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PRELIMINARY DESIGN OF AN AUXILIARY POWER UNIT FOR THE SPACE SHUTTLE

Volume I - Summary

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16. Abstract
This study has considered numerous candidate APU concepts, each meeting the Space Shuttle APU problem statement. Evaluation of these concepts indicates that the optimum concept is a hydrogen-oxygen APU incorporating a recuperator to utilize the exhaust energy and using the cycle hydrogen flow as a means of cooling the component heat loads. The initial portion of the study (Phase I) was concerned with evaluation of the candidate concepts; this information is presented in Volume II. The Phase II work accomplished preliminary design of the selected APU concept, placing primary emphasis on the cycle thermal management and the controls (to maintain desired turbine inlet temperature and rotational speed). The Phase II work is presented in Volumes III, IV, and V. Volumes III, IV, and V also present results for both steady-state and transient APU performance, based on digital computer programs developed during the study. The selected APU provides up to 400 hp out of the gearbox, has a fixed weight of about 277 lb, and requires about 2 lb/shp-hr of propellants.

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FOREWORD

This report is the first volume of a series that comprises the following:

Volume I - Summary
Volume II - Component and System Configuration Screening Analysis
Volume III - Details of System Analysis, Engineering, and Design for Selected System
Volume IV - Selected System Supporting Studies
Volume V - Selected System Cycle Performance Data

Volume II summarizes the Phase I portion of the program, in which the various component and system concepts were compared and evaluated. Volumes III, IV, and V contain the Phase II work, in which preliminary design of the selected APU system concept was performed.

CONTENTS

INTRODUCTION

This volume summarizes Contract NAS 3-14408, "Preliminary Design of an Auxiliary Power Unit (APU) for the Space Shuttle." The APU supplies hydraulic and electric power for the booster and orbiter vehicles. As stated in the Foreword, Volume II contains the Phase I work in which various candidate system concepts were compared and the optimum selected for preliminary design during Phase II. Volumes III, IV, and V present a preliminary design of the selected system. Volume III contains the selected design performance and description; Volume IV gives supporting studies leading to definition of the system; and Volume V contains performance data.

This volume describes the selected system, outlines recommendations for future technology development programs and summarizes the Phase I and Phase II work leading to the selected concept.

SELECTED SYSTEM

Description

The system, shown in Figure I, consists of a two-stage turbine expanding 2060°R hydrogen-oxygen combustion products to drive gearbox mounted hydraulic pumps and an alternator operated on hydrogen-oxygen combustion gases. The cycle performance is enhanced by recuperation, using the turbine exhaust gas to preheat the hydrogen prior to combustion. The internal APU heat loads (hydraulic pumps, alternator, gearbox, and lube pump) are cooled by the cycle hydrogen flow, using a lube oil cooler and two hydraulic fluid coolers (one for each independent hydraulic pump circuit). Lube and hydraulic fluid temperature control is accomplished by recycling a portion of the hot hydrogen to maintain the minimum hydrogen cooling loop temperature at or above 400°R. In this manner, congealing of either lube or hydraulic fluids can be avoided under all possible operating conditions, including stagnation of the hydraulic fluid in the cooler-possible when one hydraulic pump is shutdown. Because of the low heat capacity of oxygen, there is no incentive to use the oxygen flow as a heat sink or to preheat it prior to combustion.

I. Advantages of Selected Component Arrangement

Putting the lube oil cooler in front of the hydraulic oil cooler, and placing both coolers upstream of the recuperator insure lube oil cooling and all possible cycle operating conditions. In contrast to the hydraulic fluid circuit, the lube oil circuit has a low thermal inertia and therefore can not tolerate any cooling deficit. Further, the minimum lube oil temperature to avoid congealing is somewhat less than that for the hydraulic fluid; thus, placing the lube oil cooler first results in an increased cycle cooling capacity.

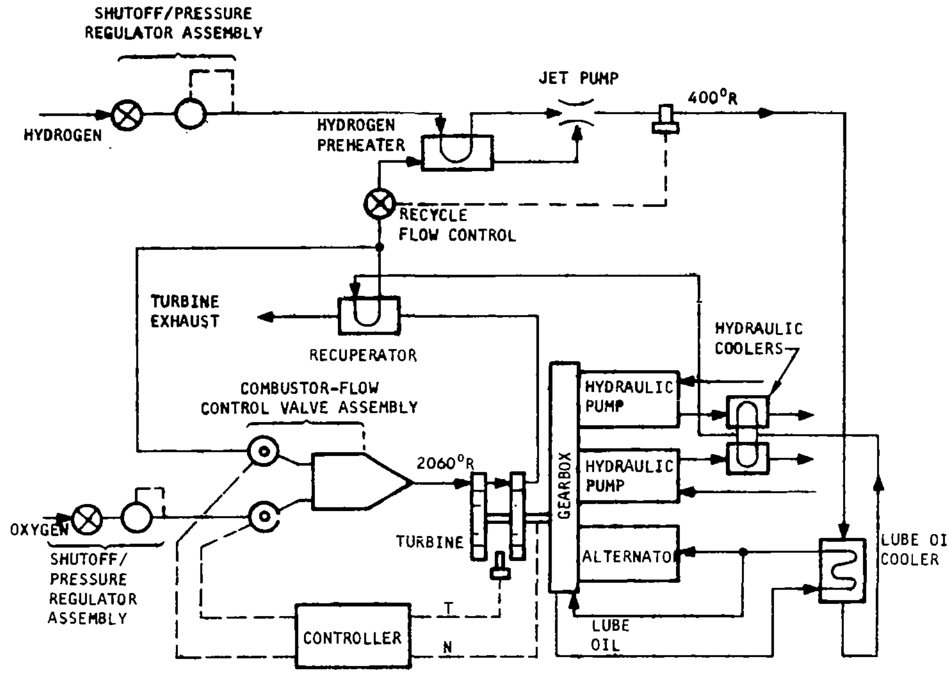

Figure 1. Selected APU System Schematic

Locating the recuperator after the oil coolers results in the maximum hydrogen temperature into the combustor commensurate with maintaining a minimum temperature of about 700°R in the exhaust duct. Hence the cycle O/F (oxygen to fuel) ratio is minimized. This location also allows all of the cycle hydrogen flow to be recuperated. Alternatively, locating the recuperator upstream of the oil coolers would necessitate several hydrogen bypass loops (around the recuperator and the oil coolers) to provide component cooling at acceptable temperature levels.

2. Advantages of Selected Control Concept

The APU primary controls consist of turbine inlet temperature control (to maintain desired turbine disk life), turbine speed control (to provide a power balance and to generate correct electrical frequency), and hydrogen recycle loop jet pump discharge temperature. Both the turbine inlet temperature and speed are controlled by modulating the position of the hydrogen and oxygen flow control valves in front of the combustor. Modulation changes the total flow passing through the turbine at constant inlet temperature, hence altering the power. Because closed-loop circuits are used in all primary controls, control performance is independent of the exact component performance since the controls adjust the valve positions as required. Thus, mismatch in valve gains, variations in valve inlet pressures and temperatures, changes in combustor performance, etc., do not affect the overall APU performance since the controls compensate to maintain the controlled parameters at the desired levels.

Vehicle/APU Interface

Table I summarizes interfaces between the vehicle and the APU. The APU obtains its propellant from another vehicle subsystem (the Auxiliary Propulsion System, APS) and outputs exhaust gases and useful hydraulic and electric power. Although propellant supply from the APS is considered the baseline approach, the selected concept can also obtain its propellant by employing liquid-fed pumps, as described in Volume III.

TABLE I

VEHICLE/APU INTERFACES

VEHICLE/APU INTERFACE	INTERFACE CONDITIONS
PROPELLANT SUPPLY CONDITIONS	Hydrogen at 75and200-500°R,500-1000psia Oxygen at 300-500°R, 500-1000 psia Transients over full range of pressures and/or temperatures occurring in 2 sec
PROPELLANT EXHAUST CONDITIONS AT RECUPERATOR DISCHARGE	0-4 psia above ambient pressure 690-1094°R 53.5-61.5 percent hydrogen by mass 38.5-46.5 percent water by mass
OUTPUT POWER LEVEL/QUALITY	0-400 hp at gearbox output shafts 2 90-120 gpm hydraulic pumps at 6000 rpm 1 60/75 kw alternator at 12,000 rpm Speed control to ±1.7 percent during worst-case transients
HYDRAULIC FLUID INLET/OUTLET CONDITIONS	Inlet at 530-750°R Outlet at 490-745°R At high power output, APU cooling more than dissipates hydraulic pump heat generation At low power output (less than 75 hp out of gearbox), APU cooling is less than heat generated by hydraulic pumps, resulting in gradual increase in hydraulic fluid temperature(see Volumes III, IV, and V)

Performance

1. Steady-State

Figure 2 shows the selected APU system specific propellant consumption (SPC) vs the turbine shaft power for representative propellant supply and hydraulic fluid conditions. Data in Volume III, Section 4 present a method for determining SPC over the entire range of system operating conditions (variations in propellant supply temperatures, hydraulic fluid inlet temperature, output power and ambient pressure). Detailed performance data for the selected APU system concept are given in Volume V.

Table 2 shows the mission-averaged APU performance for the NASA-specified booster and orbiter missions (shown in Figures 4-21 and 4-22 of Volume III); the data indicate a SPC of 2.08 lb/shp-hr for the booster and 1.82 for the orbiter.

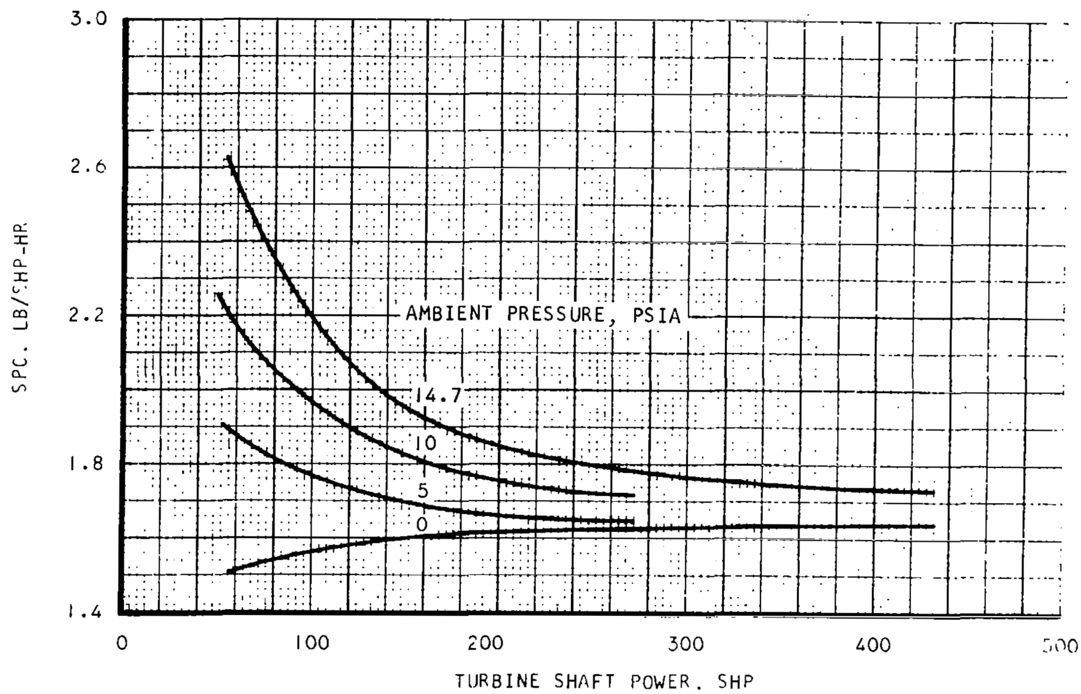

Figure 2. APU Typical Specific Propellant Consumption

TABLE 2

MISSION-AVERAGED APU PERFORMANCE

	Mission Energy Required		Propellant Required		O/F Ratio	
Vehicle	At Turbine Shaft hp-hr	Net Useful Power hp-hr	With 300°R Hydrogen lb/shp-hr	With 75°R Hydrogen, lb/shp-hr	With 300°R Hydrogen	With 75°R Hydrogen
Booster	148.0	50.2	2.08	2.10	0.575	0.597
Orbiter	158.0	62.0	1.82	1.83	0.614	0.627

2. Transient

A digital computer program was used to assess APU performance during the following transients:

startup
changes in propellant inlet temperatures
changes in power output
shutdown

Tables 3 and 4 summarize the APU transient performance.

TABLE 3

SYSTEM TRANSIENT PERFORMANCE SUMMARY

Transient	Maximum Error Range, Percent		
	Turbine Inlet Temperature	Turbine Speed	Jet Pump Discharge Temperature
Startup with 500°R Ambient Propellants	+0 -35.6*	+0.35	-
Startup with Cold Propellants(300°R,O_2,75°R H_2)	+1.94 -11.4*	+0.35	+1.5 -1.25
Inlet Oxygen Temperature Ramp(10 times maximum anticipated rate)(200°R/Sec)	±2.04	±0.0013	-
Load Steps(0 to 300hp)	±3.15	±1.71	±2.25

*Controls intentionally designed for low turbine inlet temperature at speeds below 20,000 rpm

TABLE 4

HEAT EXCHANGER EQUILIBRIUM TEMPERATURES AFTER SHUTDOWN

Heat Exchanger	Temperature, °R
Hydrogen preheater	383
Lube oil cooler	521
Hydraulic oil cooler	520
Recuperator	962

Shutdown conditions: Steady-state at 0 hp useful output with 75°R hydrogen and 300°R oxygen inlet temperatures, 550°R hydraulic fluid heat exchanger inlet temperature, 10 psia ambient

3. Ground Operation

While the vehicle is on the ground, the APU must be operable from ground-supplied inert gas. Figure 3 shows the inert gas flow vs power for various gas pressures and temperatures. During ground operation, turbine speed is reduced to 40,000 rpm from its normal 70,000 rpm. The speed reduction improves turbine performance on inert gas and reduces disk stresses; the required hydraulic power is easily obtainable at the selected operating speed.

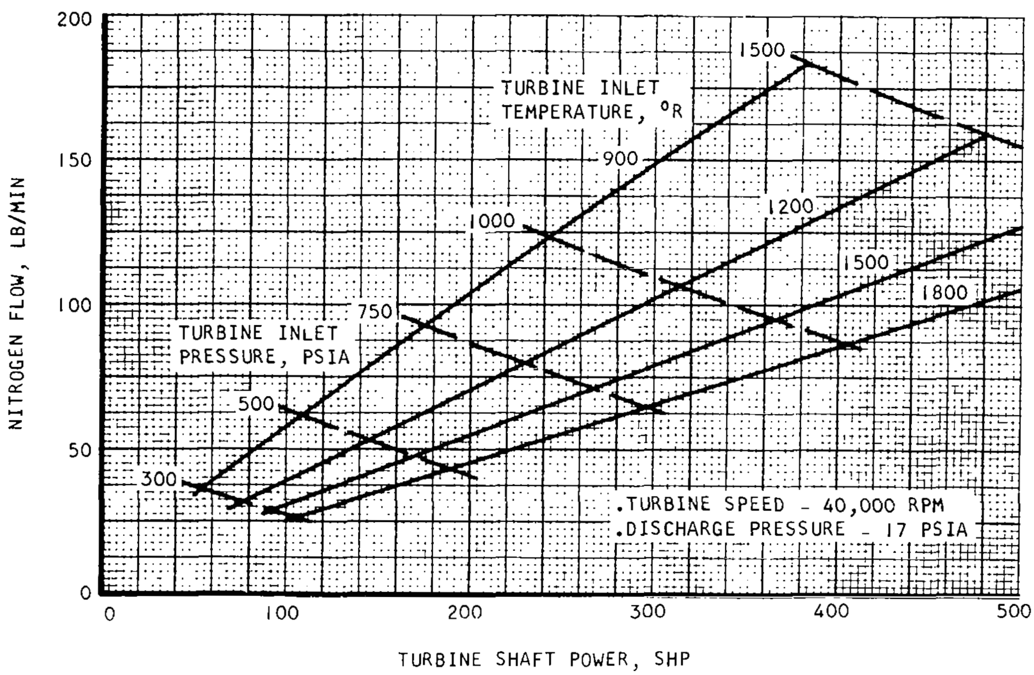

Figure 3. APU Ground Inert Gas Flow vs Developed Power

Packaging

With the exception of the electronic controller, the APU components are packaged into an integrated assembly shown in Figure 4. The package connections are tungsten-inert gas welded joints, except for the recuperator discharge flange. Thus, leakage problems within the package are virtually eliminated. Each joint is repairable to permit duct cutting for disassembly/maintenance.

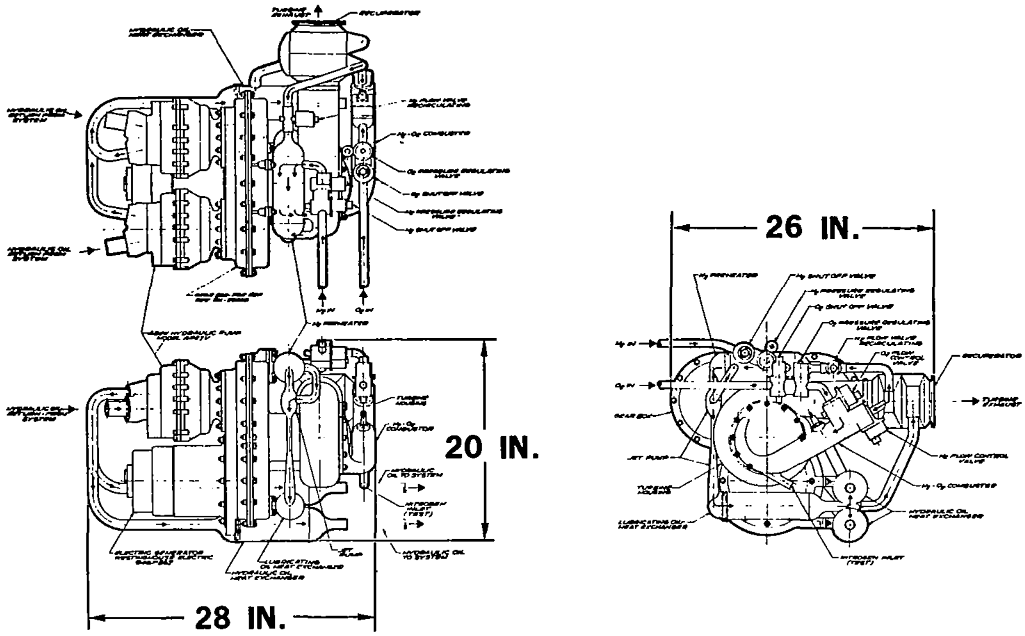

Figure 4. Space Shuttle APU Package Configuration

The controls are mounted separately in an adjacent electronic equipment bay. They are compatible with the vehicle data multiplexing system to permit remote location without the necessity for direct wiring. A 3/8 ATR short box with approximate dimensions of 4 x 8 x 14 in is used for packaging; alternatively, the controls can be mounted directly on the APU at a modest weight and cost penalty.

Weight

Table 5 lists the total weight of a single APU, including propellants. The APU fixed weight is about 0.69 lb/hp of gearbox output power.

Technology Basis

The system utilizes design concepts employed in AiResearch-manufactured components. Particular emphasis has been placed on meeting the desired life and maintainability goals for the Space Shuttle vehicle. These goals are similar (although not as stringent) to those regularly imposed by commercial aircraft manufacturers and operators. Volume III presents the design basis for each component.

TABLE 5

APU SYSTEM WEIGHT SUMMARY

Item	Weight, lb		Item	Weight, lb
COMPONENTS			PROPELLANT FOR BOOSTER	
Hydrogen Preheater	6.1		Hydrogen	195.9
Lube and Hydraulic Oil Coolers	31.6		Oxygen	112.7
Recuperator	11.8		Propellant Conditioning Penalty	83.5
Ducting (including exhaust duct)	34.4		Total Propellant Weight	392.1
Valving	8.6		PROPELLANT FOR ORBITER	
Combustor/Flow Control Assembly	5.6		Hydrogen	177.5
Turbine/Gearbox Assembly	71.7		Oxygen	109.0
Hydraulic Pumps and Alternator	100.0		Propellant Conditioning Penalty	77.4
Controls and Sensors	7.0		Total Propellant Weight	363.9
Total Fixed Weight		276.8	TOTAL BOOSTER INDIVIDUAL APU WEIGHT	668.9
			TOTAL ORBITER INDIVIDUAL APU WEIGHT	640.7

At the system level, AiResearch has built and tested a cryogenically-supplied hydrogen-oxygen APU using closed-loop controls similar to those selected for the Space Shuttle APU. This earlier system (called IPECS, Integrated Power and Environmental Control System) also dissipated the component heat to the cycle hydrogen flow. Some typical IPECS transient performance test data are presented in Volume III, Section 7. These data indicate that fast, stable response over a wide range of operating conditions (a turndown ratio in power of 15:1) is achievable with pressure-modulated control.

TECHNOLOGY DEVELOPMENT RECOMMENDATIONS

The present study has demonstrated that the analytical design of a hydrogen-oxygen APU is feasible and that there is an adequate technology base for the system components, but it remains to demonstrate the concept at the system level. Therefore, it is recommended that a breadboard demonstration program, similar to the AiResearch-funded IPECS program be initiated. Such a program would:

- demonstrate system dynamic performance, particularly the ability to maintain control during startup, step load changes, and shutdown
- prove adequacy of the cycle component arrangement, particularly the ability to obtain the desired heat transfer without freezing, congealing, or excessive thermal stresses in the heat exchangers

A second area requiring development is the low flow, high head cryogenic pumps required if the APU is to supply its own propellant pressurization. Volume III, Section 8 shows that pump designs for the required problem statements are both heavy and inefficient. Therefore, it is recommended that a two-phase program be pursued. The first phase would study methods of obtaining the desired pressures (either pumps or high-pressure tankage) and the second phase would demonstrate the selected concepts through a development/ test program.

PHASE I STUDIES SUMMARY

The objective of the Phase I studies (described in Volume II) was comparison of the various candidate systems to select that concept best suited for the Space Shuttle application. A set of NASA-provided evaluation criteria were used for system comparisons.

Procedure

The procedure used was to select representative, optimized designs for the individual cycle components and to use these data to establish the resulting cycle performance. Because of its importance in setting propellent consumption, turbine performance was evaluated in detail, including investigation of the effect of turbine design point on cycle performance.

Candidate Cycle Concepts

The five candidate cycles considered in detail in Phase I are described in Volume II and summarized in Table 6. Table 6 also lists some of the preliminary concepts rejected prior to the final evaluation.

Cycle Performance Determination

Figure 5 shows the process used to establish the mission-averaged performance of each cycle. One program was used to determine steady-state cycle performance at a series of different operating conditions and another program integrated the performance over the specified mission profiles. The steady-state program uses 13 subroutines, 50 component off-design performance maps, and real fluid thermodynamic properties (pressure, temperature, density, and enthalpy) for hydrogen, oxygen, and water vapor. It uses 5 nested iteration loops with approximate equations for initial guesses to solve the cycle.

A principal feature of the steady-state program is that it allows determination of exact system performance throughout the complete APU operating regime. Variables such as ducting losses, component pressure losses, and overboard expansion losses are all accounted for. Additionally, by using actual fluid thermodynamic properties, the program accounts for the fluid specific heat variations.

TABLE 6

CANDIDATE APU SYSTEM CONCEPTS

FINAL CONCEPTS

CANDIDATE SYSTEM	PROPELLANTS	PROPELLANT TANKAGE	SYSTEM HEAT SINK	EXHAUST ENERGY UTILIZATION	COMBUSTOR PRESSURIZATION METHOD
Low-Pressure Cryogenic Liquid Supplied	H_2-O_2	Low-Pressure Cryogenic	H_2	Recuperation	Electric-Drive Cryogenic Pumps
Integral High-Pressure Cryogenic Supplied	H_2-O_2	High-Pressure Cryogenic	H_2	Recuperation	Direct Feed
High-Pressure Gaseous Supplied	H_2-O_2	None	H_2	Recuperation	Direct Feed
Dual-Mode	H_2-O_2 H_2-AIR	High-Pressure Cryogenic	H_2 or Air	H_2 Recuperation, None with Air	Direct Feed
Monopropellant	75-24-1	Low-Pressure with Bladders	Water	None	Electric-Drive Monopropellant Pumps

PRELIMINARY, REJECTED CONCEPTS

- Low-Pressure Hydrogen-Oxygen Gas Feed
- All Non-Recuperated Hydrogen-Oxygen Cycles
- Open Brayton Cycle Using Hydrogen-Oxygen

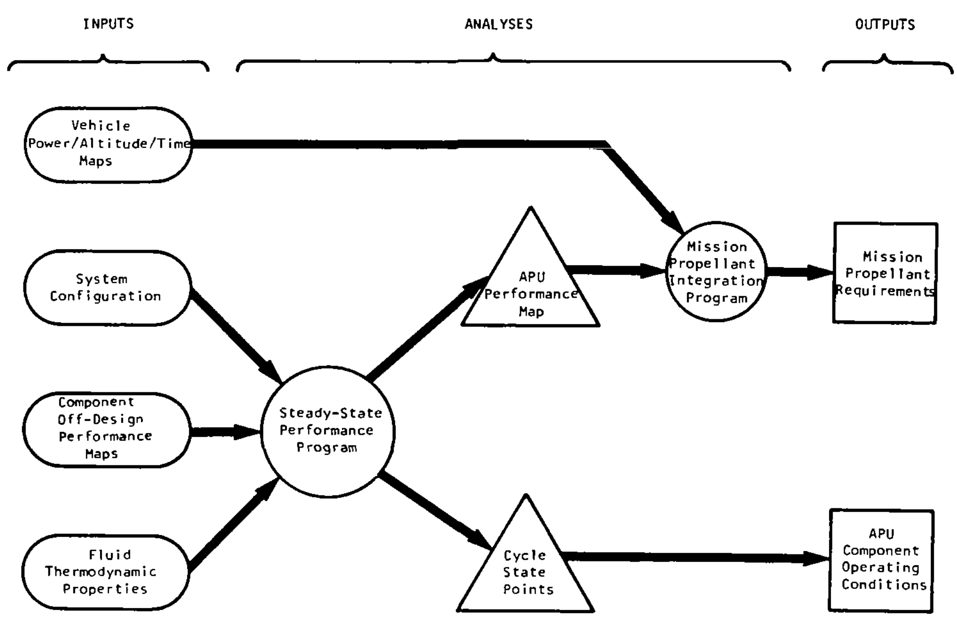

Figure 5. Evaluation Process for Candidate Cycles

Equivalent system analysis by hand calculations would be extremely difficult and tedious because of the iterations required with the recycle loop, jet pump, and O/F ratio. It is estimated that a minimum of 4 to 6 man-hours would be required to solve a point by hand. About 10 sec of computer time are required per point.

Turbine Design Point Optimization

Appendix A of Volume II summarizes the turbine optimizations performed during Phase I. Various turbine types were considered with pressure-compounded impulse turbines being optimum. Tradeoffs were performed to select the number of turbine stages, rotational speed, pitch line velocity, etc. Of particular importance was selection of the power and altitude combination at which the turbine nozzles should be optimized. Mission propellant consumption studies indicated that about 10 percent propellant reduction could be achieved in a pressure modulated system by designing the nozzles for optimum performance at a low pressure ratio (occurring at an altitude, part power condition), in comparison to designing for the sea level, full power condition.

Cycle Evaluation

Table 7 gives the NASA-specified evaluation criteria. Table 8 shows results of the evaluations for the final candidate cycles. The data indicate a decided advantage for the high-pressure gas-fed system shown in Figure 6, which was selected as the concept for preliminary design during Phase II. Because of its desirability from an overall vehicle standpoint (considering effects on the APS), the low-pressure cryogenic liquid supplied system using pumps to provide propellant pressurization also was considered as an alternate during Phase II.

TABLE 7

NASA-SUPPLIED EVALUATION CRITERIA

Cost		Reliability	
Item	Weighting	Item	Weighting
Low Weight	25	Simplicity	30
High Flexibility	20	Experience	5
Ease of Development	10		
Ease of Manufacturing	5		
Ease of Maintenance	5		

TABLE 8

SUMMARY OF APU EVALUATION

	SYSTEM RATINGS				
	Low-Pressure Cryo Liquid	Integral High-Pressure Cryo	High-Pressure Gas-Feed	Dual Mode	Monopropellant
RELATIVE RANKING	3	2	1	5	4
TOTAL WEIGHTED RATING	73.0	73.1	93.4	52.7	69.9
Weight	1.00	0.74	0.99	0.69	0.52
Flexibility	0.65	0.69	0.92	0.42	0.69
Ease of Development	0.53	0.73	0.89	0.53	1.00
Ease of Manufacturing	0.63	0.76	0.90	0.49	0.76
Ease of Maintenance	1.00	0.56	1.00	0.42	0.71
Simplicity	0.69	0.78	0.95	0.49	0.86
Experience	0.17	0.50	0.50	0.50	1.00

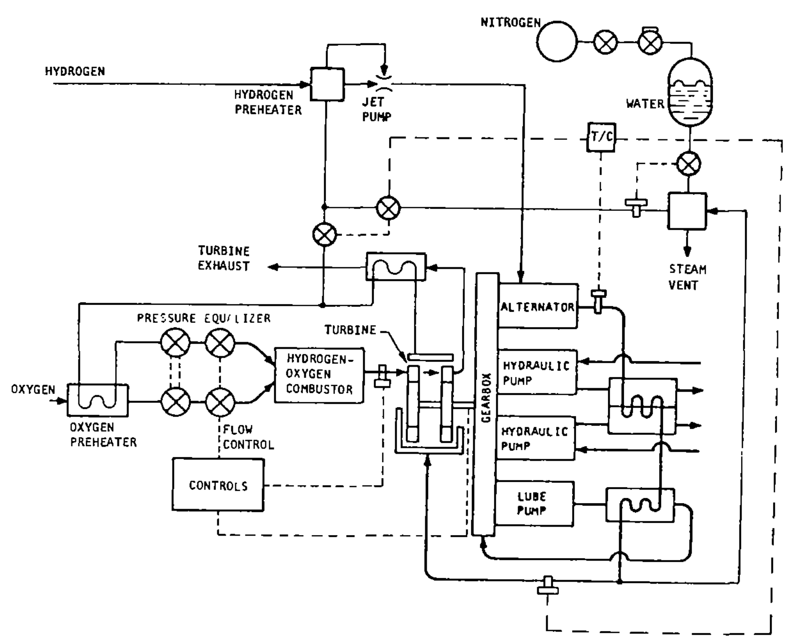

Figure 6. High-Pressure Gaseous Hydrogen-Oxygen Supplied System Configuration at End of Phase I

PHASE II STUDIES SUMMARY

The Phase II studies were concentrated in three areas:

- selecting methods of controlling turbine speed and inlet temperature
- determining system transient performance and controls configuration
- generating component designs

Changes in the APU requirements (increased power output, changed mission profile, etc.) at the start of Phase II, necessitated redesign of the system components rather than building the Phase I designs. Table 9 presents the principal groundrules specified by NASA during Phase II.

Modifications to Phase I System Configuration

Table 10 summarizes the major system changes from the Phase I configuration of Figure 6. Some changes evolved from the continuing system studies conducted during Phase II, although most were by NASA direction.

Selection of Turbine Speed and Inlet Temperature Control

Sections 3 and 4 of Volume IV summarize the turbine speed and inlet temperature control studies. Of the two types of speed control considered, pressure modulation has been selected. In comparison to pulse modulation, pressure modulation offers signifcantly better speed control, lighter fixed system weight for equivalent performance, and an established technology basis. Pulse modulation, on the other hand, requires less propellant. These comparisons are summarized in Table 11.

TABLE 9

PRINCIPAL PHASE II GROUND RULES

DESIGN PHILOSOPHY	PROPELLANT SUPPLY CONDITIONS
Maximize proven design concepts	Hydrogen = 75,200 to 500°R,500 to 1000psia
Monitor for failure detection	Oxygen = 300 to 500°R, 500 to 1000 psia
LIFE	Transients in propellant temperatures or pressures can cover entire range in 2 sec at APS accumulators
1000 hr on H_2-O_2 plus 2000 hr on inert gas	TURBINE DESIGN REQUIREMENTS
900 H_2-O_2 starts plus 600 inert gas starts	Material = Udimet 700
AMBIENT ENVIRONMENT	Type = 2 stage axial, pressure-compounded
Temperature = 400 to 700°R	Inlet temperature = 2060°R
Pressure = sea level to vacuum	Rotational speed = 70,000 rpm
POWER OUTPUT	Speed control = ± 5 percent
400 shp out of gearbox	Design for containment with tri-hub burst
100 shp out of gearbox for ground checkout with inert gas	LUBE AND HYDRAULIC FLUID REQUIREMENTS
Output pads for 2 90-120 gpm hydraulic pumps, 1 60/75 kw alternator	MIL-L-7808 lube oil, 750°R maximum
Power turndown ratio = 16:1	H2V hydraulic oil, 530°R minimum, 750°R maximum

TABLE 10

SUMMARY OF MAJOR SYSTEM CONFIGURATION CHANGES FROM PHASE I

Configuration Change	Reason
1. Supplemental cooling provisions (water boiler) eliminated	NASA directive
2. Turbine cooling provisions eliminated	NASA directive
3. Turbine inlet temperature = 2060°R	NASA directive
4. Use of a lube-oil-cooled alternator specified	NASA directive
5. Propellant pressure regulators and shutoff valves added	NASA directive
6. Lube oil cooler upstream from hydraulic cooler	Consequence of changes 1 and 2
7. Low-temperature recycle loop eliminated	Consequence of change 1
8. Temperature and pressure equalizers eliminated	Shown unnecessary by controls studies
9. Turbine inlet temperature sensor relocated to interstage location	Favored by response, packaging, and life considerations
10. Lube pump second stage eliminated	Pitot scavenge pump provides sufficient ΔP
11. Turbine pitch-line velocity reduced to 1700 fps	Consequence of changes 2 and 3

TABLE 11

COMPARISON OF SPEED CONTROL CONCEPTS

Concept	Relative Mission Propellant Consumption	Speed Control	Control Valve Cycles	Relative Fixed Weight
Pressure Modulation	116.8 % for booster 106.9 % for orbiter	±0.3 % steady-state ±1.7 % during transients	modulating	100.0%
Pulse Modulation	100.0 % for booster 100.0 % for orbiter	±5 % steady-* state and transient	18,000/mission for booster 13,000/mission for orbiter	109.0%

* Contract requirement

Table 12 compares the four classes of turbine inlet temperature control for pressure modulated systems. It indicates that maintaining constant turbine inlet temperature provides minimum propellant consumption. Further, the data show that operating with a variable O/F ratio (allowing the hydrogen temperature into the combustor to always be maximized, rather than fixing it by use of bypass at the minimum obtainable value), provides performance superior to that obtainable with fixed O/F.

TABLE 12

COMPARISON OF TURBINE INLET TEMPERATURE CONTROL CONCEPTS

Concept	Relative Mission Propellant Consumption	Heat Sink Penalty	Heat Exchanger Design Risk
Constant Temperature, Variable O/F	100 %	None	Low
Floating Temperature, Variable O/F	150 "	None	Low
Constant Temperature, Constant O/F 1. Recycle Loop 2. Split Recuperator 3. Recuperator Bypass	 102 " 105 " 105 "	 None 150-200 lb None	 Low Moderate High
Floating Temperature, Constant O/F	113 "	None	Low

System Transient Performance/Controls Configuration

The steady-state program developed during Phase I was expanded and modified during Phase II to provide both transient and steady-state performance prediction. The solution method and analytical models are based on similar programs used for design of AiResearch-manufactured APU's and primary propulsion engines. Some initial controls studies were performed using the analog computer (described in Volume IV, Section 7) to establish conditions for flow stability. However, the precise modeling required for optimization of the control logic was performed on a digital computer. The digital transient program output is identical to that for the steady-state program (sample outputs in Volume V), with the addition of heat exchanger metal temperatures and turbine speed.

Both integrating and droop (or proportional) controls were analyzed and integrating control was found to offer superior performance. The resulting primary control arrangement is shown in Figure 7. The frequency compensation transfer functions were determined by assessing the "controlless" system response to changes in the controlled valve positions. The frequency compensation is then designed to offset the system response. The result is a system which closely controls turbine speed, turbine inlet temperature, and jet pump discharge temperature. Typical transient performance is shown in Figure 8, startup with 75^{0}R hydrogen introduced into the 500^{0}R ambient temperature APU.

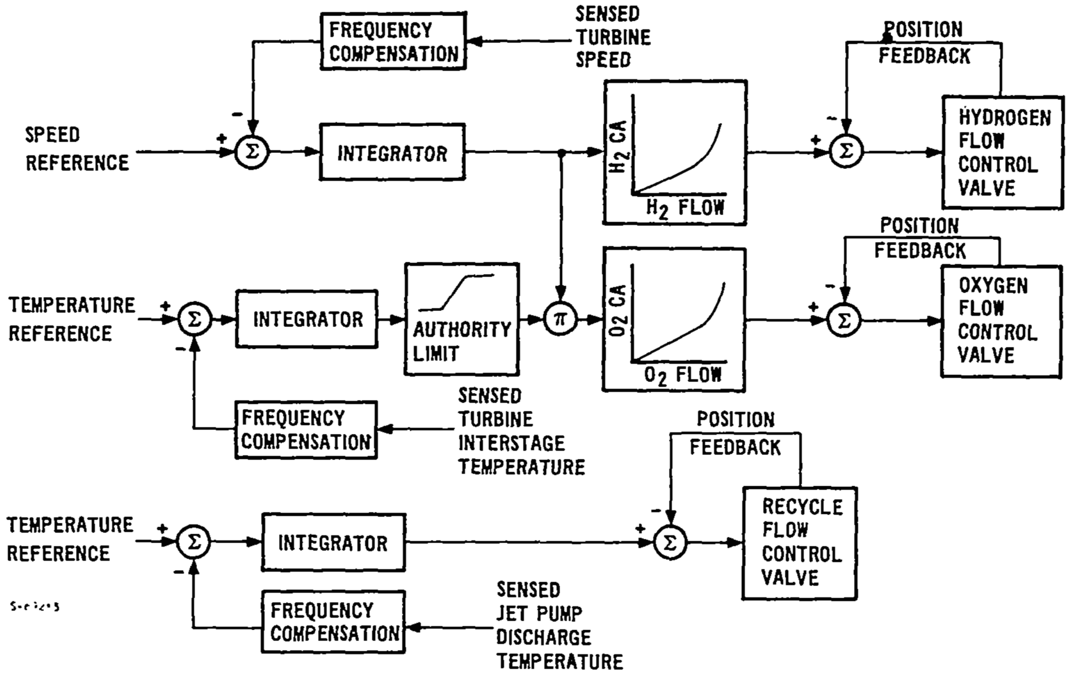

Figure 7. Primary Control Circuits - Block Diagram

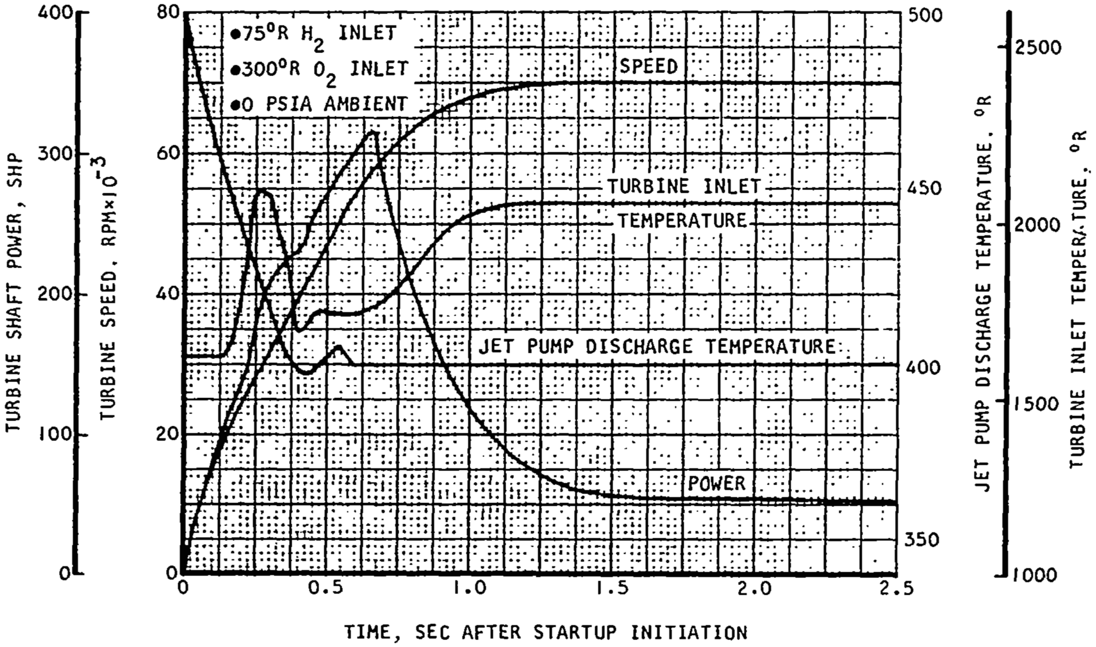

Figure 8. Typical APU Transient Performance - Startup with 75°R Hydrogen at 500°R Ambient

Component Designs

Drawings and performance data for the selected component designs are presented in Sections 5,6, and 7 of Volume III. The APU system has been subdivided into 3 major equipment groups as shown in Figure 9.

I. Propellant Conditioning/Thermal Control Subsystem

This subsystem provides the following functions:

- supplies propellants at proper temperature and pressure to the turbine power unit
- dissipates waste heat generated internally in the turbine power unit at suitable temperature levels for the various system components

It uses waste heat from the lubricant, hydraulic fluid, and turbine exhaust gas to preheat the incoming hydrogen. A recycle loop is used to maintain proper hydrogen inlet temperatures to the various heat exchangers. This eliminates heat exchanger design problems with flow instability and maldistribution leading to fluid congealing or freezing (as discussed in Volume IV). It also avoids heat exchanger designs which depend upon accurate predictions of heat transfer coefficients to maintain wall temperatures at acceptable values. AiResearch experience has shown that in practice such designs are extremely difficult to effect.

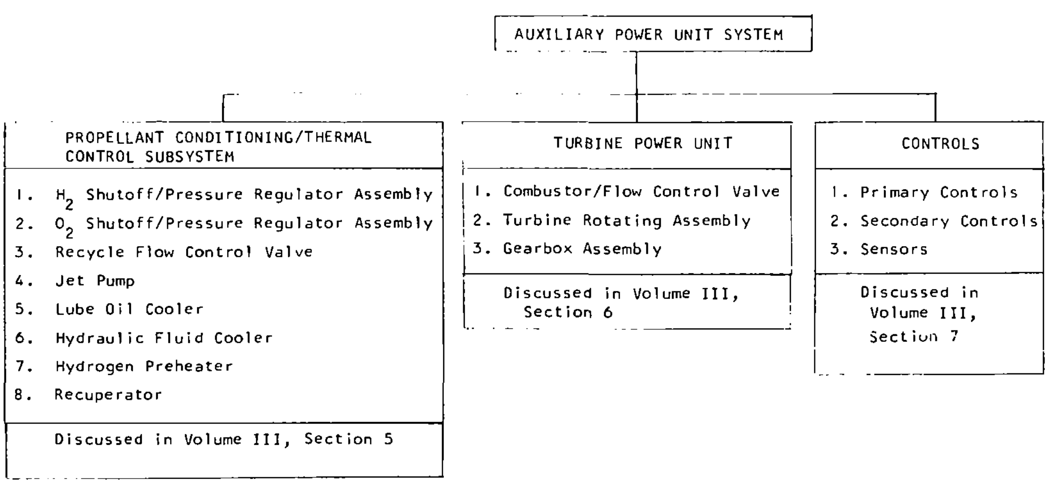

Figure 9. APU Subsystems and Components

The heat exchangers are all of the shell-and-tube type. Their construction allows accomodation of the large thermal gradients that can occur both during operation and during startup/shutdown. The functions of the lube oil cooler, the hydraulic oil cooler, and the recuperator are straight-forward. The hydrogen preheater is required to equalize the incoming and recycle hydrogen flow temperatures to obtain optimum jet pump performance.

2. Turbine Power Unit

The turbine power unit combusts the hydrogen and oxygen and converts the resulting gas energy into shaft power available for driving the hydraulic pumps and alternator. The combustor/flow control assembly uses separate electrically-driven flow modulating valves to control the throughflow and the turbine inlet temperature. The combustor itself is of the diffusion type, having a low hydrogen pressure drop and a low wall temperature (because of hydrogen film cooling).

The turbine is a two-stage pressure-compounded axial-flow impulse design running at 70,000 rpm, $2060^{0}R$ inlet temperature, and 1700 fps pitch-line velocity. Proper selection of its nozzle design point (at a low pressure ratio) insures high efficiency over the entire range of operation.

The gearbox uses spur gearing to reduce the turbine shaft speed to that required by the hydraulic pumps and alternator. Proper design of the gearing allows the lube pump function to be integrated into one of the gears (centrifugal force at the gear rim is used to provide pressure head for lube flow). The gearbox casing provides structural mounts for the APU components and the mounting points to vehicle structure for the entire APU package.

3. Controls

The controls include the primary control functions (turbine speed control, turbine inlet temperature control, and hydrogen loop jet pump discharge temperature control), secondary control functions (startup, shutdown, component monitoring, fault detection/emergency shutdown), and sensors (thermocouples, pressure transducers, speed pickups, etc). The controls (excepting sensors) are packaged as a single unit using printed circuit boards for rapid maintenance. The electronic controller will have its own internal circuit monitoring to insure fault detection.

NASA-Langley, 1972 —— 3 F-6732