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ADVANCED EXPANDER TEST BED PROGRAM

FINAL ANNUAL TECHNICAL PROGRESS REPORT

Pratt & Whitney
Government Engines & Space Propulsion
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16. Abstract

The Advanced Expander Test Bed (AETB) is a key element in NASA's Exploration Technology Program for development and demonstration of expander cycle oxygen/hydrogen engine technology component technology for the next space engine. The AETB will be used to validate the high-pressure expander cycle concept, investigate system interactions, and conduct investigations of advanced mission focused components and new health monitoring techniques. The split-expander cycle AETB will operate at combustion chamber pressures up to 1200 psia with propellant flow rates equivalent to 20,000 lbf vacuum thrust.

Work under the contract began 27 April 1990. Effort during 1990 focused on: (1) definition of the key methodologies to be applied to the test bed design and to be verified as part of the AETB program, (2) developement of transient and steady state AETB models, and (3) preparation of the AETB preliminary design.

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CONTENTS

SECTION I
INTRODUCTION

Mission studies at NASA have identified the need for a new Space Transfer Vehicle (STV) Propulsion System. The new system will be an oxygen/hydrogen expander cycle engine and must achieve high performance through efficient combustion, high combustion pressure, and high area ratio exhaust nozzle expansion. The engine should feature a high degree of versatility in terms of throttleability, operation over a wide range of mixture ratios, autogenous pressurization, in-flight engine cooldown, and propellant settling. Firm engine requirements include long life, man-rating, reusability, space-basing, and fault tolerant operation.

The Advanced Expander Test Bed (AETB) is a key element in NASA's Chemical Transfer Propulsion Program for development and demonstration of expander cycle oxygen/hydrogen engine technology component technology for the next space engine. The AETB will be used to validate the high-pressure expander cycle concept, investigate system interactions, and conduct investigations of advanced mission focused components and new health monitoring techniques. The split-expander cycle AETB will operate at combustion chamber pressures up to 1200 psia with propellant flow rates equivalent to 20,000 lbf vacuum thrust. The requirements are summarized in Table 1.

TABLE 1. — ADVANCED EXPANDER TEST BED REQUIREMENTS

Propellants	Oxygen/Hydrogen
Cycle	Expander
Thrust	> 7500 lb (20,000 lb Selected)
Pressure	Nominal 1200 psia
Mixture Ratio	6.0 ± 1.0 (Optional Operation at 12.0)
Throttling	20% Min (5% Desirable)
Propellant Inlet Conditions	
Hydrogen	38°R, 70 psia
Oxygen	163°R, 70 psia
Idle Modes	Tankhead (Nonrotating Pumps) Pumped (Low-NPSH Pumping)
Life	100 Starts 2 hr (5 hr Desirable)

The program is divided into eight tasks, totalling 60 months. A 9-month preliminary design (Task 3.0) will be followed by a 6-month final design (Task 4.0). The AETB will be fabricated, assembled, and acceptance tested at Pratt & Whitney (P&W). AETB delivery to NASA-Lewis Research Center (NASA-LeRC) is planned 40 months after contract start. The bulk of the testing will be conducted at NASA-LeRC after delivery. Work began on 27 April 1990. Development and verification of advanced design methods is another goal of the AETB Program. Under Task 2.0, steady-state and transient simulation codes will be produced. These two codes and selected design models will be verified during component and engine acceptance testing. The remaining tasks deal with Program Management (Task 1.0), Fabrication (Task 5.0), Component Tests (Task 6.0), Engine Acceptance (Task 7.0), and NASA Technical Assistance (Task 8.0).

SECTION II
EXECUTIVE SUMMARY

Work under the contract began 27 April 1990. Effort during 1990 focused on: (1) definition of the key methodologies to be applied to the test bed design and to be verified as part of the AETB program, (2) development of transient and steady state AETB models, and (3) preparation of the AETB preliminary design. The program is progressing on schedule, as indicated in Figure 1, and the Preliminary Design Review is scheduled for 29-31 January 1991.

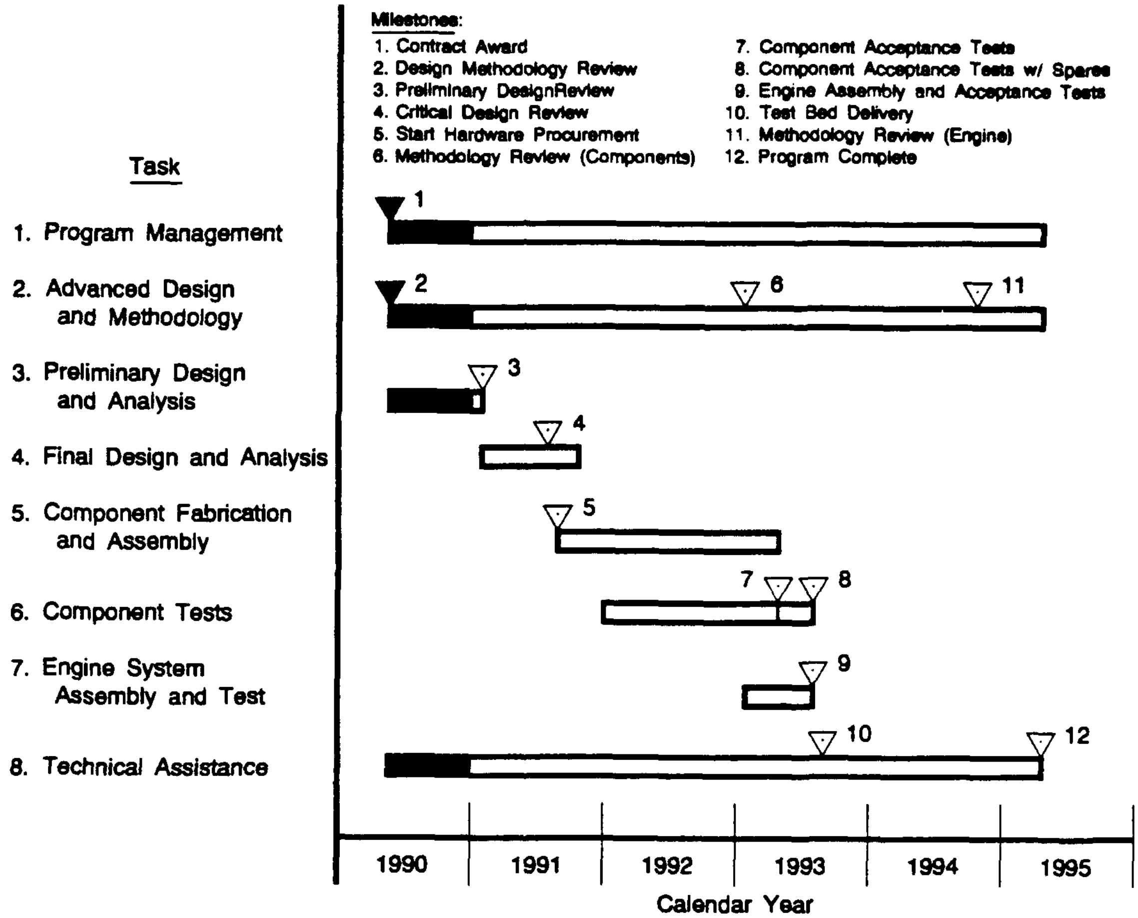

Figure 1. Advanced Expander Test Bed Program Schedule

A. DESIGN METHODOLOGY

The Program Methodology Review was held 12-13 July 1990. The review focused on the design methods and component and engine models that would be employed in the design effort. The review also touched on selection of models for verification later in the contract. The features and applicability of more than 60 computer codes were reviewed. NASA personnel were generally in agreement with the planned methodology with one exception. At their request, a Navier-Stokes three-dimensional analysis of the first-stage fuel pump impeller was substituted for a previously planned computational fluid dynamic (CFD) analysis of the combustion chamber hot gas flow field. At the Preliminary Design Review P&W will recommend a list of critical codes and procedures for verification during AETB component and engine tests.

B. ENGINE SIMULATION MODELS

The AETB steady-state and transient engine models are being built around the Rocket Engine Transient Simulation (ROCETS) system developed under NASA/MSFC Contract NAS8-36994. ROCETS is a highly flexible modular system using real gas properties and sophisticated iteration and integration techniques. It includes software for switching from steady-state to transient predictions. By combining the two decks, changes made to individual modules are automatically incorporated in both prediction modes.

The AETB models are now operational and have been used to generate new cycles. A summary of the updated cycle data is given in Table 2. A preliminary copy of this deck has been provided to the NASA-Lewis Research Center. The transient model has only recently become operational and is still undergoing modifications. It is currently being used to define control system valve and abort requirements.

TABLE 2. — ADVANCED EXPANDER TEST BED CYCLE DATA

	Normal Operating Point	*Uprated Design Point*	*5% Thrust*	*Full Expander Cycle*	*High Mixture Ratio*
Thrust-lbf (Vacuum Equivalent)	20,000	25,000	1,000	16,400	17,000
Chamber Pressure — psia	1,200	1,500	65	980	1,000
Mixture Ratio	6.0	6.0	3.5	6.0	12.0
Nozzle/Chamber Coolant Exit Temperature — R	957	1,020	750	1,000	805
Fuel Pump Speed — rpm	87,700	99,200	18,900	90,000	79,000
Fuel Pump First-Stage Discharge Pressure — psia	1,640	1,920	103	1,840	1,490
Fuel Pump Third-Stage Discharge Pressure — psia	3,500	4,500	251	3,300	2,670
Fuel Turbopump Horsepower	1,670	2,520	22	1,690	966
Oxidizer Pump Speed	42,500	48,900	8,240	38,300	40,100
Oxidizer Pump Discharge Pressure — psia	1,900	2,360	154	1,630	1,500
Oxidizer Turopump Horsepower	348	530	4	296	362

C. ENGINE PRELIMINARY DESIGN

The AETB preliminary design is approximately 90 percent complete as of 31 December 1990. The design is based on five unique features that contribute to its capabilities and flexibility: the split expander cycle, dual orifice injection, a twin-shaft fuel pump, a 25 percent cycle thrust margin, and use of a proven electronic control system.

In the split expander cycle, shown in Figure 2, a portion of the 1st-stage fuel pump discharge flow is routed directly to the injector. The remainder of the fuel passes through the 2nd- and 3rd-stages of the pump to cool the thrust chamber and nozzle as well as to drive the turbopumps. The two fuel streams are mixed prior to injection. The split-expander cycle reduces the energy needed to drive the fuel turbopump. The increase of energy efficiency allows higher combustion chamber pressure to be achieved. An important advantage of the split-expander cycle is that control of the flow split between thrust chamber cooling flow and bypass flow benefits engine throttling and high mixture ratio operation. At reduced thrust or high mixture ratio, the fraction of the fuel passing through the thrust chamber cooling jacket can be increased. This results in lower turbine inlet temperatures and lower thrust chamber wall temperatures. The AETB split expander cycle also has the advantage of being operable as a full expander cycle. The full expander cycle could prove more desirable if only minimal off-design operation were required. The flexibility to conduct tests of both cycles will substantially benefit AETB utility.

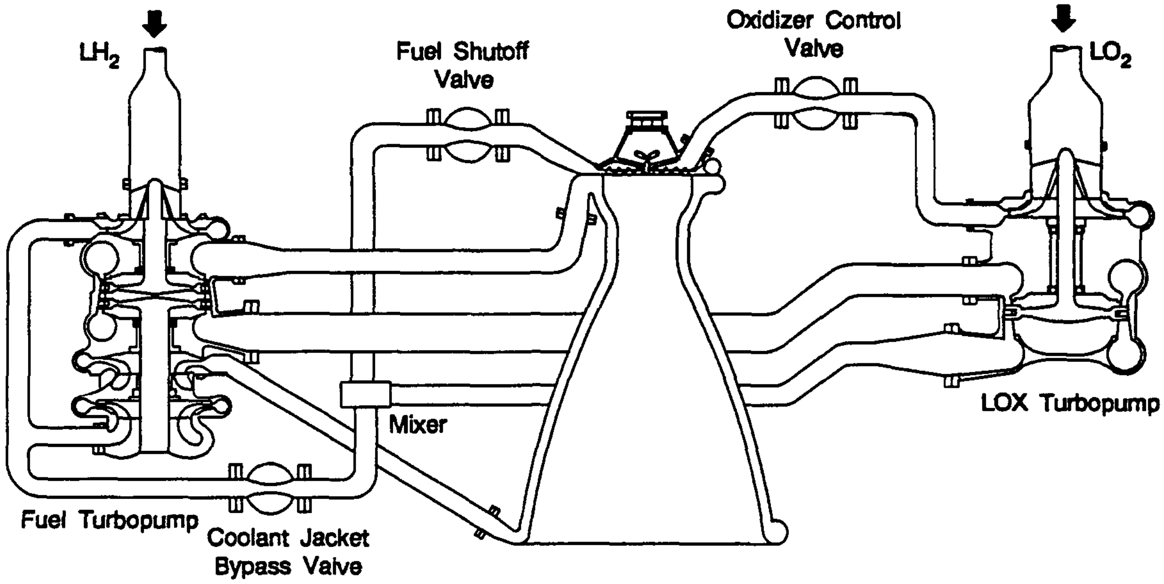

Figure 2. Split Expander Cycle

The AETB injector has 65 dual-orifice tangential entry injection elements. The thrust chamber is 15.0 inches long and has a contraction ratio of 3.0. Nozzle throat area is 8.15 in.^{2}. A zirconium copper alloy thrust chamber cooling jacket with machined cooling passages and 1.5:1 expansion ratio is attached to a 7.5:1 conical nozzle extension. The nozzle extension is conventional tube bundle construction. The design provides total heat transfer equal to a 210:1 cooled nozzle section of the 1000:1 altitude nozzle. This nozzle will provide a convenient means of conducting high-power sea level testing and throttling tests to five percent thrust.

The AETB turbopump design consists of a twin-shaft, three-stage fuel pump and a single-stage oxidizer pump with a single-stage full-admission turbine. This configuration was selected to allow a fuel turbopump speed of 100,000 rpm for high turbopump efficiency while maintaining acceptable rotor-dynamic stability. The fuel turbopump consists of the inducer, 1st-stage impeller, and a single-stage, full-admission turbine mounted on one shaft; and the 2nd- and 3rd-stage impellers and a single-stage, full admission turbine mounted on the second shaft. The two turbines are arranged back-to-back and designed to operate at the same speed at the design point.

The AETB breadboard controller is an electronic rack-mounted system that is a modified version of a controller used in P&W's National Aerospace Plane program. The breadboard controller functions as a full authority controller during pre-run checks, cooldown, start, throttling, steady-state operation, and shutdown. The monitor system is used to simulate the vehicle interface, download programs to the breadboard, control execution, and record and analyze data. A device termed "EMPRESS" (Experimental Multiprocessing Realtime Engine Simulation System) will be used to facilitate control software development and system and engine checkout.

Test bed cycle and component design margin is achieved by designing the engine and components for a higher design point thrust and chamber pressure than the point at which the engine will normally operate. This overdesign will: (1) reduce risk of delays during the brief acceptance phase or failure during normal operation, (2) provide increased component flexibility when test bed components are matched with non-test bed components, and (3) provide an eventual uprated capability if desired.

SECTION III
TECHNICAL PROGRESS

A. TASK 1.0 — PROGRAM MANAGEMENT

The Program Management Task includes program control and administration; reports; travel; meetings; and system safety, reliability, and quality control.

- *Meetings* — Technical Progress Reviews were held each month, beginning with the project kickoff meeting on 9 May 1990. Topics emphasized in these meetings included the electronic control system, engine steady-state and transient models, test stand capabilities, and turbomachinery. The P&W test stands were toured and one monthly meeting served as a design briefing for NASA-LeRC personnel.

  — A Design Methodology Review was held 12-13 June 1990.

  — An AETB Program Review was held 10 July 1990 in Washington DC for NASA Headquarters personnel.

- *Reports* — The following reports were submitted during 1990:

  Monthly Technical Progress Reports .... FR-21318-1 through -7
  Program Work Plan (May, 1990) FR-21306
  Product Assurance Plan (August, 1990) ....FR-21320.

  — The Failure Modes and Effects Analysis was completed. Of the 87 items reviewed, four were classified as Critical 1, i.e., failure could result in a major loss of hardware. The Preliminary Hazards Analysis was also completed, revealing no items identified as catastrophically severe of the 46 items reviewed.

- *Technical Papers* — One technical paper was published and presented at the AIAA Space Programs and Technologies Conference on 26 September 1990 at Huntsville AL (Ref. AIAA 90-3708-CP, "The Advanced Expander Test Bed" by A.I. Masters and W.K. Tabata).

B. TASK 2.0 — DESIGN AND ANALYSIS METHODOLOGY

Under Task 2.0, two computer models, a steady-state and a dynamic simulation of the AETB, will be formulated and delivered to NASA-LeRC. Initially, these models were patterned after the P&W Orbital Transfer Vehicle (OTV) models originally developed in 1980 under Contract NAS8-33567. During the first two months of the AETB contract, P&W examined the feasibility of constructing these engine models using the newly developed ROCETS modeling system. The preliminary evaluation of the ROCETS steady-state model showed comparable results with the baseline program and the transient version showed promising initial results. Based on this early evaluation, it was recommended and accepted by NASA-LeRC that the AETB engine simulation models be delivered in a form compatible with the ROCETS system. In late November 1990 P&W sent NASA-LeRC a preliminary version of the AETB steady-state engine model for familiarization and checkout of the ROCETS system.

1. Methodology Review

In June 1990, the Program Methodology Review was held at P&W and focused on the design methods and component and engine models that would be employed in the design effort. The review also touched on selection of models for verification later in the contract. The features and applicability of more than 60 computer codes were reviewed. A summary of the most pertinent codes and tentative plans for code verification is presented in Appendix A.

2. Steady-State Cycle Analysis

During the preliminary design effort conducted in 1990, the emphasis in the AETB steady-state cycle analysis was concentrated in three major areas. First, the engine simulation model was formulated within the ROCETS system to match the proposal design configuration. Then, preliminary design component performance and estimates of turbopump secondary flows were incorporated into the model; a sensitivity study of the secondary flows impact on the cycle was conducted and considerable effort was expended on minimizing those effects. Finally, an evaluation of designing the AETB as a full expander engine and operating it off-design as a split expander was made. These three major areas of study are discussed further in the following paragraphs.

Rocket Engine Transient Simulation (ROCETS) is a new system developed by P&W over the last three years for NASA under Contract NAS8-36994. The system allows steady-state and transient cycle decks to be combined into one program. ROCETS aids the user to create and use a simulation by automatically generating an executable model from input, scanning the model for undefined variables or variables which require algebraic loops, and supplying state-of-the-art numerical techniques. A flexible run-time processor aids in defining inputs for a particular model experiment. The system also has provisions to generate linear partial derivatives at user selected points for subset models. The AETB steady-state engine simulation was formulated within the ROCETS system converting the previous turbomachinery and heat transfer modules to the ROCETS environment. A comparison was made at the design point between the engine model used for the initial conceptual design and the new ROCETS model. Tables 3 and 4 present the two cycle output sheets and show some differences. The ROCETS turbine modules use real gas properties instead of an ideal gas assumption to determine the ideal turbine enthalpy drop. At the AETB design point, the real gas properties provide a greater ideal enthalpy drop and, therefore, more power at the same turbine pressure ratio. The net result on the cycle is a reduction in both turbine pressure ratio and pump exit pressure as compared to the previously recorded design point in the AETB Work Plan, FR-21306, May 1990.

Prior to the preliminary design of the turbopumps, initial internal flow estimates were formulated based on previous design studies (Table 5). The impact of each of these secondary flows on important cycle parameters was characterized at the design point. The individual effects of the flows are presented as generalized influence coefficients in Table 6. The effect on the engine cycles of each internal flow can be determined by multiplying the flow rate by the appropriate coefficient. Because of the low pressure required by the thrust balance piston, its internal flow rate severely impacts system performance since it cannot be reintroduced into the flow upstream of the fuel turbines. For this reason, options for balancing the oxygen turbopump thrust loads were explored and means of reducing the other flows sought.

TABLE 3. — ADVANCED EXPANDER TEST BED STEADY STATE PERFORMANCE USING ORIGINAL (CONCEPTUAL DESIGN) ENGINE SIMULATION

DESIGN POINT
ADVANCED EXPANDER TEST BED ENGINE

ENGINE PERFORMANCE PARAMETERS
****

CHAMBER PRESSURE	1500.0
S.L. ENGINE THRUST	19880.
TOTAL ENGINE FLOW RATE	52.08
DEL. S.L. ISP	381.7
THROAT AREA	8.145
VAC ENGINE THRUST AR = 1000	25000.
DEL. VAC. ISP AR = 1000	480.0
NOZZLE AREA RATIO	7.5
ENGINE MIXTURE RATIO	6.00
CHAMBER COOLANT DP	503.
CHAMBER COOLANT DT	896.
ETA C*	0.993
CHAMBER Q	12371.

ENGINE STATION CONDITIONS
****

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
ENGINE INLET	70.0	38.0	7.44	-104.8	4.39
PUMP ONE INLET	70.0	38.0	7.44	-104.8	4.39
PUMP ONE EXIT	2030.2	68.0	7.44	24.1	4.36
JBV INLET	1989.5	68.3	3.73	24.1	4.34
JBV EXIT	1690.1	70.6	3.73	24.1	4.12
PUMP TWO INLET	2000.0	68.3	3.71	24.1	4.34
1ST STAGE EXIT	3384.2	91.9	3.71	124.3	4.29
PUMP EXIT	4719.7	114.3	3.71	220.6	4.29
COOLANT INLET	4672.3	114.6	3.71	220.6	4.27
COOLANT EXIT	4169.3	1011.0	3.71	3553.8	0.70
OTBV INLET	4126.5	1011.3	0.22	3553.8	0.70
OTBV EXIT	1771.9	1027.7	0.22	3553.8	0.31
LOX TRB INLET	4126.5	1011.3	3.49	3553.8	0.70
LOX TRB EXIT	3603.2	984.0	3.49	3445.4	0.59
LOX TRB DIFF	3588.4	984.1	3.49	3445.4	0.63
FTBV INLET	3516.3	1015.6	0.00	3553.8	0.60
FTBV EXIT	1771.9	1027.7	0.00	3553.8	0.31
H2 TRB1 INLET	3516.3	984.6	3.49	3445.4	0.62
H2 TRB1 EXIT	2371.6	913.8	3.49	3170.6	0.46
H2 TRB2 INLET	2371.6	913.8	3.49	3170.6	0.46
H2 TRB2 EXIT	1786.6	858.0	3.49	2961.6	0.37
H2 TRB2 DIFF	1771.9	858.1	3.49	2961.6	0.37
MIXER HOT IN	1762.0	868.2	3.71	2997.0	0.36
MIXER COLD IN	1690.1	70.6	3.73	24.1	4.12
MIXER OUT	1673.1	452.3	7.44	1507.1	0.65
FSOV INLET	1673.1	452.3	7.44	1507.1	0.65
FSOV EXIT	1630.9	452.4	7.44	1507.1	0.63
INJ MANIFOLD	1614.4	452.5	7.44	1507.1	0.62
CHAMBER INJ	1597.3	452.5	7.44	1507.1	0.62
CHAMBER	1500.0				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
ENGINE INLET	70.0	163.0	44.64	61.2	71.18
PUMP INLET	70.0	163.0	44.64	61.2	71.18
PUMP EXIT	2458.6	174.5	44.64	69.7	71.57
POSV INLET	2433.8	174.6	4.57	69.7	71.53
POSV EXIT	1577.9	177.9	4.57	69.7	70.19
SOCV INLET	2433.8	174.6	40.07	69.7	71.53
SOCV EXIT	1685.7	177.5	40.07	69.7	70.36
PRIMARY INJ MAN	1577.9	177.9	4.57	69.7	70.19
SECONDARY INJ MAN	1685.7	177.5	40.07	69.7	70.36
PRIMARY INJ	1570.1	177.9	4.57	69.7	70.18
SECONDARY INJ	1667.1	177.5	40.07	69.7	70.33
CHAMBER	1500.0				

TABLE 3. — ADVANCED EXPANDER TEST BED STEADY STATE PERFORMANCE USING ORIGINAL (CONCEPTUAL DESIGN) ENGINE SIMULATION (CONTINUED)

DESIGN POINT
ADVANCED EXPANDER TEST BED ENGINE

****
* TURBOMACHINERY PERFORMANCE DATA *
****

* FUEL TURBINES *

	TURB 1	TURB 2
EFFICIENCY(T/T)	0.762	0.855
HORSEPOWER	1357.	1032.
SPEED (RPM)	100050.	99344.
DIAMETER (IN)	3.85	3.85
BLADE HT. (IN)	0.25	0.25
U/C (IDEAL)	0.395	0.477
MEAN TIP SPEED	1682.	1670.
DELTA H (ACT)	274.8	209.1
GAMMA	1.41	1.41
FLOW PARAMETER	0.0311	0.0445
PR. RATIO (T/T)	1.483	1.327

* FUEL PUMPS *

	STG ONE	STG ONE	STG TWO
EFFICIENCY	0.644	0.592	0.598
HORSEPOWER	1357.	526.	506.
SPEED (RPM)	100050.	99344.	99344.
S SPEED	683.	621.	636.
HEAD (FT)	64617.	46196.	44813.
DIA. (IN)	4.43	3.85	3.85
TIP SPEED	1935.	1671.	1671.
VOL FLOW	766.	388.	388.
HEAD COEF	0.555	0.532	0.516
FLOW COEF	0.088	0.084	0.085
SS SPEED REQ	12493.0		
SS SPEED AVA	10107.7		
NPSH REQ.	1246.1		
NPSH AVA.	1682.2		

* O2 TURBINE *

EFFICIENCY(T/T)	0.819
HORSEPOWER	535.
SPEED (RPM)	49267.
DIAMETER (IN)	3.70
BLADE HT. (IN)	0.30
U/C (IDEAL)	0.437
MEAN TIP SPEED	796.
DELTA H (ACT)	108.3
GAMMA	1.45
FLOW PARAMETER	0.0269
PR. RATIO (T/T)	1.145

* O2 PUMP *

EFFICIENCY	0.729
HORSEPOWER	535.
SPEED (RPM)	49267.
S SPEED	1428.
HEAD (FT)	4805.
DIA. (IN)	2.67
TIP SPEED	575.
VOL FLOW	280.
HEAD COEF	0.468
FLOW COEF	0.135
SS SPEED REQ	27737.9
SS SPEED AVA	22627.0
NPSH REQ.	82.1
NPSH AVA.	110.8

VALVE DATA

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	316.41	0.155	3.73	50.12
OTBV	2354.60	0.012	0.22	5.98
FTBV	1744.41	0.000	0.00	0.00
FSOV	42.24	2.082	7.44	
POSV	855.99	0.028	4.57	
SOCV	748.17	0.259	40.07	

* INJECTOR DATA *

INJECTOR	DELTA P	AREA	FLOW
FUEL	97.28	1.435	7.44
PRIMARY LOX	70.07	0.098	4.57
SECONDARY LOX	167.11	0.553	40.07

TABLE 4. — ADVANCED EXPANDER TEST BED STEADY-STATE PERFORMANCE USING ROCETS

ENGINE PERFORMANCE

THRUST (VACUUM)	(LB)	25000.
THRUST (SEA LEVEL)	(LB)	23341.
SPECIFIC IMPULSE (VACUUM)	(SEC)	480.00
SPECIFIC IMPULSE (S.L. / AR=7.5)	(SEC)	367.51
TOTAL ENGINE INLET FLOW RATE	(LB/SEC)	52.08
ENGINE MIXTURE RATIO		6.00

CHAMBER PERFORMANCE

THROAT PRESSURE (TOTAL)	(PSIA)	1499.8
MIXTURE RATIO - CHAMBER		6.000
FLOW RATE (THROAT)	(LB/SEC)	52.08
THROAT AREA	(IN2)	8.145
NOZZLE AREA RATIO		1000.0
THEORETICAL CHAR. VELOCITY	(FT/SEC)	7599.5
CHAR. VELOCITY EFFICIENCY		0.993

ENGINE HEAT TRANSFER

CHAMBER/NOZL COOLANT DELTA P	(PSIA)	503.0
CHAMBER/NOZL COOLANT DELTA T	(DEG R)	892.8
CHAMBER/NOZL HEAT TRANSFER	(BTU/SEC)	12343.2

FUEL SYSTEM CONDITIONS

STATION	PRESS (PSIA)	TEMP (DEG R)	FLOW (LB/SEC)	ENTHALPY (BTU/LB)	DENSITY (LB/FT3)
ENGINE INLET	73.0	38.0	7.440	-104.8	4.389
PUMP A INLET	70.0	38.0	7.440	-104.8	4.386
PUMP A EXIT	2026.4	67.9	7.440	23.7	4.363
FJBV INLET	1984.2	68.3	3.720	23.7	4.335
FJBV EXIT	1686.9	70.5	3.720	23.7	4.126
PUMP B INLET	1996.1	68.2	3.720	23.7	4.343
PUMP B EXIT	3321.0	90.9	3.720	119.8	4.292
PUMP C EXIT	4598.2	112.3	3.720	212.1	4.288
NOZZLE COOL EX	4047.5	1005.1	3.720	3530.1	0.688
MTBV INLET	4003.8	1005.4	0.350	3530.1	0.681
MTBV EXIT	1768.2	1020.9	0.350	3530.1	0.312
O2 TURB IN	4003.8	1005.4	3.370	3530.1	0.681
O2 TURB EX	3498.8	975.3	3.370	3412.7	0.620
H2 TURB A IN	3416.3	975.9	3.370	3412.7	0.606
H2 TURB A EX	2329.1	902.1	3.370	3128.9	0.456
H2 TURB B IN	2329.1	902.1	3.370	3128.9	0.456
H2 TURB B EX	1781.8	846.6	3.370	2921.0	0.377
TURB MIX IN	1781.8	846.6	3.370	2921.0	0.377
TBY MIX IN	1768.2	1020.9	0.350	3530.1	0.312
JBY MIX IN	1686.9	70.5	3.720	23.7	4.126
MIXER EXIT	1669.6	450.7	7.440	1501.1	0.647
FSOV INLET	1669.6	450.7	7.440	1501.1	0.647
FSOV EXIT	1625.4	450.8	7.440	1501.1	0.627
INJECTOR INLET	1613.7	450.8	7.440	1501.1	0.627
INJECTOR FACE	1499.8				

OXIDIZER SYSTEM CONDITIONS

STATION	PRESS (PSIA)	TEMP (DEG R)	FLOW (LB/SEC)	ENTHALPY (BTU/LB)	DENSITY (LB/FT3)
ENGINE INLET	73.0	161.8	44.643	61.2	71.38
PUMP INLET	70.0	161.8	44.643	61.2	71.38
PUMP EXIT	2569.5	174.0	44.643	70.1	71.67
POSV INLET	2544.7	174.1	4.850	70.1	71.63
POSV EXIT	1580.9	177.9	4.850	70.1	70.13
SOCV INLET	2544.7	174.1	39.792	70.1	71.63
SOCV EXIT	1676.5	177.6	39.792	70.1	70.29
PRIMARY INJ	1580.9	177.9	4.850	70.1	70.13
SECONDARY INJ	1676.5	177.6	39.792	70.1	70.29
INJECTOR FACE	1499.8				

TABLE 4. — ADVANCED EXPANDER TEST BED STEADY-STATE PERFORMANCE USING ROCETS (CONTINUED)

		FUEL PUMP A	FUEL PUMP B		LOX PUMP
		1ST STAGE	1ST STAGE	2ND STAGE	
		*********	*********	*********	
EFFICIENCY		0.645	0.592	0.597	0.729
HORSEPOWER		1353.	505.	486.	560.
TORQUE	(FT-LB)	71.1	27.1	26.1	58.7
SPEED	(RPM)	99985.	97836.	97836.	50094.
HEAD RISE	(FT)	64480.	44212.	42870.	5027.
DIAMETER	(IN)	4.43	3.85	3.85	2.67
TIP SPEED	(FT/SEC)	1932.	1644.	1644.	584.
VOLUMETRIC FLOW	(GPM)	765.	389.	389.	280.
HEAD COEFFICIENT		0.5550	0.5253	0.5093	0.4735
FLOW COEFFICIENT		0.0884	0.0851	0.0863	0.1330

		FUEL TURBINES		LOX TURBINE
		TURBINE A	TURBINE B	
		*********	*********	
EFFICIENCY	(T/T)	0.746	0.850	0.809
HORSEPOWER		1353.	991.	560.
TORQUE	(FT-LB)	71.1	53.2	58.7
SPEED	(RPM)	99985.	97836.	50094.
MEAN DIAMETER	(IN)	3.85	3.85	3.70
MEAN TIP SPEED	(FT/SEC)	1679.6	1643.5	808.7
FLOW PARAMETER	(IN2)	0.03	0.04	0.03
PRES.RATIO	(T/T)	1.47	1.31	1.14
GAMMA		1.398	1.398	1.398

* VALVE DATA *

STATION	DELTA P (PSIA)	AREA (IN2)	FLOW (LB/SEC)
FUEL JACKET BYPASS VALVE	297.4	0.155	3.720
MAIN TURBINE BYPASS VALVE	2235.6	0.020	0.350
FUEL SHUT OFF VALVE	44.2	2.082	7.440
PRIMARY OXID. SHUT VALVE	963.8	0.028	4.850
SECONDARY OXID. CONTROL VLV	868.2	0.239	39.792

* INJECTOR ELEMENT DATA *

STATION	DELTA P (PSIA)	AREA (IN2)	FLOW (LB/SEC)
FUEL INJECTOR	97.00	1.435	7.440
PRIMARY LOX INJECTOR	79.00	0.098	4.850
SECONDARY LOX INJECTOR	165.0	0.553	39.792

TABLE 5. — PRELIMINARY HYDROGEN INTERNAL FLOWS (OT = OXYGEN TURBOPUMP/FT = FUEL TURBOPUMP)

Flow (pps)	*Description*	*Source*	*Sink*
0.781	OT Thrust Balance	3rd pump exit	FSOV inlet
0.219	OT Interpropellant Seal	LO_2 turbine	Overboard
0.227	OT Turbine Leakage	LO_2 turbine	FSOV inlet
0.192	FT Shroud Flow	3rd pump exit	Fuel turbines
0.174	FT Disk Flow	3rd pump exit	Fuel turbines
0.215	FT 3rd Bearing Flow	2nd pump inlet	Fuel turbines
0.392	FT 2nd Bearing Flow	3rd pump exit	Fuel turbines/1st pump exit

TABLE 6. — ADVANCED EXPANDER TEST BED INTERNAL FLOW INFLUENCE COEFFICIENTS — CHAMBER PRESSURE = 1500 PSIA, INLET MIXTURE RATIO = 6.0, JACKET COOLANT FLOW RATE = 3.71 PPS — ALL FLOWS ARE HYDROGEN

	Oxygen Turbopump			*Fuel Turbopump*			
Change from Baseline Condition	*Thrust Balance*	*Turbine Leakage*	*IPS*	*2nd Bearing Coolant*	*Shroud Coolant*	*Disk Coolant*	*3rd Bearing Coolant*
LH_2 Pump A Speed (Delta rpm/pps)	+9065	+2308	−1775	+10900	+7156	−9098	+420
LH_2 Pump B Speed (Delta rpm/pps)	+7461	+3312	−800	+11010	+6979	−16161	+280
LO_2 Pump Speed (Delta rpm/pps)	+3562	+16748	−950	+2140	−3875	−2396	+225
Turbine Bypass Margin (Delta %/pps)	−11.3	−29.3	−23.2	−7.9	+1.3	+2.2	−0.9
SOCV Area (Delta in.^{2}/pps)	−0.115	−0.445	+0.03	−0.06	+0.104	+0.06	−0.01
Coolant Bypass Flow (Delta pps/pps)	−1.0	0	+0.13	−1.0	−1.0	−1.0	−1.0

Subsequent analysis by the P&W component groups during preliminary design refined these estimates, which are shown in Table 7, compared to the initial values. The thrust balance piston was taken out of the oxygen turbopump eliminating the need for this secondary flow. Other internal flows were reduced through means of tighter seal clearances and re-routed flowpaths. To reduce liquid oxygen (LO_2) overboard leakage to a minimum while providing adequate bearing coolant flowrate, a vaporizer was incorporated in combination with a series of labyrinth seals, in the LO_2 turbopump design. The required horsepower for this vaporizer was initially quite high. After several design iterations, the horsepower was lowered to between 25 and 40, and was incorporated into the model. A slight decrease in the secondary oxidizer control valve (SOCV) pressure loss allowed the additional vaporizer horsepower to be absorbed without reducing the cycle control margin at the design point.

During the later months of 1990, the secondary flow analysis effort focused on optimizing the coolant flow scheme for the fuel turbopump 3rd bearing. As shown in Figure 3, this coolant flow is provided by the 2nd-stage fuel pump inlet, circulates through the bearing and three knife-edge seals, and exits into the fuel turbine exit volute. At the design point, the area between the coolant source and the bearing was set to provide the required 0.2 pound/second coolant flow. The pressure differential between the source and sink was low, approximately 90 psid at the design thrust level. At throttled conditions this pressure loss did not decrease proportionally, so that at the 4000-pound thrust level, the fuel turbopump 3rd-bearing coolant flow was excessive.

Also, a parametric study conducted at the design thrust level (Table 8), showed the sensitivity of this pressure differential to component performance. The study showed that the pressure loss between the 2nd-stage fuel pump inlet and the fuel turbine discharge could vary excessively.

TABLE 7. — REFINED PRELIMINARY HYDROGEN INTERNAL FLOWS (OT = OXYGEN TURBOPUMP / FT = FUEL TURBOPUMP)

Design Flow (pps)				
Refined	*Initial*	*Description*	*Source*	*Sink*
0.0	0.781	OT Thrust Balance	3rd Pump Exit	FSOV Inlet
0.0	0.227	OT Turbine Leakage	LO_2 Turbine	FSOV Inlet
0.147	0.219	OT Interpropellant Seal	LO_2 Turbine	Overboard
0.084	0.0	OT Front Disk Flow	3rd Pump Exit	LO_2 Turbine Inlet
0.100	0.0	OT Rear Disk Flow	3rd Pump Exit	LO_2 Turbine Exit
0.192	0.192	FT Shroud Flow	3rd Pump Exit	Fuel Turbines
0.128	0.174	FT Disk Flow	3rd Pump Exit	Fuel Turbines
0.200	0.215	FT 3rd Bearing Flow	2nd Pump Inlet	Fuel Turbines
0.337	0.392	FT 2nd Bearing Flow	3rd Pump Inlet	Fuel Turbines/ 1st Pump Exit

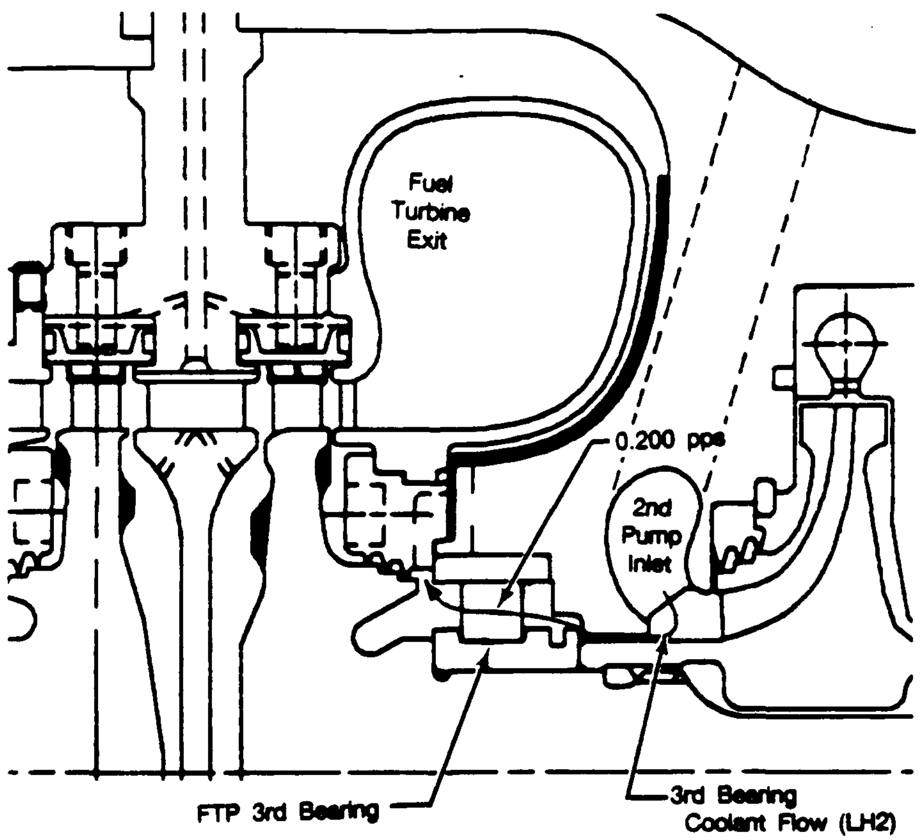

Figure 3. Fuel Turbopump 3rd-Bearing Coolant Flow

TABLE 8. — ADVANCED EXPANDER TEST BED FTP 3RD-BEARING COOLANT SENSITIVITY STUDY

	2nd-Stage Impeller Inlet to Turbine Pump		*From 2nd-Stage Exit*	*From 3rd-Stage Exit*	
Thrust Level (lbs)	*Delta Pressure (psid)*	*% Change*	*% Change*	*% Change*	*Condition Description*
25000.0	85.8389	0.0	0.0	0.0	Baseline (Original 3rd-Bearing Coolant Scheme)
25000.0	59.7754	−30.3633	−2.71778	−1.84880	+10% Jacket Heat Transfer
25000.0	126.087	46.8878	3.46775	2.08216	−10% Jacket Heat Transfer
25000.0	107.925	25.7295	2.79970	2.10075	+10% Jacket Pressure Loss
25000.0	63.1265	−26.4594	−2.88561	−2.17040	−10% Jacket Pressure Loss
25000.0	88.3601	2.93713	0.348949	0.271702	+5% LO_2 Turbine Efficiency
25000.0	83.2744	−2.98756	−0.337172	−0.257802	−5% LO_2 Turbine Efficiency
25000.0	87.2893	1.68962	0.210476	0.166321	+5% LO_2 Pump Efficiency
25000.0	84.5859	−1.45967	−0.172186	−0.134277	−5% LO_2 Pump Efficiency
25000.0	147.916	72.3178	−1.95022	−4.61713	+5% 1st Fuel Pump Efficiency
25000.0	20.7571	−75.8186	2.46696	5.33886	−5% 1st Fuel Pump Efficiency
25000.0	9.7480	−88.6441	−5.52252	−2.56780	+5% 2nd Fuel Pump Efficiency
25000.0	175.712	104.700	6.34546	2.86846	−5% 2nd Fuel Pump Efficiency
25000.0	21.0203	−75.5119	−5.01314	−2.14480	+5% 3rd Fuel Pump Efficiency
25000.0	161.457	88.0933	5.72901	2.39534	−5% 3rd Fuel Pump Efficiency
25000.0	147.636	71.9922	0.526905	−1.90411	−5% 1st Fuel Turbine Efficiency
25000.0	21.8955	74.4923	0.537968	1.93148	−5% 1st Fuel Turbine Efficiency
25000.0	5.69604	−93.3643	−5.56312	−2.75381	+5% 2nd Fuel Turbine Efficiency
25000.0	173.790	102.460	5.94425	2.83318	−5% 2nd Fuel Turbine Efficiency

Two alternate sources of bearing coolant were considered. Table 8 shows the flow change sensitivity if the source were either the 2nd-stage fuel pump exit or the 3rd-stage fuel pump exit. As shown, either source provides acceptable flow stability at the design point, however, at throttled conditions the flow is still higher than desired. Investigation of alternative bearing coolant control schemes is continuing at the time of this report.

An analysis was also performed to evaluate possible benefits of making the AETB baseline cycle a full expander cycle while maintaining the ability for split expander operation. The alternative cycle approach was evaluated during this reporting period and was found to be less desirable than the baseline AETB split expander cycle design approach. An increase in hardware was required for the alternative approach and there was a decrease in the achievable chamber pressure level compared to the current design. Table 9 presents a 25,000-pound thrust full expander design achieving a chamber pressure of 1425 psia. This configuration has a coolant bypass leg requiring only 50 percent of the fuel flow to cool the chamber assembly. There is no jacket bypass. In generating an off-design split expander cycle at the design thrust level, an attempt was made to run with 50 percent jacket bypass flow and no coolant bypass flow. This scheme proved to be unachievable due to a fuel system pressure mismatch at the mixer and insufficient oxidizer turbine flow. Two alternative approaches were taken to generate a split expander cycle at the design thrust level.

TABLE 9. — CYCLE FOR FULL EXPANDER OPERATION

ENGINE PERFORMANCE PARAMETERS
****

CHAMBER PRESSURE	1425.0
S.L. ENGINE THRUST	19090.
TOTAL ENGINE FLOW RATE	52.08
DEL. S.L. ISP	366.5
THROAT AREA	8.571
VAC ENGINE THRUST AR = 1000	25000.
DEL. VAC. ISP AR = 1000	480.0
NOZZLE AREA RATIO	7.5
ENGINE MIXTURE RATIO	6.00
CHAMBER COOLANT DP	459.
CHAMBER COOLANT DT	889.
ETA C*	0.993
CHAMBER Q	12280.

ENGINE STATION CONDITIONS
****

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
ENGINE INLET	70.0	38.0	7.44	-104.8	4.39
PUMP ONE INLET	70.0	38.0	7.44	-104.8	4.39
PUMP ONE EXIT	2037.3	68.1	7.44	24.6	4.36
JBV INLET	2037.3	68.1	0.00	24.6	4.36
JBV EXIT	1586.8	449.7	0.00	1496.5	0.62
PUMP TWO INLET	2006.9	68.4	7.44	24.6	4.34
1ST STAGE EXIT	3483.6	88.2	7.44	115.8	4.41
PUMP EXIT	4965.4	107.2	7.44	205.9	4.48
CBV INLET	4915.8	107.7	3.72	205.9	4.46
CBV EXIT	4345.6	112.1	3.72	205.9	4.21
COOLANT INLET	4915.8	107.7	3.72	205.9	4.46
COOLANT EXIT	4456.9	995.5	3.72	3506.6	0.76
COOLANT MIXED EX	4345.6	534.7	7.44	1856.3	1.29
OTBV INLET	4302.1	534.9	0.35	1856.3	1.28
OTBV EXIT	1595.7	548.0	0.35	1856.3	0.51
LOX TRB INLET	4302.1	534.9	7.09	1856.3	1.28
LOX TRB EXIT	3828.0	523.4	7.09	1804.8	1.24
LOX TRB DIFF	3814.0	523.5	7.09	1804.8	1.17
FTBV INLET	3737.2	537.8	0.00	1856.3	1.13
FTBV EXIT	1595.7	548.0	0.00	1856.3	0.51
H2 TRB1 INLET	3737.2	523.9	7.09	1804.8	1.15
H2 TRB1 EXIT	2649.9	492.1	7.09	1668.9	0.91
H2 TRB2 INLET	2649.9	492.1	7.09	1668.9	0.91
H2 TRB2 EXIT	1627.9	444.8	7.09	1478.6	0.64
H2 TRB2 DIFF	1595.7	444.9	7.09	1478.6	0.63
MIXER HOT IN	1586.8	449.7	7.44	1496.5	0.62
MIXER COLD IN	1586.8	449.7	0.00	1496.5	0.62
MIXER OUT	1586.8	449.7	7.44	1496.5	0.62
FSOV INLET	1586.8	449.7	7.44	1496.5	0.62
FSOV EXIT	1547.2	449.8	7.44	1496.5	0.60
INJ MANIFOLD	1531.7	449.9	7.44	1496.5	0.60
CHAMBER INJ	1515.6	449.9	7.44	1496.5	0.59
CHAMBER	1425.0				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
ENGINE INLET	70.0	163.0	44.64	61.2	71.18
PUMP INLET	70.0	163.0	44.64	61.2	71.18
PUMP EXIT	2381.8	174.1	44.64	69.4	71.56
POSV INLET	2358.3	174.2	7.08	69.4	71.53
POSV EXIT	1601.8	177.1	7.08	69.4	70.35
SOCV INLET	2358.3	174.2	37.57	69.4	71.53
SOCV EXIT	1580.3	177.2	37.57	69.4	70.31
PRIMARY INJ MAN	1601.8	177.1	7.08	69.4	70.35
SECONDARY INJ MAN	1580.3	177.2	37.57	69.4	70.31
PRIMARY INJ	1584.1	177.2	7.08	69.4	70.32
SECONDARY INJ	1564.8	177.2	37.57	69.4	70.29
CHAMBER	1425.0				

TABLE 9. — CYCLE FOR FULL EXPANDER OPERATION (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

FUEL TURBINES

	TURB 1	TURB 2
EFFICIENCY(T/T)	0.804	0.864
HORSEPOWER	1362.	1909.
SPEED (RPM)	100129.	99895.
DIAMETER (IN)	3.24	3.24
BLADE HT. (IN)	0.15	0.18
U/C (IDEAL)	0.487	0.426
MEAN TIP SPEED	1418.	1415.
DELTA H (ACT)	135.8	190.4
GAMMA	1.40	1.40
FLOW PARAMETER	0.0434	0.0593
PR. RATIO (T/T)	1.410	1.628

FUEL PUMPS

	STG ONE	STG ONE	STG TWO
EFFICIENCY	0.644	0.684	0.684
HORSEPOWER	1362.	960.	949.
SPEED (RPM)	100129.	99895.	99895.
S SPEED	682.	840.	841.
HEAD (FT)	64853.	48570.	47990.
DIA. (IN)	4.43	3.93	3.93
TIP SPEED	1938.	1716.	1716.
VOL FLOW	766.	758.	745.
HEAD COEF	0.556	0.531	0.524
FLOW COEF	0.088	0.100	0.100
SS SPEED REQ	12503.0		
SS SPEED AVA	10115.8		
NPSH REQ.	1246.1		
NPSH AVA.	1682.2		

O2 TURBINE

	STAGE 1	STAGE 2
EFFICIENCY(T/T)	0.854	0.843
HORSEPOWER	258.	259.
SPEED (RPM)	48680.	48680.
DIAMETER (IN)	2.95	2.95
BLADE HT. (IN)	0.22	0.22
U/C (IDEAL)	0.512	0.507
MEAN TIP SPEED	628.	628.
DELTA H (ACT)	25.7	25.8
GAMMA	1.38	1.38
FLOW PARAMETER	0.0381	0.0401
PR. RATIO (T/T)	1.059	1.061

O2 PUMP

EFFICIENCY	0.731
HORSEPOWER	516.
SPEED (RPM)	48680.
S SPEED	1446.
HEAD (FT)	4651.
DIA. (IN)	2.66
TIP SPEED	566.
VOL FLOW	280.
HEAD COEF	0.467
FLOW COEF	0.136
SS SPEED REQ	27408.4
SS SPEED AVA	22358.2
NPSH REQ.	82.1
NPSH AVA.	110.8

VALVE DATA

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	450.50	0.000	0.00	0.00
CBV	570.22	0.110	3.72	50.00
OTBV	2706.44	0.014	0.35	4.76
FTBV	2141.57	0.000	0.00	0.00
FSOV	39.65	2.201	7.44	
POSV	756.48	0.046	7.08	
SOCV	778.01	0.238	37.57	

INJECTOR DATA

INJECTOR	DELTA P	AREA	FLOW
FUEL	90.65	1.520	7.44
PRIMARY LOX	159.15	0.100	7.08
SECONDARY LOX	139.76	0.567	37.57

For the first alternative, the percentage of jacket bypass was decreased from 50 to 24 percent and the coolant bypass leg was retained to provide the design coolant flow to the chamber/nozzle circuit. This cycle, shown in Table 10, would require additional lines and an extra control valve and mixer compared to the original design.

For the second alternative, shown in Table 11, the jacket bypass was decreased from 50 to 36 percent and the primary fuel turbine was modified (i.e., blade/disk replacement) to provide more power to the primary pump with a sacrifice in turbine efficiency. The coolant bypass leg was deleted and the flow required for turbine power was used to cool the chamber with an increase in pressure loss. The turbine bypass is insufficient to provide adequate margin for any design deficiencies, and the achievable chamber pressure is 1425 psia.

The full expander design approach provides the ability to run the AETB as both a full and split expander at chamber pressures up to 1425 psia, however, additional hardware is required, design margins are reduced, and system flexibility is lost. Presented with these results and P&W's recommendation, the NASA Program Manager directed P&W to complete the design of the AETB as a split expander with the capability of being tested as a full expander.

The AETB split expander design approach allows off-design operation as a full expander. With no hardware changes, the cycle can achieve a chamber pressure of 750 psia. However, with the jacket bypass leg moved to provide a coolant bypass, and the fuel turbine inlet vanes modified, a chamber pressure of approximately 1000 psia can be realized. A study was initiated to determine the achievable chamber pressure for the full expander configuration without any hardware design changes. Table 12 presents the resultant cycle and shows that a chamber pressure of 940 psia can be achieved by maintaining the turbine original design and moving only the jacket bypass leg to a coolant bypass position. Based on this study, P&W recommended that the new baseline full expander operating point become the 940 psia cycle.

3. Transient Cycle Analysis

The AETB transient engine simulation was also converted to the ROCETS system. Improvements such as a multi-mode heat exchanger module and additional fluid volumes were added to improve the simulations modeling capability. During the preliminary design phase, the AETB transient model was used to characterize an acceptable abort shutdown and to help define control valve requirements.

The AETB control valve scheduling during emergency abort shutdown was defined. Analysis indicates that a successful abort shutdown can be accomplished through valve slew rate adjustment. The fuel shutoff valve (FSOV) must be closed in approximately 400 milliseconds (msec), and the cooldown valve (FCDV) opened in the same amount of time to avoid stalling the primary fuel pump and choking the secondary fuel pump (Figures 4 and 5). The jacket bypass valve (FJBV) must close in 200 msec to prevent reverse hydrogen flow from the mixer to the secondary fuel pump inlet (Figure 5), however the margin on flow reversal is low at 15 msec (Figure 6).

TABLE 10. — CYCLE FOR A FULL EXPANDER AND OPERATING AS A SPLIT EXPANDER (1ST ALTERNATIVE)

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	1425.0
S.L. ENGINE THRUST	19090.
TOTAL ENGINE FLOW RATE	52.08
DEL. S.L. ISP	366.5
THROAT AREA	8.571
VAC ENGINE THRUST AR = 1000	25000.
DEL. VAC. ISP AR = 1000	480.0
NOZZLE AREA RATIO	7.5
ENGINE MIXTURE RATIO	6.00
CHAMBER COOLANT DP	459.
CHAMBER COOLANT DT	890.
ETA C*	0.993
CHAMBER Q	12280.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
ENGINE INLET	70.0	38.0	7.44	-104.8	4.39
PUMP ONE INLET	70.0	38.0	7.44	-104.8	4.39
PUMP ONE EXIT	1673.4	63.0	7.44	1.6	4.35
JBV INLET	1673.4	63.0	1.82	1.6	4.35
JBV EXIT	1602.7	63.6	1.82	1.6	4.30
PUMP TWO INLET	1656.0	63.2	5.62	1.6	4.34
1ST STAGE EXIT	3010.9	82.1	5.62	87.3	4.38
PUMP EXIT	4361.9	100.4	5.62	171.7	4.43
CBV INLET	4333.2	100.6	1.90	171.7	4.42
CBV EXIT	3802.6	104.8	1.90	171.7	4.17
COOLANT INLET	4333.2	100.6	3.72	171.7	4.42
COOLANT EXIT	3874.4	989.8	3.72	3472.4	0.67
COOLANT MIXED EX	3802.6	674.3	5.62	2355.2	0.94
OTBV INLET	3768.6	674.5	0.21	2355.2	0.93
OTBV EXIT	1657.1	687.1	0.21	2355.2	0.43
LOX TRB INLET	3768.6	674.5	5.41	2355.2	0.93
LOX TRB EXIT	3372.2	660.7	5.41	2297.7	0.91
LOX TRB DIFF	3360.5	660.8	5.41	2297.7	0.86
FTBV INLET	3299.3	677.4	0.00	2355.2	0.83
FTBV EXIT	1657.1	687.1	0.00	2355.2	0.43
H2 TRB1 INLET	3299.3	661.2	5.41	2297.7	0.84
H2 TRB1 EXIT	2414.0	625.3	5.41	2151.3	0.67
H2 TRB2 INLET	2414.0	625.3	5.41	2151.3	0.67
H2 TRB2 EXIT	1680.7	580.1	5.41	1974.6	0.51
H2 TRB2 DIFF	1657.1	580.2	5.41	1974.6	0.50
MIXER HOT IN	1650.8	584.2	5.62	1988.9	0.50
MIXER COLD IN	1602.7	63.6	1.82	1.6	4.30
MIXER OUT	1587.4	451.6	7.44	1503.7	0.62
FSOV INLET	1587.4	451.6	7.44	1503.7	0.62
FSOV EXIT	1547.6	451.8	7.44	1503.7	0.60
INJ MANIFOLD	1532.0	451.8	7.44	1503.7	0.60
CHAMBER INJ	1515.9	451.9	7.44	1503.7	0.59
CHAMBER	1425.0				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
ENGINE INLET	70.0	163.0	44.64	61.2	71.18
PUMP INLET	70.0	163.0	44.64	61.2	71.18
PUMP EXIT	2030.6	172.6	44.64	68.2	71.49
POSV INLET	2007.1	172.6	5.59	68.2	71.46
POSV EXIT	1534.6	174.4	5.59	68.2	70.72
SOCV INLET	2007.1	172.6	39.05	68.2	71.46
SOCV EXIT	1591.6	174.2	39.05	68.2	70.81
PRIMARY INJ MAN	1534.6	174.4	5.59	68.2	70.72
SECONDARY INJ MAN	1591.6	174.2	39.05	68.2	70.81
PRIMARY INJ	1523.7	174.5	5.59	68.2	70.70
SECONDARY INJ	1575.0	174.3	39.05	68.2	70.78
CHAMBER	1424.9				

TABLE 10. — CYCLE FOR A FULL EXPANDER AND OPERATING AS A SPLIT EXPANDER (1ST ALTERNATIVE) (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

FUEL TURBINES

	TURB 1	TURB 2
EFFICIENCY(T/T)	0.750	0.831
HORSEPOWER	1121.	1353.
SPEED (RPM)	93084.	91522.
DIAMETER (IN)	3.24	3.24
BLADE HT. (IN)	0.15	0.18
U/C (IDEAL)	0.421	0.397
MEAN TIP SPEED	1319.	1296.
DELTA H (ACT)	146.3	176.7
GAMMA	1.36	1.36
FLOW PARAMETER	0.0422	0.0561
PR. RATIO (T/T)	1.367	1.436

FUEL PUMPS

	STG ONE	STG ONE	STG TWO
EFFICIENCY	0.639	0.671	0.671
HORSEPOWER	1121.	681.	672.
SPEED (RPM)	93084.	91522.	91522.
S SPEED	739.	714.	717.
HEAD (FT)	52953.	44726.	44120.
DIA. (IN)	4.43	3.93	3.93
TIP SPEED	1802.	1572.	1573.
VOL FLOW	768.	576.	569.
HEAD COEF	0.525	0.582	0.574
FLOW COEF	0.095	0.083	0.083
SS SPEED REQ	11623.3		
SS SPEED AVA	9404.1		
NPSH REQ.	1246.1		
NPSH AVA.	1682.2		

O2 TURBINE

	STAGE 1	STAGE 2
EFFICIENCY(T/T)	0.795	0.785
HORSEPOWER	220.	221.
SPEED (RPM)	45892.	45892.
DIAMETER (IN)	2.95	2.95
BLADE HT. (IN)	0.22	0.22
U/C (IDEAL)	0.440	0.436
MEAN TIP SPEED	592.	592.
DELTA H (ACT)	28.8	28.8
GAMMA	1.38	1.38
FLOW PARAMETER	0.0373	0.0392
PR. RATIO (T/T)	1.056	1.058

O2 PUMP

EFFICIENCY	0.727
HORSEPOWER	441.
SPEED (RPM)	45892.
S SPEED	1543.
HEAD (FT)	3948.
DIA. (IN)	2.66
TIP SPEED	533.
VOL FLOW	280.
HEAD COEF	0.446
FLOW COEF	0.144
SS SPEED REQ	25852.0
SS SPEED AVA	21088.6
NPSH REQ.	82.1
NPSH AVA.	110.8

VALVE DATA

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	86.06	0.155	1.82	24.42
CBV	530.67	0.059	1.90	33.85
OTBV	2111.48	0.010	0.21	3.77
FTBV	1642.18	0.000	0.00	0.00
FSOV	39.81	2.201	7.44	
POSV	472.45	0.046	5.59	
SOCV	415.43	0.339	39.05	

INJECTOR DATA

INJECTOR	DELTA P	AREA	FLOW
FUEL	90.91	1.520	7.44
PRIMARY LOX	98.76	0.100	5.59
SECONDARY LOX	149.98	0.567	39.05

TABLE 11. — CYCLE FOR A FULL EXPANDER AND OPERATING AS A SPLIT EXPANDER (2ND ALTERNATIVE)

ENGINE PERFORMANCE PARAMETERS

****

CHAMBER PRESSURE	1425.0
S.L. ENGINE THRUST	19090.
TOTAL ENGINE FLOW RATE	52.08
DEL. S.L. ISP	366.5
THROAT AREA	8.571
VAC ENGINE THRUST AR = 1000	25000.
DEL. VAC. ISP AR = 1000	480.0
NOZZLE AREA RATIO	7.5
ENGINE MIXTURE RATIO	6.00
CHAMBER COOLANT DP	756.
CHAMBER COOLANT DT	683.
ETA C*	0.993
CHAMBER Q	12280.

ENGINE STATION CONDITIONS

****

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
ENGINE INLET	70.0	38.0	7.44	-104.8	4.39
PUMP ONE INLET	70.0	38.0	7.44	-104.8	4.39
PUMP ONE EXIT	1773.1	64.4	7.44	7.9	4.35
JBV INLET	1773.1	64.4	2.66	7.9	4.35
JBV EXIT	1621.2	65.7	2.66	7.9	4.25
PUMP TWO INLET	1760.5	64.5	4.78	7.9	4.35
1ST STAGE EXIT	3200.6	86.0	4.78	102.9	4.36
PUMP EXIT	4628.8	106.7	4.78	196.4	4.39
CBV INLET	4608.0	106.9	0.00	196.4	4.39
CBV EXIT	3809.3	112.8	0.00	196.4	4.01
COOLANT INLET	4608.0	106.9	4.78	196.4	4.39
COOLANT EXIT	3851.6	790.1	4.78	2767.4	0.82
COOLANT MIXED EX	3809.3	790.3	4.78	2767.4	0.81
OTBV INLET	3781.0	790.5	0.03	2767.4	0.81
OTBV EXIT	1646.3	804.0	0.03	2767.4	0.37
LOX TRB INLET	3781.0	790.5	4.75	2767.4	0.81
LOX TRB EXIT	3427.6	776.6	4.75	2709.8	0.79
LOX TRB DIFF	3417.2	776.7	4.75	2709.8	0.75
FTBV INLET	3363.3	793.2	0.00	2767.4	0.73
FTBV EXIT	1646.3	804.0	0.00	2767.4	0.37
H2 TRB1 INLET	3363.3	777.0	4.75	2709.8	0.74
H2 TRB1 EXIT	2333.0	733.6	4.75	2533.2	0.56
H2 TRB2 INLET	2333.0	733.6	4.75	2533.2	0.56
H2 TRB2 EXIT	1667.8	683.7	4.75	2343.7	0.44
H2 TRB2 DIFF	1646.3	683.8	4.75	2343.7	0.43
MIXER HOT IN	1640.9	684.5	4.78	2346.0	0.43
MIXER COLD IN	1621.2	65.7	2.66	7.9	4.25
MIXER OUT	1587.7	453.0	7.44	1508.8	0.61
FSOV INLET	1587.7	453.0	7.44	1508.8	0.61
FSOV EXIT	1547.8	453.1	7.44	1508.8	0.60
INJ MANIFOLD	1532.2	453.2	7.44	1508.8	0.59
CHAMBER INJ	1516.1	453.2	7.44	1508.8	0.59
CHAMBER	1425.0				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
ENGINE INLET	70.0	163.0	44.64	61.2	71.18
PUMP INLET	70.0	163.0	44.64	61.2	71.18
PUMP EXIT	1779.6	171.5	44.64	67.4	71.44
POSV INLET	1756.0	171.6	4.21	67.4	71.41
POSV EXIT	1487.2	172.6	4.21	67.4	70.98
SOCV INLET	1756.0	171.6	40.43	67.4	71.41
SOCV EXIT	1602.7	172.1	40.43	67.4	71.17
PRIMARY INJ MAN	1487.2	172.6	4.21	67.4	70.98
SECONDARY INJ MAN	1602.7	172.1	40.43	67.4	71.17
PRIMARY INJ	1480.9	172.6	4.21	67.4	70.97
SECONDARY INJ	1584.9	172.2	40.43	67.4	71.14
CHAMBER	1425.0				

TABLE 11. — CYCLE FOR A FULL EXPANDER AND OPERATING AS A SPLIT EXPANDER (2ND ALTERNATIVE) (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

FUEL TURBINES

	TURB 1	TURB 2
EFFICIENCY(T/T)	0.662	0.817
HORSEPOWER	1187.	1274.
SPEED (RPM)	95083.	92167.
DIAMETER (IN)	3.24	3.24
BLADE HT. (IN)	0.15	0.18
U/C (IDEAL)	0.368	0.383
MEAN TIP SPEED	1347.	1306.
DELTA H (ACT)	176.6	189.5
GAMMA	1.36	1.36
FLOW PARAMETER	0.0394	0.0551
PR. RATIO (T/T)	1.442	1.399

FUEL PUMPS

	STG ONE	STG ONE	STG TWO
EFFICIENCY	0.641	0.645	0.646
HORSEPOWER	1187.	642.	632.
SPEED (RPM)	95083.	92167.	92167.
S SPEED	721.	634.	638.
HEAD (FT)	56217.	47647.	46985.
DIA. (IN)	4.43	3.93	3.93
TIP SPEED	1840.	1583.	1584.
VOL FLOW	767.	492.	488.
HEAD COEF	0.534	0.611	0.603
FLOW COEF	0.093	0.070	0.071
SS SPEED REQ	11872.9		
SS SPEED AVA	9606.0		
NPSH REQ.	1246.1		
NPSH AVA.	1682.2		

O2 TURBINE

	STAGE 1	STAGE 2
EFFICIENCY(T/T)	0.767	0.759
HORSEPOWER	194.	193.
SPEED (RPM)	43773.	43773.
DIAMETER (IN)	2.95	2.95
BLADE HT. (IN)	0.22	0.22
U/C (IDEAL)	0.411	0.410
MEAN TIP SPEED	565.	565.
DELTA H (ACT)	28.9	28.7
GAMMA	1.38	1.38
FLOW PARAMETER	0.0353	0.0369
PR. RATIO (T/T)	1.050	1.051

O2 PUMP

EFFICIENCY	0.722
HORSEPOWER	387.
SPEED (RPM)	43773.
S SPEED	1630.
HEAD (FT)	3445.
DIA. (IN)	2.66
TIP SPEED	509.
VOL FLOW	280.
HEAD COEF	0.428
FLOW COEF	0.151
SS SPEED REQ	24666.9
SS SPEED AVA	20121.9
NPSH REQ.	82.1
NPSH AVA.	110.8

VALVE DATA

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	185.34	0.155	2.66	35.81
CBV	798.67	0.000	0.00	0.00
OTBV	2134.73	0.001	0.03	0.55
FTBV	1717.00	0.000	0.00	0.00
FSOV	39.92	2.201	7.44	
POSV	268.85	0.046	4.21	
SOCV	153.33	0.578	40.43	

INJECTOR DATA

INJECTOR	DELTA P	AREA	FLOW
FUEL	91.06	1.520	7.44
PRIMARY LOX	55.94	0.100	4.21
SECONDARY LOX	159.92	0.567	40.43

TABLE 12. — CYCLE FOR A FULL EXPANDER AND OPERATING AS A FULL EXPANDER WITH ADDED COOLANT BYPASS

ENGINE PERFORMANCE PARAMETERS

CHAMBER PRESSURE	942.1
S.L. ENGINE THRUST	11708.
TOTAL ENGINE FLOW RATE	32.84
DEL. S.L. ISP	356.6
THROAT AREA	8.145
VAC ENGINE THRUST AR = 1000	15756.
DEL. VAC. ISP AR = 1000	479.8
NOZZLE AREA RATIO	7.5
ENGINE MIXTURE RATIO	6.00
CHAMBER COOLANT DP	296.
CHAMBER COOLANT DT	886.
ETA C*	0.993
CHAMBER Q	8596.

ENGINE STATION CONDITIONS

* FUEL SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
ENGINE INLET	70.0	38.0	4.69	-104.8	4.39
PUMP ONE INLET	70.0	38.0	4.69	-104.8	4.39
PUMP ONE EXIT	2291.6	78.0	4.69	58.8	4.20
JBV INLET	2291.6	78.0	0.00	58.8	4.20
JBV EXIT	1063.6	506.5	0.00	1698.2	0.38
PUMP TWO INLET	2241.4	78.4	4.69	58.8	4.17
1ST STAGE EXIT	2938.0	96.4	4.69	127.8	4.02
PUMP EXIT	3536.4	113.5	4.69	193.1	3.90
CBV INLET	3510.7	113.7	2.09	193.1	3.88
CBV EXIT	3215.0	115.4	2.09	193.1	3.72
COOLANT INLET	3510.7	113.7	2.61	193.1	3.88
COOLANT EXIT	3215.0	1000.0	2.61	3492.0	0.56
OTBV INLET	3198.8	586.4	1.71	2025.5	0.91
OTBV EXIT	2861.4	588.2	1.71	2025.5	0.82
LOX TRB INLET	3198.8	586.4	2.98	2025.5	0.91
LOX TRB EXIT	2908.1	575.3	2.98	1979.3	0.96
LOX TRB DIFF	2900.3	575.4	2.98	1979.3	0.85
FTBV INLET	2861.4	588.2	0.90	2025.5	0.82
FTBV EXIT	1199.5	596.5	0.90	2025.5	0.36
H2 TRB1 INLET	2861.4	578.2	3.79	1989.2	0.83
H2 TRB1 EXIT	1792.2	528.0	3.79	1786.6	0.59
H2 TRB2 INLET	1792.2	528.0	3.79	1786.6	0.59
H2 TRB2 EXIT	1213.9	484.4	3.79	1620.4	0.45
H2 TRB2 DIFF	1199.5	484.5	3.79	1620.4	0.44
MIXER HOT IN	1186.3	506.1	4.69	1698.2	0.42
MIXER COLD IN	1063.6	506.5	0.00	1698.2	0.38
MIXER OUT	1063.6	506.5	4.69	1698.2	0.38
FSOV INLET	1063.6	506.5	4.69	1698.2	0.38
FSOV EXIT	1033.9	506.6	4.69	1698.2	0.37
INJ MANIFOLD	1022.7	506.7	4.69	1698.2	0.36
CHAMBER INJ	1011.0	506.7	4.69	1698.2	0.36
CHAMBER	942.1				

* OXYGEN SYSTEM CONDITIONS *

STATION	PRESS	TEMP	FLOW	ENTHALPY	DENSITY
ENGINE INLET	70.0	163.0	28.15	61.2	71.18
PUMP INLET	70.0	163.0	28.15	61.2	71.18
PUMP EXIT	1431.4	169.8	28.15	66.1	71.39
POSV INLET	1421.5	169.8	3.27	66.1	71.38
POSV EXIT	981.8	171.4	3.27	66.1	70.66
SOCV INLET	1421.5	169.8	24.87	66.1	71.38
SOCV EXIT	1013.3	171.3	24.87	66.1	70.72
PRIMARY INJ MAN	981.8	171.4	3.27	66.1	70.66
SECONDARY INJ MAN	1013.3	171.3	24.87	66.1	70.72
PRIMARY INJ	977.8	171.4	3.27	66.1	70.66
SECONDARY INJ	1006.2	171.3	24.87	66.1	70.70
CHAMBER	942.1				

TABLE 12. — CYCLE FOR A FULL EXPANDER AND OPERATING AS A FULL EXPANDER WITH ADDED COOLANT BYPASS (CONTINUED)

TURBOMACHINERY PERFORMANCE DATA

FUEL TURBINES

	TURB 1	TURB 2
EFFICIENCY(T/T)	0.811	0.866
HORSEPOWER	1086.	891.
SPEED (RPM)	100000.	92910.
DIAMETER (IN)	3.85	3.85
BLADE HT. (IN)	0.25	0.25
U/C (IDEAL)	0.475	0.504
MEAN TIP SPEED	1681.	1562.
DELTA H (ACT)	202.5	166.3
GAMMA	1.39	1.39
FLOW PARAMETER	0.0318	0.0486
PR. RATIO (T/T)	1.597	1.476

FUEL PUMPS

	STG ONE	STG ONE	STG TWO
EFFICIENCY	0.592	0.457	0.428
HORSEPOWER	1086.	458.	434.
SPEED (RPM)	100000.	92910.	92910.
S SPEED	492.	1085.	1205.
HEAD (FT)	75322.	24521.	21773.
DIA. (IN)	4.43	3.85	3.85
TIP SPEED	1934.	1563.	1563.
VOL FLOW	501.	524.	540.
HEAD COEF	0.648	0.323	0.287
FLOW COEF	0.058	0.121	0.126
SS SPEED REQ	9914.7		
SS SPEED AVA	8021.7		
NPSH REQ.	1246.1		
NPSH AVA.	1682.2		

O2 TURBINE

EFFICIENCY(T/T)	0.850
HORSEPOWER	195.
SPEED (RPM)	35792.
DIAMETER (IN)	3.70
BLADE HT. (IN)	0.30
U/C (IDEAL)	0.495
MEAN TIP SPEED	578.
DELTA H (ACT)	46.2
GAMMA	1.36
FLOW PARAMETER	0.0225
PR. RATIO (T/T)	1.100

O2 PUMP

EFFICIENCY	0.722
HORSEPOWER	195.
SPEED (RPM)	35792.
S SPEED	1255.
HEAD (FT)	2746.
DIA. (IN)	2.67
TIP SPEED	418.
VOL FLOW	177.
HEAD COEF	0.507
FLOW COEF	0.118
SS SPEED REQ	16020.2
SS SPEED AVA	13068.4
NPSH REQ.	82.1
NPSH AVA.	110.8

VALVE DATA

VALVE	DELTA P	AREA	FLOW	% BYPASS
JBV	1228.02	0.000	0.00	0.00
CBV	295.66	0.092	2.09	44.46
OTBV	337.42	0.147	1.71	36.55
FTBV	1661.94	0.055	0.90	-27.30
FSOV	29.67	2.082	4.69	
POSV	439.75	0.028	3.27	
SOCV	408.19	0.218	24.87	

INJECTOR DATA

INJECTOR	DELTA P	AREA	FLOW
FUEL	68.85	1.435	4.69
PRIMARY LOX	35.68	0.098	3.27
SECONDARY LOX	64.10	0.553	24.87

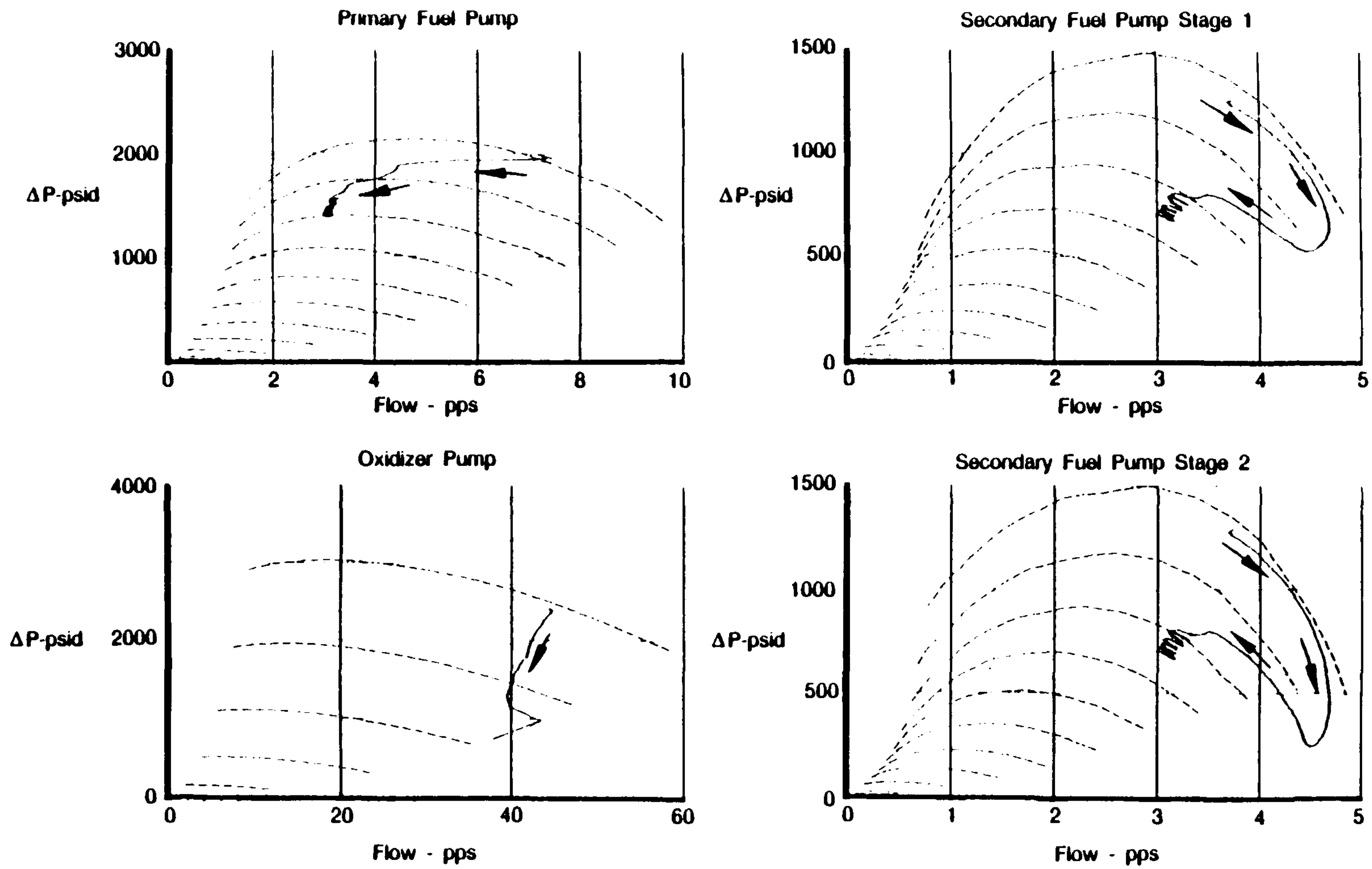

Figure 4. Pump Flow Characteristics With Shutdown Transients Plotted

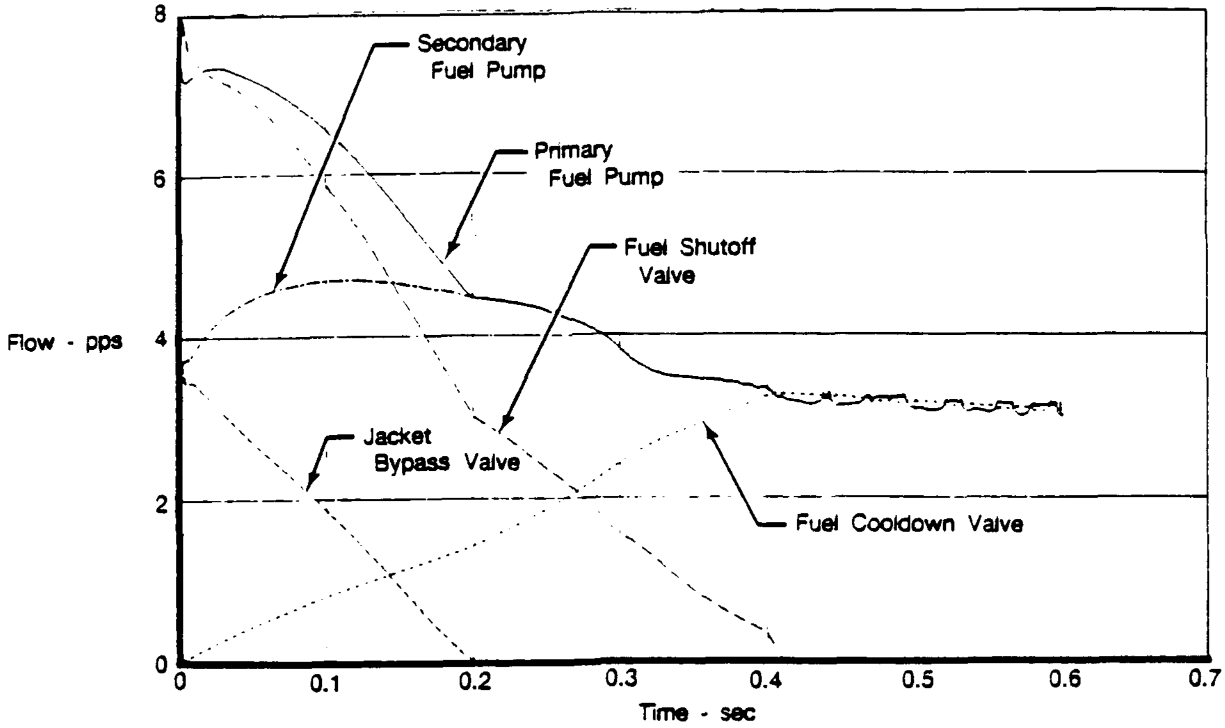

Figure 5. Flow Conditions During FSOV Abort Closure

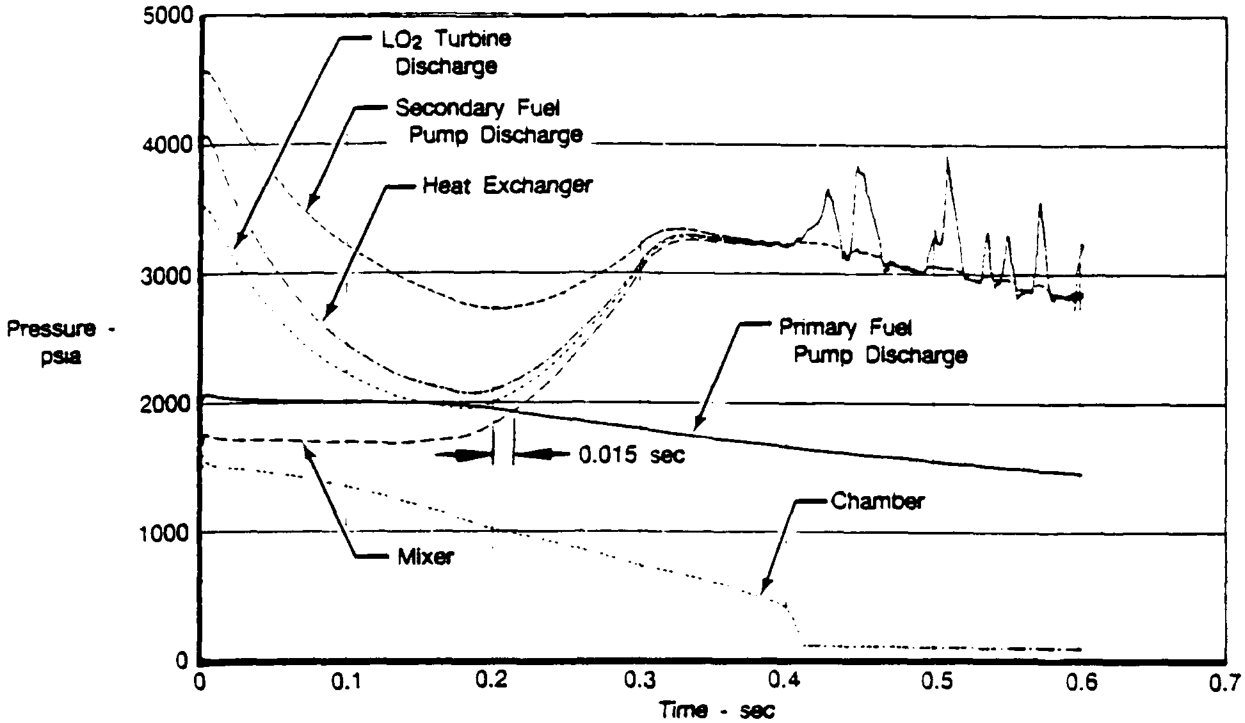

Figure 6. Pressure Transients During Shutdown (With 15 msec Margin for Avoiding Flow Reversal)

C. TASK 3.0 — PRELIMINARY DESIGN

The starting point for the AETB preliminary design was a conceptual state-of-the-art engine design completed by P&W in 1989. The preliminary design is now approximately 90 percent complete and is progressing toward a Preliminary Design Review on 29-31 January 1991. Manufacturing personnel are closely involved in the design process through implementation of the P&W Integrated Product Team concept. Integrated product development ensures that producibility is built into the design and that all design requirements are addressed. The following paragraphs describe the preliminary design resulting from work performed in 1990.

1. Oxygen Turbopump

Major differences discussed below between the original oxygen pump conceptual design and the current design are pointed out in Figure 7.

- *Inducer/Impeller* — The original conceptual design of the oxygen turbopump used INCO 718 for both the inducer and impeller. The inducer is a three-blade design with moderate suction specific speed (Nss) for low-speed performance. The impeller is a shrouded design with a low discharge blade angle for improved throttleability.

  During 1990, worked focused on defining an impeller configuration that was not only hydrodynamically sound and structurally acceptable but was also economical to produce. Manufacturing capabilities proved to be the most limiting requirements for the impeller.

Fortunately, the design did not have to be compromised for manufacturability and all design hydrodynamic parameters fell well within P&W's design experience.

Early in the design phase, IN 100 material was thought to be necessary to achieve the required structural margins for LCF life. This material selection was a concern because IN 100 did not rate well in oxygen promoted combustion tests. However, preliminary structural analysis shows that INCO 718 will achieve the required structural margins and is currently the material of choice.

Significant effort has gone into maintaining rotor critical speed margins. The pump bounce mode is very dependent upon the inducer/impeller length and weight. The latest impeller definition is 0.070" shorter than the proposal configuration. The resultant critical speed is 122 percent of the design point speed of 49,400 rpm.

- *Turbine Blisk and Shaft* — The conceptual turbine configuration consisted of a two-stage, full admission, 50 percent reaction turbine with a mean tip diameter of four inches. This configuration was proposed because it offered the best chance of achieving the turbine efficiencies necessary to meet engine cycle requirements. However, a concerted effort to define an acceptable mechanical joint that would permit the machining of the two disks as separate entities was unsuccessful. Every alternative studied resulted in decreased critical speed margin. Fortunately, a search for vendors capable of producing turbines of this size and design brought a specialized manufacturing capability to light that made it possible to incorporate a single-stage turbine in the LO_2 turbopump.

  The current design of the AETB oxygen turbopump now features a single-stage, full-admission, 50 percent reaction turbine with a 7.00-inch tip diameter. Turbine efficiency is predicted to be 82 percent at the design point thrust of 25,000 pounds. The turbine disk is integral with the rotor shaft to maintain rotor critical speed margin and Interpropellant Seal (IPS) clearance control.

- *Interpropellant Seal/Vaporizer* — The conceptual IPS configuration consisted of a helium gas purge with labyrinth seals consisting of seven knife edges on both the oxygen and hydrogen sides. Original internal flow and leakage analysis assumed 0.005-inch radial clearances throughout the IPS package.

  The high leakage rates predicted by analysis on the oxygen end of the turbopump led to investigation of other seal configurations. These configurations included contacting and non-contacting ring and face seals. A review of experience indicated that there was no significant benefit or that alternate seal designs were unproven for the AETB. Therefore, development of the labyrinth seal configuration continued.

  The amount of LO_2 leakage in the IPS is driven by the density of the oxygen entering the IPS. Reducing the density reduces the oxygen lost overboard. Therefore, a vaporizer design that has been successfully demonstrated in the

SSME/ATD LO_2 turbopump was proposed in the original IPS. Although the vaporizer requires additional turbine horsepower, trade studies for the AETB LO_2 turbopump showed the net result was a 90 percent reduction in oxygen lost overboard.

Additional seal capability was also needed on the hydrogen side of the IPS. Trade studies were used to evaluate the effectiveness of additional knife edges, reduced diameters and clearances, and local gas temperatures. The current configuration is a blend of all the beneficial features that could be incorporated without compromising other important design features. For instance, the improvement gained from adding one more knife edge was offset by a decrease in rotor critical speed margin caused by the resultant increase in rotor length. Another example is that the decrease in seal diameter and rotor diameter at the same time would decrease rotor stiffness and decrease the chances of maintaining tight seal clearances.

The IPS package consists of a helium dam with 11 knife edges on the hydrogen side and 10 on the oxygen side. Concern about rubbing in LO_2 led to the use of 0.005-inch radial clearances for the oxygen side of the IPS. Leakage control requirements have necessitated the use of 0.003-inch radial clearances on the hydrogen side of the IPS.

Additional benefit on the LO_2 side was gained from the incorporation of a stationary vane system upstream of the vaporizer. This vane counteracts the pumping action on the backside of the vaporizer and reduces the downstream pressure. The lower pressure results in less leakage overboard.

- *Bearings* — The conceptual rotor support configuration consisted of two 24mm ball bearings for axial load control and a single 27mm roller bearing for radial stiffness and critical speed margin. Many bearing configurations were evaluated as the pump design progressed. At one time, it was believed that the rotor would be small enough that the ball bearings along would be sufficient for rotor support. However, when the turbine evolved to a single, large diameter turbine, the roller bearing became indispensable for turbine support.

  As the LO_2 turbopump design developed, the rotor size increased, as did the bearing loads. To maintain design parameters within current experience levels, the ball bearing size was increased to 35mm. This bearing design is very similar to a bearing used in the P&W RL-10 rocket engine. The RL-10 test and operating experience adds significant credibility and confidence to the design.

  Material selection for each bearing was based on its location. For bearings exposed to liquid oxygen, 440C steel was chosen for the application based on experience and LO_2 compatibility tests. This choice creates a design hardship with the bearing inner races. When the race is installed on the A286 shaft, the required fit for anti-rotation is so tight that the bearing race has a limited shelf life. However, material processing and design changes have improved the life expectancy of the bearing inner race to acceptable levels. Bearing coolant flows are provided through constant area orifices and are sufficient to achieve the desired bearing life of five hours.

- *Housings* — The pump housing designs feature vaneless volutes. The pump discharge volute is double discharge for reduced radial loads. The turbine inlet and exit volutes are a single inlet (exit) design providing high efficiency and low losses. To provide manufacturing producibility, a unique configuration was developed to allow the turbine volutes to be easily produced. These two volutes are a semicircular design originating at a parting line in the turbine housings. The strategic location of the parting lines allows these volutes to be machined with conventional techniques.

The pump discharge volute is a traditional configuration that will be produced in two halves and welded together. It was originally thought that the two halves could remain separate pieces and be axially loaded by the housings. However, preliminary analysis has shown that the pressure and thermal loadings are too high to consider this a viable design.

The major structural housings are relatively large, reflecting the test rig approach to the design. The robustness of the housings adds radial and axial stiffness to the rotor, providing increased confidence to critical speed predictions.

The thermal gradients in the housings are quite significant and preliminary analysis has indicated some isolated high stress areas. Minor configuration changes and thermal conditioning that may be needed before these housing designs will be considered acceptable.

The turbine blade outer air seal radial tip clearance has a significant impact on turbine efficiency. To maximize turbine efficiency, a tip clearance control scheme has been added to provide thermal conditioning to achieve the required diameter for proper turbine tip clearances.

- *Structural Analysis* — Preliminary structural analysis was completed for several of the AETB LO_2 turbopump components. The components analyzed include the inducer blade, the impeller blade and hub, the turbine disk, and the turbine inlet housing.

Structural analysis of the inducer blade included a two-dimensional (2D) finite element plate model for blade stresses and vibratory responses. Results indicate that the blade aerodynamic design will meet all structural requirements. Hub analysis is pending.

Analysis of the impeller consisted of a finite element 2D Body-of-Revolution model for hub stresses and a 2D plate model in space for blade stress estimates. All analyses of the impeller are favorable.

The structural analysis of the turbine disk was completed with a 2D structural analysis computer deck, 5362. Axial thermal gradients caused unacceptable axial deflections, indicating a need to change the internal flow scheme around the turbine. The current flow scheme eliminates the disk axial gradient, and analysis indicates acceptable stresses and deflections. A plastic/residual membrane stress analysis (computer deck 5138) shows adequate burst margin for the disk.

A 2D boundary element analysis program (BEASY) was used to generate thermal gradients for the turbine inlet housing based on predicted surface temperatures and film coefficients. A 2D finite element structural analysis was then used to predict the thermal stresses and deflections. The analysis pointed out one location that was overstressed due to the thermal gradient. A detailed thermal model is currently being constructed which will determine the validity of this preliminary analysis. Thermal conditioning of the housings may be needed to achieve the desired durability at all locations.

- *Thrust Balance* — Rotor thrust balance in the conceptual design configuration was controlled through the use of a thrust balance piston. This thrust balance piston generated balance loads through the use of high-pressure hydrogen from the 3rd-stage fuel pump discharge. Internal flow and cycle analysis predicted that the flows required to make the thrust piston work would have a significant detrimental effect on cycle efficiencies. Therefore, design studies evaluated the possibility of eliminating the thrust balance piston and taking the axial loads out through the ball bearings.

  The axial loads on the LO_2 rotor were balanced at the 25,000-pound thrust level by adjusting seal diameters and slightly changing the turbine reaction. Thrust loads have been calculated at the 4,000-pound thrust level and are less than 500 lbf. At the 4,000-pound thrust level, the rotor rotational speeds and bearing cooling flow rates are such that the ball bearings are capable of operating with the 500-lbf axial load.

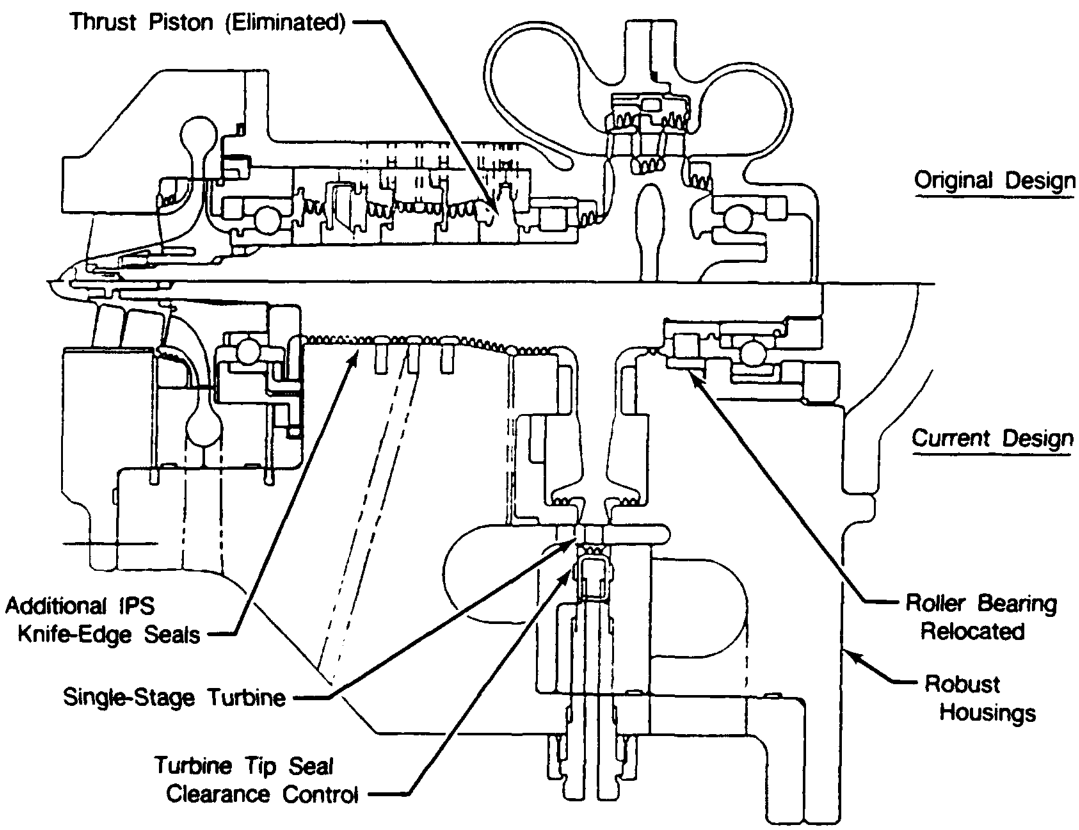

Figure 7. Oxygen Turbopump Configuration Comparison

2. Hydrogen Turbopump

The following is a summary of work accomplished during 1990 on the three-stage, twin-spool hydrogen turbopump shown in Figure 8.

- *Inducer/Impellers* —

  Primary Pump — The original conceptual design of the primary pump featured a titanium A-110 impeller with a long inlet side integral arm. The titanium A-110 inducer was snapped to the impeller integral arm. The impeller was splined to the shaft and the inducer was splined to the impeller.

  The current design impeller has a very short front integral arm to improve accessibility to the shrouded blade passages for machining. The inducer now has the long integral arm because the arm poses no problem in the machining of the unshrouded blades. The impeller is still splined to the shaft but the inducer is now pinned to the impeller to simplify machining.

  The original first stage impeller blading geometry featured a constant 0.060-inch blade thickness with a 212-degree wrap angle and a 25-degree blade exit angle. The blading pattern has gone through several iterations to satisfy the requirements of structures, hydrodynamics and producibility. The current blading pattern, which consists of six blades, six long splitters, and twelve short splitters, has a contoured blade thickness of 0.125-inch maximum to a minimum of 0.070 inch at the exit, a 130-degree wrap angle, a 40-degree blade exit angle and a 0.100-inch exit blade height. The current pattern meets hydrodynamic and structural criteria, but still presents a producibility challenge. The current plan to produce the impeller calls for electrodischarge machining of the flow passages in two or more pieces of titanium, then diffusion bonding the sections.

  Secondary Pump — The original conceptual design of the secondary pump had two titanium A-110 impeller stages. The second-stage impeller was splined to the shaft while the third-stage impeller was attached to the second stage with a curvic coupling.

  The blading pattern of the second and third-stage impellers consists of six blades and six splitters and has a 40-degree exit angle and a 0.100-inch exit blade height. The hub side blade thickness is contoured from 0.030 inch at the inlet to 0.090 inch maximum and then down to 0.060 inch at the blade exit. The shroud side blade thickness varies from 0.025 inch at the inlet to 0.075 inch maximum and then down to 0.060 inch at the blade exit. The blade exit diameter on both stages has been reduced from 3.85 to 3.58 inches. The second-stage impeller is now coupled to the third stage by axial pins rather than by a curvic coupling. In general, the goal has been to reduce mass from the impellers and thicken the arms. The thicker arms will increase axial stiffness and improve rotor dynamics.

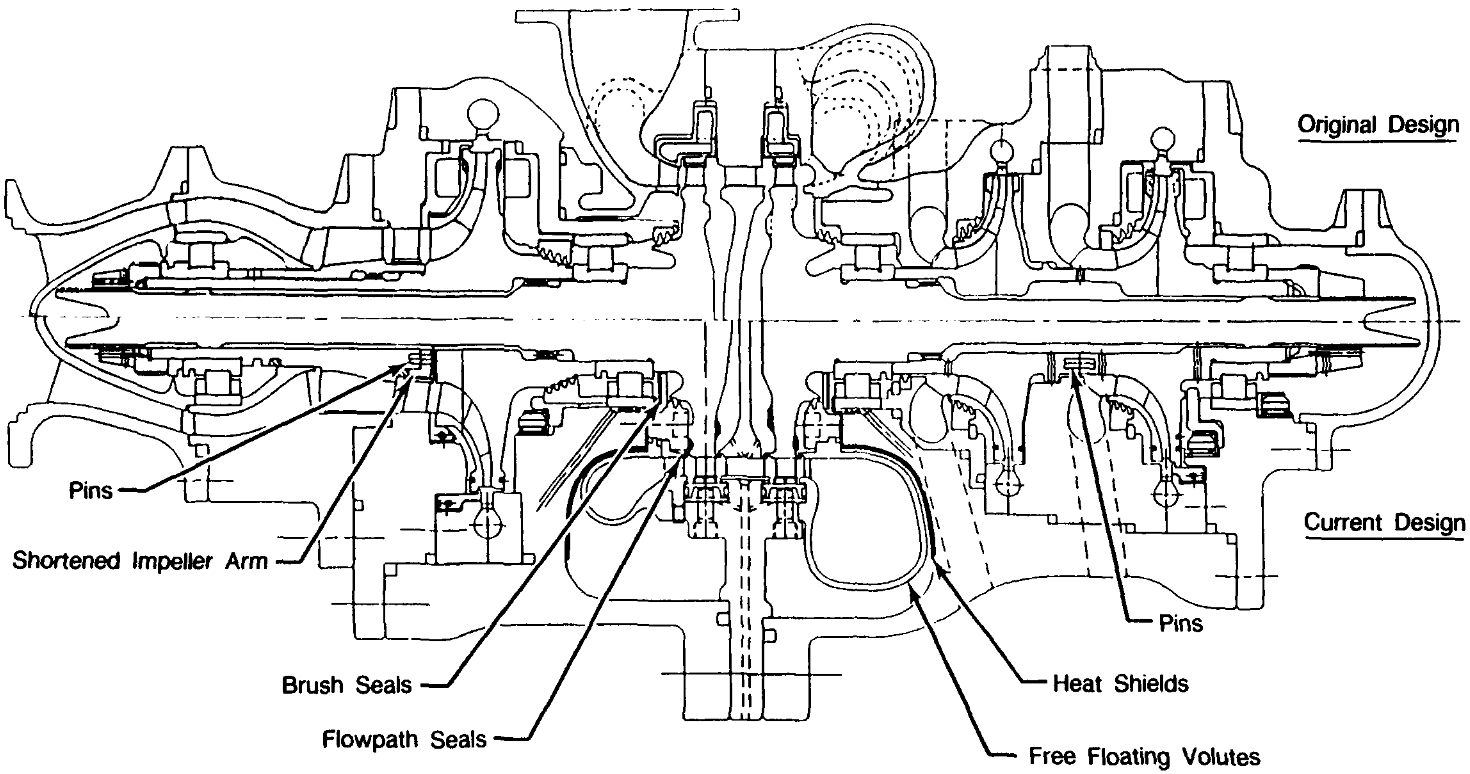

Figure 8. Fuel Turbopump Configuration Comparison

- *Turbines* — Since the original conceptual design, flowpath seals have been added to the primary and secondary turbine disk rims to reduce hot gas inflow and maximize efficiency. Blade airfoils have been modified in response to performance analysis updates. The area between the hub region of the disk and the bearing of both primary and secondary turbines, has been revised to accommodate brush seals for reduced leakage.

  Primary disk burst margin calculations, using deck W140 and based on residual growth criteria, indicate a margin of 32 percent for the primary stage, and 33 percent for the secondary stage, compared to the design criteria minimum acceptable of 22 percent.

  A preliminary finite element stress analysis (BEASY) of the primary disk has shown that bore stresses are acceptable. A more detailed element breakdown is required for further analysis.

  Work is proceeding to attain the goal critical speed margin of 20 percent at design point by reducing the integrally bladed disk-to-bearing overhangs and the bearing-to-bearing spans.

- *Housings* — The conceptual design of the turbine inlet volute was single radial entry. Both inlet and exit volutes were also integral with the turbine housing. Currently the turbine volutes are single tangential entry and are free floating radially to eliminate thermal stresses that could result from the 916°F temperature gradient caused by 524°F fuel inlet temperature and −392°F bearing coolant temperature. A heat shield is used to minimize heat transfer from the volutes to the housings.

  In the original design, the turbine vanes and turbine static tip seals were integral and it would have been difficult to control the radial clearance between the blade tip and static seal during operations. In the present design, turbine vanes and tip seals are radially independent of each other and thermal radial movement of vanes has no effect on the seals. The static tip seals are positioned by six radial pins. Clearance between the blade tips and tip seals is controlled by coolant flow to maintain turbine performance.

  The pump exit volutes are made in two halves and welded to ease manufacturing. The volutes are also pressurized externally to reduce stresses on the volute cutwater.

- *Bearings* — A single roller bearing configuration has been designed for use in all four bearing positions in the fuel turbopump. For the preliminary design, a parametric analysis was conducted to optimize the rolling element size, quantity of rolling elements, geometry of rings and rolling elements, and negative internal clearance requirement. Design guidelines established under the SSME/ATD program aided the geometry selection. Careful consideration was given to the tradeoff of sufficient roller preload with maximum allowable contact stress.

  A stress analysis of the outer ring was conducted to verify HCF life. The outer ring is designed to flex over the rollers for preload which induces alternating bending stresses.

  A heat generation analysis was conducted to determine the cooling flow requirements. The analysis indicates that 0.2 pps of hydrogen would provide the desired bearing temperatures.

The negative internal radial clearance (IRC) of the bearing was calculated using a model that simplifies the fit analysis procedure. The CYLFLEX model eliminates the iterations required to determine the interaction of roller load on shaft and housing fits.

An alternate roller bearing design using cage-assisted rollers was also completed. This design uses the cage to guide the rollers instead of relying totally on the negative internal clearance for roller stability. Another advantage is that it eliminates the potential for metal-to-metal contact at the inner ring guide flange.

- *Structural Analysis* — Structural analysis of the preliminary AETB fuel turbopump design was completed for several components. These components include the first stage impeller, the first stage turbine disk, and the first stage turbine shroud. Structural analysis was completed for several impeller configurations with 2D and 3D structural analysis tools. The impeller analysis to date indicates blade stresses resulting in 100 cycles of LCF life. The blades have been redesigned and the structural analysis of the redesigned configuration is in progress.

  Structural analyses of the first-stage turbine disk and blades were completed with a 2D structural analysis tool. The analysis indicates adequate disk burst margin and shroud stresses which meet the 100-cycle LCF life requirement at the design point. Shroud modifications and subsequent structural analyses are in progress.

3. Thrust Chamber and Nozzle Assembly

The thrust chamber assembly consists of an injector with igniter, combustion chamber, and a conical nozzle extension. The dual-orifice injector and milled channel liner combustion chamber are based on an existing design completed and detailed under a P&W Space Engine Component Technology Program. Although contract work on the assembly in 1990 included only the detailed layout of the exhaust nozzle, the design of all the hot section components is described in the following paragraphs.

- *Injector/Igniter* — The AETB igniter uses the same design approach used in the P&W SSME/ATD hot gas system preburners and the Advanced Launch System (ALS) Technology ignition system. Figure 9 shows the H_2O_2 torch igniter design that will be employed.

  The torch igniter consist of a Haynes 230 mount flange housing with a copper combustion liner and a Haynes 230 structural jacket. The ignition chamber is constricted at the exit for use in lighting the engine at altitude. Various ports on the mount flange allow for installation of the spark plug, instrumentation, and inlet lines. The igniter is mounted through the center of the injector by studs.

  The injector assembly, Figure 10, will be manufactured from 347 stainless steel. It consists primarily of an injector housing with a fuel manifold welded on the outside. In the center of the housing, various cavities are machined to create the internal oxidizer injection manifolds. Sixty-five dual-orifice elements are uniformly spaced in a circular pattern with allowance in the center for the torch igniter.

A separation plate is brazed in the top of the assembly to separate primary and secondary oxygen plenums. A welded dome is attached on top to close out the secondary plenum and allow installation of the igniter. The fuel plenum is created with a porous faceplate welded to the housing and brazed to individual fuel sleeves. The porous plate provides transpiration cooling of the injector face.

The core of the injector consists of the 65 LO_2 elements and fuel sleeves as shown in Figure 11. The elements are of the dual-orifice tangential entry type and are brazed to the top of the housing. Primary LO_2 enters each element through three holes equally spaced, and secondary oxygen enters through three equally spaced axial slots. On the bottom of the housing are nozzles machined from the housing forging where the sleeves are brazed. The annulus created by the nozzle OD and sleeve ID meter the fuel into the combustion chamber.

- *Combustion Chamber* — The combustion chamber (Figure 12) consists of a NASA-Z copper alloy liner with 120 milled coolant channels on the outside surface. The liner cooling channels are a constant 0.040-inch wide with a maximum height-to-width ratio of 5:1. The wall thickness between hydrogen coolant and hot combustion wall is a constant 0.030-inch thick. The passage height is set to allow a maximum wall temperature of 1460 R without exceeding the allowable budgeted cycle pressure drop. At the normal operating point, the maximum wall temperature is 1355 R. Maximum heat flux at the oper ating point is 51.7 Btu/in.^{2}-second occurring 0.50 inch upstream of the throat. The configuration provides a predicted life of 200 cycles or better. The milled chamber was chosen over a tubular copper chamber design based on work done under NASA Contract NAS3-23858.

  The liner has an electroformed copper outer jacket that closes out the milled coolant channels and provides structural support for the chamber. Coolant manifolds are welded to each end of the chamber. Both manifolds, of 347 SST material, are welded forming an internal primary distribution manifold with crossover ducts to a minor manifold created where the jacket and manifold are joined.

  The inlet manifold interfaces with the nozzle extension and the outlet manifold interfaces with the injector. Both of these joints incorporate a pilot snap fit. The snap is used to control radial movement during operation and centers the mating assemblies. The injector face extends into the chamber 0.7 inch to protect the uncooled portion of the liner.

- *Exhaust Nozzle* — The conical nozzle extension consists of 160 coolant tubes brazed into a structural jacket containing the inlet and exit manifolds. The nozzle cross section is shown in Figure 13. Haynes 188 alloy is the base material for the assembly details, chosen for its ductility, weldability, and good strength in hot hydrogen. It will also facilitate brazing during nozzle assembly, provide high-temperature capability, and meet heat transfer requirements.

  The 160 coolant tubes are brazed into the inlet and exit manifold with a structural jacket joining the two. Each coolant tube is joined to the inlet and exit manifold by a simple braze joint. On the inlet end the tube will be hooked so it will fit into the inlet manifold. The tube exit will be an offset square socket joint that will fit into a machined annulus ring. Various combinations of tube attachments were examined with the current tube configuration being the best to meet test bed requirements.

The inlet manifold also contains one end of a spring arm that is used for controlling the radial thermal growth caused by the 600°F temperature differential between the cold chamber inlet and hot nozzle inlet. The spring arm between the two manifolds is designed to accommodate the relative thermal deflections of the manifolds while eliminating seal sliding and maintaining acceptable structural integrity.

A preliminary structural analysis of the arm was completed. The analysis was begun by first examining the axisymmetric loads, then expanded to include asymmetric loading caused by transient pressure loads, weight, and interface loads. A factor of safety of 1.24 is indicated. Buckling analysis was completed by evaluating loading on the spring arm from axial, transverse shear, bending, and torsion, resulting in a buckling factor greater than 10.

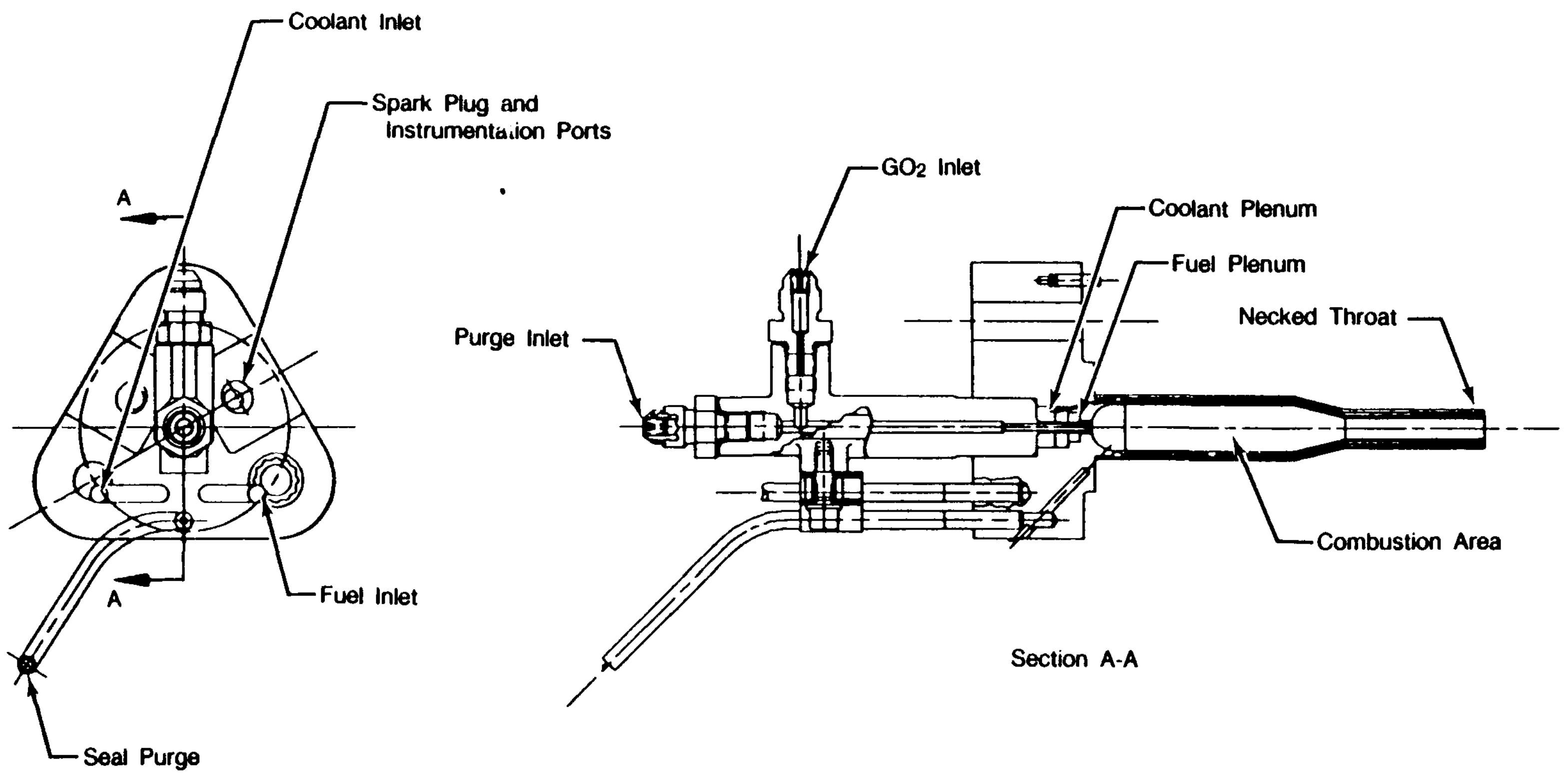

Figure 9. Igniter Assembly

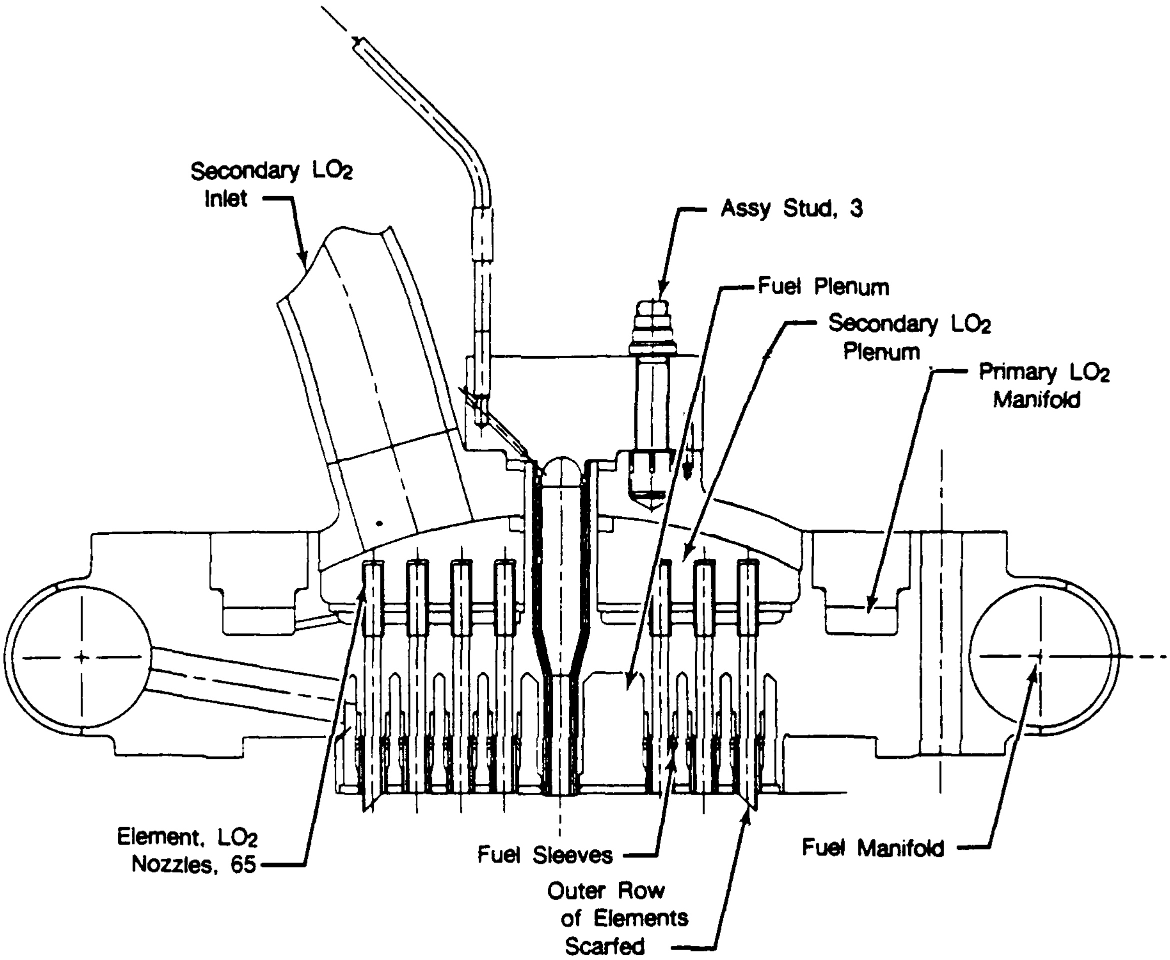

Figure 10. Injector Assembly With Igniter Mounted

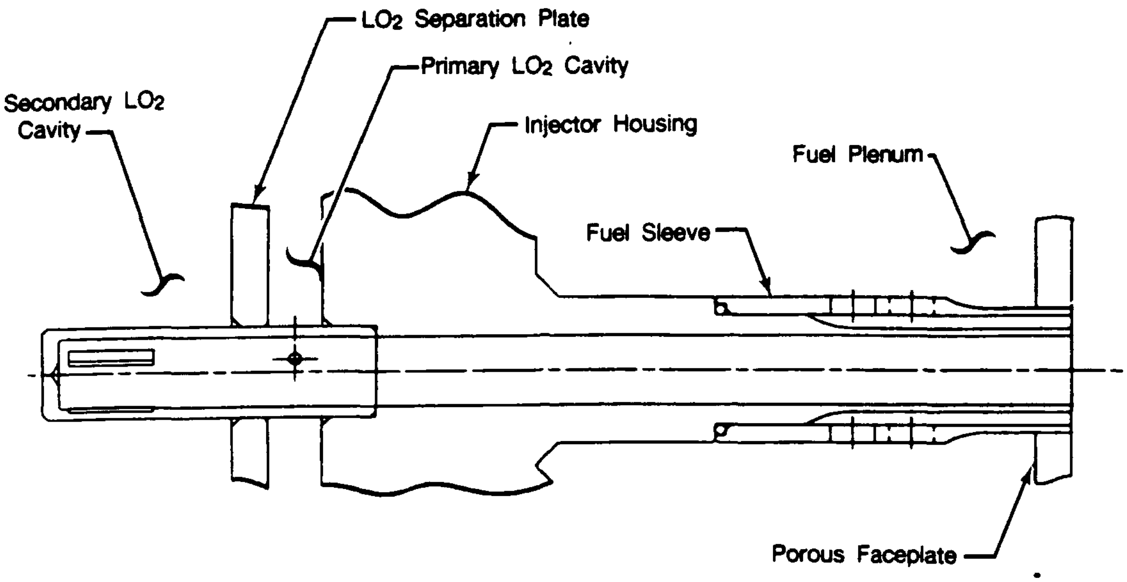

Figure 11. LO_2 Element and Fuel Sleeve

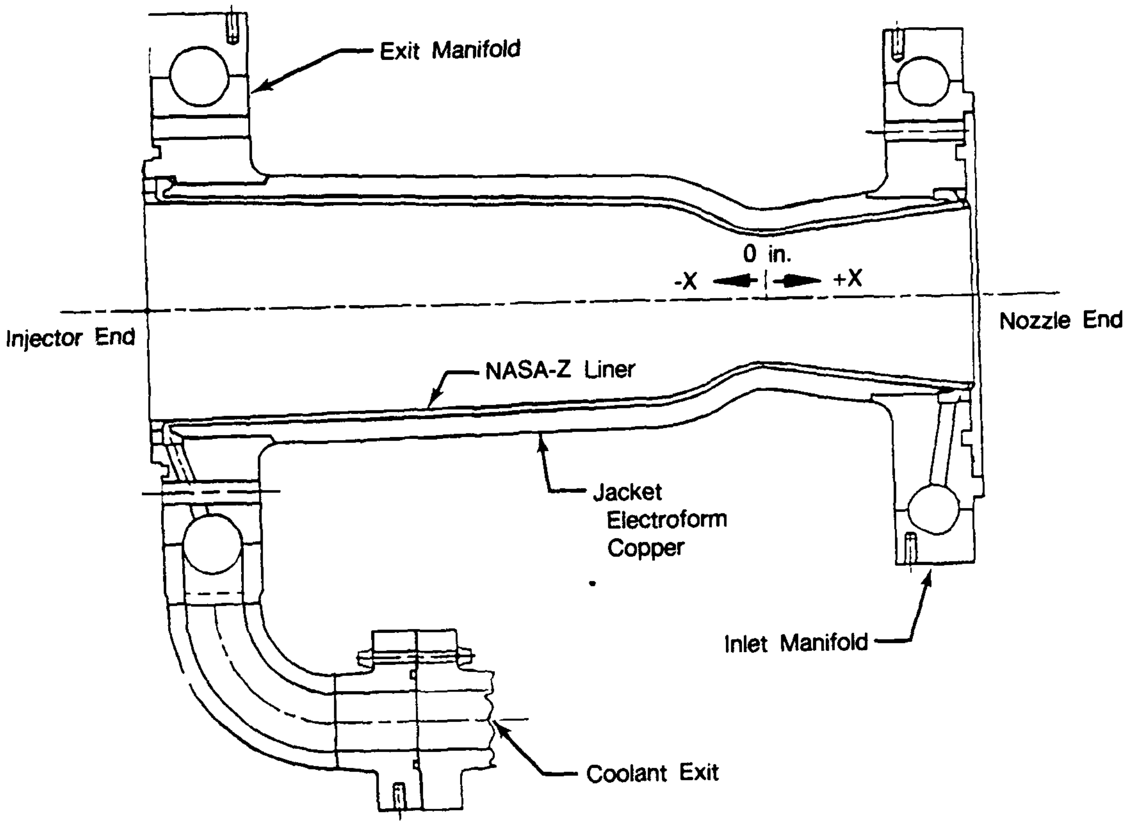

Figure 12. Combustion Chamber

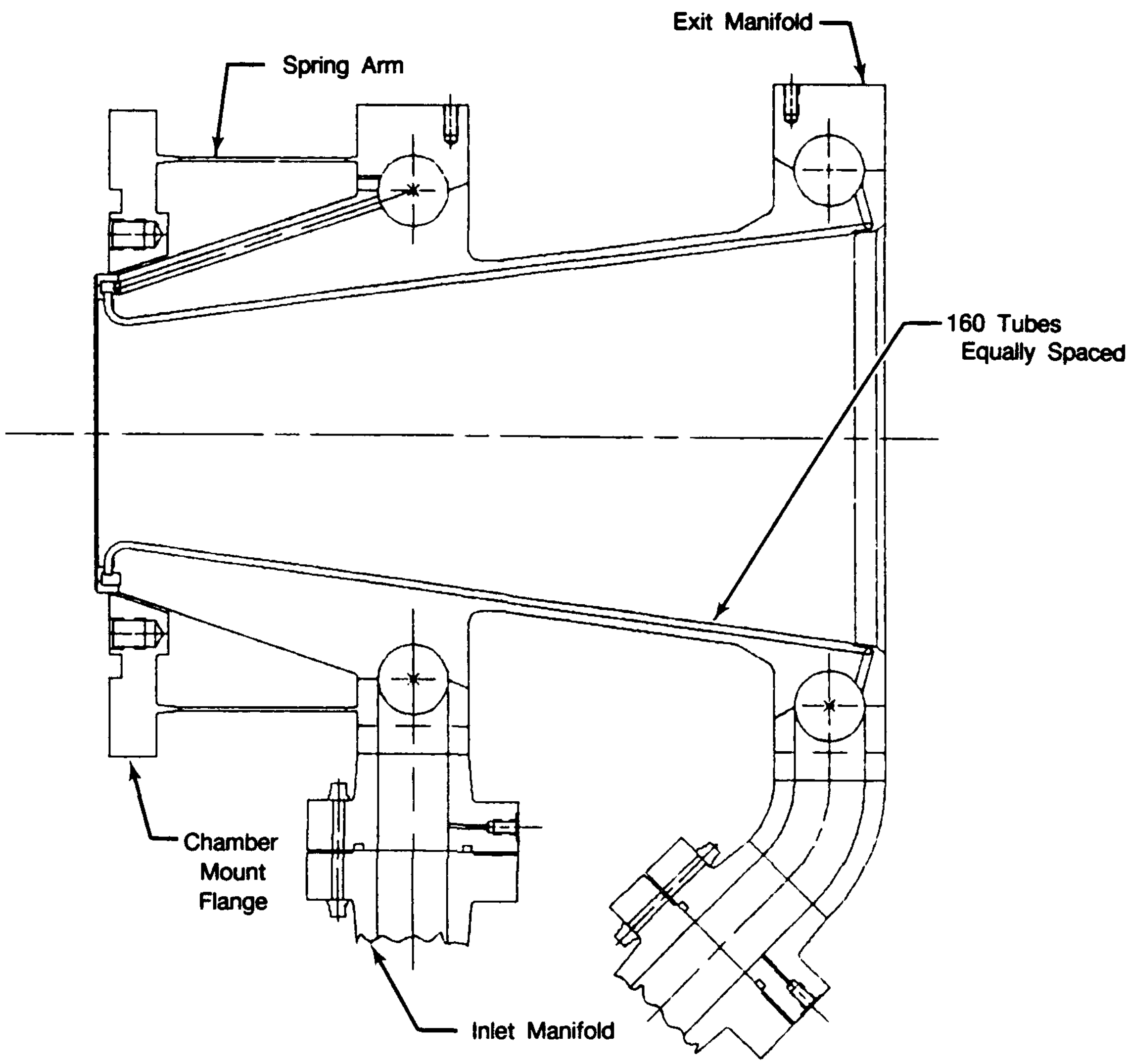

Figure 13. Exhaust Nozzle

4. Valves, Controls, and Monitoring System Components

The control system consists of the electronic controller, valves, actuators, ignition system, and feedback sensors. Significant control system accomplishments in 1990 are summarized below.

- *Electronic Controller* — Hamilton Standard (HS) was contracted to perform preliminary design of the electronic brassboard controller system for the AETB, and purchase performance specifications were issued to HS for the brassboard engine controller, monitor and brassboard test system. The HS brassboard architecture was based on an existing National Aero-Space Plane (NASP) rig controller design and was selected for its flexible and expandable design features.

  Three technical coordination meeting were held between P&W and HS.

These meetings identified many action items and were used to ensure a smooth flowdown of requirements.

Integration of the controller with the test facilities was initiated. A trip was made to NASA-LeRC RETF and NASA-Plumbrook B-2 stand to identify system locations and determine cabling requirements. Additional coordination is required to define data system, abort, and power interfaces.

Input/Output requirements were defined to perform basic test bed control and safety monitoring. These requirements exceeded the baseline definition. To accommodate these requirements, the controller has been designed with additional I/O discrete boards and a redesigned low-level board. These improvements provide spare I/O capabilities while still providing spare slots for additional boards.

Testing has been conducted on the NASP brassboard to verify the capability of the frequency board design. Test results indicate this board is capable of converting speed signals throughout the defined speed ranges. Additional testing will be performed to verify accuracy.

Throughput and memory studies were performed which verify sufficient margin exists. This study was based on information available from the NASP test configuration and provides a high confidence in accuracy of the estimates.

- *Valves and Actuators* — The valve and actuator performance requirements were defined from cycle analysis and used to create component specifications. For each valve location, specifications for the valve, actuator, and position sensing device were written as one component so each supplier would furnish a complete assembly. These specifications were then sent to potential suppliers for a Request for Quote. Several responses were received for all valve assemblies. At present, the proposals are being evaluated on both a technical and cost basis.

  The valves required for the test bed are listed in Table 13. The valve assemblies can be divided into three main categories: variable control (5), on/off (10), and purge valves (7). The variable control valves will have LVDT feedback and be actuated by hydraulics. The main on/off valves will have a discrete position indicator and be actuated by pneumatics. The purge valve solenoids will have a discrete position indicator and be operated by electrical relay. The variable control and on/off valves will require some modifications to existing designs, whereas the solenoids exist as catalogue items.

- *Ignition System* — The torch igniter will be lit by a spark plug which receives its voltage from an exciter mounted on the test bed. Voltage to the exciter will be provided by the controller. The spark plug will be identical to the plug developed and bench tested for an Advanced Launch System subscale program and fabricated from commercially available components.

- *Feedback Sensors* — The feedback sensors required for control and safety monitoring have been established. They include sensors for speed, pressure, temperature and vibration. A listing of each sensor is shown in Table 14. Sensor requirements have been established and potential suppliers selected based on past effort on various other P&W programs. Formal Request for Quotes will be sent out in 1991 to potential suppliers.

- *Cables* — The cable block diagram was completed and the electrical requirements established. The cable construction, shielding, and grounding plans will follow the same design as other major P&W programs.

TABLE 13. — ADVANCED EXPANDER TEST BED VALVE REQUIREMENTS

VALVE Name	FEEDBACK (Indicator: Open/Closed)	REQUIREMENTS					CONTROL MODE
		REDUNDANCY (Failsafe: Open/Closed)	SYSTEM ACCURACY % F.S.	BANDWIDTH Hz	SLEW TIME sec	SAMPLING sec	
FJBV/CCBV	Position	Single (C)	1.5	3	0.200	0.020	Schedule
FTBV/OTBV	Position	Single (O)	1.5	5	0.300	0.010	Closed Loop
MTBV	Position	Single (O)	1.5	5	0.300	0.010	Closed Loop
SOCV	Position	Single (C)	1.5	3	0.300	0.020	Schedule
FPRV	Discrete (C)	Single (C)	N/A	N/A	1.000	0.020	f(Pc&OF)
OPRV	Discrete (C)	Single (C)	N/A	N/A	1.000	0.020	f(Pc&OF)
EFIV	Discrete (O)	Single (C)	N/A	N/A	0.500	0.020	f(time)
EOIV	Discrete (O)	Single (C)	N/A	N/A	0.500	0.020	f(time)
FSOV	Discrete (O)	Single (C)	N/A	N/A	0.500	0.020	f(time)
POSV	Discrete (O)	Single (C)	N/A	N/A	0.300	0.020	f(time)
OISV	Discrete (O)	Single (C)	N/A	N/A	0.300	0.020	f(time)
FISV	Discrete (O)	Single (C)	N/A	N/A	0.300	0.020	f(time)
FCDV	Discrete (C)	Single (O)	N/A	N/A	0.400	0.020	f(time)
OCDV	Discrete (C)	Single (O)	N/A	N/A	0.300	0.020	f(time)
FTSV	Discrete (O)	Single (C)	N/A	N/A	0.500	0.020	f(time)
S1PV	Discrete (O)	Single (O)	N/A	N/A	0.100	0.020	f(time)
S2PV	Discrete (O)	Single (O)	N/A	N/A	0.100	0.020	f(time)
S3PV	Discrete (O)	Single (C)	N/A	N/A	0.100	0.020	f(time)
S4PV	Discrete (O)	Single (C)	N/A	N/A	0.100	0.020	f(time)
S5PV	Discrete (O)	Single (C)	N/A	N/A	0.100	0.020	f(time)
S6PV	Discrete (O)	Single (O)	N/A	N/A	0.100	0.020	f(time)
S7PV	Discrete (O)	Single (O)	N/A	N/A	0.100	0.020	f(time)

TABLE 14. — ADVANCED EXPANDER TEST BED VALVE CONTROL SENSORS

PARAMETER	REQUIREMENTS						SAFETY	
	REDUN-DANCY	SYSTEM ACCURACY (+/-)	RANGE	UNITS	SAMPLING msec	BAND-WIDTH Hz	PER-MISSIVE	REDLINE
Fuel Pump 1 Metal Temp	Single	10 deg	38-600	Deg R	80	0.2	X	
Fuel Pump 1 Inlet Press	Single	4% FS	0-75	PSIA	80	1.0	X	X
Fuel Pump 1 Speed	Single	0.5% FS	7.5K-110K	RPM	20			X
FP1 Brg. #1 Inlet Temp	Single	(2)	38-180(1)	Deg R	80	1.0		X
FP1 Brg. #1 Exit Temp	Single	(2)	38-180(1)	Deg R	80	1.0		X
FP1 Brg. #2 Inlet Temp	Single	(2)	38-180(1)	Deg R	80	1.0		X
FP1 Brg. #2 Exit Temp	Single	(2)	38-180(1)	Deg R	80	1.0		X
Fuel Pump Assembly Radial Vibration	Single	5% FS	0-20	G's	20			X
Fuel Pump 2 Speed	Single	0.5% FS	7.5K-110K	RPM	20			X
FP2 Brg. #3 Inlet Temp	Single	(2)	38-180(1)	Deg R	80	1.0		X
FP2 Brg. #3 Exit Temp	Single	(2)	38-180(1)	Deg R	80	1.0		X
FP2 Brg. #4 Inlet Temp	Single	(2)	38-180(1)	Deg R	80	1.0		X
FP2 Brg. #4 Exit Temp	Single	(2)	38-180(1)	Deg R	80	1.0		X

NOTE: (1) All cryogenic temp sensors must read up to 600 °R, but accuracy required above listed value may be reduced to ± 15 °R.
(2) Required accuracy is to measure a delta of ± 2 °R across the bearing. The absolute accuracy for the temp readings is ± 10 °R.

TABLE 14. — ADVANCED EXPANDER TEST BED VALVE CONTROL SENSORS (CONTINUED)

PARAMETER	REQUIREMENTS						SAFETY	
	REDUN-DANCY	SYSTEM ACCURACY (+/-)	RANGE	UNITS	SAMPLING msec	BAND-WIDTH Hz	PER-MISSIVE	REDLINE
LO2 Turbine Inlet Temp	Single	10 deg	500-1200	Deg R	80	0.5		X
LO2 Pump Metal Temp	Single	10 deg	160-600	Deg R	80	0.2	X	
LO2 Pump Inlet Press	Single	4% FS	0-75	PSIA	80	1.0	X	X
LO2 Pump Speed	Single	0.5% FS	5K-55K	RPM	20			X
LO2 Pump Radial Vibs	Single	5% FS	0-20	G's	20			X
LO2P Brg. #1 Inlet Temp	Single	(2)	160-215(1)	Deg R	80	1.0		X
LO2P Brg. #1 Exit Temp	Single	(2)	160-215(1)	Deg R	80	1.0		X
LO2P Brg. #2 Inlet Temp / Brg. #3 Exit Temp	Single	(2)	38-180(1)	Deg R	80	1.0		X
LO2P Brg. #2 Exit Temp	Single	(2)	38-180(1)	Deg R	80	1.0		X
LO2P Brg. #3 Inlet Temp	Single	(2)	38-180(1)	Deg R	80	1.0		X
IPS He Pressure	Dual	5% FS	15-1000	PSIA	20	1.0		X
IPS He/H2 Disch Press	Single	5% FS	0-300 (3)	PSIA	20	1.0		X
IPS He/O2 Disch Press	Single	5%FS	0-100 (3)	PSIA	20	1.0		X
Main Chamber Press,Low	Single	1% FS (5)	0-150 (4)	PSIA	20	7.0	X	X
Main Chamber Press,Med	Single	1% FS (5)	0-500 (4)	PSIA	20	7.0	X	X
Main Chamber Press,High	Single	1% FS (5)	0-1500	PSIA	20	7.0	X	X
Igniter Chamber Press	Single	1% FS (5)	0-1500	PSIA	20	7.0	X	X
Low Press He Purge	Single	5% FS	15-100	PSIA	80	1.0		X
High Press He Purge	Single	5% FS	15-1500	PSIA	80	1.0		X
Low Press N2 Purge	Single	5% FS	15-100	PSIA	80	1.0		X
High Press N2 Purge	Single	5% FS	15-1000	PSIA	80	1.0		X

(3) Rate transducer for an overpressure of 1000 psia.
(4) Rate transducer for an overpressure of 1500 psia.
(5) Transducer in a controlled temp environment (+/- 25 deg)

5. Hydrogen Mixer

The layout drawing of the mixer has been completed, and detail drawings await initiation of the detail design phase.

In the split expander cycle, the hydrogen mixer, shown in Figure 14, mixes the warm hydrogen from the turbines with the cold hydrogen from the first-stage fuel pump discharge. The combined flow then enters the main combustor chamber injector fuel manifold. Good mixing of these streams is critical to maintaining stable combustion and uniform flow through the individual fuel elements. At the design point, the flow into the mixer is evenly split between the hot and cold lines. The cold hydrogen flow is controlled by means of the fuel jacket bypass valve (FJBV). The percent of cold flow bypassed is lower at lower throttle conditions. For instance, at 20 percent thrust, the FJBV is completely closed so all the flow into the mixer is the warm hydrogen from the turbines. When bypassing cold flow to the mixer, the mixer must effectively mix the hot and cold hydrogen, yet minimize system pressure loss. To achieve the required mixing performance, the AETB will use an inline mixer similar to the one used by the Space Shuttle Main Engine system. The mixer works on the same principle as a jet pump, i.e., a high velocity stream imparts momentum to alower velocity stream. The momentum transfer creates turbulence which promotes mixing of the two streams.

The hot hydrogen from the turbine discharge forms the high-velocity stream while the cold hydrogen from the pump is the low-velocity stream. Using the established design procedure for jet pumps, the minimum mixing length for the maximum jet pump efficiency was calculated to be 10 inches for the AETB design at worst case operating conditions. Given the overall mixing length of 37 inches and the relatively high momentum ratio of 28 between streams, the AETB mixer design is conservative and will provide uniform flow to the injector.

The mixer design incorporates the following features.

- A two-piece construction that nearly eliminates the thermal stress problems that were evident with an earlier welded, one-piece design.

- A separate piece of hardware for the hot inflow, which provides the versatility of changing mixer geometry to evaluate alternative mixer designs.

- Parts that are machined entirely from 347 stainless steel using only conventional machining techniques.

- Repairability that is built into the design by allowing enough radial clearance around all tapped holes for threaded insert repairs.

- A conservative LCF that exceeds 3000 thermal cycles.

- A cantilevered tube natural frequency of 3300 Hz. This is well below either pump rotor vibration modes and well above the low energy vortex shedding frequency of 66 Hz.

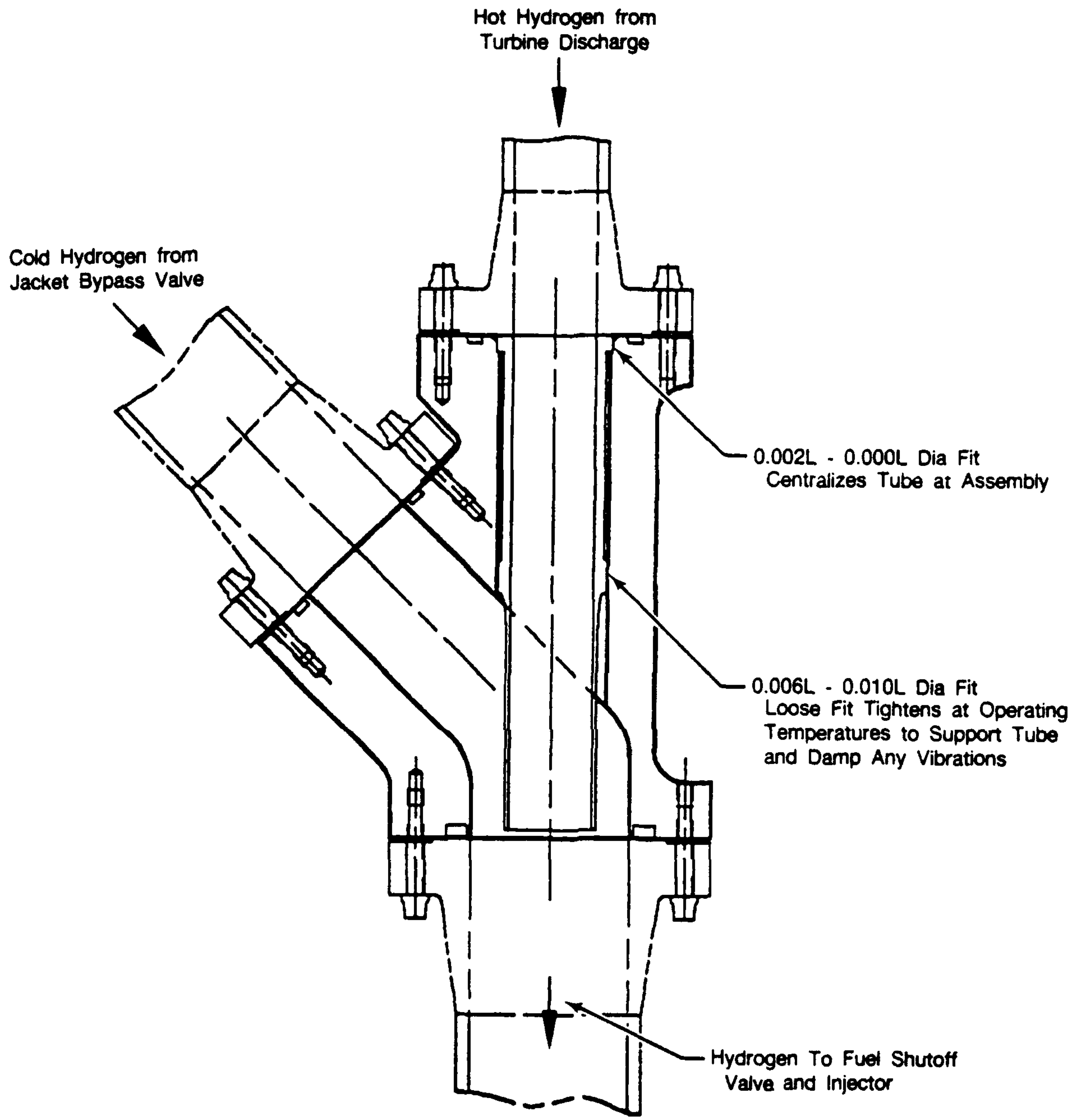

Figure 14. Hydrogen Mixer

6. System Integration

Under the system integration task, all propellant lines and component supports are being designed, and the various components are being integrated into the test bed configuration. Significant accomplishments are summarized below.

The flow schematic has been updated and is shown in Figure 15. The following improvements over the proposal schematic are included.

- The purge system has been expanded to seven purge valves. The hydrogen system will use a GHe purge and the oxidizer system will use a GN_2 purge.

- The igniter is to be supplied with facility GO_2 connected to the oxidizer igniter shutoff valve (OISV).

- The fuel supply to the igniter has been changed. At start and low chamber pressure operation, hydrogen flows from the combustion chamber coolant exit to the fuel igniter shutoff valve (FISV). This provides the necessary higher pressure for the igniter fuel supply. At higher chamber pressures, the FISV will switch to receive supply flow from downstream of the fuel shutoff valve (FSOV). This lower pressure supply, coupled with an added flow restrictor, eliminates excess cooling flow to the igniter.

- A chamber coolant bypass valve (CCBV) has been added as an option to achieve full expander operation between 750 and 940 psi chamber pressure. This is accomplished by relocating the fuel jacket bypass valve (FJBV) for this special test.

- The original plans were to relocate the variable fuel turbine bypass valve (FTBV) for tank head idle (THI) runs to the fuel turbine shutoff valve (FTSV) location. The arrangement was changed to provide a separate on/off valve for the FTSV. The change was incorporated to allow running from THI to full power without a valve configuration change. Although P&W does not plan to run this transition test, the hardware provided will have such capability for future NASA evaluations.

The preliminary 3D test bed graphic model incorporates component, valve, and actuator envelopes. The current layout is shown in Figure 16. The test bed will be fired in a vertical position at P&W and NASA, and the turbopumps will be mounted vertically. An 8-sided frame, similar to a bird cage, surrounds the thrust chamber. The pumps and major valves are mounted on the outside of the frame to provide accessibility. The frame can be disassembled for access to the thrust chamber. The test bed integrated design envelope is being driven by the requirement to fit into P&W's E-6 test facility. By staying inside the E-6 envelope, the test bed should also fit into NASA's RETF facility.

D. TASK 8.0 — TECHNICAL ASSISTANCE

During late 1990, NASA authorized P&W to assist in installation of the ROCETS computer program at NASA-LeRC, verify its proper operation, and help train operators in its use. A data link was established between P&W/GEB and NASA-LeRC and a user ID established on the government computer system. The ROCETS system was installed on the LeRC computer after being received from NASA-MSFC. P&W personnel assisted in verifying code operation and instructing Government contractor engineers in its operation. As a second part of this task, P&W electronically transmitted a preliminary version of the AETB steady-state engine model to NASA-LeRC. A backup tape and user's manual was sent by post shortly thereafter. At the time of this report, NASA contractor personnel are learning to run this deck with assistance from P&W.

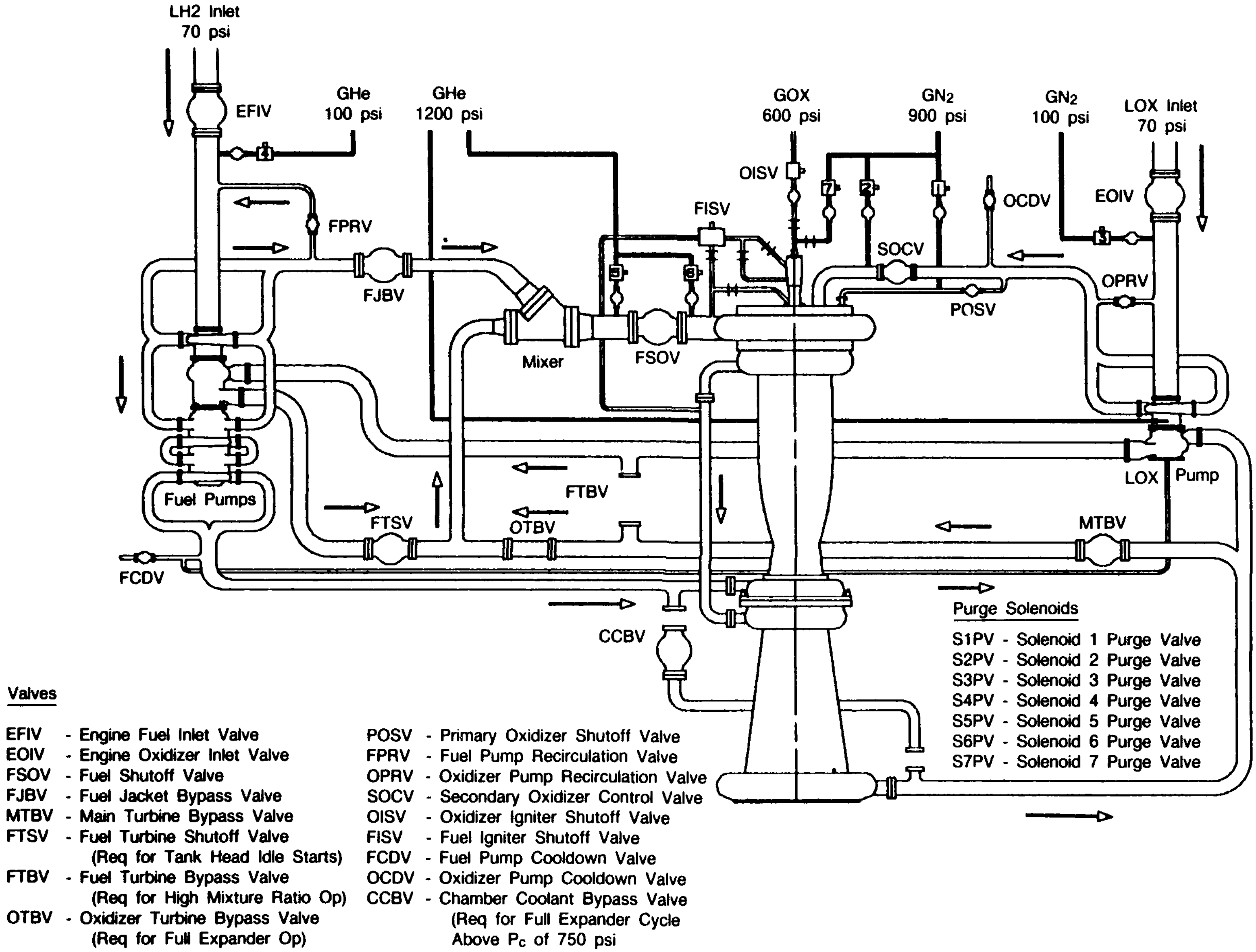

Figure 15. AETB Flow Schematic

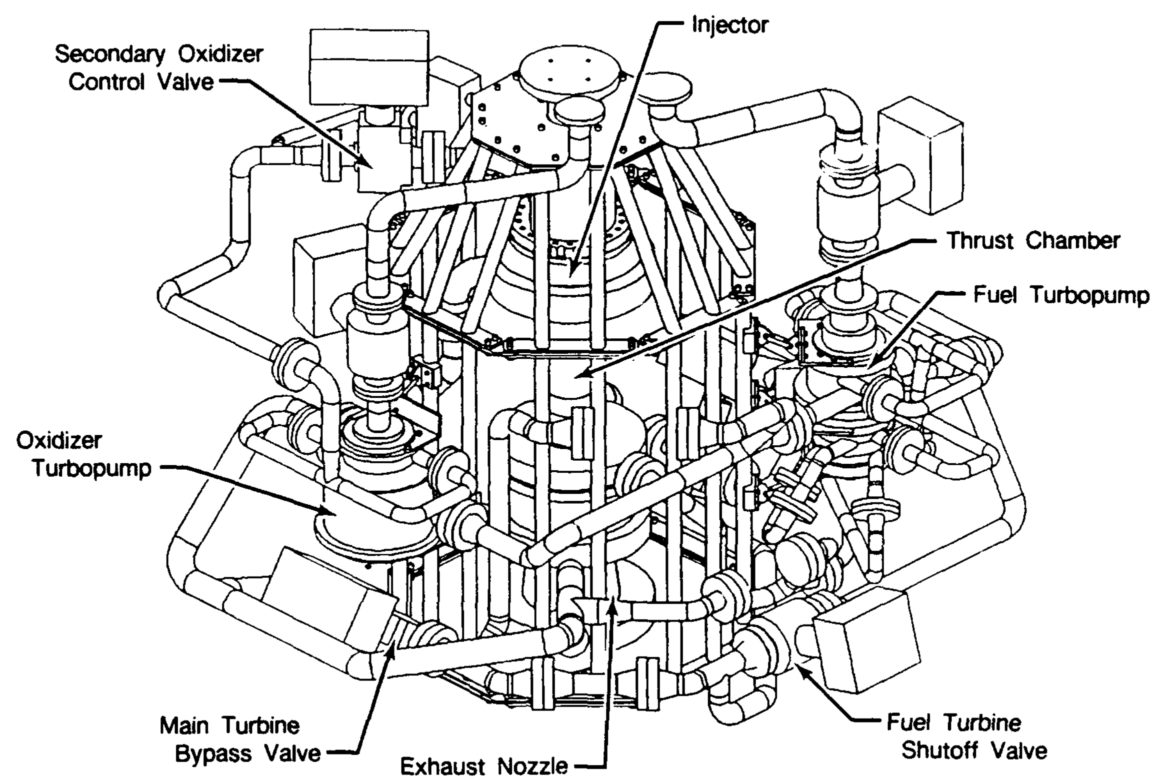

Figure 16. AETB Graphic Model

SECTION IV
CURRENT PROBLEMS AND FUTURE WORK

No technical problems have been encountered that would prevent the successful completion of the program or affect the program schedule.

Work planned for 1991 includes:

- Presentation of the Preliminary Design Review in January.
- Beginning of the Final Design phase in February, with progress toward Critical Design Review to be paced by available funding.
- Publication of a revised Program Work Plan in May.

APPENDIX A
DESIGN METHODOLOGY

ENGINE SIMULATION CODE

E38Y — AETB Engine Model

CODE, FEATURES, AND APPLICABILITY

E38Y is a new engine cycle off-design deck, which was written in the ROCETS system specifically for the AETB. E38Y uses detailed component models, the latest National Bureau of Standards (NBS) real gas properties and sophisticated simultaneous balancing techniques to achieve accurate, high-speed solutions. During the preliminary design phase of the AETB contract, this simulation will be used as a steady-state balance to generate a fluid environment at each station and component requirements over the entire range of engine operating conditions. In addition, cycle sensitivity studies will be conducted to determine the critical component performance parameters such as fuel pump efficiency or chamber heat transfer. The dynamic simulation balance includes critical volume dynamics rotor inertias, dynamic heat exchanger response, and control system characteristics. Many of the modeling techniques have been developed and substantiated in detailed SSME simulation work in support of P&W's ATD Program. The transient balance will be used in the preliminary design to identify control system requirements and provide transient data for use in component design. Various trade studies, such as valve slew rate, will be conducted in support of the design. During the preliminary design phase, the transient engine balance will provide a baseline for developing a real time engine model. The real time model will be used to checkout the engine control system prior to engine tests.

MODEL VERIFICATION

E38Y will be baselined and verified throughout the AETB component and engine acceptance testing. The decks will then be provided to NASA for use in conjunction with AETB testing.

PUMP HYDRODYNAMICS

4233 — Quasi-3-D Streamline Analysis

V080 — 2-D Cascade Potential Flow Analysis

E29X — Flow Balance Model

CODE, FEATURES, AND APPLICABILITY

Code 4233 is an Euler flow analyses of radial mixed-flow and axial impellers and diffuser vanes. Solution provides definition of velocity and pressure distributions throughout flowfield for evaluation of hydrodynamic loadings, flow separation criteria, etc. Empirical loss and slip factors are applied to the solution. Improved loss and deviation models accounting for secondary flows and incidence diffusion losses have recently been incorporated.

Code V080 provides 2-D intrablade potential flow solution for airfoil cascades. The analysis is applicable to rotating or stationary airfoil cascades. Boundary layer analysis is applied to inviscid solution. The code has recently been updated to include boundary layer, shape factor evaluations with correlations of separation limits.

E29X is used for pump performance analysis and definition of internal leakage flows and pressure distributions within pumping system. The model integrates analysis derived from the various design codes with numerous subroutines to describe internal seal leakage, disk-friction, pumping, and heat transfer effects on pump performance and axial thrust balance. The model was recently updated to incorporate new seal leakage routines, disk pumping calculations, and heat transfer subroutines in support of the SSME ATD effort.

NASTAR is a new P&W CFD code, combining the advantages of several previous codes. NASTAR is unique in handling fluid velocities that cover the subsonic to hypersonic regime. NASTAR will be used to model the AETB fuel impeller at off-design conditions.

MODEL VERIFICATION

The pump hydrodynamic design codes have previously been verified and baselined using results from XLR-129 throttleable high-pressure engine component tests and SSME ATD tests. Verification of scaling to AETB conditions will be obtained from the planned fuel and oxidizer pump tests over a wide range of operating conditions.

ROTOR DYNAMIC CODES

M636 — Engine Critical Speeds Analysis

A346 — Engine Forced Response Analysis

P871 — Engine Static Deflection Analysis

DERVA — Design of Engine Rotors by Vibration Analysis

ARDS — Analysis of Rotor Dynamic Systems

GEOBAL — Geometric Balance Correction Procedure

CODE, FEATURES, AND APPLICABILITY

Code M636 is used for rotor dynamic analysis of engine turbopumps and test rigs. The deck calculates rotor undamped critical speeds and their corresponding mode shapes based on the Prohl-Transfer Matrix Method. The proprietary P&W analysis has evolved over the past 15 years, based on work in both Florida and Connecticut facilities.

Code A346 is used to calculate the synchronous steady-state vibration response of the entire rotor system due to distributed unbalance or constant forces. The analysis is based on the Prowl Method and assumes circular whirl orbits. The program includes the capability for both linear and non-linear damped response analysis.

Code P871 predicts rotor deflected shape and bearing loads of an engine subjected to inertial loading due to static forces. The program is especially useful for calculating blade and vane tip closures due to inertial loading. The program is a proprietary P&W code that has evolved over the past 15 years.

DERVA is an interactive analysis selector and results processor. The code is a menu-driver tool which links the Critical Speed, Forced Response, and Static Deflection decks. The code is P&W proprietary and is continually updated.

The ARDS code is a finite element based analysis developed to calculate the free and forced vibration response of a turbopump rotor bearing system. The code is also used to determine the rotor stability to system damped whirl modes. The code was developed through a NASA-LeRC grant to the Department of Aerospace Engineering at Arizona State University.

GEOBAL processes geometric dimensional data from sonic or contact type inspections to calculate the part balance correction magnitude and determine the proper correction plane. The new P&W proprietary code was developed in 1989 by the Computational Structural/Design Methods group and validated in 1989 at the P&W Florida test facility. The process will be used for partial rotor balance corrections for the AETB turbopumps and all test and spin rig rotors.

MODEL VERIFICATION

The rotor dynamic codes used for the AETB engine design are a combination of industry standard codes and P&W proprietary codes. No special verification of these codes is planned for the AETB Program. However, several component verification tests, including model analysis and rotor vibration monitoring, will be conducted to confirm the components respond as predicted, and thereby substantiate the application of the analysis methods.

BEARING CODES

A926 and U092 — Ball Bearing Analysis of Stresses and Deflection

T165 — Flexible Ring Analysis of Roller Bearings

E040 — Shaberth Bearing Analysis

CODE, FEATURES, AND APPLICABILITY

A926 and U092, the latest revisions to the Jones Ball Bearing Program, are used by P&W to calculate ball dynamics, contact stresses, and bearing stiffness. The U092, or Jones V, has added capabilities to handle flexible rings and output from the program can be plotted. The A926, or Jones II, assumes rigid rings but can handle multiple bearings on a shaft.

T165, the latest revisions to the Jones Roller Bearing Program, is used by P&W to calculate roller bearing contact stresses and deflections. This version of the Jones program can handle the effects of flexible rings which is critical for the negative internal radial clearance (IRC) roller bearing.

E040, the updated Shaberth Bearing Analysis Program, is a 1988 code used to calculate frictional heat generation. The heat generation output is used in conjunction with empirically derived Viscous heat generation to define cooling requirements for the bearing. The heat generation is also input into thermal models for calculating component temperatures.

MODEL VERIFICATION

These Jones codes, A926 and U092, have been verified based on this extensive data base. During an IR&D Rig Test Program, the locations and size of the contact pattern on the ball raceway will be examined. Based on the predicted bearing internal clearance from the fit program and the loading used in the test, the actual size of the contact paths of the inner and outer race will be compared with the prediction. This will confirm the thrust loads run in the test since the contact patterns calculated by the program have been verified in previous applications.

This Jones code, T165, has b n verified based on an extensive data base. Test programs will demonstrate that the roller ıring meets the AETB life requirement.

The Shaberth (E040) heat generation calculations in conjunction with P&W developed empirical correlations for viscous effects have been verified under the SSME-ATD Program. During rig test programs, fluid thermocouples will be employed to measure bearing heat generation during the testing and compared to the analytical predictions.

INTERNAL FLOW CODES

V169 (FABL) — Flows and Bearing Loads. Predicts Internal Flows, Pressures, and Axial Thrust Load

V180 (MARCIE) — MARC CHAP Interactive Editor. Generates and Edits Geometry Models and Processes Output

V166 (BCON) — Boundary Condition Program

CODE, FEATURES, AND APPLICABILITY

FABL is a new program that has been developed over the past five years. FABL is used to produce internal flow models which calculate pressures, cooling and leakage flow rates, and the axial thrust load on the shaft. Flow models consist of a series of chambers interconnected by various flow restrictions such as metering orifices, labyrinth seals, and vortex circulations within internal cavities.

MARCIE will be used to generate new geometry or modify existing ANVIL geometry files to create data sets consisting of node systems for temperatures to be calculated. Geometry models will be created for the AETB turbopumps and rigs. MARCIE will also be used as a postprocessing tool to create plots of temperatures and colored iso-thermal plots.

BCON generates boundary data which includes boundary temperatures, film coefficients, flows, heat generation, emissivity, and engine speed values. This information is passed to CHAP through a file created by BCON.

MODEL VERIFICATION

Tests of the ISP will calibrate leakage and confirm wear rates and seal package critical dimensions (FABL). Instrumentation will include coolant inlet and discharge pressures and temperatures, coolant flows, and internal pressure taps. Additional methodology verification will be performed for the oxidizer and fuel turbopumps in conjunction with the acceptance testing.

These codes, MARCIE and BCON, will be used to support the AETB design effort but are not recommended for the model.

TURBINE AERODYNAMIC CODES

M905 — Interactive Graphics Airfoil Design System

V310 — 3-D Multistage CFD Flow Analysis

Y237 — 2-D Multistage Unsteady CFD Flow Analysis

CODE, FEATURES, AND APPLICABILITY

Code M905, the airfoil contour design system, has an improved 2-D pressure distribution analysis, and the capability to incorporate elliptical leading edges to improve airfoil performance at off-design conditions. Low loss airfoil design criteria based on modern P&W turbine engine data was incorporated into this system in 1985.

Code V310, the 3-D Multistage CFD Flow Analysis, provides highly accurate predictions of the flow conditions (pressure distribution, velocities, and angles) of the entire turbine flowpath including inlet and exit volutes. The multistage solver enables optimization of all turbine components as a unit. This multistage analysis is the only tool in the industry available for high-performance turbine design that enables interstage boundary conditions to be accurately modeled. This tool has been applied to P&W turbine designs since the middle 1980s. Improved performance and reduced risk results from this global optimization capability.

Code Y237, the 2-D multistage unsteady flow analysis, provides time accurate pressure distribution capability. This code is based on extensive analysis of unsteady turbine data obtained in the United Technologies Research Center (UTRC) large scale rotating rig. This code has been in the development stage since 1988 and has just become available as a design tool.

MODEL VERIFICATION

Stage and overall performance data obtained in a P&W IR&D Turbine Aerodynamic Rig Program will be used to verify all the previously listed models. As part of this IR&D program, measured volute pressure distribution will be compared to CFD predictions. Additional verification of model performance predictions will be obtained under turbopump component testing.

COMBUSTION CODES

QUARX — Combustion Stability Prediction

DROP — Spray Atomization Characteristics

EFFPRO — Combustion Efficiency Prediction

Fiction — Low Frequency Stability Prediction

RIGIMESH — Transpiration Cooling Flow and Temperature Prediction

CODE, FEATURES, AND APPLICABILITY

QUARX is the most up-to-date version of the sensitive time lag model and incorporates numerous new features developed by Mitchel at Colorado State over the past few years. QUARX will be used to ensure that the AETB combustor is stable over the operating range.

DROP is the only code available today that accurately predicts drop-size in swirl and gas atomized coaxial injectors. DROP is based on extensive high-pressure spray testing and modeling conducted over the past 3 years under NASA contracts, U.S. Air Force contracts, and an IR&D study.

EFFPRO will be used to predict combustion efficiency based on DROP and a sophisticated high-pressure combustion model developed over the past 4 years. The model includes ignition delay and super critical combustion effects that were not included in earlier models.

FICTION is a new low-frequency combustion model being written at P&W based on work done by NASA-LeRC. FICTION will be used to establish volumes and pressure drops to ensure low-frequency combustion stability.

RIGIMESH is a new P&W deck for optimization of RIGIMESH porosity and coolant flow. RIGIMESH is aimed at ensuring adequate face plate cooling at design and off-design conditions.

MODEL VERIFICATION

Limited verification of QUARX is planned under a P&W IR&D program. Verification under contract is not suggested, based on the large stability margin.

Spray characterization tests are planned to verify predictions of DROP drop-size predictions and spray distribution.

Limited verification is planned under a P&W IR&D program for EFFPRO. Verification under the contract is not suggested because of large combustion volume margin.

FICTION is recommended for verification under the contract.

RIGIMESH is recommended for verification under the contract with emphasis on off-design operation (throttling and high o/f).

COMBUSTION CHAMBER AND NOZZLE HEAT TRANSFER CODES

VNAP — Predicts 2-D Combustion Mach Numbers at the Wall

D5160 — Rocket Thrust Chamber Thermal Design Code

D8272 — General 2-D and 3-D Finite Difference Conduction Code

NASTAR — Navier Stokes CFD Analysis

CODE, FEATURES, AND APPLICABILITY

VNAP is a 1980 CFD code developed by Los Alamos Scientific Laboratory for calculating viscous, as well as inviscid, steady and unsteady internal flow. The code is used to predict wall curvature effects on wall Mach numbers for combustion wall heat flux calculations.

D5160 is P&W's basic rocket thrust chamber thermal design code. The code uses the Mayer Integral Method with local wall 2-D Mach numbers to calculate the convective heat transfer coefficient and the enthalpy driving potential to define the driving energy difference. During 1989, the code was upgraded to use a finite-element 2-D conduction routine to calculate liner temperature distributions, and a coolant passage optimization routine was incorporated to size coolant passages based on a wall temperature limit.

D8272 is used to thermally analysis unique features such as manifolds, which can not be analyzed using D5160.

MODEL VERIFICATION

Verification is planned for VNAP under P&W's IR&D program, and therefore, no additional verification will be required.

Verification of D5160 will be conducted in conjunction with VNAP verification.

No verification requested for D8272. This code has been validated in many ongoing programs.

STRUCTURAL ANALYSIS CODE

MSC/NASTRAN — General Purpose Structural Analysis Code

W526 — Generalized Shell Analysis Code

BEASY — General Purpose Structural Analysis Code

CODE, FEATURES, AND APPLICABILITY

MCS/NASTRAN is an advanced version of the NASTRAN (NASTRAN is a registered trademark of NASA) General Purpose Structural Analysis Program that is developed and maintained by the MacNeal-Schwendler Corporation (MSC). NASTRAN is used to solve a wide variety of engineering problems using the finite element method. This code will be used for stress and vibration analysis of numerous major engine components through preliminary and final design.

W526 is a proprietary general shell analysis finite element code used for structural analysis of axisymmetric shell structures. This code is used extensively throughout P&W structural design groups for stress and vibration analyses of thin shell structures.

The Boundary Element Analysis System (BEASY), a structural analysis computer program, is registered by Computational Mechanics, Ltd. BEASY is a general purpose program used for stress, heat, and thermostress analysis of 2-D, axisymmetric, and 3-D engineering problems.

MODEL VERIFICATION

The structural codes used for the AETB engine design are a combination of industry standard codes and P&W proprietary codes that have been well developed and refined in recent years. No special verification of these codes is planned for the AETB Program. However, several structural tests will be conducted to verify component structural integrity, and thereby substantiate the application of the analysis methods.