The Design of a Digital Data Acquisition System for Jet Engine Testing

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THE DESIGN OF A DIGITAL DATA ACQUISITION SYSTEM

FOR

JET ENGINE TESTING

BY

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ABSTRACT

This research report documents the various types of Data Acquisition Systems in use for testing jet aircraft engines. The cost trade offs and design considerations are explored for systems which employ a digital computer as the prime recording/processing element.

The digital computer has revolutionized the data acquisition field, particularly in the testing of high performance jet engines. Test data can be acquired, processed, converted to engineering units, and output via high speed line printers and cathode ray tubes (CRT's). The data acquisition system operates on-line, and interleaves the random requests for data from multiple test cells by using a specially designed software system and the multi-processing capability of the high speed digital computer.

All test data must be traceable to The National Bureau of Standards, which requires that all calibration standards also be traceable. Primary and secondary calibration methods are discussed and examples of the mathematical processes for conversion of the raw data to meaningful results are presented.

Data Acquisition Systems for jet engine testing can be logically grouped into two main categories, with the determining factor being the type of test to be conducted. Production engine testing requires rapid setup, calibration, and fast data turn around, particularly for modern automated test facilities. Development engine testing requires a large number of
data channels, infrequent setup, and complete software for extensive engine performance calculations. Both types of Data Acquisition Systems have been designed and built by Pratt & Whitney Aircraft and are used as examples of the techniques described in this report.
# TABLE OF CONTENTS

## CHAPTER I

History of Data Acquisition for Jet Engine Testing .................................................. 1
- Console Instruments and Manual Data Recording .................................................. 1
- Data Logger Systems ............................................................................................. 2
- Magnetic Tape Systems ....................................................................................... 2
- Need for On-line Processing Systems .................................................................... 4

## CHAPTER II

Design Considerations ............................................................................................... 5
- Stand-Alone vs Centralized Systems ...................................................................... 5
- Digital Processors .................................................................................................. 7
- Signal Conditioning Techniques ............................................................................ 13
- Multiplexer Speeds and Location ......................................................................... 18
- Operator/Computer Interface ................................................................................ 20
- Analog/Digital Inputs ........................................................................................... 22
- Data Output and Display ...................................................................................... 23
- Data Acquisition and Test Cell/Engine Control ................................................... 25
- Software Systems .................................................................................................. 27

## CHAPTER III

Example of an Automated Digital Data Acquisition System for Eight Jet Engine Production Test Cells .......................................................... 37

## CHAPTER IV

Example of a Digital Data Acquisition System for Eleven Jet Engine Development Test Cells .......................................................... 51

## CHAPTER V

Summary, Conclusions and Recommendations .......................................................... 67

## LIST OF REFERENCES .............................................................................................. 69
<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High Level Signal Conditioning System</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>Low Level Signal Conditioning System</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>Transducer PSI/MV Relationship</td>
<td>31</td>
</tr>
<tr>
<td>4</td>
<td>Two Test Cells Under Construction at Middletown, Conn.</td>
<td>42</td>
</tr>
<tr>
<td>5</td>
<td>Digital Acquisition System for Production Engine Testing</td>
<td>43</td>
</tr>
<tr>
<td>6</td>
<td>Operator's Console at Middletown, Conn.</td>
<td>44</td>
</tr>
<tr>
<td>7a</td>
<td>CRT Data Display</td>
<td>45</td>
</tr>
<tr>
<td>7b</td>
<td>CRT Bargraph Display</td>
<td>46</td>
</tr>
<tr>
<td>8</td>
<td>Pressure Transducer Console and the In-Place Calibration Equipment at Middletown, Conn.</td>
<td>47</td>
</tr>
<tr>
<td>9</td>
<td>Assembly Floor at Middletown, Conn.</td>
<td>48</td>
</tr>
<tr>
<td>10</td>
<td>Engine Preparation Area at Middletown, Conn.</td>
<td>49</td>
</tr>
<tr>
<td>11</td>
<td>Engine in Test Cell at Middletown, Conn.</td>
<td>50</td>
</tr>
<tr>
<td>12</td>
<td>Digital Data Acquisition System for Development Engine Testing</td>
<td>58</td>
</tr>
<tr>
<td>13a</td>
<td>P401 Engine in A-9 Test Stand</td>
<td>59</td>
</tr>
<tr>
<td>13b</td>
<td>Remote Data Acquisition System</td>
<td>60</td>
</tr>
<tr>
<td>13c</td>
<td>Control Room and Operator's Console</td>
<td>61</td>
</tr>
<tr>
<td>13d</td>
<td>Central Computer Room</td>
<td>62</td>
</tr>
<tr>
<td>14</td>
<td>Preparation Line with Engines Being Instrumented</td>
<td>63</td>
</tr>
<tr>
<td>15</td>
<td>Strongback and Engine Being Transported to Test Cell</td>
<td>64</td>
</tr>
<tr>
<td>16</td>
<td>Engine Mounted in the Test Cell</td>
<td>65</td>
</tr>
<tr>
<td>17</td>
<td>A Portion of the Analog Recording Center at FRDC</td>
<td>66</td>
</tr>
</tbody>
</table>
Chapter I

History of Data Acquisition for Jet Engine Testing

Console Instruments and Manual Data Recording

Historically, jet engine test cells have been equipped with console readout instruments to display test data. In a typical test sequence, the operator would set the engine throttle to a predetermined power setting, and he and his assistants would read each parameter displayed on the console instruments and record the test data manually. Most instruments were of the multipoint variety with many measurements of a similar type, such as thermocouples, routed to selector switches and to one readout. This method of recording test data was very slow, the data was in raw form with a large time skew between measurements, excessive run time was generated on the test engine, and a large number of men were required to manually read and record the test data. Also, since jet engine test cells represent a large capital investment, the cost of the operation per test hour was high.

Jet engine performance is calculated by normalizing all test data to standard day conditions (59°F, 14.7 psia) and to the inlet conditions (temperature and pressure) existing at the time the data point is recorded. In a manual system, all performance calculations must be made by hand from the observed data. Special slide rules have been developed for this
purpose but the time required to determine if the engine is performing
to specifications is excessive, and averages between five and ten
minutes.

Data Logger Systems

In the mid 1950's, several jet test centers had installed data logging
systems. These systems were usually relay scanners to select the test
measurement, an integrating digital voltmeter to digitize and display
the analog voltage, and a punched paper tape system to record the raw
counts, in binary coded decimal (BCD), from the digital voltmeter. The
scanners contained relays or stepping switches. These devices, in
conjunction with the relatively slow paper tape punch, usually limited
the scan rate to 10 channels per second or slower. Also, a major dis-
advantage to this type of system was the fact that no data was output
in the test cell. The paper tape had to be removed after the jet engine
test and carried to a digital computer for reduction to engineering units
and for printout. The data turnaround was usually eight to sixteen hours.
Frequently, the data or the test engine was faulty, in which case the
test would be rerun to meet customer or acceptance test criteria.

Magnetic Tape Systems

Stand-alone magnetic tape systems were introduced in the early 1960's
and were a major advance in data recording systems for jet engine
testing. These systems employed a high speed commutator to scan the
data channels, an electronic digitizer, and a magnetic tape system for
recording test data. Scanning speeds in excess of 5000 scans per second
were available and the data could be packed at 600/1200 bits per inch
(BPI) on the magnetic tape. For the first time, data skew could be held to reasonable limits. The elapsed time between scans of the same data channel was found by knowing the number of channels to be recorded and the commutator scan rate:

$$\text{Skew} = \frac{\text{scan rate (channels/second)}}{\text{No. of channels recorded}}$$

for a 100 channel system with a scan rate of 5000 channels/second:

$$\text{Skew} = \frac{5000 \text{ channels/second}}{100 \text{ channels}} = .020 \text{ seconds or}$$

20 milliseconds between samples of the same data channel.

Although the magnetic tape system represented a major advance in the state-of-the-art in jet engine data recording systems, several disadvantages were apparent:

. The equipment was predominantly vacuum tube type which required frequent maintenance and was unreliable for long duration tests.

. A separate signal conditioning amplifier was required for each data channel. Setup and calibration for each data channel was performed by adjusting zero and gain for each individual amplifier and was very time consuming. No provisions were available for compensating for signal conditioner or digitizer inaccuracies such as long term drift.

. The magnetic tape must be removed and processed on a remote digital computer to yield meaningful results. No engineering units data were available in the test cell until several hours after the engine test. This created expensive test delays and limited the output (engines per test cell) to a low number.
Need for On-Line Processing Systems

The systems described above all have one basic limitation. No engineering units data were immediately available in the test cell. The test operator had to base his decisions on whether an engine was acceptable or should be rejected on observed data from console instrumentation. All performance calculations were performed manually, which were subject to human error and individual interpretation of the data or the results. A basic need existed for a data acquisition which would perform, as a minimum, the following functions:

1. Acquire test data on demand and process it on-line.
2. Convert raw data to engineering units immediately, such that the test operator has quick access to test results.
3. Perform performance calculations immediately after the data point is recorded to support decisions that must be made on the test engine.
4. Output test data in engineering units to the test operator.
5. Record all test data on magnetic tape for historical record and for further processing.
6. Automatically perform all calibrations, reference checking, and prerun setup to shorten engine prerun and mount time.
7. Be self-compensating to maintain system accuracy over long time intervals.

The high speed digital computer, combined with modern, solid-state signal conditioning equipment, provides a system to fulfill the above criteria. The following chapters describe the equipment comprising a modern digital data acquisition system and give two examples of systems that have been built and installed.
CHAPTER II

DESIGN CONSIDERATIONS

This chapter describes the various design considerations that confront the system designer who is configuring a digital data acquisition system for jet engine testing. The designer must consider trade-offs in cost, complexity, down time, utilization, and many other factors to arrive at an optimized, cost effective system configuration. Digital computers and related equipment are produced by hundreds of manufacturers, and a myriad of system configurations are possible. The following sections discuss the most important aspects of system design and provide a rationale for equipment selection to meet the testing application.

Stand-Alone vs Centralized Systems

"Stand-alone" systems are used to provide data recording service to one or more jet engine test cells located in the immediate vicinity of the data recording equipment. A typical system will consist of a mini-computer, a teletype, a magnetic tape, an analog-to-digital converter (ADC), and a multiplexer to access the test data. This type of small system would typically service one test cell and would be dedicated to the engine under test. Limited background work may be performed, depending upon the computing power available and the test cell utilization.

"Centralized" systems are characterized by the fact that a large amount of digital equipment is usually located in a central area and that service is provided by this equipment to several remote test cells.
A typical system would consist of one or more medium-to-large size digital computers, an array of disk/drum storage devices, magnetic tape units, line printers, and other associated peripheral devices. Usually, it is more cost effective to locate the multiplexer and ADC in the remote test cells and transmit the data serially over coaxial cables to the central computing facility. Of course, analog transmission lines can be routed from each test cell to a central multiplexer, but most transducer outputs are low level (millivolt) signals and transmission problems or signal attenuation may be encountered if the distance from the test cell to the central computing equipment is excessive. Some transducer outputs, such as piezoelectric pressure or vibration transducers, require special conditioning techniques and high frequency transmission lines if the distance exceeds 200 feet.

The Remote Data Acquisition Subsystem (RDAS), or the equipment located in the remote test cell, usually contains a random access multiplexer, a programmable gain amplifier, an analog-to-digital converter, and a receiver-transmitter for interfacing the remote equipment to the central computers via the coaxial transmission lines. Data transmission rates exceeding 2 million bits per second are common.

The choice between several stand-alone systems and a one large centralized system will depend primarily on the testing philosophy in use at the jet testing facility. Table 1 below is a listing of common design constraints and the type of system which will be the most cost effective to satisfy the constraint.
<table>
<thead>
<tr>
<th>Design Constraint</th>
<th>Stand-Alone System</th>
<th>Centralized System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of test cells</td>
<td>small</td>
<td>large</td>
</tr>
<tr>
<td>Future expansion</td>
<td>limited</td>
<td>easily expandable</td>
</tr>
<tr>
<td>Test plans</td>
<td>relatively fixed</td>
<td>varying</td>
</tr>
<tr>
<td>Data feedback</td>
<td>immediate</td>
<td>1-5 minutes</td>
</tr>
<tr>
<td>Test cell locations</td>
<td>scattered</td>
<td>nearby</td>
</tr>
</tbody>
</table>

Table 1. - Comparison of Stand-Alone and Centralized Systems to Satisfy Various Design Constraints.

**Digital Processors**

The selection of the central processing unit (CPU) for the data acquisition system is the most important decision the designer must make and is usually the most difficult. The system designer is often harassed by computer vendors, each claiming his line of hardware offers significant advantages over the competition and leaving behind volumes of technical literature on each device. The designer is soon inundated with reference material which may be helpful after a manufacturer is selected but seldom gets read before the selection is made.

As previously stated, over a hundred computer companies are in existence. The most reasonable approach to selecting a CPU is to narrow the field down to a few candidates which can be investigated in detail. The following factors must be considered for any system and will eliminate many hardware vendors from the competition:
. **Maintenance.** - The vendor must offer a complete maintenance service. Most jet engine testing operations are worked on a 5-day, two or three shift basis. Expensive test cells and the operating manpower may be idled if the computer system is down. The computer vendor should offer an on-site maintenance service, provide sufficient spare parts on site (5-10% of system cost), be willing to negotiate maintenance coverage for other than prime shifts, and have a nationwide support organization at a higher level.

. **Expandability.** - The system must be readily expanded. Most systems tend to grow from the day they are installed. The efficiency of the test operation is usually greatly improved, and realizing this, the operations personnel turn over more and more of the manual work to the computer. Also, additional test cells may be required at a future date and should be easily added to the computer system. Another factor to consider, especially for leased systems, is the fact that jet engine test operations are cyclic, and periods may occur where the number of engines to be tested is low. In this case, excess peripheral equipment or front end modules may be returned to the vendor, thereby lowering the monthly lease costs.

. **Peripheral Equipment.** - The vendor should offer a complete line of peripherals and be willing to take systems responsibility. Unless a strong electronic engineering capability is existing within the jet engine testing organization, it is risky to
purchase a CPU from one vendor and peripherals from another source. Systems responsibility should be given to one vendor only. The vendor should also be willing to provide special engineering and modules to accommodate any unusual circumstance that may be encountered in the test operation. These "specials" may include:

1. Cell select modules for switching analog inputs from two or more sources to a common multiplexer.
2. Special control panels for operator-to-computer communications.
3. Receiver/transmitters for driving peripheral equipment at remote locations.
4. Special data displays such as digital panel meters for the test cell operator.

Interrupt Structure. - The testing of modern jet engines require a computer system to operate at near real time and respond to priority interrupts from several sources. The interrupt structure of the CPU must be designed for handling these remote interrupts and for queuing the random requests based on priority level.

For example, an engine experiencing a serious problem may generate a priority interrupt to acquire data at the highest possible rate which will override all previous requests for data from other cells, and terminate all other activity which may be in process within the CPU.

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Lease vs Buy. - Lease vs buy decisions are usually made by management upon the recommendations of the systems designer and of the legal department of the jet engine testing organization. Most companies prefer to lease if:

1. A short term program will utilize the equipment, particularly for Government contracts.
2. The tax benefits incurred by charging off the equipment rental each year will offset the higher cost (typically a 3 year payoff).
3. Maintenance is to be performed by the vendor. Lease payments stop when the system is down providing an incentive for the maintenance organization to quickly repair the equipment.
4. The initial capital outlay is prohibitive.

Purchase of the computer equipment represents a large capital outlay and means that the equipment will be used for many years. (Usually 10 years is considered the useful life). It is very important that purchased equipment be obtained from a large computer vendor who can support the system over its useful life.

System Software. - Most programmers and analysts prefer to write the operating software in Fortran. The vendor should, of course, offer an effective Fortran compiler and be willing to provide a bench mark test to determine its efficiency. In addition, the vendor, as a minimum, should provide the following software:

1. Comprehensive MACRO assembler.
2. Library of standard mathematic routines.
3. Utility data transfer routines for use in troubleshooting and systems maintenance functions.
4. Debugging aids - trace and core dumps.
5. I/O handlers for all devices.
6. On-line maintenance software to allow hardware problem troubleshooting on-line.

The above considerations will narrow the potential vendors down to a few large manufacturers. Small, independent computer manufacturers cannot meet the above criteria and should not appear on the bid list.

The next logical step in choosing the CPU is to write a system specification and issue it to the remaining vendors. The specification may be general in nature but should describe the tasks to be performed by the computer in detail. Information that must appear in the specification will include:

- A detailed block diagram of the proposed data acquisition system.
- The number of data channels to be acquired and processed within a specified time interval.
- End-to-end accuracy, not including the transducer.
- Data output required: CRT, magnetic tape, teletype, line printers, etc.
- Percentage of the CPU time to be utilized for background work.
- Test operator/computer control panel description.
- Sample calculations to be performed on the test data.
- Program size, which establishes the memory or disk storage capacity required.
Description of the test philosophy, including data points per hour, number of scans to be averaged, etc.

Expansion capability.

Site restrictions, such as noise, vibration, air conditioning capacity, power limitations, etc.

Maintenance considerations.

The specifications should not be restrictive and the vendors should be urged to submit their system configurations to perform the data acquisition functions. This will allow the system designer to benefit from the engineering experience available at the various vendors and allow the vendors to quote more than one system configuration. For example, a vendor may quote two small CPU's in one configuration and a large CPU in another, giving the advantages and disadvantages of each.

To evaluate the responses received from the vendors, it is advisable to form a team from the various engineering disciplines and the user groups. Knowledgeable engineers from the test operation, the analysts or programmers, the electronics groups, if available, and the systems designer should evaluate each proposal strictly on its technical merit without reference to the quoted price. A rating sheet is helpful and can be prepared by listing all the known features that the system must have and rating the vendor response from 1 to 4. A 4 would mean that the vendor was completely qualified to fulfill that particular requirement.
The proposals should be rated 1 through X depending upon the number of vendors who quoted. The top three or four candidates should be invited to present their offering and answer specific questions that may have arisen during the evaluation of the written proposal. After all verbal presentations have been heard, the vendors should again be rated 1 through X. The price for each system should then be made known to the evaluation group and a price vs performance tradeoff study be made. Usually, it is decided to eliminate some expensive features from the number one technical proposal and give the job to him. If funds are limited, the most system per dollar will govern the selection.

The last important aspect of selecting the CPU is to rewrite the specification in detail, to correspond to the proposal and the negotiated changes to provide a firm technical basis for determining vendor performance. This specification should list all acceptance tests to be performed, the responsibility for these tests, ancillary items such as mating connectors for the analog input cables, drawings, manuals, etc., and any other information that will become a contract between the procuring company and the computer vendor.

**Signal Conditioning Techniques**

This research report is primarily concerned with the digital aspects of system design for jet engine data acquisition systems, but the techniques used to condition the analog signals is of equal importance and will be briefly described.
Signal conditioners can be divided into two general classifications: high level and low level. High level systems have an amplifier per data channel to convert the low level analog signals from the transducers to a proportional high level analog voltage, usually 1-5 volts DC. The higher DC voltage allows the multiplexer scan rate to be increased. Scan rates of 20-100 KC are obtainable. Low level signal conditioners contain provisions for zeroing, or for referencing signals such as millivolt outputs from thermocouple materials to the copper transmission lines. A programmable gain amplifier with several gain ranges provides the amplification for all analog data channels. Additional features that can be incorporated into the signal conditioning circuitry include:

- **Reference Checking.** - This circuitry allows a precision, known signal to be injected into each individual analog data channel, under computer control, to determine the millivolt/count relationship. This technique is used primarily for high level, amplifier per channel systems, to avoid the manual operation of adjusting each amplifier gain. The millivolt/count relationship is described in detail in the data reduction section.

- **Zeroing.** - For most modern data systems, it is advisable to zero each channel prior to acquiring test data. This compensates for long term drift and provides the zero count level to correct all data scans.
Frequency Converters. - Test measurements such as the output from magnetic speed pickup transducers and fluid flow meters, provide a pulse train output which must be converted to a proportional DC voltage prior to being scanned by the multiplexer. Conversion accuracies of ± 0.1 percent, including linearity, are easily obtainable.

Charge Amplifiers. - Piezoelectric vibration transducers and high frequency pressure transducers require a charge amplifier to convert the output from the quartz crystal to a proportional analog voltage.

Reference Junctions. - Reference junctions are used to connect the millivolt output from thermocouple materials to the copper transmission lines. This junction can be made in two ways:

1. The junction can be maintained at a consistent temperature, usually 150 or 32 degrees Fahrenheit. The junction also contributes a known EMF which must be algebraically added to the thermocouple output by the computer.

2. The junction can be allowed to change with ambient temperature. The temperature at the junction is measured and used to correct the thermocouple output. This relationship of EMF's is discussed further in the data reduction section.

Figure 1 is a block diagram of a typical high level signal conditioning system and Figure 2 is a typical low level system.
FIGURE 1

HIGH LEVEL SIGNAL CONDITIONING SYSTEM
LOW LEVEL SIGNAL CONDITIONING SYSTEM

FIGURE 2
For stand-alone systems, the multiplexer is usually mounted in one of the computer system cabinets. For centralized systems, the multiplexer can be located near the computer and connected via analog transmission lines to the transducers, or the multiplexer can be remotely located in the test cells. The cost trade-off to consider is the cost of the analog transmission lines from each test cell to the multiplexer vs the increased equipment cost for receiver-transmitter modules to interface the remotely located multiplexer to the coaxial transmission lines. Since costs for procuring and installing cabling is very high, it is usually advantageous and more cost effective to drive the remote multiplexers via a pair of coaxial lines and have a separate multiplexer for each test cell or pair of test cells. This approach is particularly effective when the number of data channels is high. For example, development engine programs may require 750 to 2500 data channels per test cell.

Multiplexer speeds range from 30 to 200 channels per second for relay multiplexers to 100,000 channels per second for solid-state-multiplexers. Relay multiplexers are limited in scan rate but are economical, reliable, differential input devices, and are more accurate for low level signals than the present state-of-the-art solid-state devices. The lower scan rate is usually acceptable for production engine testing due to the small number of channels to be scanned. For example, if 100 channels of data are to be scanned four times and averaged, the time required for one data scan is:

\[ \text{Time} = \frac{100 \times 4}{200} = 2 \text{ seconds} \]
Since the computer is time shared, the actual time the CPU is occupied is very low. Each data scan requires five milliseconds for the relays to select and the input analog voltage to stabilize within the input filtering. The actual CPU time is only the few machine cycles required to transmit the channel address and to store the output from the analog-to-digital converter. The excess CPU time can be used to convert the previous data channel to engineering units, operate other peripheral devices, or perform background processing work.

High speed multiplexers are available which will operate at speeds in excess of 100,000 channels per second. These solid-state devices are usually high level, with input analog signals of 1-5 volts DC. The multiplexers are random access, and allow many scans of the same data channel to be acquired in a very short time interval. The high speed multiplexers are less accurate and more expensive than the relay models but provide transient capability for the data acquisition system. Vibration surveys, transient control problems, engine accelerations, and other transient engine test programs can be investigated by using a high speed multiplexer to rapidly acquire test data.

A cost effective data acquisition system for jet engine testing can be designed by using a low speed multiplexer for normal data gathering and a small (10-20 channel) high speed multiplexer for transient behavior investigations. The low speed data is processed on-line, between the five millisecond data scans, and the high speed data is recorded in raw form on magnetic tape for off-line processing and analysis. Specialized
software is available for performing transient analysis, Fourier analysis, etc. on the transient test data.

**Operator/Computer Interface**

A major item that determines the success or failure of the computerized data acquisition system is the operator console in the test cell and the methods used to enable the test operator to communicate with the computer. The test operator is, essentially, a mechanic with little or no electronic background and no experience with computers or peripherals. His major effort is installing the engine and performing the test in accordance with an established test plan. If the engine performs satisfactorily, the test will be completed under his direction; if not, the engineers or supervisors will determine the corrective action to be taken on the faulty engine. It is very important that the operator/computer interface be kept as simple and straightforward as possible. The test cell operators usually have spent many years recording test data manually, and are apprehensive that a new computerized system will detract from their responsibility, eliminate jobs, etc. Their support must be obtained if the system is to be successful, which can be accomplished through training programs and seminars before the system is installed. The data acquisition system must be presented as a tool for his use, just like any other tool he may have.

The operator/computer interface will depend primarily on the test philosophy in use at the test facility. Two methods of operation are in general use:
The operator's console can contain sufficient console instrumentation to set the engine operating point and to monitor engine health and performance. The data acquisition system would record data on demand only, after the engine operating point had been established via the console instrumentation. The operator/computer interface would be a small input switch panel to generate an interrupt to the computer and to identify the data point type, the recording mode, etc. The data output devices should operate by computer control, and should not require intervention by the operator.

A real time system can be designed to constantly acquire the test data at short intervals, convert the data to engineering units, and output the data on a CRT for the test operator. The operator would set the engine operating point and perform all functions of the test by monitoring the CRT. The amount of data that can be displayed on the CRT at any one time limits this type of system to approximately 100 channels, which makes this system more adaptable to production engine testing.

The absence of console instrumentation makes the complete test operation dependent upon the computer and data system. When the system is down, all testing must terminate. Frequent updating of the CRT requires more CPU time than the data-on-demand system which limits the number of cells that can be connected to one data acquisition system. System cost per test cell to be serviced is high.
The operator/computer interface for this type system is more interactive. The operator must select the type of CRT display and the update interval, monitor critical parameters (limit checking by the computer and flagging the output data is often used), set the engine operating point via the CRT display, and determine engine performance from the test data being displayed. The operator/computer interface panel will contain all switches, indicators, and controls to generate priority interrupts to the computer and to provide digital input/output capability.

The two types of operator consoles are shown in Figures 6 and 13c in the examples of test cells that have been built by the Florida Research and Development Center.

**Analog-Digital Inputs or Outputs**

The inputs and outputs for the computerized data acquisition system can be either analog or digital in nature. Analog inputs comprise the majority of the test measurements and are generated by the test cell transducers in response to the physical stimuli. These measurement signals are scanned by the multiplexer, and converted to digital form under computer control. Analog outputs are generated by inputting a digital count value into a digital-to-analog (DAC) converter, which converts the count value to a proportional DC voltage. The DAC unit will hold the DC level constant without further commands from the CPU. The analog outputs are used as throttle setpoint commands, zero offset feedback, inputs to analog devices such as analog recorders, etc.
Digital inputs are generated by readout devices on the operator's console (usually BCD), by the switches on the operator/computer interface panel, and by test cell relay networks. When a data point is requested by generating an interrupt to the computer, the first part of the data scan is to "read" the digital inputs to determine which cell is requesting data, what is the data point type, and other pertinent information. The digital input data can also be stored and converted from BCD to engineering units, if required.

Digital outputs are used to control event sequencing or to drive digital displays on the test cell and are either logic levels or relay contact closures. The logic levels are used to drive digital display devices, such as digital panel meters, on the operator's console. The relay contact closures are used to turn on indicator lights, control test cell circuits, or for termination systems if the computer is used to limit check critical parameters.

Data Output and Display

Test data that has been acquired and processed by the computer must be output and displayed in an effective manner for the test operator and for the engine test engineers. The data output devices can range from a simple teletypewriter to a complex graphics system with a light pen and display scope. A discussion of the various peripheral devices used for data output and display is given below.
Teletypewriters. - Teletypewriters are the most common output device due to the low cost. The teletype is very reliable, provides two-way communication with the computer, and is sufficient for small test cells with a limited amount of data. The major disadvantage is speed, approximately ten characters per second, which limits the data turnaround time to several minutes for a 100 channel data system.

Line Printers. - Line printers provide high speed output printing and are normally used to provide all hard copy data for the large test operation. Modern line printers of the impact type can operate at speeds of 1200 lines per minute with each line having a maximum of 132 characters. Newer, electrostatic printers can operate much faster, up to 5000 lines per minute. Impact printers are in general use due to the requirement to produce multiple copies of the test data.

Cathode Ray Tube (CRT). - CRT's are in general use as operator output devices. A typical alphanumeric CRT can display 20 lines of data with each line having a maximum of 80 characters. The CRT's can be updated at frequent intervals, and require little CPU time. The CRT controller provides a storage buffer for the output data and only a few machine cycles are required to move the data from memory into the controller. The computer software can be written to generate any number of CRT displays, including tables, curves, bar graphs, etc. The major disadvantage of the CRT is that no hard copy is generated. Test data cannot be
compared with previous points and/or measurement trends defined.

- **Graphics Terminals.** - Graphics terminals are used for test data that can best be displayed as curves or plots. This type of test data is usually generated by engine development programs and includes engine compressor maps, parameter profiles, etc. Graphics terminals are usually associated with large scale computing facilities and require a large amount of core storage and CPU time.

Other data output and display devices are used to a limited extent in jet engine testing. This includes digital panel meters, strip chart recorders, X-Y plotters, etc.

**Combined Data Acquisition and Test Cell/Engine Control**

The digital computer can replace the test cell operator for performing certain types of jet engine tests. Using the digital computer for closing the loop on throttle control has been successfully performed at three major test facilities in this country. This field has shown considerable promise but many problem areas limit the application of computers as the prime control element.

- The tests must be of an established, repetitive nature. A large programming staff and excessive setup time will result if the automatic control programs are frequently changed.
Since the jet engine under test represents a million dollar investment, all software generated for control purposes must be thoroughly checked out and reliable to prevent damage to the test engine.

Manpower savings usually do not justify the additional hardware and software costs. The test cell operators are still required to mount the test engine, connect and checkout the instrumentation, and to monitor the test.

An elaborate software system must be designed for each type of engine to be tested. The software must acquire test data at frequent intervals, perform limit checking on critical parameters, take corrective action if required, automatically adjust the throttle setting in accordance with a preplanned test schedule, and many other functions of a minor nature.

Test plans are constantly changing and the automatic control programs must be rapidly updated or revised. This may require a separate digital computer and an engine simulator to debug the software if the on-line machine is in use.

All decisions concerning the progress of the test must be made by the computer. Many test engines are marginal, and a judgment factor must be applied to determine if the test is acceptable. Frequently a minor adjustment to the engine control will improve its performance which must be performed by human intervention.
In summary, automatic control of the engine test has been demonstrated to be technically feasible for repetitive type testing such a production facility. Further development work, particularly in the area of software, is required before this type of testing will be in general use.

**Software Systems**

As discussed in the section on computer selection, most programmers and analysts prefer to write all programs in Fortran, knowing full well that CPU capacity and execute times will be somewhat greater than other assembly or machine languages. Fortran programs are easily understood, can be modified by inexperienced programmers after they are written, and can be used on any CPU with sufficient core capacity to contain the program segments. For early data acquisition systems, all software was written by the purchaser of the digital equipment. Modern computers are designed to operate with a vendor supplied supervisory program called an "operating system". The operating system coordinates and executes all input and output instructions, handles exceptional conditions, and supervises the scheduling and execution of a variable number of programs simultaneously.

The operating system is supplied by the computer vendor who also provides classroom training on its usage. All special software is developed by the programmers who must be familiar with the test philosophy. The following sequence is normally used to generate the required computer programs:
Flow charts for all major software programs are generated by the system designer. These flow charts depict the logic to be programmed to perform a specific task, such as operating the multiplexer to acquire test data. These flow charts are routed to the test cell operating engineers for concurrence and to the programmers to be implemented.

The programs are subdivided into "modules", depending upon the core storage available in the CPU. If a small amount of core is available, these modules may be a maximum of 2000 to 4000 words in size to prevent core fragmentation from slowing down the CPU operation.

Each module is written and debugged separately. Several programmers can be employed at the same time with one analyst acting as a coordinator for work assignments and to monitor progress.

All program modules are "linked" or integrated into the vendor supplied operating system and the resulting software package run and debugged.

Simulated test data and digital inputs are provided to verify systems operation. Control processes are simulated or tested.

A known, good test engine is used to check out the entire facility. The test data that is acquired from this engine is carefully reviewed and compared to the results obtained in other test cells.
Improvements can then be incorporated into the software system to reduce CPU execute time, reduce the size of program modules, etc., which will improve system performance.

Data Reduction Techniques

Test data are acquired through the use of various transducers (pressure, temperature, position, speed, etc.) which sense the physical stimuli and generate proportional analog output voltages. The analog signals are conditioned, scanned, converted to digital form, and transmitted to the central processor for conversion to engineering units. The mathematical processes required for conversion of transducer outputs to engineering units are described below for typical measurements associated with jet engine testing.

Pressure Measurements

All test data must be traceable to the National Bureau of Standards which requires that all calibration standards also be traceable. Primary and secondary calibration methods provide the reference data for the mathematical equations which the computer can use to convert the raw test data to meaningful results. For example, a primary calibration is made for all pressure measurements by applying precise.

known pressure levels to the pressure transducers, and reading the transducer electrical output on the computer. Upon completion of the pressure calibration, the computer will employ either a least-squares solution to fit the best-straight-line or a polynomial curve fit through the calibration data points.

\[
A = \frac{\sum_{i=1}^{N} P_i C_i - \sum_{i=1}^{N} P_i \sum_{i=1}^{N} C_i}{\sum_{i=1}^{N} C_i^2 - \sum_{i=1}^{N} C_i^2}
\]

\[
B = \frac{\sum_{i=1}^{N} P_i C_i^2 - \sum_{i=1}^{N} P_i \sum_{i=1}^{N} C_i}{\sum_{i=1}^{N} C_i^2 - \sum_{i=1}^{N} C_i^2}
\]

Where:

\( A \) = transducer and DAS sensitivity in psi/ct at time of the primary calibration.\(^3\).

\( B \) = transducer and DAS intercept in psi at primary calibration

\( N \) = number of calibration points.

\(^3\)J. E. Mills, CAPJET Program Criteria (West Palm Beach, Florida: Florida Research and Development Center, 1973), p. 36.
\[ P_i = \text{applied pressure} \]

\[ C_i = \text{DAS count corresponding } P_i \]

When a more accurate conversion than the straight-line fit is required, a polynomial curve fit is employed. The order and number of sections and the degree of the polynomial is determined by the computer and depends upon the nonlinearity of the calibration data points.

The pressure transducer calibration data is stored in the computer as a linear relationship if the least-squares curve fit is used, or:

\[ P_r = A^1 (M\bar{V}) + B^1 \]

Where:

- \( P_r \) = pressure applied
- \( A^1 \) = transducer calibration curve slope in pressure/millivolt
- \( B^1 \) = transducer calibration curve intercepts in pressure at zero millivolts
- \( M\bar{V} \) = average millivolts for pressure applied

Figure 3 represents the relationship which is stored in the computer for each data channel.

**Figure 3 - Transducer PSI/MV Relationship**
Prior to acquiring test data, it is necessary to establish the millivolt-to-digital count relationship for the analog-to-digital converter. This is provided by connecting multiplexer channels to scan known, precise, reference voltages which are permanently assigned to these multiplexer channels. A precise reference voltage is required for each gain range of the programmable gain amplifier and a zero millivolt or short circuit is also read. These values are stored in the computer in the same manner as calibration data and the computer calculates a slope/intercept (m & d) relationship which is used to reduce all incoming test data.

The pressure transducer, the programmable gain amplifier, and the data acquisition system can now be represented by the following linear relationship:

\[ a = mA^1 \]
\[ b = dA^1 + B^1 \]
\[ Pr = aCr + b \]

Where:

- \( a \) = composite slope psi/count
- \( b \) = composite intercept in engineering units (psia, psid, or psig)
- \( Cr \) = raw counts at \( Pr \) pressure
- \( Pr \) = pressure in engineering units

Experience has shown that zero shift is a common error source associated with strain gage transducers. A significant improvement in pressure measurement accuracy can be realized by the inclusion of a zero shift correction as part of the data system pre-test calibration procedure.
Mathematically, this correction manifests itself as a change to the transducer intercept.

Just before a test, an ambient or reference pressure point will be recorded and the ambient or reference pressure indicated by each transducer computed. The magnitude of the shift can be determined as follows:

\[ P_{\text{dev}} = P_A - (a_A^C + b) \]

Where:
- \( P_A \) = true pressure, zero or reference
- \( P_{\text{dev}} \) = transducer deviation or shift

The formula for corrected pressure data channels is:

\[ P_R = a_R^C + b + P_{\text{dev}} \]

Combining the ambient or reference correction and the original composite intercept gives the final intercept \((b_C)\) and the final corrected pressure data reduction formula:

\[ P_R = a_R^C + b_C \]

Intercept correction is made on all pressure measurements where air or gas is the measured medium.
Temperature Measurements

Temperature is normally measured from jet engines with thermocouple (T/C) type probes located inside the test engine or on the test facility. Chromel-alumel, iron-constantan, copper-constantan, etc. are in common usage with each thermocouple channel referenced to either a constant temperature junction or a Uniform Temperature Reference (UTR) which is allowed to change with ambient temperature. (Reference signal conditioning section) UTR's are becoming more popular and will be used in the example given below:

The relationship between temperature and thermocouple millivolt output is established in tables published by the National Bureau of Standards. The data reduction program will treat all thermocouple data as millivolts.

\[ \overline{MV} = m\overline{CR} + d \]

Where:

- \( \overline{CR} \) = average raw counts
- \( m \) = channel slope for appropriate range card
- \( d \) = channel intercept for appropriate range card

For each type of thermocouple used, a measured UTR reference temperature is required. For each UTR block, the millivolt output of multiple reference thermocouples for a given type measurement thermocouple, is averaged and stored for subsequent data reduction.

The reference \( T/C \) millivolt output corresponds to the temperatures of the UTR block.

\[ MV_{ref} = mC_{ref} + d \]
The measurement channel slope \( m \) and intercept \( d \) are determined by the following:

**Slope \((MV/CT)\)**

\[
m = \frac{MV_{fs}}{C_{fs} - C_0}
\]

**Intercept \((MV)\)**

\[
d = -mC_0
\]

The measurement channel millivolts are computed using:

\[
MV_X = m(C_R) + d
\]

Where:

\[
C_R = \text{raw counts (T/C measurement channel)}
\]

\[
MV_X = \text{millivolts at } C_R
\]

Millivolts corrected for the UTR reference are determined as follows:

\[
MV_Y = MV_X - MV_{ref}
\]

Where:

\[
MV_Y = T/C \text{ measurement channel corrected for UTR reference}
\]

Polynomial curve fits of the \( 32^\circ F \) NBS temperature tables, for the thermocouple type, are used in the data reduction program to convert millivolt readings into engineering units. To retain significant figures during a polynomial expansion, the millivolts \( (MV_Y) \) are normalized.

\[
Y = MV_Y \ (\text{Alpha}) + \text{Beta}
\]

\[
T = A_1 + A_2Y + A_3Y^2 + \ldots + A_nY^{n-1}
\]
Where:

\[ \text{Alpha} = \text{normalizing coefficient} \]
\[ \text{Beta} = \text{normalizing coefficient} \]
\[ A_n = \text{polynomial coefficients} \]
\[ T = \text{temperature } ^\circ\text{F} \]

**Other Test Data Measurements**

The examples given about are representative of how all test data is reduced to engineering units prior to being printed or displayed for the test operator.
CHAPTER III

EXAMPLE OF AN AUTOMATED DIGITAL DATA ACQUISITION SYSTEM FOR EIGHT JET ENGINE PRODUCTION TEST CELLS

Pratt & Whitney Aircraft, Florida Research and Development Center, has designed and built a digital data acquisition and control system for testing production jet engines. This facility is located in Middletown, Connecticut and is the most advanced testing facility of its kind in the United States. The facility was built to test the large diameter, high thrust JT9D jet engine which is used for the Boeing 747 aircraft and the McDonnell-Douglas DC 10-20 aircraft.

The facility consists of eight indoor test cells connected to a common engine preparation area. The inlet and exhaust stacks are acoustically treated to reduce noise emission and the entire facility and the operating philosophy is geared to rapid turnaround times for production engine mounting and testing. Figure 4 shows two test cells under construction.

Other unique features of the test cells are:

- A monorail system is used to transport test engines throughout the preparation area and test stand.
- All instrumentation is connected to the engine half of an Instrumentation Coupling Assembly (ICA) prior to moving the test engine into the cell. Upon arrival of the engine at the test cell, the test cell half of the ICA is motor driven to
engage the two halves and thereby connect all instrumentation in a single action. With this system an engine can be installed in a cell and ready to run in 15 minutes.

Large sound doors isolate the test cells from the adjoining engine preparation area. These doors are motor operated with inflatable seals to reduce noise transmission.

The data acquisition system consists of four, small, general purpose computers with each computer serving two test cells. Each computer is used to acquire and process test data from the two engines under test and to provide closed-loop control of the engine throttles. The complete engine acceptance test can be preprogrammed and executed under computer control. Figure 5 is a block diagram of a computer system and the significant features are:

- Console instrumentation is eliminated and no manual data is recorded. The operator uses the CRT for all data display. Figure 6 shows the test operator console and the operator/computer interface control panels.\(^4\).

- Several CRT formats are selectable by the operator. This includes listing of measurement types and values and bar graph displays. Figure 7 is an example of two types of CRT display formats.

All pressure measurements are routed to transducers located in a separate equipment room. The transducer cabinet contains measurement transducers, excitation power supplies, and an in-place calibration system. Transducers are calibrated in-place with pressure standards as shown in Figure 8. All calibrations are traceable to the National Bureau of Standards and are performed with the computer on-line to acquire and reduce calibration data.

During engine tests, the computer acquires and processes test data every 3 seconds to refresh the CRT display located on the operator's console. This data is not recorded.

Steady-state data points are recorded by depressing a switch on the operator/computer interface panel which interrupts the computer. All measurements are scanned 10 times and arithmetically averaged. The data is output on a line printer in each control room and is stored on magnetic tape for historical records and for further processing.

A second switch on the operator's panel will inform the computer to store the last data point recorded on the disk. During a typical test sequence, many data points are recorded but only the points "saved" on the disk are collected, collated and printed into an engine log to be delivered to the customer with the engine.
Transient test data is acquired with a high speed multiplexer, operating at 40,000 samples/second. The data from the high speed multiplexer is not processed on-line but is recorded on magnetic tape for later processing. Data usually consists of the output from accelerometers which is processed with a special software program in order to conduct a vibration survey during engine operation.

The engine preparation and testing are fully automated. The engines are assembled as shown in Figure 9 and are moved to the test building. The engines are suspended from a monorail and transported to an engine preparation station as shown in Figure 10. All transducers, probes, cables, etc. are installed on the engine and all test measurements are connected to the engine half of a quick disconnect, Instrumentation Coupling Assembly (ICA).

The mating half of the ICA is permanently connected to the test cell, the signal conditioning, and the computer. The dressed, or prepped engine travels down the monorail, through the sound doors, and into the thrust frame suspended from the ceiling, as shown in Figure 11. Pneumatic actuators couple the test cell half of the ICA to the engine half, making all pneumatic and electrical instrumentation connections. A typical engine mount time is 15 minutes.

The automated test sequencing, the computerized data acquisition system, and the modern automated engine handling facilities make this installation one of the most advanced in the United States. This test facility has been in operation for four years and has demonstrated the feasibility and cost effectiveness of computerized testing.
Figure 5
Digital Acquisition System for Production Engine Testing
Figure 6  Operator Console at Middletown, Conn.
<table>
<thead>
<tr>
<th>DPT2-1</th>
<th>TT7-1</th>
<th>TOO</th>
<th>DPT2-2</th>
<th>TT7-2</th>
<th>VIB PU 1</th>
<th>DPT2-3</th>
<th>TT7-3</th>
<th>VIB PU 2</th>
<th>DPT2-4</th>
<th>TT7-4</th>
<th>VIB PU 3</th>
<th>DPT2-5</th>
<th>TT7-5</th>
<th>VIB PU 4</th>
<th>DPT2-6</th>
<th>TT7-6</th>
<th>*VIB PU 5</th>
<th>DPT2-7</th>
<th>PT2.5</th>
<th>TT3B</th>
<th>DPT2-8</th>
<th>TT2.5</th>
<th>TT4B</th>
</tr>
</thead>
<tbody>
<tr>
<td>*PT2-1</td>
<td>*PT7</td>
<td></td>
<td>PT2-2</td>
<td>PS4</td>
<td></td>
<td>PT2-3</td>
<td>PTCA</td>
<td></td>
<td>PT2-4</td>
<td>PFUEL</td>
<td></td>
<td>PT2-5</td>
<td>OIL LEV</td>
<td></td>
<td>PT2-6</td>
<td>MOP</td>
<td></td>
<td>PT2-7</td>
<td>PBTH</td>
<td></td>
<td>PT2-8</td>
<td>TOI</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7a  CRT Data Display
Figure 8 Pressure Transducer Console and the In-Place Calibration Equipment at Middletown, Conn.
Figure 9 Assembly Floor at Middletown, Conn.
Figure 10  Engine Preparation Area at Middletown, Conn.
Figure 11  Engine in Test Cell at Middletown, Conn.
CHAPTER IV

EXAMPLE OF A DIGITAL DATA ACQUISITION SYSTEM FOR ELEVEN
JET ENGINE DEVELOPMENT TEST CELLS

The Florida Research and Development Center (FRDC) has recently completed
a program to expand and modernize its existing jet engine test area.
This modernization program was in support of the Air Force F100 Engine
Development program for the F15 aircraft and for the F401 engine which
powers the Navy F14B aircraft.

The jet engine test area at FRDC consists of 14 sea level test cells,
2 full-scale altitude test cells, 1 compressor test cell, and miscel-
aneous component test cells. The modernization program included:

- Two new test stands
- Rework and upgrading of 13 existing test stands
- New computerized data acquisition system
- Additional test support equipment
- New thrust beds and thrust sensors
- New in-place calibration systems for pressure and thrust
  measurements
- Additional engine handling equipment, including disconnect
  assemblies to allow pre-pepping of the engine instrumentation
  prior to installation in the test stand.

6

The CADRE Corporation, Turbine Engine Compressor Research Facility
(Atlanta, Georgia: The CADRE Corporation, 1972), p. V-13
For the two new sea level test stands, the control room is on ground level and contains operator consoles for both test stands. The second floor contains a pressure scanning system, a high response recording system for strain gage and inlet distortion measurements, and other supporting instrumentation.

A new digital data acquisition and processing system acquires test data from 8 sea level test stands, 2 altitude test stands and 1 compressor test stand. A maximum of 750 measurements from each test stand can be acquired and processed on-line. Table 2 shows the measurement capabilities from each engine test cell.

<table>
<thead>
<tr>
<th>Measurement Type</th>
<th>Quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure - Steady State</td>
<td>240</td>
</tr>
<tr>
<td>Pressure - Transient</td>
<td>80</td>
</tr>
<tr>
<td>Temperature - CA Thermocouples</td>
<td>336</td>
</tr>
<tr>
<td>Temperature - CC Thermocouples</td>
<td>14</td>
</tr>
<tr>
<td>Temperature - PPR Thermocouples</td>
<td>34</td>
</tr>
<tr>
<td>Flow or rpm</td>
<td>10</td>
</tr>
<tr>
<td>Position</td>
<td>16</td>
</tr>
<tr>
<td>Low Level</td>
<td>14</td>
</tr>
<tr>
<td>Calibration</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 12 is a block diagram of the data acquisition system. The significant features are:
Two small general purpose computers are installed in the central computer center and are connected to a Remote Data Acquisition Subsystem (RDAS) for each pair of test stands. One computer services 4 sea level engine test stands and the other computer services 4 sea level engine test stands, 2 altitude engine test stands, and 1 compressor test stand.

Each RDAS contains signal conditioning equipment, a random access multiplexer, and an analog-to-digital converter. Test data is acquired on demand by the test operator and is transmitted via coaxial lines, at 2 million bits per second to the central computers for on-line processing.

Test data is output on line printers in the computer center and is recorded on magnetic tape for further processing.

Engineering units data and the results of selected performance calculations are transmitted back to the test stand and displayed on an alphanumeric CRT for the test personnel, and are output to a teletype for hard copy. Figure 13 is a pictorial layout of data flow.

The Data Acquisition System consists of two digital computers and supporting peripheral equipment. This includes:

- Two CPU units - 32 K core storage, 16 bit word size, 1.6 microseconds cycle time
. Two disk storage devices, 1.5 million word storage each
. Four magnetic tape units
. Two CRT controllers and 13 CRT display units
. Two card reader/punch units, 300 cards minute
. Seven selectric typewriter units
. Five Remote Data Acquisition Systems (RDAS), multiplexer speed of 200 samples/second.

The Data Acquisition System can be operated in three acquisition modes:

. In the MONITOR quick look mode, up to 48 measured parameters and selected performance calculations may be displayed on the CRT. Also in the monitor mode, up to 20 engine health monitoring calculations are available and may be displayed. When the engine health parameters are displayed and the red limit input value is exceeded, the CRT display line will blink. The time required to display data after a request is approximately ten seconds. There is no hard copy of monitor readings.

. In the STEADY-STATE static mode, all assigned channels are scanned 10 times and the 10 scans averaged for each channel to minimize the effects of engine or facility induced fluctuations. The time required for teletype and CRT displays after a request is made is approximately 2 minutes. Up to 96 measured or calculated parameters, in two CRT display groups, may be displayed upon request. Measured parameters and performance calculations may also be printed out on the control room
teletypes.

In the TRANSIENT mode, assigned parameters are recorded continuously and output on magnetic tape and CRT. A maximum of 30, 60, and 90 measured parameters may be assigned to 3 different transient recording modes. The transient mode is typically used for engine test programs such as control system response studies, starting investigations, afterburner ignition, simulated mission cycles, and compressor surge line definition.

Additional features of the test cells which affect the Data Acquisition System philosophy are the techniques used to instrument and mount the test engines. All F100/F401 test engines are instrumented in a preparation area prior to being installed on the test stand. A quick disconnect system is provided for all instrumentation to reduce the in-stand time prior to the actual engine run as shown below.

Test engines are instrumented and all cables, probes, transducers, etc. are electrically checked in a preparation area prior to moving into the test stand. Pressure measurements are connected to a quick disconnect assembly and leak tested. Figure 14 shows the prep line with engines being instrumented for test.

The engine is mounted on a strongback assembly during the actual build. The strongback assembly and engine are designed to fit special trailers which are used to transport the engine from assembly area to the preparation area and to the test stand.
Figure 15 shows a strongback and engine being transported to a test stand.

The instrumented engine and strongback is lifted from the transport trailer and mounted into the thrust frame on the test stand. Hydraulic locking pins hold the strongback in place. Since all electrical instrumentation and the pneumatic tubes have been connected to multiple channel quick disconnects, the actual in-stand mount time is reduced from several shifts to a few hours. Figure 16 shows an F100 engine mounted in a test stand.

An analog recording center is also provided to acquire and record dynamic measurements from eight sea level test stands. These measurements include:

1. High response measurement of speed, flow, pressure, temperature, etc.
2. Dynamic pressure measurements, to 5,000 Hz
3. Continuous monitoring measurements and engine health.
4. Vibration measurements.

Figure 17 shows a portion of the vibration system which provides real-time monitoring, recording, and analysis of engine vibration characteristics.

The modernization program for the jet test area at FRDC was completed
in 1972. During the past year, significant savings have been realized in the test operation due to the computerized Data Acquisition System and the improved methods of instrumenting and mounting the test engine. The cost per test hour has been reduced, the number of men required to test each engine has been reduced by 25%, and the high quality data has shortened the overall development cycle of the jet engines. The long term benefits have proved the effectiveness of the design and the system has become a valuable addition to the test operation.
Figure 12
Digital Data Acquisition System for Development Engine Testing
Figure 13a  F401 Engine in A-9 Test Stand
Figure 13d  Central Computer Room
Figure 15  Strongback and Engine Being Transported to Test Cell
The preceding chapters illustrate how a digital Data Acquisition System can be designed for testing jet aircraft engines. Two main classifications of Data Acquisition Systems have been discussed.

- **Stand-alone Systems.** - This type of system is usually small scale, dedicated to one or two test cells, provides rapid turnaround of test data, and is expensive from a cost per test cell basis. The advantages are data processing speed, transient data gathering capability, and minimum interference from other test cells.

- **Centralized Systems.** - This type of system uses a large, centrally located computer system and remote I/O equipment at the various test cells. The data is acquired on demand only, with several test cells time sharing the computer equipment. The cost per test cell is low, the digital equipment is utilized to a maximum, and maintenance is simplified. The disadvantages are slower data feedback to the test operator and possible interferences from the testing activity on other cells.

The choice between small stand-alone systems and a larger centralized system is dependent upon the location of the cells, the number of test
cells to be serviced, and the testing philosophy in use at the jet engine testing facility.

Two examples of recent Data Acquisition Systems are described in Chapters III and IV. These systems represent several millions of dollars in Company funds and have demonstrated that computerized Data Acquisition Systems can improve the overall test operation and, as an end result, save money and engine development time.

Development programs for modern, high performance, jet engines require rapid, accurate test data in order to be successful. Present day technology can not be supported with antiquated methods of data collection and processing. Many jet engine testing facilities in this country have installed computerized Data Acquisition Systems and many are presently investigating various systems and methods. The trend to larger computers and more computing capacity is clearly defined and should be recommended to increase the efficiency of any large test operation.
LIST OF REFERENCES


