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COMPUTER-CONTROLLED REFUELING MACHINE AT FORT ST. VRAIN

by

C. W. Smith and F. Mathie

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MASTER

GULF ELECTRONIC SYSTEMS
A DIVISION OF GULF ENERGY & ENVIRONMENTAL SYSTEMS COMPANY
P.O. BOX 81608, SAN DIEGO, CALIFORNIA 92138

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*Public Service Company of Colorado, Platteville, Colorado

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ABSTRACT

This paper describes a computer-controlled fuel handling machine used to refuel a nuclear power generating station. The refueling process and the basic concepts of the electronic system controlling the process are explained. A comparison is made between manual control and automatic control, using data from actual operation.

COMPUTER-CONTROLLED REFUELING MACHINE AT FORT ST. VRAIN
Charles W. Smith, Gulf Energy & Environmental Systems
San Diego, California
Frank Mathie, Public Service Company of Colorado
Denver, Colorado

Summary

The refueling system for the Fort St. Vrain Nuclear Generating Station uses a small digital computer for automatic control to handle approximately 3000 fuel and reflector blocks which constitute the reactor core. The computer has complete control of the handling mechanism, which has four freedoms of motion, and also logs information concerning all fuel movements for inventory purposes. Since safety is a prime consideration in equipment associated with a nuclear power plant, a combination of hardware and software protection monitors provides for fail-safe operation. Operating experience has proved that automatic control of the fuel handling process is approximately five times faster than manual operation with the same machine. In addition, operator errors are eliminated and an accurate log of all fuel movements is recorded.

Introduction

Public Service Company of Colorado's Fort St. Vrain Nuclear Generating Station located outside Denver, Colorado, employs a high-temperature gas-cooled reactor (HTGR) as its nuclear steam supply. This reactor has some unusual requirements for refueling which have led to a refueling control system that is primarily computer-controlled. This type of control system was selected to reduce refueling time, to minimize the possibility of operator error, and to provide accurate logs of fuel movement. A number of types of automatic control were considered including numeric control by paper tape. However, a digital computer system was selected because of the power and flexibility of its stored software program.

Refueling Process

The reactor core of the 330-MW(e) HTGR contains about 3000 removable reflector and fuel blocks located inside a prestressed concrete pressure vessel (PCRV), shown in Fig. 1. The heat transfer medium is helium gas, which circulates vertically through the core area.

Ten to twelve blocks are arranged in vertical stacks about 20 ft high. This is referred to as a "column." Access to these blocks for refueling is gained by removing a control rod drive at the top of the pressure vessel and entering the top head penetration. Each penetration allows access to seven to ten columns of blocks. The group of columns associated with a penetration is called a "region."

A typical fuel block is shown in Fig. 2. It is hexagonal in cross section and about 14 in. across flats. The length varies from 15 to 30 in., and the weight varies from 150 to 350 lb.

Each year part (one-sixth) of the fuel blocks in the reactor are exchanged with new fuel. Because of the high radiation levels and temperatures inside the core during normal operation, the reactor is taken off-line and allowed to cool to 165°F inlet gas temperature.

New fuel is temporarily stored in storage wells beside the reactor. (See Fig. 3 for a plan view of the refueling floor.) The process of refueling consists of taking old fuel from the core and placing it in empty storage wells and then taking new fuel from storage wells and placing it in the vacant area of the core.

The fuel blocks fit closely together and require a positioning precision of 0.050 in. to locate them properly in the reactor. One of the difficulties in refueling is that the location of the fuel blocks is known only within a few inches at the time they are to be removed from the core. This uncertainty is due to a combination of pressure vessel construction tolerances and shrinkage of the fuel blocks and reactor structure with age.

Fuel Handling Machine

In order to accomplish the transfer of fuel, a large fuel handling machine is used (see Fig. 4) consisting of three major parts: a heavy lead-shielded container or cask as the outside structure, a water-cooled rack inside the cask for temporary storage of fuel blocks, and a handling mechanism to transfer the fuel elements from one place to another. Also, there is a large gate valve on the bottom to seal the machine while it is being moved.

The total machine is about 45 ft high and weighs 160 tons. It is moved between the reactor and the storage wells by an overhead crane. The storage capacity of the machine is such that it can hold from one-third to one-half of the blocks in a region, depending on the region size.

The heart of the machine is the handling mechanism. There are four controlled freedoms of motion and numerous transducers associated with the mechanism.

Vertical travel is provided by telescoping tubes held by two chains. The chains run across sprockets shown in Fig. 4. Two hydraulic pump-motor units control the sprockets. The total vertical travel is about 62 ft, and the position resolution is 0.1 in. A maximum speed of 2 ft/sec can be obtained. Position feedback is provided by both digital and analog transducers.

At the end of the lower tube, a pivoting radius arm can be extended by a ball-nut screw actuator driven by two dc torque motors. The total arm reach is 30 in. The entire lower tube assembly with the radius arm can be rotated up to 350 deg by two additional dc torque motors. These drives provide radial and azimuth positioning with dual-speed synchros for position feedback.

A TV camera is located on the radius arm to allow observation of the machine operation and to investigate unusual conditions.

On the end of the radius arm is a device called a "grappling head" (see Fig. 5). The fourth controlled motion of the machine is a rotation of the lower portion of the grappling head to "twist" the fuel blocks for proper engagement in certain operations. This positioning is accomplished by a pneumatic actuator utilizing pressured helium gas. Position feedback is provided by a linear transducer.

A fuel block is picked up by inserting the grappling head tapered probe into a hole in the block and then opening an inverted collet by releasing a pneumatic actuator to grasp under a ledge in the hole. The lower portion of the grapple head can translate on any of three axes if a force is applied to it. Linear transducers measure these translations, and the information

is used to correct head position. Also, there is a load cell to weigh the fuel block when it is being held. This is used to check for broken or incorrect blocks.

Control System

The control system has three basic modes of operation. The primary mode is automatic, in which the computer has full command of the machine and does fuel handling without operator intervention (except to start the process). The second mode of operation is manual, which is used as a backup in case of failure of the automatic system or where special unpredictable tasks are performed. The third mode of operation is semiautomatic, in which the machine may be operated manually within specified limits while the computer tracks the operation. Automatic operation can be continued when requested. This mode is used primarily when the computer fails to locate or place a block correctly or when the computer detects an incorrect parameter on the fuel block being handled.

The control console is shown in Fig. 6. The left center section is the manual control panel, which provides individual handwheel control for all four motions and both analog and digital display of position indications. The system is designed so that the computer can be physically removed from the system while manual operation may be continued.

A prime consideration in this control system is to maintain a fail-safe condition at all times and to prevent inadvertent operator error. To accomplish this, extensive hardware interlocks and failure detection devices are used. This safety system is functional in all modes of operation. An annunciator is provided with 50 status and alarm messages so that the operator will immediately be warned of a problem if it occurs and will be guided in corrective action to be taken.

The primary mode of operation for the refueling machine is automatic, in which a digital computer provides full control of all machine functions. The automatic control system is designed in such a way that the computer software can control all machine functions but requires sequence and coordinate data input prior to initiating a cycle of fuel block handling. The external data are stored on punched paper tapes and read into the computer by a high-speed paper tape reader during the refueling operation. These paper tapes are called "data tapes," of which there is a set (usually two spools) for each type of region to be refueled. This organization of control software and data allows the system to operate with minimum core memory. It also allows major changes to be made in the refueling process or sequence without reassembling the computer software system.

A block diagram of the automatic control system hardware is shown in Fig. 7. The system is built around a Digital Equipment Corporation PDP-8/S digital computer with 4096 words of core memory. Standard peripherals include an ASR-33 teleprinter, a high-speed paper tape reader, and a high-speed paper tape punch. There are a number of specialized control panels that provide communication between the computer and the operator. These include the master control panel, which selects the mode of operation, the tape control panel, which provides for the proper positioning and searching of data tapes; and the automatic control panel, used to start and stop the automatic operation as well as to indicate the phase of operation being performed.

Computer control of the four refueling machine positioning drives is done primarily by supervisory

control. Digital position feedback is read into the computer, and commanded digital position is read out of the computer. Also, velocity control is provided by the computer while the drives are moving. In the vertical drive system, a position error signal is generated by digitally subtracting the commanded position from the position feedback of shaft encoders. The digital error signal is then converted to an analog signal which drives the motors. The radius arm extension and azimuth drive systems are controlled by conventional dual-speed synchros. A digital-to-synchro converter is utilized for computer control. Shaft encoders cannot be used in these drives because of the extreme environment in which they would have to be located. The remaining drive system is the grapple head rotation, which is controlled by a voltage-to-pneumatic-pressure converter. The computer command is provided through a digital-to-analog converter, and position feedback is from an analog transducer whose signal is converted to digital form prior to being fed into the computer.

The computer uses relay contact outputs for control of the grapple, the cask isolation valve, and the photographic camera located in the machine. Also, numerous contact inputs provide machine status to the computer.

The computer software is built in modular form to allow flexibility and maintainability. It is all special-purpose code to provide maximum computer power in the limited core memory available. Figure 8 is a simplified block diagram of the software modules. The program resident in the computer has modules for operating all aspects for the refueling machine and the computer peripherals. The sequence of events and the fuel movement data are provided from data tapes. The main control module reads the data tape, checks for errors, and then executes the sequence of events indicated by transferring control to the other program modules which return control when they are finished. The operator programs allow starting and stopping the automatic refueling process. The fuel-block-handling modules provide for control of the mechanical drives during various operations. The fuel-block-transfer module is used to make major movements, while the pickup and deposit routines, as their names indicate, are used for final location of the fuel blocks. The auxiliary programs log the data from each cycle of fuel handled, calculate compensated fuel coordinates, and monitor the semiautomatic operation.

The fuel block coordinate information on the data tapes is composed of nominal values. As mentioned previously, the actual coordinates may deviate significantly from these values. When attempting to locate the first fuel block on a region of the reactor core, the software uses the nominal coordinate values to start a probing search for the fuel block. It will probe in precalculated areas around the nominal coordinate until the tapered probe starts to slide into the chamfered hole in the fuel block. Using the grapple head translation sensors, the program will track the mechanism to the exact fuel block location. The computer stores the coordinate deviations to be used to compensate all succeeding fuel block coordinates, eliminating the need for further probing searches in that region.

Whenever a fuel block is handled, it is checked for proper weight, proper height, and a proper pattern of dowel pins on top of the element. The dowel pins are coded to identify the type of fuel block and to indicate its rotational orientation. If any of these parameters is not correct, an alarm is sounded and the operator must intervene.

Each time a fuel block is moved from one location to another, a record is made of the operation on paper tape and a printer. An example of the printed log is shown in Fig. 9. The exact coordinates where the block was found and where it was placed are recorded, as well as the element weight and whether or not a picture was taken of it. These data, in conjunction with the listing of the data tape used, provide a complete inventory of fuel as it is cycled through the plant.

Since the data tapes contain the refueling sequence information, it is necessary to be able to produce them accurately, and to modify them easily if refueling requirements change. This is accomplished by a special-purpose Fortran program that runs on a large scientific computer such as the Univac 1108. The program takes as input basic to-from information, checks it for validity, and then punches a paper tape. The data tape format is shown in Fig. 10. All data are punched twice on the tape with the second time being the ones complement of the first. The fuel-handling control computer reads both sets of data and compares them to ensure that no errors have occurred either in punching or reading of the data tape.

Operating Experience

The refueling system at Fort St. Vrain has been used extensively during preliminary plant operational tests, to demonstrate its ability to refuel the reactor. Actual measurement of time required to move fuel in manual mode and automatic mode indicates that automatic control is approximately five times faster than manual control. Also, operator fatigue is greatly reduced, which means that fewer operators are required during the refueling period.

During construction and checkout of the Fort St. Vrain plant a number of minor changes were required to tailor the refueling control system to the plant. These have been made easily and with no significant effect on schedules. The primary reason for this is the ability to assemble a new control computer program on a large scientific computer using a cross assembler, and to produce new data tapes in the same manner.

The experience at Fort St. Vrain has shown some aspects of the refueling control system which might be improved. The punched paper data tapes are somewhat voluminous, usually requiring two reels for each type of fuel region, and larger computer centers are not normally equipped to punch large quantities of paper tape. This would indicate that some form of magnetic tape might be better suited for data input to the refueling system. Another area which warrants consideration in future system designs is the amount of diagnostic information provided when an error or failure is detected. Even though a large amount of such information is provided to the operator, there is always the need for more indications of the nature of an error or failure.

Conclusion

The automatic refueling system at Fort St. Vrain represents a significant step forward in the control of nuclear power plant refueling operations. The nature of the reactor core and the high cost of time lost in refueling indicated the need for such a system. This system has proved that small digital computers can reliably and effectively control a complex mechanism with high-speed-of-response servo drives. With the advancements presently being made in small computers and their peripheral equipment, it is logical to expect a continued trend toward the use of more computers in similar applications.

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K-52064

EL-0728

Fig. 1. PCRV cutaway

K-68912

EL-0729

Fig. 2. HTGR fuel block

LC-71618

EL-0730

Fig. 3. Refueling floor plan view

LC-71733

EL-0731

Fig. 4. Refueling machine cutaway

K-72377

EL-0732

Fig. 5. Grapple head

HT-85589-A

EL-0733

Fig. 6. Control console

Fig. 7. Hardware block diagram

EL-0735

Fig. 8. Software block diagram

P

16-01 BEGIN TRIP 1

OP	PICKUP POSITION			WEIGHT		DEPOSIT POSITION		
	Z(IN)	R(RNT)	T(DEG)	(LB)		Z(IN)	R(RNT)	T(DEG)
101	524.2	+17.13	-180.0	122	N	171.6	+26.01	-110.7
102	524.2	+17.10	-120.0	118	N	156.0	+26.01	-110.7
103	524.2	+17.13	-060.0	120	N	140.4	+26.01	-110.7
104	524.2	+16.98	+000.0	115	N	124.8	+26.01	-110.7
105	524.2	+16.98	+060.0	117	N	109.2	+26.01	-110.7
106	524.2	+16.98	+120.0	121	N	093.6	+26.01	-110.7
107	531.6	+37.17	-030.0	138	N	078.0	+26.01	-110.7
108	531.4	+37.11	+030.0	144	N	062.4	+26.01	-110.7
109	537.4	+47.85	+000.0	136	N	046.8	+26.01	-110.7
110	530.8	+00.00	+000.0	134	N	171.4	+25.56	-057.8
111	539.8	+17.13	-180.0	328	N	156.0	+25.89	-006.0
112	539.8	+17.10	-120.0	326	N	156.2	+26.61	+044.6
113	539.8	+17.13	-060.0	330	N	156.2	+26.10	+095.7
114	539.8	+16.98	+000.0	325	N	156.0	+25.74	+146.8
115	539.8	+16.98	+060.0	329	N	156.0	+25.77	-162.0
116	539.8	+16.98	+120.0	330	N	140.2	+25.56	-057.8
117	547.2	+37.17	-030.0	164	N	140.4	+25.89	-006.0
118	562.8	+37.17	-030.0	163	N	124.8	+25.89	-006.0
119	547.0	+37.11	+030.0	171	N	140.6	+26.61	+044.6
120	562.8	+37.11	+030.0	167	N	125.2	+26.61	+044.6
121	553.0	+47.85	+000.0	332	N	125.4	+26.10	+095.7
122	STOP END OF OPERATION							

EL-0736

Fig. 9. Log data

CYCLE NO.
Z DRIVE
Θ DRIVE
R DRIVE
PICK UP
R DRIVE
Θ DRIVE
Z DRIVE
ROTATION
Θ DRIVE
R DRIVE
Z DRIVE
DEPOSIT
Z DRIVE
R DRIVE
Θ DRIVE
PRINT
CHECK STOP
XQT

CYCLE NO
Z DRIVE
Θ DRIVE
R DRIVE

Θ DRIVE
PRINT
HALT
XQT

TYPICAL REACTOR CORE-
UNLOAD OPERATION

NOTE:

MOST COMMANDS WILL BE
FOLLOWED BY DATA.

Fig. 10. Data tape format