Hypersonic Research Engine Integated Propulsion Control

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Hardware and software aspects of the operating control system for the Hypersonic Research Engine (HRE), a Mach 3–8 ramjet being developed by AiResearch Manufacturing Company for NASA Langley, are described. The system is digital and provides automatic operation for all engine functions. In final form, the complete control is packaged within the engine centerbody. Development is progressing, including an operating breadboard that has been built and tested. The control is functionally and physically integrated. All functions (inlet control, fuel control, temperature limiting, and monitoring) are performed by a central digital processor. A single grouping of hardware is time-shared to provide the required functions. A small general-purpose digital computer permits complex functions, equations, and stored data curves to be used to obtain precise control of the HRE. The intelligence of this onboard computer is also used for ground-support maintenance functions.

Nomenclature

C	= const
$f(\Delta P/P_T)$	= venturi calibration curve (stored data)
$\dot{m}$	= air mass flow
M_0	= local Mach number
P_{RC}	= pressure ratio across the centerbody
P_T	= spike or fuel control pressure
T_T	= fuel total temperature
U_∞	= true airspeed
α_L,β_L	= local angles of attack and yaw
ΔP	= pressure drop between venturi inlet and throat
ΔP_α	= venturi pressure difference
ΔP_β	= horizontal pressure difference
ϕ	= pre-established schedule of fuel-air ratios

I. Introduction

THE problem statement directing development of the HRE propulsion control system emphasized the following:

1) A system to permit engine operation to be properly evaluated over a wide range of conditions. It need not be the optimum control for operational HRE engines, since it is to be a testing tool rather than a final solution.

2) A small package, lightweight, reliable, and mounted within the engine and suitable for flight testing aboard the X-15 aircraft. (This requirement was later revised in favor of a tunnel test program.)

3) Safe engine operation through all flight test phases. The specific functions required for the HRE control included 1) calculation of total fuel flow requirement, 2) modulation of fuel flow and proper distribution between injector locations, 3) positioning of the inlet spike, and 4) control of coolant flow quantity and distribution to maintain safe structure temperatures. The control receives signals from 35 transducers measuring inlet air pressures and temperatures, signals from 27 thermocouples measuring critical structure temperatures, and manual discrete signals from the pilot. A series of rather complex equations is then executed to determine engine airflow, fuel flow requirements, and injector distribution. Desired inlet spike position is also calculated, based on flight conditions and angle of attack. Structure temperatures are compared to stored or calculated references. Proper action must be taken rapidly when an allowable structure temperature is exceeded or an inlet unstart is detected. On the output side, the HRE control provides the electrical drive for control of electropneumatic fuel injector valves, an electrohydraulic servo valve on the inlet spike actuator, several other electropneumatic valves in the structure cooling circuits, and discrete signals to start up and purge valves.

A sophisticated but small control system is required. The program objective, therefore, was to define and develop an integrated propulsion control where all functions were performed by a single electronic data processor.

II. Mechanization Tradeoffs

Detailed studies were conducted to evaluate analog vs digital electronic control characteristics (see Table 1). The analog system considered was a conventional solid-state design, making maximum use of integrated circuits and thin- and thick-film microelectronic techniques. It had its own power supply, some adjustment capability for critical parameters, and was designed for mounting within the engine centerbody. The digital system considered was centered around a general-purpose digital computer, developed and in production for use in a commercial aircraft inertial navigation system. It had a random access core memory of 4096 words, with 18-bit word length. A separate input/output section was required for signal routing and data conversion, and additional analog circuitry was required for temperature control and spike control functions. A power supply was also required.

Both weight and volume favor the analog approach, but not significantly. Either system could meet envelope constraints. Form factor favored the analog approach, since the digital system required packaging around the $7.5 \times 4.5 \times 4.5$-in. box-like digital computer. Accuracy, of course, favored the digital approach, but the analog system, by its continuous nature, would be faster responding. However, the 2–10 Hz response of the digital system was adequate. Power consumption and reliability were about equal. Calculated analog system reliability was higher, but the digital mean time before failure (MTBF), based on a guaranteed figure for the computer, carried greater confidence. Both systems could meet temperature environments, and development costs were estimated to be within 5% of each other. The computer used in the digital approach was available as off-the-shelf hardware and carried no development cost.

Both systems will do the job, and there is little distinction between them prior to the final consideration, flexibility, which is a great advantage with the digital approach. Since the digital computer is general-purpose, changes to the control program are software rather than hardware changes, and,

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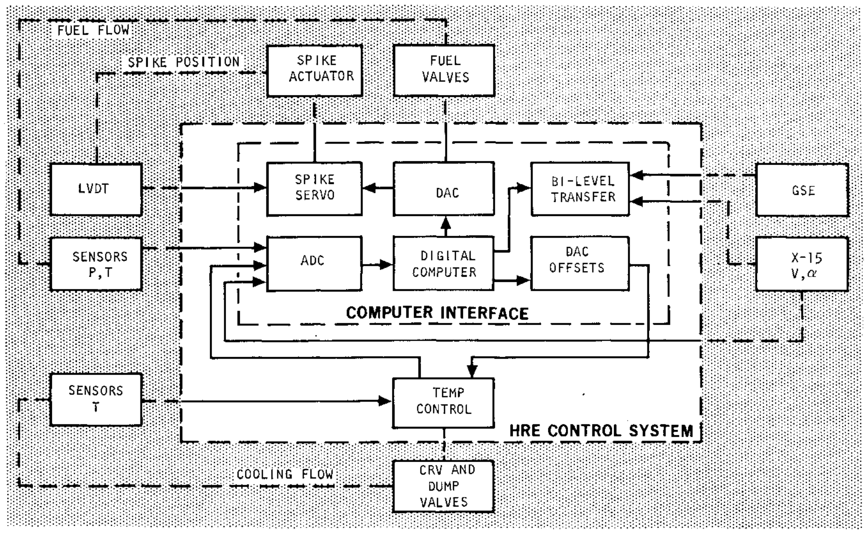

Fig. 1 Control system block diagram.

because the control is mounted in the engine centerbody, access for analog system adjustments is difficult, whereas the digital control can be easily reprogramed through an electrical umbilical. The digital approach therefore was selected.

Because of the time-sharing techniques used in digital systems, new requirements for sensors and output transducers can often be accommodated with a relatively small hardware commitment. Consequently, the digital approach provides a more stable physical hardware configuration when the machine to be controlled is in a progressive stage of development.

III. Control System Details and Operating Functions

The system block diagram in Fig. 1 shows the data flow and identifies some of the major elements in the control system. The dashed lines in the diagram between the valves and the sensors indicate the feedback loops, which are closed through the operating engine. The primary control loops include the engine inlet (spike position), engine cooling (temperature control), and the fuel flow and distribution. The block diagram shows a representative distribution of the hardware. Internal to the total control system, the hardware can be categorized in three items: the digital computer, the computer interface (the section that provides all communication between the computer and the outside world), and the temperature control. The power supply was omitted from the diagram for simplicity.

The system is actively engaged in checkout and preconditioning tasks before the actual engine test run, but its prime task is control of the engine during its operating run. This activity is under the automatic control of the digital computer program.

Table 1 Analog/digital tradeoff studies

Characteristic	Analog	Digital
Weight	6.0 lb	8.4 lb
Volume	150 in.^{3}	210 in.^{3}
Form	Variable	Constrained[a]
Accuracy	2%	0.1%
Response	30 Hz	2–10 Hz[b]
Power consumption	75 w	85 w
Reliability, MTBF	2300 hr	1880 hr[c]
Environment, capability	−40°–+160°F	−55°–+160°F
Cost, development phase	1.05	1.00
Flexibility	Fair	Excellent

[a] Because of basic rectangular shape of digital computer.
[b] Function of computer updating rate.
[c] Includes guaranteed figure for digital computer.

Application of this system to the operational engine test was to have been divided into four phases: 1) preflight, the period from ground power "on," until the X-15 is dropped from the B-52, 2) the period from the X-15 drop until the beginning of the actual engine operating test at high altitude, 3) the engine test run, and 4) the return from high-altitude, high-speed flight conditions to a subsonic flight environment. These considerations provide the basis for the various modes of the over-all control program.

The control system was to be powered and operated from the time ground power is applied. Automatic self-check was to begin immediately, and semioperational testing to continue until a few minutes prior to the X-15 release from the B-52. The operating mode was then to be changed to the flight test configuration and automatic self-test. This mode was to confirm the "go" condition prior to the drop. Self-test and monitoring functions continue throughout the flight.

The control system was to be ready to operate the engine when the X-15 was released. At the appropriate command, a series of preconditioning sequences was to bring the engine to full operational status. The hydraulic and pneumatic systems were to be pressurized, the cooling system was to be purged with helium, and, finally, the turbopump startup cycle was to be initiated.

The pilot was to initiate engine test or startup, and a further sequence of operations was to take place under computer control. The inlet geometry was to be set, and, after aerodynamic starting was confirmed, fuel was to be delivered to the combustor and ignition provided. Fuel flow and distribution in the supersonic mode were to be controlled by a computer program based on various locally sensed data. After termination of the engine burn by the pilot or the computer, the inlet was to be closed, and the control system has to regulate engine temperature until the cooling fluid was expended or engine repurge occurred. The control system was to continue to monitor all temperature data until power was removed.

Further capability to communicate with the control system was to be provided for purposes of inflight data recording and ground test.

IV. Spike Control

An electrohydraulic system is used to control the centerbody spike. A hydraulic reservoir is pressurized with nitrogen to provide a hydraulic system with a regulated supply pressure of 3000 psi. Hydraulic fluid is controlled by a 10-gpm servo valve, which drives a hydraulic ram to move the centerbody. The stall force of this actuator is almost 18,000 lb in extension and 9000 lb in retraction. Feedback is pro-

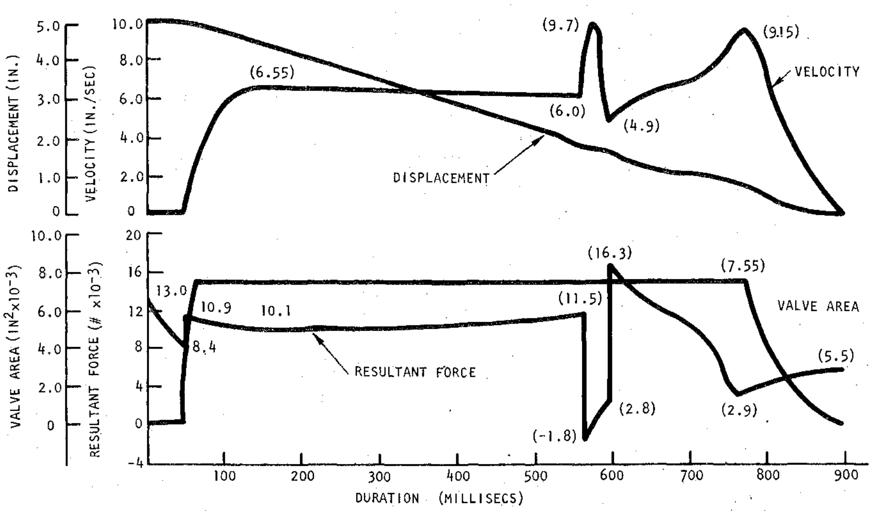

Fig. 2 Spike actuation-extension sequence.

vided by a linear variable differential transformer (LVDT). The feedback loop is closed continuously in the computer interface electronics. With this type of feedback and loop closure, steady-state errors are limited to 0.050 in. over a 5-in. stroke.

Analytical studies and a simulation model indicated that well-damped performance would be achieved for all conditions, including the abrupt changes in load which occur with inlet upstart. Experimental data shown in Fig. 2 substantiate these results. Since the loop closure is analog, the functions of the digital computer in spike positioning are monitoring and the generation of the spike position command. This command is updated at $\frac{1}{2}$-sec intervals.

In normal operation, the spike command is generated as a function of two independent variables; i.e.,

$$X_{\text{spike}} = f(M_0, P_{RC}) \approx f(M_0, \alpha)$$

The pressure ratio P_{RC} across the centerbody serves as a measure of the angle of attack α. This function, which is stored in computer memory, is shown in Fig. 3 for two α's. The local Mach number M_0 is calculated as a function of the X-15 inertial velocity, predicted wind velocity, and static temperature. The spike position deviates from the schedule shown in Fig. 3 when unstart or buzz is detected. On the first occurrence of buzz or unstart, the centerbody completely closes the inlet and then reopens. Any further occurrence will result in the inlet closing and remaining closed. Pressure ports in the inlet are used to detect unstart. A pressure ratio is computed from these measurements and is compared to a limit function, which varies with M_0. If this limit is exceeded, an unstart has occurred and the unstart procedure is initiated.

V. Fuel Flow Control and Distribution

To control fuel flow, the control system both generates the flow command and closes the fuel flow feedback loop. Fuel flow is commanded as a pre-established schedule of fuel-air ratios (ϕ) during the flight. To calculate required fuel flow, the engine airflow must first be calculated. The actual schedules are established by wind-tunnel calibration tests, although the functional relationships are already known. In the following equation, the term inlet area is implicit, since spike position is known.

Air mass flow is calculated as a function of the local Mach number, local angles of attack and yaw, spike total pressure, and true airspeed. This can be written as

$$\dot{m} = (P_T/U_\infty)F(M_0,\alpha_L) + F(M_0 + \beta_L)$$

where P_T is spike total pressure, and other symbols are defined in the Nomenclature.

The angles of attack and yaw must be calculated from differential pressure measurements across the spike cone. These calculations are

$$\alpha_L = (\Delta P_\alpha/P_T)f(M_0) \quad \beta_L = (\Delta P_\beta/P_T)f(M_0)$$

where ΔP_α and ΔP_β are vertical and horizontal pressure differences. To perform the $\dot{m}$ computation, the computer must interrogate two empirical functions, $f(M_0)$ and $F(M_0,\alpha_L)$. These curves (or surfaces, in the latter case) will be stored in the computer memory in the form of pairs or triplets of numbers. Required accuracy is achieved by interpolating between points on the stored curve data.

In addition to generating the fuel flow command, the computer also calculates the actual fuel flow and closes the feedback control loop. Actual fuel flow measurements are carried out by using venturis in the fuel lines. To determine the rate of fuel flow, the total temperature and pressure of the fuel and the pressure drop between the venturi inlet and its throat must be measured. The equation that relates these variables is

$$W_f = C[P_T/(T_T)^{1/2}]\cdot f(\Delta P/P_T)$$

where P_T and T_T are fuel total pressure and temperature, and ΔP is the pressure drop between venturi inlet and throat.

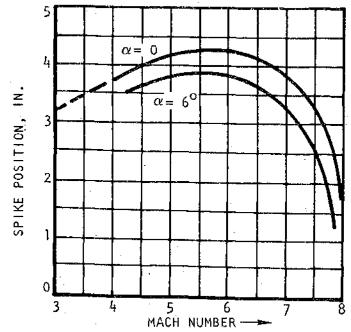

Fig. 3 Spike position computation.

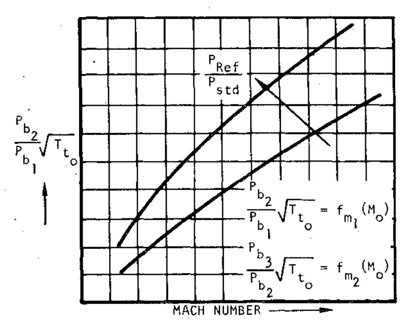

Fig. 4 Combustor flow limit definition.

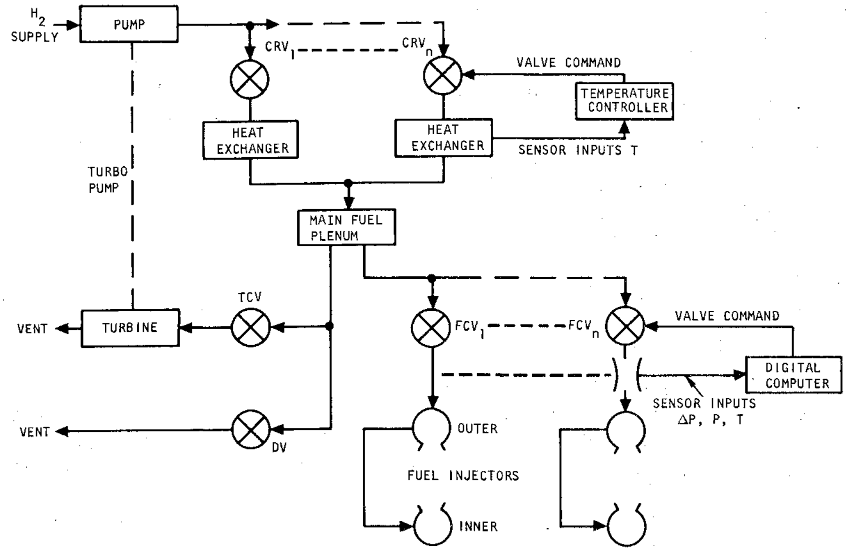

Fig. 5 Fuel system diagram.

During the subsonic combustion mode, all fuel is injected at one station, and the only consideration other than ϕ scheduling is control of the inlet shock position, which will be prevented from excessive forward excursion by comparing a measured pressure ratio to a pressure ratio limit that is a function of M_0; if this limit is exceeded, the commanded ϕ is reduced. The supersonic combustion mode uses the total fuel command as described previously and also determines the fuel split among the injectors in a manner that prevents the internal pressure gradient along the length of the combustor from exceeding predetermined limits. The pressure ratio limiting expression is shown in Fig. 4 and can be stated as

$$(Pb_2/P_{b1})(T_{TO})^{1/2} - f(M_0) < 0$$

VI. Temperature Control

During high Mach flight operation, the HRE could not survive without provisions for cooling most of its exposed surface. In addition, temperature differences must be limited between adjacent sections of the structure so that excessive stresses are not superimposed on the normal operating loads.

The temperature control samples the temperature of the cooling fluid (gaseous hydrogen) at several locations where heat loads could be critical. According to selected limits, programable for anticipated flight-test conditions and stored in the computer memory, the coolant is distributed through the regenerative jacket flow paths. The coolant is finally delivered to the injectors as the fuel supply (Fig. 5). Each flow path has a coolant regulating valve (CRV) and a regenerative cooling section. The hydrogen supply pressure is increased from ~50 psia to 600–1000 psia by a hydrogen turbopump. By the time the hydrogen has reached the main fuel plenum, its pressure has dropped to about 550 psia, and its temperature has risen from about 100° to 1500°R. The turbine control valve (TCV) maintains the pressure in the main fuel plenum at 550 psia to insure adequate fuel pressure for injection into the combustor; if the pressure decreases, the TCV opens and increases the pressure drop across the turbopump turbine. The subsequent increase in turbine speed causes the compressor to increase the upstream pressure.

If the cooling system requires more fuel than is required for combustion and for the turobpump drive, the fuel dump valve (FDV) opens and increases total flow. Several temperature sensors in each cooling jacket sense coolant temperature. These signals are multiplexed into a select-highest circuit. The highest temperature in each jacket is then used to control the corresponding coolant regulating valve. If the temperature control commands a valve opening in excess of that which the coolant regulating valve can provide, the excess error signal is then used to open the FDV.

The temperature control is implemented as a separate device because of its high data input rate requirement (1600 samples/sec). It depends, however, on the digital computer for mode control and limit setting. This function is carried out by the DAC offset block shown in Fig. 1.

VII. System Flexibility

Since the necessary electronics interface does exist in the control system, the functions of monitoring, recording, and ground testing are accomplished through computer software and generally can be tailored to suit the needs of a given situation without affecting the physical hardware. Thus, program composition, or parameters and functions of the engine control programs, may be changed as late as during flight testing (after delivery of the hardware) without interfering with hardware schedules.

The computer interface unit has two digital input/output channels and associated control lines: the teletype interface and a 12-bit digital interface. In flight, the output section of the digital interface is fed to a PCM recorder on the X-15. On the ground, both input and output sections of the digital interface are used under control of the teletype keyboard, which provides the hard copy readout facility. The input section of the digital interface is used on the ground to load the digital computer memory with the operating program, using an optical paper tape reader. The digital interface can also be used in conjunction with external facilities to do calibration tests and other GSE functions in a fully automated fashion. In this case, the computer memory would be loaded with a separate program devoted entirely to the HRE ground-testing requirements during periods when maintenance activities are taking place. Extensive automatic ground checkout, with hard copy and paper tape records, is provided at a modest cost penalty in GSE hardware.

VIII. Dynamic Analyses

System studies have been conducted on the centerbody, the fuel flow control, and the temperature control, using a combination of those nonlinear simulation and linear analytical techniques indicated in Fig. 6. A nonlinear model of the system to be controlled is first described and realized in analog computer simulation. Then the linear model is provided for one or more operating conditions, either by mathematical linearization or by frequency response testing of the nonlinear model. This linear model is used for analysis in the S plane

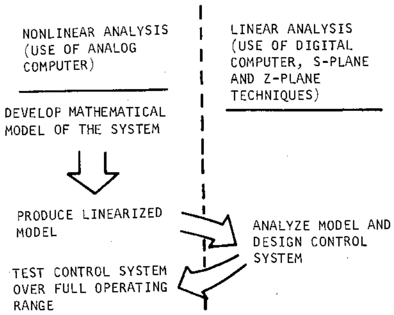

Fig. 6 Analysis procedures.

or, in the case of sampled data systems, the Z plane. This analysis leads to a controller design, which is then tested over the full operating range on the nonlinear model. The use of this approach supplies a logical progression from the original problem statement to the final control system. Of the three control subsections, simulation and analysis of the temperature control was by far the most extensive.

IX. Status and Summary

The original scope of the program included the development and construction of a "breadboard" control system to be followed by a flight-weight prototype. No constraints on packaging were imposed on the breadboard; it is presently assembled in a 6-ft-high standard rack. Electrical access and front panel readout capabilities are provided in all critical interfaces so that system operation can be easily analyzed. Interface subunits were constructed and thoroughly tested by themselves before being coupled to other sections of the computer interface unit and finally to the digital computer itself. The temperature control proceeded initially as an independent subsystem. All equipment was operated on laboratory power supplies. The breadboard power supply section, with its protective circuitry, was developed independently.

Figure 7 shows the final breadboard of the CIU extended from the console in a servicing position. (Its normal location is at the lower center of the 6-ft-high console.) One corner of the general-purpose digital computer is visible, mounted on the rear of the CIU drawer. The temperature control final breadboard occupies the bottom section in the console.

An important element of the breadboard activity is the development of the digital computer software, which continues throughout the development program as a physically independent function but requires close coordination with the interface (CIU) logic design. Engine control programs have been completed to present control design except for detailed parameter values. The inflight test plans for the monitoring programs and the temperature mode control programs and CIU test programs have been flow-charted. Several fully developed programs for engineering software tools are already in use. The resulting software tools exist in the form of program listings and their corresponding punched paper tapes.

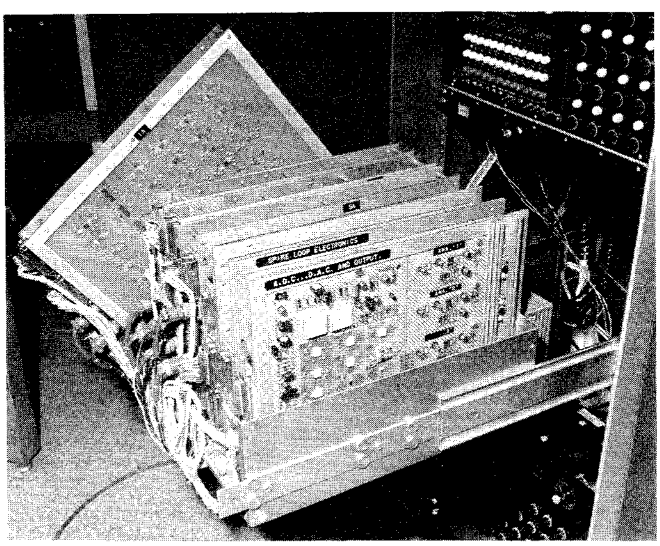

Fig. 7 Computer interface unit final breadboard.

Table 2 System features

System	Features
Fuel control	Central digital computer (sampled data system). High-speed, random-access multiplexing. Shared, high-accuracy analog-to-digital conversion (conversion time, 8 μsec/bit). Communication between asynchronous sampling systems (temperature-control, recorder, and GSE).
Inlet control	High-force, high-accuracy position control (18,000 lb, better than 0.05 in. in 5.00 in. of travel). Fully damped performance under extreme load fluctuations and wide range of environmental conditions.
Temperature control	Analog sampled data system. Variable mode control directed by digital computer. Application of temperature-compensated substrates.
Power supply	Utilization of high-efficiency switching-mode regulators. Built-in monitoring functions. Capable of meeting stringent MIL-STD-704A requirements.

In summary, the HRE control system is a fully integrated propulsion control system. It is one of a few applications in which the control problem is handled almost entirely by a central digital computer. The system exhibits a high degree of automation and maintains considerable flexibility for organizing control functions. In this latter respect, it presents a practical working tool for use with an engine that is in a progressive stage of development.

In addition to flexibility for the normal control functions, other advantages result from using a central digital computer. These are linked primarily with the ready accessibility of all data handled in the control system. In theory, any sensor, function, or operating condition of the system can be interrogated at any time for performance assessment and safety checks. In practice, the depth of this type of communication is limited because the time it consumes can interfere with the needs of the primary control program.

One objective in control system development is to avoid entanglement with basic component development. As a result, there is little to be shown in the way of unusual circuit design. There are, however, features of the hardware which are interesting and seem worthy of review because of the rather extensive application of digital computer interfacing techniques. Points of interest and system features are listed in Table 2 for the main areas of the hardware development.

The in-depth capability of the system can be appreciated from the large amount of input/output data handled by the control system as a whole, on internal and external lines:

Analog data lines	90	(sensors, valve controls, and monitoring)
Discrete data lines	71	(all internal and external digital registers and control lines)
Power	7	
Total	168	

The computer executes 50,919 instructions/sec in the flight program.