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USE OF AN ON-LINE COMPUTER IN THE TESTING OF PROTOTYPE NUCLEAR ROCKET ENGINES

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Abstract

A process computer has been incorporated in the testing of prototype nuclear rocket engines. The type of testing which led to the need for a computer is reviewed, and the testing philosophy which gave rise to its applications is discussed. The basic computer has a 16-bit word with a 16K word core memory with analog and binary input and output capability, a disc storage unit, magnetic tape input-output and two CRT displays. An executive system is employed to monitor various requests for data and assign computing priorities to assure that data and control functions are generated in the correct sequence. The computer is used to generate the run profiles which control the demanded values of various reactor and facility parameters during testing. Ten profiles are generated simultaneously by approximating the desired curve by a series of small steps which are suitably smoothed to satisfy control requirements.

I. Introduction

Reactor testing at the Nuclear Rocket Development Station, Jackass Flats, Nevada, began in 1959. This testing has been aimed at the development of facility and reactor technology which will eventually lead to a nuclear rocket propulsion engine and stage for flight applications. At the very beginning of the program, basic analog control and instrumentation techniques were used. This was due, in part, to the availability of equipment and also to the nature of testing requirements. It is necessary in reactor testing to bring the engine to power rather more slowly than is the case for a chemical rocket engine in order to stay within safe reactor operating characteristics and to prevent structural damage due to the large thermal stresses which will be encountered in a faster startup mode.

The first tests utilized rather simple facilities, and the tests themselves had, by present standards, easily attainable operating parameters in terms of the ultimate capabilities of the reactor materials. There has, of course, been a steady escalation in the sophistication of test requirements and a commensurate complexity in the facilities needed to perform these tests. In the summer of 1965, an extensive modification was performed to allow higher power and longer duration reactor testing at Test Cell "C", one of the major testing areas at NRDS. Not only was the size of the facility increased with an attendant increase in the number of valves, instrumentation channels, and other components, but many provisions were made in the design for the emergency shutdown of a reactor without damage to the facility or test article. At this point in the program, it became clear that several operational problems were likely to be encountered when the new system was readied for use. The sheer size of the modified facility led to a rethinking of the ability to monitor the facility and

reactor performance with the necessary operations and evaluation of human operators as had been the case in the testing history of the program to this point. Also the time required for the checkout and countdown leading to a major test became a potential problem area. The test program to this point had shown the need for time history displays of key facility and reactor parameters, but available space at the Control Point prohibited the use of separate recorders for each of the variables to be monitored. In addition, the requirements of the accuracy with which the control parameters are programmed and the time synchronization was an area which needed improved techniques. These considerations led, naturally, to an evaluation of the applicability of a computer to solve all or some part of the set of problems posed by the modification.

Once serious consideration is given to the incorporation of a computer in a complex facility, an evaluation must be made as to those uses to which it might most usefully be put. Some of the applications considered were: rapid system checkout in preparation for a major test, the real time display of data, the comparison of real time data with predictions programmed into the computer, and implementation of the Control Point operations by automating all or part of Control Room activity, the generation of profiles which determine the time history by which the reactor and facility are operated, and finally the use of the digital computer in the control functions. An evaluation of these possibilities was dictated by several fundamental considerations. First was the gain to the overall conduct of the test in using the computer in one or more of the above ways. The advantage of a digital computer, when compared with other techniques when performing this same operation, must also be weighed carefully. Cost and the availability of computing equipment to perform the desired tasks also comes into play in the final evaluation. For the operations at Test Cell "C" in which the principal problems are the operation of a large and complex cryogenic facility with many systems requiring simultaneous attention and the evaluation of the reactor under test during real time, it was immediately decided that the most pressing problems were those immediately prior to and during the test. System checkout was determined to be an operation which was both costly to implement by digital techniques and of insufficient advantage to the overall operation to expend funds and effort in this manner. Control Room operations during a major test were felt to be best left in the hands and to the judgement of human operators when the complexity of the logical decisions which are sometimes required during abnormal or unexpected operation is considered. It was also determined that the automation of operations was also a reasonably costly use of digital techniques in a Control Room which basically is geared to the use of analog equipment. The rather enticing idea of using a computer for control purposes was resisted on the grounds that the analog techniques in

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use suffered from no inherent shortcoming and that since control elements and instrumentation were compatible with analog control that no particular test advantage would be gained by using a digital computer in place of the existing analog equipment. The computer then has found its greatest usefulness in the ability to display important test data in real time; to use this data to perform on-line engineering calculations, a form of real time data analysis; the accurate generation of run profiles; and the display of time history information for crucial facility and reactor parameters of interest during the test period. This utilization of the computer then led to the selection of the digital equipment which is described in the next section of this paper.

II. Computer System Hardware

The computer system in use at NRDS has a 16-bit word length with 16K of core memory and a 1.7 μ sec cycle time. In addition, it has multiply/divide hardware, 16 priority interrupt lines, 5 direct multiplex channels (DMC), and a direct data channel (DDC) to permit data transfers to be interlaced with computing. The complete equipment layout is shown in Figure 1. Both CRT's have vector and character generation capability. The disc file has an average access time of 8.5 milliseconds and a word transfer rate of 88 kHz.

Figure 1. DDP-116 EQUIPMENT CONFIGURATION

III. Computer System Operation

The computer system is used to provide "on-line" monitoring of reactor and facility parameters and to generate certain control functions; the latter will be discussed in more detail later in this paper. A typical computer operational flow diagram is shown in Figure 2.

"On-line" monitoring consists of inputting analog and binary data, performing calculations and status checks, and comparing the results with predicted values. If "red-line" values are exceeded, the appropriate alarm lights are turned on indicating that an error has occurred; the parameter itself is also available for display. These parameters are displayed at the various Control Room and Test Monitor Room (TMR) consoles in one or more of the following forms: analog meters, decimal

displays, alarm lights, graphic displays, or alphanumeric data listings. This "on-line" display is used to diagnose problems and to provide the data for making corrections in operating conditions if required while the test is in progress. The graphic and alphanumeric type displays have multiple plot or data list capabilities with a push-button switch matrix provided as the display selection device. All data is recorded on digital magnetic tape for post-run analysis, and certain selected data is also recorded on a rapid access disc file storage unit for "on-line" display upon operator request.

Figure 2. DDP-116 OPERATIONAL FLOW DIAGRAM

All computing is performed at a periodic rate (typically once per second). A computing cycle is started by the inputting of new analog data in the form of counts (12 bit unipolar format). Usually a raw data point is the average (for noise reduction) of eight successive input samples spaced approximately 15 milliseconds apart; however, this mode can be suppressed if a sense switch is set during computer startup.

At the termination of input data transfer, all data is converted to engineering units using linear interpolation, or table lookup if the channel is non-linear. The next phase of the operation is to perform the various data dependent tasks (called Application Programs or AP's) in the appropriate order. This may consist of solving equations, performing status checks, and storing the results in assigned memory locations for outputting as required later in the cycle. When all data generating AP's are complete, output operations are started in a selected sequence to assure the most efficient use of the computer I/O capability. Some displays are determined by operator requests while others are fixed, with the same quantity being output each cycle. A typical computation is the equation following.

$$T_c = T_{ci} / [0.9556 + (2 \times 10^{-5})T_{ci}]$$

$$T_{ci} = [30.59 (P_c + 13) / \dot{w}_r]^2$$

T_c = Computed Reactor Chamber Temperature, °R

P_c = Reactor Chamber Pressure, psig

$\dot{w}_r$ = Reactor Computed Flow Rate, lb/sec

A typical reactor test may have 20 to 30 AP's of the general complexity of the preceding equation (although all may not be calculations), plus associated subroutines and interrupt drivers. Cathode ray tube (CRT) displays are used for the graphic and alphanumeric displays. These CRT displays provide the capability to list all input parameters and computed results, as well as to provide X-Y plots and time history displays. Time history displays fall into three types: (1) past history with operator selectable starting time, (2) automatic updating time history starting at (T-N) where (T) is the current time and (N) is the number of seconds to be displayed, and (3) similar to mode (2) above except the display starts at T_i and continues to $T_i + N$; T_i is the last time (T) that the plot initialize button was depressed. Data for these time histories is obtained from the disc storage unit. Each plot or time history may consist of up to four superimposed curves.

IV. Computer "On-Line" Executive System

When considering the number of AP's to be processed, some type of executive system is required to efficiently coordinate all of the various computer operations. Some desirable properties of an executive system are that it should do the following:

1. Handle many different AP's.
2. Have an AP priority system.
3. Handle interrupt requests.
4. Be flexible and fast.
5. Make use of vendor-supplied software where possible.
6. Require a minimum amount of core storage.
7. Require a minimum of program setup time.

Such a system has been in use at the NRDS facility for some time and is shown in Figure 3 in a block diagram form. All operational tasks are performed by AP's; as an example, in the preceding equation CRT time history displays, BCD decimal display driver, and the generation of run profiles are all separate AP's. The system has a section that initializes AP's, interrupt drivers (ID's), and subroutines during program startup. It then proceeds into a priority scan loop that executes in priority order only those AP's that are "turned on." An AP may be turned on by another AP or an ID. ID's are processed by EXEC, and control is returned to EXEC or to the AP that was currently in progress. Disc data transfers are handled by a set of disc control subroutines that establish disc transfer priorities which may be different than the requestor's own EXEC priority. AP's may request data from the disc or store data on it; when a disc data transfer is complete, the AP in question will be turned on if desired.

Figure 3. EXECUTIVE SYSTEM FLOW CHART

Parallel time code and serial pulse rates are obtained from an external time code generator which determines the basic computation cycle and provides the timing for selecting and time correlating data. If these inputs should fail, the necessary time information is automatically generated and inserted under software control by the real time clock interrupt driver.

This executive system can handle a large and variable number of AP's with a minimum of setup time required, as all AP linkages and priority tables are set up by the loader during the actual loading process. Since magnetic tape loading is employed, a complete "run program" can be loaded and running in approximately five minutes; this includes time required to change tapes.

V. Profile Generation

During test operations, the demands to a number of closed loop control systems must be varied with time so as to follow predetermined profiles. Until recently, these profiles were generated by an electromechanical curve following device. A servo driven pickup probe is continuously positioned above a plotted curve attached to the surface of a rotating drum. Three drums are coupled together by cable or chain and sprocket drive, and two such units of three drums are driven by the same time base generator. The pickup probe is coupled mechanically to a follow-up potentiometer wiper. The potentiometer is excited with a dc voltage, and the magnitude of the voltage on the wiper then follows the desired curve. There are a number of undesirable aspects of this method, among which are the following:

1. Mechanical rotational misalignment between drums, which results in loss of time synchronization between profiles.
2. Backlash effects.
3. Difficulty in accurately setting the time base length.
4. Limitation to the generation of only six distinct profiles simultaneously.
5. Lack of good repeatability.

The use of the DDP-116 to generate profiles eliminated these objectionable features. There are currently 9 distinct profiles generated. The required curves are approximated by a series of straight line segments, a different number of which can be used for each profile. The number of profiles and the total number of breakpoints are limited only by the amount of core storage available. A typical profile

is shown in Figure 4. The breakpoints $(0, Y_0)$, (X_1, Y_1) , (X_2, Y_2) , etc. are stored by the computer. A special subroutine, when entered with any value of X , say X' , performs a linear interpolation between breakpoints and obtains Y' .

Figure 4. SAMPLE PROFILE

The generation of the required profiles is done by an Application Program (named PROF), which is executed at the beginning of each second. The first step is the determination by the program of the mode being requested. The possible modes, controlled by switches at Control Room operators' consoles are: Hold, Run, Retreat, Program Shutdown, and Reset. Action is then taken by PROF appropriate to the mode selected.

A memory location is used as a counter in conjunction with an accurate clock pulse to keep track at all times of the location along the time base. If the Run mode has been selected, the counter contents are first checked to see whether the end of the time base has been reached. If so, the mode is automatically switched to Hold. If not, the counter is incremented by one, and the interpolation to obtain new profile values for all channels is performed. These new points are then sequentially generated (within a few microseconds of each other). The contents of the counter are then rechecked to see whether the end of the time base has now been reached. If so, the mode switches to Hold. If not, the executive routine causes an exit from PROF and an entry to the next highest priority Application Program.

If Retreat has been selected, PROF will check the time base counter to see whether the beginning of the time base has been reached ($X = 0$). If so, it switches to Hold. Otherwise, it decrements the counter by one. The profile points are obtained and generated the same as for the Run mode. The counter is rechecked to see whether the beginning of the time base has been reached, and execution of the next program is begun as before.

In the Hold mode, the counter is not changed, and so the same points are generated each second. The Reset mode is similar except that the counter is set to zero so that the initial points of each profile are generated during each cycle.

The Program Shutdown mode is similar to the Run mode. It is desired to be able to depart from

the normal profiles at any time during a run and to cause selected programmed variables to decrease linearly to a predetermined "shutdown level." This level could be held for extended periods while facility malfunctions were corrected and/or an emergency shutdown can be initiated from this point.

Upon recognition by PROF that this mode has been selected, a new set of profiles is generated and stored. They start at the current level of each variable and end at the "shutdown level" and are linear in between. The slopes are computed so that all variables arrive at their shutdown levels simultaneously. These profiles are then used by PROF as though the Run mode had been selected. The Reset mode restores the original profiles at the conclusion of the shutdown.

Provision has been made for several preselected but variable points along the time base at which an automatic switch to the Hold mode occurs and for several other points at which a relay contact closure occurs (binary outputs).

The hardware configuration for a single profile channel is shown in Figure 5. The D/A converter output is buffered by an operational amplifier circuit which also smooths the output steps. The Power Supply Monitor consists of circuitry which normally energizes the relay at the amplifier summing junction (it is shown de-energized). If the output of any one of the DDP-116 power supplies deviates by more than 10% from its nominal value, the Monitor de-energizes the relay and converts the amplifier to an integrator with zero input, thus holding its output constant. Control Room operators can then take appropriate manual action. This feature will prevent serious damage to the systems being controlled by the profiles in the case of a computer malfunction which is caused by power supply failure.

Figure 5. HARDWARE CONFIGURATION - SINGLE PROFILE CHANNEL

In order to facilitate the inspection of profile data in the computer memory and to make data changes methodical and rapid, PROF contains a section which allows the following to be done: Whenever it is desired to manipulate the profile data points, a sense switch on the computer console is set. The Executive routine stops cycling. The profile channel number (0 through 9) is typed in on the ASR-33. The first value of X (the breakpoint) and the corresponding value for Y are typed out by the computer. For example, in Figure 4, 0 and Y_0 would be typed. One can then change X by merely

typing in the new value desired, and it will be entered automatically in the table in memory. The value of Y can then be changed, if desired, in the same way. The computer then types the next breakpoint X_1 , Y_1 and so on until all have been typed out and changed or not as desired. A complete inspection of the contents of a 40-breakpoint table can be done in 3 or 4 minutes. A permanent record of the table values is obtained in the form of ASR-33 hard copy. Control is then returned to the Executive routine by resetting the sense switch and typing a special character.

VI. Summary

The computer system described here has proven to be a valuable tool in the management of a large scale facility during test operations. The Test Director and his assistants are presented with data in the form best suited to their use which allows them to devote their attention to the more important overall aspects of the testing. In addition, the software system is flexible enough so that rapid changes can be made whenever required based on operating experience.