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TRANSIENT ANALYSIS

ISOTOPE BRAYTON FLIGHT SYSTEM

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TABLE OF CONTENTS

	<u>Page</u>
1. INTRODUCTION	1
2. SUMMARY	2
3. CONTROL SYSTEM DESIGN PHILOSOPHY	4
4. DESCRIPTION OF PROGRAM BRTDYN	7
5. DISCUSSION OF RESULTS	11
5.1 Purpose	11
5.2 Results	12
5.2.1 Cold Starting	12
5.2.2 Hot Starting and Load Transients	17
5.2.3 Two HSA Operation	20
5.2.4 Shutdown Transients	21
6. CONCLUSIONS	23
6.1 Shutdown	23
6.2 Response and Gain Selection	23
6.3 Startup	24

APPENDIXES:

- A. DESCRIPTION OF NOMENCLATURE AND COMPONENTS (13 pages)
 USED IN PROGRAM BRTDYN
- B. DYNAMIC SIMULATION COMPUTER PLOTS (53 pages)
- C. STABILITY DISCUSSION SIMPLE LINEAR MODEL (2 pages)

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TRANSIENT ANALYSIS ISOTOPE BRAYTON FLIGHT SYSTEM

1. INTRODUCTION

This report, prepared by the AiResearch Manufacturing Company of Arizona, a Division of The Garrett Corporation, describes the results of a study of the transient performance of the Isotope Brayton Flight System (IBFS).

The IBFS consists of the Mini-Brayton rotating unit (Mini-BRU), recuperator, gas radiator, heat source assembly (HSA), and control system. A mathematical model of the complete system was constructed, using individual component performance maps, and input to an existing closed Brayton cycle transient analysis computer program. This program was used to predict thermal transients during system start-up, shut-down and step load changes. In addition, acceleration characteristics were defined for various system start modes, as were system electrical characteristics at various applied loads.

This computer program provides a powerful analytical tool to study the transient characteristics of the rather complex and interrelated thermal, aerodynamic, and physical parameters of the closed Brayton cycle. A great deal of confidence exists in the accuracy of the results as the model has been rigorously verified by comparison to the more detailed transient models which exist for some of the individual components, (refer to Appendix A).

The existence of this analytical tool will provide, in the future, an important means for studying system performance, system safety aspects, reliability design, and control characteristics for a wide variety of operating modes.

2. SUMMARY

This report presents an introduction to the procedures that exist for studying the transient performance of the closed Brayton cycle. An important analytical tool, the transient analysis computer program, will be used throughout the evolution of the system design. The data presented is for a typical system. This information is intended to allow system and component designers to generate a preliminary evaluation of the performance of the various components being subjected to the predicted transients. Several possible control variations to alter the transients were evaluated to provide trend information. The final system definition will undoubtedly require numerous iterations using this computer program.

The transient study of the reference IBFS resulted in a series of system dynamic simulation computer plots which are included as Appendix B and discussed in detail in the text of this report. Fifteen operating modes covering hot and cold starts, load transients, and shutdown for the three capsule system are presented. Load transients for the two capsule cases are also included (Table 1 in Section 5 provides a summary of the variations).

The startup simulation shows the rate of rise of temperatures around the loop, and how these rates vary using different control techniques to prolong startup time. The rate of rise of temperature is of interest from a thermal stress standpoint and is expected to be most critical in the recuperator and heat source heat exchanger. An evaluation of the rate of temperature rise and its effect on these heat exchangers must now be made. It is expected that to select a control scheme which is compatible with their requirements, further system analysis must be performed and the results continually coordinated with the component analyses.

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The data presented herein includes transient loading plots, in which step loads are applied. The margin required in the engine and alternator loading ability will depend upon the suddenness and magnitude of the load application. The allowable margin also depends upon the speed control droop characteristic, or allowable gain. This is due to the fact that the engine runs overspeed by the amount of control droop during no-user load operation, thus resulting in a reduction of heat source temperature with too low a gain. The engine cannot then be step loaded to full power because the heat source is excessively subcooled. The other limit on droop or control gain is that a very high gain causes closed loop instability. The data presented herein indicates that a control droop of two percent would be desirable for stability. Further evaluation should be made using the actual expected transient loading.

Shutdown transients were run to define the time the engine takes to traverse engine critical speeds during rolldown and to determine low thermal or electrical load requirements to effect a shutdown.

Section 6 presents the significant conclusions to be drawn from the study.

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3. CONTROL SYSTEM DESIGN PHILOSOPHY

The initial requirement in the design of any control system is proper system analysis to determine the required control functions.

Major objectives for the closed Brayton cycle controls are:

- (a) Engine startup
- (b) Engine shutdown
- (c) Provide for optimum engine-alternator performance during loading
- (d) Safeguard the system components during the above operations

Proper engine startup requires the evaluation of several parameters:

Since startup imposes thermal and pressure stresses on all components, particularly the heat exchangers, it is important that the rate of temperature increase be controlled. Gas flow rates and their temperatures determine the rate at which heat exchanger temperatures will change; as gas flow is a function of speed, acceleration control during the start will control temperature rate of change. Control of speed setpoint as a function of time or HSA inlet temperature rate are two possible methods of controlling stresses during startup.

The rate at which speed increases is a function of start motor torque, less all the drags imposed on the start motor. These include alternator windage, compressor, bearing, and at low speeds, the turbine may also exhibit a drag. This is obviously a complex phenomenon which occurs inside the engine loop. First, heat is carried from the

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heat source to the turbine, and the heat rejected from the turbine is carried into the recuperator. As the recuperator heats, the gas inlet to the heater becomes warmer which, in turn, raises the turbine inlet temperature and the temperature of the recuperator again. The time lag associated with each of these events makes the problem complex, and a computer solution is required.

When rated speed is achieved, the speed control must prevent over-speed and control speed in a stable manner.

Engine shutdown imposes conditions which are opposite to those which occur during startup. Safe shutdown of the IBFS is required during qualification and pre-flight acceptance testing.

Reduction of the heat input from the HSA by thermally shunting the insulation will not effect an immediate shutdown of the Mini-BRU since the residual heat will tend to keep the Mini-BRU rotating. Electrical load will be applied to effect a shutdown in a manner that minimizes heat exchanger thermal transients and bearing contact.

A potential shutdown concept would be to maintain the Mini-BRU at 100 percent speed as long as possible to dissipate the heat from the system. As power decreases, parasitic load decreases until the engine will no longer carry load. As power continues to decrease, the speed will droop. If the HSA cannot be sufficiently shunted to result in a shutdown, the parasitic load speed setpoint will be programmed down after the minimum power point is reached.

As the self-sustaining speed (30-40 percent of design speed) is approached, a rotor critical speed is approached as well. To ensure that the rotating group passes through the critical speed quickly, the alternator will be loaded completely at 50 percent speed. This will also ensure that the speed at which the bearing gas film collapses (about 10 percent) is passed through quickly.

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The remaining controls objective is satisfactory control during loading. The basic control philosophy is that a parasitic load bank will absorb that part of the constant electrical power output that is not needed by the vehicle. It is necessary to be able to apply vehicle load in a step manner or to a load profile without excessive engine speed droop. The parasitic load control is proportional; as user load is applied, the engine must droop in speed before parasitic load is shed. If the gain of this parasitic load to speed error is low, then the engine will experience a large droop in speed under the load application. If the gain is too high, a closed loop limit cycle instability could occur. The resulting engine performance during a load transient is again a complex phenomenon as speed changes are a function of engine inertia and all the thermal loads and gas pressure-flow lags around the loop.

Due to the complexity of the controls analyses and the desire to investigate many control concepts in a short period of time, a dynamic computer model of the entire closed cycle engine (Program BRTDYN) was used. The model contains the dynamic time-varying differential equations for the engine speed, compressor discharge pressure, turbine discharge pressure, heater temperature, radiator temperature, and recuperator discharge temperature on the high and low pressure sides. These are the major dynamic effects in the loop and represent the engine transients to a reasonable degree. This model can, of course, be updated and refined to better define the equipment used in the laboratory test. The model is currently operational for the IBFS and the GDS. It is a best estimate for all components, and a detail description of each component is included in Appendix A. The three heat source capsule system should represent a "worst case" to the controls (highest gains and largest loads). The two-capsule system is also presented.

A description of this program and a discussion of the results of the study are presented in the following sections of this document.

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4. DESCRIPTION OF PROGRAM BRTDYN

Program BRTDYN is a digital computer transient analysis program used to simulate a closed Brayton cycle engine. It includes details of the control components enabling it to be used to size and analyze performance of these components. The baseline system modeled is shown on Drawing 306960. SKP4612 shows the basic flow diagram. A simplified program flow chart (Figure 1) and a schematic diagram of the nomenclature (Figure 2) may be helpful in understanding the program and its computer model of the isotope Brayton system.

This program is written in Garrett Universal FORTRAN language which is basically FORTRAN IV. It is run on the AiResearch Control Data Corporation Model 6400 digital computer and produces plots on a Cal-Comp plotter. The program output gives the following variables as a function of time and can be read from both the printout and the Cal-Comp plots:

- o Temperature of all major stations around the loop, including heat exchangers.
- o Pressure at all major stations around the loop
- o Turbine and compressor flow, high and low pressure recuperator flow, bypass flow, bearing flow, leakage, and any other applicable flows
- o Engine speed
- o Area of bypass valves (if overspeed protection is included for the system)
- o User load and parasitic load

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SIMPLIFIED BRTDYN FLOW CHART

FIGURE 1

PROGRAM BRTDYN NOMENCLATURE

FIGURE 2

FLIGHT CONTROL & MONITORING SIMULATION

LEGEND

STATE
POINTS

0-19 PRIMARY LOOP

1 COMPRESSOR INLET

2 COMPRESSOR DISCHARGE

3 NOT USED

4 NOT USED

5 HEAT SOURCE INLET

6 TURBINE INLET

7 NOT USED

8 NOT USED

9 TURBINE DISCHARGE

D 10 RADIATOR INLET

11 RADIATOR WALL

12 HEAT SOURCE INTERNAL

13 RECUPERATOR WALL

14 TURBINE JOURNAL BRG

15 COMPRESSOR THRUST BRG

16 COMPRESSOR JOURNAL BRG

17 NOT USED

18 NOT USED

19 NOT USED

30-39 DC ELECTRICAL SYSTEM

30 DC BUSS

31 PARASITIC LOAD SUPPLY

40-49 AC ELECTRICAL SYSTEM

40 ALTERNATOR OUTPUT

41 ALTERNATOR NEUTRAL

42 FIELD SUPPLY

C 120-129 FACILITY COOLANT LOOP *

120 RADIATOR INLET

121 RADIATOR DISCHARGE

120-129 FACILITY AC ELECTRICAL *

DATA
ACQUISITION

<u>TEND</u>	<u>DIGITAL</u>
<u>RECORDER</u>	<u>DATA</u>
N1	N1
T1	N40
T5	T7
T6	T2
T11	T5
T12A	T6
T12B	T9
T13	T10
P1	T11A, B, C
P2	T12A, B, C
KW30	T13A, B, C
KW40	T15
KW31	T16
V42	T120
	T121
	P1
	P2
	P6
	P9
	P11
	P15
	P16
	V30
	I30
	I31
	V40A, B, C
	KW40
	V41
	V42
	I40A, B, C, N
	I41
	I42
	V140A, B, C
	I140A, B, C
	KW140
	F120
	V31
	KW30
	KW31

NOMENCLATURE

	FIRST LETTER	SECOND LETTER	THIRD LETTER
A		ALARM	
C	CONTROL	CONTROL	CONTROL
C _T		COUNTER	
E	ELAPSED		
F	FLOW		
H	HAND		HIGH
I	CURRENT	INDICATOR	INDICATOR
K	CONTACTOR		
K _W		POWER	
L	LEVEL		LOW
M	MOTOR	MOTOR	
N	SPEED		
P	PRESSURE		
P _Y	DIFF. PRESS.		
Q	TORQUE		
R		RELIEF	
S	SOLENOID	SWITCH	
S _T	START		
T	TEMP	TIME	TIME
V	VOLTAGE	VALVE	VALVE
X	SHUTDOWN DEVELOPMENT		

A

STATE POINTS
RELIEF VALVE
CHECK VALVE
SOLENOID OPERATED GATE VALVE
MANUALLY OPERATED GATE VALVE

QUANTITY REQ		FIG NO	PART NO OR IDENTIFYING NO	SYM	NOMENCLATURE OR DESCRIPTION	CODE IDENT	MATERIAL AND SPECIFICATION	ZONE
← PART NUMBER								
					PARTS LIST			
		SIGNATURES		DATES		AIRCOR RESEARCH MANUFACTURING COMPANY OF ARIZONA A DIVISION OF THE GARRETT CORPORATION PHOENIX, ARIZONA		
		BY <u>W. KOZAK</u>		<u>10 14 74</u>		DWG TITLE <u>MINI BRU</u> <u>BRASSBOARD SYSTEM</u>		
		CHK						
		DATE						
		TITLES						
		REV						
REQD NEXT ASSY		USED ON		PRICE		SIZE CODE IDENT NO DWG NO <u>E 99193</u> <u>306960</u>		
HEAT TREATMENT		FINISH						
HARDNESS AND SPEC		GRADE AND SPEC						
		DESIGN ACTIVITY AND		<u>11/2/74</u>		SCALE ~ WT ~ SHEET # OF 1		
		OTHER ACTIVITY AND

PROGRAM BRDYN
BLOCK DIAGRAM

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The program was written to perform calculations in a reasonable running time. All curves and maps have been reduced to equation form to avoid integrating stored data and the program uses a modified Euler integration scheme which enables it to run very fast compared with other techniques. The result is that approximately two seconds of real time are simulated for every second of computer time.

Closed Brayton cycle dynamic simulation has been performed using this programming procedure for over a year, and several engine configurations were programmed during this period.

A detailed description of the components used in the program is included in Appendix A.

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5. DISCUSSION OF RESULTS

5.1 Purpose

The purpose of this study was to provide preliminary data for system design in the following areas:

- (a) Starter Requirements - The engine variables are all described in the program. This allows selection of starter torque and cutoff speed. These variables may be applied to the simulation and start times observed.
- (b) Speed Control Gains - The results of using various control schemes and gains may be studied to find resulting stability and speed droop for any given load profile.
- (c) Temperature Transients During Startup - A profile of temperatures and flows during startup may be generated for use in heat exchanger design. The effect of various control schemes on startup temperatures may also be studied, as previously noted.
- (d) Temperature and Speed Transients During Shutdown - The temperature rate of change is of interest from thermal stress considerations, and the deceleration through critical speeds is of particular importance.

The program was used to generate the initial data required to develop control schemes. The results are presented in Section 5.2. The program is available for evaluation of various control concepts and subsequent complete evaluation of the selected controls.

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5.2 Results

The computer-generated plots presented in Appendix B represent several transient conditions that may be experienced by the system. These are identified by a computer simulation (or run) and short title. The following subsections describe the computerized studies, with comments on the input and the results. A summary of these is presented in Table 1.

5.2.1 Cold Starting

5.2.1.1 Run 101--Cold Start with Heater at 2060°R

This is a start-up transient from zero speed with all components at 450°R except the cooler (390°R) and the heat source (2060°R). This represents a start after a 12-hour cold soak in synchronous orbit.

There are four plots which present all the variables of interest. On the first plot, speed is seen to reach 100 percent in approximately 4.5 seconds, and compressor pressure ratio lags speed and peaks at approximately 5.5 seconds. Change in pressure and speed are slow after this initial response. The next plot shows DC voltage, user load, parasitic load, and applied mechanical load. The initial hump between zero and two seconds is the starter torque motoring the engine (this is really negative load but was plotted positive on the charts to prevent requiring a negative axis). Note that all load is inhibited until the engine reaches 95 percent speed. During start-up, user load was not applied, and only parasitic load contributes to the mechanical load. The load drops off with time as the heat source is cooled down, by the 450°R components. Load would recover over a long period of time. Temperature is plotted on two charts, one presenting all data on one plot and the other plot presented for clarity. In these plots turbine inlet temperature (T6) drops from 2060°R to 1827°R in 180 seconds. This appears to be near a minimum and will start to increase again toward steady-state. At

TABLE 1
COMPUTER SIMULATION SUMMARY

Run No.	Description	Gain	Initial T6 (°R)	Initial T1 (°R)	No. Heat Source Capsules	General Remarks	Observations
101	Cold Start	Nominal	2060	450*	3	Free acceleration to rated speed	
102	Cold Start	Nominal	2060	450*	3	Ramped speed from 27,000 RPM using speed control	
103	Cold Start	Nominal	2060	450*	3	Hold at 27,000 RPM using speed control	No plot, system died
104	Cold Start	Nominal	1660	450*	3	Free acceleration	Inhibit excitation below 95 percent speed
105	Cold Start	Nominal	2200	450*	3	Free acceleration	Reached alternator limit
106	Cold Start	Nominal	2060	450*	3	Ramped speed with defined speed	Represents inverter drive/brake
107	Cold Start	Nominal	2060	450*	3	Defined speed at 27,000 RPM	Represents inverter drive/brake
201	Hot Start and load transients	Nominal	2060	Steady state	3	Free acceleration	
202	Hot Start and load transients	Nominal	2200	Steady state	3	Free acceleration	Speed ran away, no plot
203	Hot Start and load transients	Nominal	2160	Steady state	3	Free acceleration	Reached alternator limit

*Cooler at 390°R

TABLE 1 (Contd)
COMPUTER SIMULATION SUMMARY

Run No.	Description	Gain	Initial T6 (°R)	Initial T1 (°R)	No. Heat Source Capsules	General Remarks and Observations
302	Startup and load transient - double speed control gain	Double	2060	Steady state	3	Unstable
303	Startup and load transient - half speed control gain	Half	2060	Steady state	3	Stable
401	Load transients	Nominal	2060	Steady state	2	This run is normal 2 HSA transients.
501	Shutdown	Nominal	2060	Steady state	3	Unstable
502	Shutdown	Half	2060	Steady state	3	Stable

this low turbine inlet temperature the parasitic load required to hold speed is only 1.1 kw. Considerable time will be required to achieve steady-state and full power. Turbine discharge temperature (T9) drops from near 2060°R, as little work is extracted during the time the engine is accelerated by the starter, to 1720°R in 5 seconds. Turbine discharge then slowly drops to 1568°R at 180 seconds. Note that this also represents recuperator inlet temperature and, although the temperature is high, initially the flow is low. After five seconds flow is well established and the 1720°R gas reaches the recuperator, which is at 450°R. The other side of the recuperator is exposed to inlet temperature from compressor discharge (T2). This temperature rises rapidly with engine speed and pressure ratio from 390°R, which was the cooler initial condition, and is 528°R in five seconds. An indication of the resultant thermal stresses imposed on the recuperator would be the ratio of rise of heater inlet temperature (T5). For this case, it goes from 450°R to 857°R in 50 seconds, or 8.14 degrees per second.

The compressor flow is seen to drop at 1.5 seconds and again at 4.5 seconds. This is caused by a combination of a reduction in engine acceleration at these points and by the pressures "catching up" after lagging during the acceleration. The pressures lag since a large volume is being pumped up on the compressor discharge side and pumped down on the compressor inlet side.

5.2.1.2 Run 102--Cold Start with Controlled Acceleration

This start is similar to that of Run 101 except the acceleration to rated speed was controlled by ramping the speed control set-point from 27,000 to 52,000 rpm at 250 rpm per second. This illustrates a method of control to reduce the thermal transient in the recuperator and heat source.

Although the speed ramp was strictly arbitrary, the two computer simulations provide time related gas temperatures and flow rate for

use in component stress analyses. The ramped start provides data for a preliminary look at controlling flow rate during the start to reduce thermal transients should the rapid start be found objectionable.

5.2.1.3 Run 103--Cold Start with Speed Held at 27,000 RPM by Speed Control

A plot of the data was not generated. A review of the data print-out disclosed that the turbine inlet temperature droop due to the cold components resulted in a non-self-sustaining condition at 27,000 rpm after 60 seconds. This simulation was to provide data for evaluating the practicality of maintaining speed at near self-sustaining levels to allow a slow preheat of the recuperator. An alternate approach of maintaining the speed at 27,000 rpm is to use the start inverter to provide positive or negative torque. This approach is illustrated by Run 107.

Although the speed control approach would work at some higher speed or by using the start inverter to augment during the low speed mode, the basic data required to evaluate the concept is provided by Run 107; therefore, no attempt was made to obtain further data for this mode of start-up.

5.2.1.4 Runs 104 and 105--Cold Starts with Limited Heat Source Start-Up Temperatures

These simulations demonstrate the minimum and maximum temperatures for a satisfactory free acceleration start. A heat source temperature resulting in a turbine inlet temperature of less than 1600°R at 27,000 rpm is insufficient to achieve self-sustaining speed. A heat source temperature of greater than 2200°R will result in an overspeed as the alternator cannot provide sufficient load to balance the available power.

The low temperature condition is significant relative to cool start considerations, whereas the high temperature condition must be considered when establishing control and protection logic and tolerances.

5.2.1.5 Run 106--Cold Start with Ramped, Inverter Controlled Speed

The start acceleration was controlled from 27,000 to 52,000 rpm at the rate of 250 rpm/sec, similar to ramping the inverter frequency and charging the batteries with excess power. This provides data for evaluating the effects of a slow start on component thermal transients.

Compressor flow and gas temperatures at various state-points are shown on the last sheet of this run.

5.2.1.6 Run 107--Cold Start, Speed Limited to 27,000 RPM by Using Start Inverter as a Brake

Again, this data was generated, assuming battery charged with excess power for evaluating alternate start modes to limit thermal transients.

5.2.2 Hot Starting and Load Transients

5.2.2.1 Run 201--Hot Start-up with T_6 at 2060°R

A startup was demonstrated with all components at steady-state temperature. This simulates a startup immediately after shutdown. The user load profile imposed on the machine is as follows:

- o Load zero until 20 seconds
- o Load stepped to 1.0 kw_e at 20 seconds and held until load ramped to 0.0 between 40 and 60 seconds.

- o Load stepped to 2.0 kw_e at 60 second and held to 80 seconds where it is again dropped to zero.

This profile is seen on the plots as user load changes and is typical of several runs.

The resultant plot shows parasitic load to be applied at 4.5 seconds as speed reaches the set-point (52,000 rpm). The alternator excitation is inhibited until 95 percent speed is achieved. The parasitic load reaches 2.25 kw and drops slightly between 5 and 20 seconds. The load is somewhat high as the heat energy going into the heater was not being removed by the working fluid during the five seconds of start-up. The user load is stepped up at 20 seconds, and the parasitic load is removed as soon as speed droop causes it to be removed. As speed does not drop immediately, the mechanical load, (which is the total of user load plus parasitic load plus accessory load) has a spike, while speed is reducing. This power required during the spike is 2.8 kw_e and saturates the alternator, causing voltage to drop below the regulated 120 vdc. It is noted that a damped oscillation of parasitic load occurs after this step. It is concluded that the speed control gain is causing this cycling, and it is a closed loop dynamic instability. Appendix C shows a linearized block diagram of this control loop and a limited discussion of this problem. Subsequent runs show this same transient with higher and lower gains. As the user load duration is reduced between 40 to 60 seconds the parasitic load increases. Another step in user load occurs at 60 seconds, and the same result occurs as during the previous step in which voltage again drops below regulation. The load is stepped to zero at 80 seconds, and speed increases slightly and parasitic load is again applied.

The "nominal" gain used in this run is 0.003846 kw_e per rpm of error (deviation from setpoint). Thus, a one percent speed change or 520 rpm produces 2 kw_e parasitic load change.

5.2.2.2 Run 203--Hot Start with Turbine Inlet (T_6) at 2160°R

This computer simulation represents the maximum T_6 at which it is safe to start, as any higher temperature would exceed the alternator loading capability. The transient imposed here is similar to Run 201, but it is noticed that the parasitic load is larger for this run since T_6 is hotter.

It is seen that the plot does not oscillate after step loads to the degree experienced on Run 201, although the gain (actually in resistance load per percent speed error) is the same as on Run 201. Several quantities are, however, different in this highly non-linear system, namely the engine speed and power level which are higher at the higher turbine inlet temperature. It appears that the voltage is off regulation longer and at higher power levels the alternator is near saturation. Figure A-7 in Appendix A shows applied mechanical (reflected) load versus the resistance load (plotted as load admittance) on the alternator. This curve rolls off the straight line 120 volt curve, and the gain is reduced severely upon alternator saturation. Such non-linearities are believed responsible for changes in stability. As further proof of the above assumption, note that parasitic load is stable between 5 and 15 seconds on this run while the alternator is saturated and vdc is below 120. The parasitic load begins to cycle at 15 seconds as voltage goes back to 120 volts and the gain increases.

5.2.2.3 Run 302--Hot Start Speed Control Double Gain

The gain of parasitic load to speed error was doubled so that essentially 2 kw_e is applied with 1/2 percent speed error.

It is seen that the speed changes resulting from step load changes are reduced, as would be expected. The higher gain also resulted in reduced dynamic stability, as would be expected, and as seen between 60 and 80 seconds during this run.

5.2.2.4 Run 303--Hot Start, Half Speed Control Gain

The gain of the parasitic load to speed error was reduced to half of the nominal value or 2 kw_e per 2 percent speed error.

It is seen that the speed changes approximately 1000 rpm with step changes of full load. This is as expected from the large droop allowed by the low gain. The plot is also seen to be the most stable of the series as there is no cycling during this simulation. This also would be expected since the lowest gain should produce the best stability.

5.2.3 Two HSA Operation

5.2.3.1 Run 401--Transient Loading Speed Set Point 52,000 RPM

This simulation is of a two HSA system and as such the value of the transient loads are different, but they are imposed over the same time cycle previously used. The first step is to 0.7 kw_e and the second step is to 1.38 kw_e . This run was made with the set point of the speed control at 52,000 rpm, meaning that parasitic load was applied as the speed exceeded 52,000 rpm and was fully removed only at speeds below 52,000 rpm. The load cycles occur as on past runs except at 60 seconds when the full 1.38 kw_e load is applied, the engine becomes overloaded. As load is applied, parasitic load is removed until speed goes down to 52,000 rpm. This speed nearly carries rated load as the speed curve becomes very flat and all torques are nearly balanced; however, the load continues slightly high and once speed starts to drop it, in turn, also drops rapidly as load remains constant. The load is shed at 95 percent speed and continues to cycle on and off until 80 seconds when load is removed. The lack of ability to hold this load may be caused by the engine running overspeed, i.e., approximately 52,360 rpm, and the engine temperatures not being exactly at the steady-state 52,000 rpm design condition when the load is stepped on. Also, the

load is so nearly balanced that this run is really only of significance in demonstrating that some margin is required, and a small parasitic load should be applied even at maximum user load to act as a "cushion" during these sudden load changes.

5.2.3.2 Run 401--Transient Loading Speed Set Point 52,200 RPM

The above run was repeated with the speed set point at 52,200 rpm. This provided the added power necessary to accept the full 1.38 kw_e step in load without drooping out in speed. The plot shows the load applied and a well behaved response. The gain during these two HSA transients was 2 kw_e parasitic load per one percent speed change which is the "nominal" value used on 11 runs.

5.2.4 Shutdown Transients

5.2.4.1 Run 501--Shutdown Load Transient

Engine shutdown was studied during these simulations. This is a possible mode of engine shutoff which could be used on the launch pad. If heat source power removal were used to shut down the system, the time required would be long as the heat source has a large heat capacity. This shutdown was accomplished by resetting the speed setpoint down as a function of time along the ramp seen in the plot. Speed is reduced as commanded until, at 67 seconds (22,000 rpm), the engine is no longer self-sustaining. The compressor inlet and discharge pressure come together as speed reduces. The turbine inlet temperature increases as gas flow decreases, and the same energy is being put into less mass flow. Compressor inlet temperature drops as the radiator becomes more effective. The parasitic load becomes unstable as the command speed ramps down. For this reason, another simulation was made at lower gain. The rapid changes in parasitic load do not drastically change engine speed and may not be objectionable in a control system.

5.2.4.2 Run 502-Shutdown Load Transient, Half Gain

This simulation is a repeat of Run 501 except the parasitic load gain is half of nominal value. That is, 2 kw_e is applied in 2 percent speed error. The plots are the same as before except the parasitic load curve does become stable at this lower gain. The voltage curve is seen to come off regulation after speed droops sufficiently so that it can no longer carry the load.

6. CONCLUSIONS

The output included in this report provides transient characteristics for various operating conditions with the baseline system. Although a control scheme has not been finalized for the system, some conclusions can be drawn from those cases which will influence the control selection. Further study will be made as selection progresses.

6.1 Shutdown

It can be seen from the traces that speed response to the removing of heat from the heat source would be very slow, since the thermal energy capacity of the heater is relatively large.

The shutdowns simulated using the computer model were caused by reducing the speed setpoint and allowing alternator load to command reduction of speed. This results in a rapid rolldown from 22,000 rpm as the engine is no longer self-sustaining below this speed (at this temperature). The critical speed is passed through rapidly, and this shutdown method appears feasible, pending further bearing design studies. The unstable cycling of parasitic load at normal gain did not affect speed to any significant degree and may not be harmful. The final gain will most likely be selected from stability criteria based upon step loading.

6.2 Response and Gain Selection

The controls simulations presented illustrate that the nominal gain selected (2 kw_e per percent speed) is marginal from a stability standpoint. It would be desirable to have half this gain. Further evaluation of this conclusion is now required as the larger droop resulting from this low gain will allow the engine to run near 53,000 rpm when user load is zero. This will, in turn, cool the heat source as the gas flow will be above the design value and, upon a step load to

full user power, the engine will not carry the load due to too low a turbine inlet temperature. Margin must be designed into the engine to account for this condition or possible control modifications are required. These will be enumerated in following paragraphs.

The two HSA load cases also demonstrated that full step load could not be carried, and the engine cycled on the 95 percent speed load-shedding control.

Two modified control schemes have been suggested which would aid in solving the overload problem and reduce the power margin which must be designed into the engine. These are:

- (a) A user load priority system whereby various user loading elements are shed if the engine speed droops below, say, 98 percent. The most critical user load items would stay on-line, and those of lesser importance would be denied power if it was not available.
- (b) Another alternative is to reduce voltage if engine speed droops below, again say, 98 percent speed. This reduces power as the square of voltage and reduces power to all user loads simultaneously.

The evaluation of the above suggestions depends upon the payload being carried and will require some study before final conclusions are drawn.

6.3 Startup

The primary purpose of the startup transient being programmed is to analyze the thermal stresses being imposed on the components. The recuperator appears to be the most critical component as the thermal stress is highest in this thin walled heat exchanger. The rate of rise

of the temperatures at the recuperator is the primary factor of interest in evaluating the thermal stress, and these data will be input to the recuperator design. A summary of the recuperator inlet and discharge temperatures obtained from the computer runs is presented, for comparison, on Figures 3, 4, and 5.

Recall that Run No. 101 is a startup from the cold soak condition, all components at 450°R except the cooler which is at 390°R , and the heat source is at 2060°R . This run represents a normal start using the starter and allowing free acceleration to 100 percent speed, and is a standard for comparison. The results of Runs 102 and 106 lie very close to those of Run 101. In these two runs, speed is ramped as a function of time up to 100 seconds. It is seen that some reduction in the rate of temperature rise does occur during the first few seconds of startup.

Run 104 is a startup with the heater at 1660°R . This produces one of the lowest temperature rates of increase, however, there is one difficulty if it is to be used as a start procedure. If the heat source is at 1660°R when a start is initiated, the time required to achieve 2060°R is extremely long. The reason for this is that heat is being removed from the heat source at nearly the same rate as it is being added, thus it requires a long period of time to raise the heat source mass temperature.

Run 105 is a 2200°R heat source start. This represents the result of a possible worst case tolerance on measuring heat source temperature and shows the resulting transient.

In Run 107, the speed is held at 27,000 rpm during the entire 180 second run by using the start inverter as a combination source and load. It is contemplated that the speed would be stepped or ramped to 52,000 rpm at some later point in time, (that time being as soon as permissible from thermal rate increase considerations). This appears to give a thermal ramp which is much better than on several other runs.

COMPRESSOR DISCHARGE TEMPERATURE
TRANSIENT SUMMARY

FIGURE 3

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HEAT SOURCE INLET TEMPERATURE
TRANSIENT SUMMARY

FIGURE 4

TURBINE DISCHARGE TEMPERATURE
TRANSIENT SUMMARY

FIGURE 5

126-22

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The final control design selection will be made following coordination with other system component designs.

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APPENDIX A

DESCRIPTION OF NOMENCLATURE AND
COMPONENTS USED IN PROGRAM BRTDYN

APPENDIX A

DESCRIPTION OF NOMENCLATURE AND
COMPONENTS USED IN PROGRAM BRTDYN

NOMENCLATURE

RPM (RPN)	Engine Speed
P1	Compressor Inlet Pressure
P2	Compressor Discharge Pressure
PMEC	Mechanical Power
PPL	Parasitic Load Power
PUSR	User Load Power
VDC	DC Voltage
T1	Compressor Inlet Temperature
T2	Compressor Discharge Temperature
T5	Recuperator HP Discharge Temperature
T6	Turbine Inlet Temperature
T9	Turbine Discharge Temperature
T10	Recuperator LP Discharge Temperature
W2	Compressor Gas Flow Rate

PROGRAM BRTDYN COMPONENTS

A. COMPRESSOR (CMPRSR)

The compressor is described in a subroutine which is called from subroutine DEREV. The input to the subroutine is compressor inlet pressure (P1), compressor inlet temperature (T1), engine speed (RPM), and compressor pressure ratio (PRC). The subroutine contains compressor maps that have been reduced to equation form so that time-consuming interpolation is not necessary. The maps of airflow versus pressure ratio for various speeds are used and also the map of temperature rise versus airflow at various speeds is defined in the subroutine. The output parameters are compressor torque (QC), compressor discharge temperature (T2), and compressor flow (W2).

B. RECUPERATOR (RECUP)

The recuperator is described in a subroutine which is called from subroutine DEREV. The input to the subroutine is time (T), high pressure side inlet temperature (T2), high pressure side flow (W5), low pressure side inlet temperature (T9), and low pressure side flow (W9). The subroutine performs the computation, including heat exchanger dynamic response, and returns high pressure side outlet temperature (T5) and low pressure side discharge temperature (T10). One other value (NR) is given to the subroutine, and this is the number of the variable being integrated for use with the time integration subroutine.

The calculation of the outlet temperatures is performed, based on the recuperator effectiveness map (Figure A-1). The effectiveness is a function of the flow on both sides of the recuperator, and this map is in equation form in the subroutine in order to save time required to interpolate a three-dimensional map. The steady state temperatures are computed from this effectiveness and represent the instantaneous

RECUPERATOR EFFECTIVENESS MAP

CORE MASS = 63.00 LBS
SPECIFIC HEAT = 0.1 BTU/LB

FIGURE A-1

values of outlet temperature. The heat exchanger does not generate this instantaneous temperature, because of the thermal lag caused by the metal mass in the heat exchanger and the heat transfer characteristics. These dynamic effects are modeled in the program by computing the time constant each pass through the subroutine and also the time derivative. The time integration is performed in subroutine SMPINT with the results of the iteration coming from RECUP. Thus, the temperature which comes from RECUP is the time lagged value and represents the true output at that point in time.

The results of this subroutine have been compared to the results obtained from larger, more detailed, programs and the results compare favorably. (See Figure A-2.)

C. TURBINE

The turbine is described completely in equation form using an analytical technique described in ASME paper 67-WA/GT-3 by Jansen and Quale. This paper is entitled, "A Rapid Method for Predicting the Off-Design Performance of Radial Inflow Turbines." The method allows computation of turbine discharge temperature (T9), flow (W9), and torque (QT) from the following input information: turbine, inlet pressure (P6), temperature (T6), pressure ratio (PRT), and speed (RPM). The data on geometric sizing of the turbine is also in the subroutine.

D. HEATER (SUBROUTINE HEAT)

The isotope heat source is modeled in this subroutine and operates in a manner similar to the recuperator. The steady state instantaneous value of temperature is computed, but the output temperature is lagged by the thermal inertia of the unit. A constant heat input is assumed, as the isotope heat output should be very steady with only a slow decay over a period of years. The time constant is calculated, based on the heat transfer calculation of thermal conductance, the

COMPARISON OF HEAT EXCHANGER DYNAMIC SIMULATION PROGRAMS

FIGURE A-2

heat exchanger mass, and specific heat of the metal. The time variable differential equation for temperature is computed. Subroutine SMPINT integrates the differential equation to arrive at the outlet temperature.

The inputs to the subroutine are time (T), inlet temperature (T5), flow (W9), heat flux (QH), and the number of the variable being integrated (NH). The output from the subroutine is heater outlet temperature (T6).

E. RADIATOR (SUBROUTINE COOL)

This is the model of the radiator. The temperature drop of the radiator in steady state was computed by an equation representation of the enclosed plot of gas temperature drop versus gas flow rate at various gas inlet temperatures (Figure A-3). The steady state outlet temperature is computed using inlet temperature less the computed temperature drop.

The heat exchanger dynamics are also included in this subroutine where the outlet temperature is computed by including the thermal lag. A time constant is computed from the radiation heat transfer characteristics and the heat exchanger mass and specific heat. The time dependent differential equation of outlet temperature was formulated. This equation is integrated in subroutine SMPINT to arrive at the correct temperature out of the radiator including the time lag caused by thermal inertia.

The input to this subroutine includes time (T), inlet temperature (T10), flow (W2), sink temperature (TS), and the number of the variable being integrated. The output from the subroutine is heat exchanger outlet temperature (T11).

MINI BRU GAS RADIATOR OFF-DESIGN PERFORMANCE

FIGURE A-3

F. ALTERNATOR

Off-design performance characteristics for the alternator were generated using the Rice alternator design program. Equations describing the reflected load and DC voltage as a function of applied load (combined user and speed control parasitic) were generated and included in the BRTDYN model.

Figure A-4 illustrates the electrical system configuration used for generating the alternator performance characteristics. As shown, series (and parallel) rectifier diodes were included, and the field current was included in the rectifier loss calculation. The speed controller control circuit losses are included with the parasitic load. A constant ten watts loss for the voltage regulator control circuitry was also included.

Figure A-5 shows the major electrical parameters as a function of applied load at 52,000 rpm. From this figure, it is apparent that the machine is saturated with three amps field excitation (four parallel windings); excitation was therefore limited at that value. Figures A-6 and A-7 show the reflected load and voltage characteristics as a function of speed and applied load with the field excitation limited to three amps.

G. START TORQUE

A start torque of $5.69 \times S^{1/2}$ (where S is the slip) was used for the system analysis. This represents a per unit torque of 1.75 for the alternator and is 28 percent greater than the predicted stall torque for the rotating group. [Reference AiResearch Progress Report Number 74-310631(10).] The voltage and current required to develop this torque is dependent upon the supply frequency; however, the unit is compatible with the requirement. See Figure A-8.

ELECTRICAL SYSTEM
FIGURE A-4

MINI BRU 2KW_e ALTERNATOR PERFORMANCE CHARACTERISTICS

FIGURE A-5

MINI BRU ALTERNATOR VOLTAGE vs LOAD

FIGURE A-6

MINI BRU 2KW_e ALTERNATOR REFLECTED _{vs} APPLIED LOAD

FIGURE A-7

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75-311279
Appendix A
Page A-13

MOTOR START CHARACTERISTICS

FIGURE A-8

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APPENDIX B

DYNAMIC SIMULATION COMPUTER PLOTS

RUN 101
MINI BRU COLD START - - ALL COMPONENTS AT 450 DEG R - - HEATER AT 2060 DEG R

4 RUN 101
MINI BRU COLD START -- ALL COMPONENTS AT 450 DEG R -- HEATER AT 2060 DEG R

5 RUN 102
MINI BRU COLD START-SPEED RAMPED FROM 27000

RUN 102
MINT BRU COLD START-SPEED RAMPED FROM 27000

RUN 102
MINI BRU COLD START-SPEED RAMPED FROM 27000

9 RUN 104 MINI BRU COLD START -- ALL COMPONENTS AT 450 DEG R -- HEATER AT 1650 DEG R

RUN 104
MINI BRU COLD START - - ALL COMPONENTS AT 450 DEG R - - HEATER AT 1660 DEG R

RUN 105

MINI BRU COLD START -- ALL COMPONENTS AT 450 DEG R -- HEATER AT 2200 DEG R

RUN 105
MINI BRU COLD START - - ALL COMPONENTS AT 450 DEG R - - HEATER AT 2200 DEG R

7

RUN 106
MINI BRU COLD START-SPEED RAMPED FROM 27000

RUN 106
MINI BRU COLD START-SPEED RAMPED FROM 27000

RUN 106
MINI BRU COLD START-SPEED RAMPED FROM 27000

RUN 107
MINT BRU COLD START-SPEED STEPPED FROM 27000

RUN 107
MINI BRU COLD START-SPEED STEPPED FROM 27000

25 RUN 201
MINI BRU HOT START---ALL COMPONENTS AT SHUTDOWN TEMP- T6 AT 2060 DEG R

RUN 201
MINI BRU HOT START---ALL COMPONENTS AT SHUTDOWN TEMP- T6 AT 2060 DEG R

RUN 203

MINI BRU HOT START---ALL COMPONENTS AT SHUTDOWN TEMP- T6 AT 2160 DEG R

31 RUN 203
MINI BRU HOT START---ALL COMPONENTS AT SHUTDOWN TEMP- I6 AT 2160 DEG R

RUN 302

MINI BRU HOT START-DOUBLE SPEED CONTROL GAIN

RUN 302

MINI BRU HOT START-DOUBLE SPEED CONTROL GAIN

RUN 303

MINI BRU HOT START-HALF SPEED CONTROL GAIN

RUN 303

MINI BRU HOT START-HALF SPEED CONTROL GAIN

□ PMEC
○ PPL
△ PUSR
+ VDC

VOLTA
GE
KILOWATTS
TIME (SECONDS)

RUN 401

MINI BRU TWO HSA SYSTEM -- TRANSIENT LOADING SPEED SETPOINT 52200RPM

RUN 401
MINT BRU TWO HSA SYSTEM - TRANSIENT LOADING SPEED SETPOINT 52200RPM

RUN: 401

MINI BRU TWO HSA SYSTEM -- TRANSIENT LOADING

SPEED SETPOINT 52000RPM

RUN 501
MINI BRU SHUTDOWN LOAD TRANSIENT

RUN 501
MINI BRU SHUTDOWN LOAD TRANSIENT

RUN 502
MINT BRU SHUTDOWN LOAD TRANSIENT-1/2 GAIN

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APPENDIX C

STABILITY DISCUSSION
SIMPLE LINEAR MODEL

APPENDIX C

STABILITY DISCUSSION
SIMPLE LINEAR MODEL

The question has been raised as to why the speed control loop becomes unstable at high gains since it is an "infinitely fast" control operating on an inertia. The enclosed simplified linear block diagram (Figure C-1) may be of assistance in understanding the system which is being controlled. The diagram presented is a linear representation of a very nonlinear system. Recall the saturation limits in the alternator, very nonlinear compressor and turbine characteristic maps, nonlinear heat exchanger effectiveness, and fluid flow nonlinearity. Also, the block diagram does not include some items which are of less significance. Several of the connecting lines were omitted for clarity. The time constants of the thermal elements are relatively long; however, in some cases, the gain of power change to temperature is relatively high so that these elements can influence high frequency dynamics. (The closed loop time constant is the open loop time constant divided by one plus the loop gain. If loop gain is high, closed loop response is fast.) There are dynamics associated with the compressor inlet and discharge pressures which are probably the most direct influence on engine dynamics. Based upon only this diagram, it is obvious that the inner loop being controlled by the parasitic load is of higher order dynamic characteristics. It would be of interest to evaluate these partials and examine the linear model. This can be done if time permits or if stability becomes of importance because of droop limitations. It now appears that if the droop increases to two percent that no instability is observed.

For the reasons outlined above, the computer model was chosen as the only reasonable means of analyzing this system.

75-311279
Appendix C
Page C-2