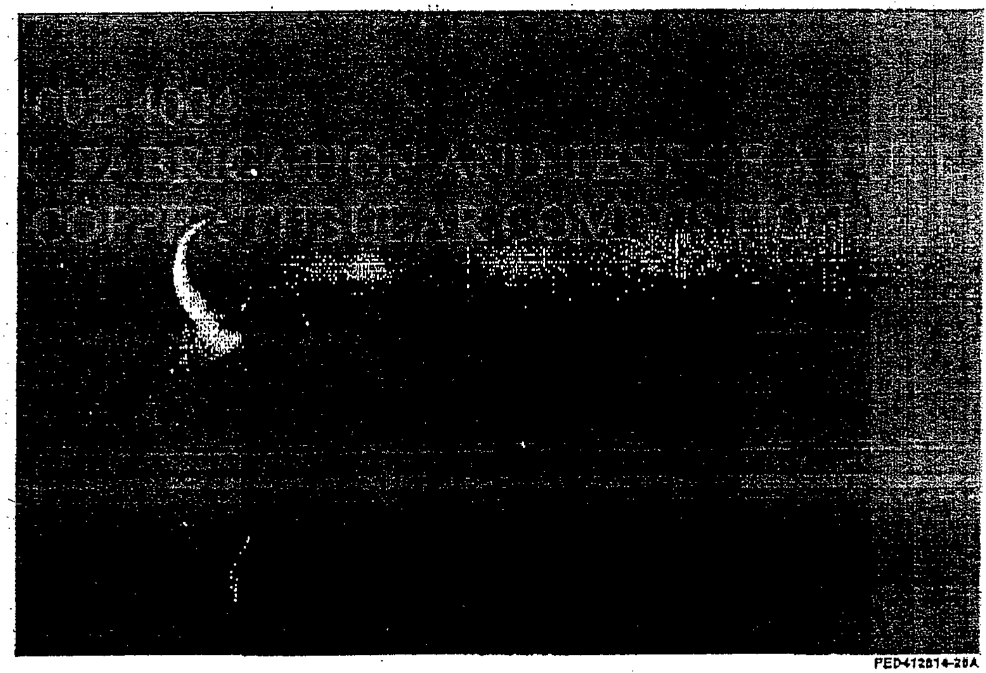

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ABSTRACT

This paper presents the design, fabrication, and test of a full-scale copper tubular combustion chamber as an enabling technology for future application in a high-thrust upper-stage expander-cycle engine. The advanced expander combustor (AEC) was developed by Pratt & Whitney Space Propulsion under contract with the United States Air Force Research Laboratory (AFRL) to support the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) initiative. The AEC copper tubular design combines high material thermal conductivity and large effective surface area in a structurally compliant coolant channel configuration to achieve significant heat pick-up from the combustion gases to the coolant. AEC hot fire test data analysis confirmed the ability to achieve high trust in an expander-cycle engine using a copper tubular construction. Heat transfer enhancement resulting from the tubular chamber liner construction was shown to be in the range of 29 to 46 percent at typical operating conditions compared to a smooth wall copper liner design. The technology developed during the AEC fabrication and test program is currently being used by Pratt & Whitney (P&W) in the development of the RL60, a high-performance 60,000-lb thrust expander-cycle engine.

INTRODUCTION

The U.S. Air Force, U.S. Army, U.S. Navy, and NASA have implemented a three-phase, 15-year rocket propulsion technology improvement effort to *double rocket propulsion technology by the year 2010*. The IHPRPT initiative, establishes performance, reliability, and cost improvement goals for each of the three phases. These goals are to be met by advancing component technology levels through design, development, and demonstration. P&W Space Propulsion, under contract to the U.S. Air Force Research Laboratory (Contract F04611-95-C-0123), developed and tested the AEC combustion chamber at their West Palm Beach facility to support these objectives.

An expander-cycle rocket engine (Figure 1) cools the chamber/nozzle components with the engine fuel flow. The turbopumps are powered with the energy picked up by the cooling process. The relatively low turbine inlet temperatures created by this cycle result in weight, cost, and reliability advantages over other cycles (i.e., gas generator, staged combustion). Expander-cycle engines have lower turbopump pressure requirements than staged combustion engines and higher performance potential than gas generator cycles. To attain the highest thrust in the smallest dimensional envelope, the combustion chamber heat pickup must be maximized.

The current family of expander engines is limited by the fuel pump discharge pressure, which is in turn limited by the heat pickup capacity of the combustor and nozzle cooling tubes. The highest performance RL10 model operates at a chamber pressure of 640 psi (44 bar) using a steel tube chamber. Increases in thermal conductivity and heat load capacity per unit area are essential to provide the energy necessary for higher turbopump output, chamber pressure, and thrust, in the advanced expander cycle. Until recently, no significant improvement in chamber tube thermal conductivity was available without an unacceptable sacrifice in material properties such as strength, low-cycle fatigue (LCF) characteristics, and oxidation/ erosion capability. The development of PWA1177 dispersion-strengthened copper addressed this unacceptable tradeoff. This proprietary material, manufactured in tubular form for this application, provides high strength, high thermal conductivity and excellent oxidation resistance. The AEC used PWA1177 in its chamber design to provide the increased heat transfer and resultant energy necessary to support the high thrust required to meet IHPRPT goals.

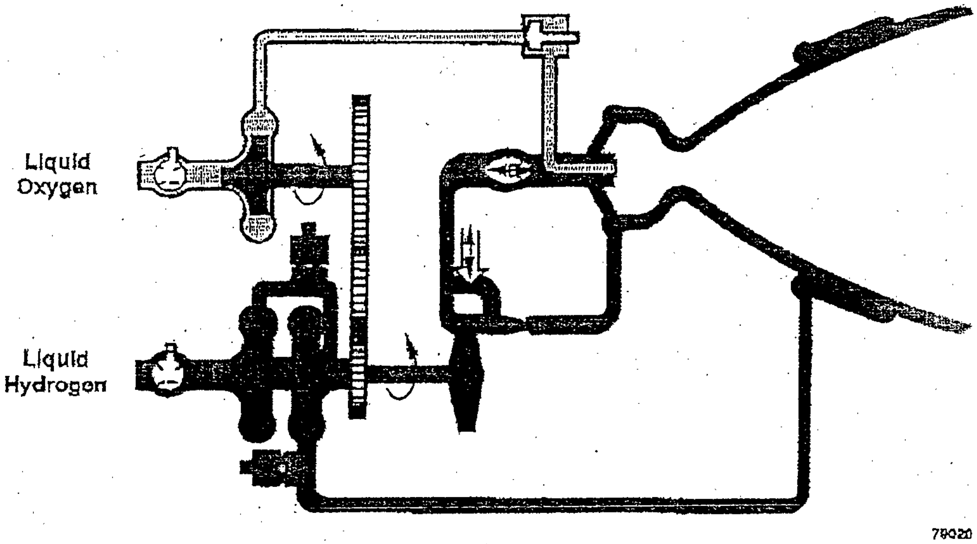


Figure 1- RL10 Expander Cycle Engine Schematic

The goal of the AEC program was the demonstration of a full-size copper tubular liner chamber to confirm the ability to provide high heat transfer in a high chamber pressure expander cycle engine application. This proof-of-concept demonstration also verifies the basic manufacturability of such a chamber and provides the heat transfer data needed for the chamber design in high-performance expander engines, such as the RL60 which is currently in development at P&W (Reference 1).

Subscale chambers with copper tubular liners were successfully tested at NASA about 10 years ago (References 2 through 4). That work was focused mainly on liner design and construction, and cyclic life testing under representative chamber conditions. A series of tests was run at 600 psi (41 bar) chamber pressure and a MR of 6.0, demonstrating compliant chamber operation and providing valuable copper tubular liner life data. The test specimens were small diameter (2.60 in./66 mm) cylindrical chambers using 72 OHFC copper tubes of constant cross-section. Unfortunately, heat transfer data was not reported and hence the level of heat transfer enhancement for a copper tubular liner was unconfirmed until AEC testing.

The main design features of the AEC were reported in References 5 and 6. This chamber resembles the RL10 chamber, having the same hot gas side contour but featuring PWA1177 high-strength, high-conductivity copper alloy tubes of varying cross-section. This paper describes the chamber design and construction, and discusses the results of a hot-fire test of the AEC that demonstrated the feasibility of the design and the heat transfer enhancement needed for high-pressure expander-cycle engine operation.

AEC DESIGN AND FABRICATION

The AEC design, shown in Figure 2, incorporated performance and life enhancing design features needed for a high performance expander cycle engine combustor. The chamber design was a proof of concept and was not intended to represent a production design. The requirements established for the AEC design are provided in Table 1.

Table 1 – AEC Design Requirements

Chamber Mixture Ratio 6.11	Chamber Coolant Q, Btu/sec 22,833
Throat Area, in**2 19.09	Chamber Length, in 26.0
Chamber Pressure, psia 1375	Chamber Contraction Ratio 4.65
Combustion C* Efficiency 0.99	

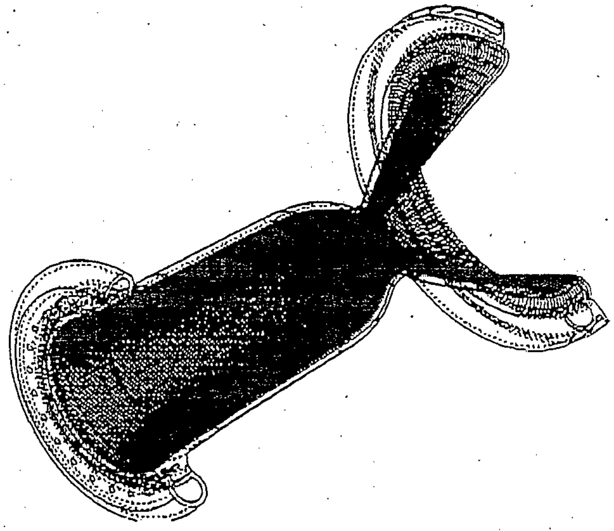


Figure 2 – AEC Design Features

Figure 3 shows a cross-section of the chamber highlighting some of the design details. The AEC chamber was configured with 180 tapered tubes. PWA1177 dispersion strengthened copper was used for its high thermal conductivity and high strength with exceptional oxidation resistance. The AEC tubular configuration provided approximately 40 percent more exposed surface area than a typical flat wall liner of equal contour. Of equally significant benefit, the tubular geometry provides a structurally-compliant coolant pressure vessel that allows free expansion of the tube wall and a better distribution of strains. This results in high design life margins and would be expected to be a significant cost and schedule benefit in any future development programs that require multiple firings.

The outer jacket of the AEC tube bundle consisted of an electroform copper closeout of the tube crowns followed by an electroform nickel structural jacket. This manufacturing process has been used industry-wide in many different chamber designs. The primary benefits of this plating process were maximum exposed tube surface area to combustion gases and low processing temperatures during application.

The chamber tube ends were individually sealed to stainless steel inlet and exit manifolds using a low temperature braze process. Figures 4 and 5 show photographs of the chamber tube bundle prior to brazing, and after electroforming the tube crown closeout, respectively.

The AEC rig included a bolted, tangential swirl injector. Tangential swirl elements were selected to provide a high degree of gaseous fuel and liquid oxidizer atomization, vaporization, and mixing. Combustion efficiency was verified to be over the 99 percent requirement during hot-fire testing. A high-pressure gaseous oxygen and hydrogen torch ignitor was used for this ground test application. The injector outer row LOX elements were scarfed 15 degrees to reduce the local oxidizer-to-fuel ratio near the injector face. This was provided as risk mitigation for the chamber wall in this region of high heat flux.

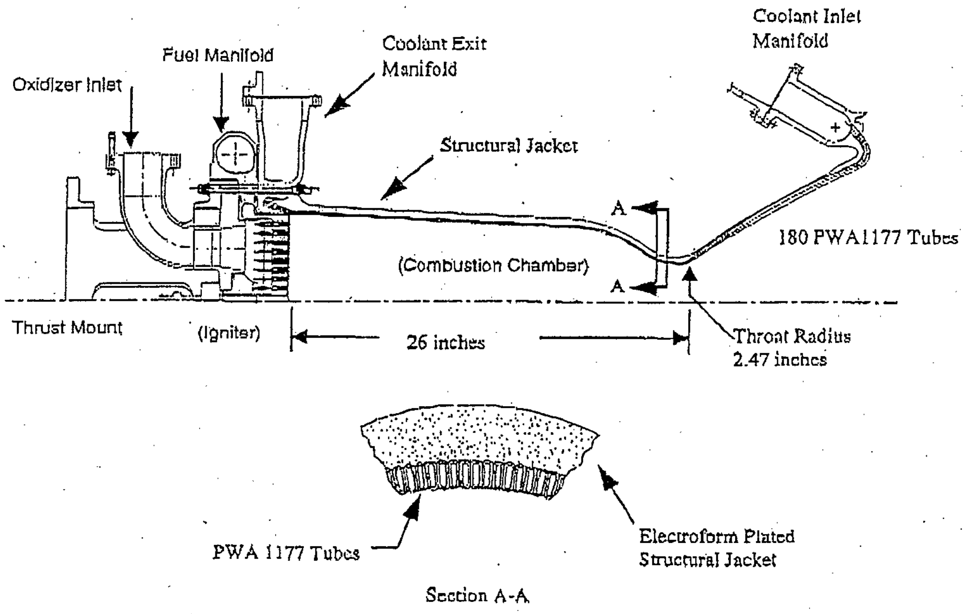


Figure 3– AEC Design Details

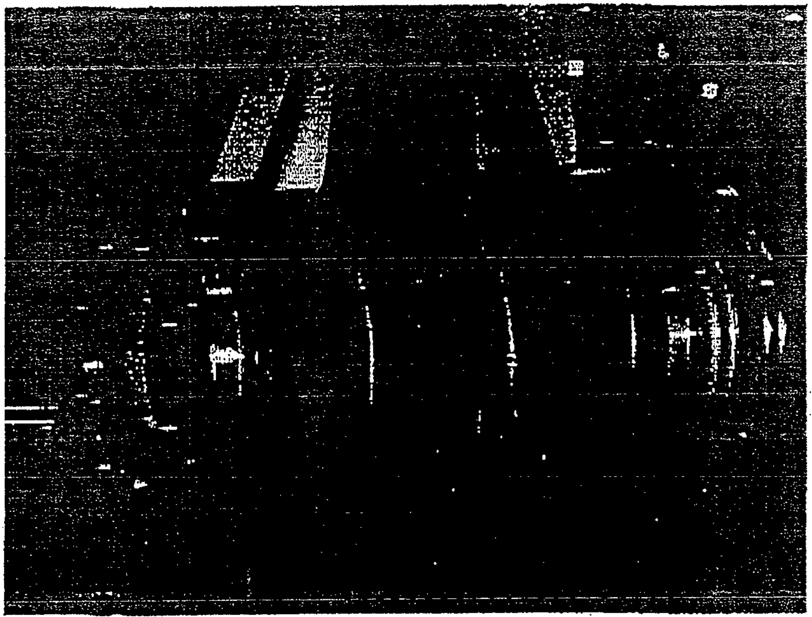


Figure 4 – Assembled Copper Tube bundle Prior to Braze

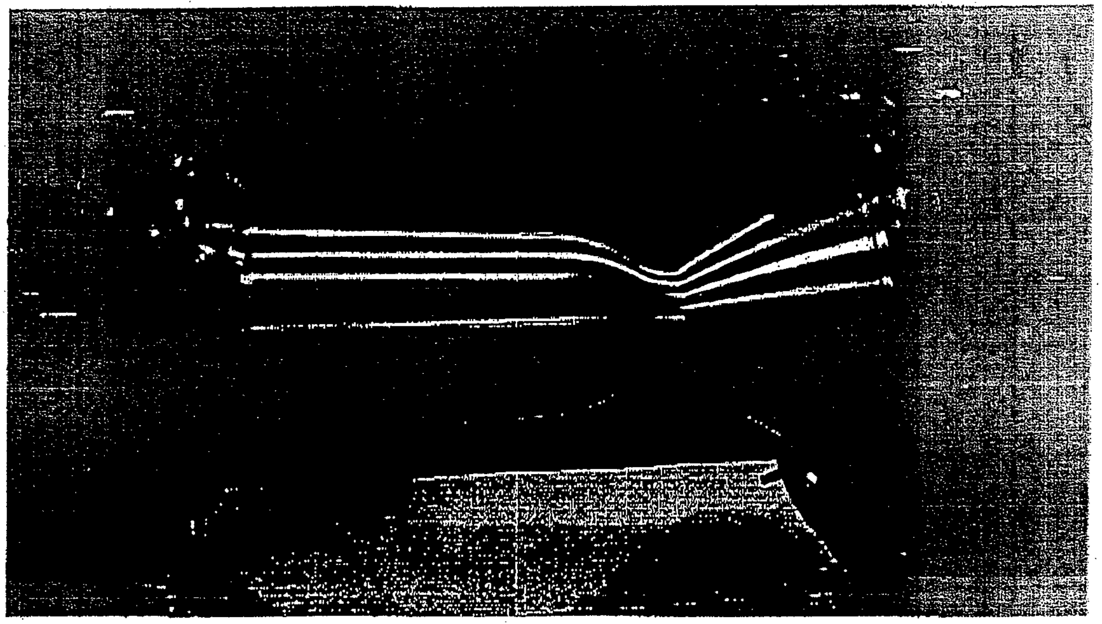


Figure 5 - AEC Following Tube Crown Closeout

Pressure and temperature instrumentation was incorporated into the AEC rig design to ensure precise combustion efficiency, pressure drop and heat load measurements. Figure 6 is a schematic representation of the measurements that were recorded during the hot fire test. Extensive facility propellant supply measurements were also recorded to ensure interface propellant and coolant conditions were achieved.

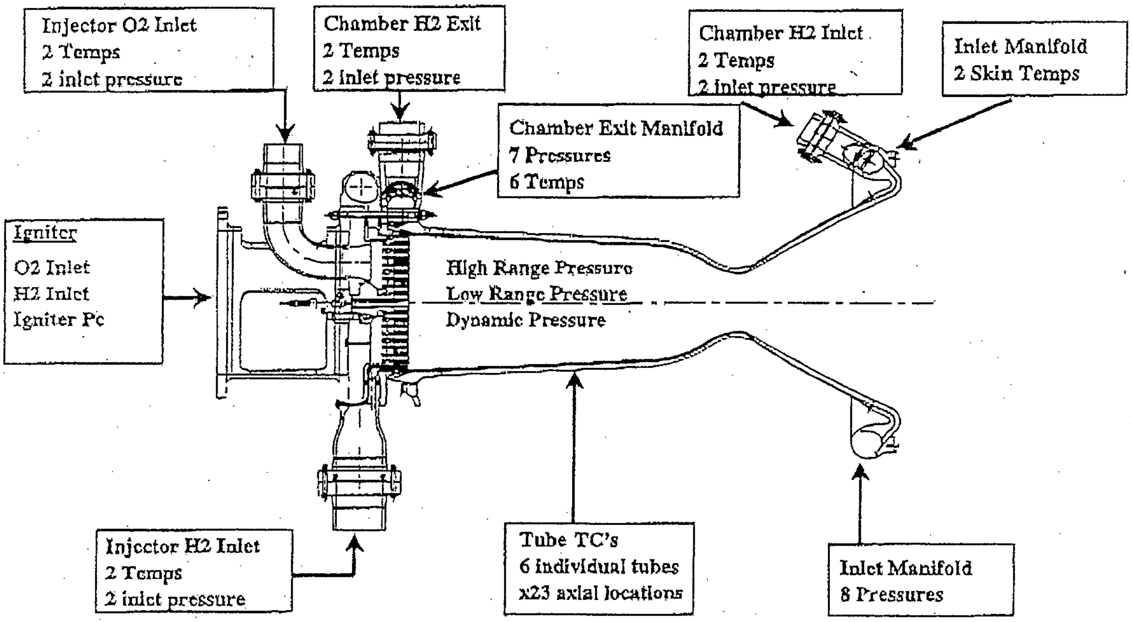


Figure 6 – AEC Instrumentation

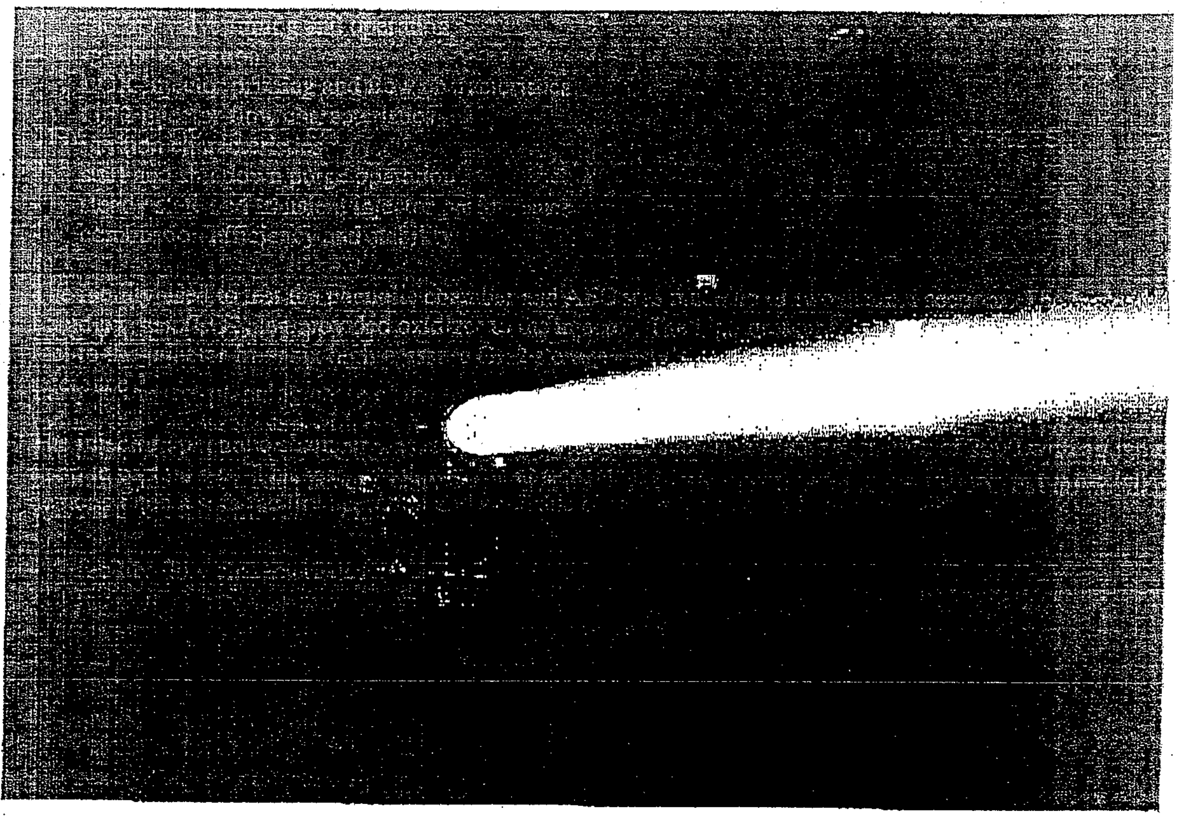
AEC VALIDATION TESTING

Early in the test-planning phase of the program, AFRL and Pratt & Whitney developed a mitigation strategy to reduce the risk associated with hot firing the AEC at the new test facility using an injector with no accumulated hot fire time. Risk mitigation included an expendable phenolic chamber to test fire the injector and facility before mounting the AEC. The phenolic chamber, which had a similar contraction ratio as the AEC but no cooling circuit, was used to verify the following:

- facility flow characteristics
- facility valve timing and operation
- ignitor operation
- LOX injector priming and flow characteristics
- GH2 injector flow characteristics
- ignition characteristics
- start and shutdown purge operation
- steady state and transient injector performance
- combustion efficiency and stability

The facility used to test the phenolic chamber and AEC was made up of two distinct sections. The high pressure liquid oxygen (LO2) leg provided oxidizer to the injector. The high pressure gaseous hydrogen (GH2) leg provided fuel to the injector from six high pressure GH2 storage vessels. For a more detailed description of this system, see reference 3.

The injector / phenolic chamber was successfully tested, as shown in Figure 8, in July of 2000 with an ignition and ramp to part power. This test, which was run at a chamber pressure of 420 psi and a MR of approximately 3.5, demonstrated a safe facility operation and a reliable chamber ignition and run sequence.



Information from the phenolic chamber test was used to calibrate the transient math model in preparation for hot firing of the AEC. High-response pressure transducers in the chamber showed stable combustion at all power levels while the tangential swirl injector provided characteristic velocity efficiency (C*) in excess of 99%.

AEC TEST RESULTS

Manufacturing nonconformances and repairs made to the chamber raised durability issues and ultimately limited the maximum chamber pressure that could be achieved during testing. Obtaining the heat transfer data for future expander cycle development was the key objective of the AEC test. Therefore, the decision was made to run at part power conditions in order to increase the probability of obtaining useful heat transfer and pressure drop test data and to lower the overall technical risk to the hardware. A full duration test was conducted on July 12, 2001, and the necessary data was obtained and analyzed. A second test was not considered a reasonable investment of further funds due to the combination of hardware distress experienced on the chamber, budget constraints, and the fact that a similar chamber was already under construction for the RL60 program. Figure 9 shows the AEC mounted on E-8 stand.

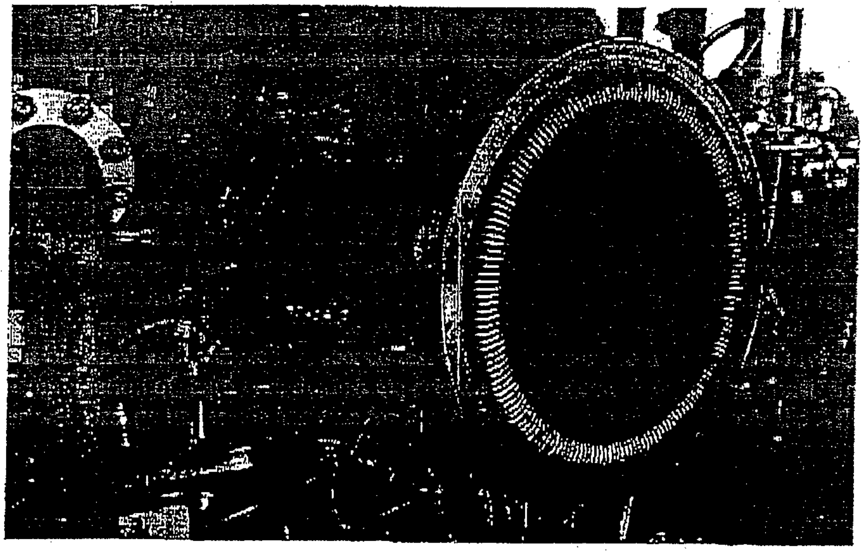


Figure 9 - Advanced Expander Combustion Chamber on Pratt & Whitney's E-8 Test Stand

The AEC copper tubular chamber was successfully tested, as shown in Figure 10, in July of 2001 with an ignition and ramp to part power.

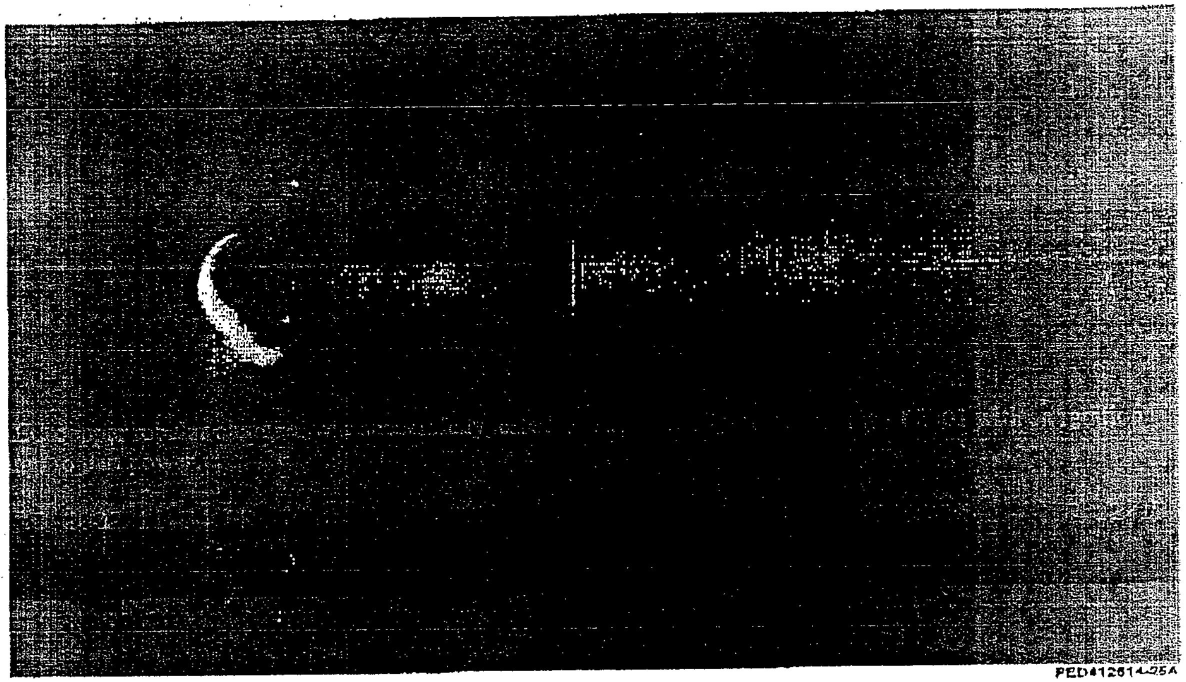


Figure 10 - AEC Hot Fire

The AEC start was similar to the phenolic chamber test start procedure with the addition of the LH2 coolant system. The LH2 tank was pressurized during the transition from cooldown to engine start. Coolant flow was introduced into the tubes just prior to chamber ignition. The cooling flow, which was held constant during the entire run, was shutoff during the shutdown sequence just after GH2 cutoff to the fuel injector. The test ran for its full planned duration of 13 seconds. The steady state test conditions achieved were Pc = 507 psi (35 bar) and MR = 3.6. These test conditions were below the intended run conditions of Pc = 680 psi (47 bar) and MR=5.3 due to overboard LOX leakage in a facility pressure relief device.

Test results, as shown in Figure 11, showed higher than predicted heat transfer. The predicted heat transfer enhancement for the tubular construction vs. a smooth wall construction was 16 percent. Data from the AEC test shows the tubular wall construction provided heat transfer enhancement approximately 38 percent higher than the heat transfer from a smooth channel wall chamber.

Because of the lower than expected mixture ratio a study was conducted to determine the effect of mixture ratio on heat transfer, so that the AEC test data could be extrapolated to higher mixture ratios. RL10 historical data provided confirmation that the analytical code used to predict mixture ratio vs. heat load was valid in the range of the AEC data point and could be used to extrapolate to higher mixture ratios. Limited data from previous testing on a 25K milled channel copper chamber combined with industry literature suggests that the mixture ratio effect curve is shallower than what the analytical code anchored to RL10 data represents. Using the AEC data point and accounting for the uncertainty of mixture ratio effects, the range of possible heat transfer enhancement for the tubular construction vs. a smooth wall construction is between 29% and 46%. This amount of heat transfer enhancement exceeds the requirements for a 50K cycle.

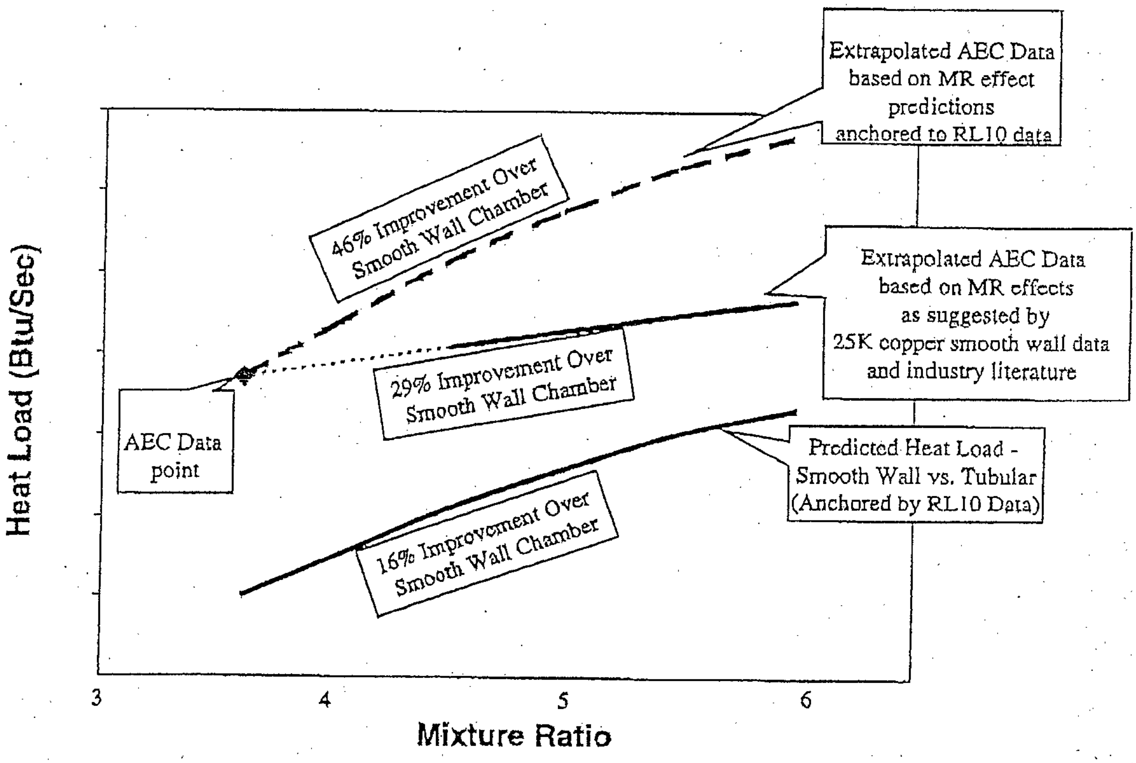


Figure 11 - AEC Hot Fire Test Results:
Heat Load vs. Mixture Ratio

COPPER TUBULAR CHAMBER TECHNOLOGY APPLIED TO RL60 DEMONSTRATOR ENGINE

The lessons learned from the AEC design, fabrication and hot firing are currently being applied in the design and development of the RL60, a 60,000 lb thrust upper stage expander cycle engine. The RL60 is the first development engine application of a full scale copper tubular combustion chamber. The RL60 chamber tubes recently completed fabrication at LeFiell Manufacturing Company in Santa Fe Springs, California. See Figure 12.

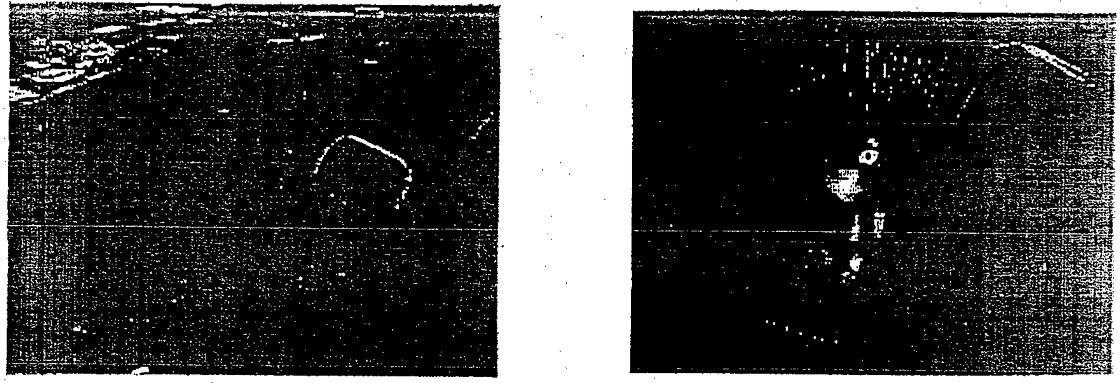


Figure 12. RL60 Chamber Tube Stack

The RL60 chamber assembly has been initiated. New structural jacket and tube joining processes are being incorporated into the design based on AEC lessons learned to minimize brazed assembly requirements and improve overall reliability and producibility. Chamber component testing is currently scheduled in early 2003, and will be followed by demonstrator engine testing.

In addition to the copper tubular chamber, RL60 engine configuration includes a flat face injector design, a low pressure direct spark ignition system, a regeneratively cooled nozzle section and a radiation cooled nozzle extension. Thrust chamber assembly component fabrications are in process. The RL60 injector is being mounted for hot fire testing using an ablative chamber in May 2002.

SUMMARY AND CONCLUSION

The AEC fabrication and test accomplished many of the defined IHPRPT goals. A tapered chamber tube was designed and manufactured by P&W and LeFiell Manufacturing Company using PWA1177 copper alloy. The measured heat pick-up resulting from the use of PWA1177 copper alloy in the AEC tubular construction was approximately 38 percent greater than that predicted for a similar flat wall geometry milled-channel construction. Test results showed that the effective surface area of the tubes was considerably higher than originally predicted. This resulted from a manufacturing approach that enabled a large amount of tube surface area to be exposed to the hot gas. Coolant system pressure drop was also characterized during the test and the measured pressure drop exceeded predictions due to the higher than expected heat transfer.

Testing of this first-ever, full-scale copper tubular thrust chamber was considered a major success in that it confirmed the large increase in heat transfer enabled by the tubular geometry. This in turn validated feasibility of the expander cycle well beyond the 50k lb thrust category. The high predicted chamber life for a tubular geometry, combined with the high heat transfer demonstrated within the AEC program ensures the ability to produce a reliable, high-thrust expander-cycle engine. Advancements in fabrication techniques and lessons learned during the AEC program provide the foundation for a highly producible, low-cost, high-impulse engine configuration for future upperstage propulsion applications. P&W is currently developing a 60k lb thrust combustion chamber based on the AEC, and is incorporating new fabrication technologies that address the lessons learned in the AEC program. This chamber, being developed as part of the RL60 engine program, will use production-type materials and fabrication technologies, and will demonstrate the performance and operability characteristics of the chamber at a range of operating conditions (P_c and MR) that supports a full-scale engine demonstration. This chamber will also be integrated into the RL60 demonstrator engine for a full-scale engine test at operating conditions equivalent to 60k lb of thrust.

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REFERENCES:

1. Bullock, J.R., Popp, M., and Santiago, J., "Development Status of the Pratt & Whitney RL60 Engine", Paper S10.2, AAAF 2002 Symposium on Propulsion for Space Transportation of the XXIst Century, Versailles, France, May 2002.

2. Kazaroff, J.M., and Pavli, A.J., "Advanced Tube-Bundle Rocket Thrust Chamber", AIAA 90-2726, 26th Joint Propulsion Conference, Orlando, FL, 1990.

3. Cooley, C., Fentress, S., Jennings, T., "Hot Firing of a Full Scale Copper Tubular Combustion Chamber", AAAF 2002-S.18.02, 6th International Symposium Propulsion for Space Transportation of the XXIst Century, Versailles, France, May 2002.

4. Kazaroff, J.M., Jankovsky, R.S., and Pavli, A.J., "Hot Fire Test Results of Subscale Tubular Combustion Chambers", NASA Technical Paper 3222, November 1992.

5. Jankovsky, R.S., Arya, V.K., Kazaroff, J.M., and Halford, G.R., "Structurally Compliant Rocket Engine Combustion Chamber - Experimental and Analytical Validation", Journal of Spacecraft and Rockets, Vol. 32, No. 4, July 1995.

6. Peery, S., and Minick, A., "Design and Development of an Advanced Expander Combustor", AIAA-98-3675, 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 1998.

7. Jennings, T., Fentress, S., Lyda, R. "Fabrication and Test of an Advanced Expander Combustor", AIAA-2000-3776, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, AL, July 2000.