NASA TECHNICAL MEMORANDUM

AUTOMATED ENDURANCE TESTING OF A BRAYTON POWER CONVERSION SYSTEM

by R. A. Edkin, R. P. Macosko, and R. Kruchowy
Lewis Research Center
Cleveland, Ohio

ABSTRACT

To demonstrate endurance of a 2-to-15 kWe Brayton power system, a test system was designed and constructed at the NASA, Lewis Research Center. The system included the following Brayton prototype components: Brayton rotating unit, Brayton heat exchanger unit, interconnecting piping and gimbals, system check valve, coolant pump, electronic voltage regulator and series field controller, parasitic speed control and load resistor. Additional pieces of test support equipment were provided to simulate remaining system hardware not available at the time of construction.

The test system was designed with two goals in mind. The first was to measure system and component performance. The second was to use a computer for monitoring and controlling a long-term steady-state endurance test. The system has been operated for more than 5300 hours under computer control; in excess of 4600 hours of testing were unattended by test personnel. During this time there have been no Brayton component failures and test support equipment problems have been minor in nature.

The data acquisition and control system provided the following automatic functions:
(1) data recording and reduction;
(2) control room alarms on selected data channels (high and low limits);
(3) system control and adjustment;
(4) data storage for analysis of failures; and
(5) alarms to central fire station to select channels and computer failure.

An extensive automatic protective system was also designed for the test and functioned separately from and as a backup to the computerized control system. The experience acquired in designing and working with such an automated test is discussed in this paper.

THE NASA, LEWIS RESEARCH CENTER, has been engaged in the development of electric power generating systems for long-term use in space. The systems have been designed for as high as 50,000 hours of continuous, unattended operation with no maintenance of any kind required during that time. This design goal dictates that the systems be thoroughly tested in ground-based facilities to determine if this goal might be achieved. In addition to extensive system and component performance mapping, a candidate system must be life tested to determine its true endurance or reliability. An ideal goal would be to operate a system for its total design life without a shutdown. Test facilities and test support equipment (TSE) are generally not designed for 50,000 hours of life simply due to the cost involved and, as a result, the facilities require constant surveillance. A 50,000-hour life test would require over $5\frac{1}{2}$ years of continuous operation and surveillance, not counting time lost during shutdowns. The cost of staffing a facility for this time period is a burden that few organizations can afford to pay.

NASA (Lewis) is presently engaged in life testing a Brayton power conversion system (BPCS) which has been designed for at least a 50,000-hour life. To accomplish this test with a minimum man-hour expenditure, an automated test facility was designed and constructed. The test facility provides:
(1) automated data acquisition and data reduction;
(2) unattended control of the system; and
(3) complete system and component protection.

To date the facility has accrued over 5,300 hours of testing with the longest continuous run being 1800 hours. A total of 10 unplanned automatic shutdowns and 25 planned shutdowns have been experienced with no resultant harm to the system. The unplanned shutdowns have been caused by instrumentation and TSE failures as expected. The design philosophy and approach that were taken for the data acquisition system, the control system, and the protection system are discussed in this paper.

SYSTEM DESCRIPTION

A simplified schematic of the test system is presented in Fig. 1. The power conversion system under test (1)* consists of the Brayton rotating

_____
*Numbers in parentheses designate References at end of paper.

unit (BRU), Brayton heat exchanger unit (BHXU), and associated piping, gimbals, and check valve. Also included in this test and not shown in the schematic are selected Brayton electrical system components and related hardware. An electric heat source (2) was provided as TSE in place of the nuclear or isotope heat source under consideration for this system. The equipment shown schematically in the gas management module and heat rejection module was provided as TSE with the exception of the main coolant pump which is a flight prototype unit (3). For simplicity, much of the TSE (valves, filters, etc.) has been omitted from the schematic and only major components are shown.

The test system is a closed-loop BPCS operating with a He-Xe gas mixture as the working fluid. Design temperatures for the system are 1600° F at the turbine inlet and 80° F at the compressor inlet. With a compressor discharge pressure of 42 psia, the system produces a net electrical output of 10.7 kW at 0.95 lagging power factor (11.3 kVA).

BRAYTON ROTATING UNIT - The BRU shown in Fig. 2 consists of a turbine, an alternator and a compressor mounted on a single shaft designed to operate at 36,000 rpm. The shaft is supported by gas-lubricated journal and thrust bearings. Detailed descriptions of the radial inflow turbine and radial outflow compressor may be found in Refs. 4 and 5. The alternator, which is described in Ref. 6, is a modified Lundell alternator having a solid-bimetallic rotor, two stationary field windings, and a stationary armature winding. The rated output is 14.3 kilovolt-amperes at 0.75 lagging power factor, 120/208 volts, and 1200 hertz.

BRAYTON HEAT EXCHANGER UNIT - The BHXU shown in Fig. 3 incorporates a recuperator with a waste heat exchanger. The recuperator core consists of plate-fin sandwich construction brazed as a single unit. The heat exchanger is a cross-counterflow unit with similar plate-fin construction as in the recuperator. The cores of both units were assembled into a single unit (BHXU) by welding to transition sections and headers.

BRAYTON ELECTRICAL COMPONENTS - The alternator is integrated with an electrical subsystem. Figure 4 is a block diagram of the Brayton electrical components tested. Photographs of the breadboard voltage regulator, series field controller, and speed controller are shown in Fig. 5. The series field controller delivers current to the series field in direct proportion to armature current. The voltage

regulator provides excitation to the shunt field to maintain constant voltage at the useful load. The three-speed controllers vary the current into the parasitic load resistor as a function of line frequency. The parasitic load automatically compensates for variations in the useful load and thereby maintains constant BRU speed. More detailed descriptions of these electrical controls may be found in Refs. 7 and 8.

AUTOMATING THE TEST SYSTEM

The design considerations for achieving test system automation ranged from complete computer control to the use of hardware devices such as pressure switches, meter relays, analog controllers, etc. for the automatic control and protection of the BPCS. A digital data acquisition system (DDAS) was purchased for the test primarily to provide continuous data acquisition and test system control. Test system control was provided by the DDAS by means of software-controlled output switches. Due to the uncertainty of the DDAS hardware and software reliability, the following design philosophy was established:

(1) The DDAS would be used to provide automatic data acquisition and reduction and sampled-data system control where time response was not critical.

(2) Test system adjustments requiring continuous control would be handled by conventional electro-pneumatic controllers.

(3) An automatic protection system would be provided separate from the DDAS.

(4) Test system shutdown would be initiated solely by the automatic protection system.

With the above philosophy in effect, the automatic control and protection system was designed and fabricated. DDAS hardware and software requirements for data reduction and system control were established and a contract was awarded to provide the hardware and software as a complete system. The DDAS, the control system, and the protection system are discussed in the following sections of this report.

DIGITAL DATA ACQUISITION SYSTEM

The digital data acquisition system (DDAS) is shown schematically in Fig. 6. The analog inputs from 200 laboratory instruments are distributed by means of a central patchboard system to four points or any combination thereof. Signals may be routed directly or through signal

2

conditioning equipment (amplifiers, frequency converters, etc.) to the protection circuitry, the control panel display devices, and the scanner for insertion into the data system. The central patchboard system provides flexibility for instrumentation changes, trouble shooting, quick replacement of signal conditioning equipment, and simplifies the task of calibration by providing a single access point to all instrumentation.

Control panel displays were accomplished with conventional meters for temperature, pressure, frequency, etc. A graphic test system display was provided to ease manual operation of the facility. (See fig. 7.) The automatic protection system is discussed later in this paper. The remaining discussion in this section is concerned with the DDAS which is schematically shown within the dashed area of Fig. 6.

The 200 data channels wired to the scanner can be sampled in total or individually by the computer under program control. The scanner employed in this facility contains modular groups of 10 channels each and is expandable to a maximum of 1000 channels.

Data are passed from the scanner to the integrating digital voltmeter (IDVM) where the voltage signals are averaged and converted from analog to digital form. The data flow from the IDVM is through the coupler to the computer where it is either stored, processed, or passed on to the various peripheral devices. The DDAS was supplied to NASA specifications by the Vidar Corporation. The data system consists of both Vidar and Digital Equipment Corporation hardware while the software was provided by Delphic Industries under subcontract to Vidar. Table 1 is a listing of the hardware used in this system.

The software system designed for this facility provides three data acquisition modes:
    (1) Data acquisition for processing
    (2) Data acquisition and storage for failure analysis
    (3) Data acquisition for limit checking
The various modes are controlled by tables that are generated prior to program startup. The tables are easily changed on an off-line basis to account for new or bad channels, new limit conditions, different integration times, etc.

PROCESSED DATA - For this test facility, data are acquired on an hourly basis for processing. Processing includes conversion of the raw data to corrected engineering unit values,

and the performance of various calculations as system and component efficiencies, heat transfer parameters, power factors, etc. The data are processed for a single scan of data (200 channels) and printed out on a teletype when computer time is available. Data scans are not stored in the computer for later output. If so desired, a paper tape of the raw data can be produced for later processing by larger computers at the Lewis Center. A typical data scan (200 channels) is accomplished in 8 seconds. Full processing of the data (engineering units and calculated outputs) requires approximately 10 minutes including printout time. The time interval between successive data scans is adjustable with the minimum time determined by the time period required to process and output the previous scan.

FAILURE ANALYSIS - In tests that involve new components and systems, failures and shutdowns may occur frequently. To properly analyze these failures, key parameters must be constantly recorded. In some cases the parameters needed for analysis are easily determined but this is not generally the case. In addition, equipment such as tape recorders, pen recorders, etc., are expensive and require constant surveillance. To avoid this problem a disc file was included in the data system. All 200 data channels are continuously scanned by the computer and stored on the disc. Approximately 3/4 of the disc capacity has been set aside for this purpose. This provides a $1\frac{1}{2}$ hour backlog of data with data channel repeats every 8 seconds. If an automatic test system shutdown occurs, the computer receives an interrupt which automatically schedules 15 additional minutes of failure analysis data and a computer shutdown at the end of that time. It should be noted here that certain system parameters required continuous monitoring which was not possible with the DDAS. These parameters were recorded on a 32 channel magnetic tape recorder modified for automatic recycling of the tape. In this way a 3 hour backlog of continuous analog data was available at all times.

The software designed for this test includes a failure analysis program which provides for off-line retrieval of the data stored on the disc file. The program provides a link to the basic program so that all engineering unit conversions, calculations, etc., can be performed and outputed exactly as the on-line data. In addition, a disc-search routine enables individual channels or groups of channels to be converted to engineering units and printed out for discrete time

intervals. This feature greatly eases the task of analyzing failures. It should be noted here that all times and data rates discussed are easily changed on an off-line basis prior to startup of the failure analysis portion of the software system.

LIMIT CHECKING - For this test 42 data channels were selected for limit checking. The computer checks every 5 minutes for high or low limits or both as required by a limit check table which is generated prior to software system startup. On an out-of-limit condition, the computer will either generate an alarm message or momentarily close one of the 32 output control switches and generate a control message. All alarm and control messages are printed out on a second teletype so that messages do not interfere with normal data outputs. The alarm messages are useful during attended operation as an indication of drift in steady-state conditions or as a warning for pending problems. During unattended operation any selected parameter can produce the same warning by tripping a central alarm circuit to the NASA fire station via one of the control switches. Fire station personnel then call in appropriate test system personnel to attend to the problem. This method has been used with good success for this particular application.

CONTROL SYSTEM

Conventional electro-pneumatic controllers were used in the test system where continuous system control was required. The reliability of this type of controller is well established and no problems with this type of device were encountered during the endurance testing.

To demonstrate the capability of the computerized controls, five system adjustments were selected to be performed by the DDAS. These are shown in Fig. 8 along with additional actions initiated by the DDAS. In order to accomplish system adjustments, two methods of valve control were employed:

(1) An out-of-limit condition sensed by the DDAS initiated a timed valve opening. The control action was repeated every five minutes during each limit check cycle until the out-of-limit condition was satisfied.

(2) A control band (a high and a low limit) was established for the controlled parameter. A high-limit condition sensed by the DDAS initiated a valve opening. If during subsequent limit

check cycles the low limit was reached, the DDAS closed the valve.

All of these involved the operation of pneumatically-positioned valves. The air pressure which operated the valves was supplied to the valve positioners through computer-operated solenoid valves. This pressure was preset to achieve the amount of valve opening desired. A typical system adjustment was accomplished as follows:

Since the compressor discharge pressure is directly related to the amount of gas in the system, this parameter was used for inventory control. A high limit condition resulted in a 20 ms pulse on one of the output switches located in the DDAS coupler. The pulse was sensed by external circuitry which opened a system vent valve for a preset time interval (approximately 10 sec). This procedure was repeated during subsequent limit checks until the out-of-limit condition was cleared. The amount of gas removed during one valve cycle was adjustable both by regulating the amount of valve opening and by adjusting the time interval. A low compressor discharge pressure resulted in gas being added to the system in a similar manner. With this method of adjustment compressor discharge pressure was easily maintained at nominal value ±0.2 psi.

The computerized controls proved to be very reliable throughout the 5300 hours of testing. Computer failures resulted in the loss of the automatic controls until test personnel could arrive on the scene and re-start the DDAS. False control actions were not experienced during normal computer operation or as a result of computer failure.

AUTOMATIC PROTECTION SYSTEM

An automatic protection system (fig. 9) was designed to protect the BRU from destructive overspeed and provide complete system shutdown in case of any one test system component failure. All circuits were designed for ground test only and no attempt was made to miniaturize the circuitry for flight system application. Figure 9 shows each type of fault detected and its corresponding control action.

The design of this protection system was based upon the following considerations:

(1) Any one test system component failure or loss of the electrical subsystem shall not result in destructive overspeed of the BRU.

(2) Critical protection system circuits shall be redundant and permit normal protection system operation even if a protective system device failure occurred.

(3) When any critical fault is detected, first priority is to initiate a system shutdown rather than providing corrective action to permit continued operation.

(4) Provide maximum protection to all Brayton components and TSE.

(5) Record the fault that caused a system shutdown and initiate a computer interrupt to stop the recording of failure analysis data after 15 minutes.

(6) Provide protection for the system completely independent of any computer control functions.

(7) The shutdown controls must operate in the proper sequence to avoid other faults which could cause damage to the system.

Most of the protection was applied to the BRU (turbine, alternator and compressor), the prototype coolant pump, and the electric heat source (heater and power controller). Protection against loss of control power was included, so that if this type of fault occurred, all relays, valves, etc., would go to a "fail-safe" position and complete system shutdown would occur.

Protection system redundancy was achieved in some cases due to the fact that many system operating conditions are interrelated. For example, a failure in the heater power controller might result in high power applied to the heater first causing the heater tubes to overheat and, secondly, resulting in high turbine inlet temperature. Protection system redundancy was also obtained by using redundant shutdown circuits as in the case of BRU overspeed. Since BRU overspeed is considered as the most critical parameter, three independent methods of detecting rotative speed were used:

(1) A capacitance probe located within the BRU

(2) Two magnetic pickups mounted on the compressor housing

(3) Alternator line frequency

All three methods use a frequency signal which is directly proportional to rotative speed.

The alternator overfrequency shutdown limit was set beyond the control range of the speed control and provided a normal shutdown mode. A magnetic pickup was used as backup protection and also provided a normal shutdown. If, however, the BRU speed continued to increase beyond

the first limit, another circuit employing a capacitance probe and a magnetic pickup was set to initiate an emergency shutdown mode to prevent destructive overspeed.

Some of the protection logic was designed to sense a fault condition and permit continued system operation via appropriate control actions. For example, protection was provided for the loss of the prototype coolant pump. A pump failure would result in low pump outlet pressure which initiates an automatic transfer to a backup pump. If the backup pump fails to operate, as indicated by continued low pressure, an automatic system shutdown would be initiated.

A central alarm circuit was incorporated into the protection system so that the test engineers could be notified in the case of computer failure, system parameters exceeding specified control limits, or automatic system shutdown. This central alarm circuit used a telephone line to interconnect the test facility control room with the NASA fire station (staffed around the clock). A voltage was applied to the telephone line and, whenever any of the above problems would occur in the control room, the alarm circuitry opened series contacts in the telephone line resulting in an annunciator alarm at the fire station.

It was possible to connect any critical parameter into the central alarm circuit. A special circuit interconnected with the central alarm circuit was designed to give warning of computer failure. This circuit monitored the DDAS limit checking and tripped the fire station alarm if the limit checking stopped. The automatic shutdown circuit was also designed to initiate a fire station alarm when a system shutdown occurred.

SYSTEM SHUTDOWN - The protection system was designed to detect a fault and provide the proper control sequence for a safe shutdown. The detection of any critical fault, except for control power loss, provided a shutdown signal which tripped lockout relays and activated an event recorder. Since this was a critical circuit, redundant lockout relays were used to provide a normal shutdown in case one relay failed to operate. As soon as the lockout relays tripped, several events occurred simultaneously in order to decelerate the BRU to zero speed. Figure 9 gives a list of all functions controlled during the shutdown mode. The basic requirements for system shutdown are as follows:

(1) Apply jacking gas to the gas bearings in the BRU.

(2) Turn off input power to the heater.

(3) Vent the gas from the system.

(4) Apply parasitic load.

Loss of the 120 volt control bus prevents a lockout relay trip. However, all valves, relays, etc., required to accomplish the above shutdown requirements are immediately activated due to loss of power.

For unattended system operation it was necessary:

(1) To record the fault that caused a shutdown,

(2) To initiate a fire station alarm, and

(3) To initiate a computer interrupt to stop the recording of failure analysis data after 15 minutes.

One important consideration during shutdown was that as the BRU approached zero speed, it was necessary to turn off the jacking gas to the gas bearings in order to conserve the gas in the main supply bottle. Therefore, a special circuit was designed for this purpose. This circuit detected low BRU speed and automatically applied current from a battery to the alternator field to stop BRU rotation. After a time delay, the circuit closed the jacking gas valves. The Brayton test system was shut down successfully 35 times, without any malfunctions in the protection system or the controls.

CONCLUDING REMARKS

An automated-test system was designed, constructed, and tested. A computerized system was used successfully for monitoring and controlling the test system during more than 5300 hours of steady-state endurance testing; in excess of 4600 hours of testing were unattended by test personnel. The test system was protected with an automatic protection system which functioned independently of the computerized system. During the endurance testing, there were no Brayton component failures and only minor problems with test support equipment. Automatic shut downs were experienced without any malfunctions in the protection system or the controls.

A digital data acquisition system (DDAS) provided continuous data acquisition and reduction. The DDAS also provided unattended test system control via software-controlled output switches. Experience with the DDAS controls demonstrated high reliability and precise test system control. Computer failures resulted in the loss of control only. False control actions were not experienced during the 5300 hours of

testing. DDAS hardware and software proved to be very versatile. Experience showed that it could be adaptable to other experiments with similar basic requirements (data acquisition, data reduction, and control). For most applications, only the programs associated with system calculations and output formats would have to be changed.

An automatic protection system was provided to operate separately from the DDAS and backup all automatic controls. As a result, inadvertent test system shutdowns in the event of computer failure were avoided because system shutdown was initiated only by the protection system. Furthermore, there was no loss of test system protection whenever a computer failure occurred or whenever the computer was off-line to make changes to DDAS software such as calculation modifications, limit changes, etc. All critical protection circuits were designed to be redundant and permit normal protection of the test system even if a protection system device failed. Increased protection system reliability and redundancy was also achieved in some cases due to the fact that many test system operating conditions were interrelated. As a result, the protection system proved to be very reliable and provided complete test system protection. Whenever a fault was detected during the endurance testing, the protection system provided the proper shutdown sequence for a safe test system shutdown. This was demonstrated by more than 35 automatic shutdowns without any resultant damage to the test system; 25 of these shutdowns were performed intentionally during the system startup test phase of the test program.

REFERENCES

1. A. S. Valerino, R. P. Macosko, A. S. Asadourian, T. P. Hecker, and R. Kruchowy, "Preliminary Performance of a Brayton-Power-System Gas Loop Operating with Krypton over a Turbine Inlet Temperature Range of 1200° F to 1600° F." NASA TM X-52769, 1970.

2. R. P. Macosko, H. R. Block, S. Lumannick, and C. W. Richter, "A Compact 90 Kilowatt Electric Heat Source For Heating Inert Gases To 1700° F." NASA TM X-52778, 1970.

3. A. C. Spagnuolo, R. R. Secunde, and J. E. Vrancik, "Performance of a Hermetic Induction Motor-Driven Pump For Brayton Cycle Heat Rejection Loop." NASA TM X-52698, 1969.

4. R. Y. Wong, H. Klassen, R. C. Evans, and C. Winzig, "Experimental Investigation of a Single Shaft Turbine-Compressor-Alternator Unit Operating as Part of a Brayton Power Generation System." NASA TM X-1869, 1969.

5. W. J. Nusbaum and M. G. Kofskey, "Cold Performance Evaluation of 4.97-Inch Radial-Inflow Turbine Designed for Single-Shaft Brayton Cycle Space Power System." NASA TN D-5090, 1969.

6. D. S. Repas and R. A. Edkin, "Performance Characteristics of a 14.3-Kilovolt-Ampere Modified Lundell Alternator for 1200 Hertz Brayton-Cycle Space Power System." NASA TN D-5405, 1969.

7. B. D. Ingle and C. S. Corcoran, "Development of a 1200-Hertz Alternator and Controls for Space Power Systems." Intersociety Energy Conversion Engineering Conference, Vol. 1. IEEE: New York, 1968, pp. 438-447.

8. R. A. Edkin, D. A. Perz, E. A. Koutnik, and M. J. LeRoy, "Steady-State Characteristics of a 1200-Hertz Alternator and Electrical Controls Operating in a Single-Shaft Brayton-Cycle Power System Using Krypton Gas." NASA TM X-2017, 1970.

TABLE I - DIGITAL DATA ACQUISITION SYSTEM

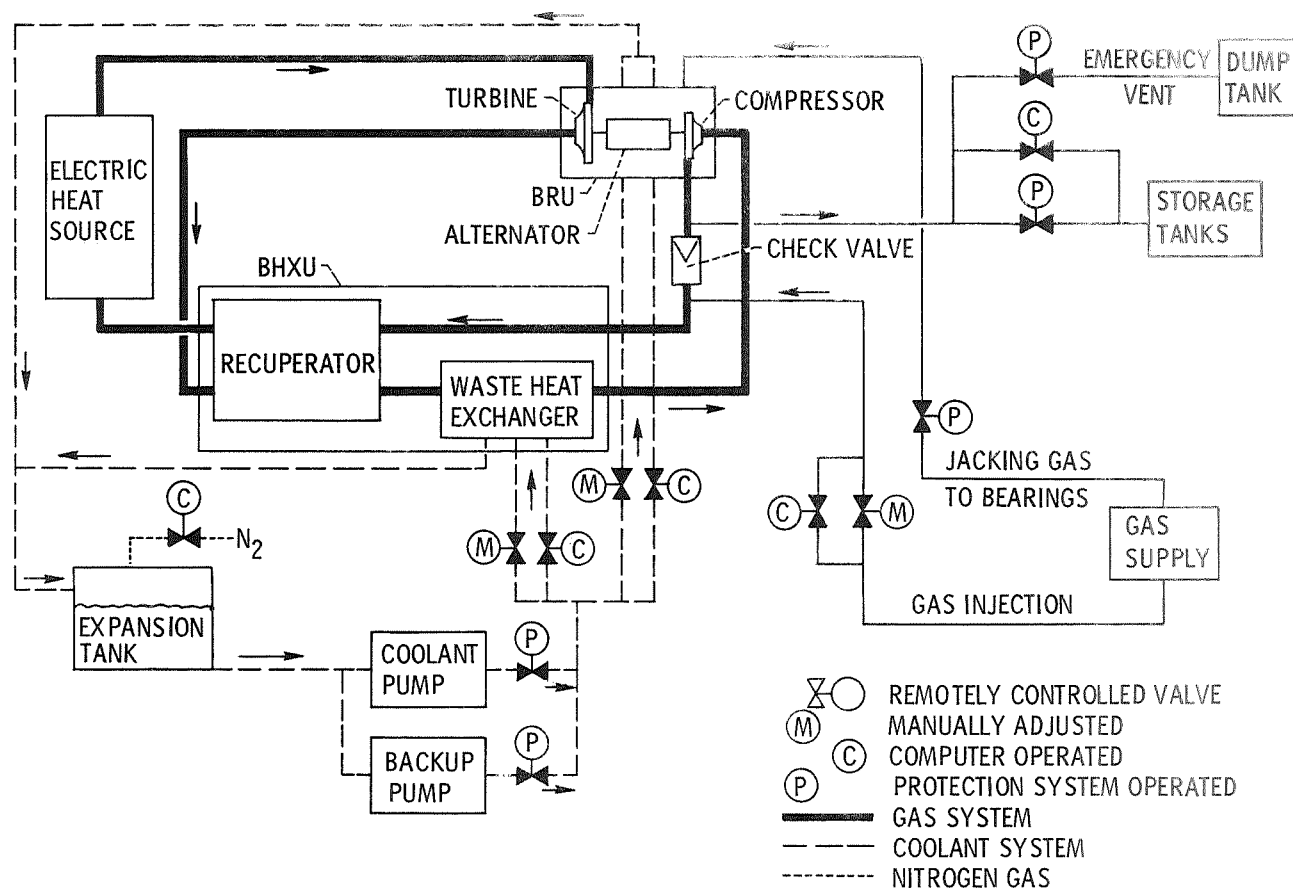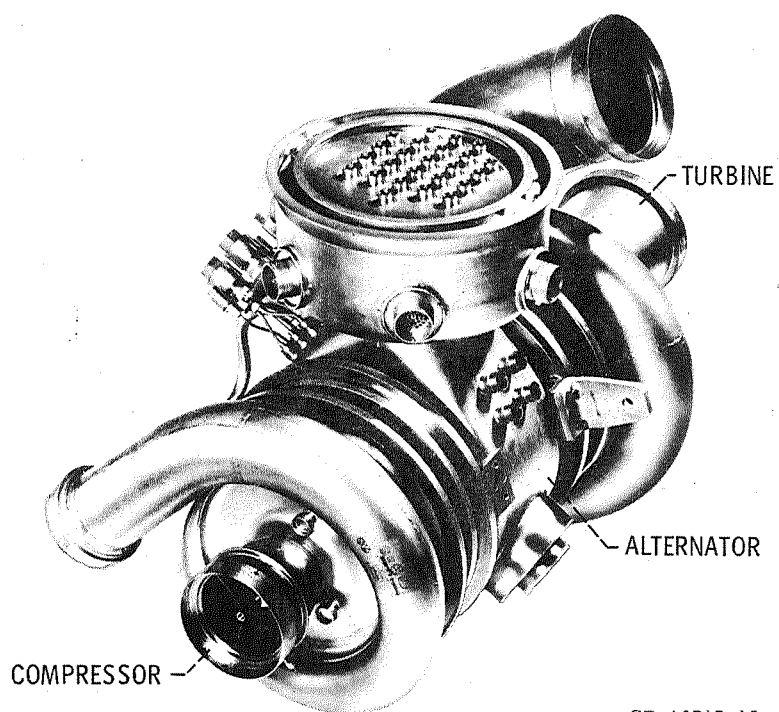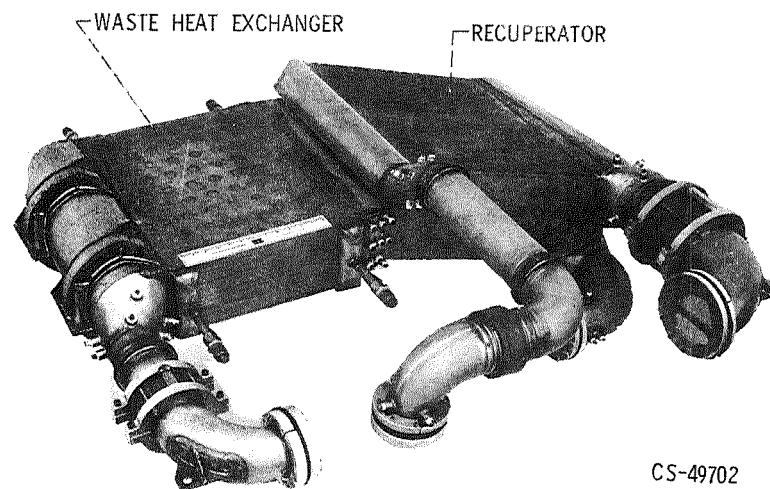| Hardware	Manufacturer and part identification	Comments
Computer	DEC-PDP-8/I	Includes 4K memory
Extended memory module	DEC-MC8/I-A	4K memory and memory control
Extended memory module	DEC-MM/8 I-A	4K memory
2 disk files	DEC-RSO8	Data storage - 3/4 capacity Program storage - 1/4 capacity Total capacity 500 K
Disk control	DEC-RFO8	
Serial line interface (disk)	DEC-PTO8B	
Send/receive typewriter with paper tape reader and punch	Teletype-ASR-35	Processed data output; some paper tape input; keyboard control of data system
Receive only typewriter	Teletype-AT-35	Alarm and control messages
Coupler	Vidar 653-06	
Digital clock	Vidar 624-02	Data and message time base
Scanner	Vidar 610	Programmed channel sampling
Integrating digital voltmeter	Vidar 521 A/R	Analog to digital conversion
High speed reader	Vidar 556	Program loading
High speed punch	Teletype BRPE	Raw data output

Figure 1. – Simplified schematic of test system.

TURBINE
COMPRESSOR
BRU
ALTERNATOR
CHECK VALVE
BHXU
RECUPERATOR
WASTE HEAT EXCHANGER
ELECTRIC HEAT SOURCE
EXPANSION TANK
COOLANT PUMP
BACKUP PUMP
N₂
EMERGENCY VENT
DUMP TANK
STORAGE TANKS
JACKING GAS TO BEARINGS
GAS SUPPLY
GAS INJECTION

REMOTELY CONTROLLED VALVE
MANUALLY ADJUSTED
COMPUTER OPERATED
PROTECTION SYSTEM OPERATED
GAS SYSTEM
COOLANT SYSTEM
NITROGEN GAS

E-6307

TURBINE
ALTERNATOR
COMPRESSOR

CD-10717-15

Figure 2. – Brayton Rotating Unit.

WASTE HEAT EXCHANGER   RECUPERATOR

CS-49702

Figure 3. - Brayton heat exchanger unit.


```
ALTERNATOR
SHUNT   SERIES   →  SERIES FIELD  →  TO
FIELD   FIELD       CONTROLLER       USEFUL
                                     LOAD

                 VOLTAGE
                 REGULATOR

SPEED            SPEED            SPEED
CONTROLLER       CONTROLLER       CONTROLLER
1                2                3

PARASITIC LOAD RESISTOR
```
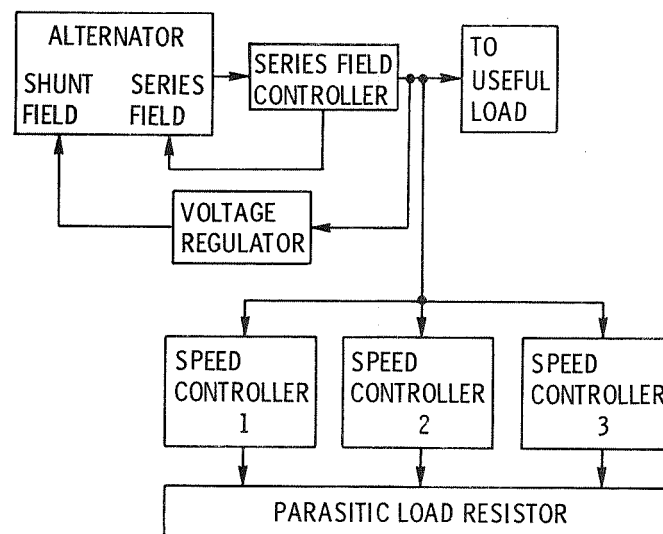
Figure 4. - Block diagram of Brayton electrical components tested.

SERIES FIELD CONTROLLER

SPEED CONTROLLER
(THREE REQUIRED)

VOLTAGE REGULATOR
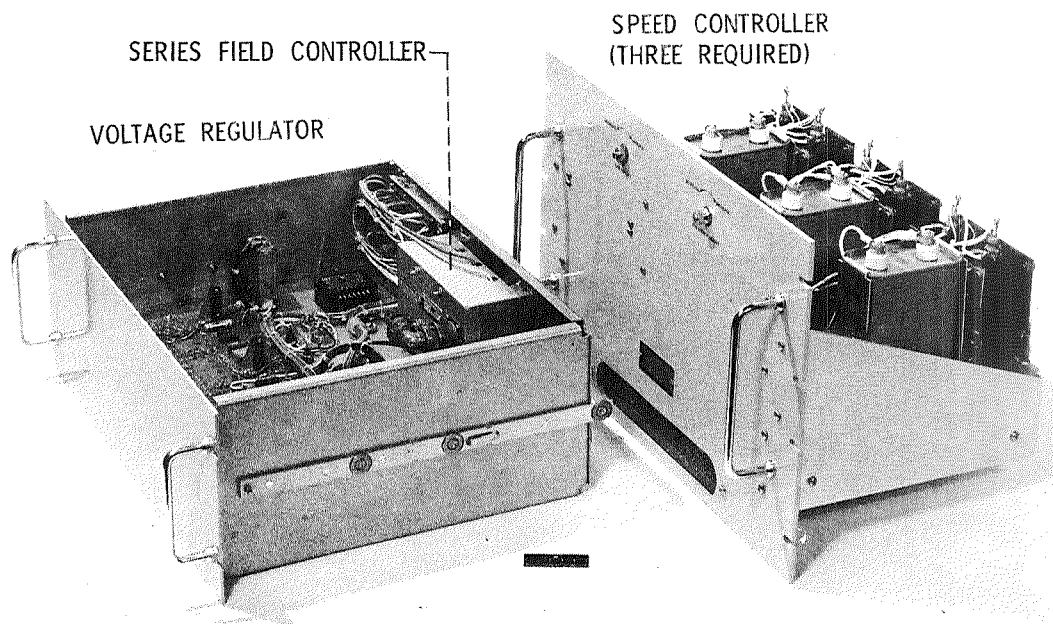
C-68-461

Figure 5. - Breadboard control devices.
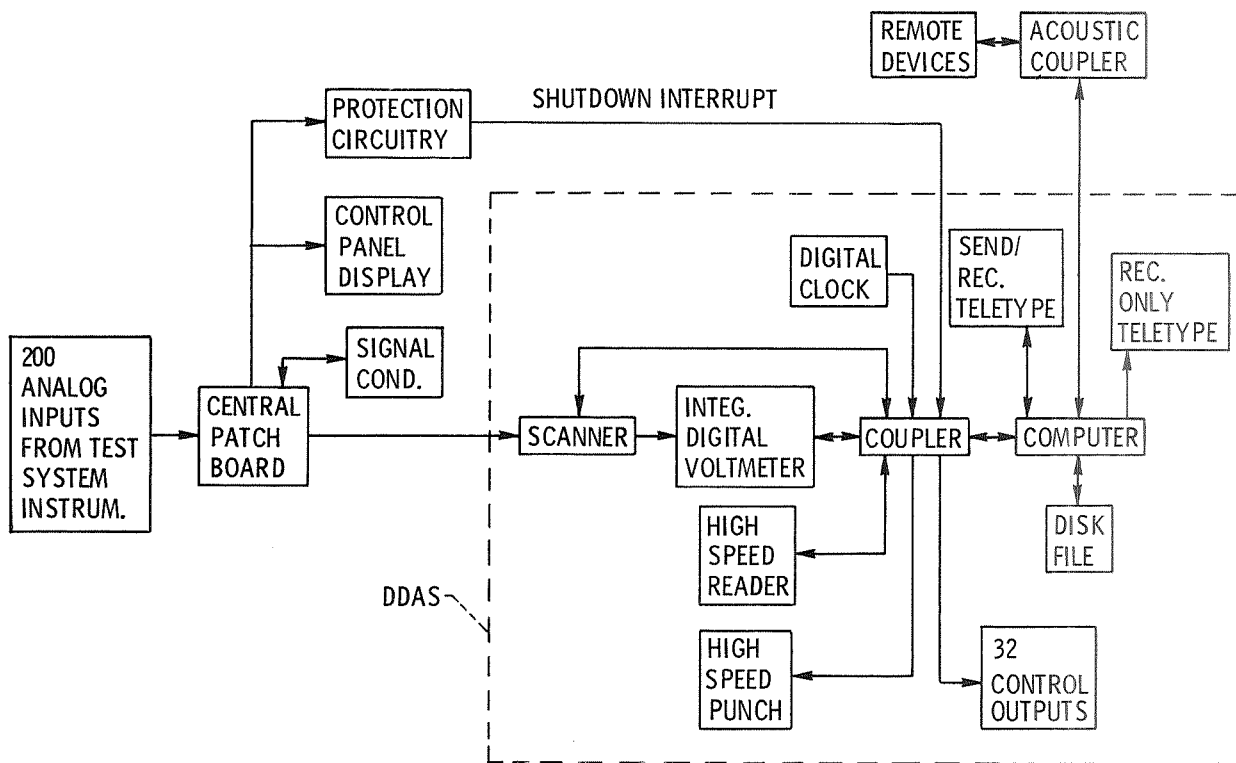
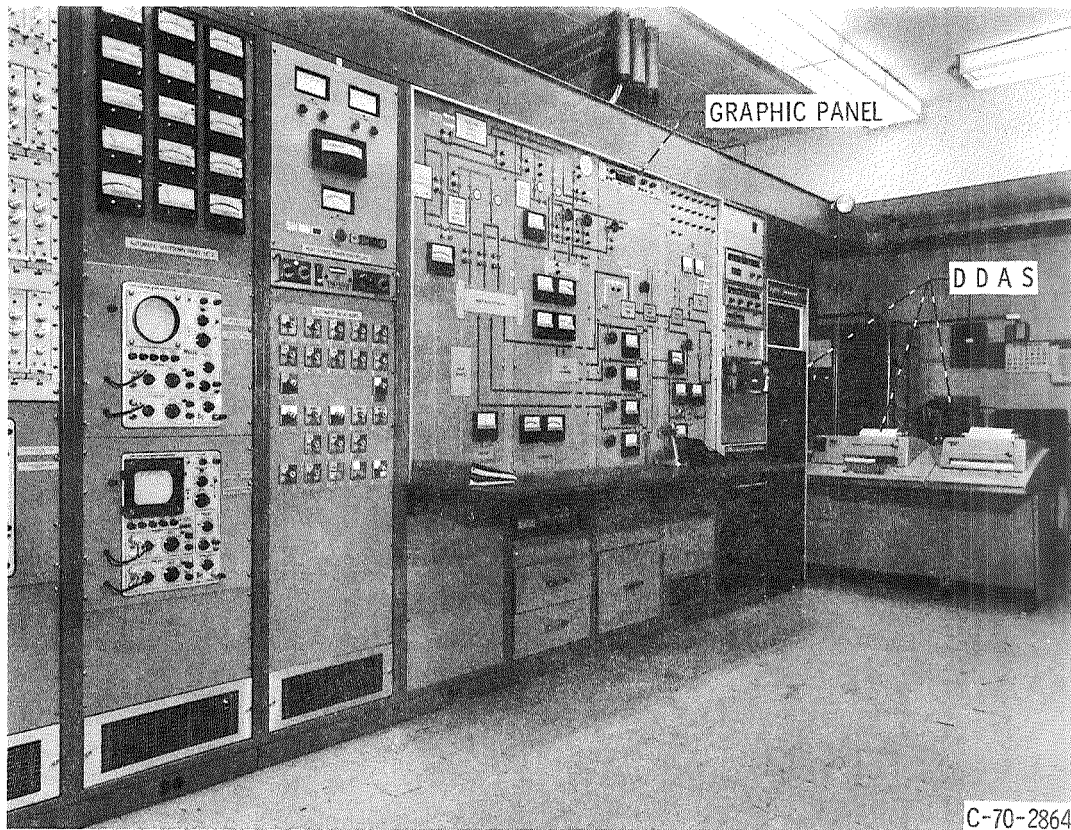Figure 6. - Digital data acquisition system.
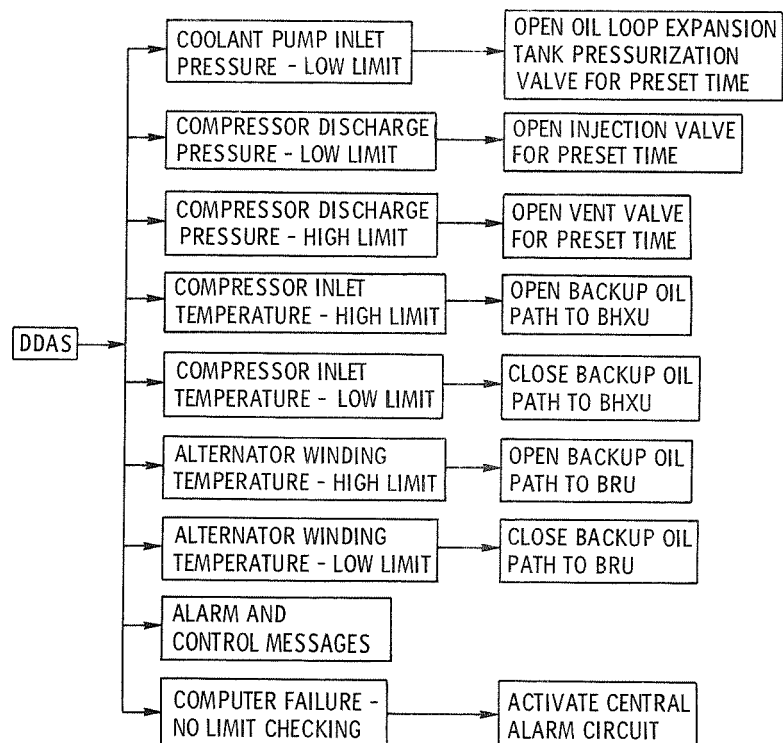
Figure 7. - Control room for test system.
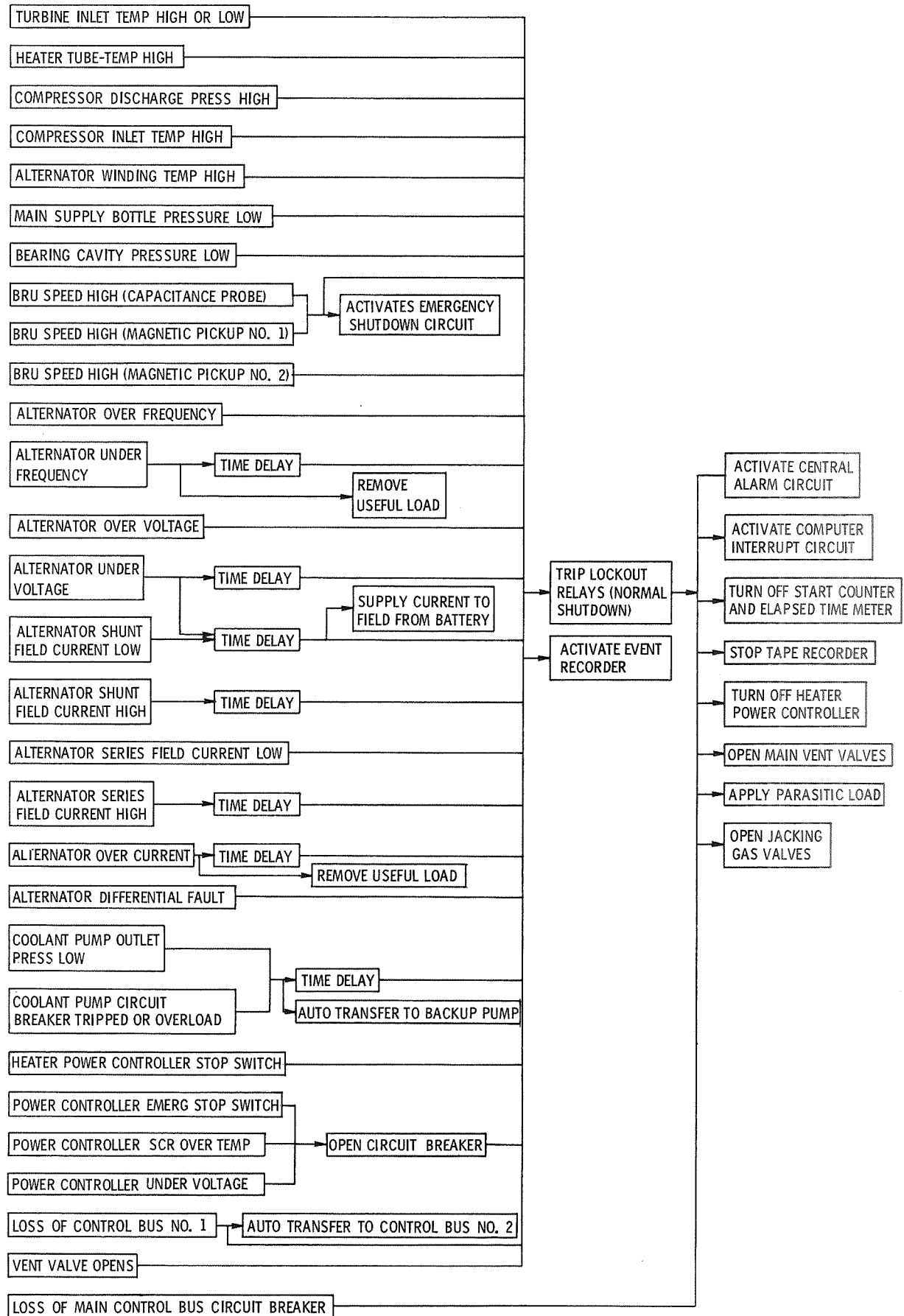

Figure 8. - System control performed by the DDAS.

Figure 9. – Automatic protection system.