TECHNOLOGY FOR SPACE SHUTTLE MAIN ENGINE CONTROL, CHECKOUT AND DIAGNOSIS (GP 70-232)

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ABSTRACT

The Space Shuttle Main Engine (SSME) performance and weight requirements are best met by a staged combustion cycle. Because a high performance light weight engine must operate close to component physical limits, control of critical engine parameters must be maintained during steady-state and transient conditions. A control system is therefore required to provide both engine protection and overall thrust and mixture ratio precision.

Based on considerations of precision, environment, and compatibility with vehicle interface commands, an electronic engine control unit appears to be best suited to the SSME design. Use of an electronic control makes available many functions that logically provide the information required for engine system checkout and diagnosis.

The performance, reliability and maintainability goals, established for the SSME, place demanding requirements on the engine sensor elements. To assure confidence that these sensor elements will perform accurately and reliably in the SSME environment, further technological development and thorough environmental testing is required.

INTRODUCTION

In the past, fixed thrust rocket engines have been generally controlled in a straight-forward manner, employing time-sequenced valves for control of the engine start and shutdown transients, and trimmable orifices for control of steady-state set points. Operational checks generally included preflight engine firing and component tests and required considerable ground test equipment. Monitoring sensors were added to the engine for flight performance assessment.

The advent of the Space Shuttle with its requirements for high specific impulse, long life and low cost have dictated a staged combustion cycle and a closed loop control system to allow the engine components to run close to operating limits. These performance requirements combined with the necessity for low operational costs have placed new demands on rocket engine control, system checkout, and diagnosis technology.

I. VALUE OF SPECIFIC IMPULSE TO THE SPACE SHUTTLE

The importance of specific impulse to the Space Shuttle is typically illustrated by a Lockheed study that showed the propellants for the Space Shuttle to represent approximately 80% of the launch weight. For a tanked 3.75-million-pound vehicle, propellants will amount to over 3 million pounds.

The Space Shuttle requires approximately 60 pounds of propellant per pound of payload, while a conventional cargo aircraft requires approximately 1 pound of propellant per pound of payload. Because of the high propellant-to-payload ratio, small specific impulse changes can have large effects on the space shuttle payload capability.

As indicated by Mr. Stewart and Mr. Wetherington during the AAS annual meeting in June, one second of impulse has been calculated by some authorities to be worth approximately $25,000,000, and 1500 and 2000 pounds of payload. The loss of one second of specific impulse is then worth 4% of the total payload for a 50,000 pound payload vehicle. With a 5.4% loss in specific impulse (25 seconds), the Space Shuttle would have no payload capability at all.

In figure 1 the demonstrated impulse capabilities of some existing engine cycles are compared to the Space Shuttle. It can be seen that in the development of the SSME, high performance is a prime criterion.

ENGINE CYCLE SELECTION

The engine cycle options are narrowed by the performance requirements and vehicle constraints on envelope and weight. The design goals for the SSME are outlined in table 1.

TABLE 1

SPACE SHUTTLE
MAIN ENGINE REQUIREMENTS

Thrust Lbs. (SL)	400K ± 3%
Propellants	O_2/H_2
ISP, Min. (Sec.)	
- Booster (SL/VAC) = 55.1	382/442
- Orbiter (VAC) = 220:1	459
Mixture Ratio	6.0
Throttling Range	2:1
PU Range	±0.5 ± 2%
Gimbal Angle - Degrees	±7.0
NPSH (Ft.)	
- Oxidizer	16
- Fuel	60
Burn Time (Sec.)	250
Time to Overhaul	10 Hrs. or 100 starts

The candidates considered included the bootstrap, gas generator, staged combustion and tapoff cycles. These cycles are shown schematically in figure 2.

The boot-strap cycle obtains the drive horsepower by heat transfer through the chamber wall to the fuel, which then expands through a turbine to drive the pumps. It is not within the state of the art to transfer sufficient horsepower to obtain the 3,000 psia main chamber pressure required for the SSME. The gas generator and tapoff cycles can obtain the horsepower but suffer impulse loss because of less than optimum expansion of the turbine exhaust gases. The staged-combustion cycle avoids these constraints by using a precombustor to supply the turbine drive gas and then passes all the propellants through the main combustion chamber. This paper will simply state, without further discussion, that the selected staged combustion cycle can deliver a higher specific impulse than the other candidates.

ENGINE LIMITS

The staged combustion cycle shown in figure 3 has several critical performance parameters that must be controlled to obtain the desired specific impulse with a minimum engine weight. Each of these parameters has an established limit that must not be exceeded. Repeated minor violations of these limits can reduce engine life; major violations of these limits, even for short time periods as in an engine transient, can produce component failures. The engine operational boundaries are shown in figure 4.

The critical engine performance parameters include turbine inlet temperature, main chamber wall temperature, turbopump speed and turbopump NPSH margin. If the engine is designed for wide margins between the operational boundaries and the established physical limits, this will result in additional weight for a given engine performance. A low turbine inlet temperature requires a higher preburner chamber pressure with additional turbopump and chamber weight. A lower chamber wall temperature requires additional coolant, which can reduce specific impulse by distorting the main chamber exit temperature profile. To restore specific impulse, a higher main chamber pressure and chamber weight is required. Additional main turbopump NPSH margin results in either: larger low speed inducers to provide additional main turbopump inlet pressure, or a reduction in speed of the main turbopumps. For the same discharge pressures the turbopump impeller diameters and turbopump weight will increase. Efficient engine design, therefore, dictates that the engine operate close to the performance parameter limits.

An engine designed to operate close to limits is sensitive to changes in inlet conditions or degradations in component performance. The engine will be exposed to variations in inlet pressure and temperature, which will affect turbopump NPSH margin and, unless accounted for, will affect such critical engine parameters as turbine inlet temperature and main chamber temperature. Gradual degradations in component performance may be encountered for a long-life engine, or minor component malfunctions may produce step changes in performance. Unless wide steady state operating margins are provided to account for these changes and the weight penalty accepted, a closed loop control is required. A closed loop control that senses selected engine parameters not only protects the engine from steady state environmental change and degradations in component performance, but can also provide protection during transient operation.

Open loop influence factors will differ slightly for each staged combustion engine arrangement but typically, turbine temperature will change approximately 35°R for a 1.0°R change in fuel temperature and 50°R for 100 psi change in oxidizer supply pressure. This is significant if the engine is running at the maximum thrust and maximum allowable turbine temperature where it is life limited by turbine creep. If the engine is operated at this power point with a 25°R overtemperature it will last approximately one-half of its design life.

II. APPROACH TO CONTROL SYSTEM DEVELOPMENT

A. Selection of Valve Locations

To determine the best control arrangement for a given engine, the valves are first identified as power controls or load controls. Power controls modulate power delivered by the turbines and load controls modulate the power required to drive the pumps. Power controls can be further subdivided into variable area turbines and turbine throttles. For each general category the best valve location is selected primarily by its effect on specific impulse. Then a minimum number of valves is added until the combination can modulate the engine over the desired thrust and mixture ratio range. A fairly complete steady-state thermodynamic model of the engine is required in this analysis for the results to be meaningful in terms of engine performance. For the case studied here, the model required 225,000 bytes of core storage in an IBM-360 computer.

Figure 5 shows the best combination identified in each category and figure 6 shows the typical performance trade-offs that must be considered in the selection of category. The choice here is the load controls combination based on minimum impulse penalty if the pump speed and turbine temperature boundaries are acceptable.

B. Dynamic Analysis

A parallel study must also be conducted to evaluate the dynamic requirements the control system must satisfy. As shown in figure 7, the steady-state performance studies and the dynamic analysis both influence the engine design and arrangement. Application of the three dynamic modeling methods will be necessary to properly assess the control performance. An analog model, a digital dynamic model and finally a hybrid model will be required. The importance of dynamic evaluation can be visualized by considering figure 8, which shows the typical response characteristics of the engine to a thrust command (2.8 cps). For a valve to reasonably control any loop within the engine, its response should be approximately 5 times as fast or 14 cps. For a control to track and modulate this valve position, its response should be approximately 5 times as fast as the valve, or 70 cps. The basic engine thrust response appears slow, primarily because of propellant compressibility in the heat exchangers; however, inner loops of the engine are extremely fast. In comparison, a turbojet engine with similar control requirements, has approximately 15 times the SSME rotor inertia and only 40% of the steady-state turbine power, and is, therefore, slower in response and easier to control.

In formulating the engine dynamic simulations each component must be described in sufficient mathematical detail to define its time-dependent character in terms of hydrodynamic and thermodynamic performance, and its time-dependent relation to adjacent components. This constitutes the digital dynamic model used for accurate analysis. A simpler analog model is also constructed, which represents components with non-linear partial derivatives, and is used for initial control system evaluation. With these tools available, a preliminary selection of the control elements (sensors, actuators and control computer logic) is made and a dynamic model is constructed. This control simulation is married to the appropriate engine model and evaluation of control modes can begin. Because the primary function of the control system is to protect the engine components, the system is evolved until adequate engine protection is afforded under all steady-state and transient conditions.

Typical problems and solutions are evaluated as shown in figure 9 where speed overshoot and a cooling margin deficiency are identified in the open-loop "gross mode" of control and are corrected by addition of the feedback loops.

C. Logic Mode

A potential logic mode for the SSME control consists of a basic open loop scheduled system, with supervisory trim for precision and overrides for failure protection. The basic open loop system runs the engine through its normal operating range with an absolute minimum dependence on measurements. The propellant modulating elements of the engine are moved in response to vehicle requests in accordance with a predetermined schedule of effective flow area as a function of the requested power or mixture ratio. Dynamic compensation is accomplished in this system by directly relating flow area change with time (rate control). Information to establish these schedules and rate limits is obtained from prior analysis and confirmed by engine and valve test data. The schedules are stored in the digital control permanent memory. A typical basic schedule control loop is shown in figure 10.

A secondary mode of control is the supervisory, or limited authority trim function that employs some process measurements for its operation. This mode improves thrust and mixture ratio precision by sensing engine parameters such as total flow or flow ratio and trimming the basic control to within the allowable error limits. A typical supervisory trim control loop is shown in figure 11.

While the primary function of the control system is to protect the engine during steady-state and transient operation, an important secondary function is to protect the engine against the effects of deterioration of any component part of the engine or control system. Critical engine parameters must be monitored to keep the engine within its design operating limits even though an unanticipated environmental change or a component malfunction has changed the basic engine characteristics so that the predetermined schedules are no longer valid. A limit override system senses the critical engine parameters and functions only when an established limit has been exceeded. A typical limit override system is shown in figure 12.

Redundancy in sensing elements with voting logic to select the sensor which is functioning properly can reduce the effect of sensor malfunction. Typical redundant sensor inputs are shown in figure 13.

Safety and reliability must be considered in the control system arrangement. The basic control mode should permit safe engine operation with reduced accuracy after loss of the supervisory trim system. The supervisory trim system should provide protection from the effects of performance degradation of engine components which alter the desired predetermined valve schedules. In addition, the redundant sensors and electronic control logic, employing self test techniques, can assure the required reliability levels and confidence.

Computer Configuration

Hydromechanical and electronic configurations were considered for the Space Shuttle Engine Control Unit (ECU). Hydromechanical control has been adequate on turbojet engines and on a development model of the P&WA RL10 throttling rocket engine but the requirement for improved engine performance and the acceptance of "fly-by-wire" vehicle controls has accelerated the introduction of electronic controls. Fortunately, major advances in solid state electronic equipment have made the change possible at this time. P&WA is currently applying engine-mounted electronic controls to gas turbine engines under development; many thousands of hours of operational experience will be accumulated in these programs. Solutions to the environmental problems obtained in these programs will be available to supplement the SSME control design and later development. Hydromechanical control applications for the SSME are handicapped by the lack of a suitable working fluid; the engine propellants are compressible and their properties vary over the engine operating range, introducing inaccuracy in a hydromechanical computer. The addition of a third fluid as a working medium necessitates careful conditioning to maintain properties and prevent freezing during engine tanking and hold operations. Environmental conditioning can be accomplished for electronic controls and the desired computation precision can be attained. The electronic control interfaces readily with the vehicle and connects easily with remotely located valve actuators. Based on these considerations for precision, environment, and compatibility with interface commands, an electronic engine command unit is best suited for the SSME.

Engine-mounting the engine command unit not only simplifies the engine/vehicle interface but provides a special-purpose computer dedicated solely to engine protection. This is an important safety consideration for manned systems as outlined in a paper by Operations Research Incorporated. Seven safety principles were outlined and seem appropriate:

- Separate vital functions
- Isolate vital equipment
- Employ fail-safe bias
- Design for serial independence
- Employ positive sequences
- Design for consistent behavior
- Design for physical strength

These considerations should be applied in the concepts for design, production and operation of the SSME control system.

III. ENGINE CHECKOUT AND DIAGNOSIS

A prime goal in the space shuttle is economy. The airlines have found that this requires high utilization of a small fleet through efficient checkout and maintenance. Automated on-board checkout and recording systems minimize the need for ground based special-test equipment and their associated maintenance and reliability problems. An operational readiness signal will indicate that the engine can start and accelerate to any thrust level. The engine inlet conditions will be measured and compared to limits stored in the control.

The vehicle operational readiness checks will include self test of the control. If all systems are within the limits, a signal will be provided to the vehicle. If any parameter is out of limits, it can be identified to the vehicle. These checks will be made prior to start.

Parameters presently included in the operational readiness check are:

1. Electical Power
2. Control Operation (Self Test Program)
3. Helium System Pressure
4. Propellant Inlet Conditions
5. Main Turbopump Housing Temperature

The sensors and control logic required for engine control and protection also provides most, if not all the information which should be monitored for engine performance assessment, check-out, diagnosis and malfunction isolation. The availability of this information is evident in figure 14 which shows one of the control loops in block diagram form. Uncorrected error signals which persist after a normal transient are indicative of a system fault. An uncorrected trim error signal indicates that the engine component characteristics have degraded beyond the capacity of the limited authority trim loop. An uncorrected valve position error indicates a malfunction in the valve or actuator. An active override signal denotes that a major change in component characteristics has occurred. Signals are also available from the sensor and voting logic networks.

Since it is not desirable to hot fire the SSME for ground checks, inflight data recording and telemetry of available parameters is most important to expedite the maintenance turnaround. Interrogation and multiplexing procedures for the monitored parameters must be coordinated with the vehicle to assure that adequate vehicle computer memory capacity is available and that fault indications are properly assessed by the vehicle for corrective action.

Malfunctions may be classified as to effect on engine and vehicle operation.

Failure Type	Effect on Engine	Vehicle Action Required
Failure of a component which has a redundant backup	None	Identify for ground maintenance
Failure of a component requiring a switch to a backup control mode	Reduced engine precision and reliability	Assess effects on mission
Degradation of a subsystem requiring override trim	Reduced engine thrust	Assess effects on mission. Minor trim compensation in thrust
Failure of a subsystem requiring advance to shutdown	Engine shutdown	Assess effects on mission. Major trim compensation in thrust and possibly gimbal angle

The following signals are being considered for monitoring and recording in the vehicle.

1. Uncorrected Valve Position Error Signals
2. Uncorrected Flow or Chamber Pressure Error
3. Uncorrected Mixture Ratio Error
4. Operation of backup control modes
5. Control system override signals
    a. Turbopump speeds
    b. Turbopump vibration
    c. Turbopump NPSP
    d. Turbine discharge temperatures
    e. Nozzle coolant flow

Engine monitoring during preflight and flight operation can provide the data necessary to identify failed Line Replaceable Units and schedule maintenance activity.

IV. SENSOR TECHNOLOGY

Although basic schedules for the SSME control components will be predetermined and scheduled as open loop, supervisory trim systems for precise thrust and mixture ratio control, and overrides for engine protection are planned and sensors are used in these control loops. The supervisory trim loops will require propellant flow or chamber pressure measurement; override loops utilize turbine exit temperature, turbopump speeds and some engine pressure measurements. Sensor accuracy will be confirmed by calibrations compared to the reference standards. The precision and accuracy of the reference standards, the engine trim procedure for thrust and mixture ratio and the precision of remaining system components will define a precision band for engine mounted sensor elements. In addition, these sensors should not introduce biases which are a function of the operating environment and result in an output shift. The sensor elements should be stable with ambient temperature changes, vibration, acoustic noise, varying ambient pressure, G loads, and changes in attitude.

Propellant flow measurement must be made on a mass basis to account for range in propellant inlet conditions encountered on the SSME. In lieu of a pure mass flow measurement system, density must be calculated from additional pressure and temperature measurements. Successful development of a pure mass flow measurement device for the SSME would result in an overall system improvement. Some of the problems encountered with typical flow measurement devices are illustrated in figure 15 where the effects of installation on sensor output are shown.

Pressure sensors for the SSME control will probably be of the diffused strain gage or deposited strain gage type. These devices are precise when used in a reasonable environment. Acceptable steady-state temperature compensation methods are available but we have found that a change in output will be experienced for substantial time after an ambient temperature change. Typical test results are shown in figure 16. The calibration results are shown as percent deviation in output signal from the signal obtained in a standard setup. A controlled environment for the strain gage can be added but it would be better if a thermally insensitive instrument could be developed.

Turbine temperature is an excellent parameter to use for engine protection and diagnosis. Chromel Alumel thermocouples will probably be used for this application but we are continually searching for more precise and reliable devices. One candidate is the infrared sensor which is now being tested for application to gas turbine engine blade temperature measurement. However, this sensor requires control of the environment, and a window access through the high pressure burner will be difficult to produce. Another candidate is the acoustic thermometer which measures temperature with a sonar technique. Some cyclic endurance test results are shown in figure 17 that indicate a repeatability problem in the unit tested, and a drift in output with time. Post-test inspection of the sample revealed evidence of oxidation which may have caused the drift, perhaps this characteristic can be used to assess turbine life.

The performance, reliability and maintenance goals for the Space Shuttle Main Engine place demanding performance requirements on the engine sensors. To assure that these sensors will perform accurately and reliably in the SSME environment, further technological development and thorough environmental testing are required.

V. CONCLUSION

The technology for successful development of the SSME control system, checkout and diagnosis systems is presently available in most areas. Existing techniques for development of control system logic modes through dynamic analysis have been proved effective. The engine control system design will require thorough dynamic evaluation for application to the SSME. Extensive coordination between the engine, vehicle, and operational personnel will be required to formulate effective engine checkout and diagnosis procedures. Advances in technology for process sensors are needed to improve reliability, reduce sensitivity to environmental changes, and provide the confidence levels necessary for space shuttle applications.

VI. REFERENCES

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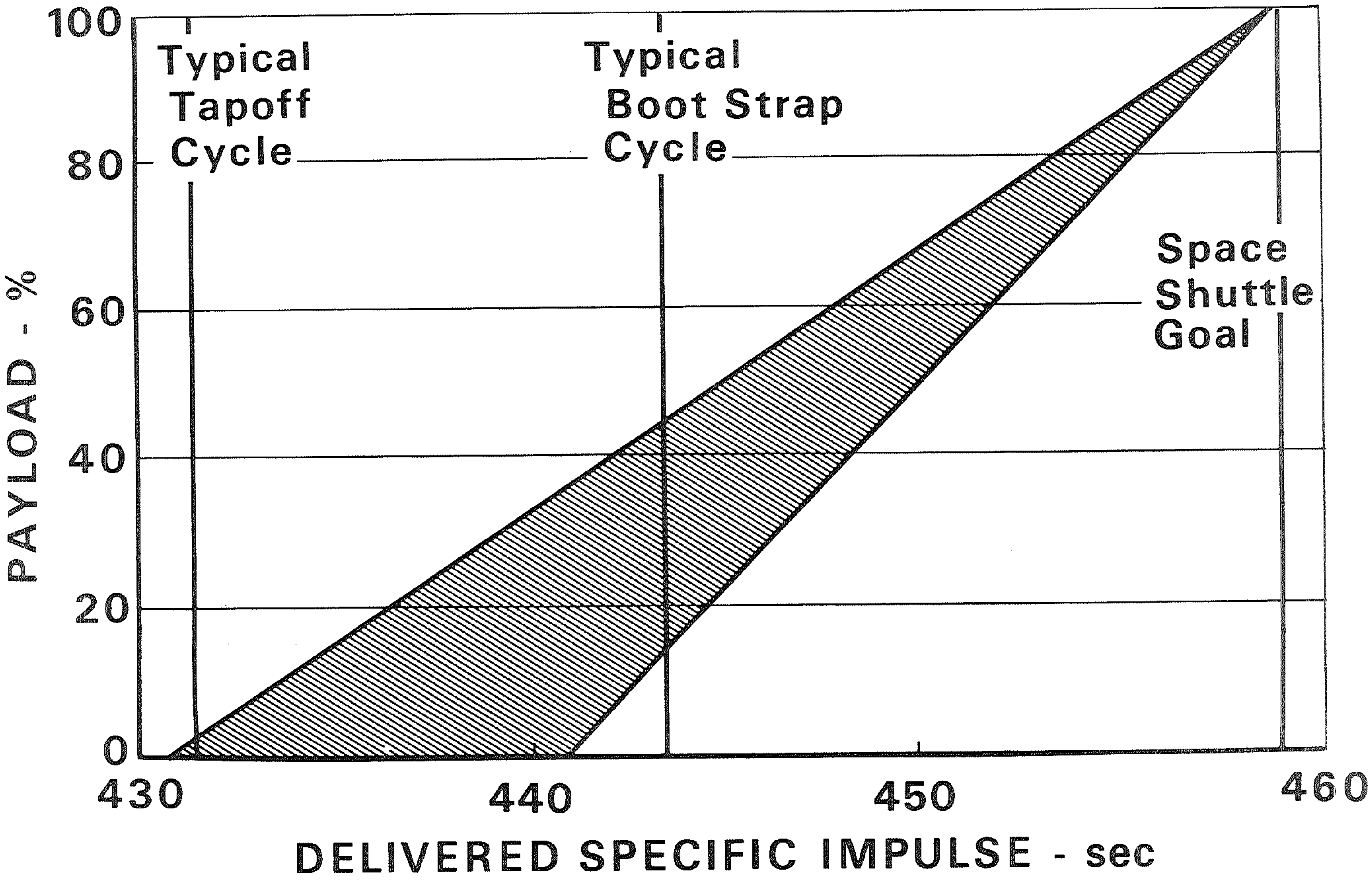


Figure 1. Shuttle Payload is very Sensitive to Specific Impulse

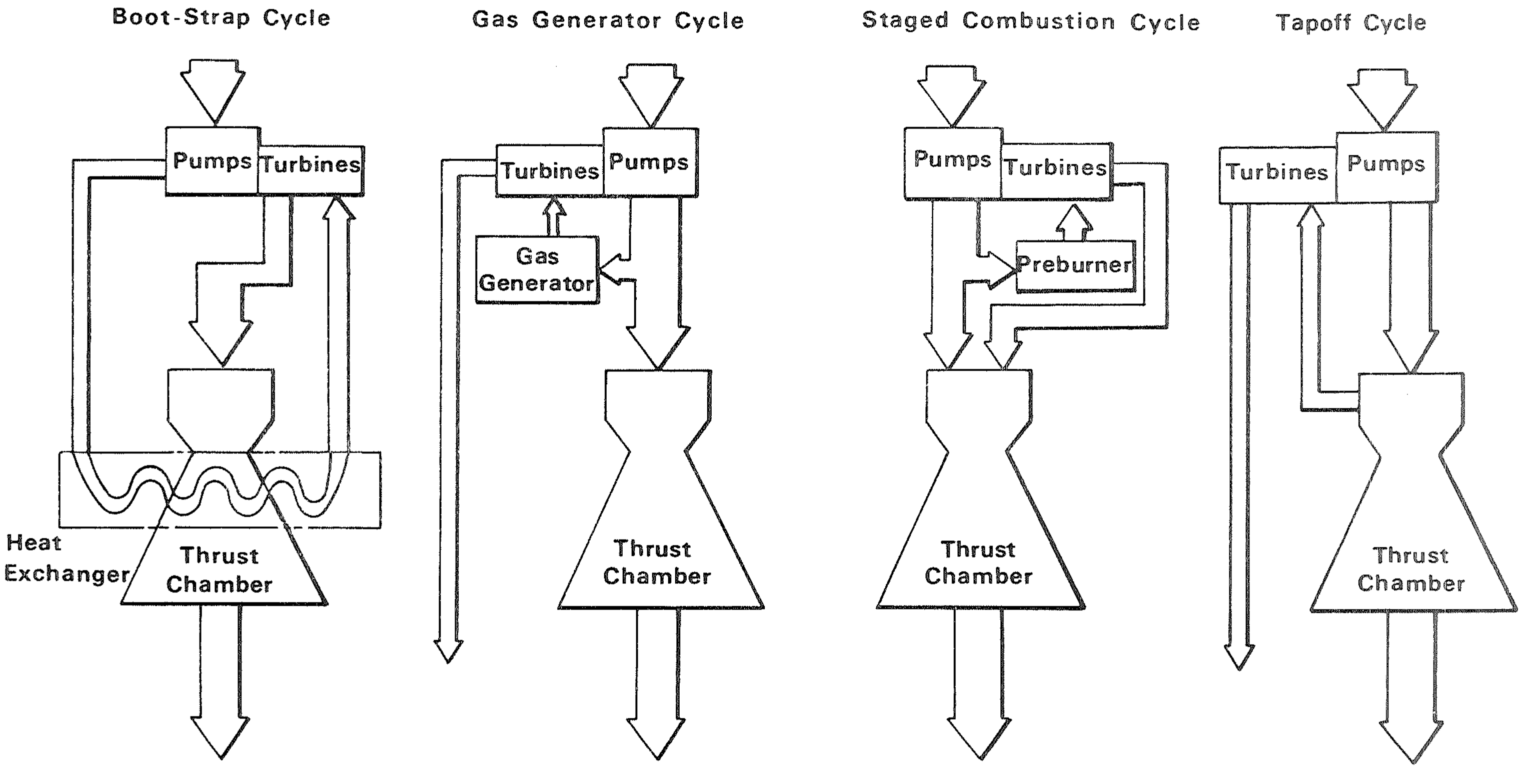


Figure 2. Candidate Engine Cycles

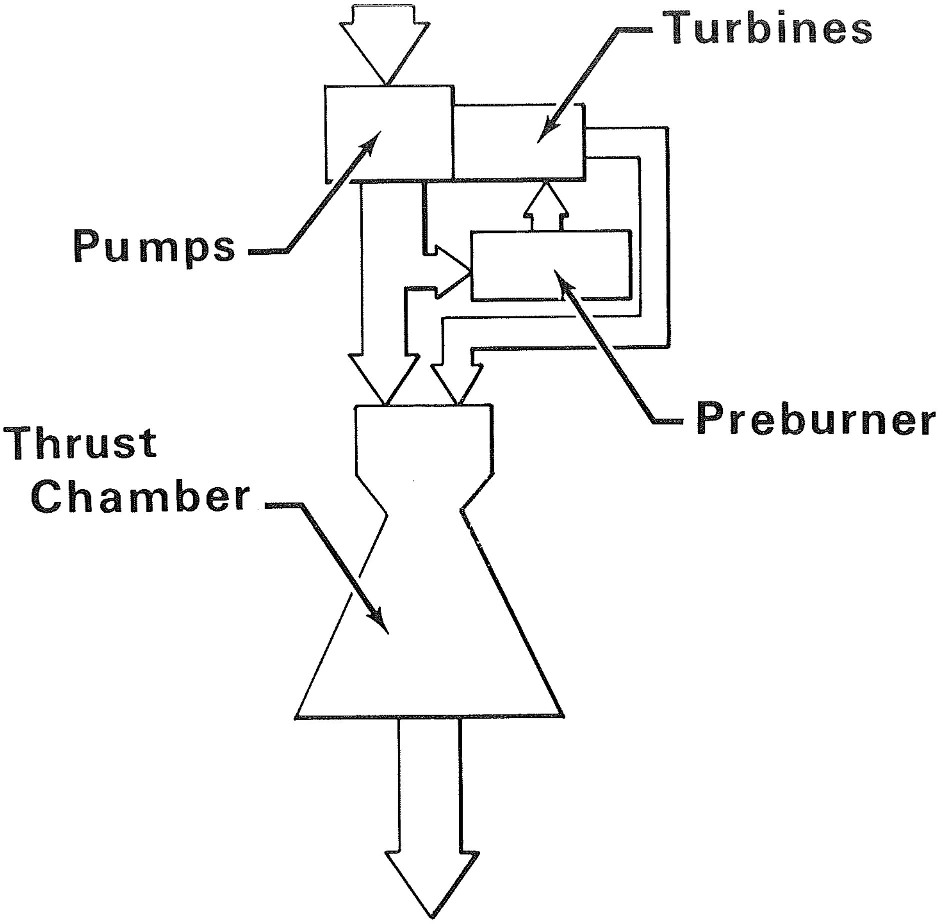


Figure 3. Staged-Combustion Cycle

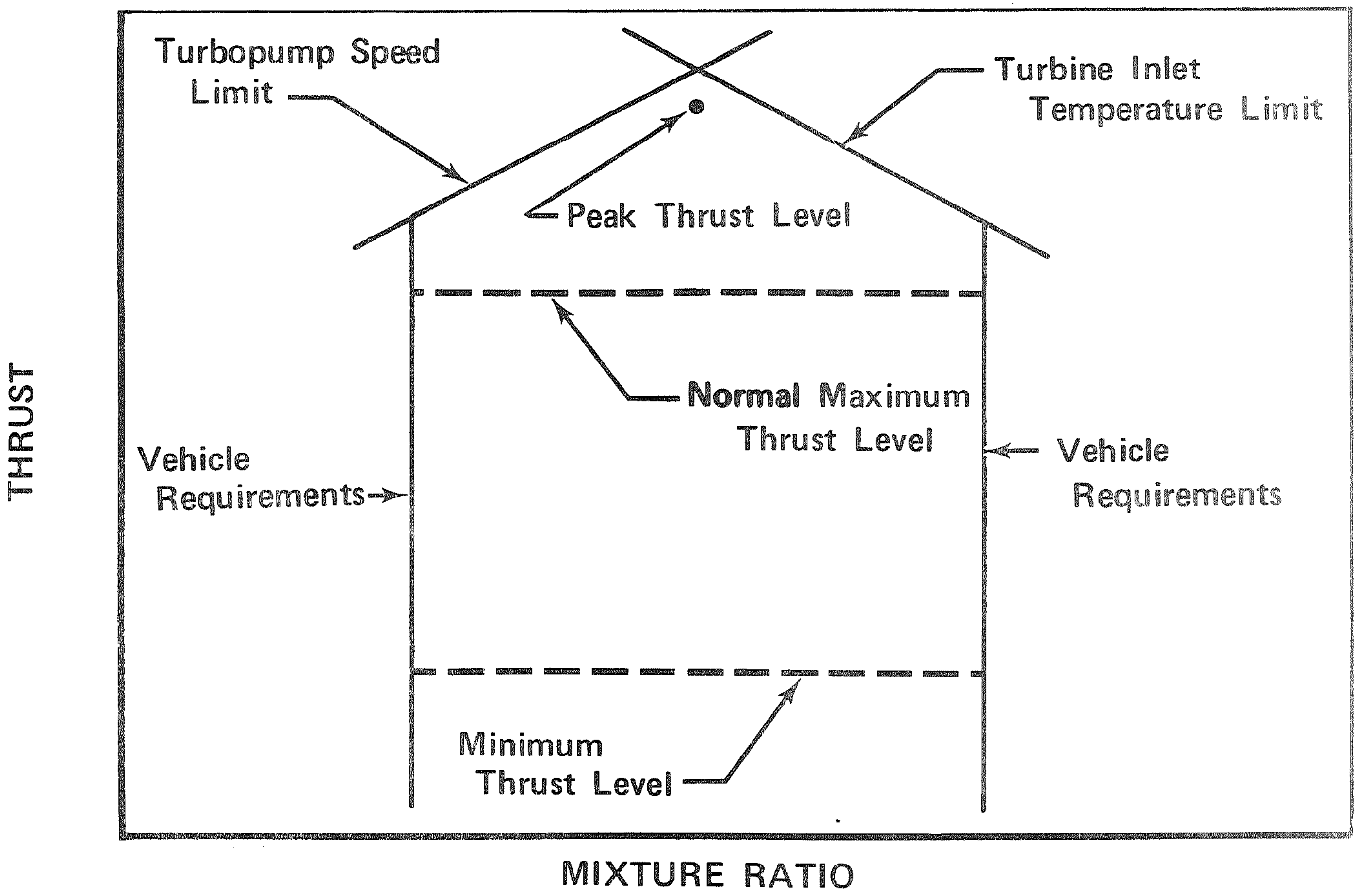


Figure 4. Engine Operating Limits

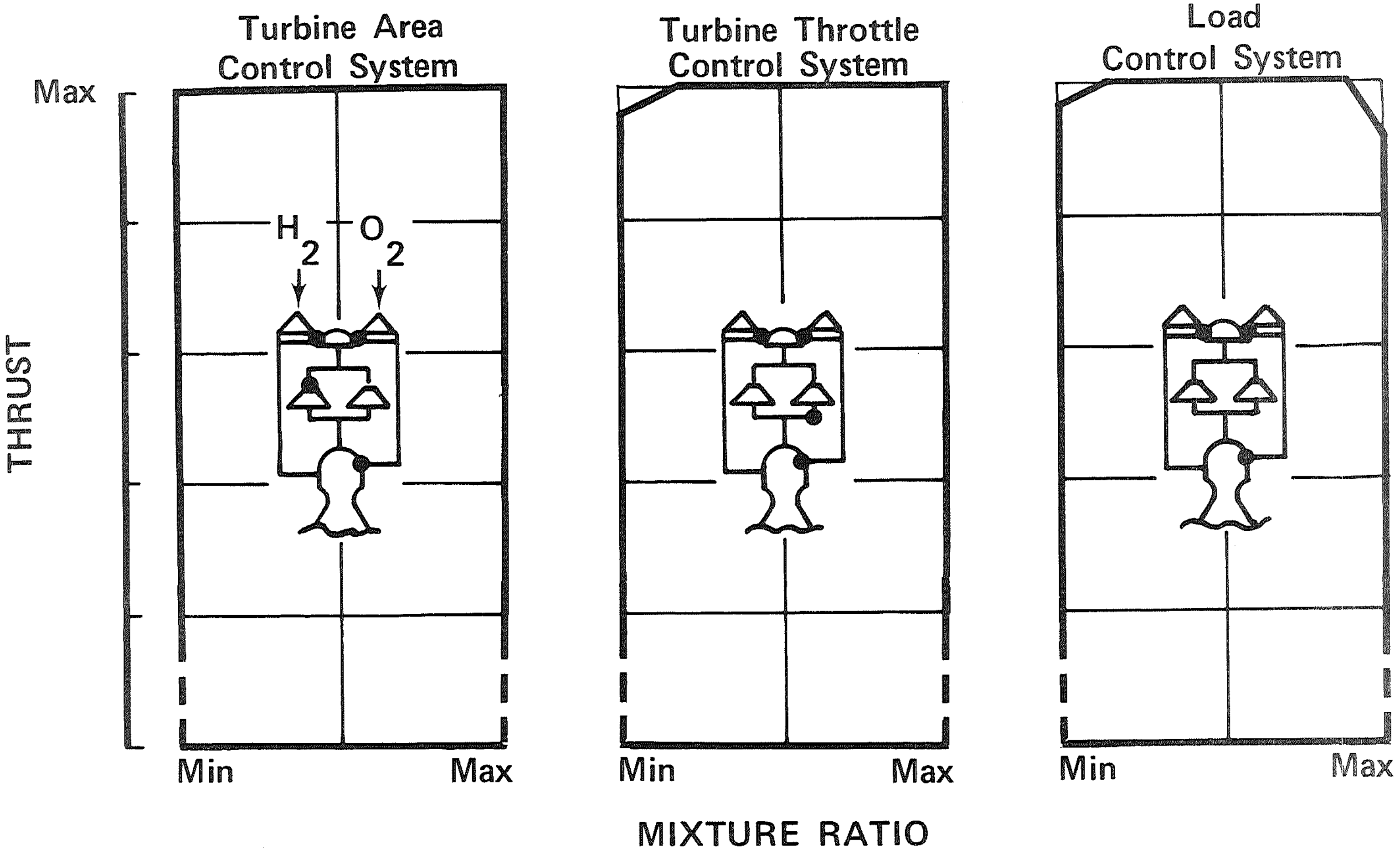


Figure 5. Comparison of Control Systems Operating Regions

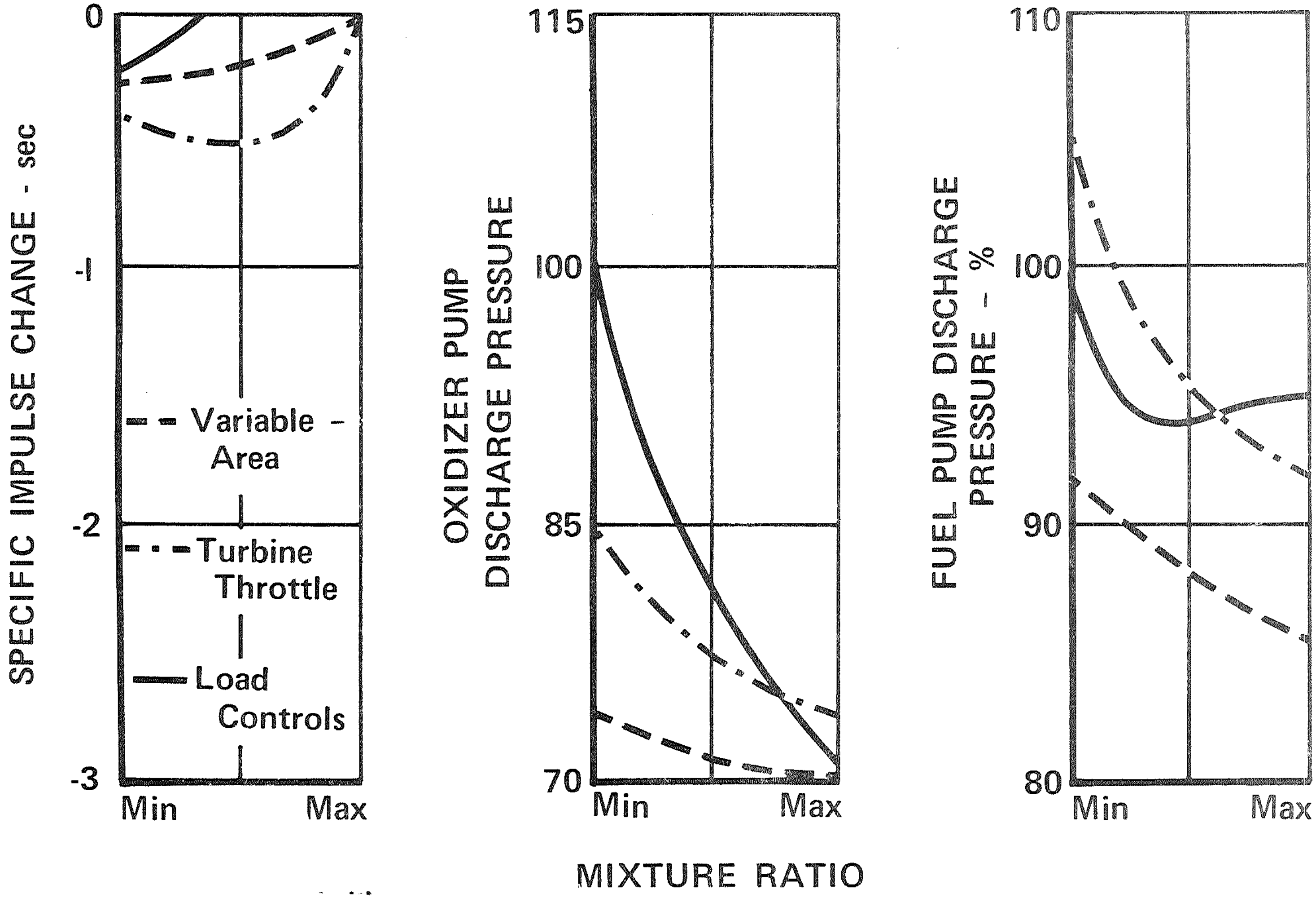


Figure 6. Control System Study - Engine Characteristics

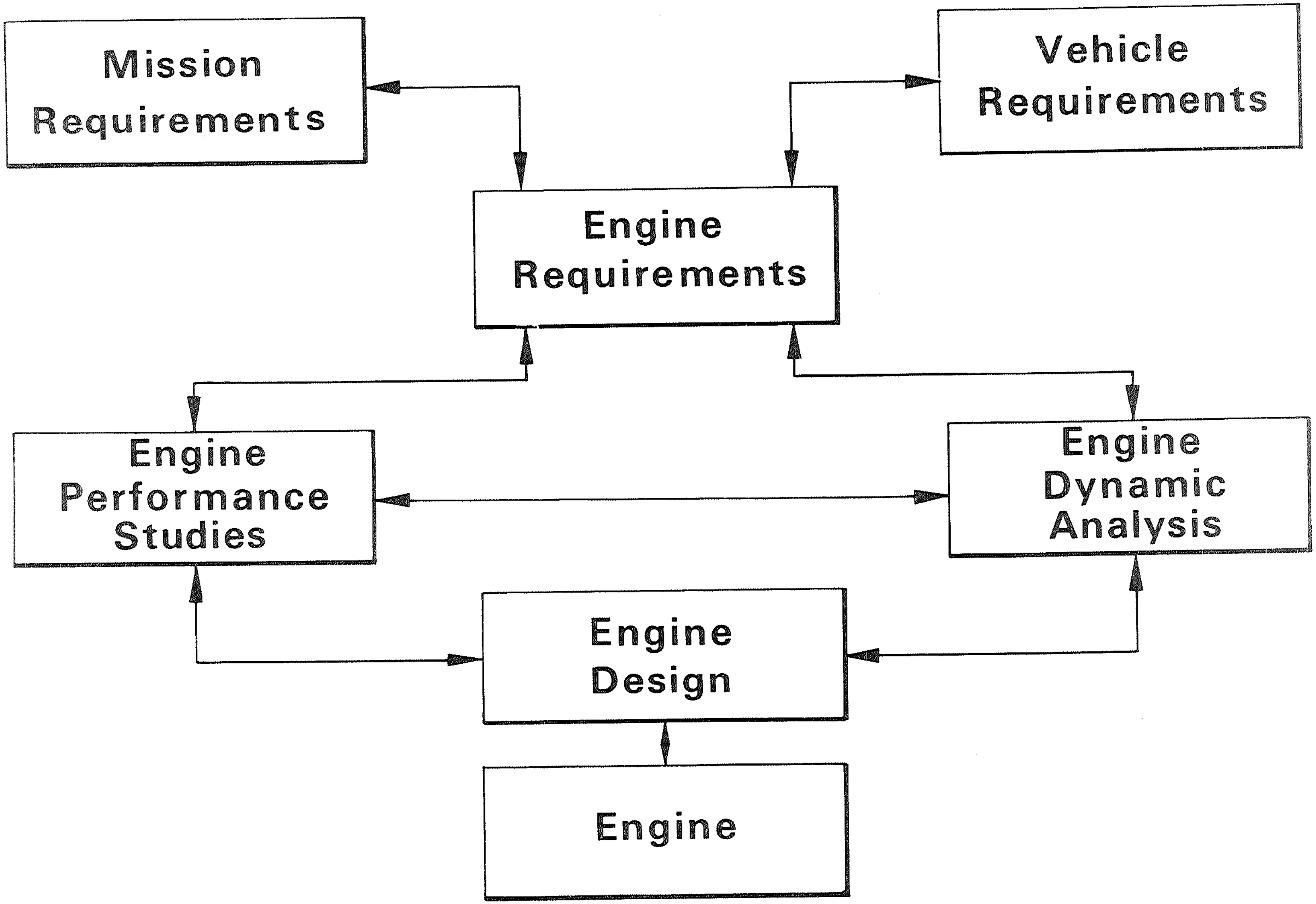


Figure 7. Engine Dynamic Analysis is an Integral Part of System Analysis

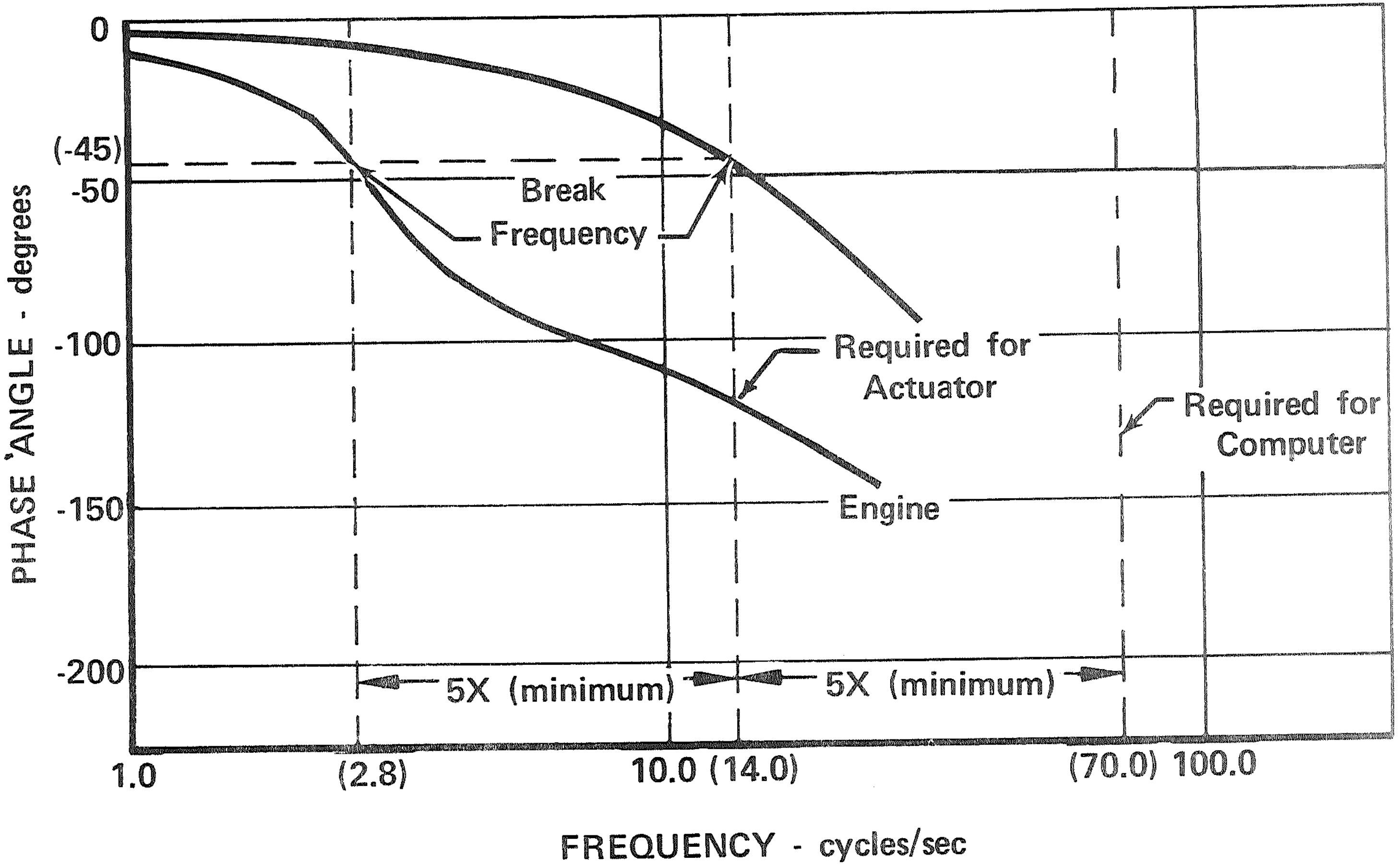


Figure 8. Engine Dynamics Dictate Normal Control Response

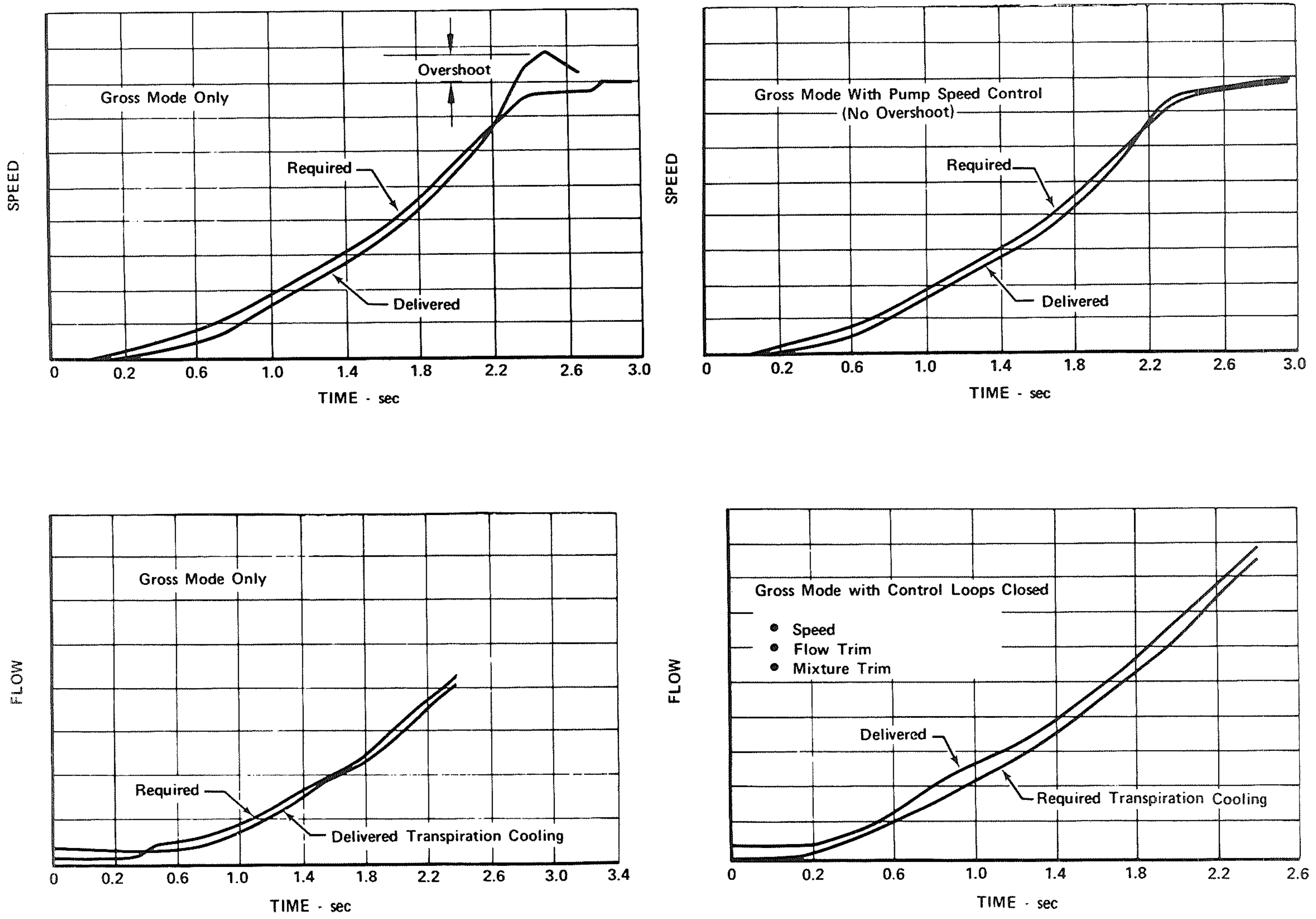


Figure 9. Acceleration

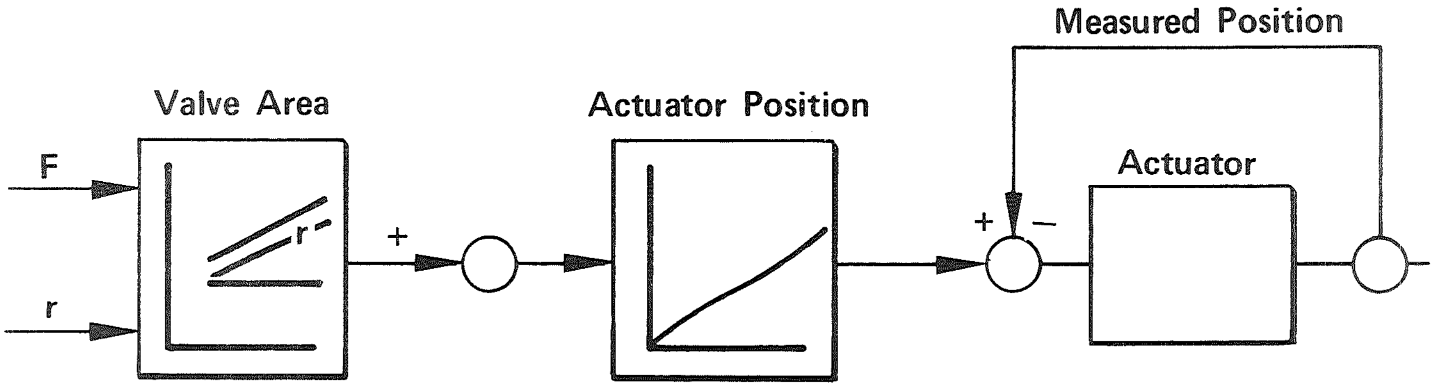


Figure 10. Basic Schedule

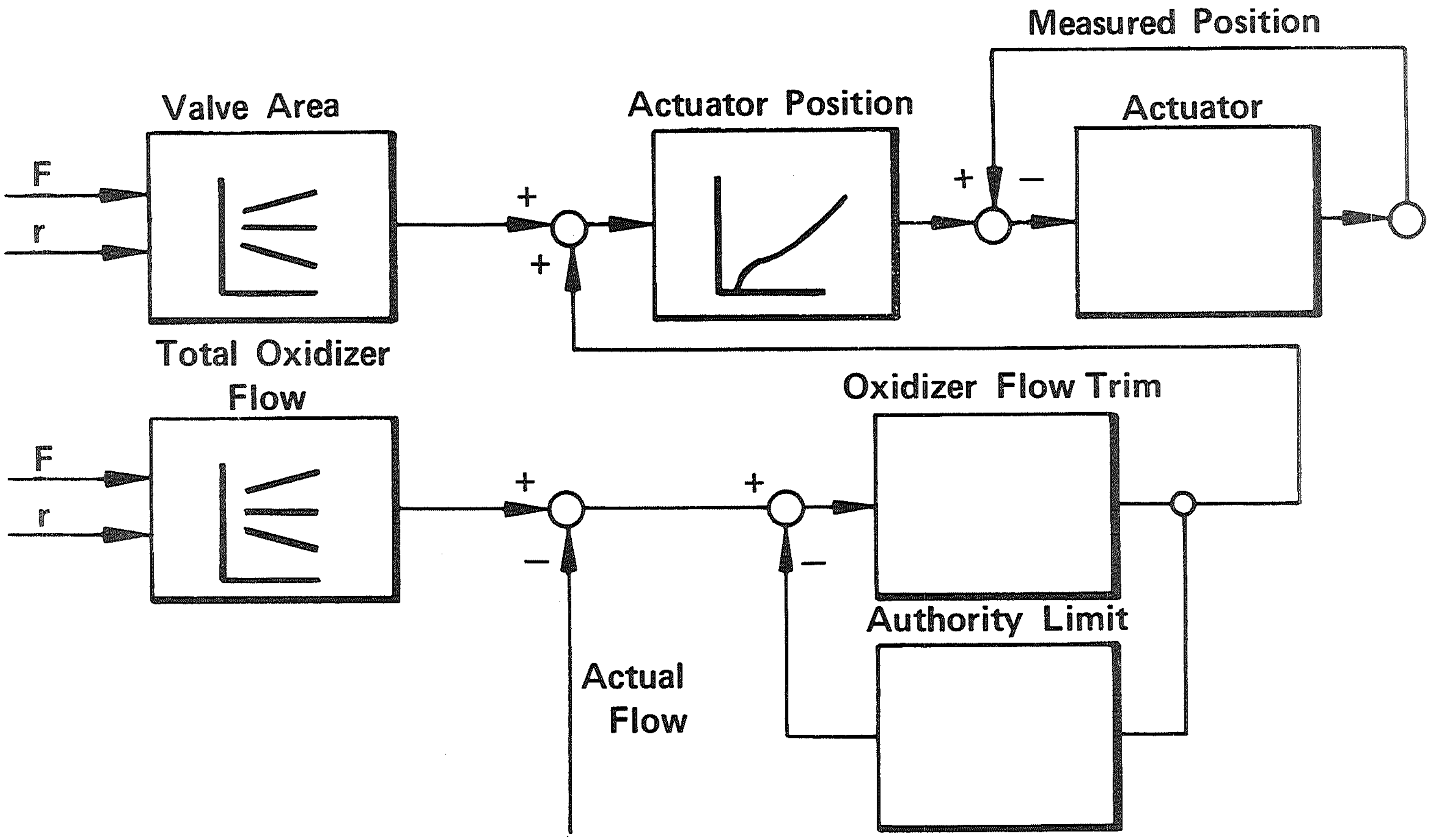


Figure 11. Supervisory Trim

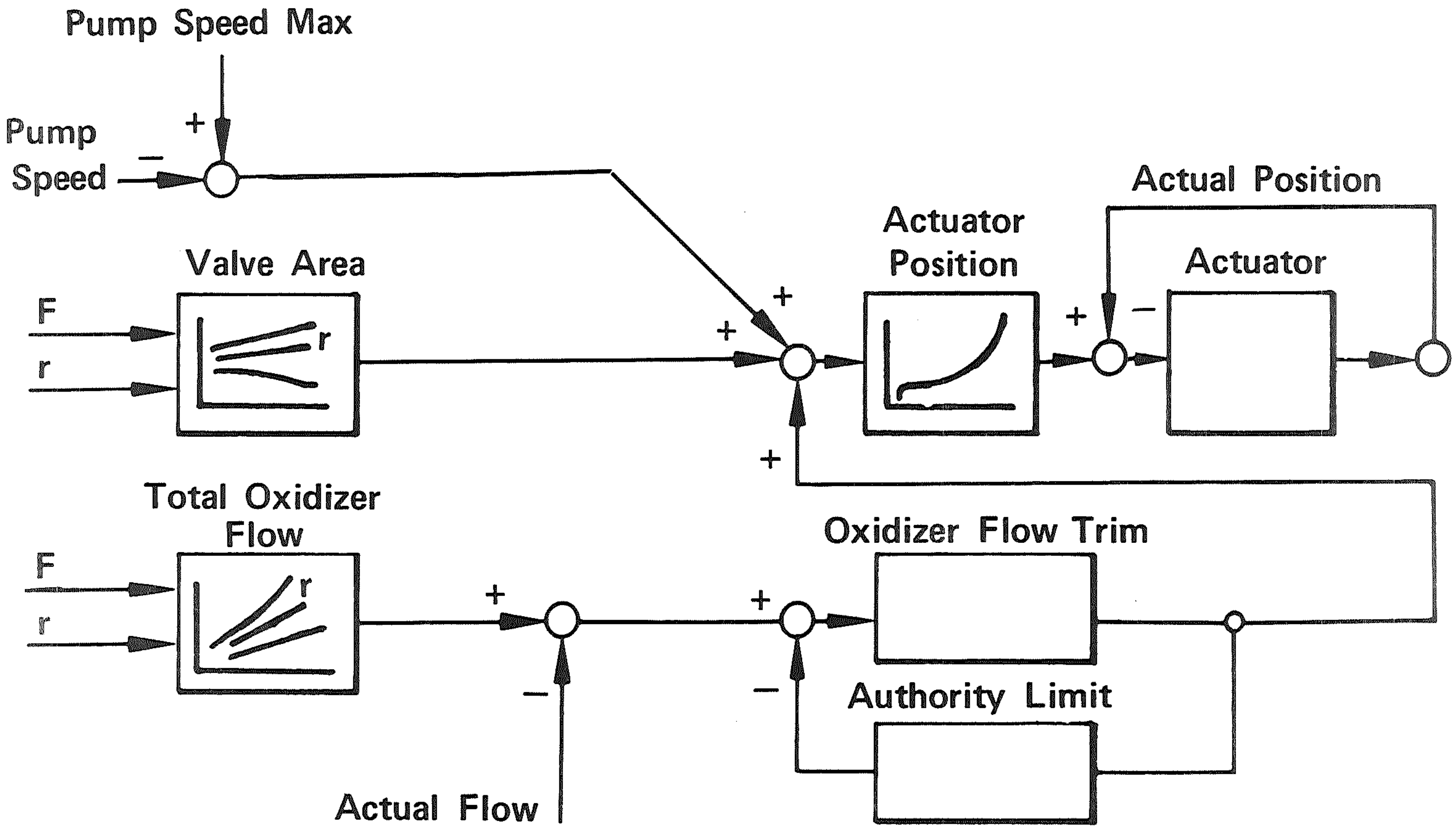


Figure 12. Limit Override

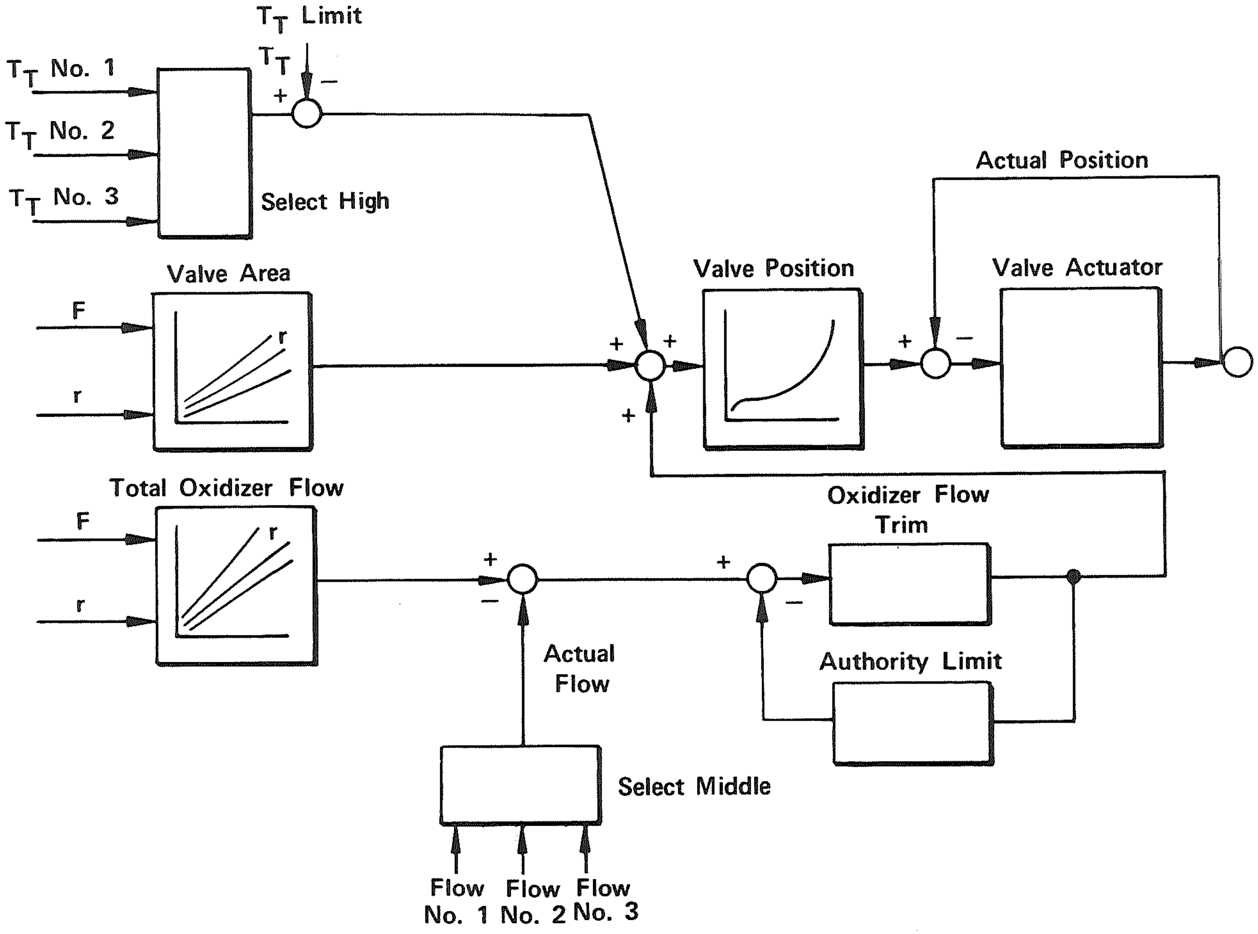


Figure 13. Redundant Sensors

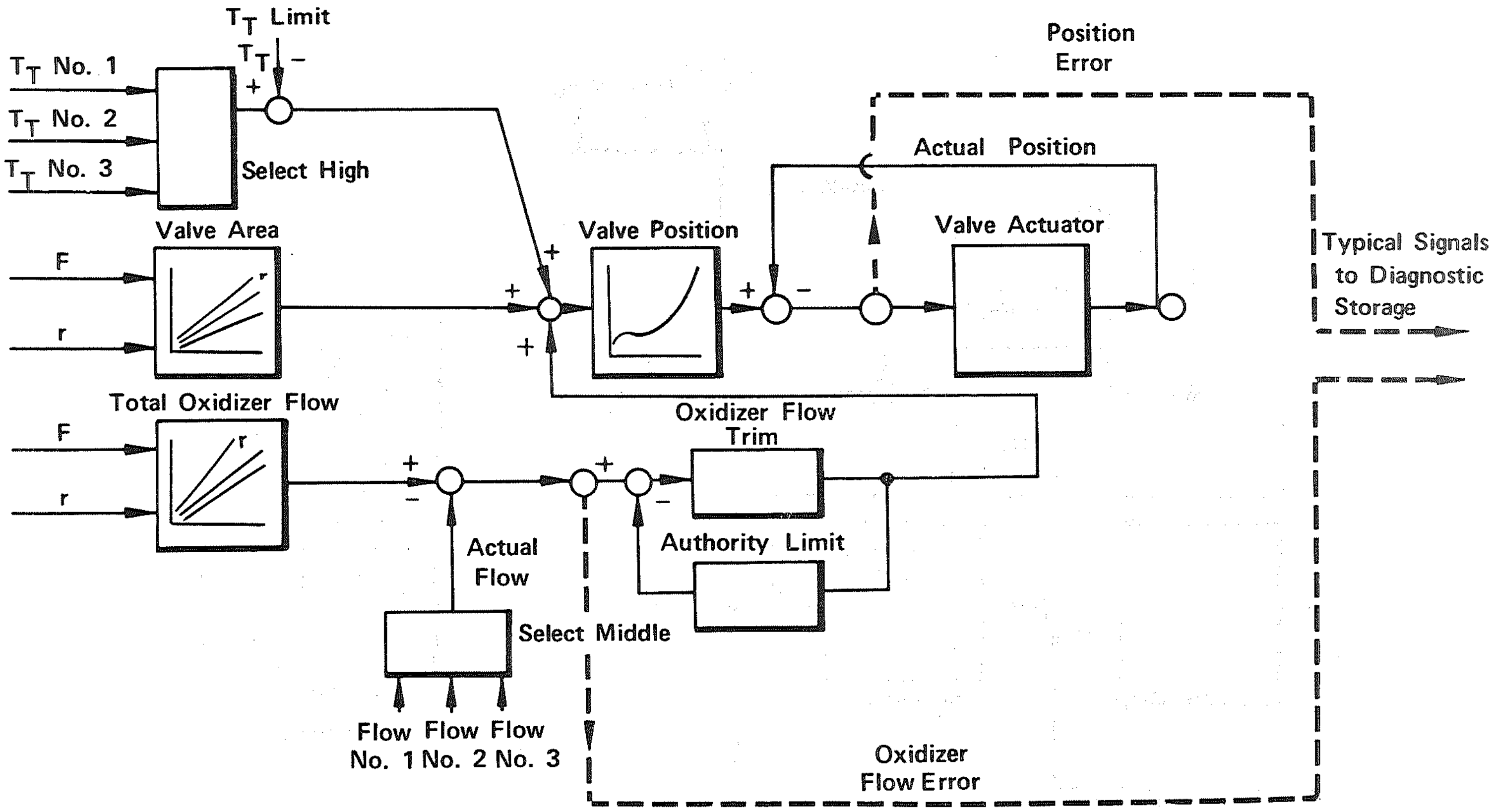


Figure 14. Diagnostic Signals are Available

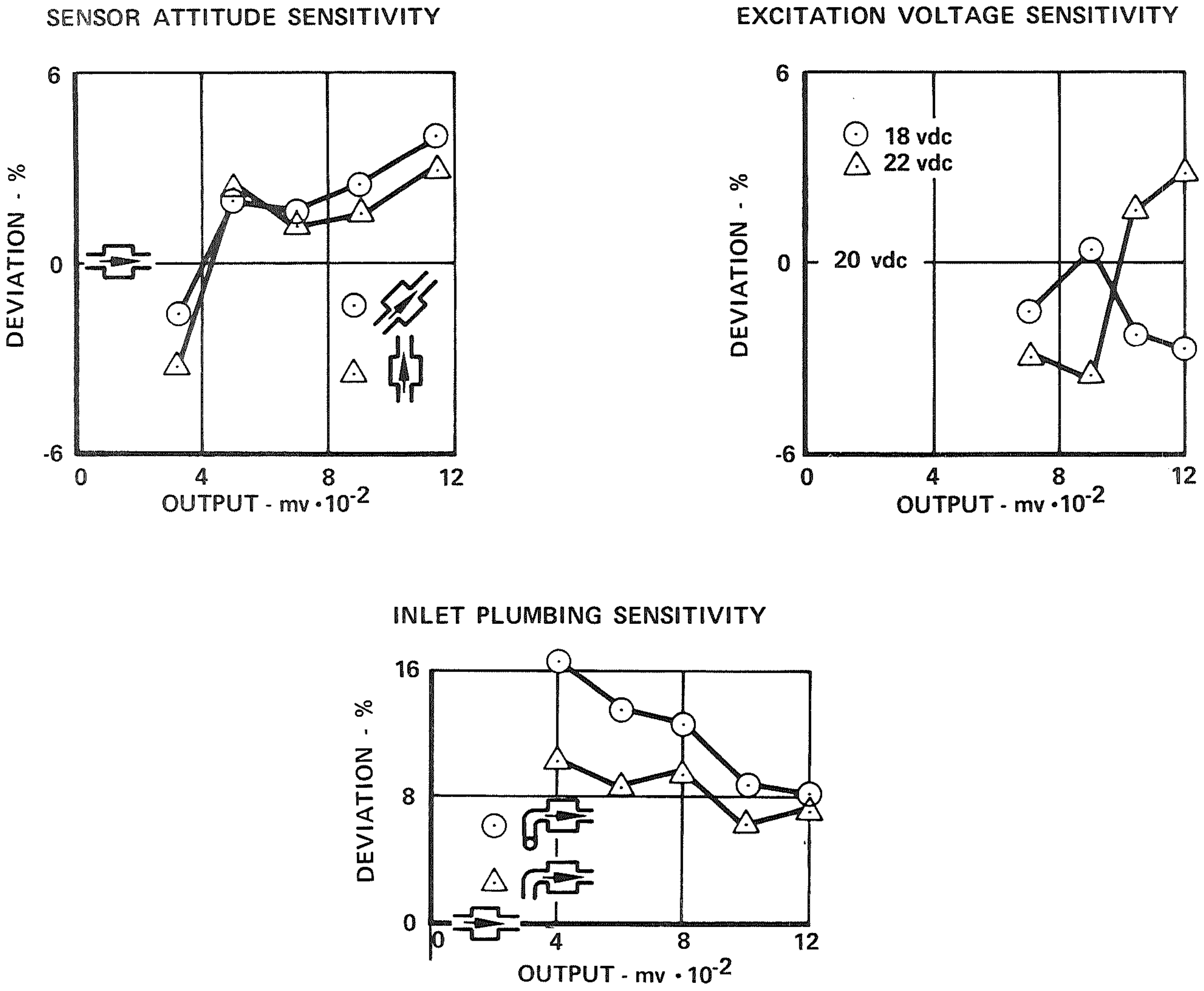
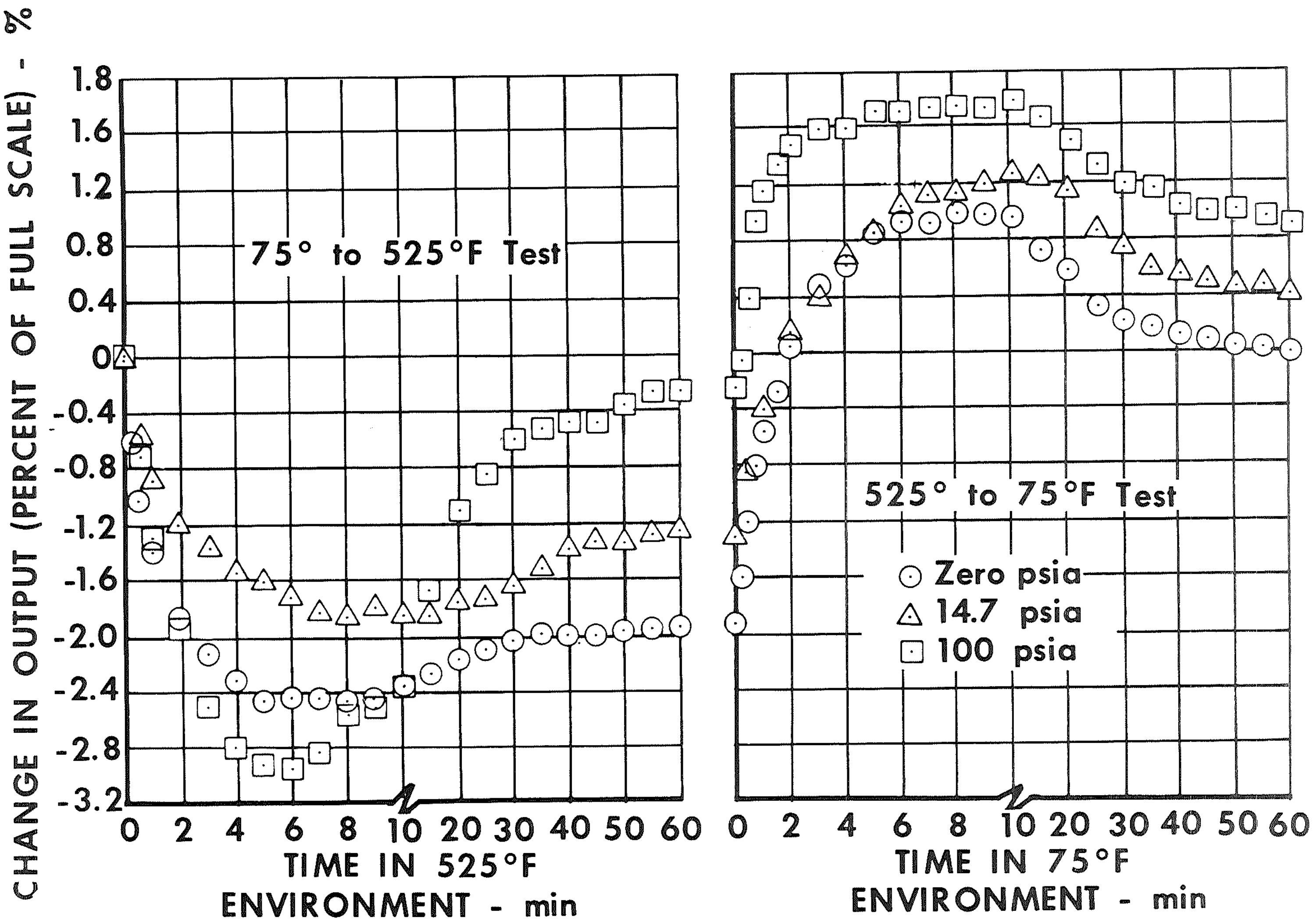


Figure 15. Flow Sensor Calibrations


CHANGE IN OUTPUT (PERCENT OF FULL SCALE) - %
1.8
1.6
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
-1.6
-2.0
-2.4
-2.8
-3.2
75° to 525°F Test
0 2 4 6 8 10 20 30 40 50 60
TIME IN 525°F ENVIRONMENT - min
525° to 75°F Test
Zero psia
14.7 psia
100 psia
0 2 4 6 8 10 20 30 40 50 60
TIME IN 75°F ENVIRONMENT - min

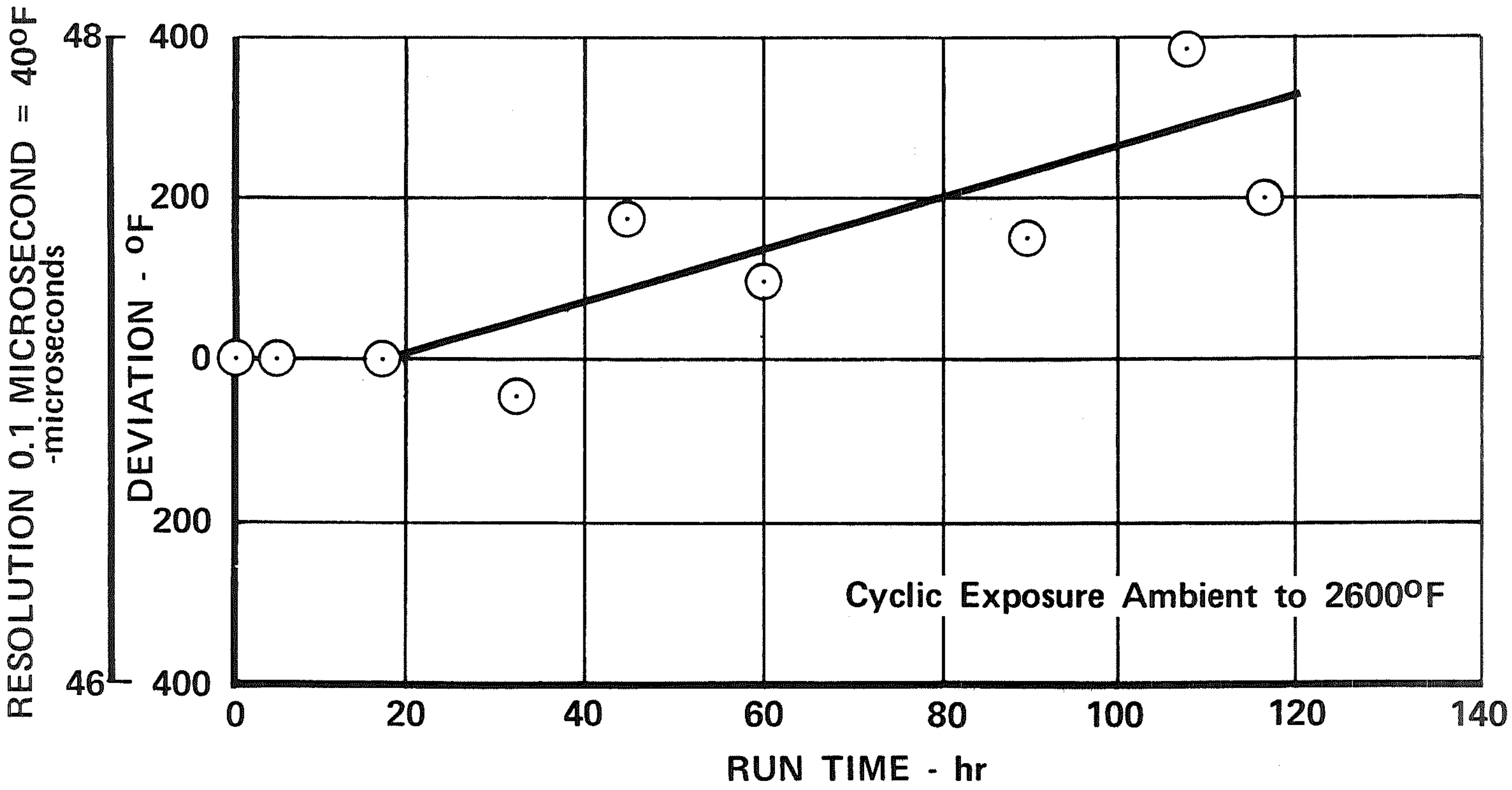


Figure 17. Signal Output Drift. Acoustic Thermometer; Iridium Wire Sensor.