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AUTOMATED AIRBREATHING PROPULSION TEST FACILITIES

The development of airbreathing propulsion systems requires ground test facilities that provide true simulation of flight Mach number, altitude, and angle of attack for testing full-scale engines and components. These facilities must therefore have large systems for the storage and supply of air to the test article, and the air heaters and exhaust systems are powered by the discharge of large heat-energy sources during brief test runs. APL's Propulsion Research Laboratory and other such facilities require automated systems for accurate control and repeatibility of test conditions, and high-speed data aquisition systems.

THE PROBLEM

Early in the development of a new engine concept, great emphasis is placed on analytical evaluation of the engine cycle and its components to narrow the choice of design options to those most attractive for further development. Repeated ground testing, although expensive and difficult, is the necessary next step because it is not generally possible to model analytically all the engine's physical phenomena from first principles. This is especially true for new, high-speed (hypersonic) engines where the state of the art in most technical disciplines (fluid dynamics, combustion, materials, etc.) is pushed beyond conventional bounds. Thus, the importance of ground testing is underscored.

Flight simulation on the ground can be a complex undertaking. With the test engine mounted rigidly to the ground, flight is simulated by placing the engine in a high-speed air jet that produces the proper conditions of velocity, pressure, and temperature both external and internal to the engine. To produce this jet, air from a high-pressure and high-temperature supply is expanded through a supersonic (or hypersonic) nozzle. Consistent with the conservation of energy, when air at conditions of high supply pressure and temperature is expanded to the desired supersonic velocity, the proper conditions of local static pressure and temperature are produced to simulate the desired altitude. Ground test facilities therefore must have capacities for compressing, storing, and heating large quantities of air and must be provided with control systems to supply the proper flow for these large jets. In addition, there must be systems to supply fuel, water, exhaust suction, etc.

SIMULATION REQUIREMENTS

True simulation of flight conditions in a ground test facility involves reproducing Mach number, altitude, angle of attack, and flight duration with a full-scale engine. The engine must be tested full scale because combustion phenomena that involve turbulent mixing and chemical reaction kinetics are not amenable to scaling. Individual engine components, such as air inlets and diffusers, may be tested part scale if the Mach numbers and Reynolds numbers are properly simulated.

The facility requirements for engine testing are related to flight conditions as follows:

1. Mach number and altitude. The facility must produce the correct air velocity, total pressure, and total temperature. The velocity requirements determine the needed overall pressure ratio for the facility.
2. Angle of attack. (a) For free jet tests, the proper angular orientation of engine-air inlet to air-jet axis is required. (b) For direct-connect tests, the airflow profile into the test engine duct must be simulated.
3. Flight duration. (a) Prove-in tests of flight-weight components require full duration testing and possibly simulation of flight trajectory (altitude and Mach number as a function of time). (b) The development of optimum engine/combustor configurations is usually done with heavyweight test hardware and involves short run times, rapid data acquisition rates, and highly reproducible conditions for repeated testing.

The principal simulation requirements therefore relate to the mass flow rate and temperature of the air supply and to the evacuation pressures of the facility versus time. If the engine is not axisymmetric, angle-of-attack simulations may include both pitch and yaw.

PRIMARY FACILITY SYSTEMS

Any propulsion ground test facility (such as the APL Propulsion Research Laboratory described later) will have similar systems to meet testing requirements, although designs may differ according to the state of the art and the availability of materials at hand. Air is stored in steel tanks at high pressure (typically 2000 to 10,000 pounds per square inch) and the airflow rate is regulated by control valves to the pressure and mass flow rate required for simulation.

The air temperature is raised to the required value by means of in-line heaters using either thermal storage or chemical or electrical energy, depending on the air temperature required. These types of air heaters are illustrated (along with various engine test arrangements) in Figs. 1 to 3. A thermal storage type heater such as that indicated in Fig. 1 is used where process air temperature up to 1000°C is required to simulate moderate supersonic flight speeds (Mach 2 to 3.5). This heater uses a storage medium such as a metal or ceramic matrix that is heated over a period of several hours by means of a gas- or oil-fired burner, and the process air is then passed through the medium during test operation. A second type, illustrated in Fig. 2, is the chemical heater, which uses in-stream combustion of a fuel such as propane or hydrogen either to boost the temperature from a partially heated condition or to heat completely the process air to temperatures between 1000 and 2000°C. This heating technique permits the simulation of higher supersonic flight speeds (Mach 3 to 5). Since this mode of heating adds combustion products to the air, additional oxygen is added to the stream to reestablish the same mole fraction of oxygen as in atmospheric air. An electric arc heater such as that indicated in Fig. 3 is generally used for hypersonic flow simulation (Mach 5 and above), where the arc is in direct contact with the flow stream and air temperatures of up to 3000 and 4000°C are produced.

Altitude simulation may be provided by an exhaust system that evacuates the test chamber to low pressure by means of a steam ejector system that uses the momentum exchange principle. Energy for this system may be stored in the form of hot water that is flashed to steam, as required, during test operation.

The operation of a facility such as that described above is based upon the "blowdown principle," wherein the various forms of energy (i.e., high pressure air, heat, electrical energy, steam, etc.) are accumulated over a relatively long period of time (typically several hours) and discharged rapidly during a test run, typically seconds or minutes in duration.

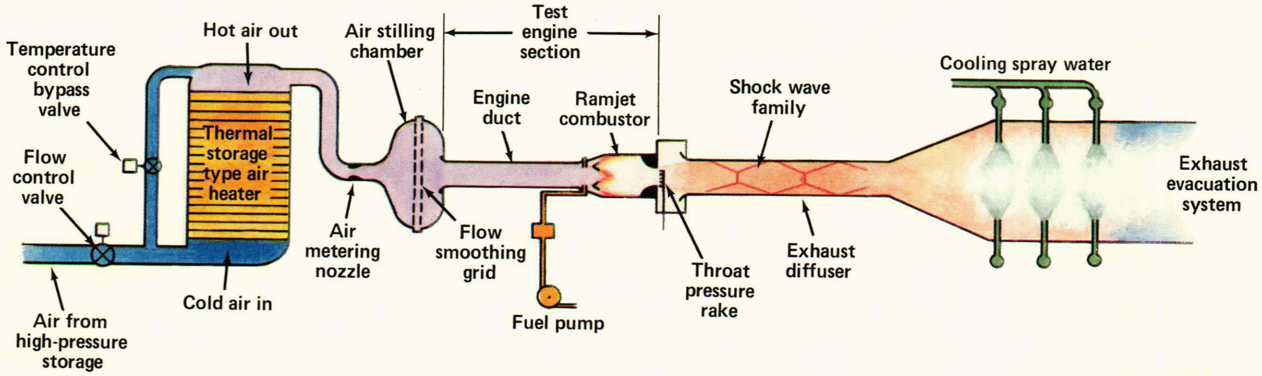

Figure 1 – A subsonic combustor being tested in direct-connect mode to determine performance. To simulate flight engine internal flow conditions, high-pressure air from the facility air storage is heated as it flows to the engine with a thermal-storage type air heater. Supersonic flight speeds in the Mach 2 to 3.5 range can be simulated using this technique.

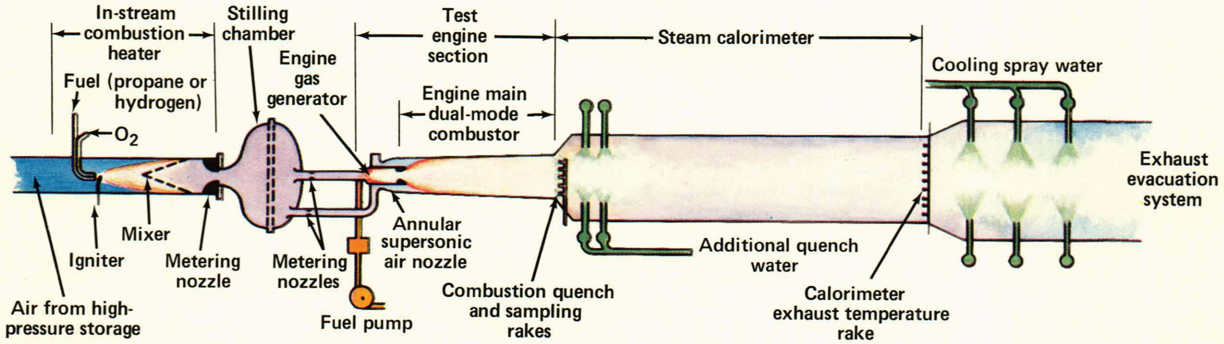

Figure 2 – A higher speed ramjet, known as a dual-mode (subsonic/supersonic combustion) ramjet, being tested in direct-connect mode to determine performance. The engine cycle shown was invented at APL and is a dual-combustor type of dual-mode ramjet. It uses a small gas generator (which uses a small portion of the engine airflow) embedded in the forward end of the main dual-mode (subsonic/supersonic) combustor to pilot the process. The in-stream combustion heater permits simulation of flight speeds up to Mach 5.

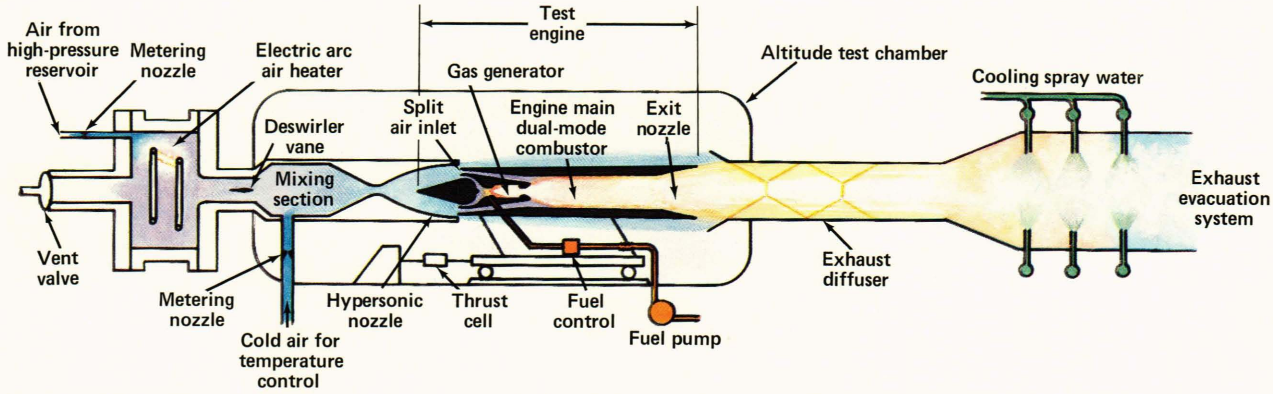

Figure 3 – A complete hypersonic dual-combustion ramjet engine, mounted on a thrust stand in a sealed test cabin to simulate high altitude, being tested in a free jet to determine performance. Note that an appreciable quantity of airflow is spilled around the engine to ensure proper simulation of air inlet flow conditions. An electric-arc heater can produce air temperatures as high as 4000°C, simulating flight up to Mach 10 in the atmosphere.

Blowdown testing operations are sometimes more practical than continuous supply test modes because of the lower demand for peak power, but they place severe constraints on testing operations because of the short test duration. Such constraints are partially mitigated by the use of automatic controls, which provide rapid, precise changes in test conditions so that more conditions are tested per run.

Figures 1 to 3 also indicate several types of airbreathing engine ground tests. Figure 1 depicts the facility to test the combustor for a subsonic combustion ramjet in a "direct-connect" mode. Each individual engine component (air inlet, combustor, exit nozzle, and fuel system) is developed first in separate tests, followed by validation of the overall engine operation in a free jet test. The direct-connect mode of operation is less demanding of the facility capabilities (flow and pumping pressure ratio) than an engine free jet test and is used in the extensive tests that are needed to optimize the combustor design (flameholders, fuel injectors, igniters, etc.). Combustor performance in this configuration is determined from measurements of total pressure using a rake at the exit-nozzle throat, or by measuring engine static pressures or thrust with the use of a thrust stand. Engine mass flow is determined from the upstream metering nozzle. The engine exit nozzle is simulated only to the sonic throat for two reasons: (a) it facilitates the measurement of the engine exit stream thrust by having a known (Mach 1.0) condition at the exit plane, and (b) it eliminates the need to know the thrust efficiency of the supersonic portion of the exit nozzle in evaluating combustor performance. The thrust efficiency of the supersonic portion of the exit nozzle is determined from separate tests.

The exhaust products from the engine are evacuated through the facility exhaust system. They are first passed through an exit diffuser, which acts as an exhaust pump by converting the kinetic energy associated with the high-speed exit jet to potential energy (higher pressure) through a series of shock waves. The exhaust combustion products are then quenched and cooled by a water spray system. Following this, the exit stream passes through other stages of facility exhauster pumps, usually steam-driven ejectors, before being discharged to the atmosphere.

Figure 2, in contrast to the setup in Fig. 1, depicts a direct-connect arrangement for testing the combustor for a higher speed ramjet, known as a dual-mode (subsonic/supersonic combustion) ramjet. The particular engine cycle shown was invented at APL and is known as a dual-combustor type of dual-mode ramjet. It involves the use of a gas generator (a small subsonic dump combustor using a small part of the engine airflow), embedded in the forward end of the main dual-mode (subsonic or supersonic) combustor, to pilot the process. The engine may operate either in a subsonic combustion mode, which is optimum for moderate supersonic speeds (Mach 3 to 5), or in a supersonic combustion mode, which is more effective for higher speeds (above Mach 5).

Although the use of this dual-mode propulsion cycle permits a single airbreathing engine to operate efficiently over a broad Mach number range, it presents a more difficult problem in ground testing for performance evaluation than the subsonic combustion ramjet, because the exit of the combustor will not necessarily have a known sonic (or choked) flow plane. For a supersonic combustion engine, the combustion efficiency as well as a representative average stream Mach number must be determined at the combustor exit plane to obtain stream thrust. These properties, together with known engine mass flow rates, are sufficient to define combustor performance but involve special measuring techniques. To make such measurements, the supersonic combustion process is quenched at the combustor exit plane by an appropriately designed water injection rake, as indicated in Fig. 2. The combustion gases are cooled by flashing this water to steam, and a careful heat balance is performed on the "steam calorimeter" to determine the gas enthalpy at the supersonic combustor exit plane. The process requires an accurate evaluation of total enthalpy of the entire stream (exhaust gas plus water vapor) at the calorimeter exit plane. The water injection must be carefully controlled to produce a temperature high enough to ensure that all the water within the calorimeter is vaporized.

This calorimetric information, together with measurements of all other system enthalpies (inlet air, cooling water, fuel, etc.), permits the determination of combustion efficiency. The adiabatic flame temperature at the exit plane of the supersonic combustor can then be approximated, assuming average gas properties (specific heats). Gas sampling is helpful in defining the constituent products. To obtain the combustor exit Mach number, "representative" pressures are measured at that plane using rakes that sample across the stream. This is a difficult undertaking, and much development testing is required to evolve appropriate probe designs and suitable probe locations within the stream that do not interfere with the supersonic combustion process being measured.

Figure 3 depicts a complete dual-combustion ramjet engine being tested. Here the engine is placed in a sealed test cabin, with the engine inlet immersed in a supersonic free jet that simulates high-speed flight in the atmosphere. The quantity of airflow required for testing a complete engine is greater than that passing through the engine because in producing a realistic flow field at the air inlet much of the air in the jet is spilled around the engine. A shock system is formed by the flow at the inlet, such as that shown in the spark photograph (Fig. 4). All engine internal flow characteristics (aerodynamics and combustion) properly simulate free flight, and overall performance is measured with a thrust stand. Many detailed measurements of pressure, temperature, fuel flow rate, heat flux, etc. are also made within the engine and are used to analyze the operation of engine components. The exhaust system must have the capacity to pump the total exhaust mass flow (including water vapor) from a low pressure in the sealed test cabin (corresponding to the required test altitude) to an atmospheric final-discharge condition.

Other engine components such as air inlets and fuel systems and portions of the vehicle structure (radomes, inlet leading edges, engine tailpipe and exit nozzles, etc.) are tested and developed individually. Figure 5, which shows a radome being tested under conditions that simulate a Mach 8 flight, indicates the severe aerodynamic heating at hypersonic speeds.

The requirement for repeated ground testing for the development of advanced propulsion systems also places emphasis on proper facility control system design so that test conditions can be reproduced accurately. Great emphasis also is placed on high-speed data acquisition and real-time display of engineering data for test control and monitoring, especially for tests at hypersonic speeds, where run times are of short duration.

TESTING OPERATIONS

The simulation parameters described above are applied in a sequence of operations that is normally described as a "test" or "run." The test sequence is sometimes performed manually and sometimes automatically, but it generally will include the following steps:

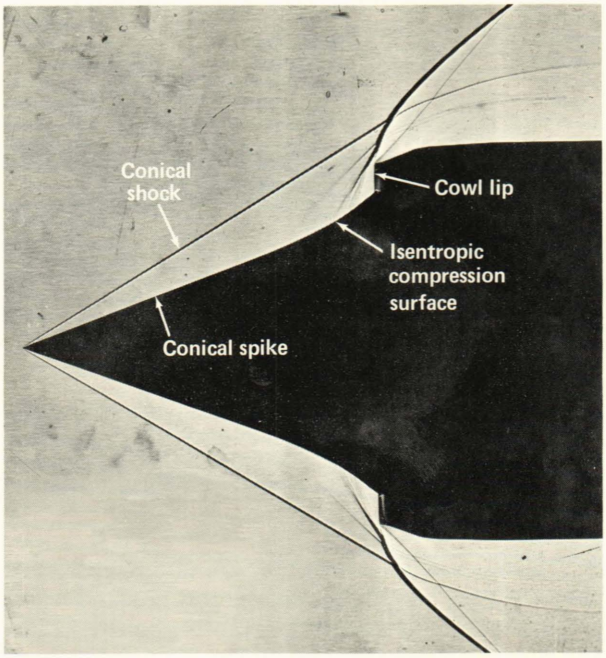

Figure 4 – An "isentropic-spike" type of air inlet operating at supersonic conditions. A conical shock is generated from the conical spike tip, followed by a series of weaker compression waves ahead of the cowl lip. High inlet efficiency is achieved in this manner. The family of weak compression waves coalesce to form a strong shock outboard of the cowl lip.

Figure 5 – A missile radome test under conditions that simulate a Mach 8 flight indicates the severe aerodynamic heating at hypersonic speeds. Other missile components such as leading edges are also developed in ground test facilities.

Pretest Checkout

1. Test and calibrate (end-to-end simulation) all instrumentation signals and control channels.
2. Measure energy levels of all supplies:
   Air supply system
   Fuel and air heater temperatures

  Steam accumulator
  Fuel system(s)
  Water system(s)
  Battery power supply
3. Operate and check out engine fuel and ignitor systems.

Facility Startup

1. Start data acquisition, display, safety monitoring, and recording systems
2. Start airflow and bring to required flow rate
3. Start heater and set air temperature
4. Set cooling water flows to initial levels
5. Set steam ejector (altitude) vacuum level
6. Check that facility is "on the point."

Engine Startup

1. Set fuel flow to initial conditions, bypassing engine
2. Set fuel heater temperature
3. Start ignitor sequence:
   Start oxygen
   Start hydrogen
   Activate spark
   Check "ignitor lit" signal
4. Divert fuel flow from bypass to the engine
5. Check "engine lit" signal.

Sequencing of Engine and Facility Conditions

The primary variable in the engine test sequence is usually the fuel flow rate expressed as an equivalence ratio (ER), which is a ratio of the actual fuel flow to the stoichiometric rate. When the fuel flow rate is changed to a new equivalence ratio setting and stabilized, the engine controls are said to be "on the point," and data are taken before moving to the next condition. Probe sampling or injector combinations are often sequenced as well. Whenever feasible, the facility air mass flow or temperature is changed to a new set of simulated altitude and speed conditions, and the engine fuel flow rates are resequenced.

This exploration of "test space" whose dimensions are speed, altitude, and fuel flow rate is limited in magnitude and duration by the quantities of stored energy in the various facility systems (air, heat energy, steam, water, etc.). In some tests, significant savings can be made in the cost of the model and associated test hardware by using uncooled or "heat sink" combustors and hardware. In that case, the test duration is limited by the maximum permissible combustor wall temperature.

Engine and Facility Shutdown

Following the final engine sequence, the engine fuel flow is cut off and all fuel lines are purged, generally with gaseous nitrogen. The facility airflow and temperature are then sent through a programmed shutdown sequence to provide gradual cooling of the hardware, thus avoiding excessive thermal shock.

Shutdown of the facility and engine test operation may be performed in an "abort" mode, an emergency shutdown mode, or the standard shutdown mode. In any of these modes, the systems are sequenced according to a predetermined plan.

TEST OPERATIONAL PROCESSES

The various operations required as part of a propulsion test can be arranged into groups of tasks called processes. These processes can be classified according to function in a hierarchical arrangement such as that shown in Fig. 6. This arrangement of processes or something similar will be seen for various types of tests and is almost always used in propulsion tests. Task groupings such as these were originated in manual operations, where test hardware was grouped around a human operator. In those applications, interprocess synchronization was accomplished by verbal communication among the operators, each one having the equipment required for his process clustered about him. Of course, even in manual tests, certain tasks have been automated for years, but they too were clustered together under the control of an operator. When considering automation of a test operation, it is attractive to adopt this same organization for the design of the Instrument and Control System, to minimize interprocess communications at these proven functional interfaces.

Supervisory Control Process

This type of control is concerned with the scheduling, synchronization, and coordination of all the subordinate test processes. Such control can be as simple as strict synchronization, called a sequencer, or can be more sophisticated – proceeding through a simple, logical progression while receiving status feedback from the controlled processes. It may be even more sophisticated, as implemented in a "programmable

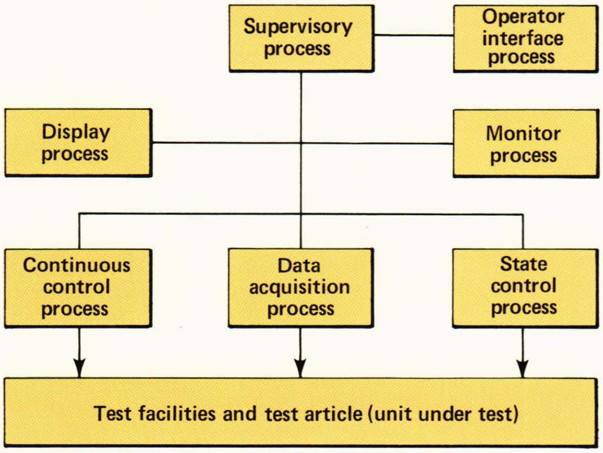

Figure 6 – Test operational processes are groups of tasks performed in real time. They are allocated to hardware in many different arrangements in actual instrument and control systems.

controller,'' in which case it proceeds in a preprogrammed logical progression with preprogrammed alternative sequences that can be chosen on the basis of an internal program interacting with status feedback from the controlled processes. The designs of the alternative sequences are implemented to react to any of the likely failures in the test operation or the test equipment. Such sequences would provide an automatic shutdown based on the particular fault and the test conditions at the time the fault was detected or a relight cycle might be originated if an engine ''flameout'' occurs early in a run.

A fully implemented supervisory control process is resident in a digital computer directs dependent processes resident in the same or in other computers. It communicates with the other processes in transactions involving the bilateral exchange of data, e.g., transmitting set point values and other process control instructions, and receiving status feedback confirming that control action has been achieved. It can respond to external events in the dependent system in a way that tends to stabilize the overall test operation and drive it to a successful conclusion, even under conditions of failure in the operation or hardware.

Continuous Control

All control processes are, by nature, temporal. However, a distinction is made between ''continuous'' processes and ''state'' control of a test. Because of hardware considerations, the continuous control process is further classified into direct digital and analog control.

Direct Digital Control. Originally, in the process control industry, supervisory control systems did not have computers in the subordinate processes; they made use of existing banks of pneumatic and electronic analog controllers for the closed loop control of individual parameters. As individual groups of electronic controllers were replaced by computers, the hierarchical relationship was often retained, but this newer type of implementation was referred to as ''direct digital control,'' as opposed to ''supervisory control,'' of which it was a dependent part.

As defined in this article, direct digital control uses digital techniques for the continuous control of individual parameters in a test or in the facility operation. With it, the control algorithm or transfer function for each individual parameter is resident in a central processor (computer). Its use in propulsion tests has been mainly to provide a more rapid response of gaseous flows by means of metered flow control (as with digital valves) to generate the required downstream pressure response through the use of feed-forward predictive control in connection with a simple system model. Open-loop flow control of this type gets around the limitation of closed-loop response times for major flow changes. Flow is then ''trimmed'' using closed-loop response. Forms of this type of control have been used for both fuel flows and process airflows at APL and elsewhere.

Analog Control. Analog control, in our context, refers to a process associated with a particular type of closed-loop control hardware used in industry. These systems (to be described below) preceded the use of computer control and are still widely used today.

In an analog control system or subsystem, there are a number of electronic amplifier controllers. Each controller is used to regulate a particular parameter to the series of ''set-point'' values corresponding to various test conditions.

In propulsion research, analog systems are often still used to control the temperature, pressure, and flow rate of liquids, such as water and hydrocarbon fuels, and of gases, such as hydrogen, oxygen, propane, and steam.

The electronic controllers used in these systems are designed to take manual or computer input of a set-point value, and to provide a control signal to a final control element such as a valve or positioner. The controller regulates the controlled parameter to the required value by comparing the set-point value with the measured value (feedback error). The units are called proportional integral derivative (PID) controllers because they generate a control signal that is proportional to the sum of three components: the error signal, the integral of the error signal, and the time derivative of the error signal. The proportional component of each error signal is adjusted in the initial setup of the system during the tuning process.

In supervisory control applications, set points for each loop are dictated from the supervisory control process for each test condition in the sequence, and loop status is fed back for each condition.

A typical loop status consists of three binary signals:

1. On the point. The controlled parameter is, or is not, within the allowed error band from the set point.
2. High saturation. The final control element (valve or positioner) is, or is not, nearing the open end of its control range.
3. Low saturation. The final control element is, or is not, nearing the closed end of its control range.

All three loop status signals are conditioned to ignore transient conditions such as oscillation or overshoot that could lead to an erroneous response. A typical response for an indication that a valve was almost wide open (high saturation) would be for the supervisor process to call for a new test condition at lower flows, which would permit the valve to move back to midrange operation.

State Control Process

The state control process determines the physical configuration of the facility and the test article for various test conditions. The final control elements in this process are binary in nature, so that the valves, positioners, and switches would be ''on'' or ''off'' or, in the case of steering (three-way) valves, flow would be from the normally open or normally closed port. For fault detection and synchronization, the state of each final control element is sensed and compared with the command signal. When all of the final control elements have reached their commanded state, within the permitted operational time, the state control system is on the point.

Data Acquisition Process

In an automated facility, the data acquisition process includes the acquisition of all data and also encompasses the operation of transducers, signal conditioning, remote submultiplexers, multiplexers, and analog-to-digital converters, as well as data formatting and recording. Computer-controlled data acquisition techniques are used routinely in most modern facilities because computer control of data acquisition equipment provides the capability to specify (under program control) such items as sampling rate and sequence, channel gain, and the format for the data recording media. In addition, if the data acquisition system is coupled to the test controller, it can be commanded by the controller to provide data processing and data compression aids such as variable sampling rates, variable sampling sequences, and critical data flagging. Use of a computer can also provide a capability for post-test data processing and engineering units display of key test parameters immediately after a run. The computer can also be used as a tool for automatic pretest checkout of the data system itself.

Monitor Process

The monitor process includes the special real-time data processing required to determine actual or impending fault conditions, unsafe trends, parameters that are out of limits, and the routing of messages, data, and indicators to the supervisor process or to displays for the test facility operators.

In any test, failure of test articles in performance or in hardware can cause damage to the facility or other test hardware. In propulsion testing, the energy levels are so high that failure can result in very serious damage, causing delays to the program for weeks or even months, in addition to hardware replacement costs. For these reasons, there has long been a requirement to provide a capability for monitoring test data in real time so as to provide an output signal or action in response to off-normal test conditions. Many times in the past, the condition to be monitored could not be measured directly, and much time and effort was spent developing, building, and installing "black boxes" that could input signals from directly measurable parameters and perform calculations to determine the occurrence of a condition to be monitored. The major drawback to the provision of these protective items usually was related to the narrow applicability of the devices and the difficulty of testing and debugging them in the propulsion testing environment. Final debugging of such a device *in situ* usually involved monitoring its performance in connection with a propulsion test.

Implementation of the display and monitor process on a digital computer provides the flexibility and capability required to perform this task efficiently, using existing signals and without regard for the environmental or reliability concerns of a new hardware design. Test parameters can be measured and manipulated as a function of the test sequence and related test conditions, and results can be output as status signals or fault alarms to the supervisor process. The supervisor process then adapts the test sequence or shuts down the test under way, and key data can be displayed in graphical form at the test operator's panel.

A properly designed and implemented monitor process will have a highly significant effect on the efficient operation of a test facility and on the successful and timely conduct of experimental programs conducted in it.

THE APL PROPULSION RESEARCH LABORATORY (PRL)

The Propulsion Research Laboratory, shown in Fig. 7, is an automated test facility. Since its construction at APL's Howard County site in 1961, test programs have been carried out on a wide variety of airbreathing missile research engines and related components over a Mach number range from subsonic to Mach 7 and at simulated altitudes from sea level to 120,000 feet. In developing the facility, emphasis has been placed on the flexibility of test conditions and on maximizing data obtained in short blowdown runs.

The principal elements of the facility are the air systems (storage, supply, and heating), the steam and exhauster systems, the fuel systems, the water cooling and quench systems, and the instrumentation and control systems.

Air Systems

A total of 58,000 pounds of air is stored in tanks at a pressure of 3000 pounds per square inch (psi). A 10,000-psi storage system also exists at PRL but has not been used in a number of years. High-pressure air is supplied to any of the five test cells at flow rates up to 150 pounds per second. The flow is controlled either by the analog control system in connection with three conventional analog control valves or by computer-controlled digital control valves, depending on the test requirements.

To simulate flight conditions properly in the test cell, the high-pressure process air must be heated. Three different types of heaters are used, depending on the temperature required. The storage heater (Fig. 1) contains a stainless steel matrix core that is preheated by an oil burner to a temperature of 1800°F. This core has a total heat capacity (referred to atmospheric reference temperature) of 3.2×10^6 British thermal units, and heat energy is added to the process air as it passes through the core. The air temperature is controlled by varying the ratio of bypass air to that

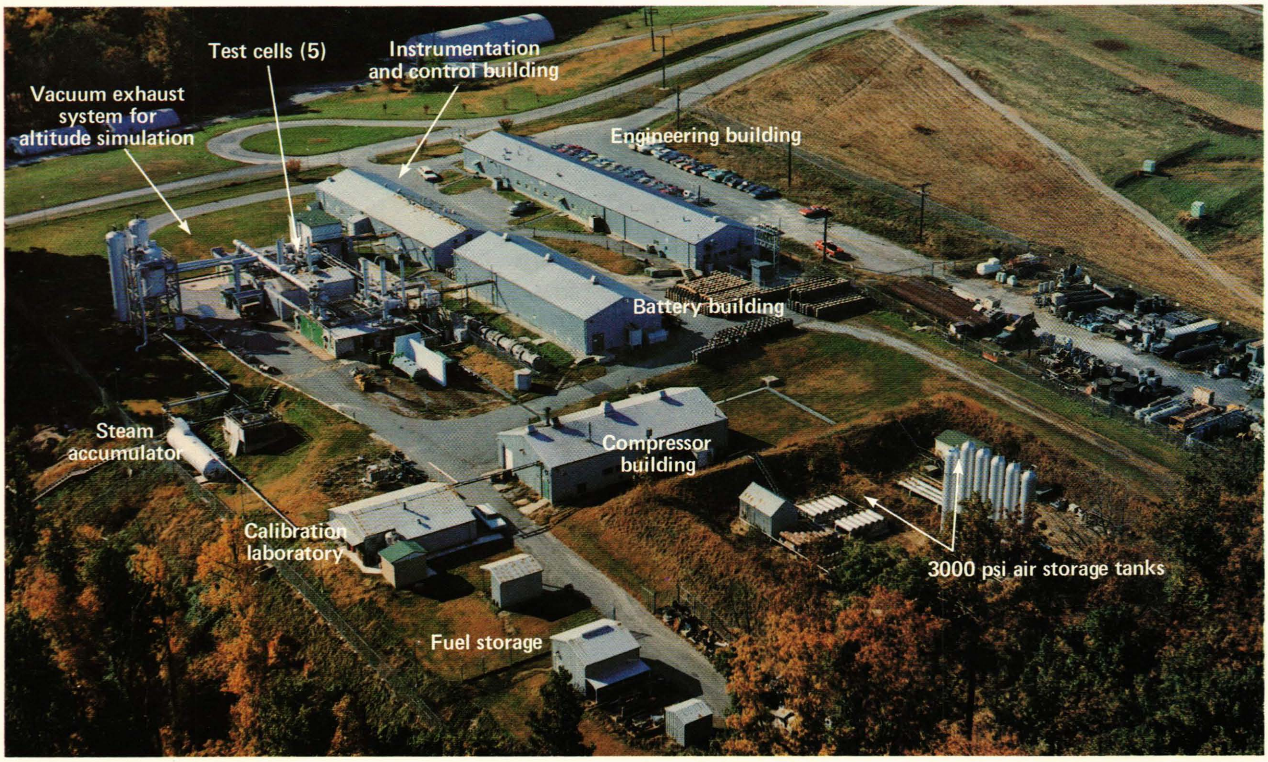

Figure 7 – The APL Propulsion Research Laboratory, a highly automated test facility. Since its construction in 1961, test programs have been carried out on a wide variety of airbreathing missile research engines and related components over a Mach number range from subsonic to Mach 7 and at simulated altitudes from sea level to 120,000 feet.

passing through the core. This heater can be used to supply air to the test cells at a maximum flow rate of 100 pounds per second at 800°F, down to 10 pounds per second at up to 1500°F.

For higher temperatures, a vitiation (in-stream combustion) heater (Fig. 2), which uses either hydrogen or propane and oxygen, can be used alone or as a topping heater in conjunction with the storage heater. The combustion heater can raise the air temperature to over 3000°F, has a 1000-psi maximum pressure, and has a maximum flow rate of 80 pounds per second (these three maxima cannot be attained simultaneously).

For still higher air temperatures, the DC electric arc heater is used (Fig. 3). Arc heaters are available to heat the air to total enthalpies greater than 3000 British thermal units per pound (approximately 7400°F) at 500 psi. In those heaters, an arc is struck between two parallel copper-tube electrodes in a chamber through which process air is flowing. Both the electrodes and the chamber are water cooled. The power supply for driving the arc is a DC battery consisting of 1216 2.1-volt submarine cells; the battery is housed in a separate building (see Fig. 7). This battery can deliver up to 14 megawatts, depending on the charge state and mode of connection, but it is usually run at about 10 megawatts or less.

Steam and Exhauster Systems

If required, an exhaust system with two steam ejectors removes the engine exhaust products and air from the test section and provides altitude simulation. The steam for driving these ejectors is generated by flashing hot water from a pressurized accumulator as it is expanded through a valve. The blow-down steam system can operate for as long as 4 to 5 minutes during a run, after which replenishment is required. The steam exhauster will pump air and combustion products at a rate of 20 pounds per second at atmospheric pressure (sea level). At a minimum pressure of 0.75 psia (67,000 feet), it pumps at a rate of 1 pound per second.

Fuel Systems

Special fuel handling and supply systems involving pyrophoric and toxic fuels have been developed for the extensive experimental supersonic combustion programs conducted at APL since 1961. Typical of these fuels were the boranes (ethyldecaborane and pentaborane) and tri-ethyl aluminum. Fuel systems were also developed for metal slurries, but current programs concentrate on more conventional hydrocarbon fuels.

Water Systems

These systems are needed in propulsion testing for quenching and cooling exhaust products as well as cooling facility and test equipment. Five separate water systems are used to support the wide variety of testing at PRL. They vary from low-pressure, high-flow-rate systems to a high-pressure (2000 psi) blowdown system where two 300-cubic-foot steel tanks are filled with water, which is then expelled under pressurized conditions provided by the 3000-psi air storage system. The lower pressure systems are used for such purposes as cooling the air compressors, the storage air heater, the arc heater ballast resistor, and other facility components, as well as for quenching combustion products. The high-pressure system is required for cooling arc heater electrodes, nozzles, heaters, and other equipment where more severe heating is experienced.

Instrument and Control System

The requirement for remote control of a complex test sequence involving 50 to 100 on/off valves and positioners, 3 to 10 proportional control loops, and possibly 350 channels of test measurement instrumentation, coupled with the monitoring of facility and test article operation in this high-energy environment, has led to the development of a hierarchical computer control and data acquisition system. The system includes a capability for joint operation of the facility and the test article with both a facility operator and a test operator in the loop. For the more complex tests, the supervisor computer memory contains the complete test sequence and preprogrammed alternative sequences. During test operation, the actual sequence path is chosen in real time by the computer on the basis of status feedback from the test or commands from the operators or both.

The present implementation of the instrumentation and control system is shown diagrammatically in Fig. 8. In this system, the supervisory control process is resident in a Texas Instruments 960 minicomputer. This supervisor computer is connected to several other minicomputers and microcomputers that, together, implement the test operational processes described earlier, in the subsystems shown. The monitor and the analog control subsystems are not implemented in a computer in the present system. Planning calls for the monitor process to be implemented in the host processor of the data acquisition subsystem. Real-time display of test data is currently available using that same processor.

The direct digital control process is also implemented in another Texas Instruments 960 minicomputer and includes dedicated sensors for measuring temperatures and pressures for the control of facility process air mass flow and temperature when the storage heater is used. It interacts with the supervisor in the same way as the other control subsystems, in that it is continuously looking to the supervisor computer for the set-point value of each of the controlled parameters and it is continuously generating status feedback data on those same parameters.

The analog control subsystem consists of a number of PID controllers that regulate the value of the controlled parameter to that commanded by the supervisor. Set-point values for each condition are output to the analog control subsystem in voltage levels corresponding to engineering unit values (psi, degrees Celsius, etc.) through a programmable translator unit. This unit, which is part of the analog control subsystem, is designed to enable the test engineer to

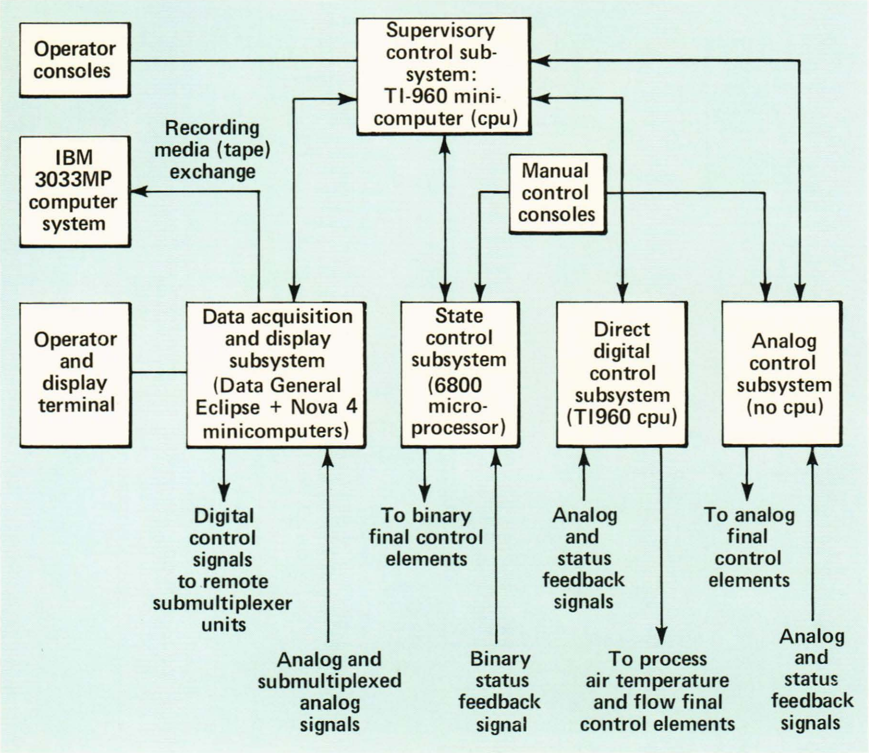

Figure 8 – The implementation of the PRL instrument and control system shown here illustrates the present allocation of operational processes to hardware having different computers, software, and communications protocols, thus making it difficult to maintain and upgrade the system. To remedy this problem, a new system is being designed that will build on the existing (new) data acquisition system hardware. The probable configuration of this system is shown in Fig. 9.

redefine the values in his set-point sequence for each analog control loop without changing the supervisor computer software.

Status feedback for each analog and digital control channel includes an "on the point" signal indicating regulation within tolerable limits and a "HIGH" or "LOW" saturation signal indicating that the control valve is almost wide open or almost closed and that the channel is about to go out of control. The appropriate response to a saturation signal is often to jump ahead in the supervisory control sequence to some less stringent set-point value that will bring the control channel back into regulation. Test condition sequences in a blow-down facility such as PRL are usually constructed to go from the more stringent conditions (higher temperatures, pressures, and flows) to the less.

At present, the state control subsystem is implemented using a Motorola 6800 microprocessor in conjunction with a diode-programmable read-only memory that serves as a programmable translator for this system. It contains 64 words addressable from the supervisor computer. Each word is 128 bits long, so that each can represent a required state of a system having up to 100 on/off valves or other such binary devices (28 bits are used internally). The state of each binary device (called a final control element) is measured using position or proximity switches, and the status is fed back and compared with the output command of the read-only memory by the 6800 microprocessor. When all of the final control elements have reached their commanded state, an "on the point" signal is transmitted to the supervisor. If any element does not change state within the time permitted for that valve, or if it fails in an illegal state (neither open nor closed), then the supervisor is notified so that an appropriate action can be taken.

Future plans call for the state control process to be implemented in a minicomputer on the bus network described below.

A new data acquisition and display subsystem has recently been installed. It has been designed to permit expansion to meet the complete testing requirements for some years to come. It was designed to provide the kernel of a refurbished instrument and control system that can be expanded to take over from existing subsystems that are obsolete or inadequate for the task.

The new system (Fig. 9) consists of two computers configured in a master/slave arrangement. During data acquisition, all the high-speed multiplexing, analog-to-digital conversion, and operation of remote submultiplexers are under control of the slave processor, whereas the operations requiring more memory and computing power such as on-line data reduction for display, the monitor process, and data formatting

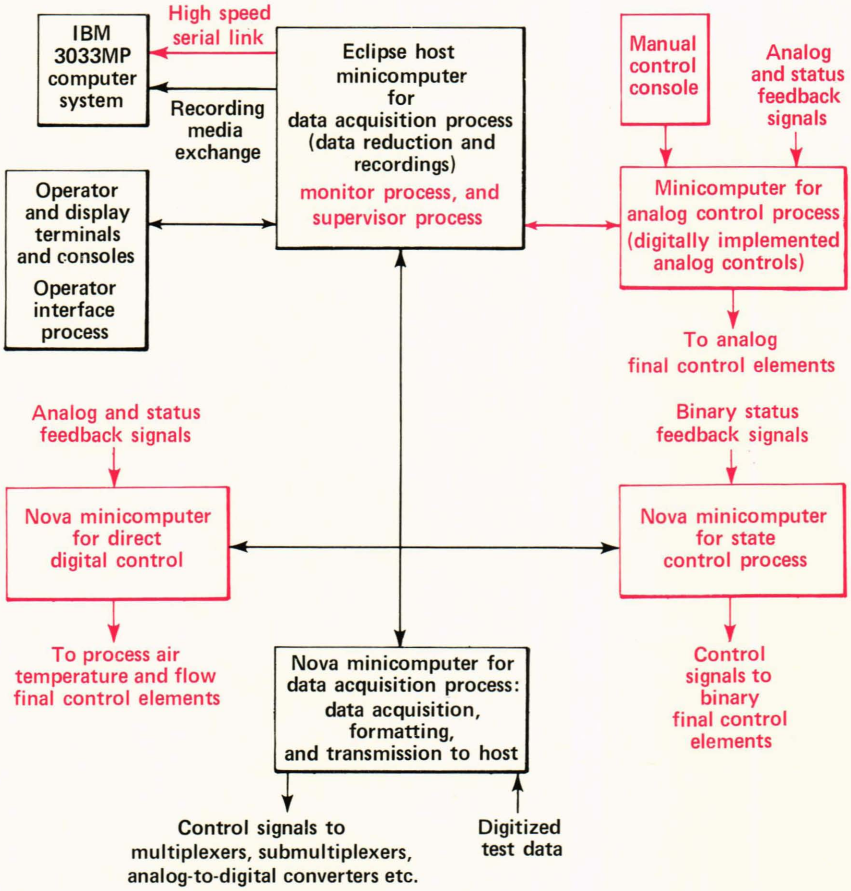

Figure 9 – This figure shows (in black) the existing data acquisition and display subsystem at PRL and also illustrates the difficulty in evolving and implementing a new design while continuing to use the old. Modern developments in computer technology involving multitasking systems usable in real-time control applications have led us to consider reallocation of operational processes to the hardware as shown in red. High-speed direct memory access interprocessor communications and larger random access memory, coupled with multitasking, suggest a shared data base design with the monitor and the supervisor processes in the host computer, in addition to the real-time display and recording currently implemented.

and recording are performed in the host. The data acquisition software resident in the NOVA 4 operates analog multiplexers to acquire high-speed data at sampling rates of up to 1000 samples per second per channel. Simultaneously, remote submultiplexers in the test cell are being driven under program control to sample up to 640 additional channels at sampling rates of up to 20 samples per second. All of these data are transmitted via direct memory access to the host computer, where they are formatted and recorded on 9-track magnetic tape. Copies of those data that are required to support the monitor or the display processes are also retained for processing in the multitasking environment of the host. After processing, the data for real-time display are output to display terminals in formats requested by operators at the terminals. Output from the monitor process is used for decision making either at the test engineer's terminal or directly in the supervisor process.

Off line, the host processor (Data General Eclipse) is used for all software development and for maintenance of the various data bases required in the operation of the facility. Software for the slave processor is down-loaded from the host for real-time operation. With this arrangement, all of the expensive programming-support peripherals (mass storage, printer, etc.) need not be replicated when additional processors are added for real-time applications. Up to 14 computers (including the host processor) may be connected to the bus.

Current plans call for moving the supervisory control process to the host processor and adding additional computers to the bus to provide input/output ports and signal processing for state input/output and direct digital control. This may change somewhat if there is insufficient room (and processor time) in the host for the supervisor, the display, and the monitor process. Since the monitor process requires immediate access to the data and faster, more powerful, arithmetic capability it will reside in the host processor to minimize communications requirements.

During the pretest checkout phase, all of the multiplexers and submultiplexers in the system can be operated from terminals via the host computer. In addition, software routines can be invoked to operate the signal conditioning, the data acquisition system, and certain diagnostic hardware (voltmeters, counters, etc.) in an automatic (diagnostic monitor) process that checks operation of the system end to end and prints out error messages listing any malfunctioning equipment. The diagnostic monitor saves many hours of manual checking of the sensors, signal conditioning, and digital recording hardware, and permits additional checks to be made right up until test time. The need for automatic testing of equipment of this type has required that a built-in test capability be designed into all subsystems and interfaced to the data acquisition system computer.

A data base management capability exists in the host in connection with the Advanced Operating Systems™ (AOS), the multiprocessing operating system. Word processing and other applications software running under AOS permits various facility support personnel to create, store, retrieve, and sort data, records, and textual documentation in the system. The data are accessible on terminals throughout the facility. To directly support the data acquisition process, the complete sensor inventory is included in one such data base along with the historical calibration records for each unit. When the data acquisition program is initialized for a particular experiment, the latest calibration data from all the sensors listed in the data acquisition sequence for that experiment are automatically retrieved from the inventory data base. Calibration constants required for data reduction in APL's IBM 3033 facility are recorded on the same 9-track tape on which the test data will be logged. Calibration constants are also retained in the host for sensors where output data are to be displayed in real time in engineering units.

The sensor inventory data base is accessed when new tests are being designed in order to locate and designate sensors for the measurement of various parameters. Drawing documentation records, technical memoranda, and manuals for various facility equipment are also stored in the host processor for instant access to determine the latest issue available. Textual documentation is updated, making use of the word processor software resident in the system.